Electric Bicycle with Fully Electric Architecture

By

Ellie Urish

Jason Zou

Willard Sullivan

Final Report for ECE 445, Senior Design, Spring 2023

TA: Matthew Qi

May 2, 2023

Project No. 15

Abstract

The electric bicycle with fully electric architecture is a fully battery-operated bicycle, where the pedals are used to generate electricity to extend the range of the bike. If the user chooses to extend the range of the bike, the power generated from the pedal generator is routed through an onboard PCB that controls the output voltage. Due to several constraints described later in the document, we did not successfully charge the battery with this system. However, the user can fully control the functionality of the bicycle with the onboard throttle control and the cable front brake.

Contents

1. Introduction

Most current electric bikes use the combination of a chain and a motor to provide pedal assistance. The exposed mechanical components on such vehicles, such as the chain and gears, create durability concerns with prolonged exposure to the elements. The goal of our project was to simplify the mechanical components of an electric bike by replacing traditionally mechanical systems with fully electrical systems. In our configuration, the bike is propelled only through an electric motor with a battery, with the pedals instead serving to provide a means of power generation for the bicycle. While this configuration is not as efficient for driving the wheels in terms of translation from human power to the rear wheel, it provides an opportunity for a more simplistic mechanical design with less moving parts that are sealed from the elements. Such an electric bicycle design would be beneficial in applications such as bicycle ride sharing, where long-term durability is important, and the bicycle can be charged at designated ride sharing stations.

In this report, we describe our implementation of our project idea. This will include the design and development of the three subsystems, the testing of the product as a whole and as individual subsystems, as well as our conclusions. Overall, our Powered Wheel and Controls Subsystems worked very well, however, there were issues with our Power Subsystem with power output and efficiency.

1.1 High Level Requirements and Block Diagram

Throughout the semester, we aimed to build a product that would satisfy our high level requirements, which is a list of criteria that the product should satisfy. Our high level requirements are as follows:

1. The Power System will be able to effectively charge the 36V battery with power from the pedal generator and then route 40V +/- 1V from the battery to the hub motor. The Power System must also be able to supply the 5V that is required to power the microcontroller.
2. The rear wheel motor can propel the vehicle to 5 mph on flat ground with ~180 pounds of load.
3. The motor speed can be controlled through a throttle system by the user.
4. The Power Subsystem must have at least 40% efficiency of power conversion from pedaling to electricity.

We also developed a Block Diagram, which details the components of each subsystem and how they link together. Our most recent Block Diagram is shown in *Figure 1*. Our original Block Diagram included an electronic linkage between the microcontroller and the hand brake, which we did not have time to implement. Additionally, the original design included a system to lower the battery's voltage to 5V to use with the microcontroller. We deemed this too costly and complicated and instead used the 5V supply from the motor controller that is meant to be used with throttle control.

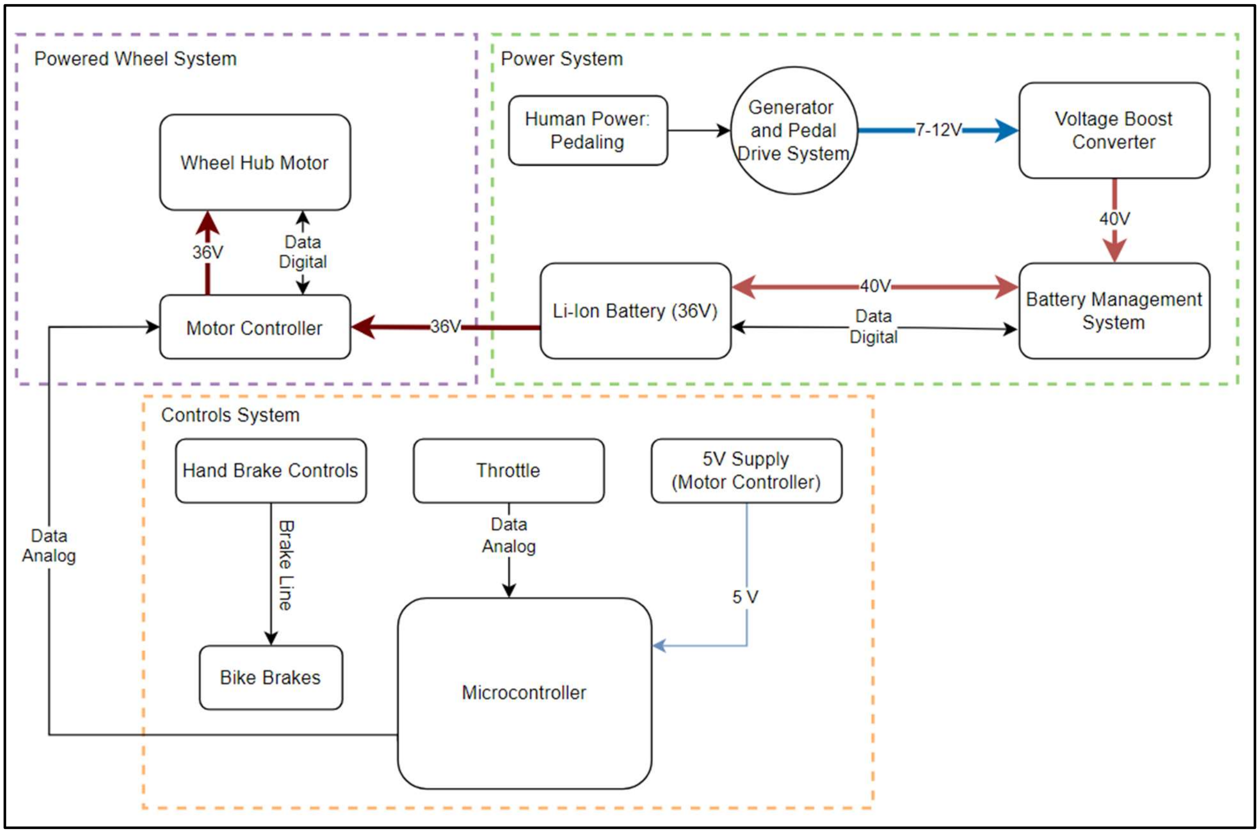

Figure 1: Our Block Diagram.

2 Design

2.1 Powered Wheel Subsystem

The powered wheel subsystem consists of the components required to spin the rear wheel given a 36 V supply from the battery. Towards this end, we use both an off the shelf motor controller and a wheel with an integrated DC brushless hub motor. The motor controller interfaces with the rest of our design, accepting throttle input as a 5 V analog signal from the control system and receiving 36 V at up to 12 A from the battery. The motor controller also provides 3 phase power to the hub motor. A wiring diagram of the powered wheel subsystem is shown in Figure 2.

The most critical aspect of this subsystem is the throttle control. The motor controller provides a 3-pin wire interface for throttle control; two pins provide 5 V and the third accepts a 0-5 V analog signal which sets the desired throttle level. We used the 5 V supply to power to the microcontroller in our controls subsystem, which sends the analog throttle signal back to the motor controller. More details on the microcontroller's output are described in Section 2.3.

To power the hub motor, the motor controller accepts 36 V power from the battery. The typical current load is 8 A at full throttle; we also have startup loads of up to 12 A when powering the motor from a standstill. We opted to use the hub motor in coast mode as opposed to braking mode, which that when power is removed from the motor the wheel will continue spinning as opposed to reversing power to the motor to force it to brake. This makes for a more comfortable riding experience, as the user can get the bike up to speed and then release the throttle to coast with the bike's momentum.

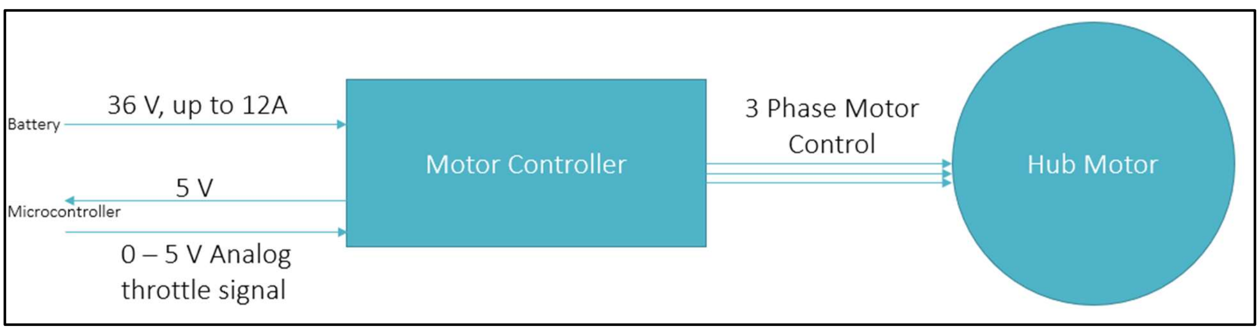

Figure 2: High level wiring diagram for powered wheel subsystem

2.2 Power Subsystem

The power subsystem is designed to provide a steady supply of power to the other two subsystems. We used an off the shelf Lithium-Ion battery with a built in Battery Management System (BMS). We chose this over designing a BMS system ourselves on our PCB for two main reasons: time constraints, and safety. Li-Ion batteries can be tricky to work with, so using a commercially available and tested designs was the best choice from our perspective. The battery provides a 36V output capable of supplying up to 20 A of current, so well within the range of our needs. The BMS of the battery has software limits of 25 A of output current, and also includes 30 A fuses on the output. In addition to the internal battery protections, we also added a 25 A circuit breaker to the output of the battery. This provides a secondary method of overcurrent protection and also allows us to quickly cut power to the rest of the bike with the quick disconnect switch.

2.2.1 Pedal Generator and Boost Converter

Contained within the power subsystem is a core component of our design: the pedal generator. The purpose of this component is to allow the user to charge the battery with the power they generate from pedaling. To accomplish this, we connected the pedals to a generator with a chain and sprockets. Although we initially wanted to implement an enclosed driveshaft for this connection to reduce exposed mechanical components, we determined after discussions with the machine shop that this would not be feasible to construct in our time frame. With the chain setup, we see between 7-12 V output from the generator with comfortable pedaling. As the battery in our design is 36 V, this output voltage is not sufficiently high enough to directly charge it. Therefore, we designed a boost converter circuit to increase the generator voltage to 40 V. A boost converter uses an inductor to store current on the input, and then rapidly switches MOSFETs to allow the current to charge a capacitor on the output to the desired voltage. The control of these MOSFETs requires gate drivers and some form of control loop to regulate the switching speed. Although we could've implemented this circuitry on our PCB, we opted to use an off the shelf chip from Texas Instruments, the LM5157, which has internal circuitry containing the MOSFETs and their control loop while also allowing for tuning of control parameters. Implementation of the power components is done on the PCB external to the LM5157, including the inductor and output capacitors. We used an online tool called TI Webench to generate a design for the LM5157 for our desired performance characteristics. A schematic of the full boost converter circuit is shown in Figure 3.

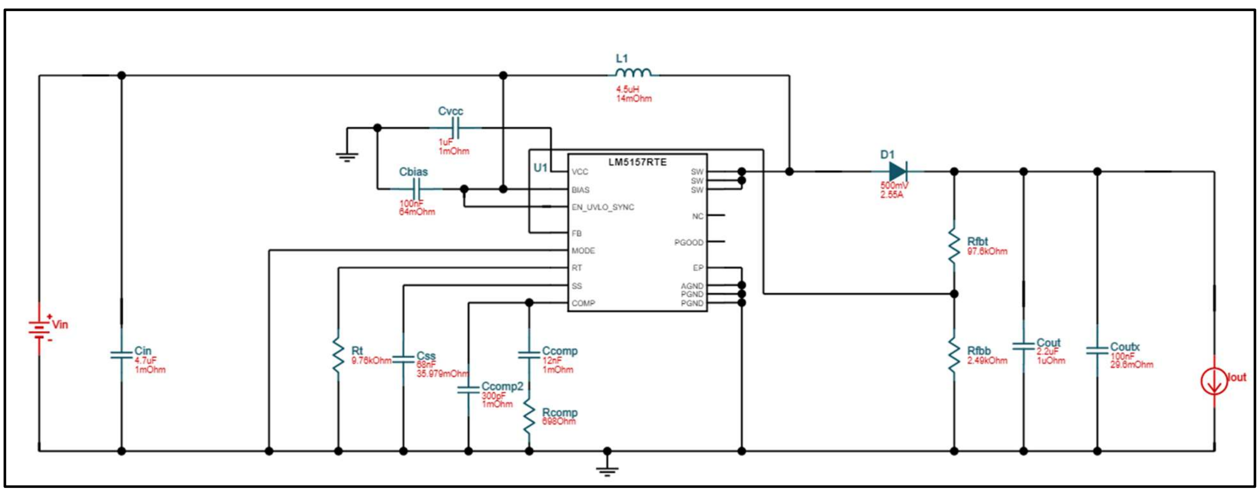

Figure 3: LM5157 Boost Converter Circuit designed with TI Webench

One difficult aspect of incorporating the LM5157 into our PCB was its package size. The chip uses a WQFN footprint that requires a stencil with solder paste and an oven and measures only 3 mm x 3 mm. To ease the development process, we purchased a breakout board for the LM5157 that allowed us to solder the chip in the oven separately from the rest of the board. This allowed us to test the LM5157 separately from the rest of our PCB and, more importantly, prevented us from messing up an entire PCB because of one hard to solder component. For our final PCB, we included two rows of headers in the boost converter circuit that allowed us to insert and remove the LM5157 breakout board as needed. An image of the boost converter circuitry implemented in our PCB is shown in Figure 4.

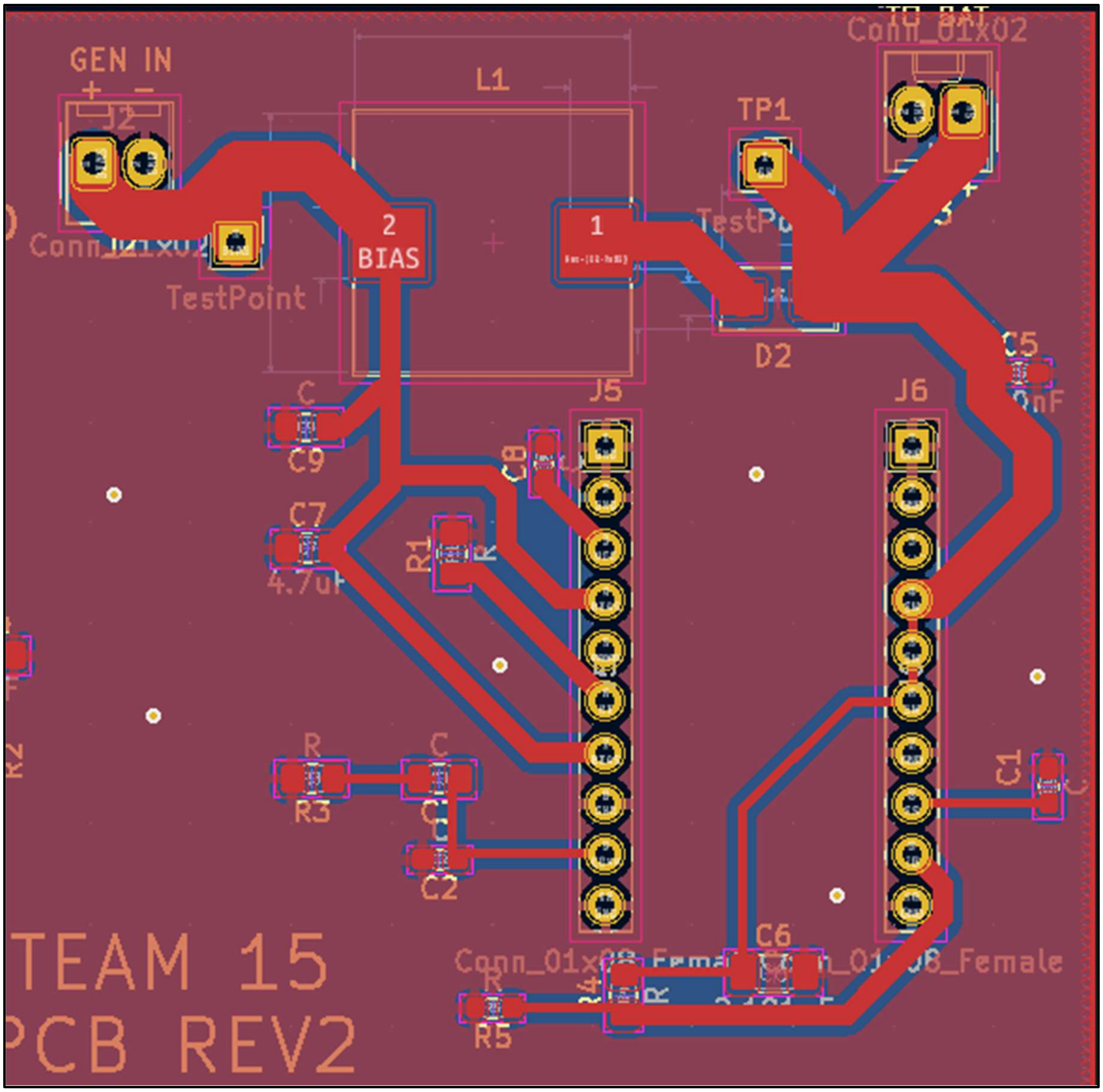

Figure 4: Boost converter circuitry on the PCB. Note the large inductor in the top middle, L1, and the header pins for inserting the LM5157 chip in the bottom right.

2.3 Controls Subsystem

The controls subsystem is based around an Atmega328 microcontroller on our PCB. We supply 5 V to the microcontroller's power input, taken from the throttle power pins on the motor controller. In our design, we used a standard 6-pin ISP programming interface, which allows us to flash the microcontroller using an Arduino as a serial programmer. A circuit schematic for the controls subsystem is shown in Figure 5.

2.3.1 Throttle Control with the Microcontroller

The main purpose of the microcontroller is to read the user's desired throttle level from the physical throttle on the handlebars, apply any safety limits to the throttle, and then transmit an analog throttle signal to the motor controller. To do this, we provide 5 V to the handlebar throttle, which acts as a potentiometer voltage divider to supply an analog signal corresponding to how much the user has twisted the throttle. We read this analog signal using pin 23 of the microcontroller. We then output the modified signal on pin 15, which can produce an analog equivalent signal by creating a PWM wave. There are three modes that we have for our throttle: unlimited, safe, and battery shutoff. In unlimited mode, the throttle output is directly mapped to the hand throttle, thus the full power of the bike is available. This mode can be enabled by holding the throttle at full power when starting up the bike. In the default safe mode, the throttle output is mapped to one third of the value of the hand throttle. This means the user can access at most 33% of the full power of the bike, a level that we found was sufficient for propelling the bike without reaching unsafe speeds. Finally, we have an emergency battery shutoff mode, which would be enabled when the battery charge level was too low to provide a constant voltage to the motor. This simply ignores the hand throttle and sets the output to a constant value of 0 V. An excerpt of the code used for regulating the throttle level is shown in Figure 6.

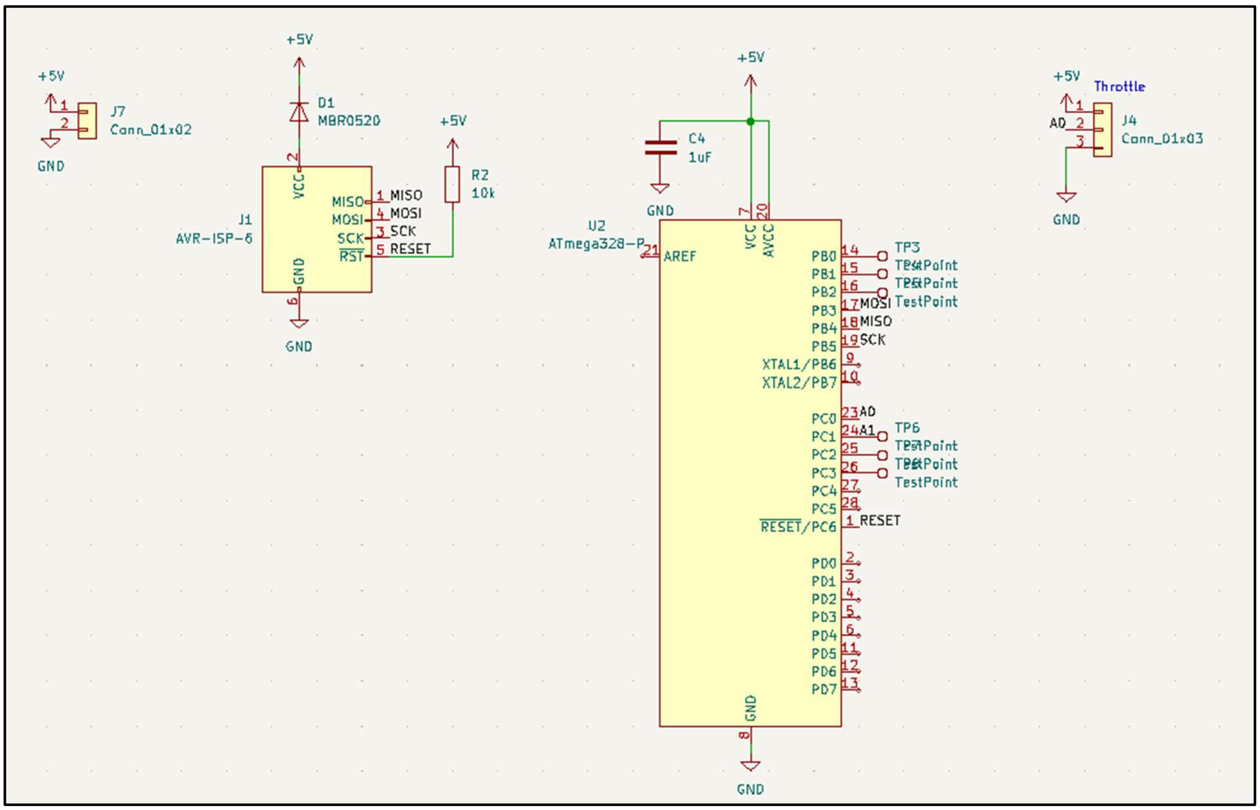

Figure 5: Circuit design for controls subsystem, including the Atmega328, programming header, and power and throttle interface pins.

```
int STATE = 0;// 0 for normal,
              // 1 for bat low/motor off,
              / /2 for safety mode

void setup() {
    // declare the ledPin as an OUTPUT:
    pinMode(outPin, OUTPUT);
    sensorValue = analogRead(sensorPin);
    if(sensorValue > 512)
        STATE = 0;
    else
        STATE = 2;
}
```

```
void loop() {
    updateState();
    // read the value from the throttle:
    sensorValue = analogRead(sensorPin) / 4; // in range 0-255

    if(STATE == 1){
        analogWrite(outPin, 0);
    }else if (STATE == 2){
        analogWrite(outPin, sensorValue / 2);
    }else{
        analogWrite(outPin, sensorValue);
    }
}
```

Figure 6: Excerpt of throttle control code on microcontroller, the left contains the startup code for setting unlimited mode, the right contains the main loop that sets the output throttle.

3. Design Verification

3.1 E-Bike Functionality

The main test of functionality for our design is that it can be ridden and controlled by the user. To demonstrate this, we performed several tests of our bike's capabilities. The first was an endurance test of sorts, we rode the bike around the engineering quad with a GPS tracker active to gauge the maximum speed and acceleration speed. From this test we found the maximum speed of the bike to be around 20mph. We were able to adequately accelerate the bike from rest. A screenshot of the bike's speed over time is shown in Figure 7; on this chart we can see the acceleration from rest at about 0.15 miles as well as a decent average speed of 12 mph while cruising around. From this test, we were able to confirm the accomplishment of our high-level requirements related to bike performance.

Another goal for our bike was to minimize exposed mechanical components and achieve a clean, durable look. As discussed in section 2.1, we were unable to create an entirely chainless design, but thanks to the help of the machine shop the pedal and generator system were robustly constructed. The bike also proved to be robust during testing; we took the bike through several tricky environments, like bumpy roads and grass, and throughout this there was no loss of power or any connection issues between the subsystems. This demonstrates that our bike is usable for daily riders and can withstand the normal wear and tear of outdoor use. A picture of the finished bike frame, including the mounting of the PCB, battery, and motor controller, is shown in Figure 8.

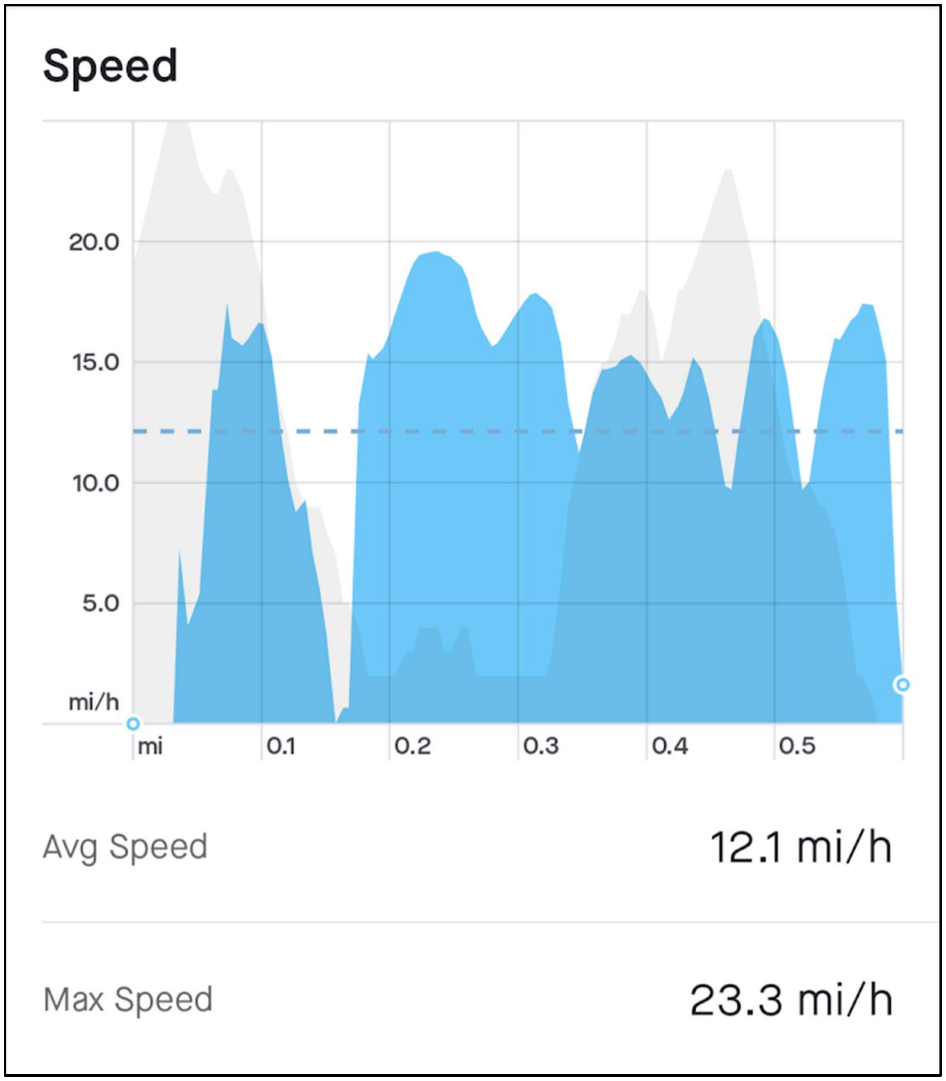

Figure 7: Speed over distance, recorded by the GPS tracker app ‘Strava.’

Figure 8: Images of the final layout of the bike frame, with components mounted.

3.2 Power Subsystem – Boost Converter

Testing the Boost Converter circuit extensively was crucial to the functionality and the safety of this project, as our intent was to route power from the boost converter to the battery directly. To test the circuit, we initially controlled the input voltage and current output from the lab's power supply and measured the output of the circuit with the oscilloscope. With out initial design, we began by limiting the current to 1 A and slowly raised the voltage from 0 V to 12 V, where we observed the initial changes of the turn-on voltage. With this test, we noticed that the boost converter was not properly boosting to the output voltage. We expected an input voltage of 7 V with an output voltage of 40 V; however, we observed only a 5 V boost and noticeable heat generation. This observation was detrimental to our design – we would not be able to remotely charge the battery with this output. Fortunately, we discovered a bug in our PCB, where the SW/switching pins of the boost converter were routed to the wrong pin on the board. The fix is shown in Figure 9, where we removed three header pins on the breakout board and rerouted them with a wire.

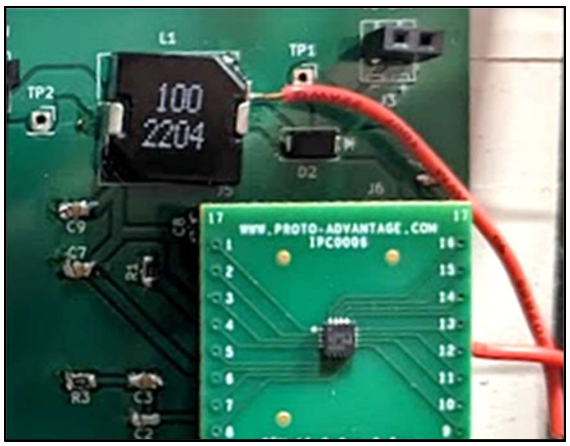

Figure 9: We added an additional wire to reroute the switching pins.

With this fix, our boost converter began to output the required 40 V. We tested this functionality thoroughly with the lab power supply, then moved on to the pedal generator when we were comfortable. Below in Figure 10 is the output of the boost converter with the designed input voltage range from the pedal generator. While there was some noise, we were satisfied with the result.

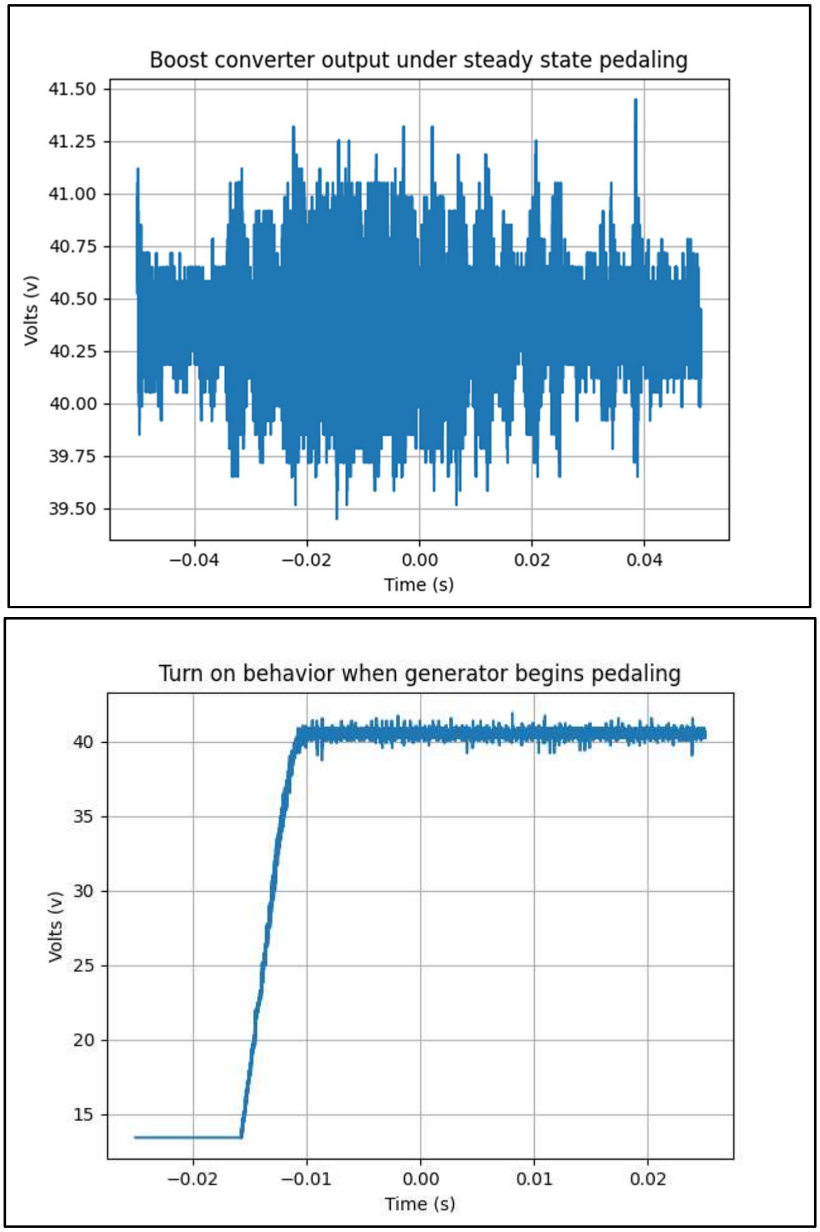

Figure 10: Oscilloscope output of the boost converter with the pedal generator.

The next step was to attach a load to the output of the boost converter so we could control the output current and analyze the behavior of the circuit. We developed two resistor networks, 330 Ohm and 10,000 Ohm, to test whether the boost converter could output the maximum of 0.9 A we designed it for. Unfortunately, we observed that there is a sag in the output voltage with a higher current output; the output voltage of the 330 Ohm network was 28 V. This sag is shown in Figure 11. On the other hand, the 10,000 Ohm network still outputs at 40 V but only at 4 mA.

Finally, we calculated the observed efficiency of each network; our high-level requirement was 40%. We measured power with Ohm's law: $P = IV$ for the input power and $P = V^2/R$ for the output power. With the 330 Ohm network, we observed an efficiency 73.5%, while the 10,000 Ohm network was 20.75% efficient. This was unsatisfactory to our requirement, as we did not reach 40% efficiency across all of the networks. Unfortunately, we ran out of resources to effectively diagnose the issue.

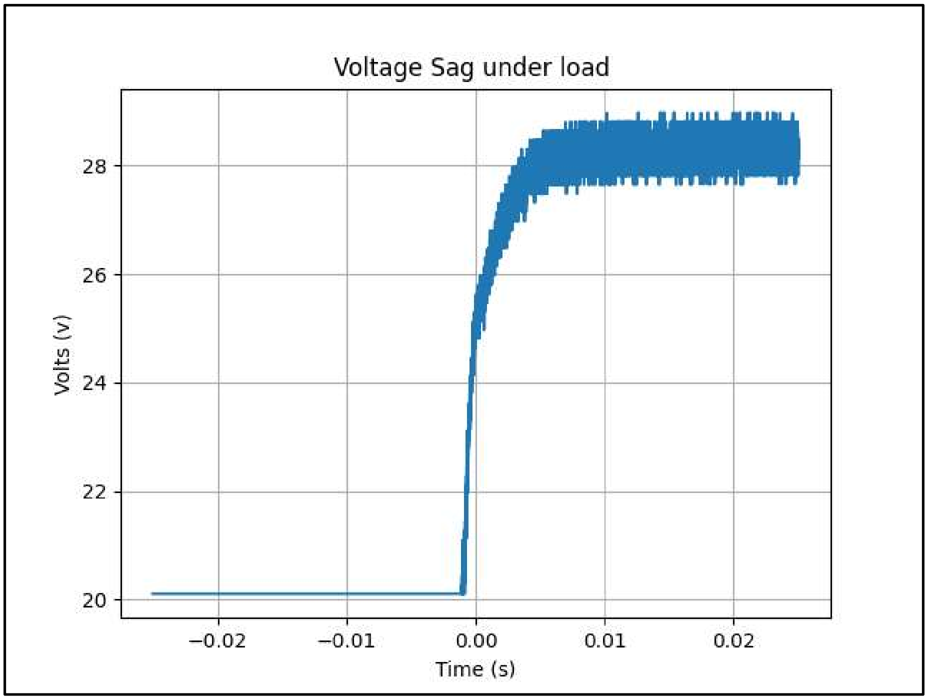

Figure 11: Voltage sag from increased current output.

4. Costs

Below are itemized lists of the components, products, and estimated labor that we needed to completely implement our project. We would like to thank the Machine Shop and Matthew Novelli for their various donations to this project. Without these donations, this project would not have come to fruition. With parts and estimated labor costs, the grand total for this project is $43,394.45.

4.1 Parts

Table 1: PCB Component Costs

Part	Notes	Source	Retail Cost	Quantity	Total Cost
4.7 uF Capacitor	CIN	Digi-Key Electronics	$0.18	4	$0.72
.068 uF Capacitor	CSS	Digi-Key Electronics	$0.10	4	$0.40
10 uH Inductor	L1	Digi-Key Electronics	$1.68	4	$6.72
698 Ohm Resistor	RCOMP	Digi-Key Electronics	$0.10	4	$0.40
2.49 kOhm Resistor	RFBB	Digi-Key Electronics	$0.10	4	$0.40
7.6 kOhm Resistor	RFBT	Digi-Key Electronics	$0.10	4	$0.40
9.76 kOhm Resistor	RT	Digi-Key Electronics	$0.10	4	$0.40
.1 uF Capacitor	CBIAS	Digi-Key Electronics	$0.10	4	$0.40
.022 uF Capacitor	CCOMP	Digi-Key Electronics	$0.10	4	$0.40
300 pF Capacitor	CCOMP2	Digi-Key Electronics	$0.17	4	$0.68
.1 uF Capacitor	COUTX	Digi-Key Electronics	$0.10	4	$0.40
1 uF Capacitor	CVCC	Digi-Key Electronics	$0.10	4	$0.40
60V, 2A Diode	D1	Digi-Key Electronics	$0.46	4	$1.84
2.2 uF Capacitor	COUT	Digi-Key Electronics	$0.97	4	$3.88
QFN-16 TO DIP-20 SMT ADAPTER	Breakout Board for Boost	Digi-Key Electronics	$7.11	2	$14.22
IPC0006-S	Stencil for QFN-16 adapter	Digi-Key Electronics	$10.44	1	$10.44
LM5157	Boost Converter	Digi-Key Electronics	$3.29	4	$13.16
SSW-102-01-F-S	Connector	Digi-Key Electronics	$0.74	2	$1.48
M20-7820346	Connector	Digi-Key Electronics	$0.85	4	$3.40
M20-7821046	Connector	Digi-Key Electronics	$1.32	6	$7.92
SSW-101-01-T-S	Connector	Digi-Key Electronics	$0.23	6	$1.38
PRT-11864	Adapter	Digi-Key Electronics	$0.95	4	$3.80
FIT0586	Adapter	Digi-Key Electronics	$1.80	2	$3.60
ATMEGA328-PU	Microcontroller	Digi-Key Electronics	$2.61	1	$2.61
PCB Component Total Cost: $79.45					

Table 2: Larger Item Costs

Part	Source	Retail Cost	Quantity	Total Cost
36V DC Electric Front Bike Wheel	JAG45	$45.00	1	$0.00
36V DC BY1020D Motor	Machine Shop	$40.00	1	$0.00
36V 8A eBike Battery	JAG45	$45.00	1	$45.00
36V Motor Controller	JAG45	$35.00	1	$0.00
eBike Handlebar Throttle Control	JAG45	$5.00	1	$0.00
Bike	Machine Shop	$100.00	1	$0.00
PCB	PCBWay	$10.00	2 Sets	$20.00
Metal Mounting Plate	Machine Shop	$10.00	1	$10.00
Switching Fuse	Amazon	$25.00	1	$25.00
Extra Parts	N/A	$15.00	1	$15.00
Total Cost: $115.00				

4.2 Labor

To calculate the cost of labor, we assumed that, over 16 weeks, group members worked 10 hours per week and Machine Shop employees worked 3 hours per week. Furthermore, we assumed that each individual was working at a rate of $30 per hour, where we use the following expression to calculate the final labor cost:

$$\$30/hour * hours/week * 16weeks * 2.5$$

The final group member cost is $12,000 per person, or $36,000 total. The final Machine Shop cost is $7,200.

5. Conclusion

Unfortunately, as described in the verification of this product, we were unable to fully implement all of our outlined subsystems. While the pedal generator was able to output the 40V we designed it to, the converter cannot perform well under high current loads. Despite this, the rest of our e-bike works well and has exceeded some of our expectations.

We hope that our project can serve as an inspiration for future bike sharing programs and those who commute via bike. Our system will encourage others who typically can't or don't ride bikes to do so – reducing their carbon footprint and allowing for less traffic congestion. We foresee issues with such a product in the biking community, where many people show dislike towards pedal assist or ride sharing bicycles. Our project is another demonstration of the effectiveness of bicycles and one that gives hope that there is a bright future for bicycle commuting and infrastructure.

5.1 Accomplishment

Our major accomplishments with this product include being able to propel a user of roughly 180 pounds to speeds of upwards of 20 miles per hour, far higher than our original high level requirement target of 5 miles per hour. Furthermore, the throttle control with the safety and unlimited modes functions quite well and is very user friendly. The Safety mode effectively reduced the output power of the motor controller, which keeps the user under 10 miles per hour. Finally, the power system is able to generate 40V with the pedal generator and was able to achieve our requirement of 40V +/- 1V despite the varying input voltage from the generator.

5.2 Uncertainties

We struggled with the implementation of the power and powered wheel subsystems throughout the development of this product. With the power subsystem, we need to explore a more efficient and effective way of charging the battery as our current implementation would do so very slowly if employed. Described in the testing procedures, the boost converter struggled under high current loads despite being designed for a maximum output of .9 Amps. Additionally, there was a severe lack of documentation with our chosen motor controller, which increased the development time of this subsystem. We resorted to trial-and-error approach and scoured the internet to find clues in how to properly wire the controller.

5.3 Ethical considerations

With any transportation device, the user not only assumes various types of risk, but also is able to assume a level of trust with their vehicle. As outlined in Section 1.2 in the ACM Code of Ethics, the statement "ensure that all harm is minimized" [1] stands out to us. To ensure this statement, we implemented a Safety Mode where the motor controller output is limited, keeping the rider at speeds less than 10 miles per hour. Furthermore, a more developed prototype will have a completely enclosed electrical system, which eliminates the risk of shock or fires as it is separated from contact with the user or outside environment. Our current prototype is protected from the user, however, is not resistant to the environment.

Our product falls into a gray area - it is not necessarily a bicycle, nor is it a Moped. In the State of Illinois, our type of vehicle falls best in the Electric Bicycle category, which is a bicycle that has some sort of assistance by a gas or electric motor. These vehicles, in the state of Illinois, "are legally bicycles, as long as their motors are smaller than 750W (one horsepower) and their pedals are fully functional." [2].

Electric Bicycles are subject to the same laws as bicycles, but also do not require insurance nor registration - to abide by the ACM Code of Ethics, we will encourage users to have some type of liability insurance or make sure they are well versed in the risks of using this type of vehicle, including wearing usual protective equipment such as a bicycle helmet.

5.4 Future work

If we were to continue efforts on this project, we would first make several revisions to the current design so that it better matches our envisioned goals. This mostly includes improving the power subsystem so that the pedal generator can effectively charge the battery, which will involve improving the gear ratios and increasing the output current of the converter. Furthermore, our current design will need to be revised and improved so that it is more polished, user friendly, and able to resist environmental influences.

References

1. “The code affirms an obligation of computing professionals to use their skills for the benefit of society.,” Code of Ethics. [Online]. Available: https://www.acm.org/code-of-ethics. [Accessed: 09-Feb-2023].
2. “Illinois laws for moped, scooter, and Electric Bikes,” Horwitz, Horwitz & Associates, Ltd., 16-Sep-2022. [Online]. Available: https://www.horwitzlaw.com/blog/illinois-moped-laws/. [Accessed: 09-Feb-2023].
3. “LM5157,” LM5157 data sheet, product information and support | TI.com. [Online]. Available: https://www.ti.com/product/LM5157. [Accessed: 29-Mar-2023].
4. “Boost Converter,” Mathworks [Online]. Available: https://www.mathworks.com/help/sps/ug/boost-converter.html [Accessed 23-Feb-2023]

Appendix A: Requirement and Verification Tables

Table 3: Power Subsystem RV Table

Requirement	Verification	Verification Status
Supply 40V +/- 1V to the Powered Wheel System at up to 12A transient.	Measure the output voltage and current of the battery, which is connected directly to the motor controller of the Powered Wheel System. Run the system at full speed and measure.	Yes
Supply 5V +/- 0.1V to the Controls System to satisfy the microcontroller's power draw.	Measure voltage from the power source and ensure the microcontroller operates properly.	Yes
Create a 40V output from the generator to the switching converter system with a peak to peak voltage of less than 5 V.	Measure voltage output from the switching converter while pedals are turning using an oscilloscope, ensuring that it is a 40V output with peak to peak voltages less than 5V. Bring the generator to a stop, and ensure that the switching converter turns off when the generator is no longer producing sufficient voltage.	No

Table 4: Powered Wheel Subsystem RV Table

Requirement	Verification	Verification Status
Drive hub motor with power from the Power System.	Connect to the battery, ensure wheel turns with throttle input.	Yes
Accept speed control from MCU as an analog 5V signal.	Turn throttle from off to full, ensure wheel ramps up in speed and remains steady when throttle is held at a fixed setpoint.	Yes

Table 5: Controls Subsystem RV Table

Requirement	Verification	Verification Status
Read the desired speed from throttle as a 0-5V analog signal.	Turn throttle back and forth, ensuring that the hub motor acts accordingly.	Yes
Regulate speed mode of the hub motor with the throttle signal to the MCU.	Set the rear wheel to demonstrate the Safety and Unlimited Modes.	Yes