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March 27, 2017

Steve Whitmore
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Re: ENSC 405W Design Specifications for PowerPad

Dear Mr. Whitmore:

The attached document, *Disconnect Electronics PowerPad Design Specifications,* provides a breakdown of the design and UI of our ENSC 405W/ENSC 440 project. We are developing a wireless power transfer prototype specifically to be implemented for golf carts. This will be executed in conjunction with Delta-Q Technologies in order to interface with their existing technology, allowing for more intelligent battery management and charging capabilities.

This document will provide an outline UI and design choices of our product as well as justification for these design choices.

We are *Disconnect Electronics* and our team consists of six dedicated upper year engineering students: Connor Floyd, Amar Masalmeh, Paul Vu, Michael Hsiao, Thomas Prettejohn, and Valery Ushakov. If there are any further questions about this document, I can be reached by email at vushakov@sfu.ca.

Sincerely,

Valery Ushakov

Enclosure: *Disconnect Electronics PowerPad Design Specifications Document*

School of Engineering Science
Simon Fraser University
ENSC 405W

Disconnect Electronics PowerPad Design Specifications

Team 2

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Contributions

Each member of the group has put in an equal amount of effort in the writing of this design document.

Abstract

Disconnect Electronics is developing the *PowerPad*, a wireless power transfer solution intended for mid-range electric vehicles that require charging in the range of approximately 500 watts up to 1.5 kilowatts. The *PowerPad* will transfer power from a primary transmitter, connected to AC mains, to a secondary receiver connected to an on-board battery charger. It will focus on applications concerning golf carts, since they make up a large portion of the global electric slow motor vehicle market.

The *PowerPad* is being designed with the vision of having charging stations at strategic locations around a golf course. These stations will automatically transfer power to the battery charger once the user parks, and must be completely weather resistant, sealed to foreign particles, and withstand significant mechanical forces.

This document will outline *Disconnect Electronics'* design choices and methodology for the *PowerPad*. We will differentiate our current design for the alpha prototype, which will be demonstrated at the poster presentation on April 5th, as well as our expected design implementation for the gamma prototype, which will be presented in August. We will focus on three subsections of the design: hardware, software, and mechanical.

Hardware design will outline the selection and implementation of all electronic components, as well as a description of the electronic interaction between the primary and secondary terminals.

Software Design describes how the hardware is controlled and how the feedback is processed. The software is implemented using Arduino microcontrollers in the alpha stage, and with the ATmega328p chip in the gamma stage.

Mechanical Design presents materials chosen for various parts of the project, and will discuss all electromechanical relationships.

We will also outline a developer's test plan, meant to be used in the final stages of the project's development. Finally, we will present the user interface for the *PowerPad*, describing the behaviour of the product and the interaction between indicators on the *PowerPad* and the user. We also outline a UI test plan, discussing steps that a user can take to ensure proper operation of the *PowerPad*.

Disconnect Electronics would like to thank Delta-Q Technologies for their support in the development of the PowerPad.

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1. Introduction and Background

The *PowerPad* is motivated by the need for a wireless power transfer solution for mid-range electric devices that operate in a range of roughly 300-1500W. Currently, no such power transfer products exist that can fill this market. There are existing wireless power transfer products for small scale devices such as mobile devices, and large scale devices such as electric vehicles. The *PowerPad* will fill the market for mid-range devices including low speed electric vehicles such as golf carts, electric scooters, boom lifts, dirt bikes, and floor care machines.

In partnership with Delta-Q Technologies Corp., *Disconnect Electronics* intends to fill this market gap with the *PowerPad*, using their proprietary coil technology to optimize the efficiency of power transfer. The *PowerPad* will consist of a primary transmitter and a secondary receiver connected to an on-board battery charger. The design presented in this document is meant to meet the requirements specifications that were previously proposed. The *PowerPad* will have the ability to detect foreign objects that may disrupt charge, and manage automatic terminal alignment to ensure optimal power transfer. It will wirelessly transfer power using magnetic resonance, and will manage the AC input via IGBTs. This will ideally result in an efficiency of 80%. The *PowerPad* is intended to be compatible with chargers developed by Delta-Q Technologies, which develops 300-1500W wired battery chargers for OEM applications.

To ensure that the *PowerPad* can safely and reliably meet the requirements outlined in the requirements specifications document, *Disconnect Electronics* will follow guidelines set by various governing bodies such as the Canadian Standards Association, International Electrotechnical Commission, and many more. The *PowerPad* will be targeting an Ingress Protection rating of 66. Protection ratings are vital to ensuring the durability of our product is more than sufficient.

In development, we are focusing on applications concerning golf carts because they make up a large portion of the global electric vehicle market. Therefore, the ultimate vision for the *PowerPad* is to have charging stations at strategic locations around a golf course, which will automatically transfer power to the battery charger once the user parks. The concept of the *PowerPad*architecture is provided in Fig. 1. However, the technology would ultimately have the capacity to be applied to any mid-range electric vehicle.

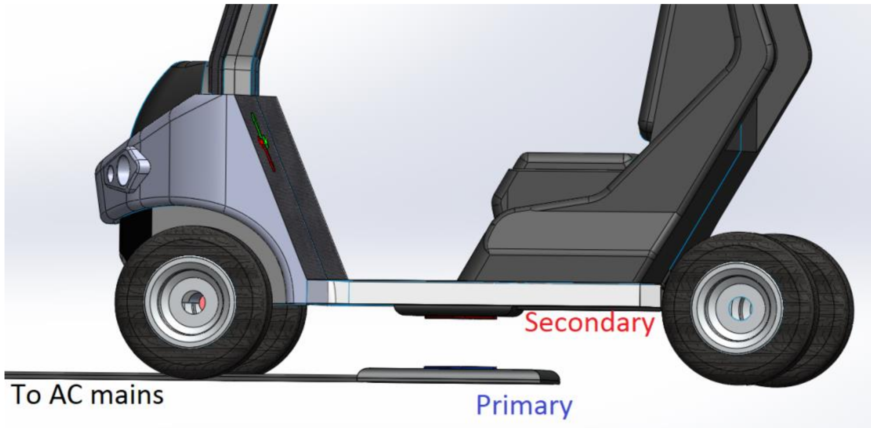

Figure 1: *PowerPad* concept with primary and secondary devices indicated. 3D golf cart model [1], primary, and secondary representations were modeled by *Disconnect Electronics* using SolidWorks.

A reasonable vision for a wireless power transfer system would be to simply power an existing battery charger. Such a device would not consider battery management requirements in the design, which would be carried out by the charger and the battery's own battery management system (BMS). In addition, this solution could be applied to existing golf carts and chargers, and customers would not necessarily need to purchase entirely new golf carts in order to use the product. However, it would admittedly be optimal if this design were integrated into the golf cart by the OEM so that the charger could be completely sealed into an on-board environment. Ultimately, the vision is to place *PowerPad(s)* at strategic points around a golf course to allow a few minutes of automated charging when the golf cart is stopped during use. It is necessary to burden the user as little as possible to make this solution feasible. Therefore, the *PowerPad*must be able to automatically transfer power to the golf cart if the user parks within a reasonable distance. The concept of opportunity charging, where the golf cart can be charged when stopped on the course, will allow for a lower capacity battery and will ultimately reduce the weight and cost of each individual golf cart.

2. Design Overview

The *PowerPad* will consist of a primary transmitter (or primary terminal) and a secondary receiver (or secondary terminal). The primary transmitter will be connected to the AC line indefinitely, and will resemble a large pad either on, inset to, or buried under the ground. It will have signifiers to indicate where the user must park to allow for power transfer. This pad will transmit power to the secondary receiver when the secondary is in range; however, it will not do so if there is a not a valid secondary terminal in proximity for obvious safety and efficiency reasons.

The secondary receiver will be mounted on the golf cart, though ultimately a marketable product would be sealed inside the golf cart. The primary terminal must be able to detect the proximity of the secondary terminal in order to initiate power transfer. Furthermore, it must continuously report measured power values to the primary terminal for the purposes of efficiency calculations, alignment, obstacle detection, and safety shutdown.

Both the primary and secondary terminals will require microcontrollers to manage the overall system and terminal-to-terminal communication. The primary microcontroller will be powered by the AC line, while the secondary will be powered by the golf cart battery. We assume that the golf cart will never be discharged fully, to the point where the secondary terminal will lose power, because the maximum safe discharge for a lead acid battery is 80%; any further discharge will permanently damage the battery meaning, it should not be charged in that state [2]. Lithium ion batteries have a BMS to manage battery discharge and also will not allow a 100% battery discharge, meaning our secondary will always have available power if the battery is in a safe charging state.

In this section, we will outline our design for the *PowerPad*, which we split into two sections: 1) Alpha Prototype Design, and 2) Gamma Prototype Design. Each of these are split into an additional three sections pertaining to three design aspects for each terminal: 1) Hardware Design, 2) Software Design, and 3) Mechanical Design. Each section will discuss the interactions and interface between the primary and secondary terminals, as well as how each of these three design aspects will interface, where applicable.

When relevant, we will reference specific requirements from our *Requirements Specifications* document, and our implementation strategy for those requirements. Each requirement is categorized using the following notation:

[Rn - x] The requirement.

i.e: [R1-A] ThePowerPad must track the input voltage in order to monitor efficiency

In this convention, ***n*** represents the requirement number and ***x*** represents the design stage for which the requirement applies to. The design stage, ***x***, can either be ***A*** for the alpha prototype that proves the validity of the *PowerPad*, or ***G*** for the gamma prototype, which is a pre-production version of the *PowerPad*.

2.1. Alpha Prototype Design

The design of the alpha prototype will implement hardware and software to allow for power transfer. *PowerPad* features such as foreign object detection and self-alignment will be implemented in a later stage. For the proof of concept, the *PowerPad* will demonstrate sufficient power transfer, and will track the temperature of the secondary terminal.

2.1.1. Hardware Design

The hardware design of the alpha prototype is relatively simple. The primary and secondary terminal schematics are presented below in Fig. 2 and Fig. 3.

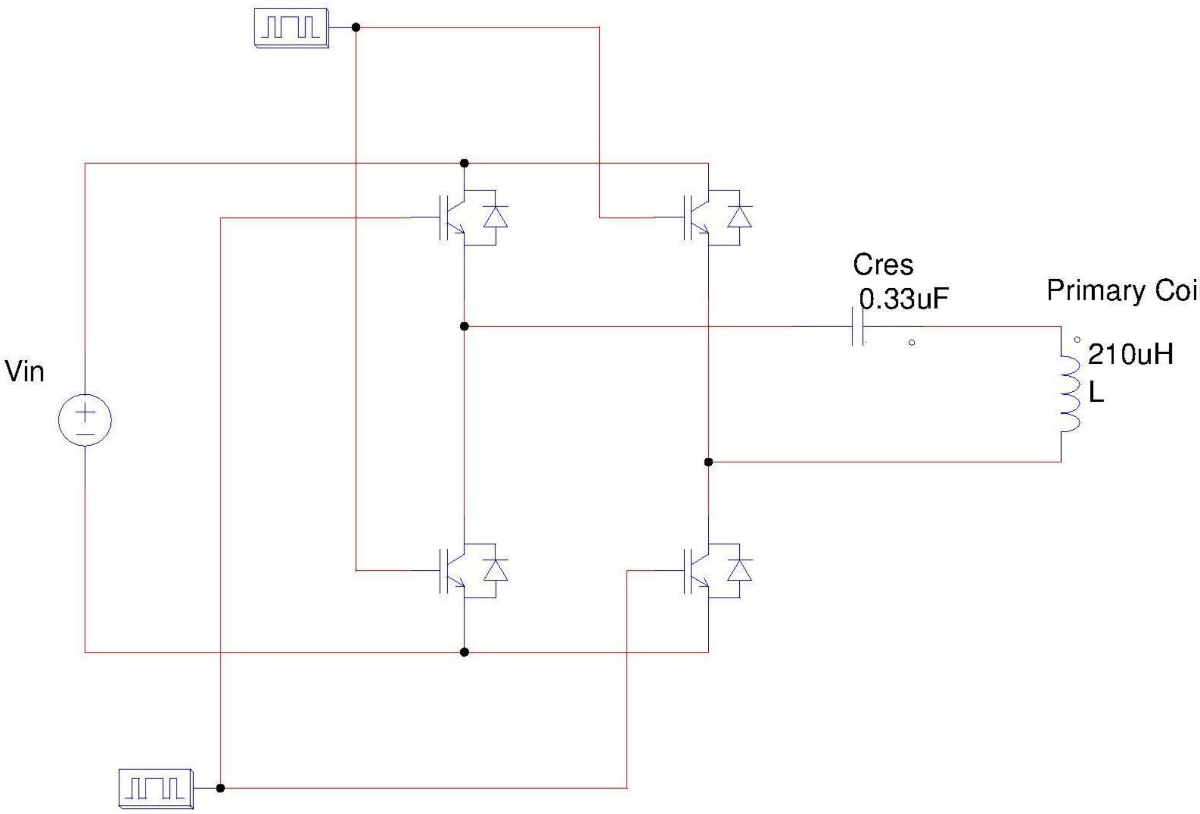

Figure 2: Schematic for the primary side of the *PowerPad*alpha prototype

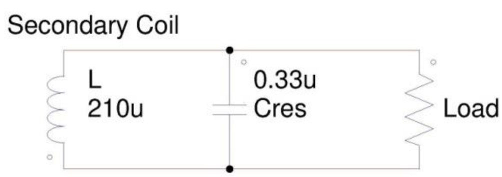

Figure 3: Schematic for the secondary side of the *PowerPad* alpha prototype

The chosen switches for the H-bridge are MG1250S-BA11M IGBT modules. An upside to using IGBTs is their receptiveness to large bi-directional current flows [3]. These were chosen due to their high frequency switching capabilities as well as their high power rating: 1200V, 50A [4]. The IGBTs will be driven with a BG2C-5015 gate drive module to supply the required +15V and -8V gate voltages. To achieve resonance, this gate driver will be supplied with an input square wave from the Arduino at approximately 19 kHz [R15-A]. This frequency can be changed to adjust the power transfer. The input signal will have 47% duty cycle in order to facilitate “dead time” between the switching cycles. This dead time will allow current to start flowing through the flyback diodes in the IGBTs and create smoother current transitions.

The resonant capacitors will be high power film capacitors, which allow bi-directional current, have high precision, and allow for high frequency oscillations [4] [5]. The primary and secondary coils are wound in a 1:1 with proprietary topology in order to maximize efficiency during power transfer.

2.1.2. Software Design

Each of the primary and secondary terminals will be controlled by a microcontroller. The primary microcontroller will have the majority of the computational load and will act as the master, while the secondary microcontroller will simply report information to the primary. The primary microcontroller will be an Arduino Mega 2560, and will use an HC-05 Bluetooth module. The secondary microcontroller will be an Arduino Uno, connected to an HC-06 Bluetooth Module.

The state machines for the primary and secondary microcontrollers are presented in Fig. 4 and Fig. 5 below. In the alpha prototype stage, the *PowerPad* will transfer power once the two microcontrollers are connected via Bluetooth; if the Bluetooth connection is disrupted at any time, power transfer will stop and will wait for the Bluetooth connection to be reestablished. At this stage, the secondary will continuously report the ambient temperature seen by the Arduino; if this temperature leaves the standard operating temperature range of -40-65°C, as specified by [R26-G], power transfer will suspend. It will resume once standard operating temperatures are restored (with a 10°C hysteresis).

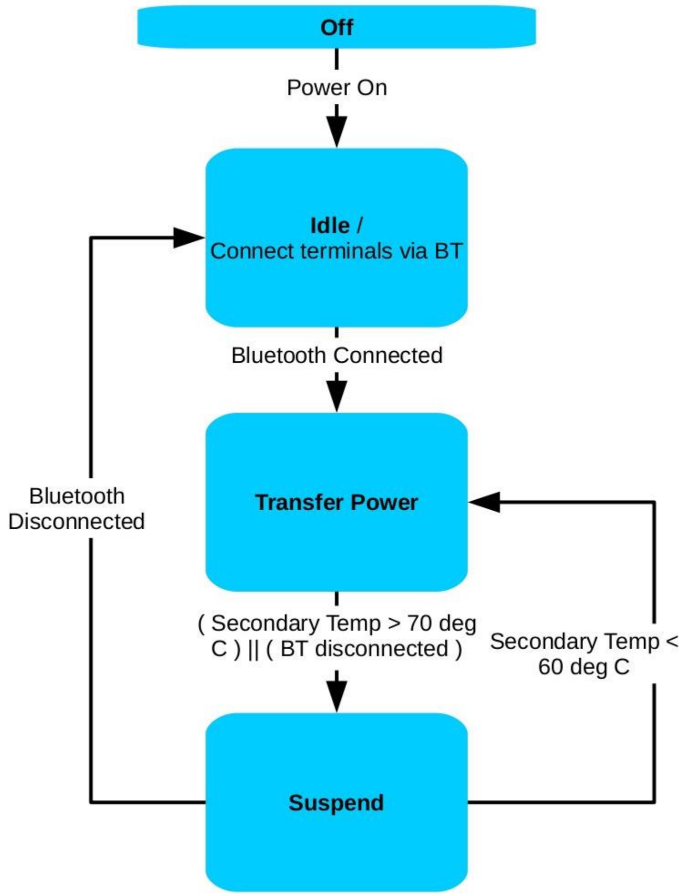

Figure 4: State Machine for the primary terminal of the alpha prototype.

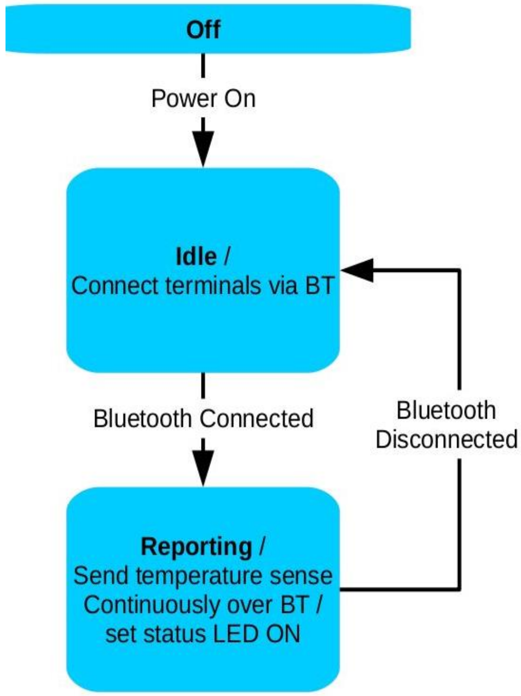

Figure 5: State Machine for the secondary terminal of the alpha prototype.

2.1.2.1. IGBT Control

In order to drive the IGBTs [R5-A], the primary microcontroller must provide two 19 kHz square waves at a 47% duty cycle, where one wave is the inverse of the other. As mentioned above, the duty cycle was selected in order to allow for the IGBTs to switch at the optimal moment, and the frequency was dictated by the components used to assemble the alpha prototype. To operate at a frequency this high, we disabled the Arduino watchdog timers, which were disrupting the timing of the waves.

2.1.2.2. Primary-Secondary Terminal Communication

Both terminals will immediately attempt to establish a Bluetooth connection on start-up. The primary Bluetooth module is the HC-05, and the secondary is the HC-06. Bluetooth communication was selected as our method of communication in order to meet [R2-G]. Once this occurs, the primary will output power to the secondary. Although this is not ideal for safety or practicality, features for efficiency tracking, safety shutdown, automatic alignment, and foreign object detection - all of which are dependent on terminal communication - will be implemented in later stages of the project.

2.1.2.3. Secondary Terminal Measurements

In the alpha stage of this project, the measurement that will be reported by the secondary microcontroller will be the in-built ambient temperature sense of the Arduino Uno. After a Bluetooth connection is established, the temperature will be reported to the primary continuously. This parameter is monitored to ensure that the system stays within the standard operating temperature of -40°C to 65°C [R26-G], [R62-G]. A solid green LED will indicate power transfer in the alpha prototype [R8-A].

2.1.3. Mechanical Design

The alpha prototype of the *PowerPad* will showcase power transfer by encasing the primary terminal in a box laying on a hard, flat surface. The secondary coil, also encased, will be suspended 5-10cm away from the primary.

2.2. Gamma Prototype Design

The design of the gamma prototype of the *PowerPad* will build upon the design choices implemented for the alpha prototype. Features such as terminal proximity detection, foreign object detection and automatic terminal alignment will be implemented in order to meet the requirements outlined in the requirements specifications document.

The hardware for the gamma prototype will be very similar to that of the alpha design. However, hardware level current monitoring will be implemented to track efficiency in real time. Additionally, the input stage will be modified with a rectifier and low pass filter to accept a 120V AC input from the mains. The topology of the primary and secondary coils will also be adjusted to accommodate transfer across a larger gap.

Terminal proximity will be implemented by using four weight sensors, meant to correspond to each tire of the golf cart. Foreign object detection will be implemented by monitoring the weight sensors that will be embedded into the top side of the transmitter. Finally, automatic terminal alignment will include the use of an XY stage, consisting of two linear servo motors in the x- and y-directions, and will also analyze the change in efficiency with terminal movement.

2.2.1. Hardware Design

The primary side circuit schematic for the gamma prototype is shown below in Fig. 6. The secondary side schematic is identical to that of the alpha prototype.

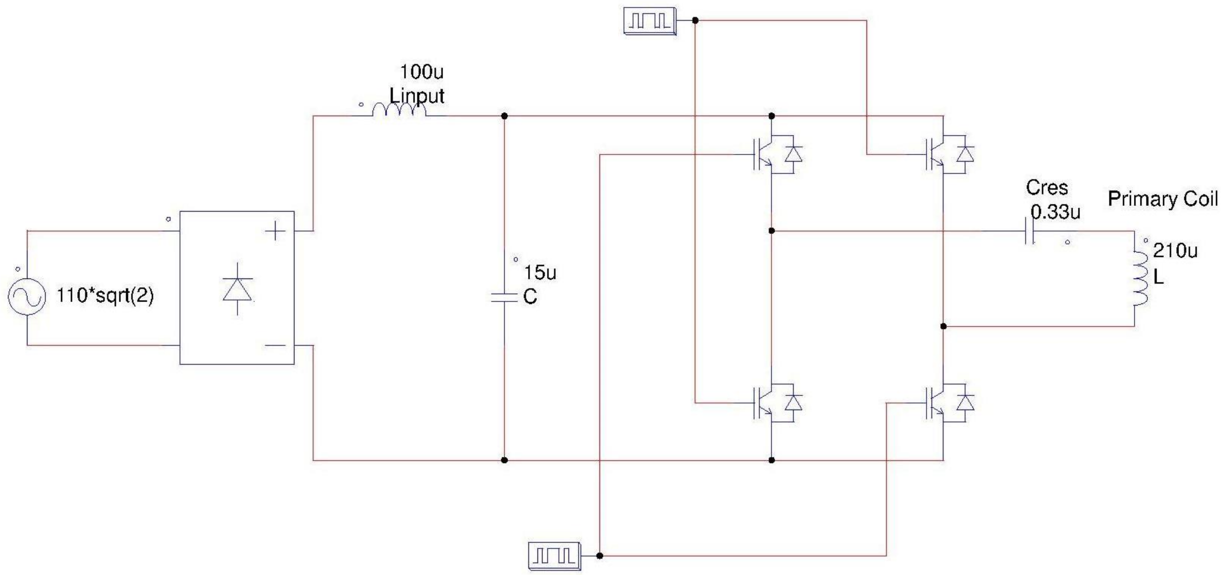

Figure 6: Schematic for the primary side of the *PowerPad* gamma prototype

The IGBTs and driver module will remain the same as in the alpha prototype. The capacitors will also remain as film capacitors, however the topology of the primary and secondary coils will be adjusted to accommodate the larger air gap between the terminals. The input stage will consist of a two phase bridge rectifier and a LC low pass filter to provide the H-bridge with a DC supply. Additionally, the AC input will be fused with a 30A fuse to prevent the device drawing a dangerous amount of current [R17-A].

The current monitoring for efficiency measurements will be implemented with current transformers to avoid unnecessary additional loading of our system that would cause parasitic power consumption and reduced efficiency.

The circuits will also implement a 5V voltage regulator to supply the microcontrollers with the correct input power, both on the primary and secondary sides [R13-A].

2.2.2. Software Design

As in the alpha prototype, the gamma prototype will also consist of two microcontrollers - one for the primary and one for the secondary, with the primary controller acting as the master. However, the gamma prototype will be a more streamlined design, with each microcontroller being an ATmega328p chip. The HC-05 and HC-06 Bluetooth modules will be used again in the gamma prototype.

The state machine for the primary microcontroller is presented in Fig. 7 below. The main differences between the alpha and gamma state machines are: golf cart weight detection, the additional "Alignment" state, foreign object detection, and efficiency tracking. Once the weight sensors for the golf cart are activated, the primary will send a notice to the secondary, beginning a "power transfer session" and requesting measurement reports. Automatic alignment must complete before power transfer at maximum efficiency can begin; we outline our strategy for automatic terminal alignment in the *Automatic Terminal Alignment* section below. Efficiency tracking involves the secondary reporting voltage and current measurements to the primary over Bluetooth, where the primary will then calculate the efficiency of the power transfer. If this efficiency is below a threshold of 70%, power transfer is suspended as the *PowerPad* will deem this efficiency as insufficient. If an object above a threshold weight is resting on the weight sensors of the primary transmitter, the power transfer will suspend for safety reasons. Power transfer will only resume once the object is removed. If power transfer is suspended more than 5 times, the power transfer session will end, and the primary terminal will return to the "Idle" state [R10-G]. A new session can only begin once the golf cart is removed from the weight pads. This is to prevent an attempt at power transfer in multiple error conditions: presence of a foreign object, incorrect parking, and incompatible object on the weight sensors [R7-G].

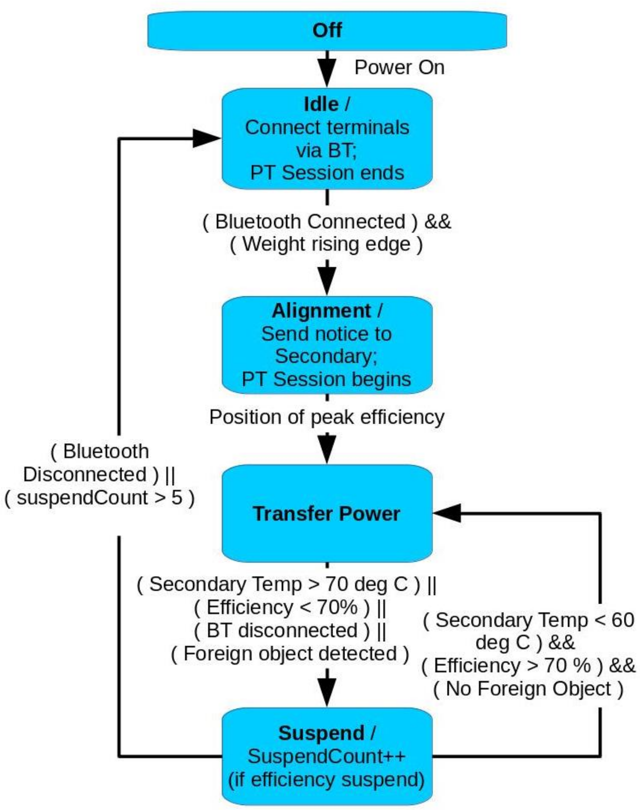

Figure 7: State Machine for the primary terminal of the gamma prototype.

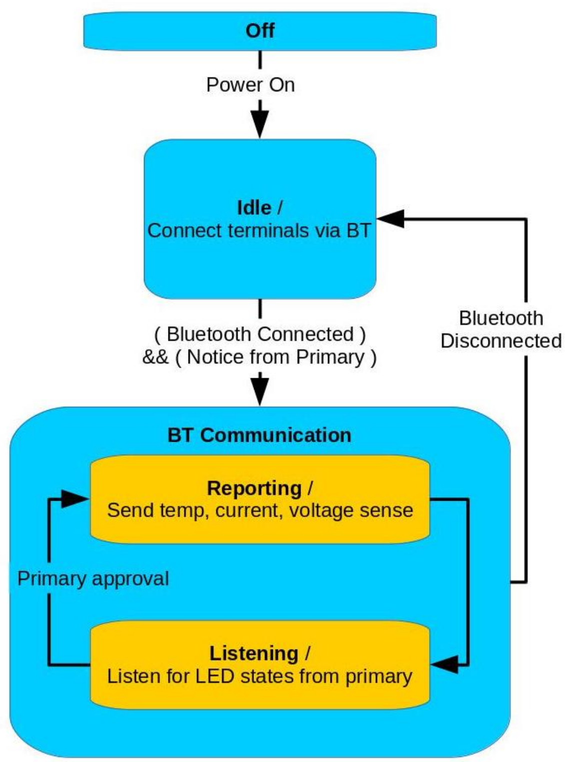

Figure 8: State Machine for the secondary terminal of the gamma prototype.

The state machine for the secondary terminal is displayed in Fig. 8 above. Compared to the alpha prototype, this state machine has a more detailed state for terminal-terminal communication, titled "BT Communication". In this state, the secondary MCU will send current and voltage measurements - in addition to temperature - to the primary via BT. It will then wait for the primary MCU to send an "approval" bit-field, which will contain instructions pertaining to the settings of the indicator LEDs. This will be a cyclical relationship, and will continue as long as there is a reliable BT connection. To enter the "BT Communication" state, the secondary will wait for notice from the primary, indicating the alignment and power transfer process is ready to begin.

Note that the state machines presented in Fig. 7 and Fig. 8 above assume that the golf cart does not move after automatic alignment has completed, or during power transfer; in other words, movement of the golf cart is assumed not to be a potential reason for a drop in efficiency.

2.2.2.1. IGBT Control

IGBT control will be identical to the alpha stages of the project.

2.2.2.2. Primary-Secondary Terminal Communication

Terminal communication via Bluetooth will commence once the golf cart signals the primary terminal by activating the weight sensors on the ground. Then, the secondary will continuously report voltage, current, and temperature measurements, and the primary will send the status of the indicator LEDs, which are under the control of the secondary. This will be a cyclical communication, where each terminal will transmit information then wait for information from the other before transmitting again.

2.2.2.3. Electronic Measurements

The microcontrollers will sample voltage and current data as specified in the *Hardware Design* section. The secondary will transmit these measurements to the primary terminal for efficiency calculations [R27-G].

2.2.2.4. Efficiency Calculations

To satisfy [R1-G], the primary terminal will calculate efficiency as:

$$Efficiency = \frac{P_2}{P_1} = \frac{V_2 * I_2}{V_1 * I_1}$$

Where P_1, V_1 and I_1 are the power, voltage and current on the primary terminal, and P_2, V_2 and I_2 are those on the secondary. This calculation will be carried out periodically to detect terminal misalignment or movement. The primary will see a drop in efficiency to 70% as an indicator of these cases.

2.2.2.5. Power Transfer Session Behaviour

A "power transfer session" is defined as a primary and secondary terminal interacting to wirelessly transfer power. A session will begin when a Bluetooth connection is established between the terminals, and a golf cart initially activates the weight sensors, indicating it is in position. If the efficiency calculated by the primary terminal is not sufficient (>70%), the power transfer session will end after the *PowerPad* attempts to restart power transfer 5 times. This drop in efficiency may be due to terminal misalignment or movement. The presence of a foreign object will also cause the power transfer to suspend.

The primary terminal will execute its state machine as long as it is powered by AC mains. The secondary terminal will be powered by the golf cart battery, and will also execute its state machine as long as it is powered. It will only report data to the primary once a reliable Bluetooth connection is established.

2.2.2.6. Terminal Proximity Detection & Behaviour

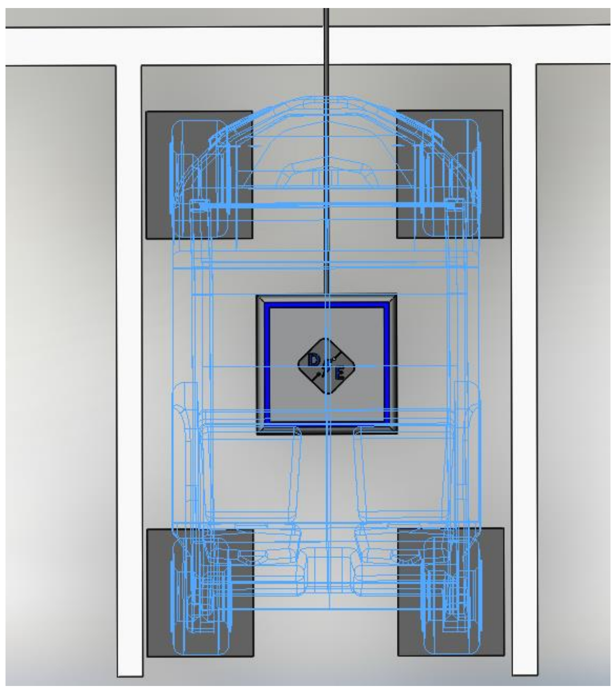

Figure 9: Bird's eye view of the golf cart on the weight sensors

Proximity of the secondary terminal to the primary is detected using four weight sensors - one for each tire. Fig. 9 depicts the weight sensors that will be used to detect the golf cart. This replaces efficiency as our method of determining terminal proximity [R3-G]. These sensors must be active simultaneously, providing an interlock mechanism to prevent a false trigger by an incompatible object. Each sensor will be large enough to afford easy parking from multiple directions of approach. Once the user is parked and all four sensors are active, we can guarantee that the *PowerPad* will be able to automatically align the two terminals, since we will know the maximum misalignment distances.

2.2.2.7. Automatic Terminal Alignment

The primary terminal will be mounted on an XY stage, consisting of two linear actuators that move a platform. To automatically adjust the primary terminal to the position of optimal alignment, the primary terminal will first output power and continuously monitor power transfer efficiency from values reported by the secondary. This is the beginning of a power transfer session. It will then move in the X-direction, and locate the position of maximum efficiency by analyzing the change in efficiency as the terminal moves. After, it will repeat the process in the Y-direction. The resulting (x,y) coordinates will be the position of optimal alignment. If this position is still not above the efficiency threshold of 70%, power transfer will be suspended and eventually the session will end; this can be seen in the state machine.

2.2.2.8. Foreign Object Detection

The primary will detect the presence of foreign objects by monitoring the weight imposed upon the primary transmitter of the *PowerPad*. If a foreign object is detected, the primary terminal will suspend power transfer to give the foreign object a chance to move before reattempting power transfer. After doing so five times, the primary terminal will enter the “Idle” state, and will not attempt power transfer again until the rising edge of the other weight sensors is detected [R59-G].

Suspension of power transfer due to overheating will not increment the suspend count.

2.2.2.9. Indicator LEDs

The indicator LEDs, which are outlined in the User Interface Appendix, will be controlled by the MCU on the secondary terminal. However, the status of the LEDs will be determined by the primary and sent to the secondary for display.

2.2.3. Mechanical Design

Mechanical elements of the gamma prototype include the weight sensors, meant to detect the presence of a golf cart once all four are activated by a tire at the same time, and the XY stage. The XY stage consists of two linear actuators in x- and y-directions attached to rails, which move a platform. The primary terminal is to be mounted to this platform. The XY stage will have a resolution of 0.5cm. There will also be weight sensors on the transmitter in order to detect the presence of a foreign object.

In the gamma prototype, the secondary terminal will be mounted to the bottom of a golf cart, and the primary will lay on the ground. Encasing the terminals in a material that is resistant to high forces, water, and weather will be included in this stage as the gamma prototype is a pre-production prototype. Each terminal will be securely enclosed for safety purposes [R18-G], [R20-G].

Table I below outlines the selection of materials for various parts of the *PowerPad*.

TABLE I
SUMMARY OF MATERIALS CHOSEN FOR COMPONENTS OF THE *POWERPAD*

***PowerPad* Component**	**Selected Material**	**Notes**
Plastic Casing	PLA [9]	PLA is a biodegradable material chosen for minimal environmental impact
Primary/Secondary Coils	Magnet wire	Copper wire coated with a thin layer of enamel
Ferrite Core of Coils	Iron	
Weight Sensors	Resistive ink FSRs	These could be just singular (0-dimensional) or XY pressure sensors

3. Design Verification Test Plans

The preliminary test plans to be employed to validate the various features of the *PowerPad* are outlined in Section 9 of this document, the Design Verification Test Plan Appendix. Verification of the hardware will be managed by the software through tracking of the power transfer efficiency. The test plans will cover software, hardware, and mechanical use cases in order to verify each aspect of the components of the *PowerPad*. These test plans are intended to be executed upon the gamma prototype of the *PowerPad*, and instructions have been given to match the predicted form of the *PowerPad*.

4. Safety and Sustainability

Since the *PowerPad* will rely on existing battery chargers to recharge batteries, the efficiency must be maximized in order to allow battery charger manufacturers to meet or maintain their existing standards for efficiency. Requirements imposed upon the enclosures of the *PowerPad* are vital to ensuring a long lifetime for the product. To help with this, the *PowerPad* will be built following the specifications of many industry standards such as ISO 9001, IP66, and more. Keeping the safety of our consumers in mind, the *PowerPad* will meet several safety requirements that can alert the user to the status of the *PowerPad* as well as requirements that will minimize interfering with other electronic devices. Finally, the primary and secondary devices will be composed of modular circuits such that if a component were to fail, the consumer could order replacement components to repair the *PowerPad*. As a result, the environment will benefit from reduced circuitry waste.

4.1. Safety

The *PowerPad* will have an input fuse to prevent current draw in excess of 30A. Additionally the primary and secondary microcontrollers will continually monitor efficiency and if the efficiency falls below the acceptable threshold the power transfer will stop. This will ensure that if an animal or other object were to obstruct the terminals that no harm would occur. The *PowerPad* will also conform to an IP66 rating which will prevent environmental factors from potentially damaging the device and rendering it unsafe. The full enclosure will also prevent access to the high power components to remove shock hazard. The circuitry will also feature adequate heat sinking in order to maintain the enclosure at a touch safe temperature of less than 65°C [R62 - G]. Additionally the high frequency switching will occur at 16kHz and above, which is above the audible range for a human.

4.2. Sustainability

The *PowerPad* will be constructed in a modular fashion with discrete components in order to aid in repairability, thus reducing waste [R68 - G]. Additionally, the enclosure shall be constructed from PLA plastics which are fully biodegradable [R69 - G] [9]. This product will be designed to withstand impacts and harsh environmental conditions, which will increase its lifespan and reduce the requirements for maintenance.

5. Conclusion

The design decisions laid out in this document will ensure that the *PowerPad* will adhere to the requirements proposed in the *Requirements Specifications* document, which are also cross referenced in the *Design Overview* section.

To achieve efficient power transfer for mid-range vehicles, the *PowerPad* is designed with the ATMega328P microcontroller. Communication between the primary and secondary terminals is carried out via Bluetooth. This also affords an easy and intuitive alignment mechanism: initial (coarse) alignment is a manual process, using guide rails/weight sensors situated around the primary terminal, while (fine) automatic alignment will be accomplished using an XY stage inside the primary terminal, which requires terminal-terminal communication.

The *PowerPad* will be designed to avoid causing harm, should it be misused. Weight sensors will be implemented inside the primary terminal as a mechanism to detect foreign objects. Also, total power draw from the primary and secondary sides will be compared to ensure a minimum threshold of efficiency. Below this threshold, the system will determine that power is being dissipated in undesirable areas, and will trigger an automatic suspension of power transfer.

The *PowerPad* will feature a clear and intuitive user interface. LED indicators will be utilized on both sides of the *PowerPad* to signal alignment, object detection, and power transfer. The primary enclosure will feature a strip of LEDs to indicate power transfer, while the secondary will be connected to a dashboard interface inside the golf cart. The two terminals of the *PowerPad* will be synchronized through the Bluetooth communication outlined above. For more details, refer to the User Interface appendix below.

A test plan was put in place to ensure correct operation both during the development stage and as a final product. *Disconnect Electronics* will abide by these details to our best ability. However, these are prone to minor revisions with changing circumstances as we move forward in this project.

The *PowerPad* could be integral in forming the next generation of small electric vehicles. The scope of the *PowerPad* can be extended beyond battery charging, possibly to the household domain where non-portable appliances could be powered wirelessly. The existing market gap for the power range of the *PowerPad* ensures that our product will be a success.

6. User Interface Appendix

6.0.1. Purpose

The purpose of this Appendix is to illustrate to readers the user interactions with the *PowerPad*. This document overviews the thought process that went into the design of *Disconnect Electronic's PowerPad*. This document reviews the user considerations that went behind our design choices in manufacturing our product.

6.0.2. Scope

We first discuss an analysis of our user base, taking considerations to demographic, age, and skill set. We then review the seven elements of UI interaction discussing a high level technical analysis of the *PowerPad* product. This section provides an overview of the considerations which were taken into account such as our user's potential discoverability and conceptual model in using our *PowerPad*.

We will discuss the analytical and empirical usability tests and testing procedures. Analytical testing will focus on modeling, theoretical analysis and feedback from industry professionals. Here we will uncover usability problems of our product. In the empirical usability testing we will describe in detail how the alpha and gamma prototypes will be tested. Our design will be iterative based on feedback and considerations provided by future end users.

6.1. User Analysis

Users require a minimal amount of qualifications to use the *PowerPad* solution effectively. It is important to note that although the product is marketed towards golf park owners, its primary users will be golfers and caddie drivers.

With this in mind, it is important to consider the ages of these users both on the young and elderly end of the spectrum, as these will be the two demographics which will have an impact on the required driving experience and user limitations of the *PowerPad*.

6.1.1. User Age Analysis

According to statisticbrain, only 5% of golfers are below the age of 30, 58% are between ages 30 and 60, while 37% are elderly golfers above the age of 60 [7]. Therefore, it is realistic for us to predict that these numbers will correlate to our user base, namely 5% of our users will be under the age of 30, 37% above the age of 60 and 58% in between.

Of the 5% of users under the age of 30 we identify that the age restriction is variable from state to state in the U.S. In North America, the youngest age permitted is found in the state of Florida, where drivers can be as young as 14 [8]

6.3.2 Required Knowledge & Skill Analysis

Driving Experience: Since the *PowerPad*'s secondary receiver is mounted to the golf cart, our users need to be experienced golf cart drivers, with the ability to drive, steer, brake and park.

Driving Skill: In order to initiate power transfer the cart must be parked above the *PowerPad*. This means the golf cart must not be parked on the physical *PowerPad*, or such that the *PowerPad* is to the side, behind or in front of the golf cart entirely. An example of good and bad parking practices is shown in Fig. 10.

6.3.3 User Limitations

Any user deemed unqualified to drive the golf cart due to being underaged, visually impaired, or disabled such that they cannot maneuver a vehicle coherently will be limited from using the *PowerPad* effectively. Fig. 10 depicts how a user should park.

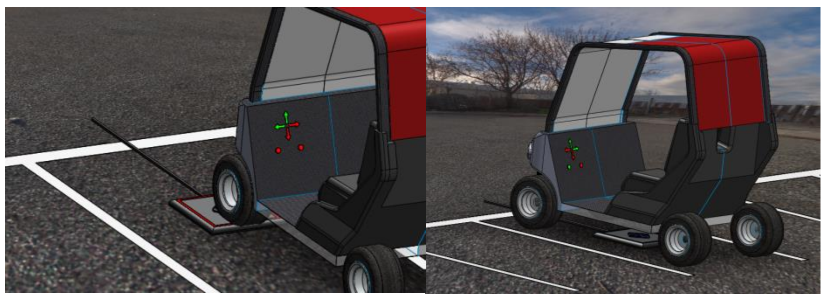

Figure 10: Incorrect vs. Correct Parking for charging.

6.2. Technical Analysis

6.2.1. Power Pad Interfaces

Although the *PowerPad* product includes both hardware, mechanical and software requirements the product itself only contains a hardware interface. The software components of the design is embedded within the micro controllers in each of the primary and secondary devices. In addition, since there is no app there is also no software interface for users. The secondary receiver is mounted underneath the golf cart therefore there is no interface between the user aside from a few LEDs indicating power transfer status mounted to the dashboard. The primary transmitter will lay on the golf course and have an interface with users to indicate if it is emitting power or not.

6.2.2. Discoverability

When connected to an AC outlet, the *PowerPad* will reside on the golf course flashing a blue light around the *PowerPad* indicating that it has the ability to start power transfer. As soon as the *PowerPad* is transmitting power the blue LEDs stabilizes to indicate to the user that it is on. This behaviour is illustrated in Fig. 11. These LED's will also indicate if the *PowerPad* is malfunctioning, in the case where the *PowerPad* is emitting power without any golf cart around it. This will indicate to park workers and golfers to not walk on top of the *PowerPad*.

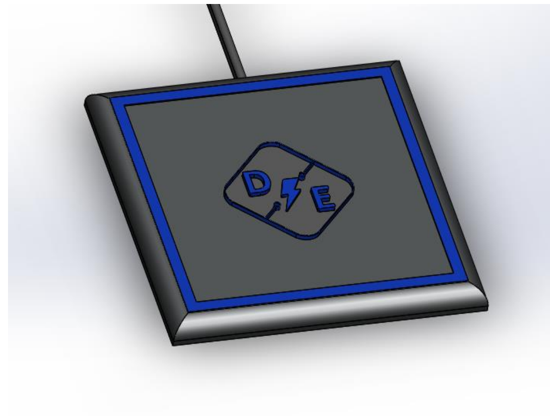

Figure 11: *PowerPad* in charging state

The secondary receiver is mounted beneath the golf cart, its only interface to the user is through LEDs mounted to the golf cart's dashboard. Fig. 12 depicts a dashboard panel which is the *PowerPad's* method for communicating information to the user in this design. These LEDs will indicate to the user if power transfer is successful or not. This feedback is required to tell users if they need to re-park the golf cart.

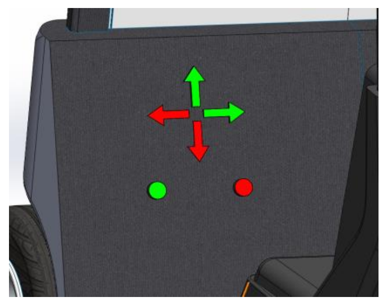

Figure 12: Dashboard Panel

6.2.3. Affordance

The *PowerPad* will be placed throughout a golf course upon grass or concrete floors. The design is smaller than a golf cart therefore users will understand that parking the entire cart on the *PowerPad* is not possible. Should they attempt to, only one wheel would fit on top of the *PowerPad*, thus leaving the cart uneven to the user and intuitively users will see that the *PowerPad* does not afford physically parking on top of. Thus, based on the size users can see that the *PowerPad* affords being parked above rather than on top of. In order to communicate more clearly to the user of the affordance of *PowerPad* we can use signifiers.

6.2.4. Signifiers

By surrounding the *PowerPad* with blinking LEDs users driving golf carts will be able to see it from far distances. Park workers will need to instruct these users to know to keep an eye on these charging pads throughout the park, and to park the carts above the *PowerPad* to enable power transfer. If a user were to stand on the *PowerPad*, they will be considered a "foreign object" and the *PowerPad* will rapidly flash red LEDs indicating to the user intuitively they should not be standing on the pad. In Fig. 13 we show what the *PowerPad* would look like should a user stand on it. In these ways we indicate to the user that this product does not afford the ability to stand upon.

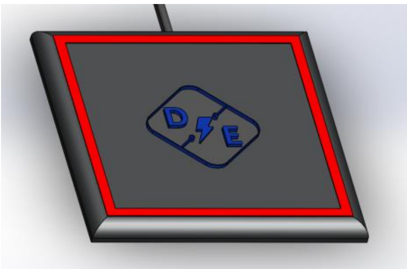

Figure 13: *PowerPad* indicating a foreign object is on top of it with a red LED strip

6.2.5. Feedback

In using our product, the secondary receiver mounted beneath the golf cart will propagate feedback to the user through the LEDs mounted on the dashboard of the golf cart. If the user parks incorrectly such that the cart needs to be realigned by the user, our directional lights will light up in real time, to indicate how to reposition the cart. This is shown in Fig. 14. Once alignment is achieved and successful power transfer is established a "success" LED will emit to notify the user that connection is established and that they can leave the cart.

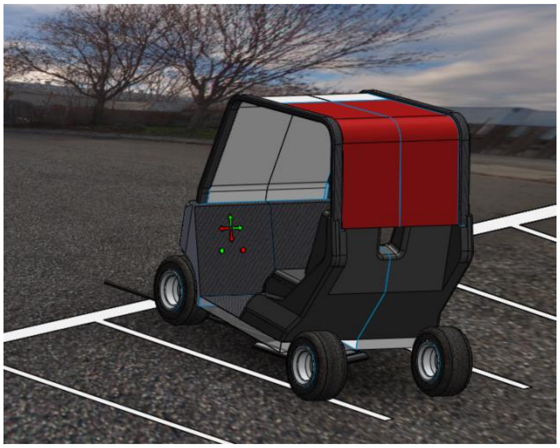

Figure 14: Suboptimal Parking

6.2.6. Mappings

In designing our UI for the dashboard we mapped the directional LED's to correspond to the topology of the golf cart. Should the cart be misaligned to the left, the "Right Direction" LED will be green indicating to the user that they need to move the cart further to the right side.

6.2.7. Conceptual model

In combining our signifiers and feedback our user will have a conceptual model on how to operate the *PowerPad*. With the growing popularity of wireless charging on mobile devices, users will already have a general idea of how to operate a charging pad. Normally, users will place their phones on the charging pad and ensure proper alignment and will receive feedback on the UI of their phone that successful power transfer was achieved. In designing our *PowerPad* we wanted our users to use this conceptual model to aid in using our product. We designed our *PowerPad* such that it resembles the shape of most phone chargers. Users will easily spot this black, square shaped pad in a golf course field and understand that to charge their golf carts they must drive above the *PowerPad* and pay attention to the dashboard of their golf cart for the "Charging" LED to turn on. In addition to this, park owners can draw parking stalls such that users will understand exactly how to park and orientate their car. As many users will have experience with driving, if they see a parking stall in the field they will understand exactly how to park the golf cart and thus use the *PowerPad* properly.

6.2.8. Constraints

As a wireless product, users will be constrained in power transfer. They simply cannot park anywhere they want on the golf course, they must park in a specific location to charge their carts. Users will be unable to start the *PowerPad* if the cart is parked incorrectly, such as if they parked too far from the *PowerPad*. Our product is limited to power transfer given its size, the user needs to park with accuracy above the *PowerPad* in order to establish connection. To address this constraint we have designed a self-alignment system where the user need not park perfectly above the *PowerPad* which allows some error in parking alignment. Our self-alignment system will dynamically shift around to obtain optimal power transfer positioning. Fig. 15 illustrates the interior design of our *PowerPad's* self-alignment solution. This will continue until that position is achieved as long as Bluetooth connection is established.

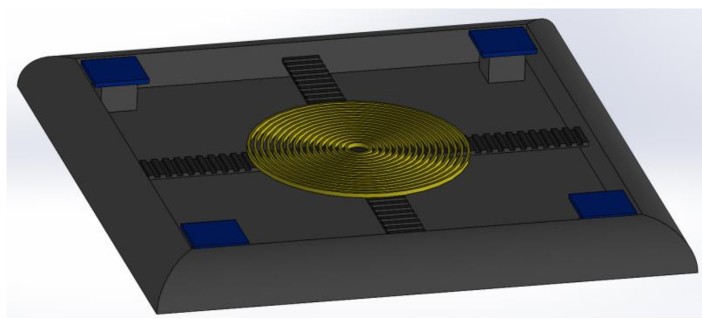

Figure 15: Internal View of the Primary Transmitter

6.3. Engineering Standards

The *PowerPad* will have a very simplistic user interface to afford ease of use. The user interface will consist of the LED alignment indicators on the dash of the cart, the main terminal power indication LED on the main terminal, and a secondary terminal power indicator LED on the dash. Additionally, the user will have to install and plug in the primary terminal of the *PowerPad*. Due to the limited user interaction with our product, there are few standards associated with the user interface portion of our design. The physical terminals of our device will conform to UL 101 - Leakage Current for Appliances [6] to prevent shock hazard while handling the device. Additionally, the enclosures will conform to IP66 [R25-G] and NEMA 4 ingress protection standards to further isolate the user from potential shock hazards. The AC power cable for the primary will conform to NEMA 5-15 connector requirements to further mitigate shock hazards. The LED indicators have no relevant engineering standards associated with them.

6.4. Analytical Usability Testing

Analytical testing typically involves modeling, theoretical analysis and feedback from industry experts. In designing the *PowerPad* we've performed extensive analytical tests through PSIM simulations and have collaborated with experienced engineers from Delta-Q in optimizing our circuit design. The goal of our analytical testing was to discover possible usability problems which we've kept in mind when designing our product. We've looked at other power transfer products currently available on the market and weighed the benefits and downfalls for each of them and made a conclusion on what our design should include.

6.4.1. Cell Phone Wireless Charging

There are many companies such as Apple and Samsung that are currently selling their wireless charging pads for cellphones. Each has a very minimal user interface and is simple to use so those products are a good example of what we should and shouldn't do in order to simplify the user interface for our customers.

Pros:
In order to start the wireless power transfer the only thing user needs to do is to plug the transmitter into the power outlet and then place their phone onto the transmitter. At that time, the phone lights up and a lightning icon indicates that the power transfer has started.

Cons:
Sometimes when the phone is placed on the edge of the transmitter the phone will still light up to indicate that the power transfer has started, however, through experimentation and personal use we have found that it can take longer for the phone to charge and therefore the efficiency is suboptimal. There are no lights to indicate that the alignment isn't perfect and that the user needs to place the phone closer to the center of the pad.

Design Choice:
In our design, we decided to keep the user interface simple while making sure that we have all of the necessary indicators to suggest that alignment is not sufficiently done and that the user needs to reposition the golf cart closer to the center of the transmitter. We also will be placing labels next to each of the LEDs to make sure the user won't have any problems understanding the instructions.

6.4.2. Tesla Car Chargers

A company called Plugless designed a wireless charger for Tesla cars and many other electric vehicles [10]. We were interested in how the company implemented the user interface for the alignment of the car. The Fig. 16 below shows the alignment indicator for the driver.

Figure 16: Plugless Alignment solution

Pros:

Simple user interface and the arrow lights pointing to different directions are clear indicators for the user to know which direction he or she has to drive in order to align the car with the transmitter.

Cons:

A wall mounted interface would not work very well for our solution as golf course owners might not want to have poles sticking out from the ground at charging stations.

Design Choice:

We decided to go with a simple LED display on the driver's dashboard to indicate the alignment in the same manner using arrow pointing in four different directions

6.5. Empirical Usability Testing

The following empirical usability testing procedures will describe in detail how we will be testing the alpha and gamma prototype in the lab environment. The focus will be to create a user interface based on results and data gathered from usage and user testing. Empirical usability testing will be divided in two main stages: alpha prototype testing and gamma prototype testing.

6.5.1. Alpha Prototype Usability Testing

At this point in our design the usability testing is done by the members of our team and the Delta-Q employees. For the alpha prototype, we had a minimal user interface that would use green LEDs to indicate the efficiency of the power transfer through the transmitter and receiver. A green LED was placed on the transmitter to indicate that the transmitter is connected to the outlet. A second green LED on the receiver indicates that the secondary coil is receiving power transfer of at least 70% at distances ranging between 5 and 10 cm.

Safety was our main priority during testing of the alpha prototype since all of the wires are still exposed and input current is between 1-3A. To ensure safety, we had to isolate coils from each other by placing them into separate enclosures for testing.

6.5.2. Gamma Prototype Usability Testing

Testing of the gamma prototype is a vital part of testing the user interface. In this part, we will gather a group of randomly selected users that will test our product and give us feedback on issues that they found and features that they liked. In order to simplify usability, we've created a test plan that will be given to each of the users and outline the steps necessary to complete the testing. This test plan is attached in the UI test plan appendix in section 8.

Our Gamma prototype will have a minimalistic and simple user interface. This interface was separated in two main parts: Transmitter UI, and Dashboard Panel UI.

Transmitter UI:

Our transmitter will have an LED strip that will glow flashing blue light to signify that AC power is connected. When the connection with the receiver is established, the LED strip will turn steady blue to indicate that power transfer has started. Finally, if a foreign object is detected the LED strip will change its colour to steady blue. The red and blue LED strip is depicted in Fig. 17

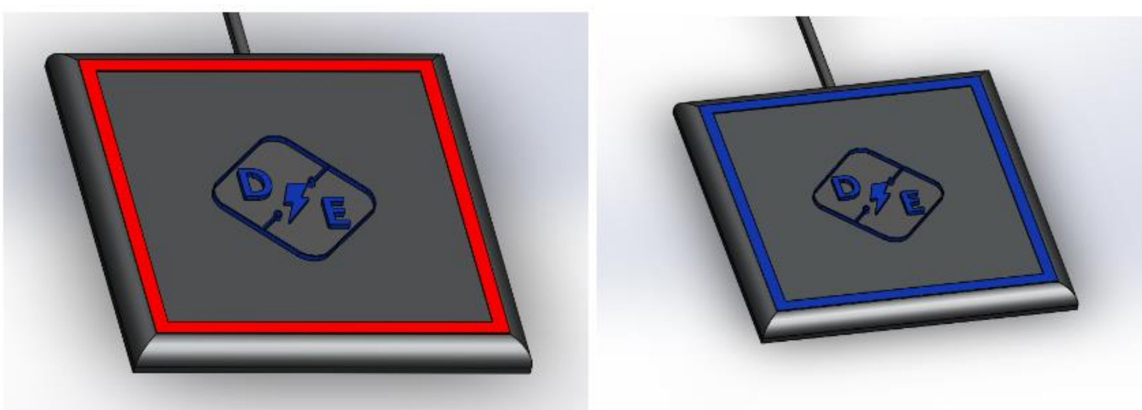

Figure 17: LED Strip around the transmitter

Dashboard Panel UI

The dashboard panel is the main part of the user interface. There will be two lights indicating power transfer and foreign object detection. Both will be labeled and easy for the user to understand. There will also be 4 directional arrows that will indicate the alignment issues and suggest the direction in which the user should move the cart for better power transfer. Fig. 18 below shows the dashboard panel for the gamma prototype.

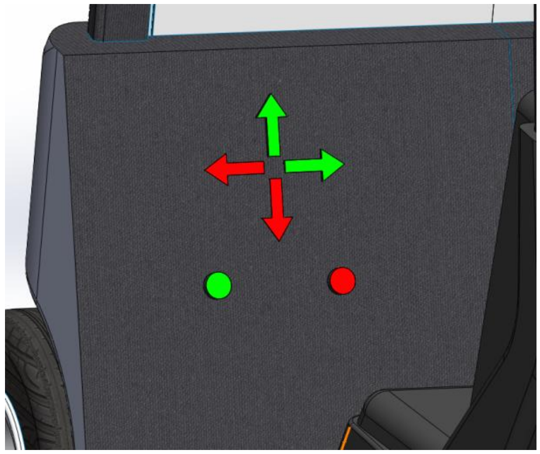

Figure 18: Dashboard panel

6.6. Conclusion

In performing a user analysis of our user base, we have an understanding of what skill set to expect from our users. The successful use of our product requires our users to have an adequate amount of driving and parking experience. Additionally, in considering the seven elements of UI design we consider optimizing the design of the *PowerPad* such that users can leverage their experience and conceptual model of how wireless phone chargers work. We take into account various ways to provide feedback and signifiers through dashboard LEDs to illustrate to the user our product is working properly.

During our analytical usability testing we've taken steps in comparing our future gamma prototype to other products already existing in the market. We've evaluated pros and cons of each of those products and came up with the design choices that would best fit our prototype. We have also came up with alpha and gamma usability tests and have discussed different set ups of the user interface for the transmitter and the dashboard panels of the gamma prototype. Based on the user response to our product other changes to the gamma prototype will be made to guarantee users satisfaction.

We note that UI design is an iterative process which will require dynamic adjustments as the project evolves. Throughout this evolution, we must consider user feedback in optimizing the ease and intuitive use of the *PowerPad*. We accept the fact that the best products are the most user friendly, and in order to achieve this we must continue to perform empirical tests while keeping our user's conceptual model of wireless charging pads in mind.

7. References

[1] E. Gomez Auad. (2013, May 14) "Golf Cart Project 1," *GrabCAD Community*. [Online]. Available: https://grabcad.com/library/golf-cart-project-1. [Accessed: 26 - Feb - 2017].

[2] EZGO. "Energy Management," in *EZGO Smart Manual*, 2015. [Online]. Available: http://ezgo.smartmanual.biz/energy-management/energy-management_en.html. [Accessed:29 - Feb - 2017].

[3] V. Roederstein, *Film Capacitors: General Technical Information*, 1st ed. 2012. Available: http://www.ixys.com/Documents/AppNotes/IXYS_IGBT_Basic_I.pdf. [Accessed: 29- Mar- 2017].

[4] C. Botting. "Delta-Q Wireless Power Transfer Meeting," *Delta-Q Office*, 3755 Willingdon Ave, Burnaby, BC V5G 3H3, 2017.

[5] A. Sattar, *Insulated Gate Bipolar Transistor (IGBT) Basics*, 1st ed. Available: http://www.vishay.com/docs/26033/gentechinfofilm.pdf. [Accessed: 30- Mar- 2017].

[6] UL. "Leakage Current for Appliances," UL LLC, 2017. [Online]. Available: https://standardscatalog.ul.com/standards/en/standard_101_5. [Accessed: 19- Mar- 2017].

[7] Statistic Brain. "Golf Player Demographic Statistics", Statistic Brain, 2017. [Online]. Available: http://www.statisticbrain.com/golf-player-demographic-statistics/. [Accessed: 26- Mar- 2017].

[8] "Golf Cart and LSV Questions & Answers - Golf Cart Safety", *Golfcartsafety.com*, 2017. [Online]. Available: http://www.golfcartsafety.com/questions-answers#q_gc_9. [Accessed: 20- Mar- 2017].

[9]"PLA Copolymer | Agro-based Polymers | Thermoplastics | Material Categories | Matbase: the independent online material selection resource", *Matbase.com*, 2017. [Online]. Available: https://www.matbase.com/material-categories/natural-and-synthetic-polymers/thermoplastics/agro-based-polymers/material-properties-of-polyactic-acid-copolymer-pla-c.html. [Accessed: 30- Mar- 2017].

[10] Plugless Power. (2017) "About | Plugless Power" [Online] Available: https://www.pluglesspower.com/about/. [Accessed: 24 - Feb - 2017].

8. UI Test Plan Appendix

The following procedure defines the action sequence of required inputs from the user to test the Gamma prototype:

1. Plug the power cord into the 120V outlet
2. A flashing blue LED strip on the transmitter shows that the primary is connected and is receiving power but is in the idle mode until the receiver is in the range.
3. Move the receiver attached to the golf cart into the range of within 20cm with the primary transmitter and look for the flashing blue LED strip turns steady blue. This means that the power transfer to the primary has started and the alignment is in progress.
4. Once the alignment is done the directional LEDs on the dashboard panel will turn off and the power transfer LED will turn green

Next we've created a heuristic evaluation where our team designed the steps that the users could take to potentially disrupt the functionality of the prototype. The following steps were taken in order to uncover common usability difficulties.

1. Plug the power cord into the 120V outlet
2. A flashing blue LED strip on the transmitter shows that the primary is connected and is receiving power but is in the idle mode until the receiver is in the range.
3. Place a random object other than the receiver on top of the transmitter
4. Look for the blue strip on the transmitter to change its colour to red
5. If the golf cart is above the primary when a foreign object is detected the dashboard light signifying foreign object detection will turn red. At this point power transfer is paused until the object is removed from the transmitter
6. Once the foreign object is removed from the transmitter the red LED strip will change its colour back to flashing blue
7. In case of the golf cart being above the transmitter the dashboard light signifying foreign object detection will turn off.

These two cases cover general usability tests for the users. Other issues may or may not come up during future user tests. Based off the feedback we get back from the users our gamma prototype will change accordingly.

9. Design Verification Test Plan Appendix

Disconnect Electronics Test Case Form			
Test Case ID: TC-SW-00	Date:	Performed By:	Reviewed By:
Description:	Verification of the *PowerPad*s efficiency and self-alignment feature		
Operating Conditions & Inputs	Operating Conditions: Room temperature, Secondary terminal mounted to golf cart Inputs: 120VAC		
Execution Steps:	1. Drive the golf cart over the *PowerPad* 2. Park the golf cart on top of the weight sensors		
Expected Results:	Terminals should self-align. Efficiency should be greater than 80% at a distance of 10 cm.The LED strip on the primary transmitter will shift from flashing blue to a steady blue. The dashboard interface will have a solid green LED.		
Actual Results:			
Comments:			
Approved	Not Approved	Signature	

Disconnect Electronics Test Case Form

Test Case ID: TC-SW-001	Date:	Performed By:	Reviewed By:
Description:	Verification of the *PowerPad*s foreign object detection feature		
Operating Conditions & Inputs	Operating Conditions: Room temperature, Secondary terminal mounted to golf cart Inputs: 120VAC		
Execution Steps:	1. Place a foreign object on the *PowerPad* 2. Drive the golf cart over the *PowerPad* 3. Park the golf cart on top of the weight sensors 4. Remove the foreign object		
Expected Results:	The *PowerPad* will glow red until the foreign object is removed. A red LED will shine on the dashboard interface. Once removed, the *PowerPad* will begin alignment and power transfer. The dashboard LED will turn off and the LED strip on the *PowerPad* will go from flashing blue to steady blue.		
Actual Results:			
Comments:			
Approved	Not Approved	Signature	

Disconnect Electronics Test Case Form

Test Case ID: TC-SW-002	Date:	Performed By:	Reviewed By:
Description:	Verification of a corner case for the *PowerPad* with multiple vehicles.		
Operating Conditions & Inputs	Operating Conditions: Room temperature, Secondary terminal mounted to golf cart Inputs: 120VAC		
Execution Steps:	1. Drive the golf cart over the *PowerPad* 2. Park the golf cart on top of the weight sensors 3. Drive a second golf cart past the *PowerPad*		
Expected Results:	The power transfer should continue uninterrupted.		
Actual Results:			
Comments:			
Approved	Not Approved	Signature	

<table>
<tr><th colspan="4">Disconnect Electronics Test Case Form</th></tr>
<tr><td>Test Case ID:
TC-ME-000</td><td>Date:</td><td>Performed By:</td><td>Reviewed By:</td></tr>
<tr><td>Description:</td><td colspan="3">Verification of the PowerPads durability and resilience.</td></tr>
<tr><td>Operating Conditions & Inputs</td><td colspan="3">Operating Conditions: Room temperature, Secondary terminal mounted to golf cart
Inputs: 120VAC</td></tr>
<tr><td>Execution Steps:</td><td colspan="3">1. Pour water onto the PowerPad
2. Crush the PowerPad with one of the golf cart wheels
3. Drive the golf cart over the PowerPad
4. Park the golf cart on top of the weight sensors</td></tr>
<tr><td>Expected Results:</td><td colspan="3">The PowerPad should still perform self-alignment and transfer power.</td></tr>
<tr><td>Actual Results:</td><td colspan="3"></td></tr>
<tr><td>Comments:</td><td colspan="3"></td></tr>
<tr><td>Approved</td><td>Not Approved</td><td colspan="2">Signature</td></tr>
</table>

10. Glossary

AC - Alternating current

CSA - Canadian Standards Association

DC - Direct current

BMS - Battery management system

BT - Bluetooth

EV - Electric vehicle

FSR - Force sensitive resistor

IEC - International Electrotechnical Committee

IGBT - Insulated-gate bipolar transistors

IP66 - An Ingress Protection rating of 66

MCU - Microcontroller

NEMA4 - A set of standards for electrical enclosures that are intended for outdoor use

OEM - Original equipment manufacturer

On-boardcharger - A charger that is mounted onto the vehicle or machine that it will charge

Opportunity charging - Recharging a battery whenever possible, in order to maintain the highest charge possible

PLA - Polylactic Acid

PSIM - Software for power electronics simulations

PWM - Pulse width modulation

UL - Underwriters' Laboratories of Canada