MODEL FOR WIRELESS CHARGING FOR E-BIKES

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Final Report for ECE 445, Senior Design, Fall 2020

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December 2020

Project No. 30

Abstract

Our team created a model of a wireless charging station for electric bikes for our senior design project. We created a bike rack charging station and tested it using a model of a E-Bike which had a Li-Ion battery pack. With our project, we were able to fully charge 13.6V batteries in 7 hours using Qi coils on 1.25 amps. The sensors and electrical components were properly integrated with our charging rack and properly charges the bike based on different conditions. The mechanical design optimizes charging efficiently by minimalizing the spacing between our transmitter and receiver coils.

With the success of our project, we believe that we can improve upon this model and scale this to use in the real world.

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1. Introduction

Electric bikes are becoming an increasing popular transportation option in cities. Companies such as Lime and Bird provide electric bikes and scooters for customers to rent. Currently, these companies must hire people to pick up their fleet of bikes and charge them overnight. It is expensive and inefficient to hire contractors to manually charge these bikes every day; this is also not a reliable solution since these contractors are only part-time workers and some bikes may still not be fully charged in the morning. Our system provides an easy interface for users to charge E-bikes as users only must insert the bike in the custom bike rack. The bike racks are easily scalable as multiple racks can be right next to each other and all they would need is 12V power source for each rack. Each rack would act independently when multiple racks are in use in proximity. Our racks can charge a 13.6V, 6000mAh battery in 7 hours when running at 1.25 A.

The key idea behind wireless charging is using a transmitter coil to generate magnetic fields and using a receiver coil to turn the magnetic field into an induced current. The coil system follows Ampere's law, where Ampere's law is defined by Figure 1.

$$\oint B ds = \mu_0 I$$

Figure 1: Ampere's Law

Ampere's law describes how a magnetic field around a closed path can generate a current on the path. Taking advantage of Ampere's Law, we placed the transmitter coil on the rack and the receiver on the bike so that when the coils are aligned, we can have current being induced on the bike circuit to charge the battery. We also have microcontrollers to take in sensor data on both sides. On the rack side we are taking in data on if the bike is inserted into the rack using an ultrasonic sensor, if there is a safety condition on the bike using an IR sensor, and the temperature of the TX (transmitter) coil. We use these data points to drive the gate of the N-channel MOSFET as a latch on the power path to control when the TX coil is powered. Likewise, on the bike side, we use a microcontroller to process the temperature of the Li-Ion battery pack and the cell voltage of the battery pack to drive IR LEDs. These IR LEDS act as a signal to stop charging and this signal should be processed IR sensor on the bike rack side. By monitoring these conditions on both the rack and bike side we can prevent safety issues and ensure our system is safe for users. Using this system, we can save money for companies like Lime, Bird, and Veoride while increasing the popularity of E-bikes as a low-cost and low carbon emission method of transportation.

2 Design

The main design is centered around the Qi Coil Modules and using them to charge the Li-ion battery pack and other electronics have been implemented to have more control over charging. This process is done by using microcontrollers to monitor sensors and voltage levels and drive outputs to control the charging process. Below are the 2 block diagrams for the design.

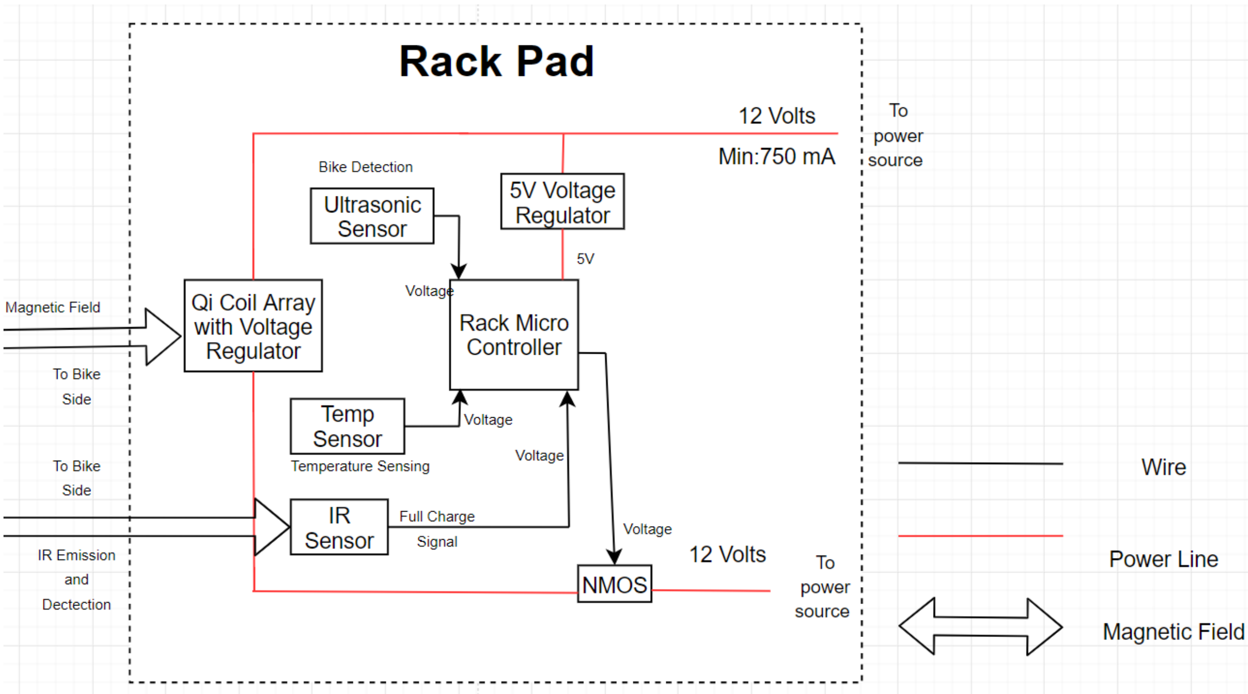

Figure 2: Rack Side Block Diagram

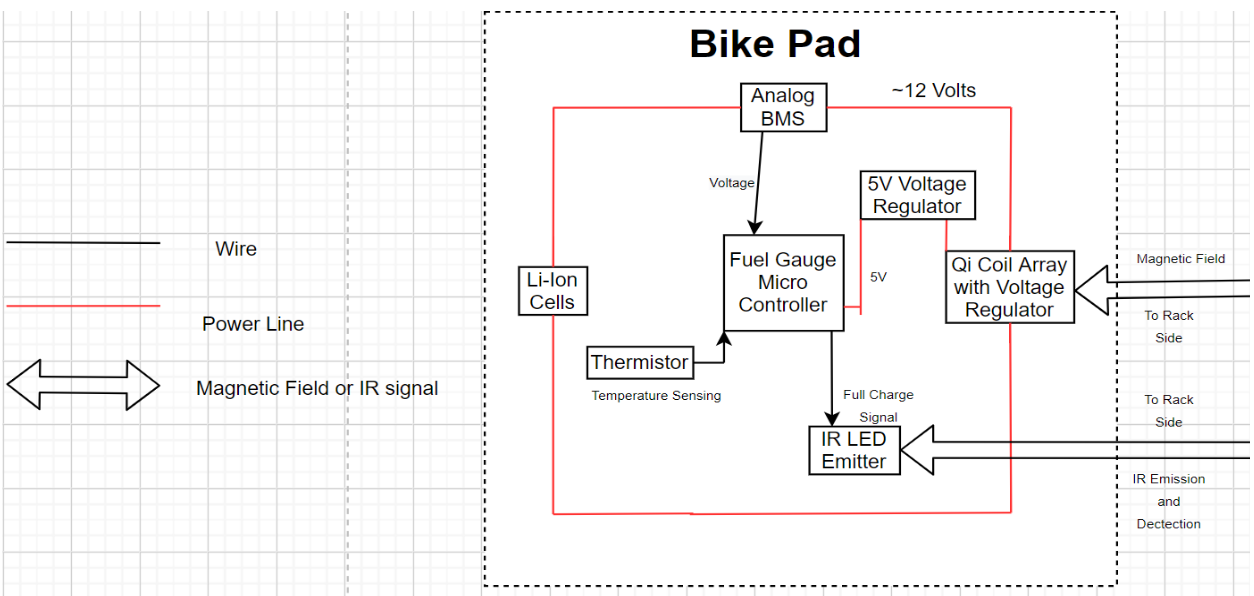

Figure 3: Bike Side Block Diagram

There are some space and mechanical tolerances we must consider when making this design. The first one will be that the Qi coils must as close as possible and make sure they are overlaying on top of each other. Secondly, we must make sure that the IR signal on the bike side is in range of the IR sensor on the rack side. Lastly, the ultrasonic sensor has be in the correct place to detect the front tire of the bike.

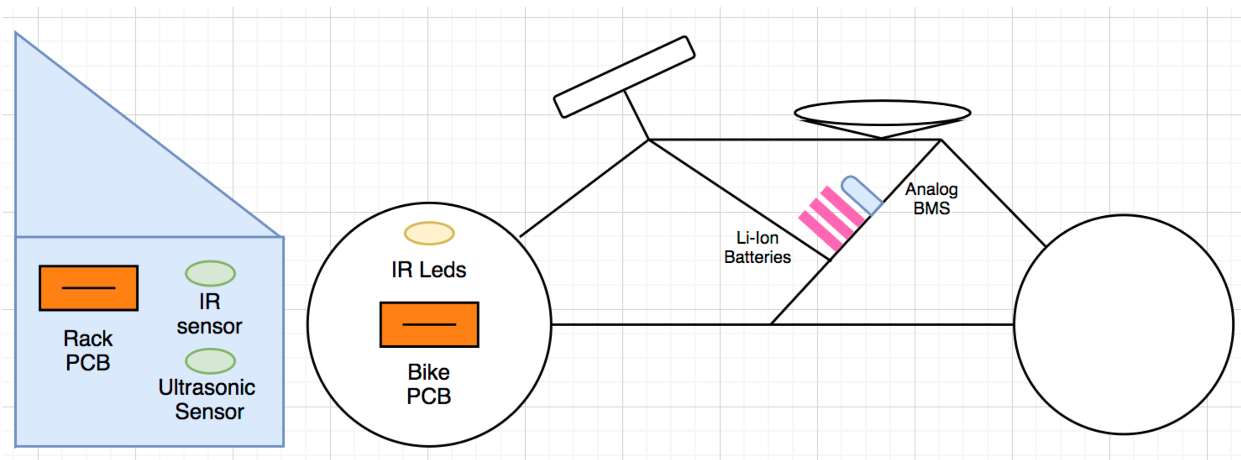

Figure 4: Mechanical Intolerant Model of Electronics Layout

2.1 Rack Side

The Rack side has a 2-terminal input to the system which requires 12 volts and a minimum of 0.75 amps which powers the entire system. The Qi Coil is directly on this power path as well as the N-channel MOSFET. The gate of the MOSFET is controlled by the microcontroller and can be at 0 or 4V which can disconnect or connect the power path, respectively. The microcontroller and the sensors are powered by 5V which comes from the voltage regulator which bucks the voltage from 12V to 5V. The ultrasonic sensor measures the distance between the walls of the bike rack and will detect a change in that distance if a bike is placed inside the rack. When a bike is placed inside the rack the power path should be connected. The IR sensor detects any IR signal, and any IR signal detection will result in the power path being disconnected. On the bike side, which will be explained later we will emit an IR signal as a signal to stop charging. For multiple bike racks, an IR blocking material will be applied to each rack to provide an extra layer of protection for each rack so that multiple bike racks will not interfere with each other. The temperature sensor is used to measure the temperature of the TX coil and any temperature measured over 45 C will result in the power path being disconnected as a safety precaution.

2.1.1 Transmitter Qi Coil Module

The transmitter Qi Coil module is a 2-terminal device which takes a 12V input and uses the input voltage to produce a magnetic field. The module does this by boosting the voltage to a higher level to drive more current the coil and a higher current should result in a stronger produced magnetic field. If there is no or low voltage across the TX Coil module there will be no produced magnetic field. Many Qi Coil modules exist however most only exist for 5V devices and are low wattage. We chose these higher voltage and wattage coils since they will allow us to create a stronger magnetic field and drive more current on the bike side.

2.1.2 N-Channel MOSFET

The N-channel MOSFET is used as a power path latch to attach and detach the TX Qi Coil module from the power path, effectively turning the TX Qi Coil module on and off. The drain of the MOSFET is connected the TX Qi Coil – and the source of the MOSFET is connected to ground. The gate of the MOSFET is connected to a digital pin of the ATMEGA328P-PU microcontroller which can set the gate to be either 0V or 4V. When the gate is 0V, the MOSFET will be in the off region of operation and will allow no/low current to flow from drain to source which will detach/break the power path. When the gate is set to 4V then the MOSFET will be in the saturation region of operation since 4V is higher than the gate threshold voltage and the drain-source voltage is greater than the difference between the gate-source voltage and the gate threshold voltage. When the MOSFET is in saturation it will allow current to flow and complete the power path which will allow the TX Coil to be powered. We chose to use a N-channel MOSFET since it is typical to use MOSFET as latch for power applications.

2.1.3 ATMEGA328P-PU Microcontroller

The microcontroller is used to read all the sensor data and control the N-channel MOSFET to decide whether to connect the Qi Coils to the power source or not. The microcontroller uses the ultrasonic sensor to detect if a bike is in the rack and whether to start charging or not. The microcontroller also uses the input from the IR sensor to determine if the bike is charged and if the rack should stop charging. Finally, the microcontroller uses the temperature sensor to make sure the Qi Coils are not overheating and to turn off the coils if they are. The pseudocode for this can be seen below.

```
bikeRackLoop:
    dist = ultrasonicDistance()

    if(irrecv detects signal):
        ir = true
    else:
        ir = false

    tempC = getTemperature()

    if(dist < BIKE_RACK_DIST && tempC < CUTOFF_TEMP && !ir):
        send4VoltsToNMOS()
    else:
        send0VoltsToNMOS()
```

Figure 5: Bike Rack Pseudocode

2.1.4 Ultrasonic Sensor

The ultrasonic sensor sends an ultrasonic sound that humans cannot hear and measures how long the reflected wave takes to reach the sensor. The sensor has 4 terminals. The sensor is powered with 5V and grounded using the power and ground pins. The sensor will send a voltage based on how long it took for the reflected wave to reach the sensor through the echo pin which is connected to the ATMEGA328P. Once the microcontroller receives this voltage the conversion to cm will be done. The trig pin will be connected to a PWM pin on the ATMEGA328P which will being an oscillating square wave of 66.666 kHz and the ultrasonic sensor will take a new reading for every rising edge of the square wave. We chose to use an ultrasonic sensor over a laser distance measurement device since a laser measurement device measures distance at a very specific point, whereas an ultrasonic sensor uses reflectance and will measure distance over an area. Since we have a mechanical tolerance on checking distance, having a sensor that measures distance over a bigger area than a laser is beneficial for our design. This can also be useful for bikes that will have different tires and allows us more flexibility.

2.1.5 IR Sensor

The IR Sensor is a 3 terminal device which has power, ground, and data pins. The sensor is powered by 5V on the power pin and connected to ground using the ground pin. The data pin is connected to a digital pin on the ATMEGA328P and sends a voltage when an IR signal is detected. Different IR signals will send different voltage readings, but we just care about detecting any IR signal for our project; we only differentiate between no voltage/no IR reading and voltage/IR reading when processing this data on the microcontroller. We are using IR emission and detection as a signal to stop charging. We chose to use IR over RF with multiple racks and bikes, because each bike and rack would need a specific frequency to not have cross interference with multiple bikes and racks. Using a RF system would also lead to only one bike being charged with one rack; using our IR system would allow our e-bikes to be charged with any bike rack.

2.1.6 Temperature Sensor

The temperature sensor is a 3 terminal device which has power, ground, and data pins. The sensor is powered by 5V on the power pin and connected to ground using the ground pin. The data pin is connected to an analog pin on the ATMEGA328P and reads a voltage correlated to a temperature. The voltage of the data pin should be read in millivolts and conversion to degrees C is done on the microcontroller. The temperature range of the sensor is from –40C to 150C and the sensor is measuring the temperature of the TX Qi Coil.

2.2 Bike Side

The bike side consists of the receiver Qi Coil module, Li-Ion battery pack, Analog BMS, ATMEGA328P, temperature sensor and IR LEDs. When the TX and RX Qi Coils are lined up the RX Qi Coils should produce 12 V and drive current to charge the battery as well as power the microcontrollers and the sensors. The microcontroller on the bike side is the used to monitor the charge status and make sure we have no safety issues on the bike side while charging. A 5V voltage regulator was used on the bike side to buck the voltage from 12V to 5V to power the microcontroller and temperature sensor.

2.2.1 Receiver Qi Coil Module

The RX Qi Coil module is a device that turns a magnetic field into an induced current to power the bike side system. If the magnetic field is strong enough the RX module will output 12V to power the system and the output current will depend on the magnetic field but will be capped at max output current of 3A. A red LED on the module should light up when the Qi Coil is active and producing 12V.

2.2.2 Analog BMS

An analog BMS is used to protect our Li-Ion battery pack from cases of overcharge, overcurrent, undercharge and performs cell balancing. Overcharge is set at 4.08V +/- .1V per cell and undercharge is set at 2.55V +/- .05V per cell. Overcurrent is set at 30 A; however, we expect to never reach an overcharge condition. Cell balancing is done with capacitors by sending more charge to lower voltage cells than higher voltage cells. Access to the battery pack is done through the analog BMS to enforce this safety conditions.

2.2.3 Li-Ion Battery Pack

We have 8 Li-ion cells connected in a 4S 2P configuration on the electric bike. Normally a battery pack is used to power the motor and all the other electrical components on the bike, however we have just attached the batteries for our model e-bike. We can charge the batteries using the RX Qi coil on the bike pad. The battery pack is also connected to the Analog BMS control circuit to help monitor the battery voltage.

2.2.4 ATMEGA328-PU Microcontroller

The microcontroller is used to detect the voltage of the Li-Ion battery pack and the temperature sensor. If the microcontroller detects that the battery was charged, then it turns on the IR LEDs to signal the bike rack to stop charging. Additionally, if the microcontroller detects that the battery is too hot via the temperature sensor then it turns on the IR LEDs to signal to the rack to stop charging. This logic can be seen in the pseudocode below.

```
bikeLoop:
    voltage = readBatteryVoltage()

    tempC = getTemperature()

    if(voltage > CUTOFF_VOLTAGE || tempC > CUTOFF_TEMP):
        turnOnLedsPin1()
        turnOnLedsPin2()
    else:
        turnOffLedsPin1()
        turnOffLedsPin2()
```

Figure 6: Bike Pseudocode

2.2.5 Temperature Sensor

The temperature sensor is a 3 terminal device which has power, ground, and data pins. The sensor is powered by 5V on the power pin and connected to ground using the ground pin. The data pin is connected to an analog pin on the ATMEGA328P and reads a voltage correlated to a temperature. The voltage of the data pin should be read in millivolts and conversion to degrees C is done on the microcontroller. The temperature range of the sensor is from –40C to 150C and the sensor is measuring the temperature of the Li-ion battery pack.

2.2.6 IR LEDs

The IR LEDs are placed on the front tire of bike and will send a signal to the IR sensor on the rack once the bike is done charging. The voltage drop across each LED should be between 1.4V and 1.8V. The voltage we are aiming for is 1.6V to turn on the led. This signal will then be used to determine whether the bike needs to continue charging on the rack or stop.

3. Design Verification

3.1 Power

3.1.1 Qi Coil Transmitter (Rack-side)

We attached a 12V DC power source and used a magnetometer to measure the magnetic field generated. We detected a magnetic field with 12V but nothing with 0V.

3.1.2 Qi Coil Receiver (Bike-side)

After verifying the transmitter coil, we placed and aligned the receiver coil on top of the transmitter coil. Then, we measured the voltage across the terminals of both coils and used an ammeter to measure the output current.

3.1.3 N-channel MOSFET

We put 12V at the drain and 0V at the source and we changed the gate between 0V and 4V. When the gate was 0V, there was no current; when the gate was 4V, current flowed between drain and source.

3.1.4 Li-ion Battery Pack

We used a voltmeter to test the voltage of each Li-Ion battery cell (3.45V). Then, we connected the 8 cells in a 4S 2P configuration and tested the voltage of the entire battery pack (13.6V).

3.1.5 Analog BMS

Overcharge was tested by charging the Li-Ion battery with the analog BMS attached using a DC power source and the BMS automatically stopped sending current into the battery pack at 4.02V per cell. Cell balancing was tested by inserting a lower voltage cell into the 4S2P cell stack and charging the battery pack with the analog BMS attached. We used a voltmeter to measure the voltage of the cell and compared to a higher voltage cell and while charging the lower voltage cell gained more voltage over time than the cell with the higher initial voltage.

3.2 Control

3.2.1 ATMEGA328P-PU Microcontroller

We used an Arduino Development Board to test the code. We used a voltmeter on the D0-D13 pins to test the output voltages and we also tested the input voltages in pins A0-A5.

3.2.2 Ultrasonic Sensors

First, we used the 5V pin on the Arduino Uno to power the ultrasonic sensor and connected a 3V square wave to the trig pin. Then, we placed a flat surface in front of the sensor and connected the data pin to a voltmeter. We placed the flat surface at various distances, using a ruler, from the ultrasonic sensor to make sure that we read the correct voltages and compared it to the actual distance. We found all the sensors were within a +/- 1cm difference.

3.2.3 IR Sensors

We powered the sensor by connecting the Vcc pin to the 5V power pin on the Arduino. We connected the data pin to the voltmeter and used a TV remote send an IR signal to the sensor. When a button was pressed we detected a voltage spike.

3.2.4 IR LEDs

We connected a LED to 1.6V DC power source and used an IR sensor and the camera app on our iPhones to detect the IR light.

3.2.5 Temperature Sensors

We connected the temperature sensor to a 5V power source and connected the sensor's data pin to an Arduino board. Then, we used a butane torch to test the reading from our temperature sensor and compared it to the results from a laser thermometer.

3.3 System Testing

Once we built the bike and bike rack was fully assembled, we tested the charging efficiency and charge time. When compared to direct wired charging at the same current the bike rack charges at 60%-70% efficiency. Below is the charge capacity vs time graph at 1.25A. Charge capacity is a percentage where 0% is undervoltage for the battery pack and the 100% is hitting the nominal full voltage for the battery pack. The reason why the curve is not smoother is because we took measurements at the battery pack at 15-minute intervals and it would be smoother if we had a computer track voltage for the entire charge process instead of taking discrete measurements using a multimeter.

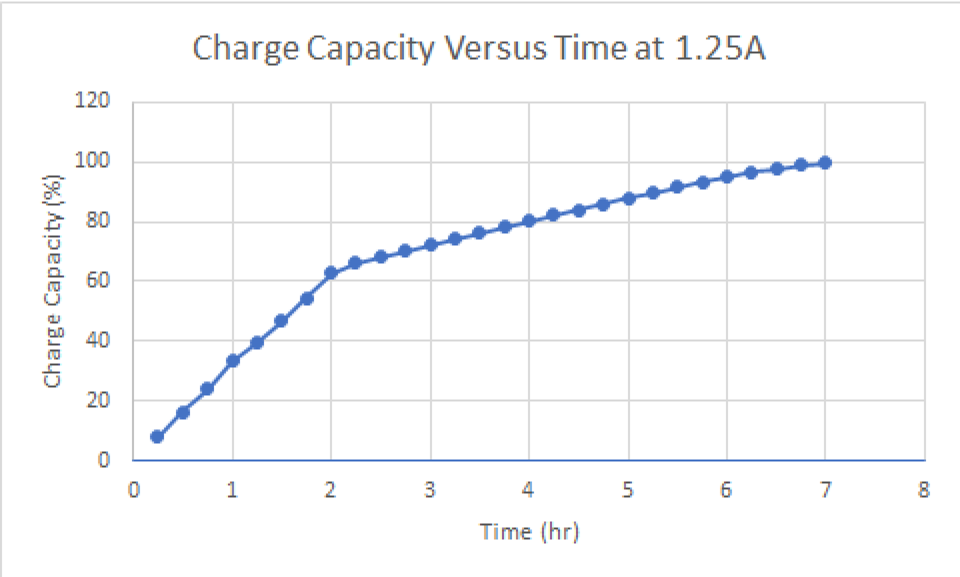

Figure 7: Charge Capacity vs Time

4. Costs

4.1 Parts

Table 1 Parts Costs

Part	Manufacturer	Part Number	Quantity	Cost ($)
MOSFET	Diodes Incorporated	2N7002	4	1.00
Qi Coils	Taida Century	B076GZ59HR	1	30.00
Ultrasonic Sensor	Adafruit Industries LLC	3942	3	11.85
IR Sensor	Vishay Semiconductor	TSOP38238	2	2.24
ATMEGA328P-PU	Analog Devices	ATMEGA328P-PU	2	4.16
Analog BMS	Daier	E880	1	9.00
Battery Cells	Samsung	INR18650-30Q	8	58.00
1.5 kOhms resistor	Panasonic	ERJ-6GEYJ152V	10	0.49
Temperature Sensor	Adafruit Industries LLC	TMP36	4	6.00
IR LEDs	Adafruit Industries LLC	ADA388	25	12.18
USB to TTL Adapter	Ardest	ESP8266	1	7.99
16 MHZ Crystal	TXC Corporation	9B-16.000MAAJ-B	4	1.56
22 pf Capacitor	Vishay BC Components	K220J15C0GF5TL2	10	1.52
100 microfarad Capacitor	Rubycon	35ZLH100MEFC6.3X11	3	0.90
Total				145.89

4.2 Labor

Based on the formula that we were given in the design doc preview; we calculated the cost of labor for our group on this project.

$40/hour * 10 hours/week * 14 weeks * 2.5 = $14,000

$14,000 * 3 teammates = $42,000

So, the total cost adding the labor and the parts up is 14,000 + 145.89 = $14,145.89

5. Conclusion

5.1 Accomplishments

Our product was a functional bike rack that wirelessly charged electric bikes. We were successfully able to charge the bike within 7-9 hours using the Qi Coils. The bike rack also properly started and stopped charging based on the safety conditions. The bike rack only started charging when the bike was detected and if the coils or battery were too hot or an IR signal was detected then the rack stopped charging. The physical design was also a success as the space between the transmitter and receiver Qi Coils was minimized to allow the most efficient charging. The physical design also integrated all the electrical components well and no sensor had to be placed in a different place than initially planned.

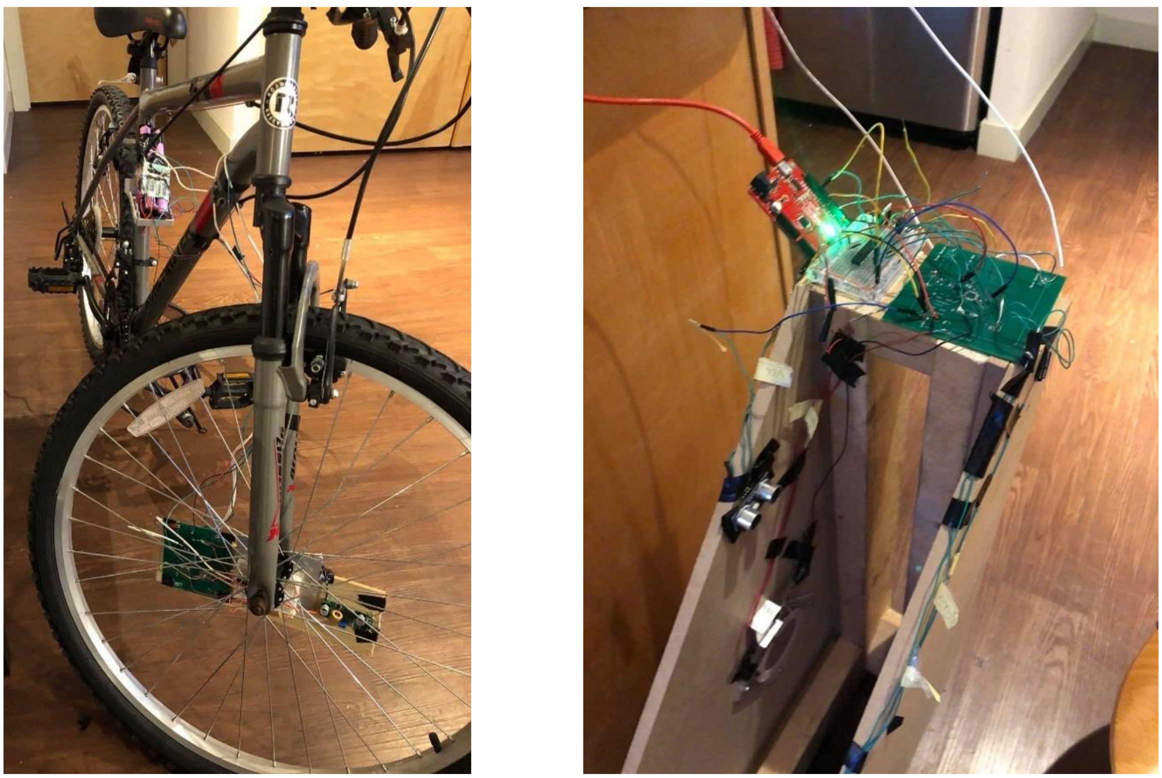

Figure 8: Fully Assembled Bike and Bike Rack System

5.2 Challenges

We faced some challenges while developing this product. The first challenge that we faced was the IR receiver we initially had did not work and we spent some time debugging to figure out if the sensor or code was the issue. Another issue we faced was testing the IR LEDs initially without a working IR sensor. We did not have a way of detecting them until we had a working IR sensor. The next issue we faced was that the original Qi Coils that we had ordered did not work as expected and we had to find and order a new Qi Coil module that would fit our purposes. Additionally, we faced issues soldering the SMT version of the microcontroller and had to switch back to the through-hole version of the microcontroller. Finally, our microcontroller on the rack side broke the night before the demo but we were able to get the system working with an Arduino so that we could still show functionality for the demo.

5.3 Ethical considerations

We did not have many safety or ethical concerns for our project, but there are still some issues. We are worried about people tampering with the electrical components on the e-bike and bike rack; anyone tampering with the bike pad or battery cells could be electrocuted. If we brought this product to market, will also make it clear that the charger can cause harm if tampered with or misused and any harm coming from misuse/tampering is not our responsibility.

If the Qi Coils or battery pack overheats during the charging process, this could be dangerous and cause burns for customers. To prevent this, we have placed temperature sensors near the Qi Coils and Li-ion batteries to detect dangerous levels of temperature. If the components get too hot, we cut off power to the Qi Coils to stop charging and let everything cool down.

Another concern that we have is accidently wiping out someone's credit card information with our bike charger. If someone drops their wallet or credit card in between the tire clamps and charging unit, nothing serious will happen. However, if someone tampers with our rack and purposely inserts a credit card between the transmitter and receiver coils, the magnetic field generated could damage the magnetic strips on the back of credit cards. In the future, we can create a physical barrier to prevent anything from being inserted between the coils.

5.4 Future work

There are some changes we would like to have done to our project with more time to work on it. Primarily we would like to redesign the PCB to use the ATMEGA328P-PU through-hole chip instead of the SMT chip that we had initially planned on using. This would lead to a cleaner PCB design without needing a breadboard to use the chips. Another change we would like to make is chose a better IR LED for the project. Currently the IR LEDs that we have do not constantly stay on. We saw that they had random peaks and did not just stay on even when the voltage and current were set to the product specifications. With better IR LEDs our design would have worked better, and we would not have needed to put visible LEDs instead for the demo. Additionally, the battery can be charged faster with higher powered Qi Coils. We chose a conservative current due to not having constant lab access, but our design could handle more current and charge faster so if we replace the current Qi Coil module with a higher wattage Qi Coil module then the battery will be able to charge faster and still be safe. Finally, we would like to have designed the bike rack to conceal the sensor wires better. Our initial concern was to make sure the Qi Coils were as close together as possible so that we would have the best charge efficiency. We can make a newer design that keeps the Qi Coils close together, but also has housing for the sensors and hides the wires so that the product looks more professional.

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Appendix Requirement and Verification Table

Table 2 System Requirements and Verifications

Module	Requirement	Verification	Verification status (Y or N)
Qi Coil Array on the Rack	1. Transmit magnetic fields to the receiver with an inductance of 12µH 2. Input should be between 12 and 15 volts and voltage should be boosted for higher performance from the internal voltage regulator	1. Attach a DC ~12 V supply 2. Use a magnetometer to measure the magnetic field and compare it to the theoretical magnetic field shown in the datasheet	Y
Qi Coil Array on the Bike	1. Receive a magnetic field with an inductance of at least 10µH 2. The output voltage from coils should be ~12V	1. After verification of the transmitter Qi coil, use the incoming magnetic field and use an ammeter to measure the output current. 2. Use a voltmeter to measure the voltage across the terminals of the coil. 3. Use a magnetometer to measure the incoming magnetic field.	Y
Analog BMS	1. NMOS will block power when the total battery voltage is greater than 14.8 V +- .5 V 2. Cell balancing will be achieved to make sure cells have similar voltages.	1. We can attach a sinking power supply as a "battery" on the B+ and B- side 2. Get the waveform over time of the current on the B+ and B- side. The current should be held constant until 50% capacity of the battery is reached and after current should be tapered down 3. Increase the voltage of the sinking supply source to 15+V and measure current at the source pins of the NMOS 4. Remove the sinking supply source and add 1 empty cell and 3 full cells in series. Charge the battery with the BMS and after 1	Y

		hour measure the voltage of each battery.	
Ultrasonic Sensors	1. We want to make sure that the measurements taken by the sensor have an accurate distance measurement of with +- 1 cm of the actual target distance. a. We will be checking the measurements in the range of 8 - 16 cm.	1. Power an Arduino Uno development board and use the 5V pin to power the ultrasonic sensor. 2. Place a flat surface in front of the ultrasonic. 3. Connect a 3V square wave to the trig pin. 4. Connect the data pin to a voltmeter and make sure the correct voltage is read out according to the datasheet.	Y
IR Receiver	1. Detect an array of IR LEDs with an intensity of 70 mW/sr +- 10mW/sr up to a max distance of 25 cm.	1. Connect the Vcc pin to a 5V power pin from an Arduino Uno Development board. 2. Connect the data pin to the voltmeter 3. Shine an IR light and verify we have a voltage spike corresponding to when the light is shined.	Y
IR LED	1. The array of LEDs will emit light having a wavelength of 940nm and an intensity of 85 mW/sr.	1. Connect a 1.6V DC power source and use an IR detector or an IR detector app on a smartphone to detect the IR light.	Y
Microcontroller	1. Be able to process analog measurements and use digital IO to drive outputs as can be seen in the software flowcharts.	1. Use an Arduino Development board to test the output voltage of the 3.3 V and 5V pins 2. Use a power supply to test the input range of the A0-A5 pins 3. Attach a voltmeter the D0-D13 pins to test the range the output voltage of the IO pins	Y
Temperature Sensor	1. Be able to detect temperatures of up to 65C to sense overheating of the coils and battery.	1. Connect the temperature sensor to a 5v power source. 2. Connect the data pin of the temperature sensor to an	Y

		Arduino development board. 3. Use a butane torch near the temperature sensor to test the temperature sensor. 4. Use a laser thermometer to measure the temperature sensor. 5. Compare the laser thermometer reading to the temperature sensor reading and compare the values.	
NMOS	1. The NMOS will have a high Vds breakdown of 30-45V	1. Ground the gate and source of the NMOS 2. Attach an ammeter between the source pin and ground 3. Set the drain pin of the NMOS to 25+V 4. Observe low current through the ammeter.	Y
Li-Ion cells	1. Li-Ion pack will have a nominal voltage of ~14.5 V and a capacity of 5Ah	1. Use a voltmeter to test voltage per cell. 2. Connect all the 8 cells in a 4S 2P configuration 3. Use a voltmeter to test overall pack voltage.	Y