Hands-free Electric Skateboard

ELECTRICAL ENGINEERING DEPARTMENT

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June 2021

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ABSTRACT

An electric skateboard functions as a skateboard propelled by electric motors. It is usually controlled with a handheld controller. This project describes an electric skateboard controlled via weight distribution. To accelerate, the rider leans forward, and to decelerate, the rider leans backward. It can travel 17 miles per hour and has regenerative braking to recharge the battery.

CHAPTER 1. INTRODUCTION

Chapter 1 discusses the background of electric skateboards. It also discusses important factors to consider while purchasing or building an electric skateboard.

Louis J. Finkle patented the first electric skateboard in 1999 with his first boards inefficient and expensive which made them hard to sell [1]. Therefore, electric skateboards slowly made their way into the market. The electric skateboard industry skyrocketed in recent years partly attributed to the increase in battery energy density. This allows for longer range and more power with a smaller battery. The energy density of commercial batteries increased about 3Wh/kg annually between 1950 and 2010 [2]. Between 1990 and 2010, this figure jumps to 5.5Wh/kg due to the invention of the lithium-ion battery [2]. John B. Goodenough, M. Stanley Whittingham, and Akira Yoshino received the 2019 Nobel prize due to their contributions in the field. This proves how much technology goes into the developing lithium-ion batteries.

Many electric skateboard companies popped up during the 2010's including Boosted in 2012 [3], Evolve in 2012 [4], and Meepo in 2017 [5]. All three of these companies had promising beginnings, but Boosted went out of business in 2020 due to increased tariffs from the trade war with China [3]. Evolve and Meepo both continue to produce and sell electric skateboards.

Electric skateboards pose many dangers which can lead to fatal wounds. California put several laws in place to minimize motorized skateboard injuries while still allowing the freedom to own one. California defines limitations on electric skateboards in the California Vehicle Code [6].

Neither Meepo, nor Evolve sell an electric skateboard that meets these requirements out of the box. They all either fail the 1,000-watt requirement, or the 20mph requirement. This means that skateboards from these two major companies need modifications for legality in California. Additionally, very few hands-free electric skateboards exist.

CHAPTER 2: PROJECT PLANNING

This chapter focuses on the plan of the entire project which includes the customer-engineer dialogue. First, the customer supplies their needs, and the engineer makes specifications. Then, to gain a better understanding of the plan, the engineer creates a functional decomposition of each subsystem. Finally, a Gantt chart and cost estimates give the customer an idea of how long the project takes and how much it costs.

2.1 Customer Needs, Requirements, and Specifications

This section focuses on the needs and requirements given by the customer and the engineering specifications to the given needs. Good communication between customer and engineer allows for a streamlined process with no ambiguities. The customer gives the engineer an idea of what they want, and the engineer creates the engineering specifications to meet the request.

2.1.1 Customer Needs Assessment

The main customers for this device want a thrilling way to get around town or simply want a fun, recreational device. Potential customers also include people who want a power efficient "last mile" device to commute. California law restricts many aspects of this project, so the first and most important customer requirement includes making this product legal in California.

This board has a more natural feeling than those with hand-held controllers to provide the user with a more thrilling experience. The compact nature of this product makes it easy to carry and its durability allows it to survive the toughest of crashes.

2.1.2 Requirements and Specifications

TABLE I

HANDS-FREE ELECTRIC SKATEBOARD REQUIREMENTS AND SPECIFICATIONS

Marketing Requirements	Engineering Specifications	Justification
1	Max speed 20 mph	California Law [6]
1	Average Power does not exceed 1000 W	California Law [6]
1	Resembles a skateboard (A board attached to 4 wheels via skateboard trucks) where dimensions do not exceed 60" x 18" x 6"	This describes what the product should look like and California Law [6]
2, 6, 7, 9	Hub motors capable of regenerative braking	Motors propel board and regenerative braking improves battery life

7, 8	Total weight less than 20 lbs.	Weight of popular boards in the market [4] [5]
2, 5, 6	Between 120 and 180 watt hour Lithium ion battery pack with BMS	Large enough for the desired range (10 miles). [4] small enough to carry on in a plane
7, 8	100-130Vrms 55-65Hz input to 42V, 2A output charging	Charged from an average U.S. outlet and accounts for variations in voltage and frequency
7, 8	Optional mounting location for charger	Allows the rider to mount the charger to reduce the number of pieces, or to take it out for a lighter board.
4, 8, 9	Controlled via weight shifting (lean forward to accelerate and lean backwards to decelerate)	Makes the device more fun, gives it a more natural feeling and eliminates the need for a handheld controller.
4, 8, 9	Ensure that board does not accelerate or decelerate while the rider only has one foot on, and stops when rider dismounts	Makes the device safer and easier to use
3, 4, 5	Deck and trucks strong enough to support up to 250 lbs	Skateboard and electronics can support a wide variety of riders
3, 5	Shock protectors for protection on crashes up to 20 mph.	Withstand crashes.
3, 4, 5	Circuits and batteries have shock dampeners contained within a water-resistant protective housing	Further minimizes shock transferred to electronics and protects the electronics
10	Parts and manufacturing cost under $500	Makes the board affordable

Marketing Requirements

1. Legal to ride in California
2. Range of 10 miles
3. Able to withstand crashes at 20 mph
4. Supports 150 – 220 lb rider
5. Water resistant
6. Power efficient
7. Compact
8. Easy use
9. Natural Feeling
10. Affordable

Table I above shows the marketing requirements and engineering specifications for the electric skateboard. The specifications follow the ACME engineering test and outline the entirety of the project. The marketing requirements derive from the customer needs and other safety factors. Each item in the justification column describes the reasoning behind the specifications.

2.2 Functional Decomposition

This section shows the breakdown of the project at 2 different levels. Level 0 shows the entire system and level 1 shows the 4 main subsystems within. Each table describes the associated systems inputs, outputs, and functionality.

2.2.1 Level 0 Decomposition

Table II and figure 1 show the entire system as a single block with inputs and outputs. The only outputs include speed and acceleration. Weight distribution controls the device, so the inputs include weight distribution and the power. The inputs also include speed and acceleration to create a feedback loop to create a stable system. An additional input incorporates the energy reclaimed during regenerative braking.

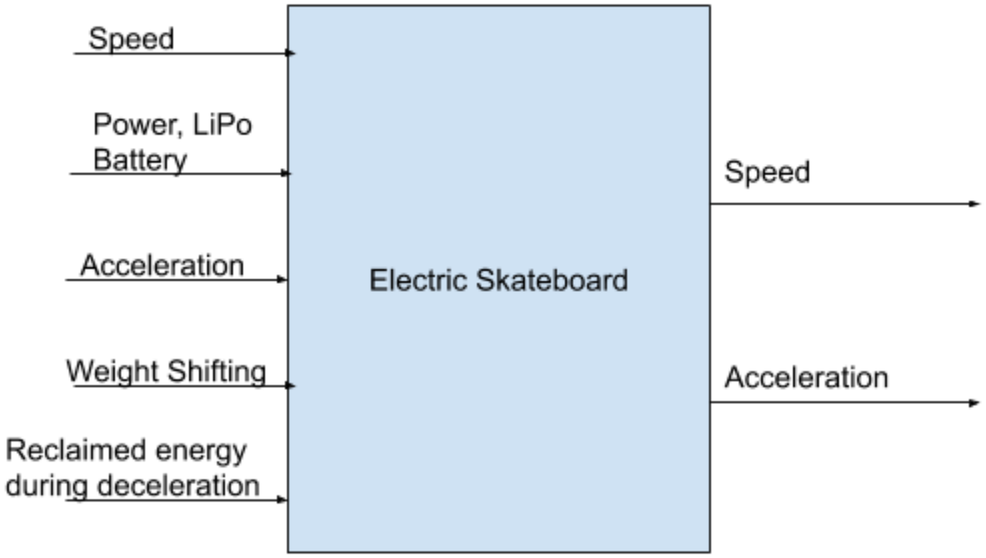


Figure 1: Level 0 block diagram

TABLE II

ELECTRIC SKATEBOARD MODULE BREAKDOWN

Module	Electric Skateboard
Inputs	Speed of the board, Power to the batteries during charging, Weight Shifting from user, Acceleration of board, Reclaimed Energy from regenerative braking
Outputs	Speed, Acceleration
Functionality	Skateboard powered by electric motors and controlled by the shifting of the rider's weight. When the rider leans forward (front foot), the board accelerates, and when the rider leans backwards (back foot), the board decelerates. The device charges via plugging it into a U.S. standard 120V wall outlet. Limits exist on speed and acceleration to make the design safe and easy to use.

2.2.2 Level 1 Decomposition

Figure 2 below shows the electric skateboard when broken down into the 4 main subsystems. The main modules consist of the weight sensors, the power circuitry, the motor control circuitry, and the motors themselves. Tables III through VI below examine each functional block.

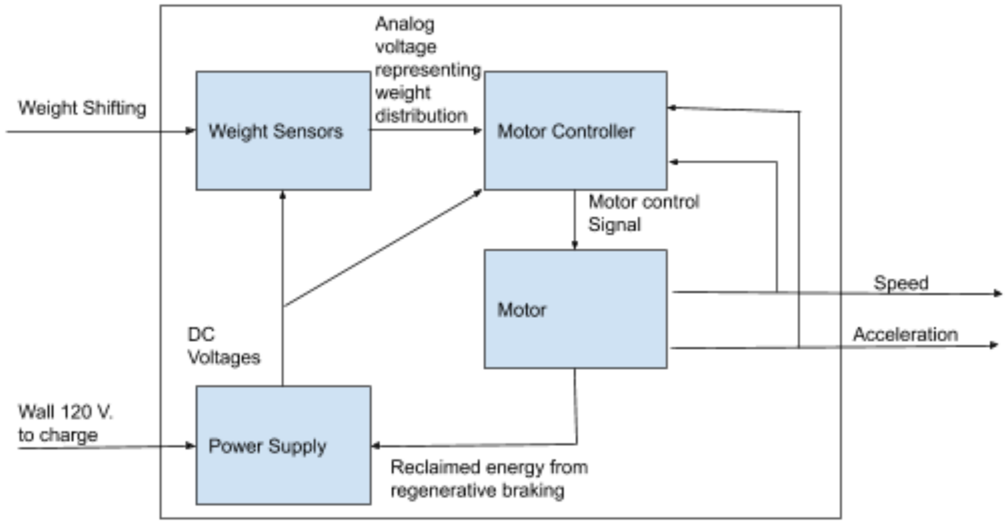


Figure 2: Level 1 block diagram

TABLE III

WEIGHT SENSORS MODULE BREAKDOWN

Module	Weight Sensors
Inputs	Weight shifting, sensor supply voltage
Outputs	Voltage representing weight distribution
Functionality	Converts weight shifting into a usable voltage signal

Table III breaks down the weight sensor module. This module uses a physical sensor to detect the weight shifting, and a subcircuit to amplify this signal for the microcontroller. The inputs for this subsystem consist of physical pressure and the supply voltage. The output represents the weight distribution via an analog signal.

TABLE IV

POWER SUPPLY MODULE BREAKDOWN

Module	Power Supply
Inputs	100-130Vrms 55-65Hz 1.5A
Outputs	Various DC voltages
Functionality	Stores electrical energy and supplies the components with their required power

Table IV shows the breakdown of the power supply. Delivering the proper voltage and power to each circuit outlines this module's primary function. The voltage for each circuit varies, so this module includes 2 DC-DC converters. This module also includes the batteries as well as a charging circuit. This module has several DC-DC converters, an AC-DC converter, and protection circuitry for the batteries.

TABLE V

MOTOR CONTROLLER MODULE BREAKDOWN

Module	PID Controller
Inputs	Speed, Acceleration, Power, Control signal to represent weight distribution
Outputs	Motor control signal
Functionality	Use the given inputs to determine the voltage supplied to the motor which determines its speed

Table V shows the breakdown of the motor controller, responsible for smoothly controlling the speed and acceleration of the skateboard. Limits exist for both speed and acceleration to ensure the safety of the rider. It includes a high-power section to drive the motors, and a low-power section to do the calculations.

TABLE VI

MOTORS MODULE BREAKDOWN

Module	Motors
Inputs	Power voltage / motor control signal
Outputs	Speed, Acceleration
Functionality	Converts the motor voltage into physical power to rotate the wheels

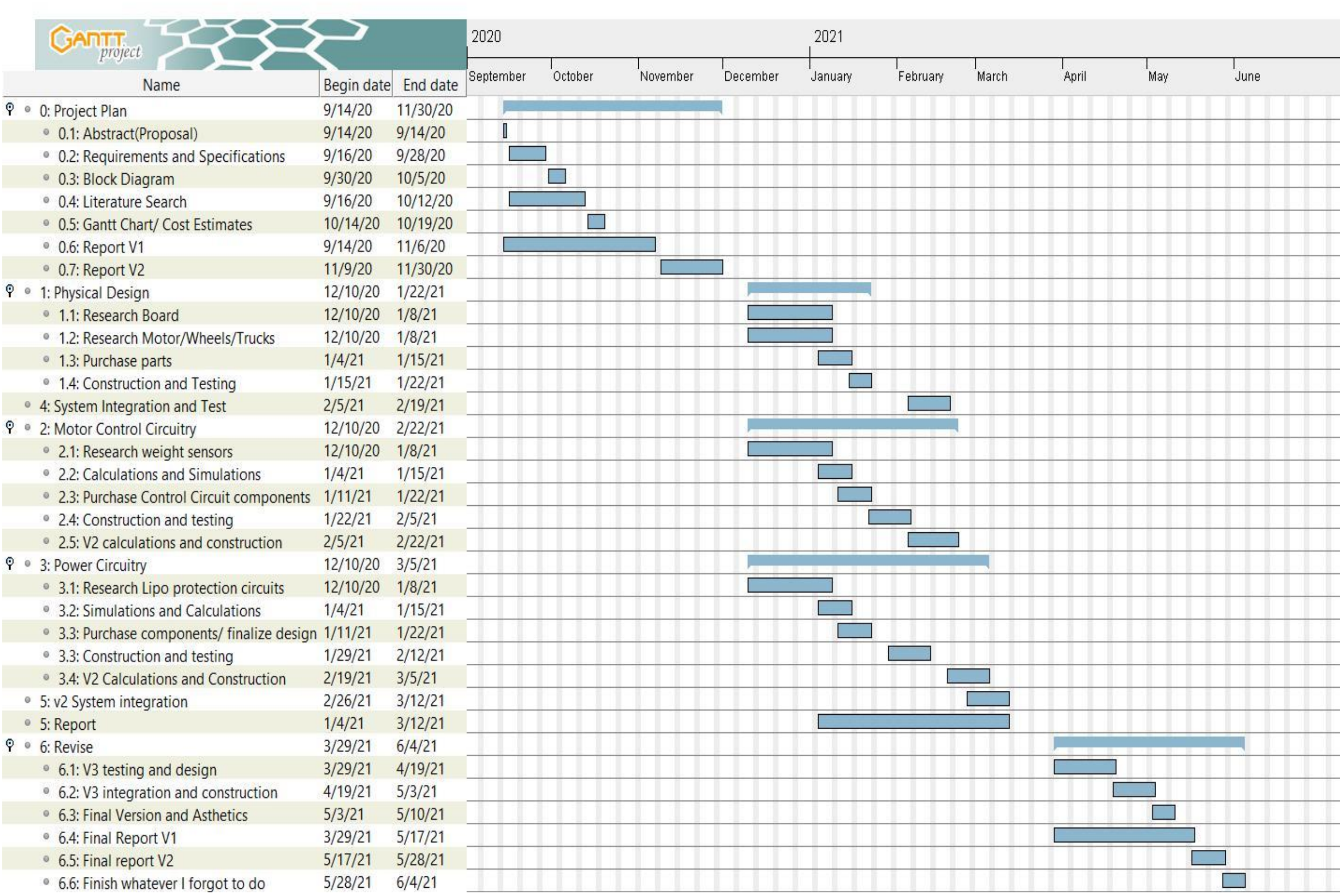
Table VI shows the breakdown of the motors. The motors make up the final module and provide less opportunities than the other aspects of this project, meaning that mainly everything depends on the motors.

2.3: Gantt Chart

Labor put into the research, design, and test phases provides the biggest cost. Most of the labor goes into designing the motor controller. The most expensive parts include the motors, battery pack, and skateboard deck/ trucks. These limit the future profits. Using the formulas below, I created the time estimate and cost estimate tables (table VII and table VIII).

$Cost = \frac{cost_a + 4cost_m + cost_b}{6}$ (eqn. 2.1) $t_e = \frac{t_a + 4t_m + t_b}{6}$ (eqn 2.2)

During winter break, the research phase begins. Purchasing the deck, motors, trucks, and wheels happens during the beginning of winter quarter. Purchasing the power circuitry also happens around the same time. This gives time to test the motors to ensure the control design works. Purchasing and testing the control components takes about 2 weeks. A functioning prototype should appear well before the end of winter quarter. This leaves enough time during the winter quarter to have two sub-system, system integration, and test cycles during EE 461. The final version and finalizing the report happens during the end of the school year during EE 462.



Name	Begin date	End date
0: Project Plan	9/14/20	11/30/20
0.1: Abstract(Proposal)	9/14/20	9/14/20
0.2: Requirements and Specifications	9/16/20	9/28/20
0.3: Block Diagram	9/30/20	10/5/20
0.4: Literature Search	9/16/20	10/12/20
0.5: Gantt Chart/ Cost Estimates	10/14/20	10/19/20
0.6: Report V1	9/14/20	11/6/20
0.7: Report V2	11/9/20	11/30/20
1: Physical Design	12/10/20	1/22/21
1.1: Research Board	12/10/20	1/8/21
1.2: Research Motor/Wheels/Trucks	12/10/20	1/8/21
1.3: Purchase parts	1/4/21	1/15/21
1.4: Construction and Testing	1/15/21	1/22/21
4: System Integration and Test	2/5/21	2/19/21
2: Motor Control Circuitry	12/10/20	2/22/21
2.1: Research weight sensors	12/10/20	1/8/21
2.2: Calculations and Simulations	1/4/21	1/15/21
2.3: Purchase Control Circuit components	1/11/21	1/22/21
2.4: Construction and testing	1/22/21	2/5/21
2.5: V2 calculations and construction	2/5/21	2/22/21
3: Power Circuitry	12/10/20	3/5/21
3.1: Research Lipo protection circuits	12/10/20	1/8/21
3.2: Simulations and Calculations	1/4/21	1/15/21
3.3: Purchase components/ finalize design	1/11/21	1/22/21
3.3: Construction and testing	1/29/21	2/12/21
3.4: V2 Calculations and Construction	2/19/21	3/5/21
5: v2 System integration	2/26/21	3/12/21
5: Report	1/4/21	3/12/21
6: Revise	3/29/21	6/4/21
6.1: V3 testing and design	3/29/21	4/19/21
6.2: V3 integration and construction	4/19/21	5/3/21
6.3: Final Version and Asthetics	5/3/21	5/10/21
6.4: Final Report V1	3/29/21	5/17/21
6.5: Final report V2	5/17/21	5/28/21
6.6: Finish whatever I forgot to do	5/28/21	6/4/21

Figure 3: Project Gantt Chart

Figure 3 shows the project Gantt chart. This serves as a visual representation of the project workflow. It helps maintain organization and shows important deadlines.

2.4: Cost Estimates

TABLE VII

TIME ESTIMATES

	Shortest time (ta)	Expected time ™	Longest time (tb)	Final time	Explanation
Time per week	5	10	30	12.5	Shortest time based on time worked this quarter. Expected and longest time estimates
Total over 30 weeks				375	Project spans over 3, 10-week quarters

Table VII shows the project time estimates. The Gantt chart in figure 3 breaks down these times further. The final time derives from Eqn. 2.2 above.

TABLE VIII

COST ESTIMATES

Part	Best cost (Ca)	Expected Cost (Cm)	Worst cost (Cb)	Total	Explanation
Deck/Grip tape	$25	$50	$100	$54.17	Based on local skate shops
Wheels/ Trucks/ Motors	$80	$200	$300	$196.67	Prices found on Meepo [5] and eBay/ Amazon
Batteries/ BMS	$100	$150	$300	$166.67	Based on prices found on Meepo [5], Evolve [4], or custom battery pack with separately bought BMS [9]
Motor Controller	$20	$30	$120	$43.33	I already have a substantial amount of high power MOSFETs and a microcontroller if I do this digitally.[8] If I choose another route, the prices become estimates [7]
Power circuitry	$30	$30	$80	$38.33	Pre-Bought charger
Weight Sensors	$10	$20	$100	$31.67	Custom weight sensors using Velostat [10], or reliable store-bought ones [11]
Labor	$10125	$14625	$20250	$14812.5	Wages for an R&D engineer range between $27, $39, and $54 [12]. Applying this to the 375-hour time metric determined above gives the total cost
Total without labor				$530.83	
Total with labor				$15343.33	

Table VIII shows the estimated cost for each part and labor. The total costs derive from Eqn. 2.1.

CHAPTER 3. RESEARCH AND DESIGN

The most important development phases include the research and design phase because it defines the parts needed and time allocated. It also decides the components and their uses. This section takes the requirements and specifications and turns them into physical components.

3.1 Physical Board

The physical board describes the deck, the trucks, the wheels, and the motors. This section includes the motor because the motors and wheels are integrated and sold as one unit. The deck determines the flexibility of the board, its ground clearance, and its turning radius. Additionally, the trucks play a significant role in the turning radius. Bigger wheels and a longer deck allow for a smoother and faster ride.

3.1.1 Skate Deck

The board must remain stable at speeds up to 20 mph and have enough clearance to house the electronics. This means that the stable nature at high speeds and large wheel diameter make a longboard the best option. However, longboard shapes with low centers of gravity such as a drop-through or drop-down do not have enough space for the electronics. This project uses a pintail longboard which does not have these problems.

3.1.2 Motors/ Wheels/ Trucks

A DC motor works best for this project because the battery pack supplies DC, which eliminates the need for complex DC-AC converters. When comparing different DC motors, a brushless DC motor sounds like the best option for this application because of its efficiency and it has a higher torque-to-weight ratio than brushed DC motors [13]. Additionally, brushless motors require theoretically no maintenance as the rotor does not contact the stator except the shaft. This increases the overall durability and shelf-life of the board. The two main competitors for electric skateboard motors include belt driven and hub motors. Some advantages of hub motors over belt driven motors include less maintenance, lighter, and less resistance. This makes the system more durable, lighter, and gives the ability to free wheel. Due to these considerations, this project uses a hub motor. Some hub motors come with the wheel and trucks integrated, selling as one package. This project uses a motor with the part number "PROMOTOR PRO-SKU103-BK." This motor kit comes with the motor, wheels, and trucks integrated. It also has hall sensors for smooth startups, which influences the motor controller. This motor did not have a datasheet or resources besides the few specifications listed. The specifications and calculations shown below define the motors limits and how they will act.

$$kV\ rating\left(\frac{rpm}{V}\right) = 70kV\ , V_i = 37V, Wheel\ Diameter = 90mm\ ,$$

$$Max\ RPM = kV\ rating * V_i \qquad \text{(eqn. 3.1)}$$

$$= 70\frac{rpm}{V} * 37V = 2590\ rpm$$

$$Max\ Speed\ = rpm\ *\ Wheel\ Circumference(mm)\ * 6.214 * 10^{-7} \frac{mm}{mile} * 60 \frac{minutes}{hour}$$

(eqn. 3.2)

$$= 2590\, rpm * 282.74mm * 6.214 * 10^{-7} \frac{mm}{mile} * 60 \frac{minutes}{hour} = 27.3mph$$

This max speed exceeds our spec maximum speed; however, friction, slippage, and the code determine the final maximum speed. Therefore, the experimental final speed differs significantly.

3.2 Motor Controller

Brushless DC motors require specific timing to control, making the motor controller very important. Many brushless motors also contain hall sensors to determine the position of the rotor which ensure smooth starting. This project uses a brushless dc motor with hall sensors, so the motor contains various inputs and outputs. For this reason, using a prebuilt motor driver, and a programmable microcontroller offer the most convenience. This allows more focus on the weight sensors. These two subcircuits make up the motor controller for this board.

3.2.1 Hardware

This project uses DC brushless motors with internal hall sensors and the part number "PROMOTOR PRO-SKU103-BK." Each motor has 8 I/O's. The main factors for the motor driver(s) include compatibility, power, and price. The driver(s) must have hall sensor inputs and it must be controllable via microcontroller. The driver(s) must supply at least 42 V and 12 A per motor. For this reason, two motor drivers (one per motor) seem like the best option. This allows greater flexibility and control when integrating the motors and motor drivers. The motor drivers selected for the project have the label "*RioRand 400W 6-60V PWM DC Brushless Electric Motor Speed Controller with Hal,"* purchased from Amazon. These fit all the requirements for the motor drivers, including low cost. However, due to the lack of documentation, a substantial amount of testing ensures their usability. Figure 4 below shows all the available information on this motor driver, except the 60 V limit and 20 A limit.

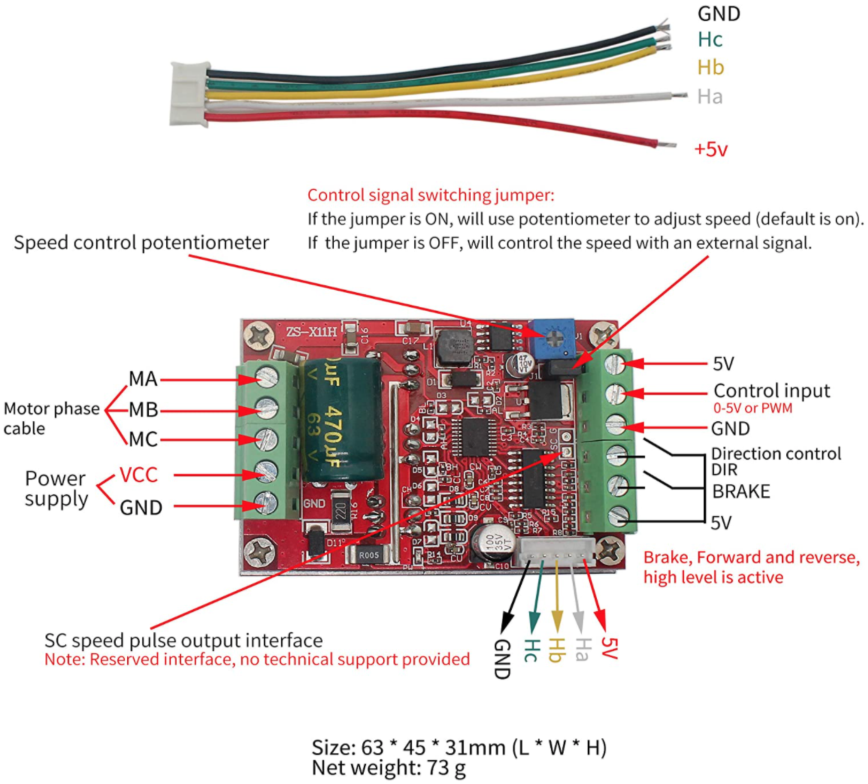


Figure 4: RioRand 400W 6-60V PWM DC Brushless Electric Motor Speed Driver with Hall "Datasheet"[18]

3.2.2 Software

This project uses an Arduino IDE compatible microcontroller because of their ease of use. The microcontroller receives power from the 5 V output ports on the motor drivers. Two analog inputs exist from the weight sensors to the Arduino, and one PWM output to control both motor drivers. One digital output exists for the brakes that go to both motor drivers. Two digital outputs exist for the motor direction, each sent to one motor driver. The motors spin in different directions relative to each other, so the controller receives different direction values from the microcontroller.

This code first takes the raw analog value from the weight sensors and normalizes it. After that, the values go through an algorithm to determine the output direction bit, brake bit, and PWM value. These outputs go to the motor drivers which dictate the speed, acceleration, and direction of rotation.

3.3 Battery Pack

The battery pack supplies power to every subsystem on the board, so its reliability is crucial. The motors selected have an input voltage of 24-42 volts, and an input current of about 12 watts, so the battery pack must satisfy these requirements. Additionally, they must store enough charge for a range of 20 miles. Common batteries for electric skateboards include Lithium-ion and lithium-polymer due to their high energy density and fast charge/ discharge rate. This project uses lithium-ion due to their versatility and durability. The two battery sizes chosen to test are a 10S1P or 10S2P setup. A 10S1P contains 10 batteries in series which raises the voltage by ten times while keeping the storage (Ah) constant. A 10S2P consists of 10 batteries in series with 2 in parallel for 20 batteries total. Putting 10 3.7 V lithium ion 18650's with 9.8Ah in series gives the voltage of 37 V. Putting two of these in parallel gives a voltage of 37 V and 19.6 Ah. Solving for the final storage of the batteries by multiplying the Ah and V gives 725 Wh. This theoretically gives a range of slightly over 20 miles for a 200 lb rider [14].

Several cells in series require a circuit so the cells charge and discharge to the same voltage. The batteries also require protection against thermal runaway. The solution to these problems comes in a compact PCB called a battery management system (BMS). For this project, the BMS must manage 10 lithium-ion cells in series with a maximum current of 20A. A simple BMS rated for 10S (37V) and 30A from Amazon provides protection for the batteries; however, due to the lack of documentation, a substantial amount of testing is needed.

3.4 Weight Sensors

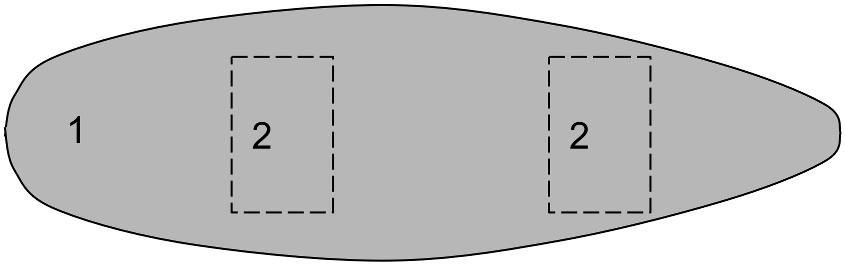
This project uses one of the following sensor options: premade or custom-made. Premade weight sensors come with drawbacks such as high cost, large size, and limited customization options. Their benefits include reliability and more documentation. The inexpensive approach uses custom made weight sensors which offer the main benefit of versatility. Electrical weight sensors depend on materials with that vary resistances with changes in shape. This includes twisting, compressing, and stretching. By applying a small voltage across this material and measuring its change, one can determine the weight of an object. Premade versions consist mainly of strain gauges and custom-made versions typically use Velostat. Strain gauges measure the bending of a metal which makes them bulky and unsuitable for this application. Velostat is a lightweight plastic-like material that varies resistance with deformation. The customizable nature and small size of Velostat makes it the ideal material for this project. Because of their finicky nature, an essential part of their success is substantial testing and calibration.

3.5 Final Design

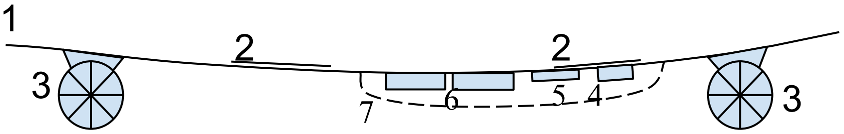
The final design should resemble a durable, sleek, and fun electric skateboard controlled via weight shifting. The electric components attach underneath the board except for the weight sensors. This ensures their protection if a crash occurs. The board flexes when an individual stands on it, so additional care must be taken when mounting the electronics. For example, the battery pack must have enough flexibility to bend with the board. The case for the electronics must protect them from crashes and other hazards, so they consist of plastic. Grip tape covers the top of the board, so the rider does not slip off. Markings on the top on the board determine the locations of the weight sensors to ensure the rider stands in the correct location. Figure 5 below shows a sketch of the top view and side view of the final product.

<u>Legend</u>

1. Deck
2. Weight Sensor
3. Wheels/ Motors/ Trucks
4. Motor Drivers
5. Arduino
6. Battery Pack
7. Electronics Cover



a. Top View



b. Side View

Figure 5: Final Configuration Sketch Top View and Side View

CHAPTER 4. CONSTRUCTION AND TESTING

After researching and designing this project, building and testing it is the next step.

4.1 Physical Board

The board was constructed by simply bolting the trucks to the board. I purchased the board from craigslist for $15 due to its low-cost. Structural integrity testing consisted of a full-grown man standing on it and jumping a few times.

4.2 Motor Controller

The hardware went through three distinct version due to power issues. The first version uses an Arduino Uno as the microcontroller and versions two and three use a Seeeduino XIAO. The microcontroller takes the raw data from the weight sensors, performs calculations, then outputs a PWM signal to the motor drivers. All three of these versions are programmed using the Arduino IDE and the only software differences between the XIAO and Uno are the pins used.

4.2.1 Hardware

The first version offers many benefits because of the Unos 5V I/O pins. First, it allows the weight sensors to be powered by 5 V which gives more resolution than 3.3 V. Second, it outputs a 5 V PWM signal which matches the recommended input value for the motor driver boards. This eliminates the need to amplify or attenuate the signal and makes the circuit simple. This version consumes more power than the 5 V pins from the motor drivers and this causes unreliable behavior such as shutting down completely.

To fix the power consumption problem, the second version implements a Seeeduino XIAO microcontroller. The 3.3V I/O pins on the XIAO do not allow for direct communication with the motor drivers because it needs a 5V PWM signal. An amplifying circuit placed in between the microcontroller output and the motor drivers input solves this problem. A seemingly simple solution uses the TX0108E logic level converter. This chip sounds perfect because it converts between known logic levels. In this case it converts 3.3V to 5V; however, it did not convert reliably and lead to more problems.

For the third and final version, instead of using the TX0108E logic level converter, this version uses 2 CMOS inverters as digital amplifiers. This version proved superior in both power consumption and usability. Appendix B shows the final application of the hardware.

4.2.2 Software

The software uses the Arduino IDE because of its ease and versatility. The Arduino IDE can upload programs to the Uno natively and with a few modifications found online, it can upload programs to the XIAO. The first version of the code, originally written for the Uno, works on the XIAO by simply changing a few pins. To accomplish this, one must look at both datasheets and ensure the pins can provide the necessary functionalities.

4.3 Battery Pack

The battery pack is constructed by spot welding 10 LiPo batteries in series and 2 in parallel to provide 37V as outlined in the design. The BMS connects to the main negative terminal and the main positive terminal and every positive terminal of the batteries. Figure 6 below shows the schematic. Testing the battery under a medium load by controlling the board shows that on a flat surface, it reliably provides about 10A at 37V.

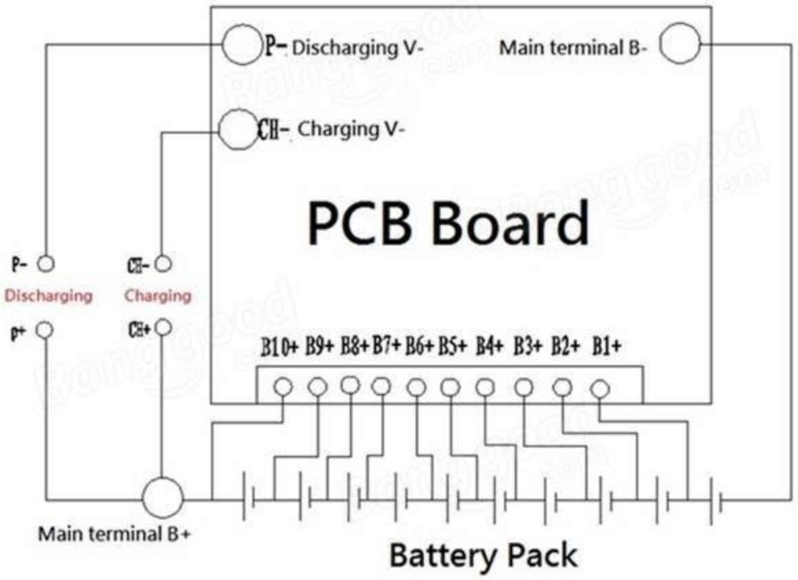


Figure 6: Battery Pack Schematic

Originally, the batteries followed the 10S1P configuration shown in figure 6 above. However, it needed an additional 10 batteries in parallel to increase the capacity. The final battery pack as two cells in parallel everywhere there is one cell in figure 6.

4.4 Weight Sensors

The weight sensors consist of Velostat, tinfoil, nickel strips, and electrical tape because of their low cost and high versatility.

4.4.1 ConfigurationV1

Figure 7 shows the original weight sensor design. It consists of a piece of Velostat with nickel strips on opposite ends in-between between 2 layers of electrical tape. Each nickel strip connects to a wire to create the contact for the microcontroller. The pressure in the middle should cause the resistance to change, resulting in a different voltage reading.

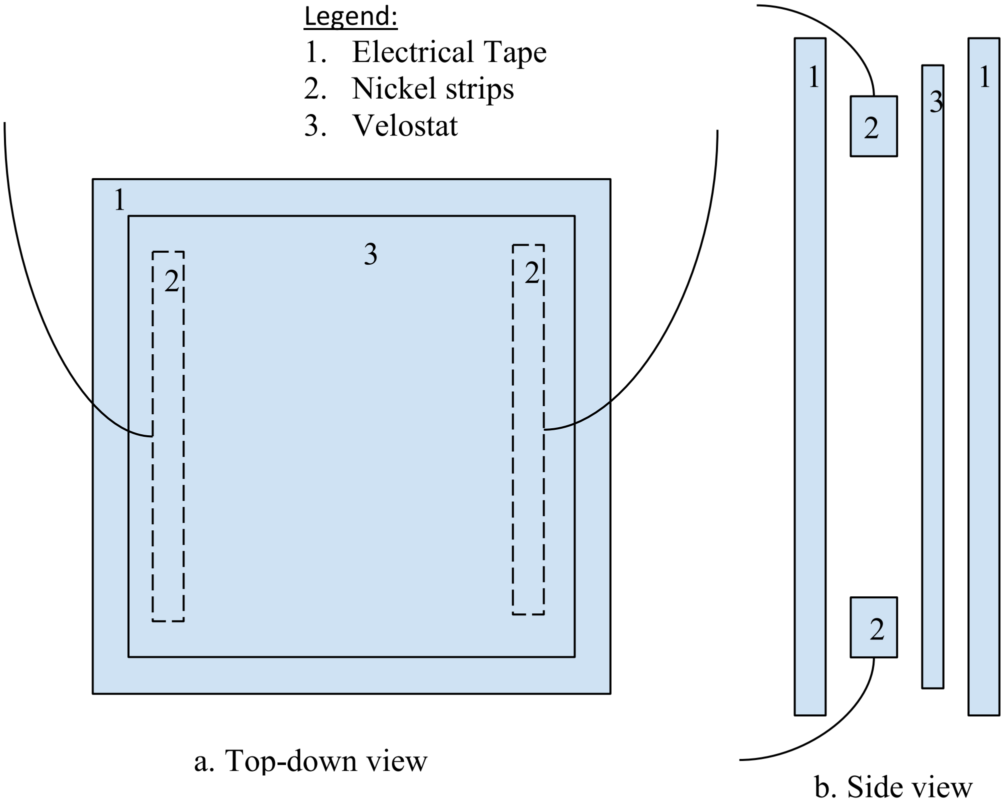


Figure 7: Weight Sensor V1

Figure 8 shows the layout of the weight sensors. They connect to each other with one end being positively charged, and the other end grounded. Measured at the middle, the voltage measures 2.5 V and changes based on the user's weight distribution. With no load on the weight sensors and a Vdd of 3.3 V, Vm measures 1.79 V. With about 200 lbs on W1, Vm measures 2.00 V +/- 0.1 V and with 200 lbs on W2, Vm measures 1.42 V +/- 0.1 V. This gives a minimum resolution of 34.5 lbs which improves by increasing the input voltage and/or changing the weight sensor design.

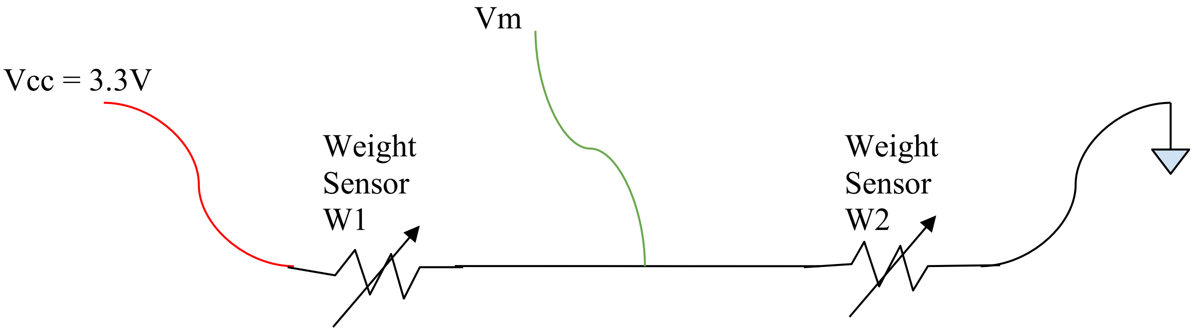
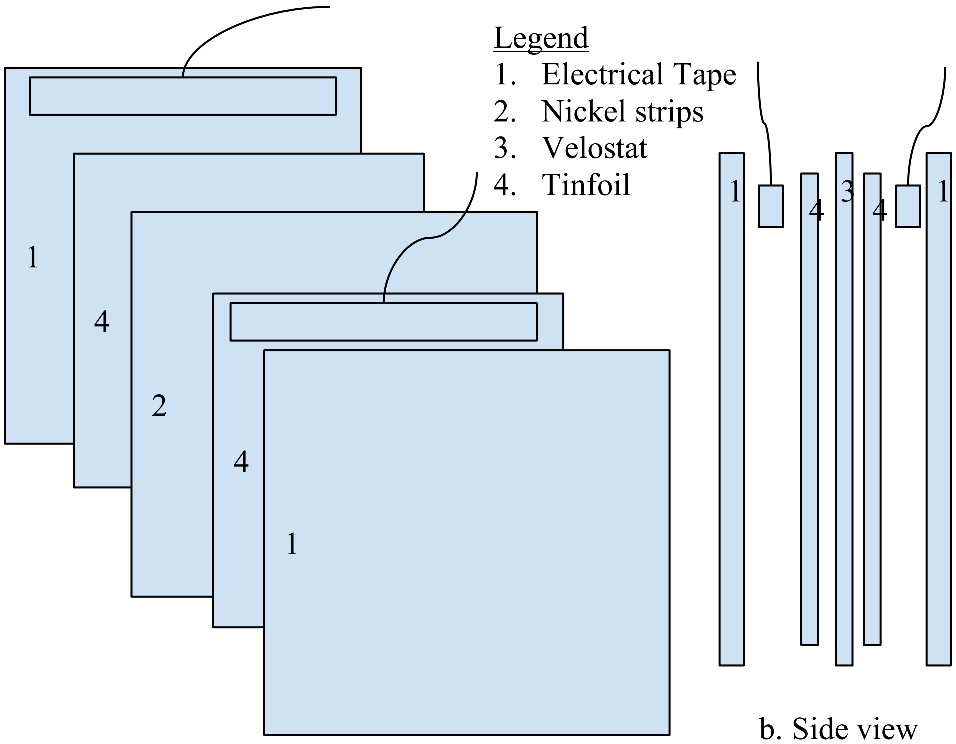


Figure 8: Weight Sensor V1 Configuration

4.4.2 Configuration V2

The first configuration had the problem of a low resolution and unreliable readings. The second version of the weight sensor design solves these problems by using a larger surface area and a Wheatstone bridge configuration. Figure 9 below shows the top view and side view of the new weight sensor. It consists of Velostat in between two pieces of tinfoil. Wires soldered onto nickel strips and placed on the tinfoil ensure a secure and thorough electrical connection. Two layers of electrical tape surround this to keep it together and electrically isolated.



a. Top-down view

b. Side view

Figure 9: Weight Sensor V2

Figure 10 shows the new weight sensor setup which consists of a half-bridge Wheatstone bridge and a filter capacitor. The Wheatstone bridge allows for more accurate readings and the capacitor helps filter out noise. With no weight on either sensor, Vm measures 2.55 V +/- 0.05 V. With 200 lbs on W1 and 0 lbs on W2, Vm = 4.95 V +/- 0.05 V. With 200 lbs on W2 and 0 lbs on W1, Vm = 0.3 +/- 0.05 V. This gives a maximum resolution of 2.12 lbs. When compared to the first configuration, this configuration has half of the noise due to the filter capacitor and a significant increase in resolution. The measured voltage (Vm) saturates to 5 V or 0.3 V at 60 lbs which can be a drawback. However, with equal pressure on both sensors (up to 100 lbs), the voltage (Vm) measures 2.55 V. This means that the measurements depend only on the difference in weight between the sensors.

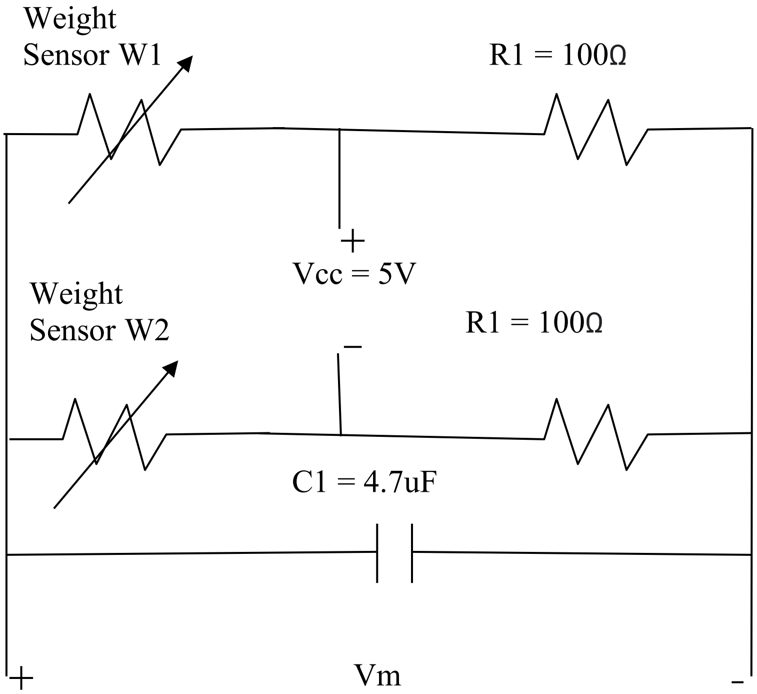


Figure 10: Weight Sensor V2 Configuration

4.5 Final Design

Figure 11 below shows the motor controller which consists mainly of the CD4007UBE to amplify the output signal and the XIAO to route signals to the motor drivers. On the underside view, the dashed yellow rectangles represent their respective chips. The three wires in the bottom view contain 3.3 V, GND, and the measured point. Then, using the setup described in figure 10, the measured signal converts to the motor driver signal through the XIAO then the amplifier. The wires on the bottom of the frontside image route to different points of the motor drivers. To view the full schematic, refer to appendix B.

Legend

1. CD4007UBE chip (contains nmos and pmos FETS)
2. Seeeduino XIAO

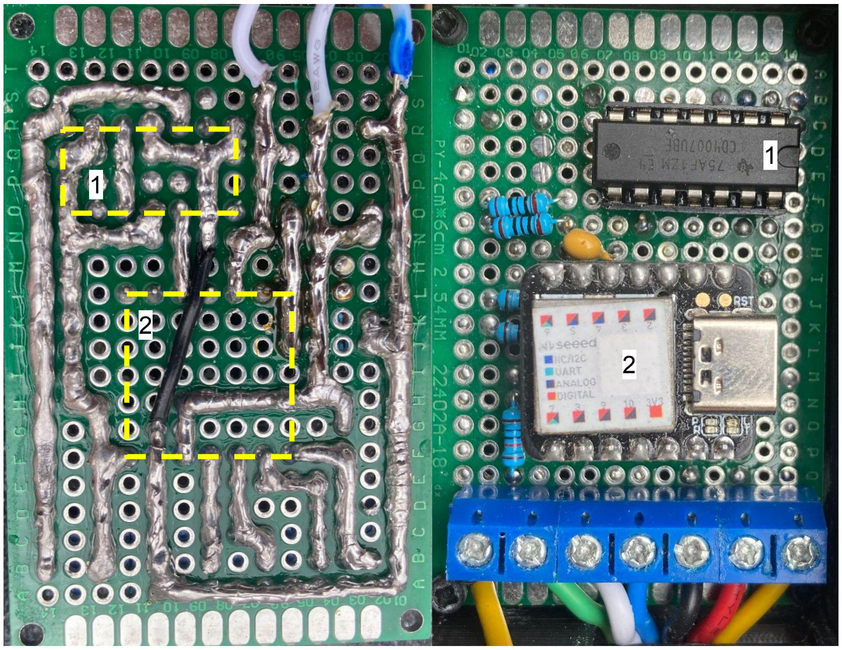


Figure 11: Motor Controller Top and Bottom View

Figure 12 below shows the final construction of the board. The cut grip tape helps identify the locations of the weight sensors and the brake. The board features two hub motors in the rear and two standard wheels in the front. The board also features an aesthetically unappealing battery mount and electronics mount. Duct-tape holds the battery to the board and elastic bands hold the electronic housings to the board. The 3D printed electronic housings and unappealing mounts provide more security than appears.

Legend

1. Weight sensors
2. Brake weight sensor
3. Motor controller
4. Battery
5. Non-motorized wheels
6. Motorized wheels

Figure 12: Final Construction Top View and Side View

CHAPTER 5. CONCLUSION

Chapter 5 outlines the successes and failures of the project. It focuses on the project with little said about the subsystems. First, it talks about the number of customer requirements met and gives explanations. Next, it shows the final Gantt chart which shows the workflow of the project throughout the year. Lastly, the conclusion contains the final cost chart which compares the expected cost of the project with the actual cost of the project.

5.1: Functionality

The functionality provided stems directly from the customer requirements; however, due to the lack of final testing, many requirements failed. All requirements tested passed which included the most important ones: legality in California, broad weight support, affordability, and ease of use.

This device fulfils the objective of providing a fun, recreational device capable of a thrilling experience. This serves as an effective "last mile" device to commute. This board has a more natural feeling than those with hand-held controllers which provides users to have a more thrilling experience. The compact nature of this product makes it easy to carry and its durability allows it to survive crashes.

TABLE IX

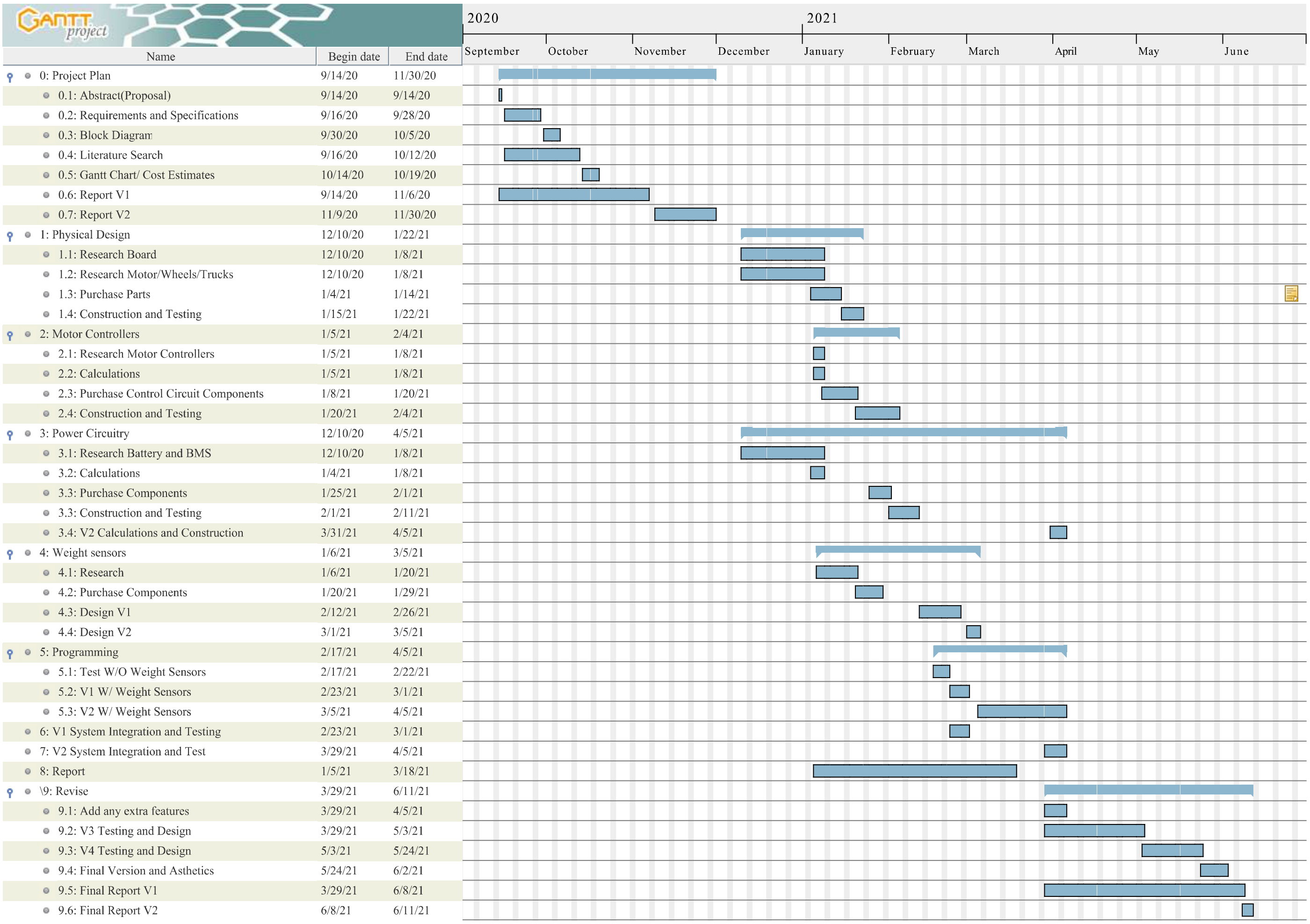
REALIZED REQUIREMENTS

Marketing Requirement	Requirement met?	Reason
Legal to Ride in California	Yes	The average power measures 600 W which falls well below the legal limit of 1000 W. The board reaches speeds up to 17 mph which falls under the 20-mph limit. The board measures 48" x 11" x 5" which falls within legal limits
Range of 10 miles	Unknown	Testing the range never occurred
Able to withstand crashes at 20 mph	Unknown	Testing crashes at 20 mph never occurred as the board could not go that fast
Supports 150 – 220 lb rider	Yes	Individuals weighing 145 lbs and 220 lbs tested it and it performed as expected in each case.
Water Resistant	No	Although testing water resistance never occurred, the exposed electronics would not last long in rain.
Power Efficient	Unknown	Due to limited power measurements the efficiency cannot be determined
Compact	Yes	The entire device weighs 17 lbs and measures no larger than a regular longboard

Easy to Use	Yes	A variety of individuals tested the board with no trouble
Natural Feeling	Yes	The leaning motion prepares an individual for the acceleration changes, so it feels less jerky and unstable than conventional remote-controlled boards.
Affordable	Yes	The actual cost beat the theoretical cost

5.2: Final Gantt Chart

This Gantt chart differs from the original mainly due to the construction length of each version. Additionally, an earlier completion of the final report allows for more revisions on the final version. Figure 13 below shows the final Gantt chart.



Name	Begin date	End date
0: Project Plan	9/14/20	11/30/20
0.1: Abstract(Proposal)	9/14/20	9/14/20
0.2: Requirements and Specifications	9/16/20	9/28/20
0.3: Block Diagram	9/30/20	10/5/20
0.4: Literature Search	9/16/20	10/12/20
0.5: Gantt Chart/ Cost Estimates	10/14/20	10/19/20
0.6: Report V1	9/14/20	11/6/20
0.7: Report V2	11/9/20	11/30/20
1: Physical Design	12/10/20	1/22/21
1.1: Research Board	12/10/20	1/8/21
1.2: Research Motor/Wheels/Trucks	12/10/20	1/8/21
1.3: Purchase Parts	1/4/21	1/14/21
1.4: Construction and Testing	1/15/21	1/22/21
2: Motor Controllers	1/5/21	2/4/21
2.1: Research Motor Controllers	1/5/21	1/8/21
2.2: Calculations	1/5/21	1/8/21
2.3: Purchase Control Circuit Components	1/8/21	1/20/21
2.4: Construction and Testing	1/20/21	2/4/21
3: Power Circuitry	12/10/20	4/5/21
3.1: Research Battery and BMS	12/10/20	1/8/21
3.2: Calculations	1/4/21	1/8/21
3.3: Purchase Components	1/25/21	2/1/21
3.3: Construction and Testing	2/1/21	2/11/21
3.4: V2 Calculations and Construction	3/31/21	4/5/21
4: Weight sensors	1/6/21	3/5/21
4.1: Research	1/6/21	1/20/21
4.2: Purchase Components	1/20/21	1/29/21
4.3: Design V1	2/12/21	2/26/21
4.4: Design V2	3/1/21	3/5/21
5: Programming	2/17/21	4/5/21
5.1: Test W/O Weight Sensors	2/17/21	2/22/21
5.2: V1 W/ Weight Sensors	2/23/21	3/1/21
5.3: V2 W/ Weight Sensors	3/5/21	4/5/21
6: V1 System Integration and Testing	2/23/21	3/1/21
7: V2 System Integration and Test	3/29/21	4/5/21
8: Report	1/5/21	3/18/21
\9: Revise	3/29/21	6/11/21
9.1: Add any extra features	3/29/21	4/5/21
9.2: V3 Testing and Design	3/29/21	5/3/21
9.3: V4 Testing and Design	5/3/21	5/24/21
9.4: Final Version and Asthetics	5/24/21	6/2/21
9.5: Final Report V1	3/29/21	6/8/21
9.6: Final Report V2	6/8/21	6/11/21

Figure 13: Final Gantt chart

5.3: Final Cost

The final cost of each board turned out much lower than expected largely due to the cheap batteries and motors used. Numerous items not taken into consideration such as backup parts, nickel strips, and connectors contributed towards a major part of the final cost. Even with money spent on these extra parts, the total cost of the project was lower than expected. Borrowing a 3-D printer and spot welder saved money when assembling the batteries and electronic enclosures. Already owning soldering equipment, wires, shrink tubes, and various components additionally helped to mitigate the cost. If scaled up, purchasing these items becomes a necessity.

TABLE X

FINAL COST

Part	Expected Cost (Cm)	Actual Cost	Explanation
Deck/Grip tape	$54.17	$29.10	Cheap board from craigslist brought this down significantly
Wheels/ Trucks/ Motors	$196.67	$132.79	Found a good deal on Amazon
Batteries/ BMS	$166.67	$82.48	Made a custom battery pack
Motor Controller	$43.33	$45.76	Bought two motor drivers and Seeeduino XIAO as the microcontroller
Power circuitry	$38.33	$20.59	Pre-Bought charger
Weight Sensors	$31.67	$17.45	Custom weight sensors using Velostat [10], or reliable store-bought ones [11]
Materials used in development		$176.39	Bought extra parts like an extra motor driver and extra Velostat in the event of broken components. Bought multiple different microcontrollers, and logic converters that were not used.
Labor	$14,812.5	$14,812.5	Still an estimate due to the educational nature of the project
Total including materials used in development without labor	$530.83	$504.56	
Total without labor	$530.83	$328.17	
Total with labor	$15,343.33	$15,317.06	

5.4: Future Improvements

While this project satisfies most of the requirements, several improvements can be made. One such improvement includes making a better braking system and adding measures in case the rider falls off. Things that increase durability include making a PCB, making watertight enclosures, and having better connectors. Shortening the wires and mounting the electronics better improves the electronics. Doing more testing would dramatically help improve this device because testing find errors and it would allow me to determine if the board meets all the requirements.

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APPENDIX A – SENIOR PROJECT ANALYSIS

Project Title: Hands Free Electric Skateboard

Student's Name: Blaise Bibolet **Student's Signature:** Blaise Bibolet

Advisor's Name: David B. Braun

• 1. Summary of Functional Requirements

This project functions as an electric skateboard controlled via weight distribution rather than a traditional handheld controller. The board accelerates if the user leans forwards and the board decelerates if the user leans backwards. It has regenerative braking and features an integrated charger to allow for one compact device with no additional parts.

• 2. Primary Constraints

Weight and price outline the key limiting factors while designing this project. The device must meet the tight constraints outlined in chapter 2. While using expensive parts, one must order the right parts and not break them. For example, one must make custom weight sensors using Velostat or spend more money to buy commercially available weight sensors.

• 3. Economic

This project increases the market for lithium-ion batteries and decreases the market for oil and gas. Most of the budget goes towards motors, batteries, and the skateboard deck. The control electronics make up only a fraction of the overall cost; however, the biggest labor factor lies within designing the control electronics.

A custom-made battery pack requires a spot welder to connect each battery. This project requires the manufacturing of PCBs and someone to solder components. Both tasks only take a few hours each. Accounting for 4 hours at a wage of $17.5, the total project costs $600 to build. The spot welder, and solder stations, and other assembling tools cost about $300. This increases the fixed cost which affects the break-even point proportionally. The devices cost $600 to make which makes up the variable price. The research time, development time, and manufacturing equipment make up the fixed cost of $15,113. These units sell for $900 because other competitors sell their boards for $600 and $1200 (Evolve [4] and Meepo [5]).

• 4. If manufactured on a commercial basis:

Using the total variable cost - $600, revenue - $900, and the total fixed cost - $15,113, the break-even point occurs after selling 51 units. If this company sold 51 units annually, the profits after breaking even are $300*51 = $15,300. These numbers reflect a side business, but not a main source of income. I would manufacture these boards in the U.S. to ensure the highest quality and to reduce shipping times.

• 5. Environmental

This project decreases CO2 emissions. It has many uses including running various errands which would otherwise require a car. The device features a bamboo deck, a renewable resource. After breaking, the user can upcycle the broken deck and use the pieces for furniture or art. The motors and trucks made largely of the non-renewable resources copper and aluminum. The largest environmental impact from this board comes from the batteries. Battery production facilities use 50-65 kWh of electricity per kWh of battery capacity [15]. Lithium mining destroys local habitats with invasive techniques and can affect people living nearby if a spill occurs [16]. One notable toxic chemical required to process lithium is hydrochloric acid which can kill animals and humans.

• 6. Manufacturability

Integrating the weight sensors into the board poses many manufacturing challenges. It requires modifying an existing skateboard deck to incorporate them or creating a new custom skateboard deck. Aside from this, the two main manufacturing costs come from soldering the components into a PCB and spot welding the battery pack. Putting together the final pieces only requires screws, nuts, and bolts. This takes no more than 4 hours per board. With an oven and solder paste, the time shortens to around 2 hours. Hiring a human requires an in-person location which increases rent and bill costs. Covid-19 would significantly slow down the production of boards due to the minimize physical contact.

• 7. Sustainability

This device primarily uses the sustainable materials bamboo, copper, and aluminum. Bamboo makes up the deck which cannot be recycled due to wood treatment techniques, but it is a renewable resource. The copper used in the wires and the motors can easily be recycled and reused for different applications. Aluminum is used for the electronic enclosures and the trucks. Aluminums low melting point makes it an easy metal to recycle.

Being enclosed in the hub of the wheel, the motor requires theoretically there no servicing. A modular device allows for easy replacements if anything breaks. One upgrade for this project could include stronger motors to go faster or climb steep hills. Another upgrade can feature a larger battery pack for a longer range, or a smaller battery pack for a more lightweight board. Having a modular device makes both upgrades simple and easy.

• 8. Ethical

This product has limitations on the acceleration and speed to ensure the safety of the user and public which follows IEEE code of ethics 1 [17]. It follows utilitarianism by abiding by California laws which protect the public. The user manual highly encourages users to wear a helmet to prevent serious injuries. Putting several warnings on the board proves that the user assumes all responsibility for injuries. The power electronics display a warning to prevent fatal electrical shocks. These ideas align with the duty ethics where one should do the right and appropriate thing. However, the IEEE code of ethics states “to hold paramount the safety, health, and welfare of the public" which this device does not follow because the brakes do not always work and the inherit safety risk of using any skateboard. Due to the lack of safety features, suing a stakeholder such as the creator becomes a viable option. Designing a fun last-mile recreational device means using the latest technology. Sharing all new technologies developed during this project further advances all electric skateboards and weight sensors. This follows the IEEE code of ethics #1 which includes "…improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies..."

• 9. Health and Safety

This electric skateboard has limits to the speed and acceleration that the rider can achieve. This helps ensure the safety of the rider and others around. As mentioned in the paragraph above, this device includes several warnings to prevent injury. The charger follows IEEE standards and cannot electrocute someone while unplugged. The wires all contain proper coverings to minimize the risk of electrical shock. If the rider falls off or jumps off, the board decelerates to a stop to prevent injuries to others. With one foot on the board, the motors spin freely so if the user loses balance, injuries are not likely. A BMS exists to prevent the battery from overheating and exploding. Aluminum and plastic encase the battery pack to protect it from the elements.

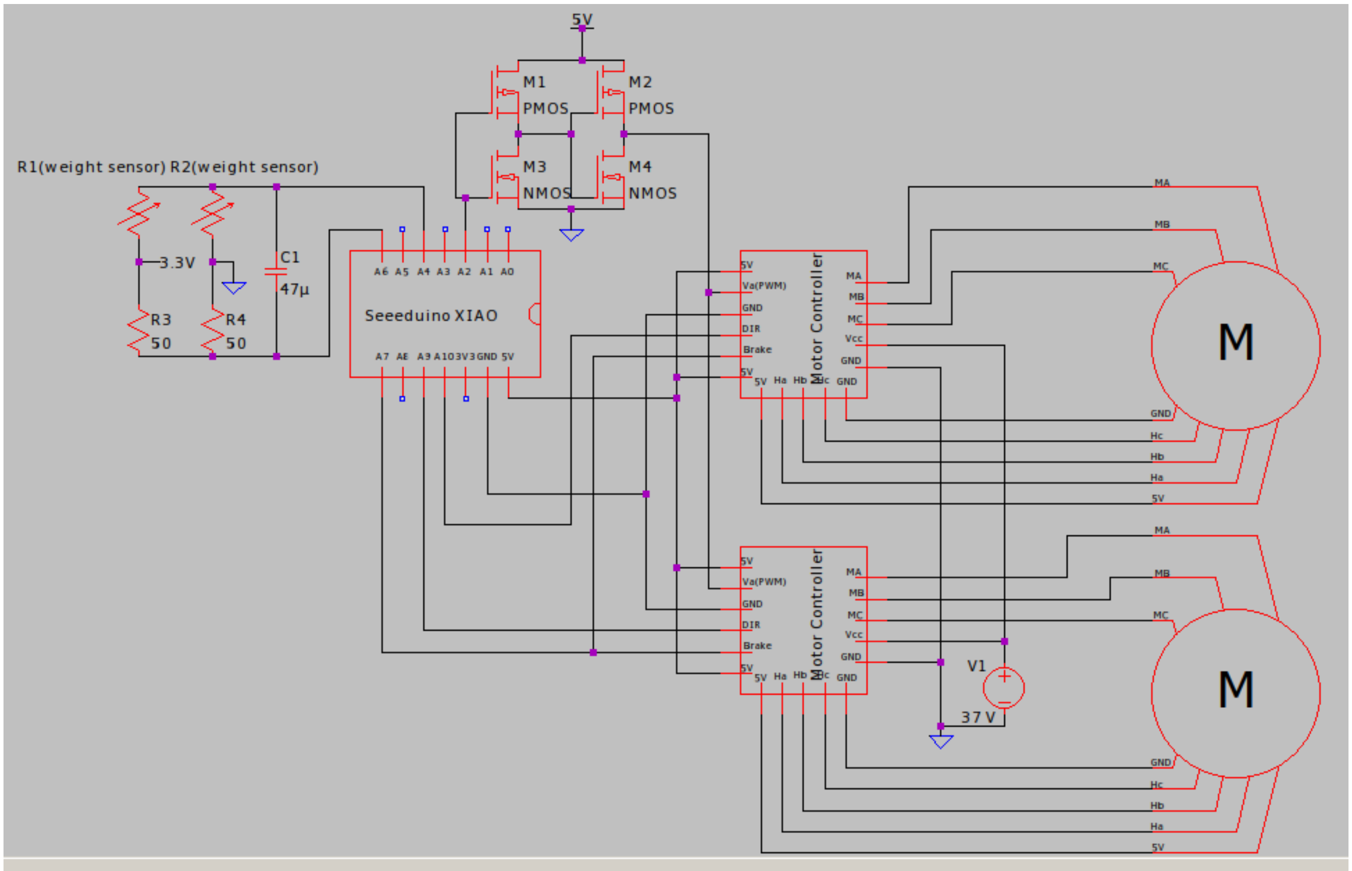
• 10. Social and Political

Direct stakeholders include the advisor, Dr. Braun and the investors which are me and the EE dept. Other direct stakeholders consist of the businesses where parts and supplies were purchased. Paying the stakeholders benefits them equally because they received what they expected. As a stakeholder, I only benefit upon completion of the project and report. If used unsafely, it has the potential to influence the creation of more laws regarding electric skateboards, or non-motorized skateboards. This gives the indirect stakeholders of every electric and non-electric skateboarder. Current EV stakeholders benefit from this project because it brings more attention to EV's and lithium batteries. This project provides equities by helping individuals without hands ride electric skateboards.

• 11. Development

Researching this project taught me about the expenses relating to an electric skateboard. The battery pack alone costs almost $100, the same price as buying an entire non-motorized skateboard. I learned how much of an impact the research and design phases have on the project budget. Politics plays a huge role in tech companies. Boosted, an electric skateboard industry leader at the time met an early end during the 2010's due to a trade war with China which started from politics [3].

APPENDIX B – FINAL SCHEMATIC



APPENDIX C – FINAL CODE

```
#define Vinp A6
#define Vinn A4
#define Vout A2
#define brake 7
#define dir1 10
#define dir2 9
#define testin 4

const int numReadings = 50;

int readings[numReadings];// the readings from the analog input
int readIndex = 0;        // the index of the current reading
long total = 0;           // the running total
int average = 0;          // the average
int outVal = 0;           // output to motors
void setup() {
  // put your setup code here, to run once:
  pinMode(Vout, OUTPUT);
  pinMode(Vinp, INPUT);
  pinMode(Vinn, INPUT);
  pinMode(brake, OUTPUT);
  pinMode(dir1, OUTPUT);
  pinMode(dir2, OUTPUT);
  pinMode(testin, INPUT);
  Serial.begin(9600);
  //Create array
  for (int i = 0; i < numReadings; i++) {
    readings[i] = 0;
  }

}

void loop() {
  int i = 0;
  //Initialize brake as off
  digitalWrite(brake, LOW);
  //initialize motor diractions
  digitalWrite(dir1, HIGH);
```

```
 digitalWrite(dir2, LOW);

 // subtract the last reading:
 total = total - readings[readIndex];
 // read from the sensor:
 readings[readIndex] = analogRead(Vinp) - analogRead(Vinn);
 // add the reading to the total:
 total = total + readings[readIndex];
 // advance to the next position in the array:
 readIndex = readIndex + 1;

 // if we end of the array...
 if (readIndex >= numReadings) {
  // go to the beginning:
  readIndex = 0;
 }

 // calculate the average:
 average = total / numReadings;

 //If average between specific readings
 if (average <= -150 && outVal > 0){
  //decrease output value
  outVal--;
  analogWrite(Vout, outVal);
 }
 //If average between specific readings
 else if (average >= 150 && outVal < 255){
  //increase output value
  outVal++;
  analogWrite(Vout, outVal);
 }
 else{
  //Output voltage remains the same
  analogWrite(Vout, outVal);
 }
}
```