Title
Design of a Power Transmission System via Inductive Coupling to a rotating LED Persistence of Vision (POV) Display

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Design of a Power Transmission System via Inductive Coupling to a rotating LED Persistence of Vision (POV) Display

A Thesis submitted in partial satisfaction of the requirements for the degree Master of Science

in

Engineering Sciences (Mechanical Engineering)

by

Janelle Arlene Duenas

Committee in charge:

Professor Thomas R. Bewley, Chair
Professor Mauricio de Oliveira
Professor Michael Tolley

2018

The Thesis of Janelle Arlene Duenas as it is listed on UCSD Academic Records is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego

2018

Dedication

To my family, you are the reason for who I am today,
Thank you for your love and care

To Axxell Palomares, my husband,
Thank you for believing I can achieve anything

Epigraph

"What we usually consider as impossible are simply engineering problems… there's no law of physics preventing them."

— Michio Kaku

Acknowledgements

I would like to acknowledge Professor Thomas R. Bewley for his support and guidance as the chair of my committee. I appreciate the feedback and encouragement he provided throughout my project.

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I much express my gratitude to Axxell Palomares, my husband, for his constant moral support and positive outlook on life. Thank you for believing that I can accomplish anything.

To my family who experience the ups and downs of my research, and supported my decisions to become anything I aspire to be.

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ABSTRACT OF THE THESIS

Design of a Power Transmission System via Inductive Coupling to a rotating LED Persistence of Vision (POV) Display

by

Janelle Arlene Duenas

Master of Science in Engineering Sciences (Mechanical Engineering)
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Professor Thomas R. Bewley, Chair

Slip rings are often used to distribute power to rotating elements, but have the disadvantages of adding friction to the system and wear over time. An alternative to this method is power by inductance through coils. Power can be transferred over an air gap by changing the magnetic flux in a coil thereby inducing voltage. In this project we will transfer power from a primary to a secondary coil to power a custom made PCB which synchronizes a row of LEDs.

As the PCB rotates, it creates a perception of 2D images. The main purpose of this prototype is to create a low cost LED display platform by rotating a motor at 40Hz+ and powering it through inductive coupling.

Introduction

Persistence of Vision (POV) is the natural phenomenon that occurs when the brain interprets an object moving at a high frequency as a single image. This occurs because an image remains in the retina for a fragment of a second, so if another image is presented before the previous retina image disappears, the brain will perceive the two images as one. This concept is especially useful in films and LED displays. Human's acceptable video rate to perceive a continuous picture is 15Hz, but a common standard for films is 24Hz [8]. LED displays synchronize a rotating row of multiple LEDs to create a 2D image. The established methods of powering LED displays are through slip-rings or by attaching a power source in the spinning part [7]. Slip rings use carbon brushes that are in constant contact with traces thereby transferring power to a rotary part. Some of the disadvantages of slip rings are: wear over time, adding friction to rotating object, and adding vibration to the system. There is a third option not being explored: wireless power of POVs.

Wireless power transfer is slowly being introduced into the consumer market. This technology transmits power through an magnetic field without the use of wires. It is being introduced into consumer products due to its practicality (since it does not require connecting cables), and it allows the charging of sealed products that are externally exposed to water, hazardous chemicals, or dust [1]. Inductive charging, also known as inductive coupling, is one technique of wireless power transfer which transfers energy through a magnetic field over coils of wire that are in close proximity and aligned. Because of its safe implementation, charging through inductance is used in consumer products such as cell phones and appliances, as opposed to radio frequency power transfer [1]. Typically the operating frequency of inductive power transfer is in the KHz range [3].

Inductive coupling works by transferring power over an air gap by inducing an alternating current in a primary coil which in turns creates a magnetic field which excites the secondary coil by causing electrons to accelerate back and forth, inducing an alternating current. Then, the alternating current in a secondary coil can be rectified to direct current to a desired voltage [4].

Inductive charging has been around more than one century, yet this technology is still not widely used. In 2008, researches, Slobodan I. Babic and Cevdet Akyel, developed a simple and accurate model for calculating mutual inductance between coils with inclined axes as an alternative to software that requires a powerful computational cost [9]. Passing power to rotating objects wirelessly is also being studied. In 2016, two coils were used with a resonant converter circuit to generate 20W with two coils mounted on L-shaped ferrite cores with a 1mm air gap to generate an 87.7% efficiency [7]. Adding resonant and ferromagnetic materials around coils increases the efficiency of the wireless power transfer. Currently, inductive coupling is being used to charge devices such as electric toothbrushes, cell phones, and even electric vehicles. Additionally, electric coupling can also be used to send information, such in the case of biomedical devices that are implanted in order to restore human sensory functions. For example, coils are being utilized to power and send information to implants that aim at restoring human vision by stimulating the retina [10]. While research on efficient power transmission and wireless communication through inductive coupling exits, this technology is being underutilized in modern electromechanical systems.

In this project we aim to design a POV LED Display with wireless power transfer through inductive coupling. Additionally, a custom Printed circuit Board (PCB) will be developed to synchronize LEDs while using an operating system called TI-RTOS. The rotation of the PCB does not have a significant effect in the power transfer between two coils [6].

The next four chapters explain the details of the electrical, mechanical, software implementation, and power transfer designs.

Introduction of Chapters

The goal of this project is to create an LED display of Pac-man mounted on top of the MIP robot. The functional requirements of the prototype can be divided into two priorities, Tier 1 and Tier Two, as seen in Table 1. The most important functional requirements include PCB must rotate at 40Hz or more with minimal vibration, an RGB LED display must be created, power must be transferred wirelessly, and there must be enough computational power to control LEDs. The secondary functional requirements can be seen in Tier 2. The MIP extension must be in similar form factor, for example, the MIP robot must not offset the center of mass or inertia extensively. It must be low cost, have the ability to be control remotely, use a simple IDE and whatever microcontroller that is use must have extensive documentation and online support community. The following Sections describe how each of these functional requirements is met through four design challenges: Mechanical Design, Electrical Design, Power Transmission, and TI-RTOS software implementation.

Table 1. Functional Requirements

Initial Functional Requirements of Deliverable System	
Tier 1	Tier 2
Minimal Vibration	Minimal Form factor changes
Spin at 40Hz+	Low Cost
RGB LED Display	Control LEDs Remotely
Power Transferred Wirelessly	Uses simple IDE
Enough Computational Power for LED display	Extensive Software Documentation

Chapter 1. Power Transmission

The fundamental power transfer goal is to transfer energy from a stationary to part to a rotating PCB. Since the goal of this project is to display a Pac-Man, the project acquired the name of PacMip. In the previous iteration of the PacMip, the PCB was supplied with up to 15V, which would be regulated to 12v to run a Brushless motor from the PCB. Additionally, the PCB was grounded through the motor shaft to complete the circuit. The power transmission was conducted by a slip-Ring with a carbon brush as seen in Figure 1.

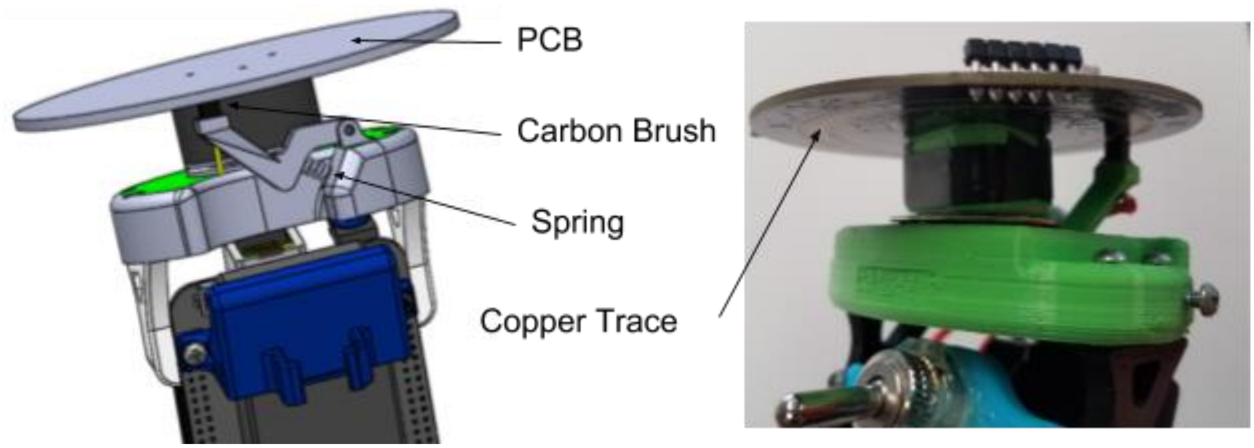

Figure 1. First Iteration of PacMip powered by custom made slip ring

To eliminate vibrations and friction that can be created from slip rings as well as avoid a technology that utilizes degrading parts (carbon brushes), the design was improved by switching to a safe wireless technology which is inductive power transfer. A 23-turn coil is used both to transmit and to receive an AC signal of 70 kHz. The frequencies and magnitude of the signal applied to the coil over different voltages can be seen in Figure 3. While there is PLA inside the coil, this can be estimated as an air fill. The coils are 2mm apart. Some disadvantages about this design is that only about 40% of the energy gets transferred (according to adafruit), this could be improved by adding a core (such as one made from iron) in the middle of the windings. The transmitter from adafruit is preserved but the receiver circuitry is removed and replaced by a full wave rectifier in the PCB.

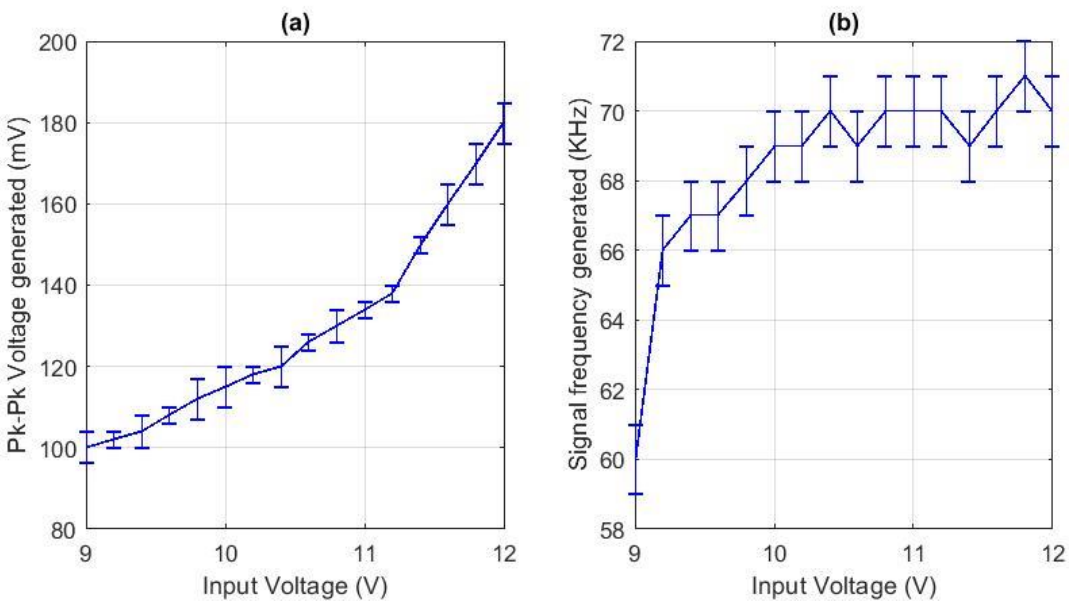

Figure 2. Signal applied on primary coil per different voltages (a) Pk-Pk voltage per input voltage of Adafruit Converter (b) Generated Signal frequency per input voltage of Adafruit Converter

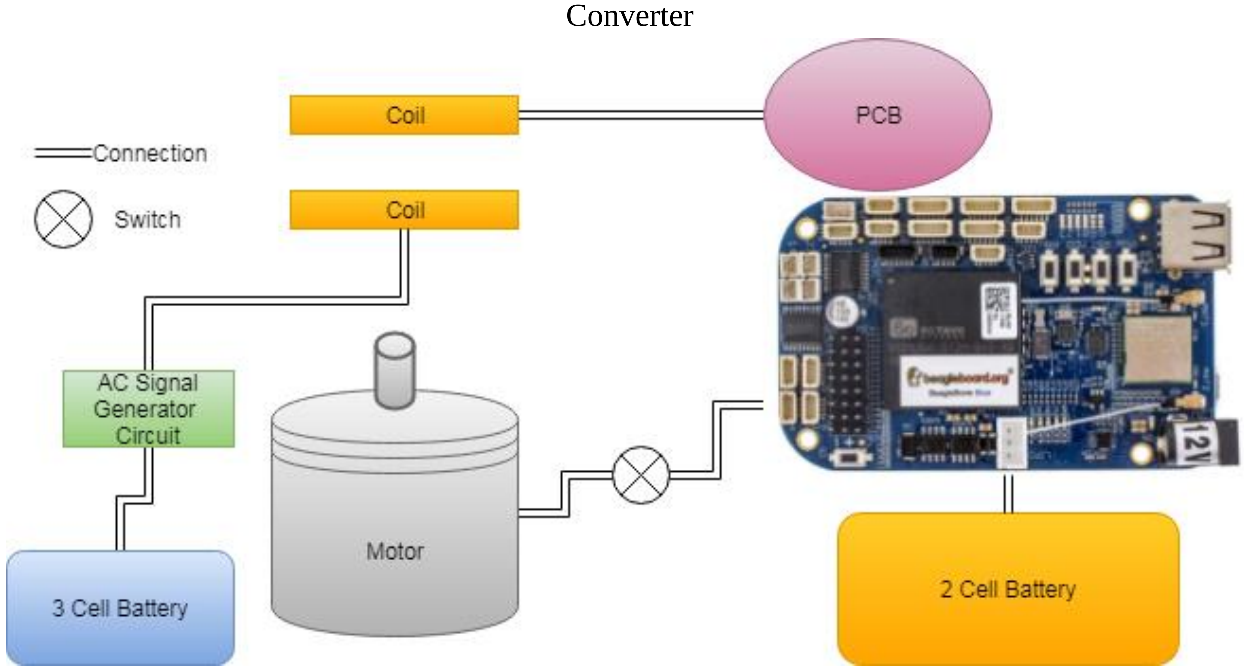

Figure 3. Power Connection Diagram

It must be noted that in order to supply the PCB, run a brushed and power the Beaglebone blue, both a 3 cell and 2 cell batteries are used. The coils circuit maximum current and Voltage transmission are .5A and 5V, meaning that ideally the power transfer will be 2.5 Amps. Each LED requires .02 Amps, meaning that a max only 25 LEDs can be turn ON at a time. Only 16 LEDs will be required to create the final display which is meant to be a Pac-Man. A safety manual switch was added to the body of the PacMip to stop power supply to the motor. By doing this, the user has control over the rotation of the PCB, since the Beaglebone Blue balancing code is constantly running, and can be reset when the MIP is laid horizontally. To see the power diagram of the system, refer to Figure 3. To see a block diagram of power transmission stages see Appendix A.1.

Chapter 2. Mechanical Design

When creating an extension to the MIP, the changes to the robots form factor were keep to a minimum to prevent changes in the balancing dynamics. In order to do this, all parts added were intended to keep the center of mass as close as possible to its original vertical axis, and the Inertia as unchanged as possible by not extending the MIP too much. However, since a motor as well as other hardware will be added the center of mass will rise away from its original horizontal axis, this also increases the inertia. However, regardless of the weight that would be added a motor had to be selected to rotate at least 40Hz to trick the human eye into seeing a continuous image. Note that the human eye will be able to see a POV at much lower frequencies. In order to reach this functional requirement a motor with a 64 CPR Encoder (Pololu Item 1440) was selected. It is intended to run at a voltage of 12V but can run with voltages as low as 1V according to their datasheet. At 6V it can reach 5500rpm which already exceeds speed requirements. PWM is used to control the speed of this motor.

A disadvantage of this motor is that it comes with a brass pinion gear attached to its 2mm shaft. Mounting to the brass gear resulted in a slanted PCB, so it was removed. A nylon hub was designed and laser cut, See Figure 4. Then it was press-fitted into the shaft. The Hub is 2.0mm±0.5 away from the top surface of the motor.

When designing the PLA mounts the printing side as well, the rigidity of the part and the feasibility of assembly had to be considered. All PLA parts that were designed can be seen in Figure 4. The Top Coil Mount was design to lift the PCB 12mm from the Coil so that the impact of the magnetic field is reduced. The Coils are adhered to their corresponding mounts with silicon. Since the Motor Hub is permanently fitted onto the motor shaft the Bottom Coil Mount can be inserted from above the Hub and the Motor Mount can be slid from the side. Additionally, the Motor Hub was shaped as seen in Figure 4 to allow for the screwing of the motor even after the Hub has been press-fitted. The Magnet Mount is place so that the center of the magnet is 65.6mm from the center of the PCB, directly below both hall sensors.

A rocker switch to cut power to the motor was added for safety, considering that the thin PCB can spin at 40Hz+. The Switch Mount is designed so that it curves around the motor to prevent the switch's wires from coming into contact with the motor. For this reason this is the only part that will require supports when 3D printed. The final mechanical design can be seen in Figure 5. The weight of the final design is 218g, See Appendix A.6.

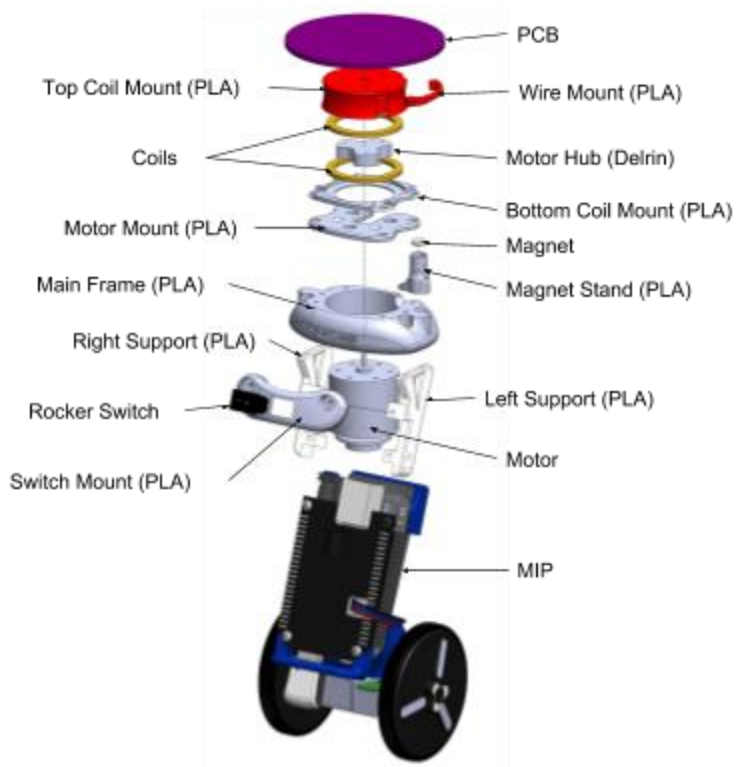

Figure 4. Exploded view of PacMip parts

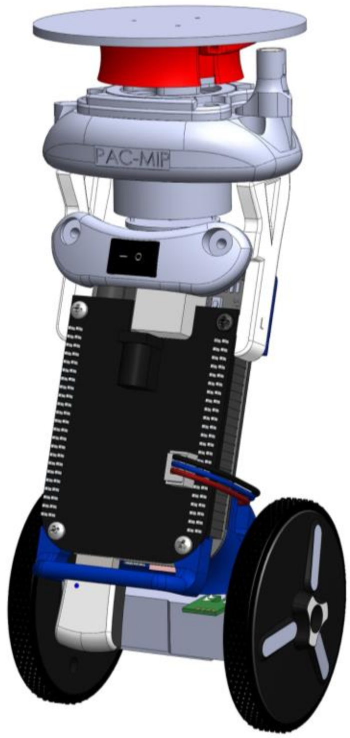

Figure 5. Final PacMip Design

Chapter 3. Electrical Design

In order to create an LED display, a four layer printed circuit board (PCB) had to be designed. Appendix A.2 shows the schematic of the PacMip PCB Board. This PCB includes a low TI bluetooth chip (CC2650MODA) which is utilized as microcontroller of the system. This microchip is a powerful ARM Cortex microcontroller with two cores (M3 and M0) with up to 48MHz clock speed. One of the limitations of using the cc2650MODA chip is that it only has 15 GPIO pins, but since two of those pins need to be used for JTAG communication, that leaves 13 usable pins. In order to reduce the number of pins require to control 16 RGB LEDs, LEDs drivers were utilized. A 10-PIN JTAG connector is added; the signals connected to it include: TDO, TDI, TCK,TMS, GND, 3.3v, 5v and NRESET. One of the Tier 2 Fundamental requirements is the remote control of LEDs, since a Bluetooth chip is being used as a microcontroller, it can be programmed remotely off-board, changing the display.

The CC2650MODA communicates with three LED drivers (MAX6969) over a serial peripheral interface (SPI) bus to control 48 individual LEDs. The PCB contains a row of 16 RGB LEDs (LTST-C19HE1WT). Each LED requires a resistor to determine the current applied to the LED and preventing from burning out over time, since current flowing through an LED is an exponential function versus the voltage applied, but a resistor's current is linearly related to voltage. [5] An interesting function of the LED driver is that it can control the current of all connected LEDs with a single resistor, reducing the output current control resistors needed to three, as opposed to 48, thereby minimized the traces in the PCB Design.

Many precautions and steps were taken to convert the inductively induced voltage to useful levels, but also to protect the accuracy of communicating signals in the PCB. For example, the layers of the PCB include GND, 3.3, GND and GND from top to bottom, extra layers of full plane GND and 3.3v have been added as signal shielding from the magnetic field created by the coils. The PCB is connected to a coil that generates an AC voltage. This is converted to DC Voltage through the use of a Schottky full bridge rectifier (750-CDBHD240-G). Each end of the coil is connected through vias by soldering the coil wires ends to them.

TPS560200DBVR was used to generate a 6.12V by following its specification sheet design requirements by using R1 = 133kOhm and R2=20kOhm in equation 1 following Figure 6. This step-down converter can take an input from 4.5V-17V and generates an output in the range 0.8V to 6.5V. See Figure 6 for TI recommended layout of this component. Note that the final implementation in Figure 6 differs from the actual layout (See Appendix A.2), since some components were changed according to datasheet specifications. After obtaining 6.12 V with the buck regulator, this is then reduced to the voltage which will power the LEDs (that is 5v) with the use of a low dropout regulator (LDO). The LDO used is the TI chip LP2989AIM-5.0/NOPB. Since the CC265OMODA microchips is powered by 3.3V, a drop in voltage is created from 5v to 3.3v with the use of the same buck regulator but with R1 = 61.9kOhm and R2=20kOhm as recommended in TI data sheet. The final PCB Power Regulation Schematic design can be seen in The Appendix A.2.

$$R_2 = (R_1 \times 0.8V)/(V_{OUT} - 0.8V) \quad (1)$$

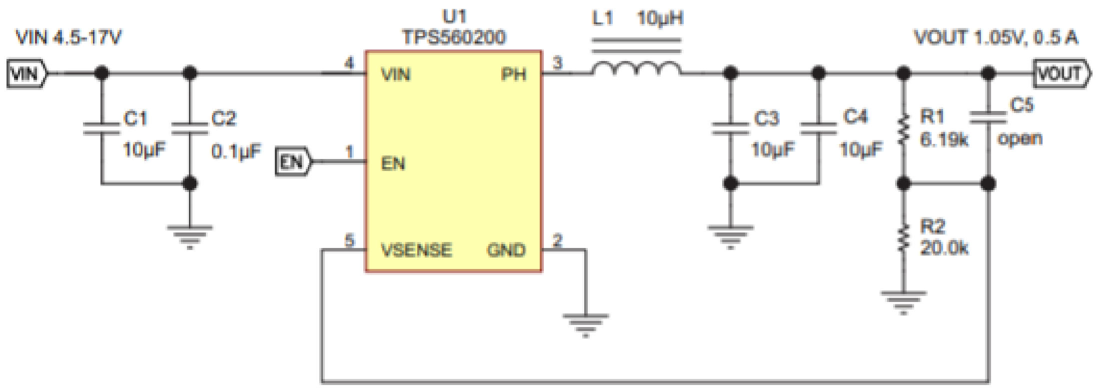

Figure 6. Step-Down Converter TPS560200DBVR layout-Obtained from TI data sheet TPS560200 4.5-V to 17-V Input, 500-mA Synchronous Step-Down Converter With Advanced Eco-Mode™

Finally, in order for the PCB to keep track of rotations and perform estimates of position two hall sensors were added, which will perceived the magnetic field of a magnet mounted below. First, it must be noted that only one hall sensor is necessary, and placing two was intended as a performance experiment between two different sensors. See Appendix A.2 to observe the layout of the two hall sensors. Hall Sensor 1 is an Allegro MicroSystems, LLC linear analog sensor (A1304ELHLX-T) with ±375 and a typical sensitivity of 4mV/G . Hall Sensor 2 is a Honeywell Sensing and Productivity Solutions analog sensor (SS39ET) with a ±1000 Gauss range and typical 1.4mV/Gauss sensitivity. Both sensors' resistor and capacitor components were added according to data sheet specifications. The magnetic field received is linearly related to voltage output of sensors. Since the analog signals of both sensors have to be read by the CC2650MODA, the supply voltage has to be 3.3V to maintain the same logic and protect the microcontroller. Additionally, the copper layers below the sensors were removed using trestric and brestric layers in board layout to allow the sensors to perceive the magnetic field without shielding on these areas.

The PCB was fabricated by ordering the board from Oshpark and utilizing the baking technique to mount all the components onto the board. The PCB is in accordance to Oshparks design guidelines and passed the Eagle Software DRC test with no errors. Then, using a stencil from OshStencils, soldering paste (SMDLTLFP-ND) is spread on the pads of the PCB. Then, the board is populated and baked on a hot plate oven. For a detailed procedure of Baking Procedure see Appendix A.3. The final PCB looks as followed:

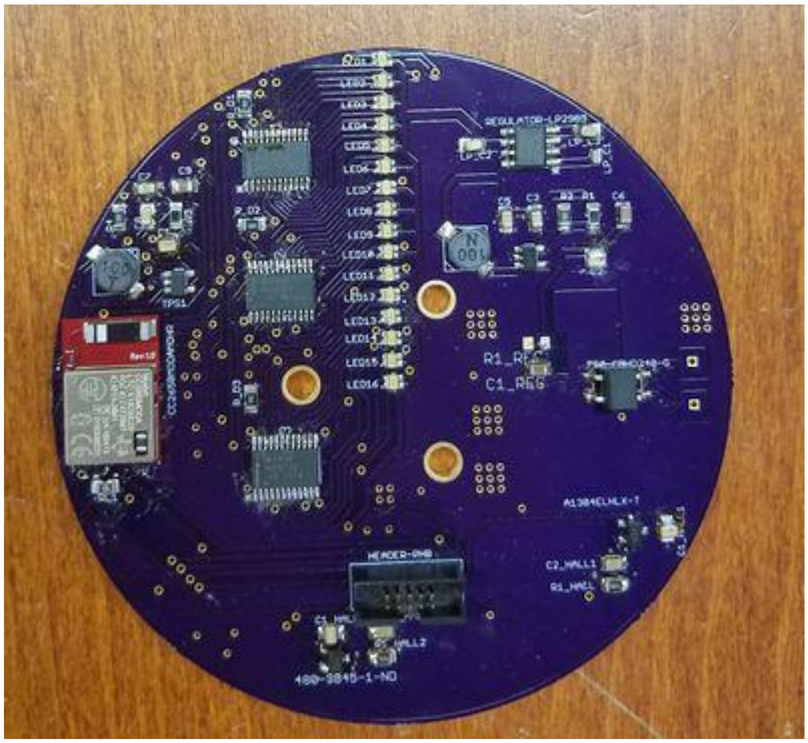

Figure 7. Final PCB fabricated

Chapter 4. Software Development

When coding the CC2650, TI-RTOS was utilized with the IDE Code Composer Studio v7.1 and the XSD110 USB Debug Probe and Compiler 5.2.6. One of the benefits of TI-RTOS is the useful APIs that come with it. For controlling the PCB there were multiple APIs used included by not limited to PWM, ADC and PIN. The RTOS handles scheduling, interrupts, memory management, and more. The CC2650MODA has two ARM Cortex-MX processors: The M3 which is the main processor, and the M0, which takes cares of Bluetooth functions.

4.1 Debugging

To communicate with the PCB the JTAG standard is used with signals TDI, TDO, TCK, TMS, GND, 3.3V, 5V and NRESET. In order to code the CC2650 only the 3.3V logic signal is necessary, but since the LEDs require 5V, the extra signal was added. The MSP432P401R microcontroller's XSD110 USB Debug Probe was disconnected and reconnected to Adafruit Cable Breakout Board (Product 2743) according to the PCB's JTAG signals. The JTAG ribbon cable can be used to communicate with the PCB (it comes with the MSP432P401R). Note that in order for this debugger to work a jumper wire has to be soldered to the debugger board as seen in Figure 8 inside the green circle.

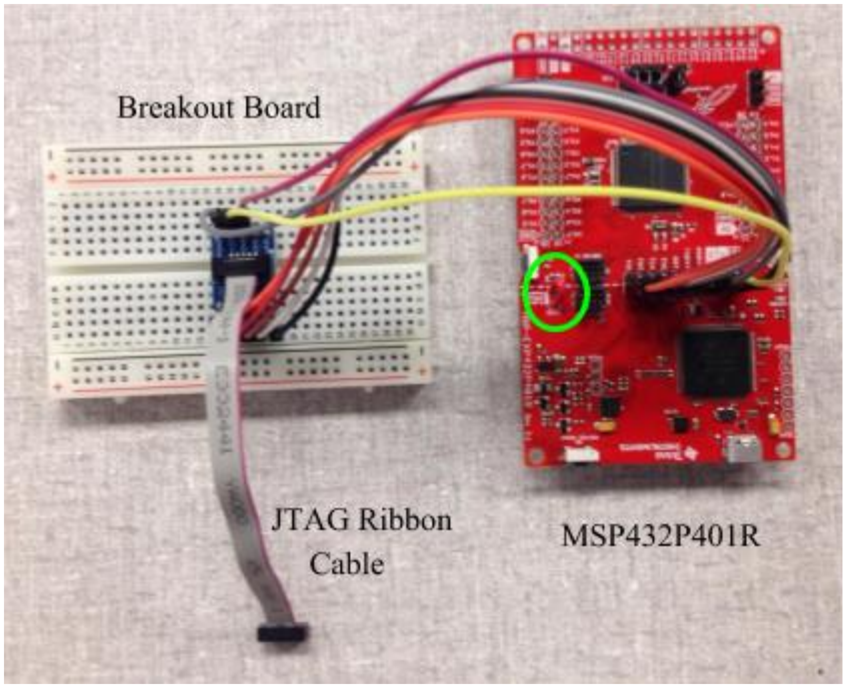

Figure 8. Debug circuit consisting of the XSD110 debugger from the MSP432P401R Launchpad connected to a breakout board with the JTAG Ribbon Cable

4.2 TI-RTOS Integration

The multitasking real-time kernel is utilized by running multiple threads, or tasks as they are called in this RTOS. In the following sections the use of important APIs is explained.

4.2.1 Pin API

By using the PIN API, the LED's can be controlled according to the LED display desired. MOSI (data in), CLK (clock), LE (Latch Enable) and OE(Output Enable) are declared, enabled and set to OFF mode in a pin configuration table. This table is referred to in main function and allocated to a handle function which will allow LED control.

4.2.2 ADC Thread

One of the threads being operated monitors the voltage generated by Hall Sensor 2. The ADC TI-RTOS API has two functions it samples and then it converts the analog reading. Figure

10 shows the analog data received from the hall sensor as it passed over the magnet mounted directly below it during one revolution. The magnet creates a distinct peak so each revolution will be counted at 1.8V. The code is formatted so that every time this threshold is reached the LEDs will be turned off for a certain time depending on how wide the Pac-Man's mouth should be opened. This can be accomplished because the Max6969 drivers have an OE switch signal, when High, the 16-bit shift register information is not latched into the output, thereby turning off the LED's.

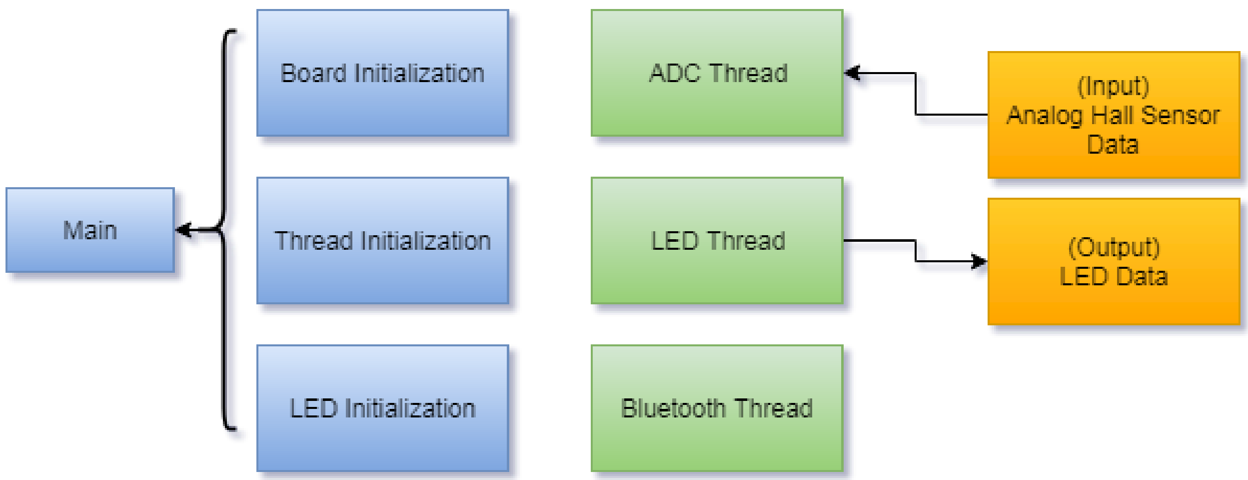

Figure 9. Software Logic

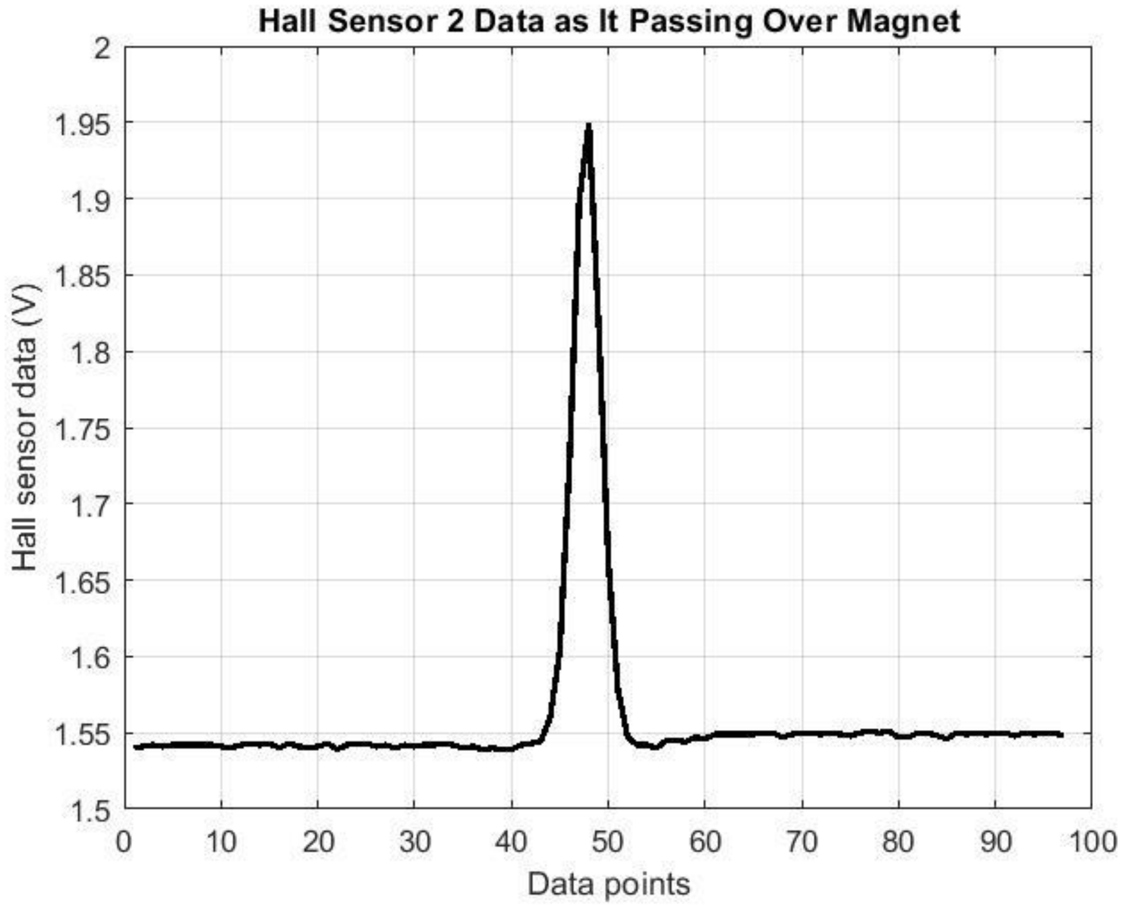

Figure 10. Hall Sensor 2 analog voltage reading as it passes over the magnet mounted below

Results

A display of Pac-Man was successfully created as shown in Figure 11 by spinning the motor at 40.3 Hz while powering the PCB through inductive coupling with a 2mm gap in between the coils. Figure 12 shows the average output voltage after rectification created by different voltage inputs into the adafruit circuitry. The system has two increasing linear regions as it can be seen on the graph. A jump in voltage occurs between 9.6V-11V input voltages. In multiple tests there is sudden increase in voltage in the mentioned region. Another characteristic of the power transmission system is that applied input voltage results in a hysteresis loop as seen in Figure 13. For this experiment the voltage was continuously applied as it increased to 11.2V and then decreased.

The PCB had 3 voltage drop goals 6.12V, 5V, and 3.3V. The Measure voltages in this nodes are 6.11V, resulting in a 2% error, 4.91V resulting in a 1.8% percent error and 3.26V, resulting in a 1.2% error.

Table 2. Voltage Target Results

Logic Level	Actual	Error
6.12	6.11	2%
5V	4.91	1.8%
3.3V	3.26	1.2%

The magnetic field can affect the performance of the PCB, for example in Figure 10 the average Hall Sensor 2 reading when passing over the PCB is 1.541±.001V but when the PCB is powered through inductance the voltage rises to 1.61±.01V as seen in Figure 14. While the voltage in the ADC reading rises due to the added magnetic field of the coils, once the magnetic field of the coils is added to the system, increasing the voltage in the input range of operation did not affect the Hall sensor readings as it can be seen in Figure 14. Note that even though the voltage is being increased the sensor still reads 1.6±1 and 2.02±.02V when above the magnet (readings being influenced by the magnetic field). The increase in voltage due to the magnetic field of the coils is 4.5% when not placed above the magnet.

Figure 11. Image of PCB spinning at 40.3Hz displaying RGB Pac-Man

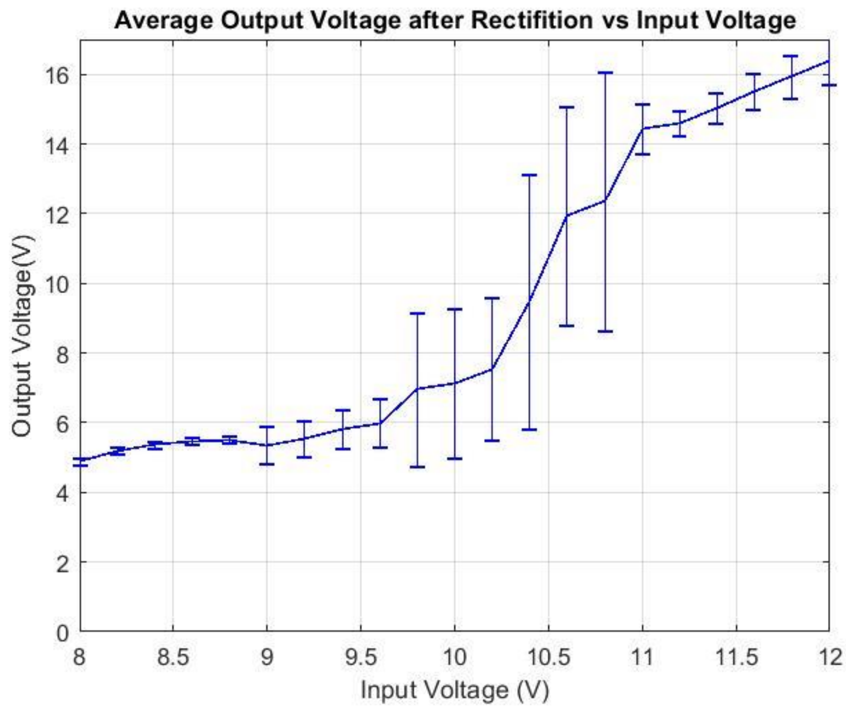

Figure 12. Input DC voltage applied on adafruit DC-AS circuitry vs output voltage obtained after rectification in the PCB circuitry

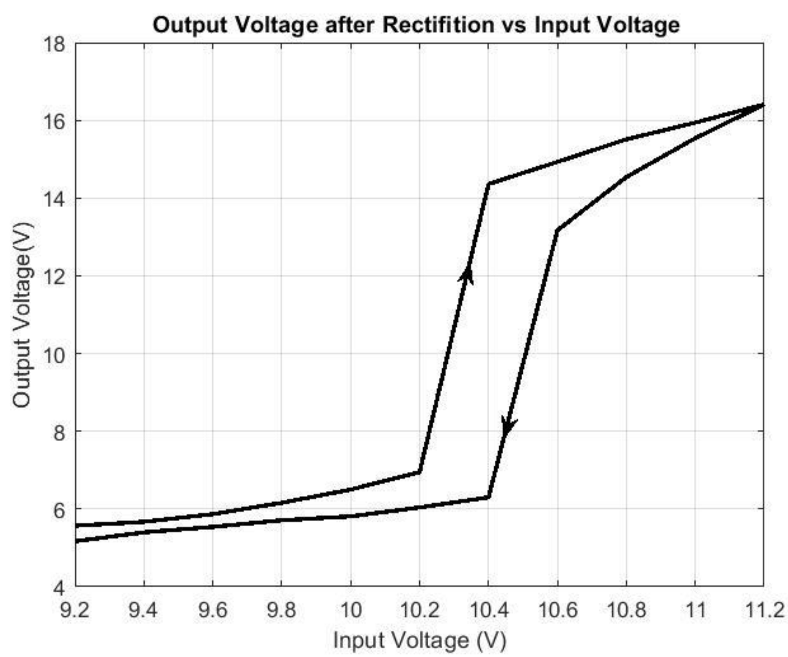

Figure 13. Increasing and decreasing input DC voltage applied on adafruit DC-AC circuit board vs output voltage obtained after rectification in the PCB circuitry

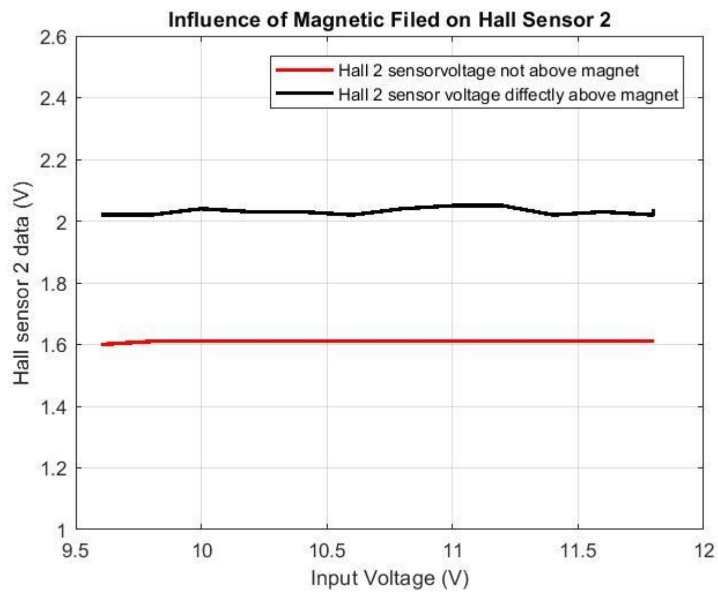

Figure 14. This graph shows how the magnetic field generated by the coils at different voltage levels affects Hall Sensor 2 analog output in the final mechanical design

Conclusion

The main objective of this project was to create a POV platform powered through inductive coupling to display a Pac-Man and accomplish Tier 1 Fundamental requirements. See Table 3 for an overview of accomplished fundamental requirements. If the box is shaded green, the requirement was accomplished, orange shading indicates somewhat accomplished and red indicates not accomplished. From Tier 1 all requirements were met and confirmed empirically, the only one that has not been empirically confirmed is the minimization of vibration but is shaded in orange because visibly it had less vibration as compared to the previous slip-ring design. Some secondary goals that were also accomplished in this project were creating a low cost platform. In Appendix A.5 it can be seen that the cost would be 110 dollars for the whole system created (Not including the MIP robot). Control LED Remotely goal is shaded orange because while a demonstration was not obtained, the Bluetooth capabilities of the PCB will allow for this to happen. Using a simple IDE was not accomplished since Code Composer is used and requires extensive practice and familiarity to be able to use it to code the microcontroller. Minimal form factor changes requirement is shaded orange because, adding inertia (a heavy motor at a higher distance) destabilized the balancing of mobile inverted pendulum. From a balancing perspective, increasing the inertia of the system should make it easier to balance, as long as there is enough torque in the wheels of the MIP. If sufficient torque is provided the PacMip will balance on two wheels, but this will require further studies. Extensive Software documentation is orange because while the CC2650MODA contains extensive documentation, using TI-RTOS is not straight forward yet enough online information is available in TI community conversations to learn its application and syntax.

Table 3. Summary of Initial Fundamental Requirements Accomplished

Initial Functional Requirements of Deliverable System	
Tier 1	Tier 2
Minimal Vibration	Minimal Form factor changes
Spin at 40Hz+	Low Cost
RGB LED Display	Control LED Remotely
Power Transferred Wirelessly	Uses simple IDE
Enough Computational Power for LED display	Extensive Software Documentation

Future Work

Inductive Coupling is technology that is being refined and understood; it should be used widely. The POV design uses a system of power transfer that can be improved. Currently the system has enough wattage to create a Pac-Man display, but not enough to power 48 LEDS. To solve this there are two options, increasing the power efficiency or decrease the power required by the PCB. LEDs can be replaced for others that require less current. The efficiency of the system can be increased by inserting a ferromagnetic core, or by introducing resonance. The state of the art of inductive coupling should be studied so that both power and information can be transmitted to a rotating mechanical part by riding information on top of the sinusoidal wave. In the future rotating POVs (or a rotating object) should be able to receive both power and information through inductive coupling.

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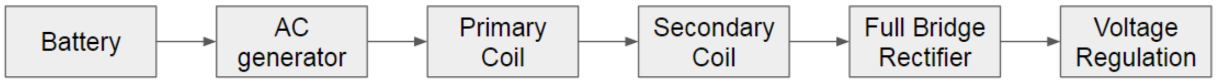
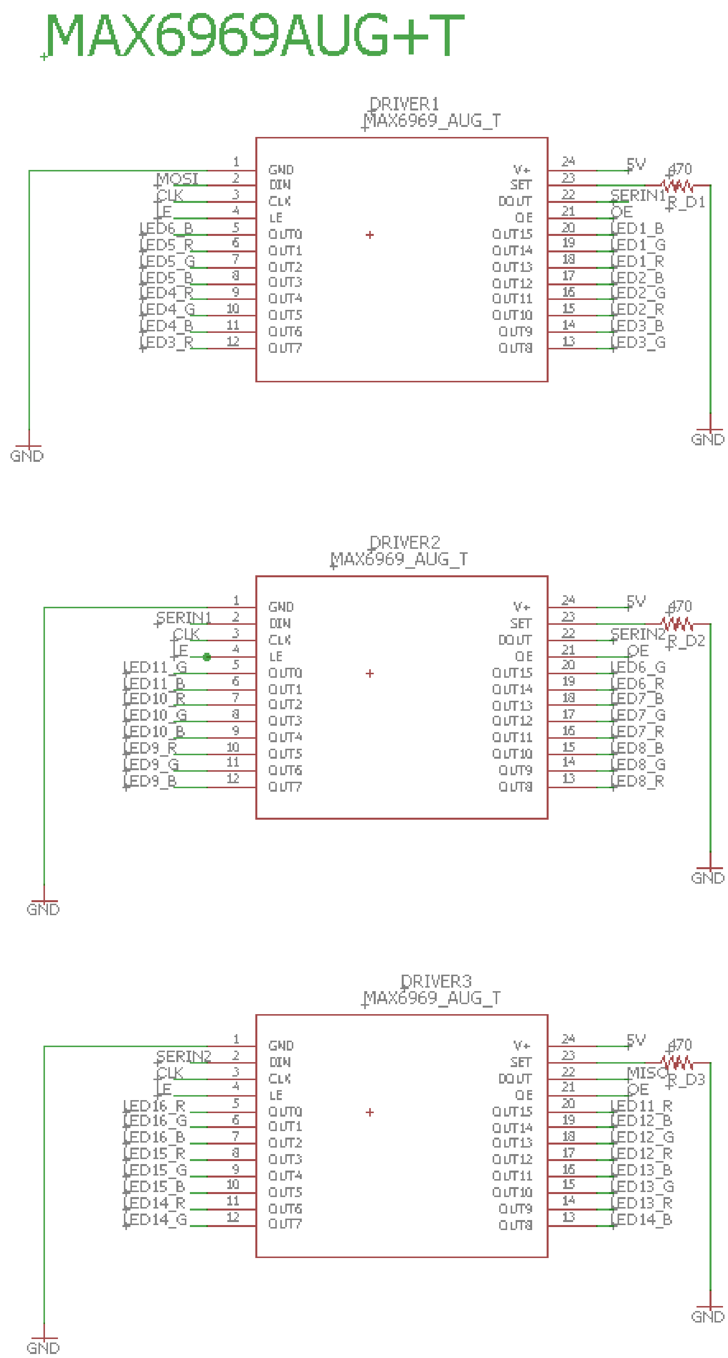
Appendix

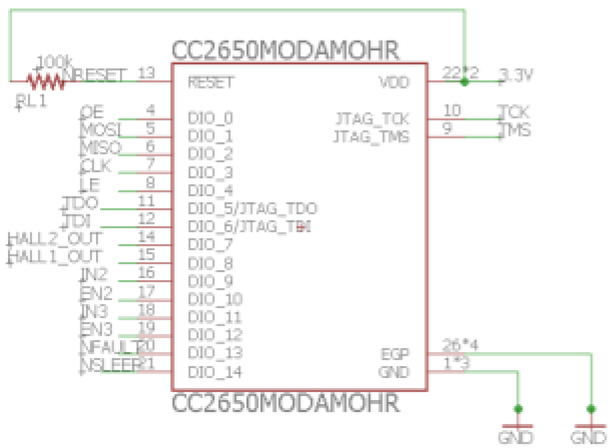
A.1 Power Transmission Diagram



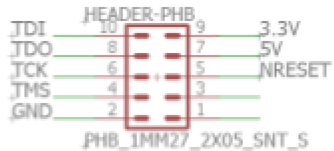
A.2 Schematic of PCB



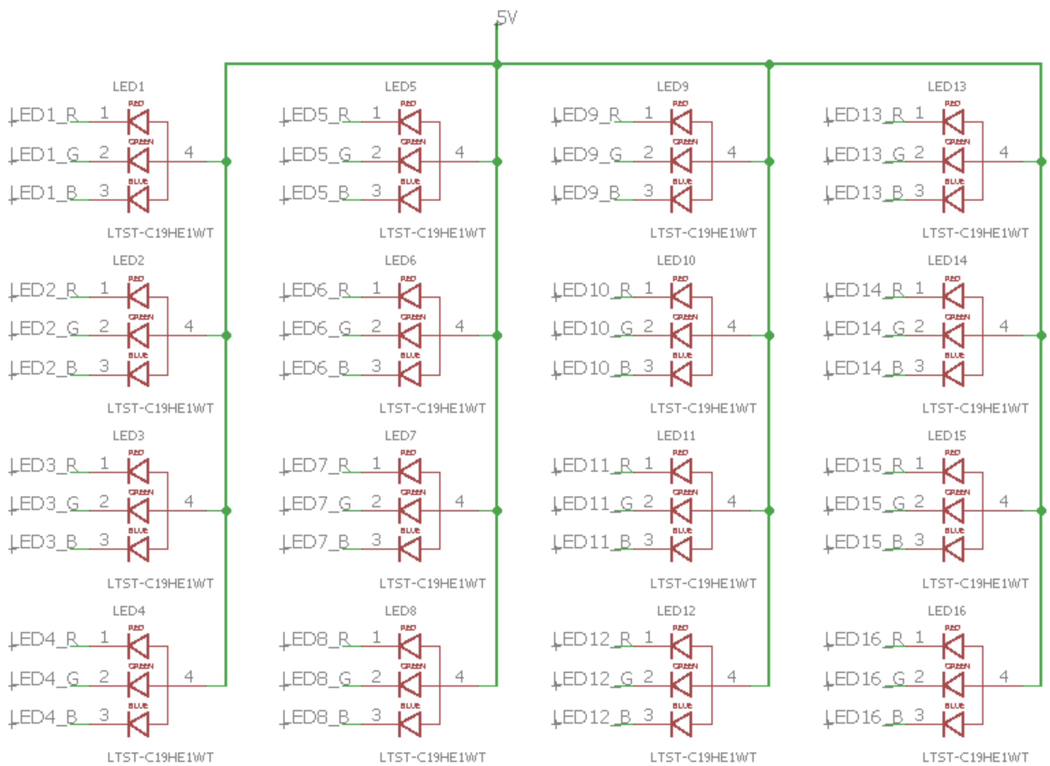
CC2650MODAMOHR Microcontroller



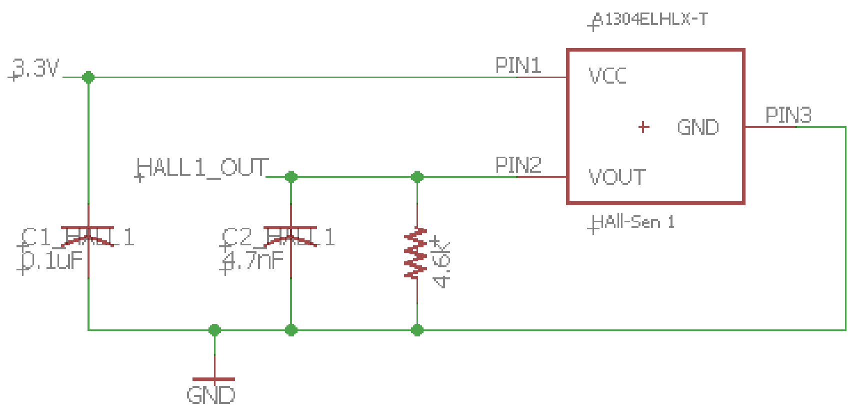
JTAG

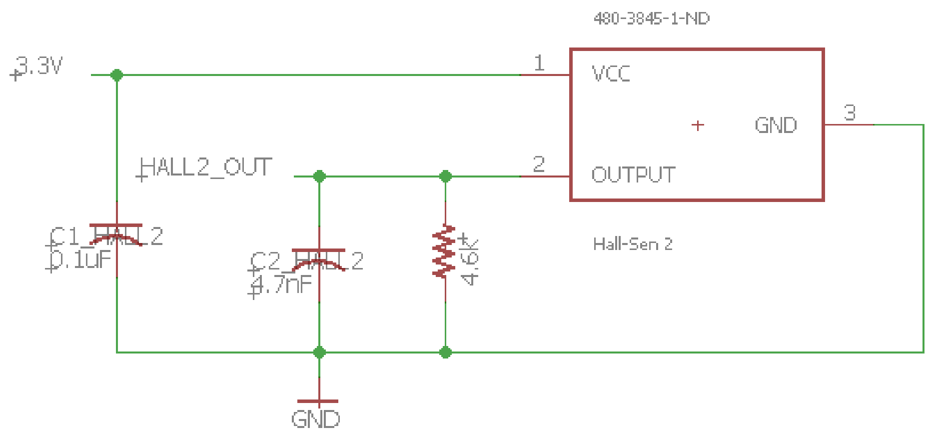


LEDs

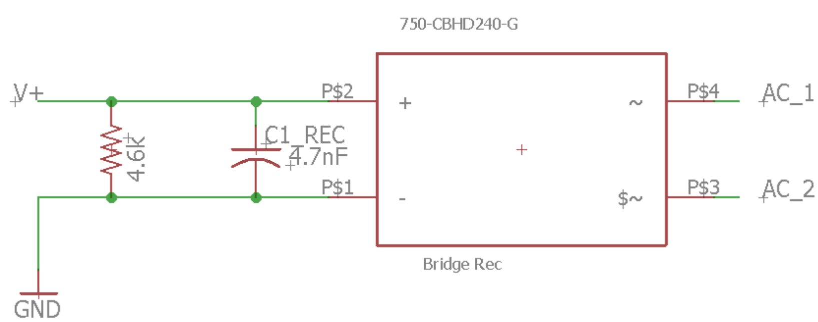


Hall Sensors

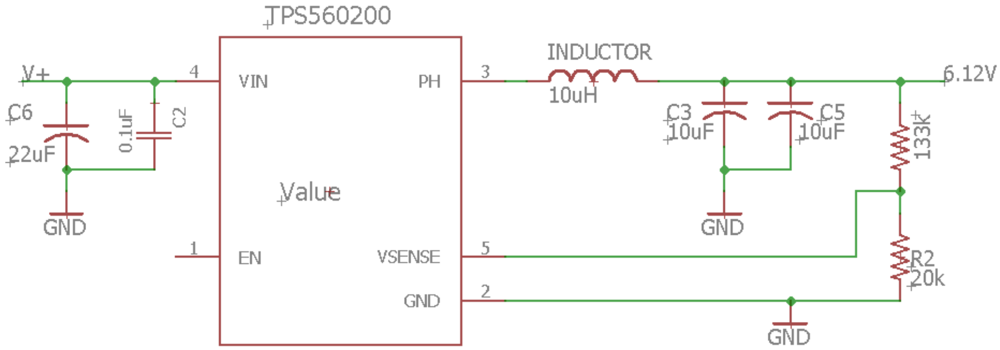


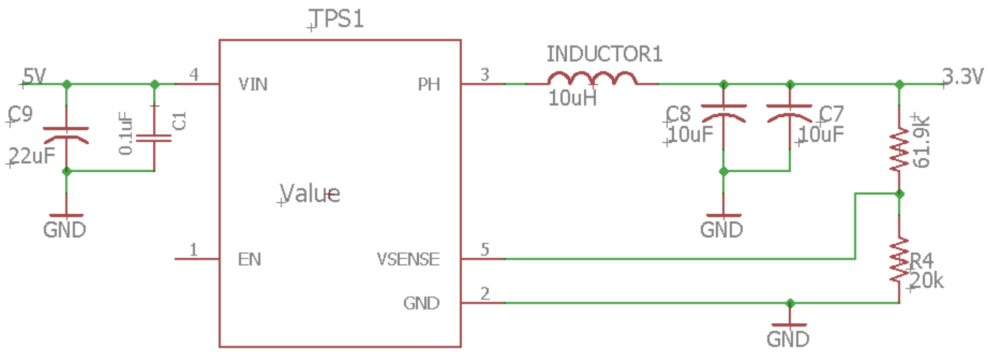


Bridge Rectifier

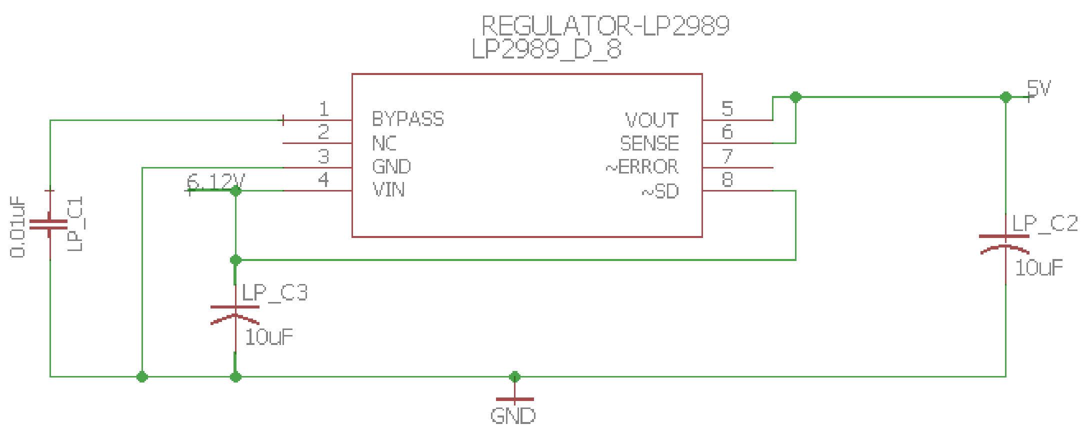


Buck Regulator



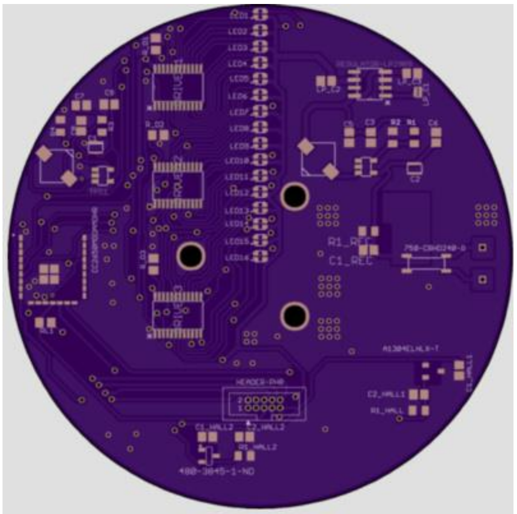
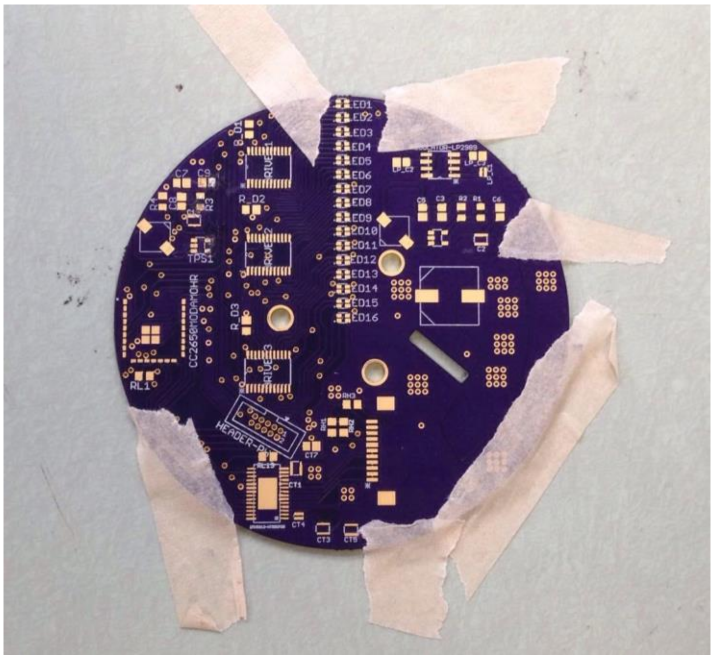


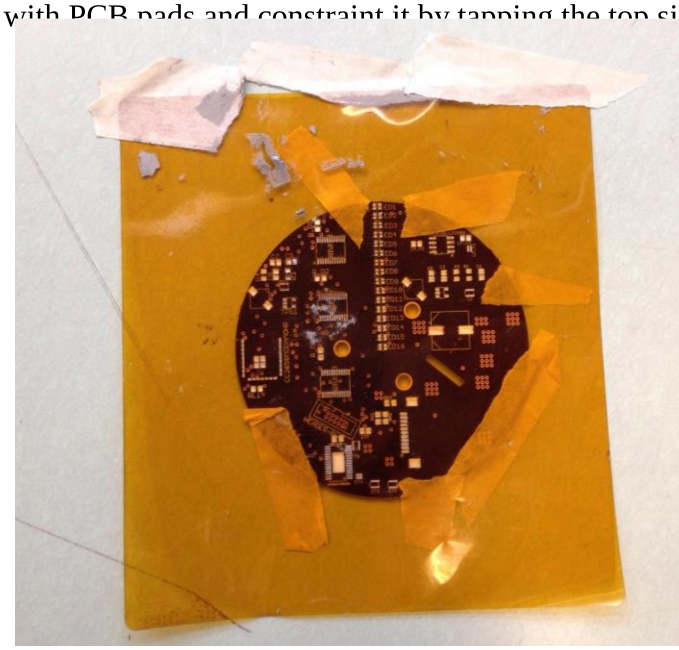
5v Low Dropout Regulator

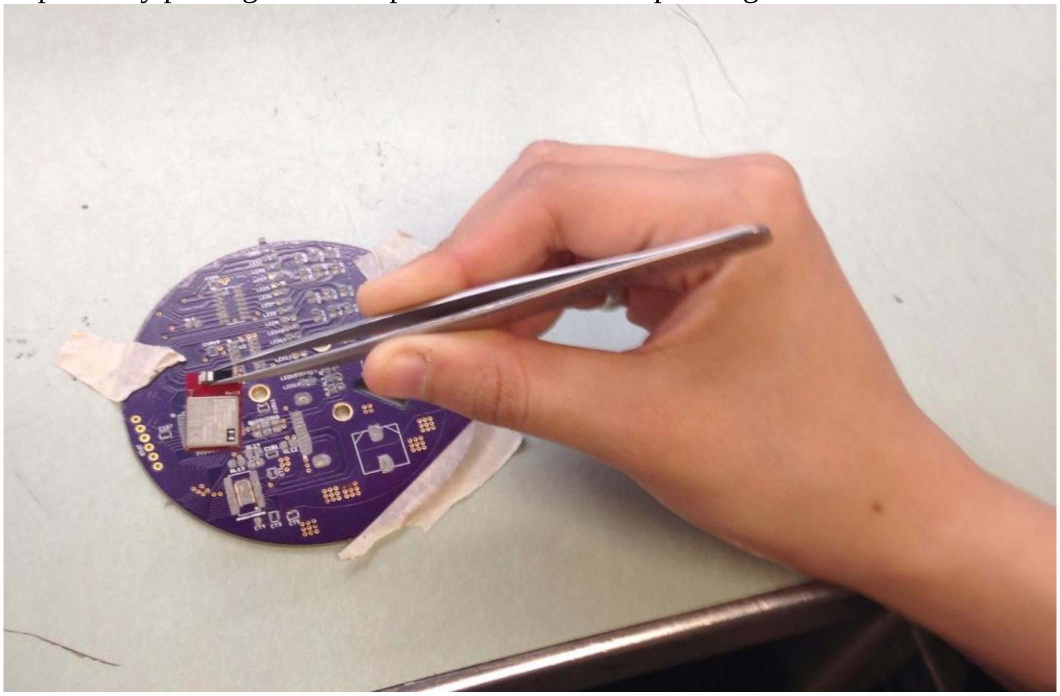
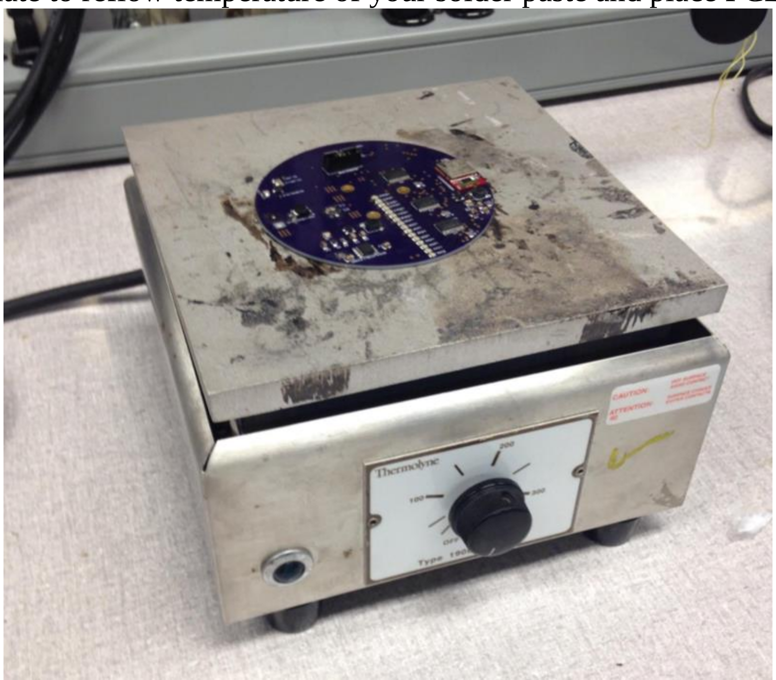


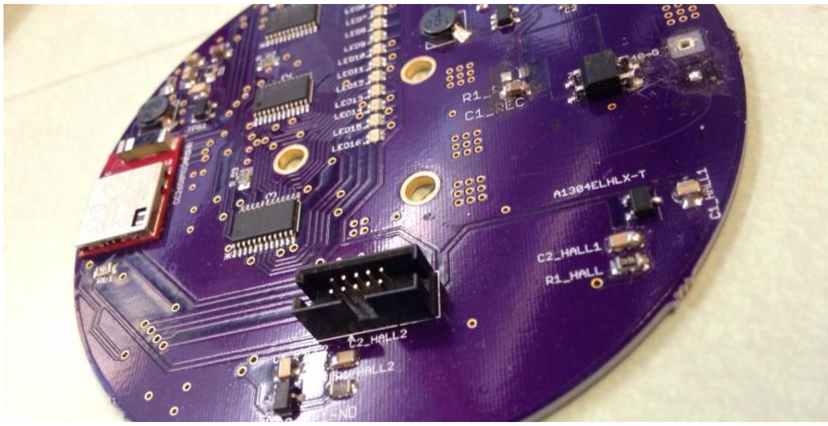
Appendix
A3 Baking Procedure

Materials
All materials including PCB, soldering paste, stencil and PCB components can be found in the Materials document XXX. The only other tools that are not listed are a Hot Plate, spatula, and tape.

Step	Procedure
1	Get PCB fabricated through Oshpark or similar company 
2	Constraint PCB to flat surface by using tape. Do not cover pads with tape 

2	Align Stencil with PCB pads and constraint it by tapping the top side 
3	Using spatula (or tool provided by PCB fabricator) spread soldering paste by pressing the spatula into the PCB from top to bottom as shown below 

4	Populate by placing PCB components on its corresponding location 
5	Heat hot plate to reflow temperature of your solder paste and place PCB on top. 
6	Remove once the solder paste melts. Be careful not to move the components when performing this step, since it might take a few seconds for the solder to solidify.
7.	Finally, solder the 10 Pin connector. The PCB is ready for use!

A1304ELHLX-T
C2_HALL1
R1_HALL
C2_HALL2
R1_
C1_REC

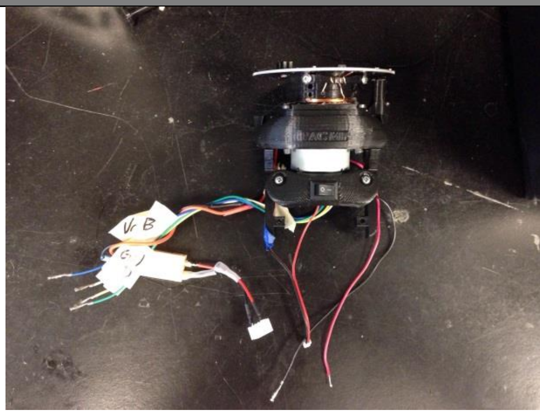
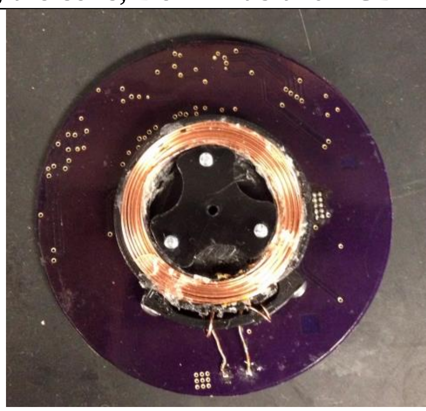
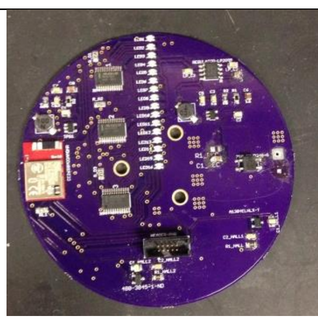
A.4 Cost Analysis for PCB

PCB Component	Part Number	Cost
Microcontroller	CC2650MODA	6.05
LEDs (16)	859-LTST-C19HE1WT	2.27
LED Drivers (3)	MAX6969	9.25
Hall Sensors	620-1548-1-ND & 480-3845-1-ND	1.22
Bridge Rectifier	750-CDBHD240-G	0.56
LDO	LP2989AIM-5.0/NOPB	1.23
Buck Regulator(2)	TPS560200DBVR	0.64
All other Components	N/A	37.78
	Total	$59

A.5 System Cost

Component	Part Number	Cost
PCB	N/A	59
Coils	1407	7.96
Motor	2821	22.46
PLA and Delrin parts	N/A	20
	Total	109.42

A.6 System Weight

Part	Weight
 This image shows all PLA parts, the motor, the switch, the coils, Delrin hub and PCB	**218g**
 This image shows the PCB, PCB Mount, upper coil and Delrin hub	**34g**
 This image shows the PCB	**12g**