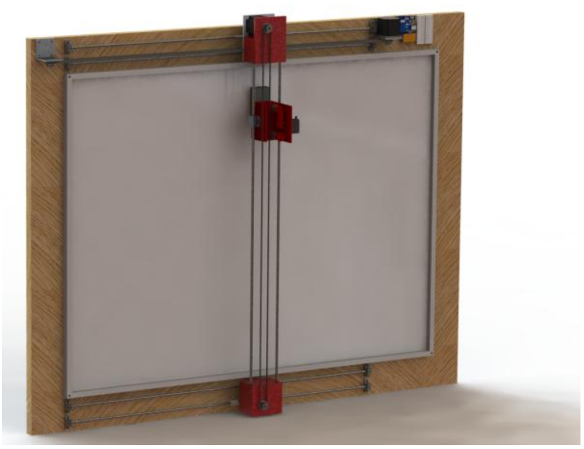
Writing/Erasing Bot (W.E.B)



MAE162E Final Project Report

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Abstract

Educators across the globe erase their whiteboards manually. This system is inefficient. When the teacher runs out of writing room, they must pause in the middle of a crucial talking point to perform the mundane task of erasing the board. Several minutes are wasted during each lecture to erase a board. If this task were automated, more time could be spent learning. At the moment, there are designs in the market that address this issue. However, current designs are expensive. For example vendors like Alibaba sell automatic chalkboard erasers at a price of no less than $3,000. In addition, these machines are lacking in erasing speed and ability. One of the biggest deficiencies is that current designs are non-selective for erasing purposes; they are limited to a single horizontal sweeping motion that erases everything in its path.

The proposed design is called the writing/erasing bot (W.E.B.) and it eliminates manual whiteboard erasing and writing. The basic systems consists of an eraser carriage equipped to move in and out of contact with the whiteboard from user input, an XY movement pulley system, and a user interface to selectively erase the whiteboard. The estimated cost for this design is less than $300. Based on price and application, this project is a feasible alternative to commercial equivalents on the market. For this quarter, the current design is a prototype for a small scale whiteboard. If the first trial proves successful, modifications will be made to the design to increase adaptability and ease of use of the design.

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1 Project Scope

1.1 Problem Statement

In the 21st century, technology has been developed enormously. One of the technological industries that showed the most growth is the robotic industry. In fact, to save human labor costs, many things in our lives have become autonomous such as robotic floor cleaner, unmanned drones, and smart manufacturing system in factories. There are even robotic doctors. Although, many things around us are becoming autonomous or robotic there are things that have not changed much throughout the century. An example of this is a whiteboard and a marker which are mostly used in a classroom. Instructors always had to grasp the marker and manually write and erase on the whiteboard. Because teachers always have to lift their arms and stay in a fixed position, many of them develop frozen shoulder through their time teaching. One solution to this would be to automate some of tasks that teacher typically perform while using a whiteboard. To prevent frozen shoulder, there is a need for inventing a robotic whiteboard writer and eraser that allows us to write and erase things on the whiteboard without using hands.

1.2 Client Identification and Recognition of Need

Our ideal client would be any consumer that purchases a chalkboard or whiteboard. While chalkboard/whiteboard manufacturers could also be potential clients, part of the design requirements included easy attachment to existing boards. Thus with our current specifications, they would not be ideal candidates. Whiteboards and chalkboards are extremely common in both school classrooms and business spaces. Thus, our focus for clients are centered around the teachers and business professionals most likely to be using the device on a daily basis.

According to the National Center for Education Statistics, there are roughly 5 million full time teachers and professors in the United States.[4][5] This number accounts for public and private, elementary and secondary schools, as well as colleges and universities in the United States. In addition to this large client base, who could potentially use our product every day, the U.S. Census Bureau's Statistics of U.S. Businesses states there are also over 7.5 million registered business with establishments in the United States.[6] We assume each business has at least one whiteboard to make announcements and collaborate ideas with. This brings our ideal candidate size to roughly 12.5 million teachers and business owners that could be saving time when they need to erase their whiteboard.

Our high level design requirements for this project are driven by affordability, thus all possible parts are 3D printed, with the majority of spending going toward the motors, so we may generate appropriate torque to drive the system, and high quality bearings to assure proper sliding. The parts are hollowed out to cut down on print time and make the project lighter. Additionally, most wires are run along the back of the whiteboard to allow for and aesthetically pleasing experience, so users do not see all of the wires running along the whiteboard. The size of the product is limited to a maximum of 1 meter by 1 meter, since that is the largest one can purchase before buying custom rods. This also contributes to the overall price of the project and keeps it quite low.

Low level design for this project includes only the necessary parts required. For example, we only have one rod on the top and bottom of our project, since they are capable of bearing the entire weight of the project. While our initial design had 2 rods along both the top and bottom, the drive for price and sleek aesthetic left the other bars redundant. We used Nema 23 motors instead of Nema 17 motors so we could generate the proper torque. Our timing belt and pulleys were limited to the ones that would fit around the Nema 23 motor, since most timing belts and pulleys were designed to fit the Nema 17 motors. With the goal of keeping the project as affordable as possible, we also 3D printed most of our parts instead of manufacturing each part in order to save both time and make the process cheaper.

1.3 Project Goals and Objectives

The goal of this project is to invent the robotic whiteboard writer and eraser that can write what users want and erase specific regions on the whiteboard from remote user input.

Project Objectives

- Erasing component will allow user to select which parts of the board to erase
- Erasing component will completely erase the selected area
- Design will contain a carriage design to allow for accurate writing capabilities
- Writing component will allow user to write time on the board
- Interface will be wireless from the carriage system (i.e. Wifi)

Team Objectives

- Achieve the goal of the project without reducing specifications and expectations.
- Finish the project on time while following project timeline.
- Stay on budget ($700 maximum).
- Organize all documents to trace the entire project development.

Individual Objectives

- Grow responsibility as a team member.
- Develop interpersonal and communication skills
- Learn about CAD, machining, assembly, electronics, and coding.

2 Project Planning and Task Definition

2.1 Task Identification

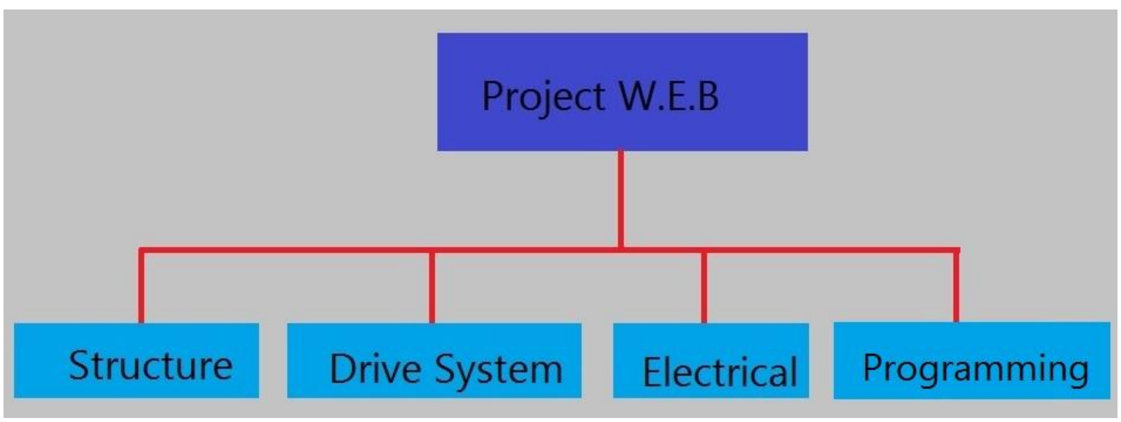

Figure 1: Main tasks that need to be completed in order for this project to be finished

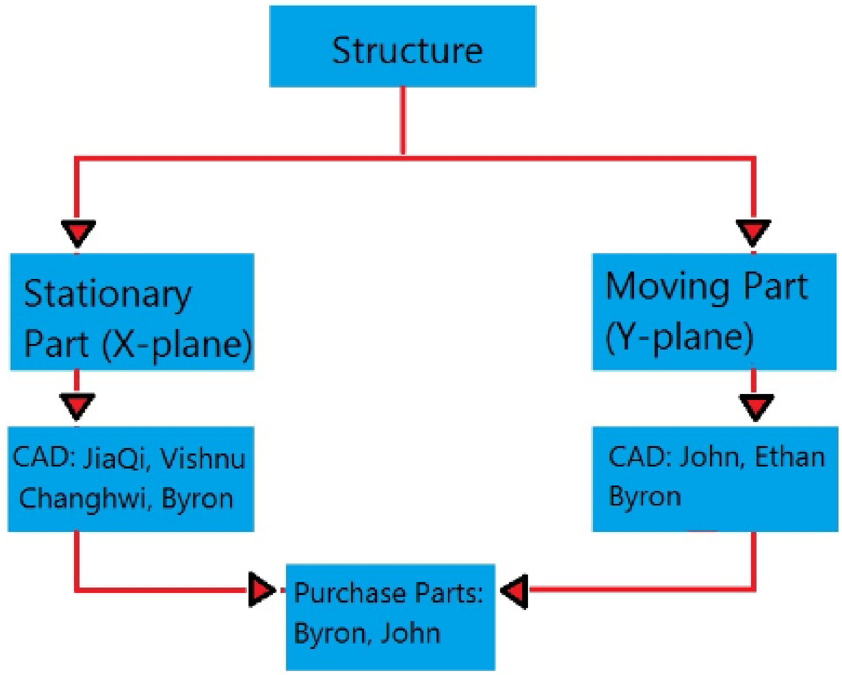

Figure 2: Subtasks for the structures section.

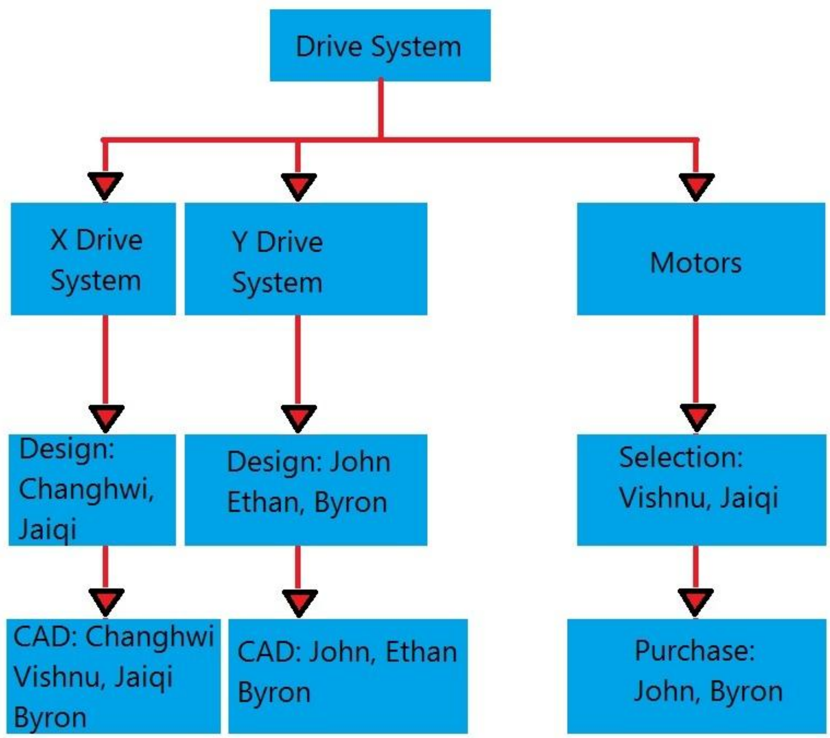

Figure 3: Subtasks for the drive system

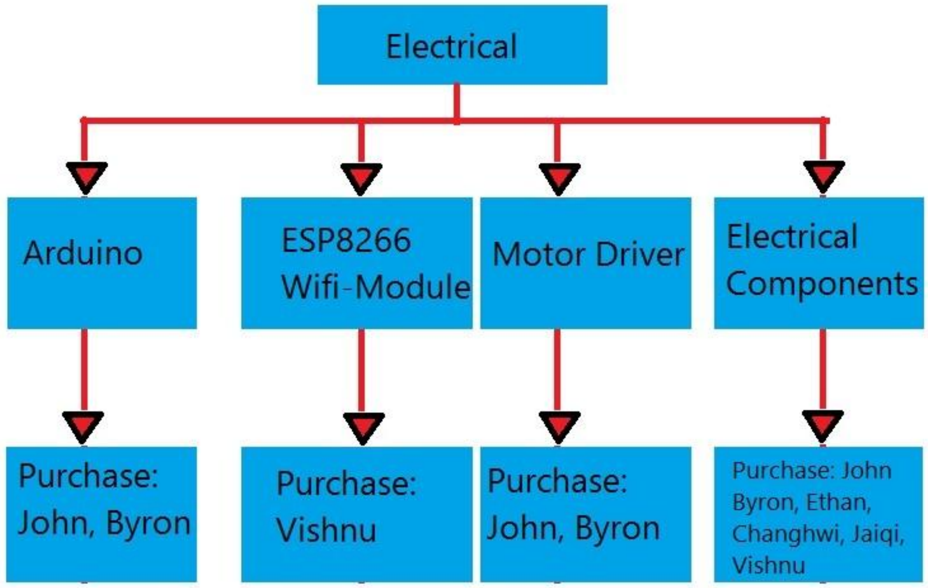

Figure 4: Subtasks that are required for the electrical section

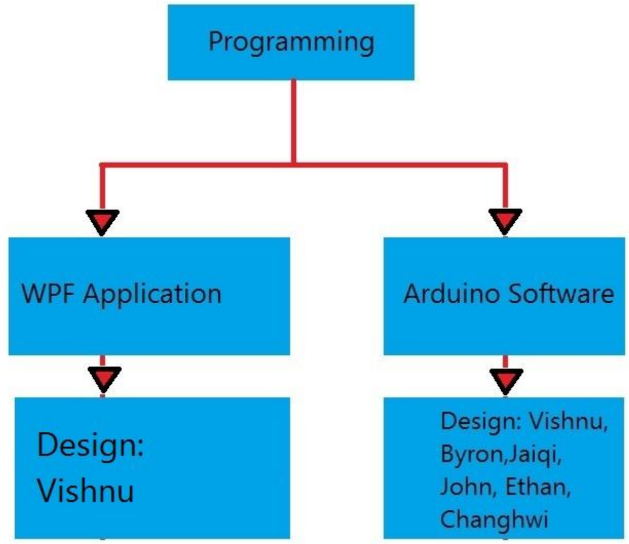

Figure 5: Subtasks required for the programming section

2.3 Gantt Chart

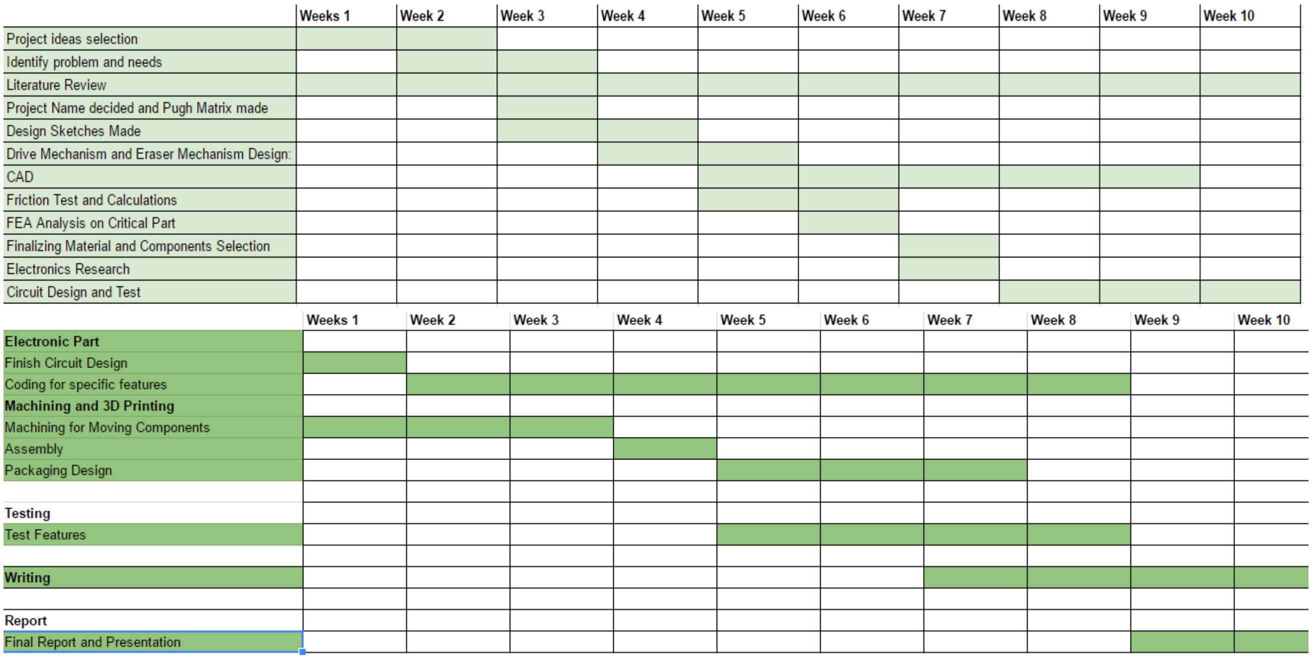

Figure 6: Gantt Chart for the Spring and Winter quarter

3 Literature Review

3.1 Methods of Erasing

Vibrations

One of the method originally discussed to accomplish the goals of this project was to use vibrations to disturb the chalk that is attached to the board. The primary forces acting on the chalk that keeps it attached to a black board is static friction. Therefore, if we overcome this static friction, the chalk should fall off the board on its own. One of the methods proposed to overcome this static friction was using vibrations.

The idea was to use acoustics to drive the chalk on the board at resonant frequency. The resonant frequency is defined as the frequency at which the a system exhibits maximum displacements when subjected to a periodic driving force.There were some problems associated with implementing this method that made it unfeasible for us to pursue. For the most part, it was theoretical “idea” and there was very little to no research that we can use as a reference if we chose to design our device using this method. As a result, we decided to scrap the idea because of our lack of confidence in the method.

Car Wash Method

One of the options to erase would be to apply the concept of cars washes. Overall design is a moving cartridge that is square shaped with two hinged covers so that the rollers may be replaced. Inside the cartridge, we have a sprayer and two rollers installed. Also, there is a tank in front to store some chemical liquid. The erasing works by first spraying some chemical liquid that helps in decomposing ink on the whiteboard then the two rotating rollers erase the ink as the moving cartridge moves.

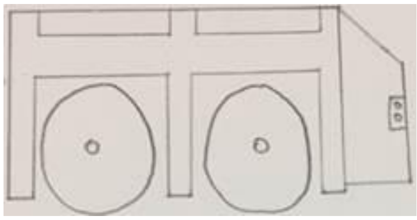

Figure 7: Moving cartridge

Chemical Reaction

Another method of removing chalk is using chemical reactions. Since the main chemical composition is $CaCO_3$, we can use vinegar to dissolve $CaCO_3$ easily. The chemical reaction is shown as follow:

$$CaCO_3(s)+2CH_3COOH(aq)==Ca(CH_3COO)_2(aq)+CO_2(g)+H_2O(l)$$

The idea was abandoned because it will introduce extra storage system for the chemical cleaner, and the chemical cleaner needs to be refill after certain time, which is not convenient. Also, it will add more complicity to our design because we need to consider how to collect the waste, or even recycle it. Another concern is that the chemical cleaner may damage the chalkboard.

Electromagnetic Dissipation

The thought is based on the idea of electromagnetic dissipation used in industry. We are thinking to first blow the chalk dust to a two parallel plate with negative charges so that the dust will be polarized then using a band of positive charged plate to attract the dusts.

But after doing some research, we found out this process is operated at high voltage, which is not a good for our design. Furthermore, blow process involves a fan which increase the noise when the device is operating. So we abandoned this idea.

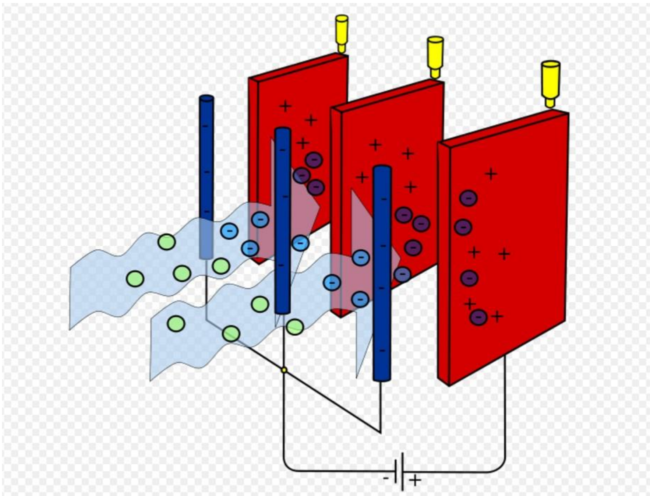

Figure 8: Electromagnetic Dissipation [13]

Heat Treatment

The thought process behind the heat treatment option was to either raise or lower the temperature of chalk (specifically calcium carbonate), to a temperature where the chalk would no longer "stick" to the chalkboard. This is due to the fact that increasing the temperature increased the free volume between molecules for various substances. By examining the change in the coefficient of friction between 89.5^{o}C and 29.6^{o}C for two experiments, the static coefficient friction mean fell from 0.429 to 0.314.[8] This would not be sufficient to be an effective means of treatment to clean the chalkboard. However, there are other studies in which they paired a canister of carbon dioxide to blow the particles in conjunction with cooling it first. However, this was deemed as an expensive alternative with a cleanliness tradeoff that was not worthwhile enough to pursue. Thus, this idea was abandoned and other methods were pursued further.

3.2 Electronics

Pulse Width Modulation

In essence, devices such as LED and motors are supplied electrical power by means of pulse width modulation. It is a digital signal square wave with constant frequency. However, the time that the signal is on can be varied between 0 and 100%(duty cycle). By controlling the width of the pulse signal(time the signal is one), one can control the effective voltage level to a device. The advantage of this is that by controlling the duty cycle of the signal one could effectively "control" a device.

For instance, if the brake on a car works by applying pressure to the wheel, one could control the amount of pressure on the wheel by means of pulse width modulation. This would work by encoding the duty cycle required for a selected brake pressure. Then, pass the duty cycle to the brake circuitry. Another simpler example is the LED bulb. By changing the duty cycle of the signal to the bulb, one could control the dimness of the bulb. The duty cycle of a pulse is defined as:

$$Duty\ Cycle = \frac{T_{on}}{T_{on} + T_{off}}$$

Because of the relative easy at which the pulse width modulation method allows for the control of analog input devices, it is usually implemented by microcontrollers like arduino.

NEMA 23 Motor

The following section is a compilation of the specifications researched for the NEMA 23 motor.

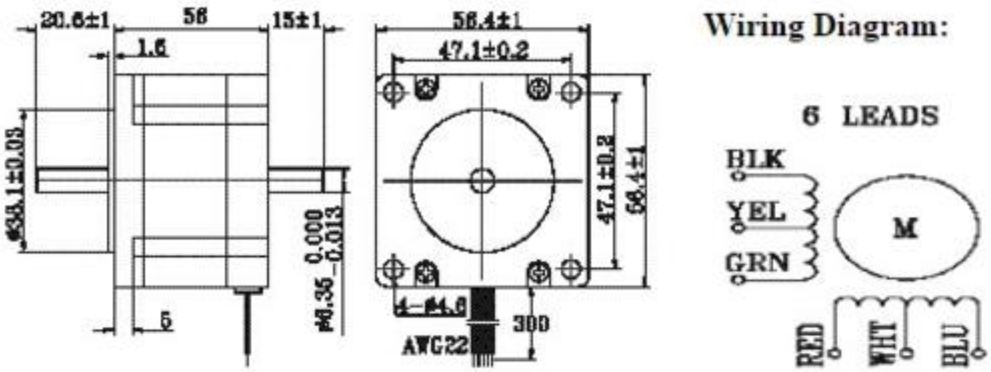

Figure 9: NEMA 23 circuit diagram

Table 1: NEMA 23 manufacturer specifications

Step Accuracy	Ambient Temp Rating	Insulation Resistance	Dielectric Strength	Radial Play	Axial Play
+/ 5%	- 10C to 50C	100 Mohm Min @ 500 VDC	500 VAC 1 Minute	0.06 Max 450 g load	0.08 Max 450 g load

The details for the NEMA 23 motor listed below are the relevant specs related to our project.

- CanaKit Stepper Motor - 125 oz.in (200 steps/rev)
- Step Angle (degrees) : 1.8
- Rated Voltage: 3V
- Rated Current: 2A/Phase
- Holding Torque: 90N.cm

Arduino Uno

Arduino Uno is a microcontroller based on ATmega328P. We decided to use Arduino Uno because it is easy to code and there are a lot of sources online.

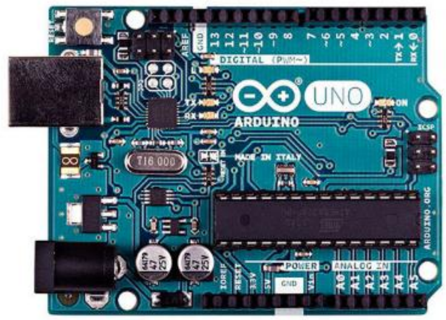

Figure 10: Physical Picture of Arduino Uno [14]

- Operating Voltage: 5 Volts
- Input Voltage: 7 ~ 12 Volts
- DC Current per I/O Pins: 14 (6 of them prove PWM output)
- Weight: 25g

DRV Motor Driver

This section shows the figure of DRV8825 motor driver and its specification. We decided to use DRV 8825 because its specification matches with requirements for our stepper motor. Also, it is relatively easier to wire and control than other motor drivers.

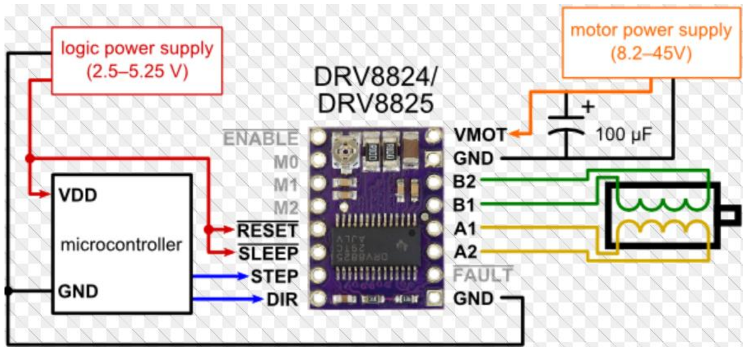

Figure 11: DRV8825 Motor Driver Schematic [12]

- Allows to control bipolar stepper motor at up to 2.2 A
- Easy and simple step & direction control interface.
- Operating voltage 8.2 ~ 45 Volts
- Logic Voltage 2.5 ~ 5.25 Volts
- Built-in regulator

Futaba Servo Motor

The following section is a compilation of the specifications researched for the Futaba S3010 standard size ball bearing high torque servo.

Figure 12: Futaba S3010 High Torque Servo

This motor is ideal for our project because it offers high-torque applications for a standard size servo. The specifications for the Futaba motor are listed below.

- Current Requirement: 2A
- Speed: 0.20 sec/60° @ 4.8V; 0.16 sec/60° @ 6.0V
- Torque: 72 oz-in (5.2 kg-cm) @ 4.8V; 90 oz-in (6.5 kg-cm) @ 6V
- Dimensions: 1.6 x 0.8 x 1.5" (1-9/16 x 13/16 x 1-1/2") (40 x 20 x 38mm)
- Weight: 1.5oz (1-7/16oz) (41g)

We tested the servo motor in our intended configuration. The test circuit and code are shown below.

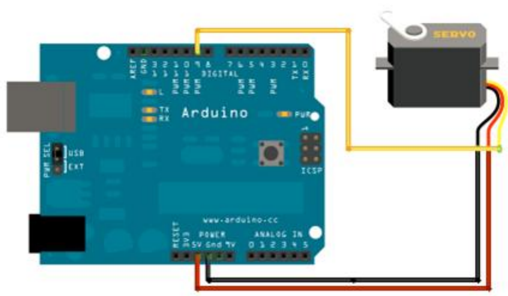

Figure 13: Servo Motor Circuit

Servo Motor Arduino Test Code

```
#include <Servo.h>
Servo myservo;  // create servo object to control a servo
// twelve servo objects can be created on most boards
int pos = 0;    // variable to store the servo position
void setup() {
 myservo.attach(9);  // attaches the servo on pin 9 to the servo object
}
 void loop() {
 for (pos = 0; pos <= 180; pos += 1) { // goes from 0 degrees to 180 degrees
   // in steps of 1 degree
  myservo.write(pos);              // tell servo to go to position in variable 'pos'
  delay(15);                       // waits 15ms for the servo to reach the position
 }
 for (pos = 180; pos >= 0; pos -= 1) { // goes from 180 degrees to 0 degrees
  myservo.write(pos);              // tell servo to go to position in variable 'pos'
```

```
  delay(15);                  // waits 15ms for the servo to reach the position
 }
}
```

Logic Voltage

Logic level is a finite number of states that a digital signal can inhabit. Logic levels are represented by the voltage difference between the signal and the ground. In binary logic, two levels are logical high and logical low which corresponds to a binary 1 and 0. Examples of common binary logic levels are shown in Table 2.

Table 2: Examples of binary levels [1]

Technology	Low Voltage	High Voltage	Notes
CMOS	0V to 1/3 V_{DD}	2/3 V_{DD} to V_{DD}	V_{DD}=supply voltage
TTL	0V to 0.8 V	2 V to V_{CC}	V_{CC}=5V ±10%

The motor driver used in our design accepts standard (Transistor-Transistor logic) TTL logic levels to drive inductive loads. TTL is a class of bipolar junction transistors and resistors called TTL because transistors perform the logic and amplifying function [1]. TTL gates operate on a nominal power supply voltage of 5 volts. Ideally, a TTL high signal would be 5.00 Volts exactly and a TTL low signal would be 0 volts exactly. However, this is not the case. Real TTL gate circuits cannot output such perfect voltage levels so they are designed to accept a range of voltage values. This range is depicted in Figure 14. As seen in Figure 14, there are ranges where the noise level is high, therefore adjustments to the voltage are required to reduce noise.

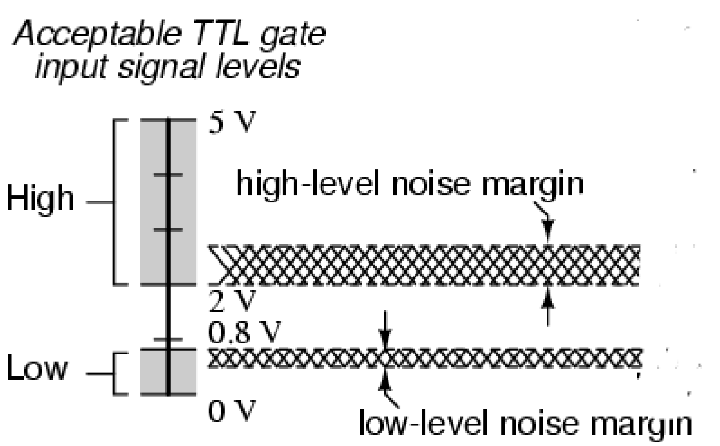

Figure 14: TTL input voltage levels[2]

CMOS logic levels require lower power consumption and run off a lower base voltage (V_{cc}=3.3V instead of 5V).

The motors will be controlled using an Arduino UNO. The microcontroller on this device is the ATMega328. The voltage levels shown in Figure 15 are different from the TTL and CMOS voltages. This is because Arduino is built on a more robust platform. This enables Arduino to have a higher threshold for a LOW signal.

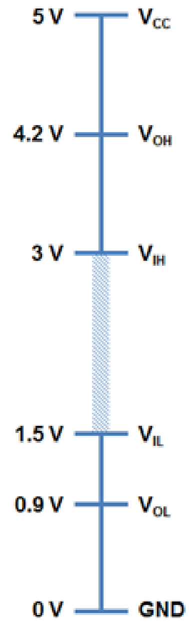

Figure 15: Arduino input voltage levels [2]

In Figure 15, the parameters are defined as follows [2].

- V_{OH}: Minimum OUTPUT Voltage level a TTL device will provide for a HIGH signal.
- V_{IH}: Minimum INPUT Voltage level to be considered a HIGH.
- V_{OL}: Maximum OUTPUT Voltage level a device will provide for a LOW signal.
- V_{IL}: Maximum INPUT Voltage level to still be considered a LOW.

4 Preliminary Design

4.1 Concept Generation and Evaluation

The initial motivation for an automatic whiteboard eraser design was for a chalkboard. Our group was aware that chalk dust may cause respiratory problems. A study published in the journal Indoor and Built Environment concluded that “chalk dust could be harmful to allergic persons and may cause lacrimation and breathing troubles in the long run” [1]. Also, erasing is a laborious task that takes away from learning. To build a prototype for the purpose of automatically erasing a chalkboard, our group would have to purchase a chalkboard. Initial research into the price of a sizeable chalkboard revealed that this purchase would be too costly considering the project budget. On the other hand, purchasing a whiteboard is inexpensive, so we opted to design an automatic whiteboard eraser. The erasing process is the same for both types of board, therefore, we figured the prototype can be applied to a chalkboard to address the initial problem. Our project goals were to design an automatic whiteboard eraser for selective user input erasing and efficiency. First, we researched methods of erasing. These methods included erasing using sound waves, erasing using a chemical reaction, erasing using electromagnetic dissipation, erasing using heat treatment, and erasing using a process similar to a car wash. After an in depth group discussion involving a pugh matrix shown in Appendix A, we concluded that the best option was the traditional erasing method due to operating costs. We separated the design process into two components: design of the erasing component and design of track for the mounting track of the erasing component. We came up with two conceptual designs for the mounting track of the erasing component and three conceptual designs for the erasing component of W.E.B.

For the first track design, we decided to use a front wheel motor drive as shown in Figure 16. All the wheels move independently. A motor torque is applied to a single wheel and the other three wheels are free of torque. One concern for this design is braking.

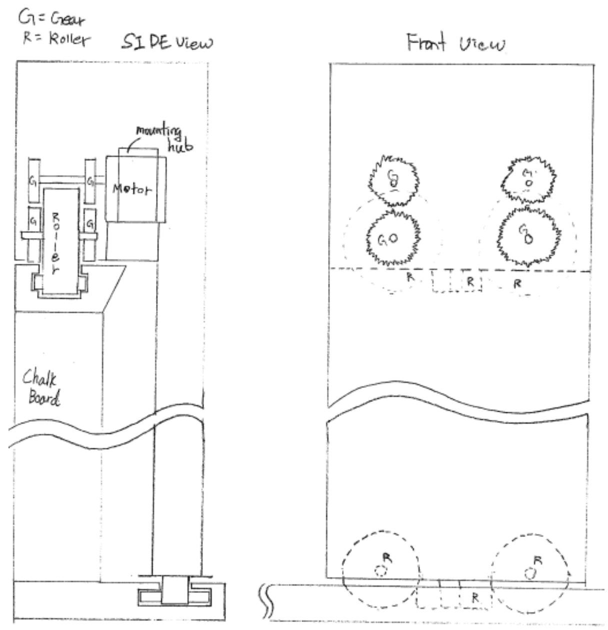

Figure 16: Horizontal motion component design

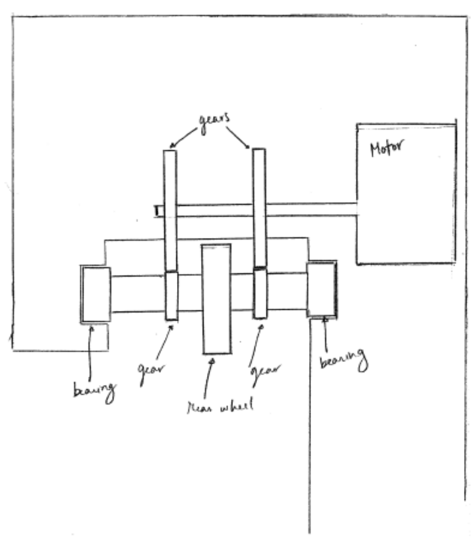

Figure 17: Drive hub closeup

The second mounting track design we considered was a pulley system. As seen in Figure 17, the design consists of two belts and four timing pulleys. The belts are attached to the pulleys and one motor drives the movement of each belt. We selected this design as an option because it has been leveraged for CNC machines. This shows that the design offers accuracy and control, both of which are key features we want to incorporate in our project.

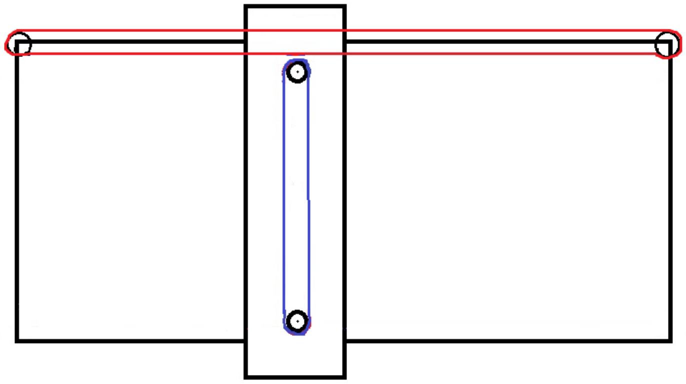

Figure 18: Rudimentary pulley system

For the erasing component, we considered three potential design concepts. The first design consisted of a set of roller carriages mounted vertically on the whiteboard. The user can select any number of the carriages to erase selected areas of the board. The design for the eraser carriage is shown in Figure 19. On the left, a motor with a gear mounted on the motor shaft meshes with gears on the roller shafts to rotate the two rollers. On the right, the same mechanism is used but the motor configuration is different.

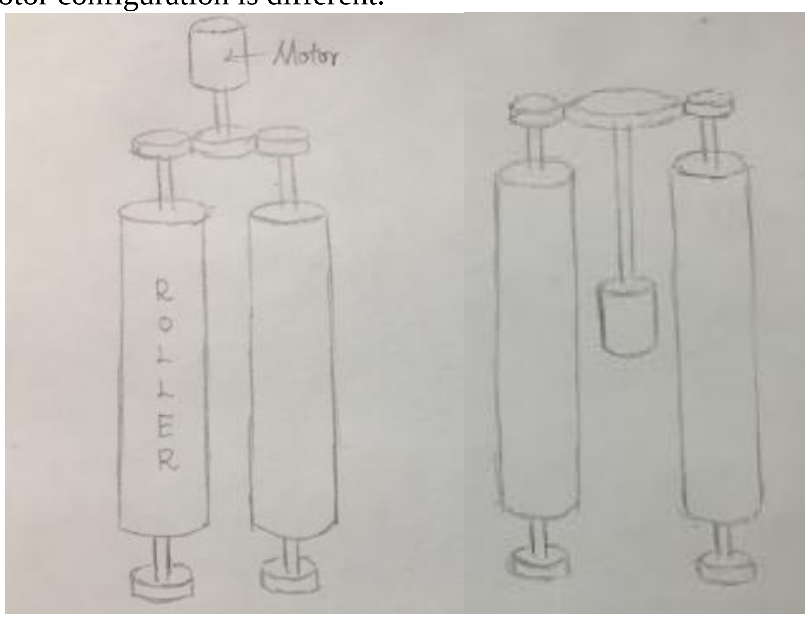

Figure 19: Design Concept 1

The second design concept made use of a set of twelve Expo erasers mounted vertically on the whiteboard. As shown in Figure 20, each eraser engages with the help of a servo spring system. The shaft of the motor is attached to the rotary linear linkage system to move fixed plate. Two springs and the Expo eraser are attached to the fixed plate. At position 0°, the eraser is in contact with the board. The springs help keep the eraser in contact with board. When the servo shaft rotates, the linkage system moves the fixed plate which moves the eraser off contact with the board.

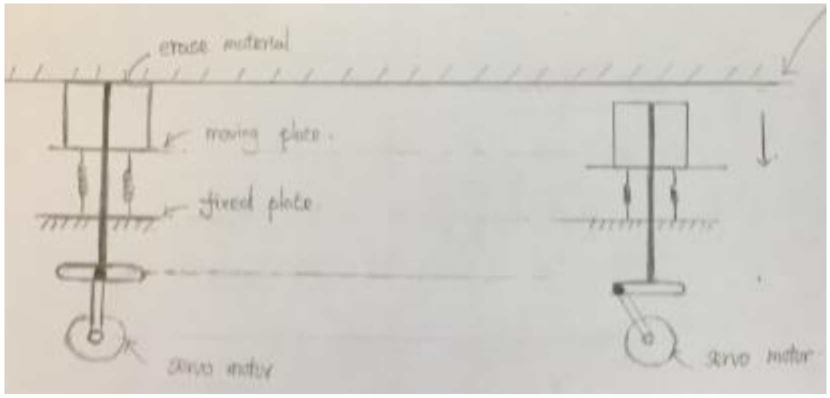

Figure 20: Design Concept 2

The third design concept was for a single eraser carriage capable of motion in the Y direction. The eraser carriage houses an Expo eraser that can move into and out of contact with the whiteboard. The basic design for this concept is shown in Figure 21. The concern for this design was that the it would not erase efficiently.

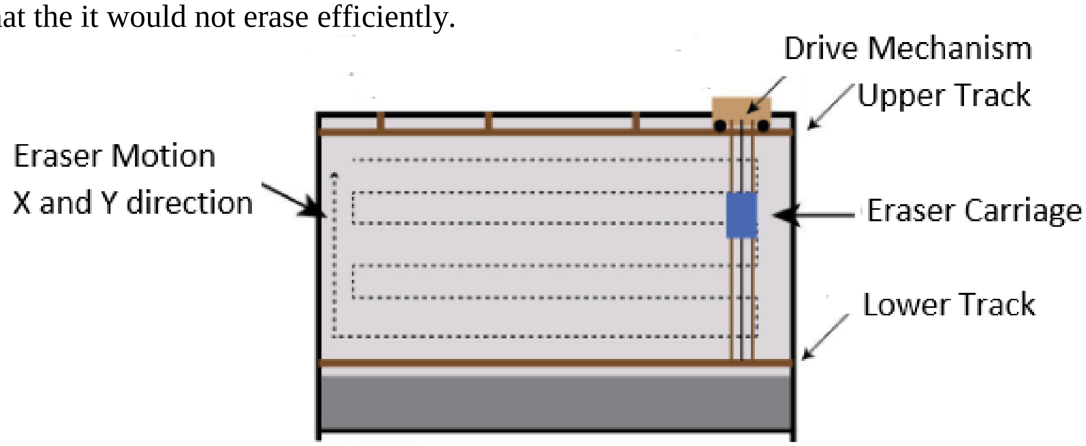

Figure 21: Design Concept 3

4.2 Selected Design

Our group opted for concept two for the mounting track and concept three for the erasing component. We selected concept two for the mounting track because it offers good repeatability and control of the erasing component, and we selected concept three for the erasing component because it erases well and offers more selective erasing for the user. The entire design is composed of three subsystems. The first subsystem is an eraser carriage. This system consists of an Expo eraser connect to a spring loaded arm. The arm is pushed down by a servo motor to create contact between the eraser and the board. A servo motor was selected because it is ideal for controlling the two positions (on and off) of the eraser. The second subsystem is a track for horizontal and vertical motion of the eraser carriage. This system consists of an upper and lower track. The horizontal motion and vertical motion are each controlled by a pulley system powered by a stepper motor. A set of stepper motors were selected because they are ideal for precise positioning and repeatability of movement. All three motors in the design are controlled by an Arduino Uno. The third subsystem is a user interface to select which areas of the board to erase. The interface is described in greater detail in the programming section of the report.

4.3 Preliminary Analysis

This section of the report shows the analysis and calculations performed for W.E.B.

Device Parameters

Table 3: X components and weights

Component	Material	Weight (kg)	Multiplier	Total(kg)
8mm Linear Shaft	Hardened Chrome Alloy	0.454	4	1.816
Linear Shaft Support	Aluminum alloy	0.024	8	0.192
GT2 Timing Pulley	Aluminum	0.012	2	0.024
GT2 Timing Belt	Rubber	0.028	1	0.028
Mounting Bracket	Aluminum 1060	0.082	2	0.164
Bolt	Alloy steel	0.001	16	0.016
Mount Screw	Alloy Steel	0.001	8	0.008
NEMA 23 Stepper Motor		0.7	1	0.7

Table 4: Y components and weights

Component	Material	Weight (kg)	Multiplier	Total(kg)
8mm Linear Shaft	Hardened Chrome Alloy	0.454	2	0.908
Linear Bearing	Aluminum alloy	0.021	4	0.084
Bearing Support	Aluminum alloy	0.034	4	0.136
GT2 Timing Pulley	Aluminum	0.012	2	0.024
GT2 Timing Belt	Rubber	0.028	1	0.028
Housing 1	ABS Plastic	0.518	1	0.518
Housing 2	ABS Plastic	0.210	1	0.210
Bolt	Alloy steel	0.001	16	0.016
NEMA 23 Stepper Motor		0.7	1	0.7

Table 5: Eraser Carriage components and weights

Component	Material	Weight (kg)	Multiplier	Total(kg)
Linear Bearing	Aluminum alloy	0.021	2	0.042
Bearing Support	Aluminum alloy	0.034	2	0.068
Bolt	Alloy steel	0.001	8	0.008
Slot Holder	ABS Plastic	0.151	1	0.151

Z-Bracket	ABS Plastic	0.066	1	0.066
Futaba Servo Motor		0.045	1	0.045
Force Arm	ABS Plastic	0.008	1	0.008
Shaft	ABS Plastic	0.005	2	0.010
Expo Eraser		0.02	1	0.02
Expo Marker		0.01	1	0.01
TOTAL				**0.428**

Table 6: Primary Electronic components and weights

Component	Weight(kg)
Arduino	0.025
DRV8825	0.002
12V Power Adapter	0.093

FEA Structural Analysis

We performed a bending test on the shaft using finite element method in Abaqus software to see of there would be any marginal deflection on any point on top and bottom horizontal steel rods. We applied the extreme weight (22N) at a point on the rod where we thought there would be the largest deflection. The deflection turned out to be around 5mm. Before proceeding to the bending test, we decided that the rod would be safe if deflection in the middle is equal or less than 5mm. The result turned out to be around 5.2mm (see Figure 22). Since our actual product is a quarter of the extreme weight, out design has safety factor of 4, which is sufficient.

Figure 22: Bending test on the steel rod using FEM, Abaqus

Motor Selection Calculations

The following sections contain a set of calculations used to select the motors for our design.

NEMA 23 Motor
This following calculations provide a relationship between the stepper motor rotation and linear motion of working piece, which can be of further use in programming.

Rotation and Linear motion relationship:

Data:

Bore Diameter	0.314 inches =0.0079756 m
Stepper Motor	200 Steps/Rev

Calculation:

Linear displacement/Step:

$$\bar{V} = \frac{\frac{Rad}{step}}{2\pi} * (2\pi * R_{pully})$$

Plug in data:

$$\bar{V} = \frac{\frac{2\pi}{200}}{2\pi} * \left(2\pi * \frac{0.0079756}{2}\right) = 1.2528 * 10^{-4}\ m/step$$

Holding Torque Calculation:

Maximum holding torque for stepper motor: 90N.cm

So the maximum load the motor can hold once it's energized before turning is calculated as:

$$F = 90N \cdot cm \cdot \frac{1}{\frac{0.0079756}{2} m \cdot \frac{100cm}{m}} = 225.68\ N = 225.68N \frac{1}{9.8\frac{m}{s^2}} = 23KG$$

So when it's stationary, the motor can hold much more weight than its maximum radial load with our selected pulley. Therefore, we made our design based on the radial load limit.

$$F = 90N \cdot cm \cdot \frac{1}{\frac{0.0079756}{2} m \cdot \frac{100cm}{m}} = 225.68\ N = 225.68N \frac{1}{9.8\frac{m}{s^2}} = 23KG$$

Futaba Servo Motor

The dimension of our servo arm design is shown in the following two pictures:

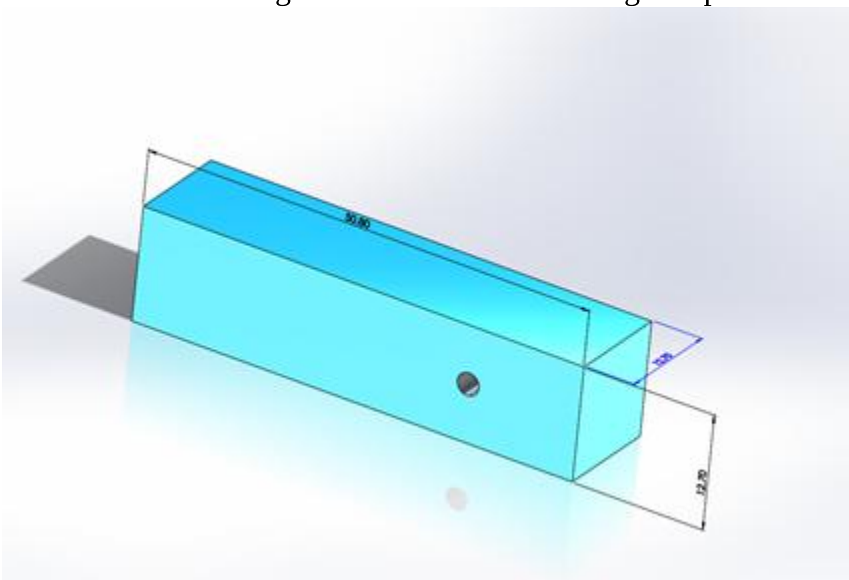

Figure 23: Servo Arm Dimension

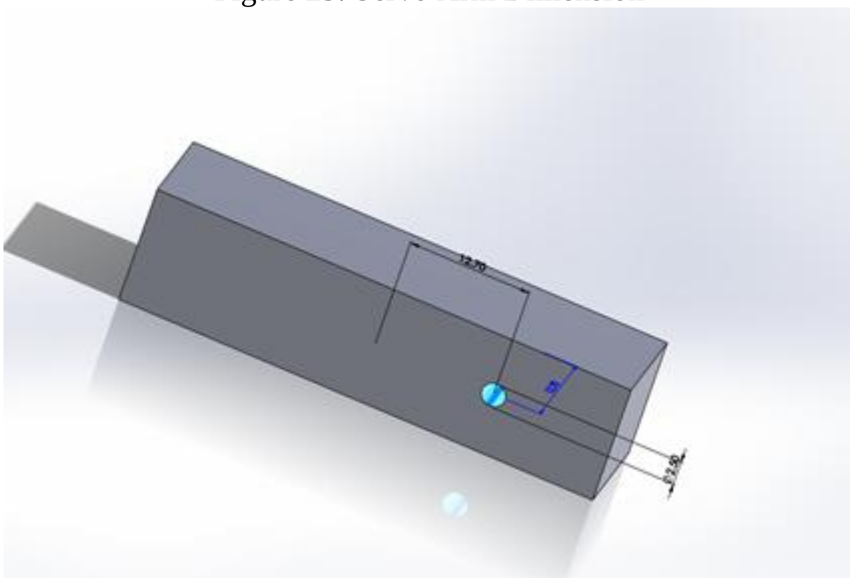

Figure 24: Servo Arm Dimension

Based on our CAD model, the moment arm was determined to be

$$l = \frac{50.80mm}{2} + 12.70mm = 0.0381m$$

The torque required to provide 20N pressure force on the eraser was determined by

$$M = \vec{L} \times \vec{F} = 0.0381\ m \times 20\ N \times \cos(90^{\circ}) = 0.762\ N \cdot m$$

Based on the calculation, the Futaba S3010 Standard High-Torque BB Servo was chosen. This motor can produce a maximum torque 6.5 kg-cm, which is 0.637 N-m based on its specification.

Expo Eraser Friction Calculation

To determine the pressure force on the eraser, one experiment has been designed and conducted by our group. Instead of testing the pressure force in a vertical white board, we test the pressure force with a white board in the horizontal plane, which makes the experiment more approachable. We attach a string to a whiteboard eraser, put weight on top of the eraser, and pull it with constant moving speed, v = 0.2 m/s. By varying the weight on top of the eraser, how clean the whiteboard after erasing is determined by a variable called cleanliness. The data is showing in the following table. Using safety factor of 2, the downward force is determined to be 20N.

Table 7: Friction test data

Load Weight(N)	Cleanliness 1st time	Cleanliness 2nd time
2	70%	80%
4	80%	90%
6	95%	98%
8	98%	99%
10	99%	99%

Preliminary Circuit Design

In the circuit design, there is one Arduino uno, two motor drivers, two stepper motors, one servo, and two 100 mf capacitors. Firstly, the stepper motors are powered in parallel by a 12 volts power adaptor from wall. Two capacitors are placed before the motor drivers in order to prevent any current spikes. Two motor drivers are connected to the motor drivers so that they can perform their tasks (i.e. one drives x-axis movement, and another drives y-axis movement). We have. The servo is powered by the arduino, and the arduino is powered by a 12 volts power adaptor, which eventually the servo gets powered 12 volts.

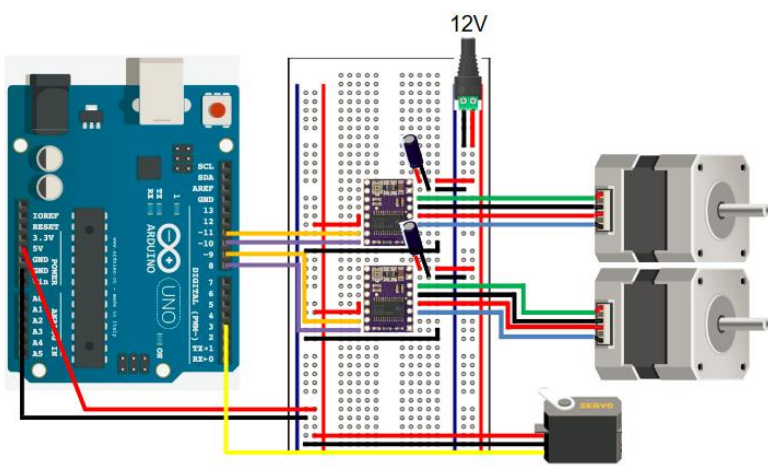

Figure 25: Preliminary Circuit Design

Catalyst Preliminary Analysis

The red components in Figure 26 are the ones we selected to 3D print. These components need to be fabricated because they are unique to our design.

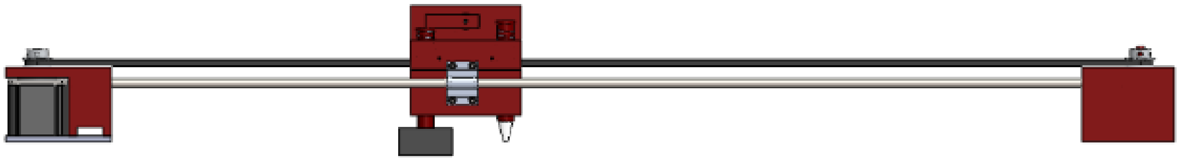

Figure 26: Y component with 3D printed parts shown in red

The two options were to machine or 3D print the parts. If we machined the parts, the components would be heavy and exert unneeded strain on the Y component motor. We chose to 3D print the components because this option offers a lightweight alternative to conventional machining. To ensure that the parts printed in a timely manner, we performed CatalystEX analysis to estimate each part print time. The CAD model and catalyst print time estimate for each component are shown in the Figures below.

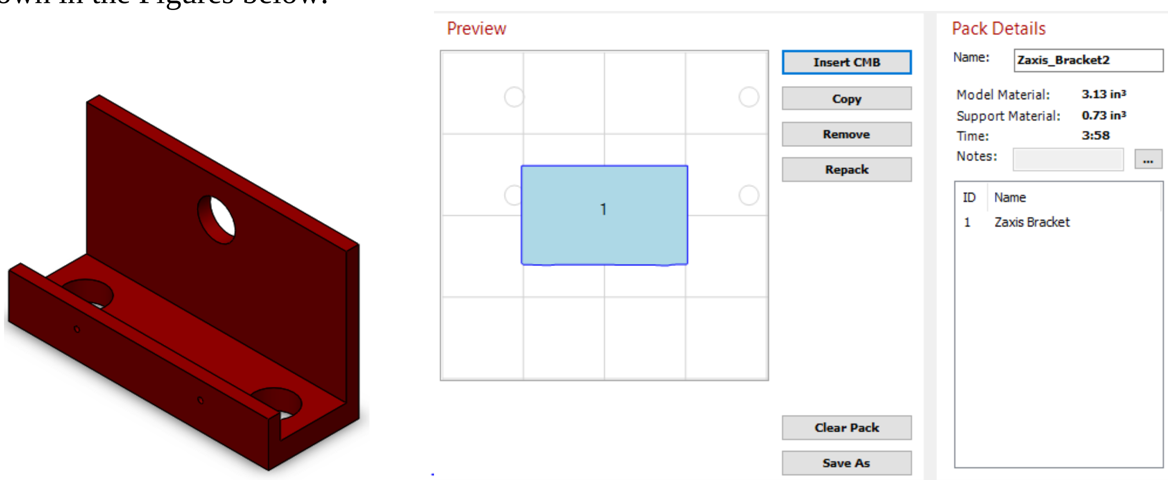

Figure 27: Carriage Z-Bracket Catalyst analysis

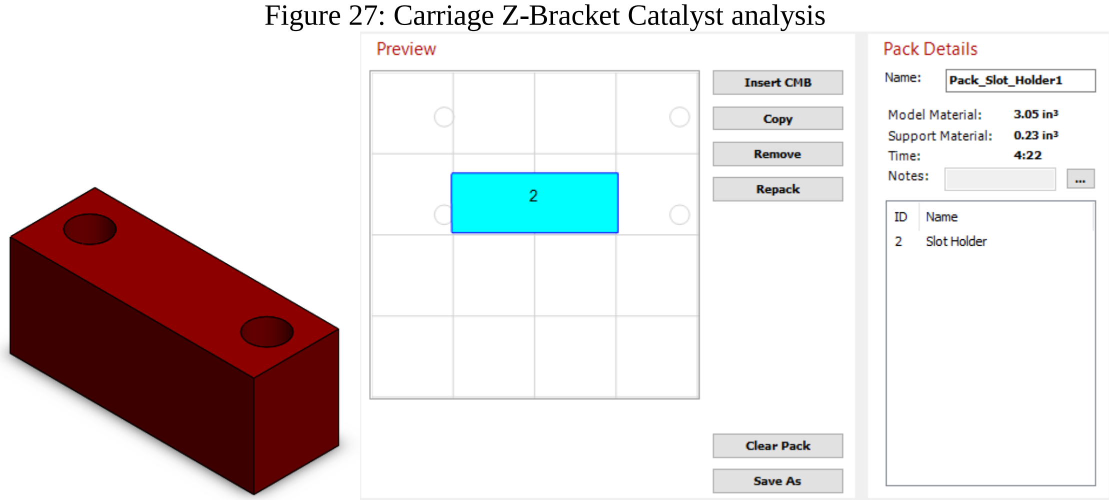

Figure 28: Carriage Slot Holder Catalyst analysis

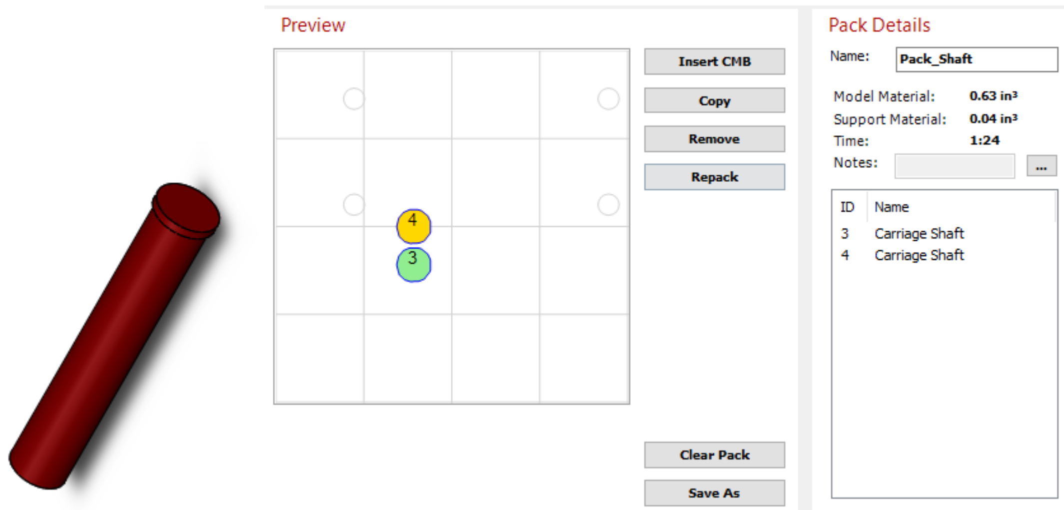

Figure 29: Carriage Eraser/Marker Shaft Catalyst analysis

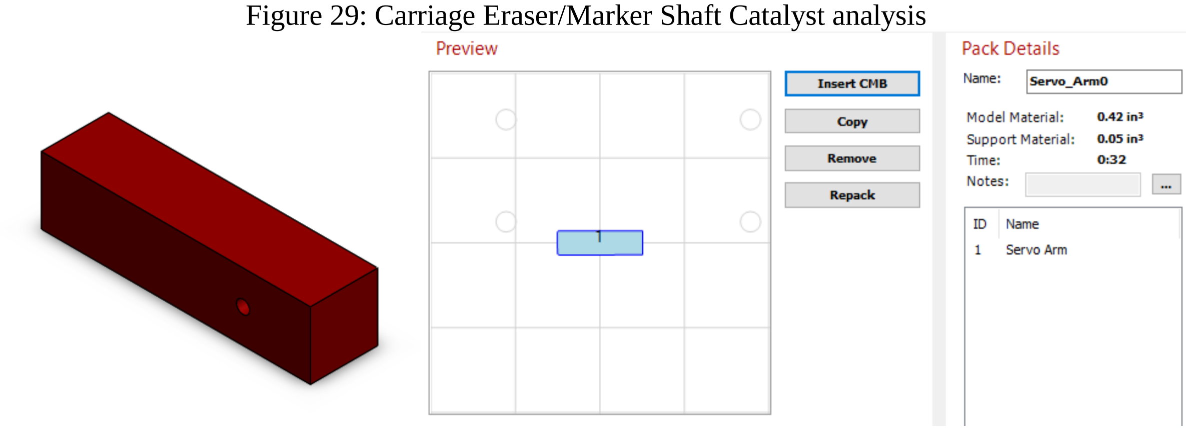

Figure 30: Carriage Force Arm Catalyst analysis

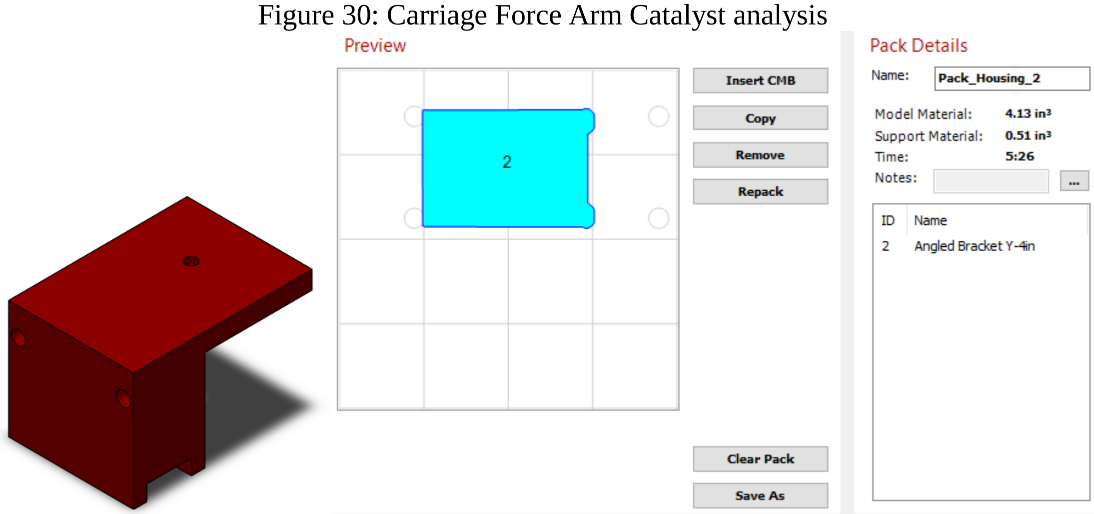

Figure 31: Housing 1 Catalyst Analysis

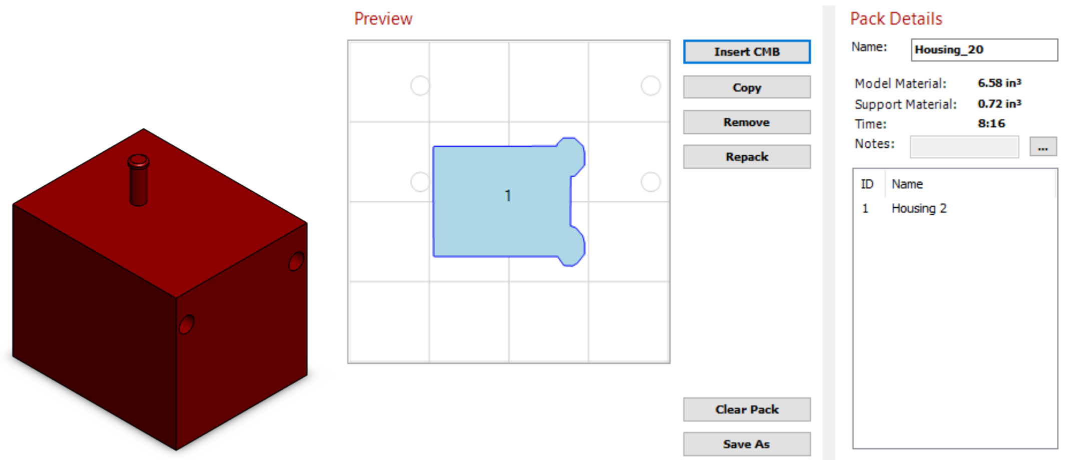

Figure 32: Housing 2 Catalyst analysis

All components were oriented to optimize the printing time. We decided to print the carriage components using the sparse-low density setting to decrease the weight of the carriage. Additionally, we opted to print the housings using sparse-low density settings to reduce printing time. Table 8 shows the total print time for the components of our design.

Table 8: Estimated 3D Print Time

Component	**Print Time**
Z-Bracket	3:58
Slot Holder	4:22
Eraser/Marker Shaft	1:24
Force Arm	0:32
Housing 1	5:26
Housing 2	8:16
TOTAL TIME	**23:58**

As seen in Table 8, the estimated print time for the preliminary design is over the allotted 20 hour print time. This is mostly because the housings take a significant portion of time to print. Consequently, adjustments need to be made to this design to reduce the print time.

4.4 CAD Model

The following section of the report contains a detailed CAD model of the preliminary design concept for W.E.B. Figure 33 shows an isometric view of the design. Figure 34 is a front view of the fdesign. The project consists of three subsystems: the eraser carriage, the system for vertical/horizontal motion, and the user interface to selectively erase the board. The CAD model shows the first two subsystems mounted on a whiteboard with a 2’’x 6’’ Douglas Fir wood frame.

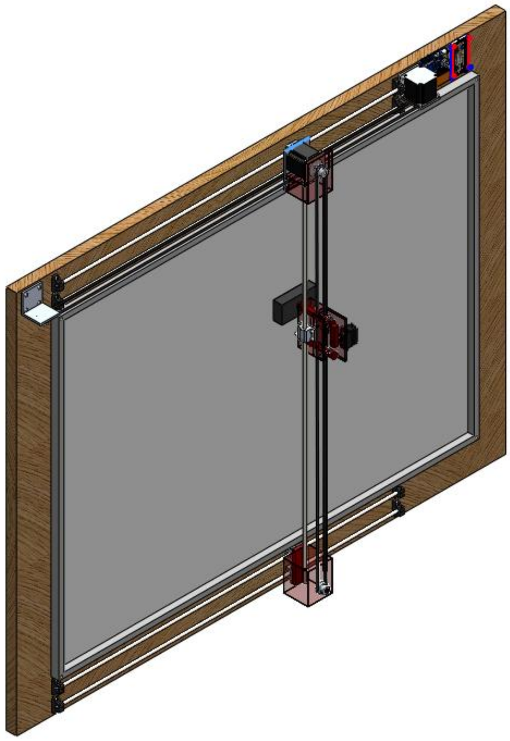

Figure 33: Isometric View

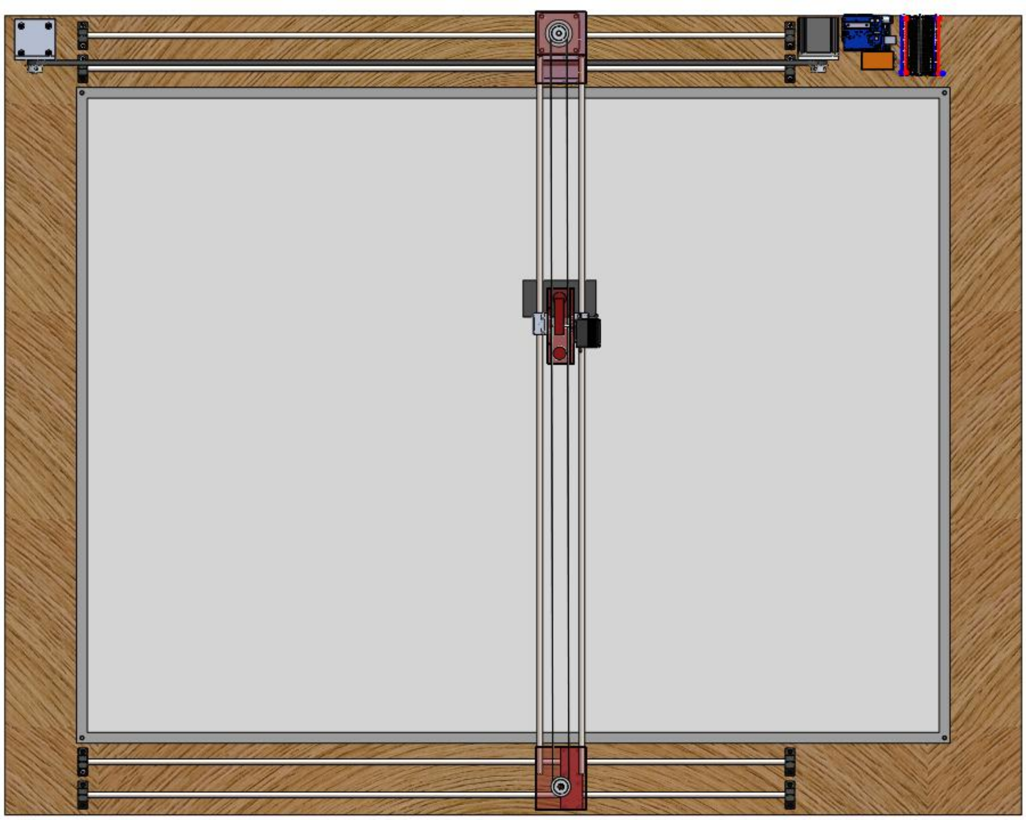

Figure 34: Front View

Due to limitations acquiring a linear shaft longer than one meter, we had to constrain the erasing width to be one meter wide.

Figure 35 shows the system for the horizontal motion of the eraser carriage. A NEMA 23 stepper motor drives the motion of the device. The motor is controlled by an Arduino Uno and DRV8825 driver. These components were selected based on the motor specifications. The motion is controlled by a pulley system. A GT2 6.5 mm timing pulley is attached to the motor shaft and a GT2 belt rotates with respect to the timing pulley's revolution. The belt is attached to the Y component system via 4mm button head screws. The Y components moves along two linear shafts with the help of 8mm linear bearings.

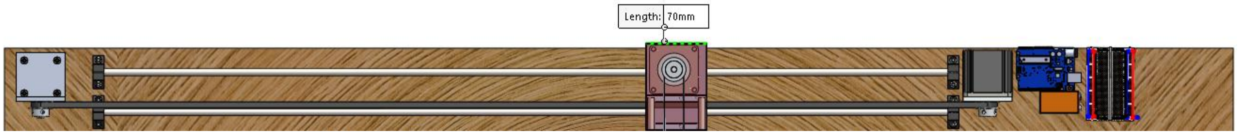

Figure 35: Preliminary X component

Figure 36 shows the system for the vertical motion of the eraser carriage. Another NEMA 23 stepper motor encased in a 3D printed housing drives the vertical belt. The components in red are the parts we have selected to be 3D printed to reduce weight. The purpose of this decision was to reduce unnecessary strain on the motors. The motor shaft is attached to a GT2 timing pulley which spins a timing pulley. The pulley is attached to the carriage containing the eraser and marker.

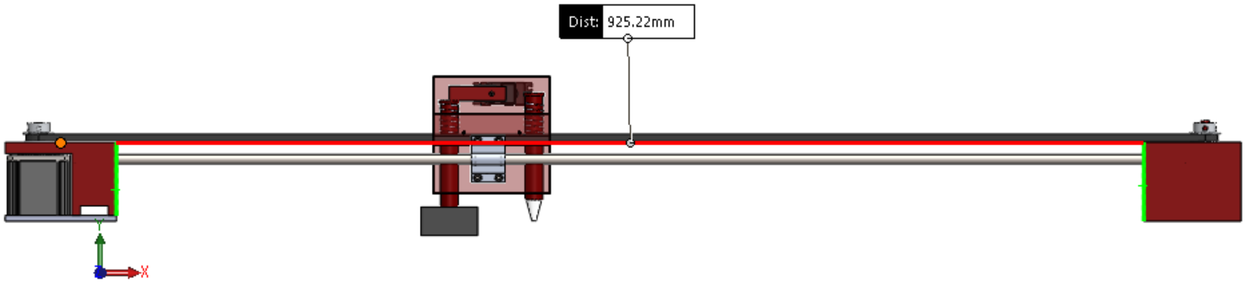

Figure 36: Preliminary Y component

Centered in between the two Y component housings is the eraser carriage. The design for the carriage is shown in Figure 37. The primary material composition for the carriage is ABS plastic to reduce stress on the NEMA 23 motor.

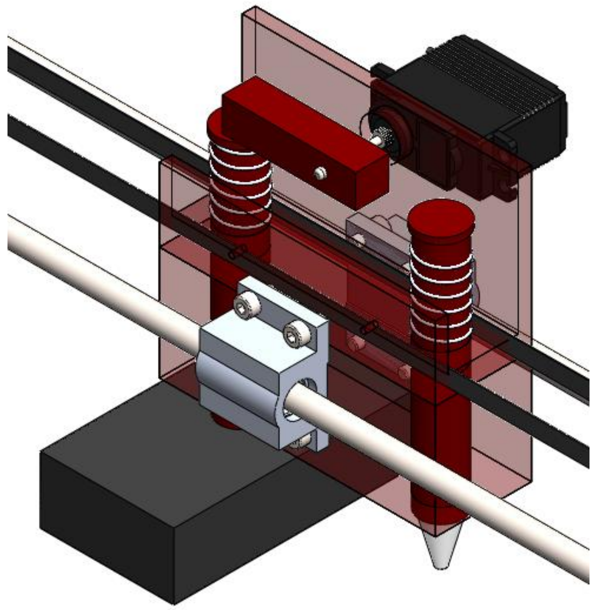

Figure 37: Eraser carriage

A Futaba 23 high torque servo motor rotates an ABS arm. The range of the arm's rotation is from 0° to 180°. At 0°, the current position in Figure 37, the arm applies a force on a spring loaded cylinder to force the Expo eraser into contact with the board. At 180°, the arm applies a force on another spring loaded cylinder to force the Expo marker in contact with the board to write. A concern for the cylinders is the effect that friction from contact between the eraser or marker will have on the security of the cylinder. Therefore, we are going to attach a second spring to each cylinder in order to increase the normal force between the eraser or marker and the board. Another concern is that the servo motor may not be able to withstand the added torque from the recoil of the spring when the arm begins to lift off contact with a cylinder. If this occurs, then we will redesign the cylinders to prevent the spring recoil.

5 Detailed System Design

One of the biggest takeaways from this project is that the design process does not take all of the factors of manufacturing into account. During our design process, we missed a few details that forces us to go back to the design and make some changes. This section provides a detailed description of the final design of the project including the changes made to the preliminary design and the reasons for these changes.

5.1 Final CAD Model/Drawings

For the assembly process, we machined four brackets and 3D printed the other components. The brackets were machined from the engineering drawings shown in Appendix D and E. For the 3D printing aspect of the project, we were concerned with printing time. To address this issue, minor changes were made to each of the components to cut down on printing time. Since the housings took longer to print, we requested low quality prints from UCLA LUX Laboratory for these parts.

After machining and 3D printing, we began assembly. We added an eraser clamp and changed the design of the servo arm on the carriage. The new design for the servo arm enabled us to have more efficient movements when switching from eraser to marker. The final design of the Y component is shown in Figure 38. A closeup of the carriage with the newly added components is shown in Figure 39.

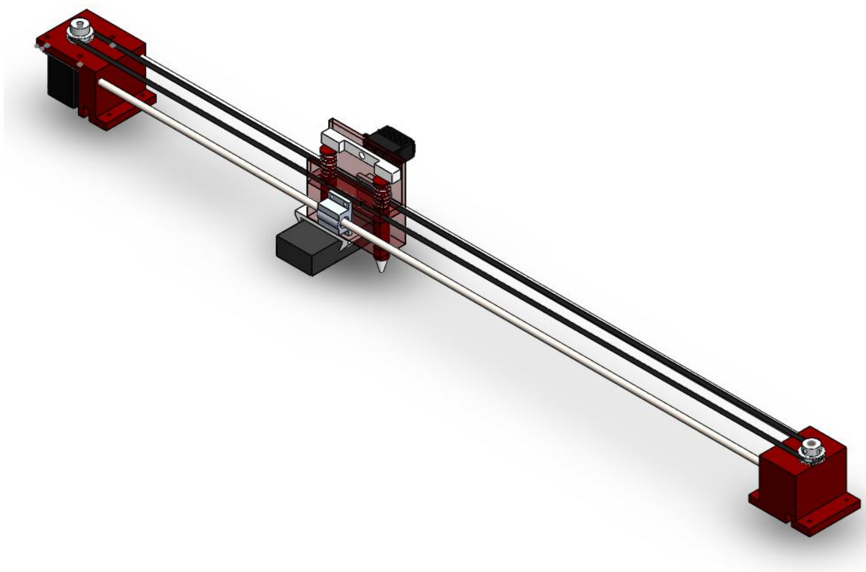

Figure 38: Y component final design

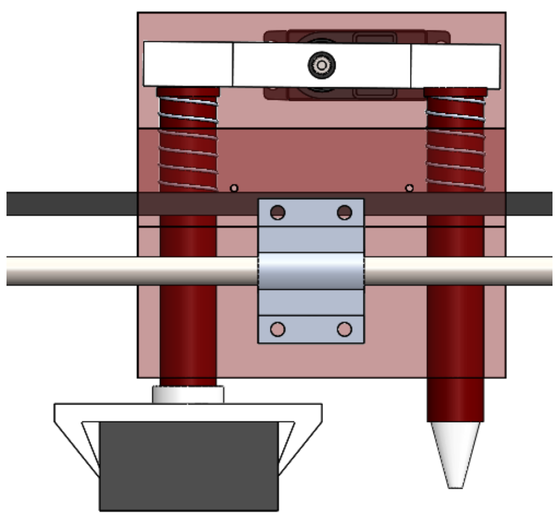

Figure 39: Carriage final design

After we attached the Y component to the X component, we tested the bearings attached to the underside of the housings. The bearings did not slide smoothly because the four shafts were not aligned perfectly parallel with one another and the bearings were not aligned perfectly with one another. After one week of troubleshooting, we removed two shafts and bearings. The Y component was supported by two shafts and we were able to align the shafts so that the Y component moved along the shafts. At this stage we encountered an issue with the bearings for horizontal motion of the Y component. We expected the bearings to slide smoothly on the shafts but this was not the case. Eventually we changed out the bearings for higher quality bearings which fixed the problem.

After completing the circuit, we tested the horizontal motion with the motor driving the belt attached to the upper housing. During the test, the lower housing lagged the upper housing. This caused the Y component to catch and stop moving. We came up with two solutions to our problem. The first solution was to add a vertical rod attached to the motor and attaching a second belt to the lower housing. The second solution was to add a second motor to drive the lower section of the Y component. Due to manufacturing capabilities and time, we selection the second solution. The final design is shown in Figure 40.

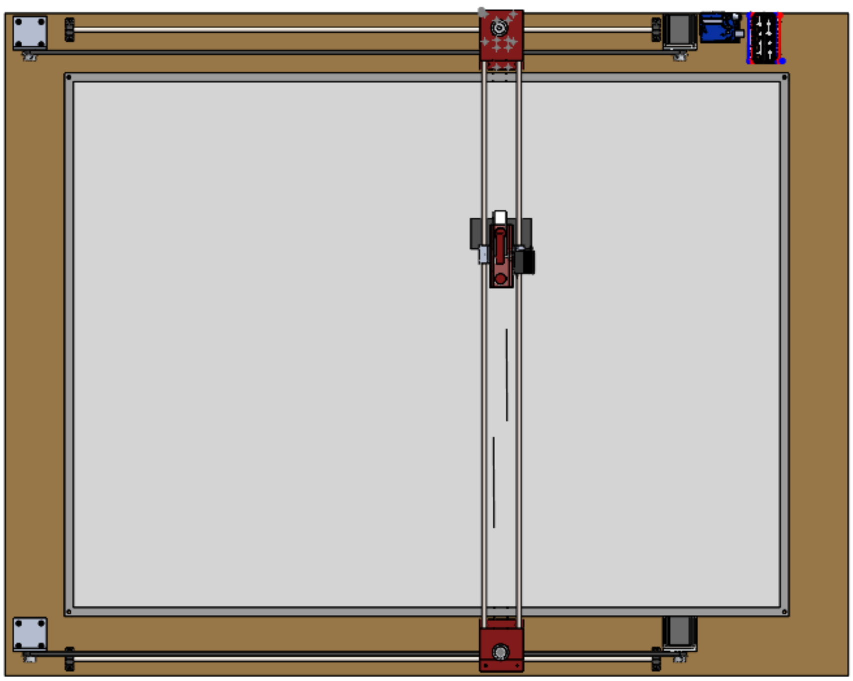

Figure 40: Final CAD model

5.2 Engineering Analysis and Simulation

Kinematics Analysis

Please refer to the preliminary design section.

Structural Analysis

During the preliminary design process, we performed FEA on the shaft to determine whether the shaft could support the weight of the Y component. During the assembly process, we had difficulty matching the bearings of the Y component on the two sets of shafts. We removed a shaft from the top and bottom of the board and used only one shaft from the top and bottom. We used the preliminary analysis to determine that this design would hold up the weight of the Y component.

During the fabrication process, we had to make a small change to the motor bracket. We performed FEA on the bracket to determine whether it could support the weight of the motors.

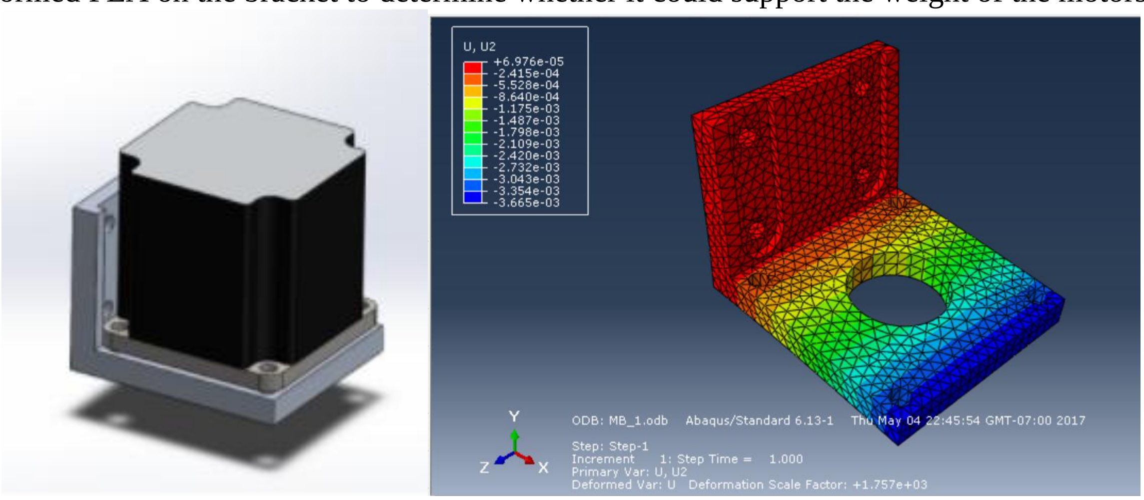

Figure 41: Motor bracket FEA

According to the analysis, the maximum deflection occurred at the tip of the plate (blue), where the deflection value was 0.003 mm. Since the deflection was very small, we concluded that the motor bracket was strong enough to handle the weight of the stepper motor.

Screw sizing

W.E.B is a lightweight design therefore we focused on screw sizing and type to fit the specs of the project. We attached the shafts and brackets to the frame using stainless steel #6 x ¾ inch wood screws.These screws were selected because they have threads which lets them grip surrounding wood with much more power. We used stainless steel #10-32 x 1 inch machine screws to attach the bearings to the carriages. These screws fit the machined holes of the bearings and they can withstand high loads. We used stainless steel #8-32 x 1 inch machine screws to attach the motors to the brackets.The weight of the motors is entirely supported by the brackets, as a result, these screws do not sustain a high load. The screws are shown in Figure 42.

Figure 42: Screw sizes

5.3 Electronics Systems Design

For the electronics system design, we started with the circuit design from Figure 25. The circuit included an Arduino Uno, two NEMA 23 motors, two DRV8825 motor drivers, two 100 mf capacitors, and a power source. After making modifications to the assembly design, we modified the preliminary circuit shown in Figure 25. First, we changed the resistors in the circuit to accommodate the third stepper motor that is now driving the lower housing. After testing this modified circuit, we installed a wifi module in the circuit. Since the logic voltage of the module is 3.3V and the logic voltage of the Arduino is 5V, we added a bidirectional converter to change the logic level of the wifi module to the logic level of the Arduino. The final circuit diagram is shown in Figure X. The bidirectional converter is the red unit and the wifi module is the unit to the left of the converter.

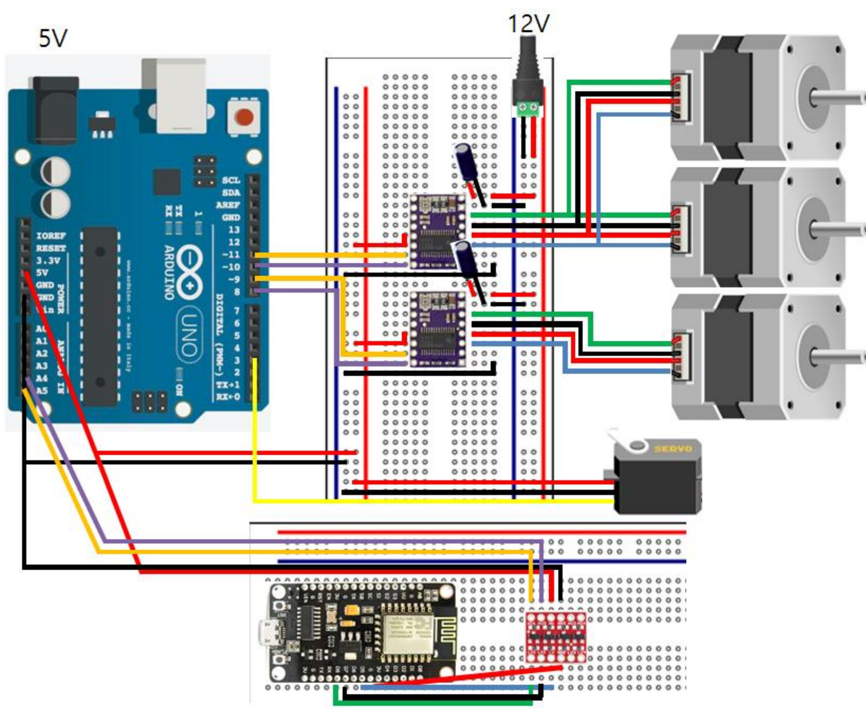

Figure 43: Final Circuit Diagram

The physical circuit was built on the back of the frame and is shown in Figure 44.

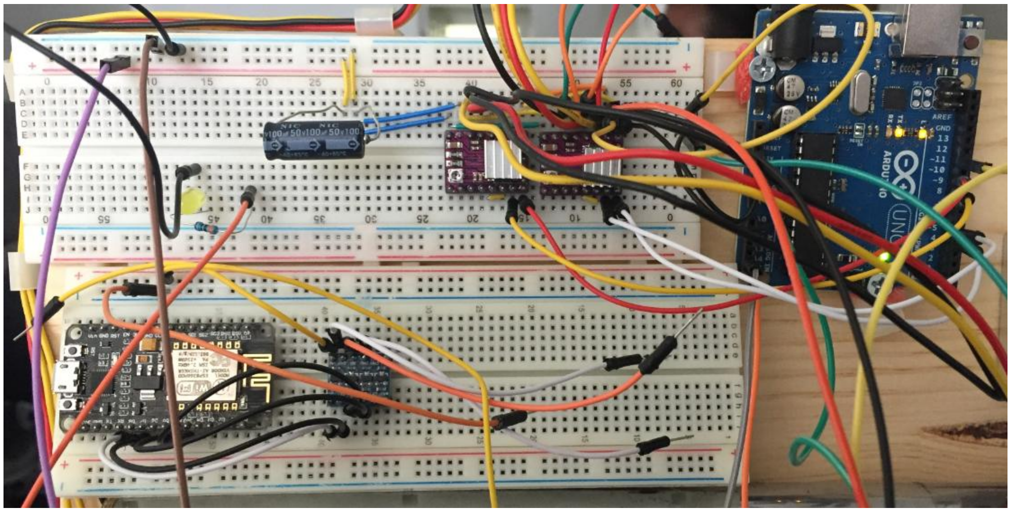

Figure 44: Physical Circuit Design

5.4 Control System Design

Programming:

The structure of the programming for this project is best illustrated by the following figure.

Figure 45: Program Flow

This figure illustrates how commands are sent to and from the machine. In essence, a desktop application called the Project E-Race Control Page sends commands to the ESP8266 wifi module via TCP client/server model. The ESP8266 then uses I2C serial communication to reroute these commands to the arduino.

Project E-Race Control Page Application:

The application is essentially the “brain” of the E-race device as it is responsible for controlling the entire machine. A figure of what this application looks like can be found further below in this section. This is a WPF application (Windows Presentation Foundation) based on Microsoft's .NET framework. The source code is written in C# and the setup file can be found in the master file for this project. Note that this application will only work on windows.

The application acts as the control hub of the E-race machine. From there, one could connect to the server, disconnect or terminate the server entirely. Once connected to the board, the user can select which section to erase, set the position of the cartridge, send the cartridge to the origin or send letters to write on the board.

There are however certain limitation for this application. For instance, I purposely left the buffer size for transferring data to and from the application to the arduino to only a 100 bytes. Larger buffer sizes are not really necessary for the commands being issued. Furthermore, I left the buffer size the same for writing commands which means that it is unlikely that the application will send sentences to the E-race board. Finally, note that this application is very basic and there may be unknown bugs because it was not programmed meticulously due to time constraints.

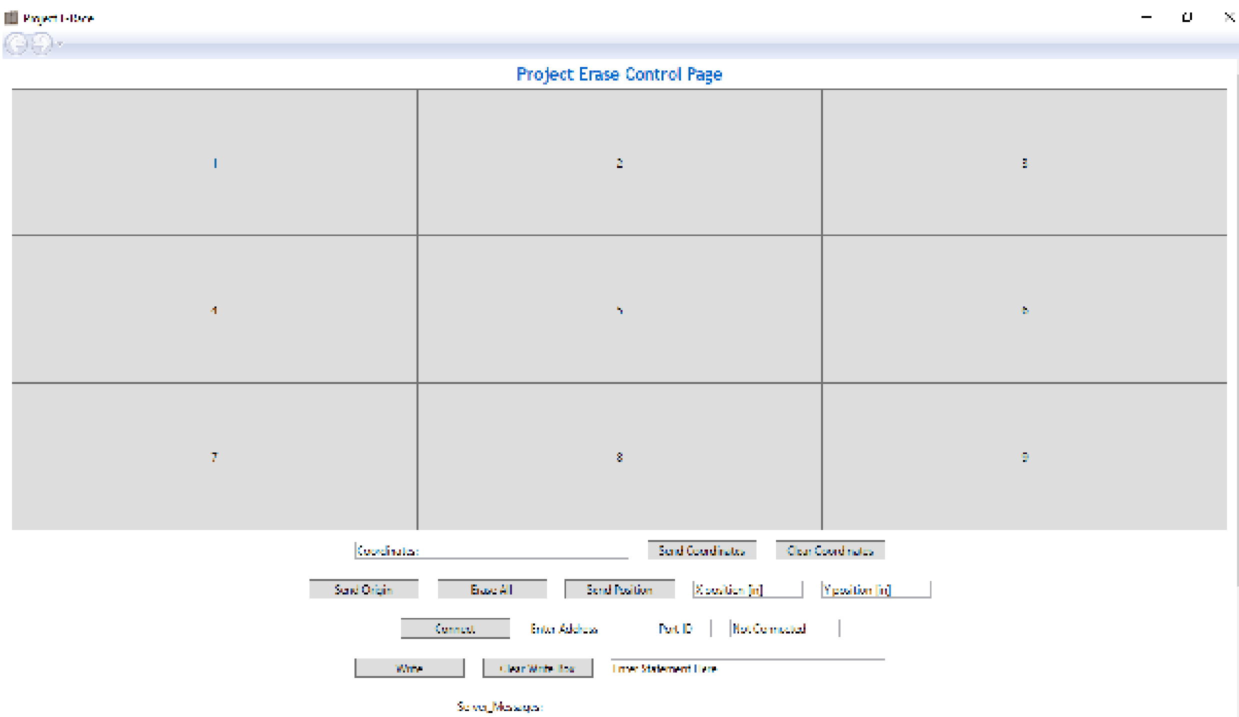

Figure 46: Application

TCP Client/Server

The transmission communication protocol is one of the main protocols of the internet that allows applications to communicate on an IP network. For the WEB device, there are two applications that are in communication: the Project E-Race Control Page on a computer running on microsoft and the server running on the ESP8266. TCP allows for a server to share data between a server and a single client.

There are several frameworks upon which the ESP8266 operates, one of which is micropython which is based on python. Therefore, the programming for the ESP8266 wifi module was done in python. The server is setup to accept data through it’s server side socket for a client and reinterpret the bytes as a string. This string contains the commands ment for the arduino.

I2C Serial Communication

The inter-integrated circuit protocol allows multiple slave integrated circuits to communicate with a single master chip. This allows for the transfer of data between two circuits by a short cable. This protocol needed to be implemented in order for the wifi module to communicate with the arduino.

For the WEB device, the ESP8266 is required to be the master chip while using I2C. This means that the arduino acts as a slave listening to data inputs from the master chip. For both the ESP8266 and arduino, it was relatively easy to implement I2C communication as it was supported by both micropython and the “Wire” library for arduino.

Arduino

Once the data reaches the arduino it causes context switch on the arduino to the “recieveEvent()” function. This function is only called when arduino detects that there is incoming data from the ESP8266. Once this function is triggered, the incoming command is stored into a global variable which means it is also available inside arduino's main loop. Once the command is stored inside a global variable, it activates a fault in the main loop that causes it to reinterpret the command as integers such that a simple *switch* statement can handle the conditional branches. The following table lists the combination of commands possible.

Table 9: List of commands

Command	Purpose	Example
Cord=/	Tells the arduino to erase the subsequent sections	Cord=/a/b/c/d
Posi=/	Moves the cartridge to the specified location x and y	Posi=/X.Y
Orig=/	Moves the cartridge to the origin	Orig=/
Writ=/	Moves the cartridge to the top most position and begins writing	Writ=/HELLO WORLD

There are something to note here. The first 6 characters of each string command contain the actual command from the user. The remaining characters of the string detail other information required to process the command. Next, the user can move the cartridge around to any position he wants on the board which means he/she needs to be careful not to enter commands outside the domain defined by the board. The user has no direct access to control the servo so that he/she may switch between the eraser and the marker. Finally, the user can only write at the top of the board and in only capital letters(no lower case letters or numbers).

Erace Class

All three stepper motors are controlled directly by one Arduino, and the two of them which are controlling horizontal direction motion are connected parallelly using the same arduino ports. Therefore, there are two direction of motor for stepper motor, and one for the servo.

The structure of code is as follows:

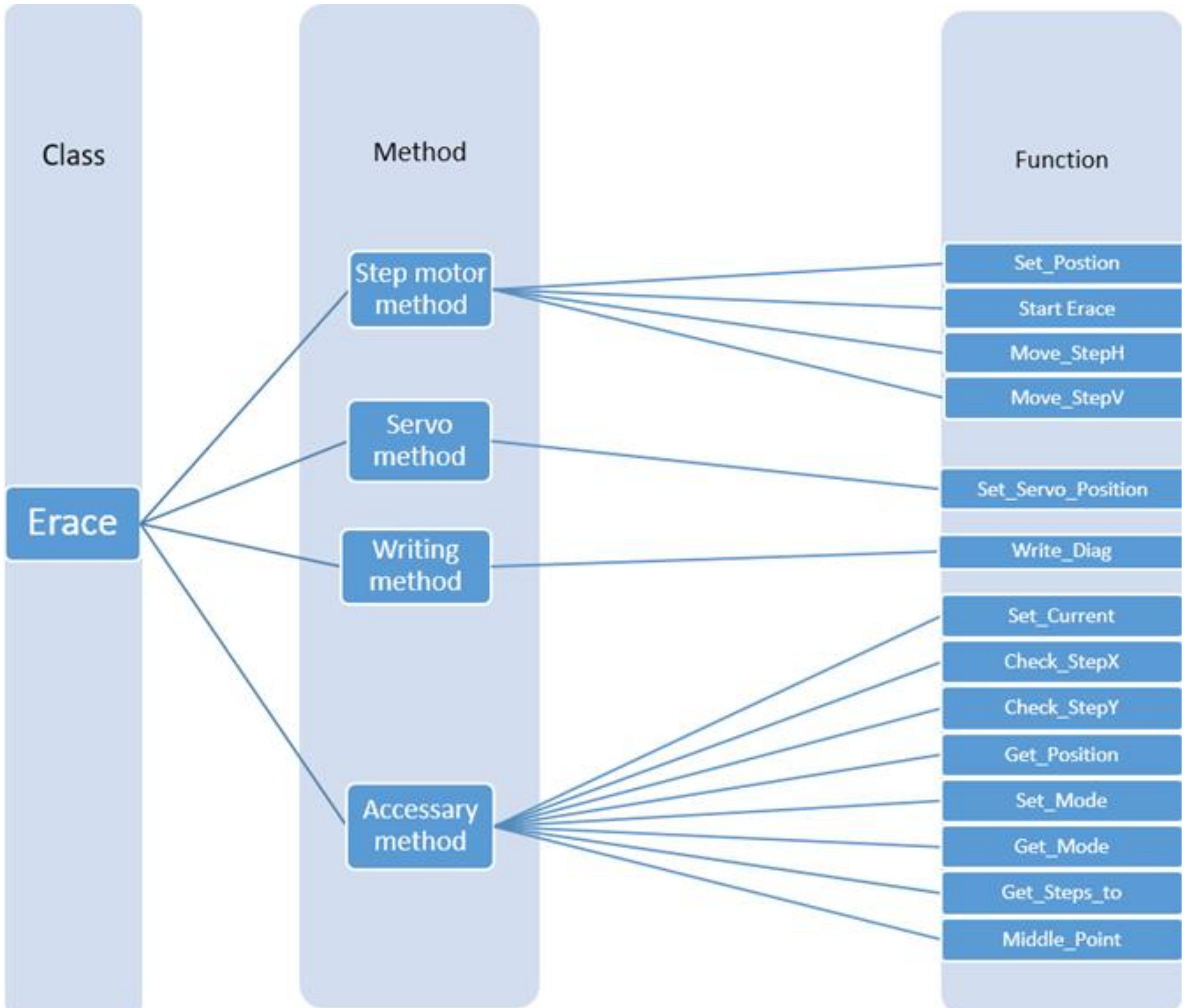

Figure 47: Coding Structure

Where everything is controlled under one class. And there are four methods in the class: “Step Motor method” contains all the functions that involves the control of stepper motor; “Servo Method” controls the angel that servo rotates in both direction, and the angel of servo indicate which mode the device is on; “Writing method” only contain one special function which is

“Write_Diag”, this function accomplish the feature of moving the pen diagonally; “Accessory method” have all the functions that are called by other functions frequently.

There are two main feature of the device, one is erasing and the other is writing, in Figures 47 and 48 are the working flow for both of them:

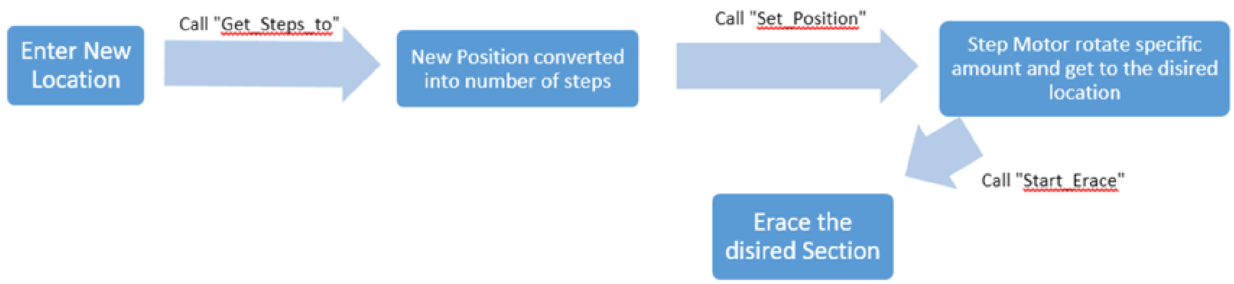

Figure 48: Working Flow for Erasing Part 1

For the erasing process, the user enter the section that need to be erased, the the location get converted into steps for x and y direction rotation by the function “Get_Steps_to”, then the step information become the input of the function “Set_Position” which rotate the stepper motors with the specific amount, after the eraser gets to the starting erase point, the “Start_Erace” function will be called, and this function will lead the eraser to move across the whole section.

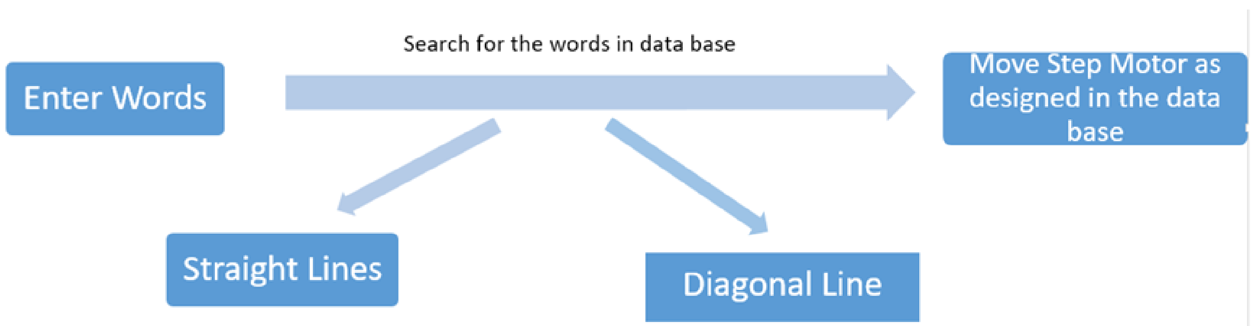

Figure 49: Working Flow for Erasing Part 2

For the writing process, the user enter the words they want the device to write, then the words get decomposed into letters. Then for writing of each letter, the letter will be matched with the one in the database we built up for each letter, and once it finds the match result, the stepper motor will move the pen as indicated in the database. Each letter can be decomposed into two kinds of lines: straight lines and diagonal lines, for straight lines, the writing process is same as erasing process. But for diagonal lines writing, the following algorithm is introduced:

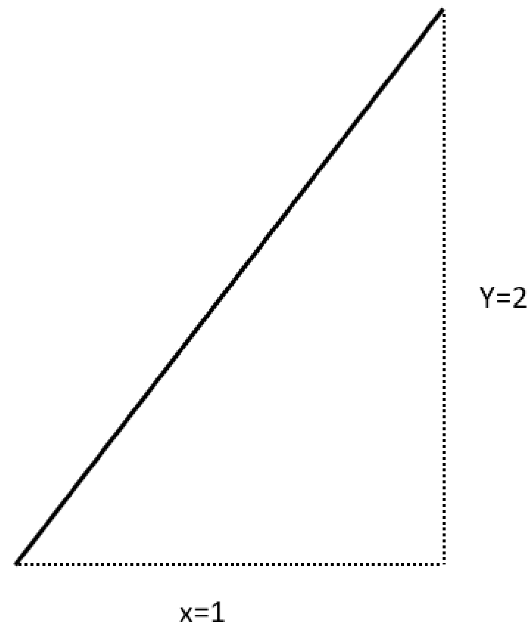

Figure 50: Decomposition of diagonal line

As shown in the figure, each diagonal line is written by moving both stepper motor in horizontal and vertical direction by the amount of x and y in each increment, the x and y is calculated from the slope of the diagonal line.

The function of writing diagonal line have the following inputs:

Table 10: Diagonal line writing function inputs

Write_diag	
Starting Position	The starting position of the diagonal line
Ending Position	The ending position of the diagonal line
X direction Increment	Steps the x direction step motor rotates in each increment
Y direction Increment	Steps the x direction step motor rotates in each increment

The starting and ending position set up the limit of motor for the stepper motors, the the x direction increment and y direction increment tell the stepper motor how much to rotate for each round until it gets to the ending position.

6 Summary and Discussion

Our goal for this project was to create something practical and innovative. The idea for our project was conceived while paying close attention to long lectures where a professor would pause mid-lecture to erase the whiteboard after filling the entire space. This pause breaks the rhythmic flow of teaching and learning. We saw the potential opportunity to fix this problem. It is much more efficient to have a machine that promptly erases the board. During winter quarter, we worked to develop a design for a writing/erasing robot. During this design phase, we decided to implement a writing feature to the design. The writing/erasing robot (W.E.B) consists of three systems: a carriage that erases and writes, a system for translating vertical and horizontal motion, and a user interface to select areas of the board to erase.

By the end of spring quarter, we successfully fabricated a writing/erasing robot (W.E.B.). Throughout the design process we attempted to uphold the ASME ethical standard of holding paramount the safety, health, and welfare of the public. We installed support brackets for the motor and used screws with high safety factor to support the design. We used our knowledge and skill to design the project in accordance with the goals and objectives delineated at the beginning of the report. For the project objectives, we designed something practical. The design contains a carriage with erasing and writing features. The erasing feature completely erases the user selected areas. The writing feature is able to write block letters and numbers. The design contains an interface to communicate via wifi. The one project objective we failed to deliver on was easy attachment of the design to everyday whiteboards. For team objectives, we were able to achieve most of our project objectives without reducing specifications and expectations. The only aspect for which we reduced specifications was writing; we were unable to code for writing curves so coded solely for block letters and numbers. We finished the project on time and in budget. Lastly, we maintained an organized record of all of our work. For individual objectives, each member grew responsibility as a team member and developed valuable skills as a result of the project. As mechanical engineers, we have to done our best to uphold and advance the integrity, honor and dignity of the engineering profession by "using our knowledge and skill for the enhancement of human welfare" [7]. W.E.B. address the unmet need for a better way to clean whiteboards. We have used our knowledge as engineers to ensure that this product functions properly. Also we have designed the product ethically, making sure that it will not pose any danger to the public.

To bring W.E.B to the market, we need to address some failure modes. First, we would need to integrate a set of sensors to stop the motion of the device if something is impeding its path. Second, we would need to install some small casings around the motor to prevent the belt from slipping. During testing, there was a small amount of slipping which does not cause any harm to the public. Lastly, we would need to design a casing so that wires and pulleys are not exposed. Adding a casing would also increase the aesthetic appeal of W.E.B. Our hope is that W.E.B. will one day be on every board across all campuses of the world.

7 Conclusions and Recommendation

With our robot, we have not only created a whiteboard eraser/writer, which will aide in the facilitation of lectures, but we have essentially created a plotting system that can map itself over an XYZ plane. This precision not only requires extensive control testing, but also could be used for more than just whiteboards. This is essentially the start of a CNC machine, and the groundwork for modern research in robotic surgery. While this project is nowhere near as advanced, the control of it over a designated space implies the beginnings of this cutting edge research.

As with every project, there are several opportunities to improve our robot. Our first improvement we would work on is to implement full writing capabilities. Our current design only includes block letters, so curved letters with various fonts and font sizes would drastically improve the aesthetic of our project. Additionally, we are only able to erase a portion of the board divided into 9 parts. Improvements would be more control over which parts of the board are erased. Another possible improvement, although not one of our initial goals, is to have better packing design. Our current design has the bracket screws in hard to reach places in order to minimize the space it takes up. By moving the screws into easier places, we can also facilitate a removal of the carriage to allow for easier access when switching the dry erase marker and eraser. Other improvements include finding better springs with more consistent k values, using gears instead of a gear belts, and switching the design from cylindrical holders for the pen and eraser to square/rectangular designs to limit the rotation of the eraser on the board. Finally, we would want to be able to control different motors at the same time, a problem we ran into with the arduino block control. The arduino blocking problem and easier facilitation of the robot onto other whiteboards are areas where future research would be needed in addition to time, while the other improvements would just be a matter of more time.

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9 Appendix

Appendix A: Methods of Erasing Pugh Matrix

The following chart represents a group evaluation for the optimal method of erasing for our project.

	Sound Wave	Car Wash	Chemical Reaction	Electro Magnetic	Heat Treatment
Perfectly erase chalk? (scale: 1-3) 1: Unlikely, 2: Okay, 3: Very Likely	2,2,2,2,1,2	3,3,3,3,3,3	3,3,3,3,3,3	2.5,2,2,2,2,2	2,2,1,1,1,1
Easy to manufacture(machine)? (scale: 1-3) 1: Hard, 2: Okay, 3: Easy	2,1,3,1,3,1	3,3,2,2,3,3	2,2,2,2,3,2	2,1,2,2,2,2	1,1,1,2,1,2

Easy to design? (scale: 1-3) 1: Hard, 2: Okay, 3: Easy	3,2,3,2,2,2	3,3,2,2,3,3	3,3,3,3,3,2	3,1,3,3,2,2	3,3,1,3,3,2
Research needed? (scale 1-3) 1: Lots of research needed 2: a bit research needed 3: Barely needed	3,2,2,1,2,2	3,2,2,1,3,2	2,2,2,3,2,2	2,2,2,2,2,1	1,2,1,3,3,2
Cost? (scale 1-3) 1: expensive (over $1000) 2: Okay (around $ 700) 3: cheap (less $700)	2,2,2,1,2,2	3,2,2,3,2,2	3,3,3,2,2,3	2,2,2,2,2,1	1,1,1,1,1,2
Can we test prototype by the end of Winter quarter? (scale either 0 or 2) 0: no 2: yes	2,2,2,2,2,0	2,2,2,2,2,2	0,2,2,2,2,2	2,0,0,2,2,0	0,0,0,0,0,0
Total Score	69	89	87	65.5	50

Appendix B: Final Expense Sheet

Table 11: Final Expense Sheet

Part #:	Part Name:	Title of Item:	Cost Per Unit:	Units:	Total Cost (+tax/shipping):
1	Spring (1 inch height)	0.72 Inch Outside Diameter, 0.047 Inch Wire, 1 Inch Free Length, Music Wire Compression Spring	$6.92	1	
2	Spring (2 inch height)	0.72 Inch Outside Diameter, 0.047 Inch Wire, 2 Inch Free Length, Music Wire Compression Spring	$6.98	1	$27.24
3	High Precision Linear Bearings	Mounted Linear Ball Bearing Fixed Alignment	$45.90	2	$105.15
4	Low Precision Linear Bearings	BQLZR SCS8UU Linear Motion Ball Bearing CNC Slide Bushing 34.5mm Length Pack Of 4	$6.80	2	$13.60
5	Linear Shafts	3pcs 8mm X 1 Meter Precision Chromed Linear Shaft Rod for 3D Printer CNC Oil	$49.99	2	$108.96
6	Linear Shaft Supports	SK8 8mm Linear Rail Shaft Guide Support CNC Aluminium Axis 4pcs/set	$10.98	2	$21.96
7	Logic Level Converter	Logic Level Converter Bi-Directional Module 5V to 3.3V for Arduino	$7.75	1	$7.75
8	AC Power Adapter	AC Adapter, YIFENG 12V 2A Switching Power Supply Adapter for 100V-240V AC 50/60Hz	$7.99	1	$7.99
9	Arduino Power Adapter	ZOZO™ 12W 3V-12V Regulated Multi Voltage Switching Replacement Power AC Adapter for	$10.98	1	$10.98
10	Timing Pulley	Anycubic XL Type 36 Teeth Alumium Timing Pulley 8mm Bore Synchronous Drive Belt Wheel	$10.98	3	
11	Servo Motor	Futaba S3010 High Torque (HT) Standard Size Ball Bearing (BB) Servo	$22.99	1	
12	X-Motion Stepper Motors	NEMA 23 CNC Stepper Motor 2A 125oz-in.	$17.95	2	
13	DC Power Supply	New DC 24V 15A Switching Power Supply Transformer Regulated for Cctv, Radio, Computer Project	$21.99	1	
14	Hoizontal Timing Belt	Mercurry 10 Meters GT2 timing belt width 6mm Fit for RepRap Mendel Rostock Prusa GT2-6mm Belt	$14.88	1	
15	Screws	290pcs M3 Phillips Pan Head Screws Bolts Nuts Lock Flat Washers Assortment	$11.99	1	
16	Motor Driver	DRV8825 High Current Stepper Motor Driver Carrier	$8.49	1	$157.33
17	Z-Motion Stepper Motor	NEMA 23 CNC Stepper Motor 2A 125oz-in.	$17.95	1	$17.95
18	Vertical Timing Belt	3GT (GT2-3M) Timing Belt - By the Foot	$3.25	14	$60.40
		TOTAL COST OF PROJECT:			**$539.31**

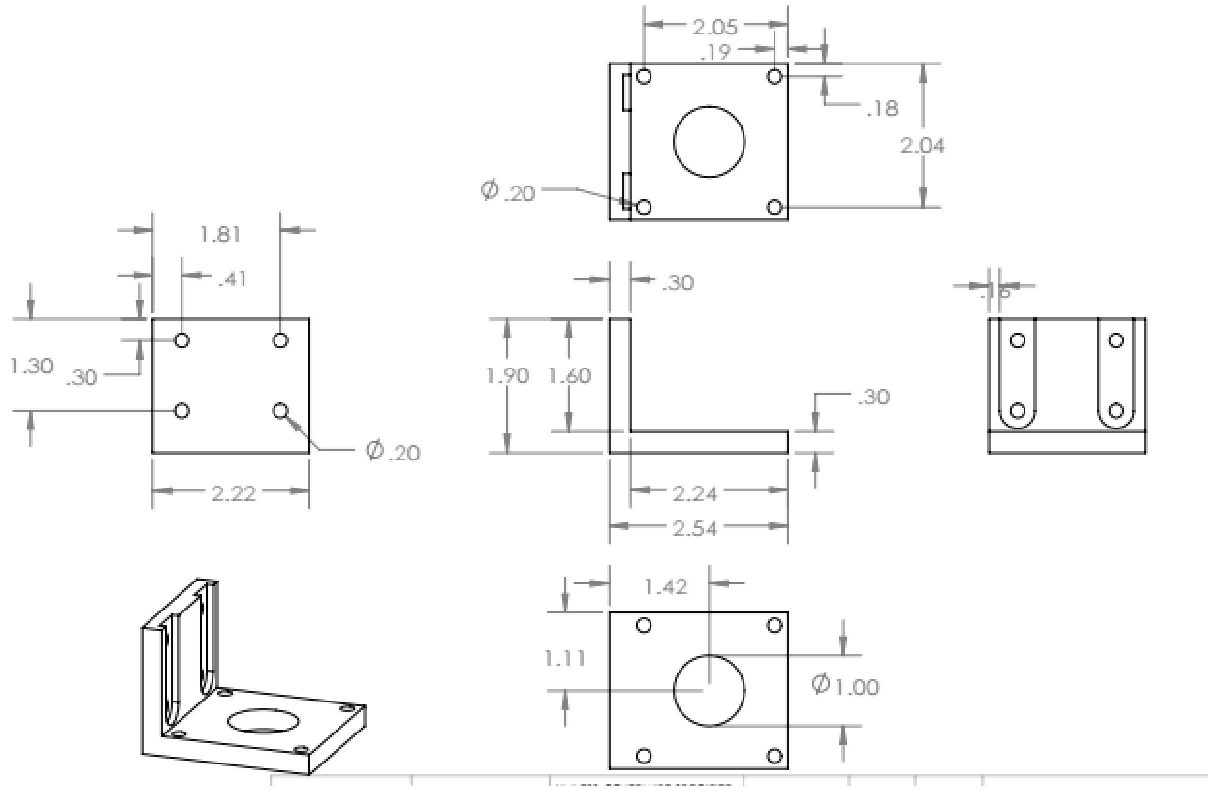
1	https://www.mscdirect.com/product/details/06812598?rItem=06812598
2	https://www.mscdirect.com/product/details/06812614?rd=k&searchAhead=true&searchAheadTerm=06812614&typahddsp=06812614&hdrsrh=true
3	https://www.mcmaster.com/#9338t51/=17r6ftf
4	https://www.amazon.com/BQLZR-SCS8UU-Linear-Bearing-Bushing/dp/B00IJ67BJA/ref=pd_sim_236_1?_encoding=UTF8&pd_rd_i=B00IJ67BJA&pd_rd_r=9J2DNHJZP9PN2QH20W11&pd_rd_w=VpoeR&pd_rd_wg=5kNil&psc=1&refRID=9J2DNHJZP9PN2QH20W1
5	https://www.amazon.com/Meter-Precision-Chromed-Linear-Printer/dp/B00Z8W4FB0/ref=sr_1_2?ie=UTF8&qid=1487379377&sr=8-2&keywords=8mmx1m+linear+shaft
6	https://www.amazon.com/Mercurry-Details-Linear-Support-Aluminium/dp/B01HGIWF06/ref=sr_1_1?s=industrial&ie=UTF8&qid=1488955900&sr=1-1&keywords=8mm+linear+support
7	https://www.amazon.com/gp/product/B014MC1OAG/ref=oh_aui_detailpage_o05_s00?ie=UTF8&psc=1
8	https://www.amazon.com/gp/product/B01D4XP6I0/ref=ox_sc_act_title_1?ie=UTF8&psc=1&smid=A2K6PNQKOKYWYC
9	https://www.amazon.com/gp/product/B015PXUHYA/ref=oh_aui_detailpage_o00_s00?ie=UTF8&psc=1
10	https://www.amazon.com/gp/product/B01C9RW4S2/ref=oh_aui_detailpage_o04_s01?ie=UTF8&psc=1
11	https://www.amazon.com/gp/product/B0015H1BUK/ref=ox_sc_act_title_1?ie=UTF8&psc=1&smid=ATVPDKIKX0DER
12	https://www.amazon.com/gp/product/B01BPN6996/ref=oh_aui_detailpage_o04_s03?ie=UTF8&psc=1
13	https://www.amazon.com/gp/product/B00ANFJ26U/ref=oh_aui_detailpage_o04_s03?ie=UTF8&psc=1
14	https://www.amazon.com/gp/product/B01E91K4N8/ref=ox_sc_act_title_2?ie=UTF8&psc=1&smid=A1C9GJC0E5I4EM
15	https://www.amazon.com/gp/product/B01K6NNYZ8/ref=oh_aui_detailpage_o04_s03?ie=UTF8&psc=1
16	https://www.amazon.com/gp/product/B00B9G8CAE/ref=ox_sc_act_title_2?ie=UTF8&psc=1&smid=A2XU70B31JRNMP
17	https://www.amazon.com/gp/product/B01BPN6996/ref=oh_aui_detailpage_o04_s03?ie=UTF8&psc=1
18	http://openbuildspartstore.com/3gt-gt2-3m-timing-belt-by-the-foot/

Appendix C: Stepper Motor Test Code

```
#include <Stepper.h>\\Using Stepper Librar
int dPin = 4;\\Direction Pin number on Arduino
int sPin = 5;\\Step Pin number on arduino
int ePin = 6;\\Enable Pin number on Arduino
int stpRev = 200;\\Total Number of steps for our motor
Stepper myStepper = Stepper(stpRev,dPin,sPin);\\Creating a Motor Object
void setup() {
  myStepper.setSpeed(180);\\Setting motor speed
  Serial.begin(9600);\\Opening Serial Prompt
}
void loop() {
  // put your main code here, to run repeatedly:
  Serial.println("Clockwise");\\Prints to Serial
  myStepper.step(10*stpRev);\\telling motor to rotate 10 revolutions
  delay(500);

  myStepper.step(-10*stpRev);\\Telling motor to rotate 10 revolutions in the opposite direction
  delay(500);
}
```

Appendix D: Motor Mount Bracket Engineering Drawing



Appendix E: Pulley Mount Bracket Engineering Drawing