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Final Design Report Draft
For

Wireless Charger Project

A design project to fulfill the requirements of Senior Design
in the Department of Electrical Engineering
at The University of Texas at Tyler

The individuals whose names and signatures appear below certify that the narrative, diagrams, figures, tables, calculations, and analyses contained within this document are their original work except as otherwise cited.

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EXECUTIVE SUMMARY

[In lieu of executive summary to be written at later date]

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I. PROJECT DESCRIPTION

Our project is a 30 watts nominal resonant wireless charger prototype for use with 4 to 6 cell lithium ion battery packs. It is managed by a microcontroller. It may be monitored and controlled by a user GUI or directly by the target application. Unlike existing customized and proprietary robotic charging systems, our product will charge a standard battery type and be suitable for both stand-alone operations and integration into the user's own design.

The team has been unable to discover any equivalent products to our own for retail. The most comparable product is the [**REQUIRES NAME AND REFERENCE**], a 90 watt magnetic resonance device that is marketed to businesses designing commercial drones and robotic systems. On the lower end, nearly all unbranded, low-cost wireless chargers that are available from mass online retailers supply no more than 5W via inductive charging. For a single industrial unit, the team has received a price quote for approximately $2000 USD. Individuals and small R&D teams that search for suitable devices through online retailers will find that these low-end transmitters are not modular and are limited to one specific purpose such as charging cell phones or key-fobs.

Our charging system employs magnetic resonance coupling to charge a lithium ion battery pack, delivering between 15 and 30 watts of power. The power transmitter and receiver communicates as a unified system that can provide battery management, protect against overcharging, and provide both diagnostic and telemetric information to the user and to an optional serial connection with the powered application's control circuitry. The charging system may be monitored and controlled by the user either through an attached LCD interface or a GUI from either a Bluetooth connected PC or smartphone.

This wireless charging alternative's intended market consists of hobbyists and prototype designers considering a self-docking direct electrical connection solution. This is the charging method used by the Roomba[**REQUIRES REFERENCE**], which engages with a custom dock and charges using metal contacts. While this is a cost-effective solution for a mass-produced product, wireless charging is a superior choice for autonomous mobile devices that might have a wide variety of sizes and shapes. The benefits offered by our product's wireless charging include flexible placement of the charger, a compact charging area, greater tolerance for misalignment between the charger and the target device, and the absence of exposed electrical connections.

To best demonstrate the full potential of our project, the team has specified optional deliverables that include a mobile robot capable of charging itself for continuous wireless operation, fully integrated with a smart Li-ion battery for detailed fuel gauge and battery health status.

The team holds that a moderate power, low cost wireless charger with accessible telemetry is useful to a small but important market of robotics hobbyists and developers, who at present, are not being served by either costly, proprietary business-to-business

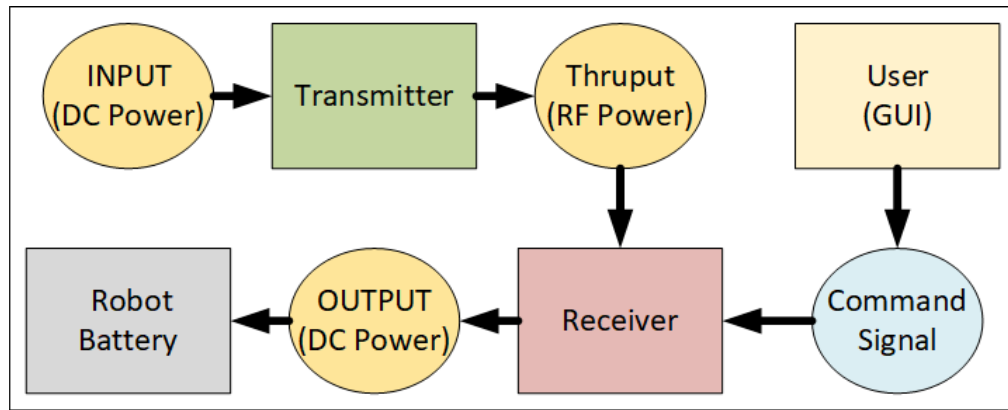solutions or the low power and poorly documented inductive chargers available on the hobby market.

Figure 1: Operation Story Block Diagram

II. TARGET SPECIFICATIONS AND ETHICAL CONSIDERATIONS

Table 1: Receiver Specifications

Charge time (4Ah Battery Pack)	5 Hours Max
Battery pack voltage	14.2 V
Coupling Efficiency Transmitter to Receiver	90%
AC-DC Conversion Efficiency	80%
Charging Controller DC-DC converter	85%
Overall Receiver Conversion Efficiency	61.2%
Maximum Battery Charging Current	1.25 A (14.7 V battery pack)
Charger Subsystem Charge Protocol	Constant Current Constant Voltage (Li-ION Battery)
Battery Type	Lithium-Ion (4 x18650 in Series or 2P4S Configuration)
Power Negotiation	Bluetooth 5 LE
Transmitter Locator Method	RF Localization [Bluetooth]
Deliverable Demo	Self-Moving Device (Robot)
Telemetry	Report State to GUI Device
LCD display	Diagnostic Character String Display

Table 2: Transmitter Specifications

Operating frequency	13.56 MHz
RF power output	30 W
Max operating range	30 cm
DC Power supply	12V 5A max.
Conversion Efficiency DC-AC	80%
Telemetry	Report State to GUI Device

Table 3: Communication Link Specifications

Communication Medium	Bluetooth 5 LE
Protocol	TBD

Table 4: GUI Specifications

GUI OS	WinOS, IOS, Linux, & Android
License	LGPL 3.0
Software Architecture	Model-Controller-View (MCV) Architecture
Delivery Model	Open Source (Free App Download)

III.   FINAL DESIGN SPECIFICATIONS

A.   Feasibility Study

The design consists of two subsystems: the transmitter and the receiver. This product is expected to be used by hobbyists and prototype designers for different applications that require contactless charging. There is no similar device available in the price range from $200 to $400. The expected cost of the charger system is $300. There are some commercial chargers available right now and the cost of that system is $2000. The price of $300 per system will make wireless charging affordable for hobbyists and freelance hardware developers.

The design tools such as Altium designer and Multisim simulator are available free of charge to all group members using the provided UT Tyler license. Also, parts manufacturers are providing free simulation and evaluation tools for development. In addition to the software evaluation kits may be required for testing certain parts of the system such as the microcontroller, Bluetooth module, and the battery charger controller. Most of those evaluation modules are already purchased and they are available to team members. Evaluation kits are purchased by Indus instruments.

The system is designed such that it uses standard components that are available at any electronic components store and they can be purchased without restrictions. PCB fabrication will be given to a company located in China that is offering quick turnaround PCB fabrication and fast shipping. Components purchasing and printed circuit board assembly will be done at Indus Instruments. Indus Instruments have all the necessary equipment that can handle surface mount components.

All test equipment required for development and testing will be available. Indus Instruments will provide space and necessary test equipment for the wireless charging system prototype evaluation and testing.

The final product cost is estimated at around $300 (for small quantities). Most likely for larger quantities, it is possible to decrease the cost even more.

B.   Microcontroller

There are four aspects to analyze: economics, technical, legal, and scheduling. A single MSP430FR5994 part costs about $3 to $4, while the MSP-EXP430FR5994 Launch-Pad kit costs $16.99. Considering the team will have only two of these microcontrollers (one for the transmitter and one for the receiver), this is a cheap and reasonable cost. [22 & 31] [2] [3]. On the technical side, this microcontroller's memory, voltage supply limitations, UART and I2Cmode specifications, and overall low power consumption makes it the ideal model for our project needs [2]. Some of the most important standards TI's MSP430FR5994 complies with include ANSI, JEDEC, and ESDA [2]. Lastly, the team already has in hands the LaunchPad kit for the microcontroller. The individual microcontrollers are also ready-to-purchase items with delivery times of less than 7 days. More

testing will be done once the team has the first PCB design in hands.

C.   Transmitter Coil

The circular planar coil was the most inexpensive approach, the copper tubing to make the coils has an approximate value of $15.99. The design properties also significantly contributed to reducing the complexity of acquiring the main coil parameters. It was important to take this factor into account because of the time constraint of two months. In order to reduce the complexity in our project, the spiral planar design was the best option.

The calculation of the inductance formula in the planar spiral design was easier to acquire than the other two proposed solutions. This was crucial because it significantly gave the project a higher chance of matching the predestined inductance of the circuit requirement of .909 μH.

The economical and ethical considerations did not affect our decision making as much, due to the fact that there were not many differences. Furthermore, this design was appropriate for our project and the team does have the budget, resources and time to successfully to implement this design.

In order for the project to have a stronger chance of successfully providing a prototype, the best option was the planar spiral coil design. This design will allow the project to more likely have a chance of being completed within the time constraint as well it reduced the complexity of the formulas implemented in the calculations. It also allowed for the project to be completed in a much easier and efficient manner.

D.   Transmitter

The transmitter class-E amplifier circuit was simulated and efficiency was 98%. The actual transmitter efficiency will likely be around 90% with the actual circuit. In the simulation, it was determined that the current required to power the class-E amplifier is 0.9 A at 30 V. The power for the transmitter will be supplied by using an external 48 V AC to DC converter followed by a step-down converter in the transmitter subsystem.

The main concern in this subsystem is the immunity of the supporting circuits to the RF electromagnetic field generated by the transmitter coil. The transmitter coil placement must be done such that the electromagnetic field has minimal effects on the electronic circuits in the transmitter. The transmitter sensitive electronic parts may require EMI shields.

During the simulation, the high voltage across the coil was observed. The highest voltage observed was 320 Vpp. That voltage poses a serious electric shock hazard. Therefore, the transmitter coil insulation must be capable of withstanding voltages that are in the 500V to 1kV range to provide a safety margin for the design. One way of achieving this

is to make a plastic box that would contain the transmitter coil and have insulation that is capable of withstanding voltages in the 500 V to 1000 V range.

Heat dissipation in the Class E amplifier circuit is expected to be around 3W (based on the efficiency of 90%). That dissipation will occur in inductors, capacitors (due to ESR), and the amplifier transistor. The transistor will have a proper heatsink to prevent overheating. Since the dissipation in the transistor is very small (on-resistance is 50 mΩ) the proper thermal management will be achieved on the printed circuit board. Coils used in the transmitter will be designed such that the col resistance is minimized which also will decrease the heat dissipation in the transmitter circuit.

E.   Receiver

There is a possibility that the receiver RF to DC stage performs with higher losses than the losses that were determined in the simulation. According to the simulation data, the RF to DC conversion will be 81% efficient. In the system specification, the conversion efficiency is set to 80%. It is important to keep efficiency above 80% to prevent excessive heat generation. If received power is 25W and efficiency is 80% then power dissipation is 5 W.

The excessive heat may have adverse effects on battery life and the speed of charging [5]. A higher temperature environment requires lower charging currents to prevent further temperature rise and damage to the battery cells. Also, excessive heat generation must be minimized to avoid the use of fans and large heat-sinks. Heat-sinks and fans would increase the cost and the size of our product. If during the prototype test phase efficiency drops below 80% the circuit must be redesigned to achieve the target specification efficiency.

One problem that is likely to occur is the interference in the battery charging and communication link circuits caused by a strong electromagnetic field generated by the transmitter coil. Even though all good practices will be followed for the circuit board design the electromagnetic interference still may not be prevented. Charging circuit disruption can cause battery failure due to overcharging or overheating. If this problem occurs the additional EMI shielding will be required. The shielding includes placing metal boxes over sensitive electronic subcircuits and placing additional filters in series with DC power supplies for sensitive parts such as a microcontroller, Bluetooth module, and charger controller.

F. Thermal Considerations for 3.3V and 5V Voltage Regulators

According to the simulation data both parts have small power dissipation. The largest power dissipation is 0.18 W (5.0V regulator).

The graph below provides thermal resistance junction to ambient as a function of the printed circuit board. The equation below can be used to find the required thermal resistance junction to ambient (Θ_{JA}). The estimated ambient temperature in the transmitter is 45°C.

$$\Theta_{JA} = \frac{125°C - T_{A(max)}}{P_{D(max)}} \left[\frac{°C}{W} \right] \tag{1}$$

$\Theta_{JA} = \frac{125-45}{0.18} = 444.44 \left[\frac{°C}{W} \right]$

The estimated transmitter PCB area will be around 100cm2. Given the board size and thermal resistance vs. board size, those regulators will have a proper heatsink.
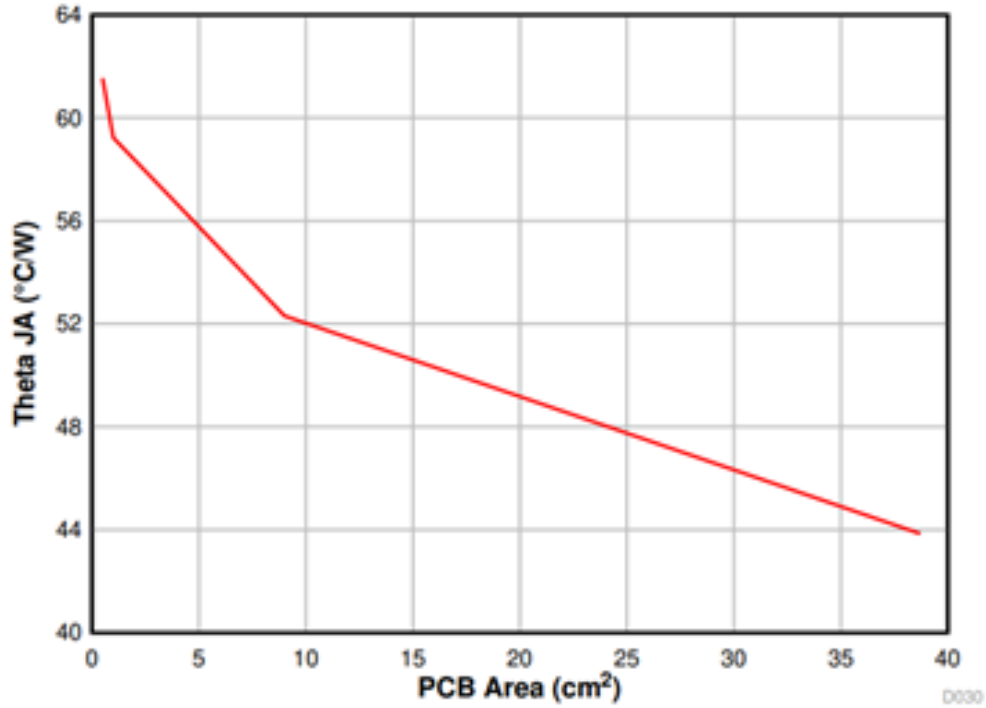

Figure 35. θ_{JA} versus PCB Area

Figure 2: Thermal Resistance vs. PCB Area [5]

Thermal considerations(for class E amplifier voltage regulator (30V, 1.0A buck converter)

$$T_{A(max)} = T_{J(max)} - R_{TH} \cdot P_{TOT} \tag{2}$$

· P_{TOT} is the total device power dissipation in [W]
· T_A is the ambient temperature in [°C]
· T_J is the junction temperature in [°C]
· R_{TH} is the thermal resistance of the package $\left[\frac{°C}{W}\right]$
· $T_{A(max)}$ is the maximum ambient temperature in [°C]
· $T_{J(max)}$ is the maximum junction temperature in [°C]

The expected ambient temperature is 40°C (that is temperature inside the transmitter enclosure).
Thermal resistance for a standard board (Θ_{JA}) is $62.5\left[\frac{°C}{W}\right]$ [4].
From the simulation the total power dissipation is 1 W.
From the recommended operating conditions the maximum junction temperature is 150°C [4].
Based on the data from the simulation and the datasheet the maximum ambient temperature can be determined
$T_{A(MAX)} = T_{J(MAX)} - R_{TH}*P_{TOT}$
$T_{A(MAX)} = 150 - 62.5*1 = 87.5°C$
The expected ambient temperature is lower than the maximum temperature calculated based on simulation data. Therefore, this part will operate within specified recommended conditions in the datasheet.

G. Charging Subsystem

The LTC4162-L is designed to manage a power path between an external input power source Vin, an output power V_{out}, and an installed battery pack. When external input power greater than the battery voltage is available at V_{in}, the LTC4162 will route V_{in} to V_{out} and charge the connected battery. If external power is interrupted or falls below V_{bat}, battery power will be automatically routed to V_{out}. As long as the battery has charge or a power source exists at V_{in}, V_{out} will be supplied with power, but the voltage will range from V_{bat} to V_{in}. In order to provide consistent voltage to the target device output power should be drawn directly from the battery. Leaving V_{out} unused allows the maximum power point tracking feature to operate with optimal efficiency.

The LTC4162 draws power directly from Vout and has its own internal LDO linear regulators. All other components of the wireless receiver PCB must be powered by an appropriate DC-DC stage at V_{out} that can convert any potential input voltage (i.e. 7.4-35 V) to the required operating voltages of 5 V and 3.3 V. These circuits will require power in order to operate and initiate charging. In the event that the battery is severely depleted and cannot power the microprocessor and Bluetooth interface, it will be necessary for the transmitter to be capable of initiating charging independently.

Since the LTC4162 has only an internal buck voltage regulator, the wireless power receiver subsystem must provide power to Vin that is higher than the voltage of the battery but below the maximum input voltage of 35V.

The LTC4162 approaches 95% efficiency at recommended switching frequency when the input voltage is no more than approximately 5V above battery charging voltage, and surpasses 90% in less ideal configurations. Heat losses will be in the range of three watts or less. It has a Θ_{JC} of 3.4 $\left[\frac{\circ C}{W}\right]$ and will be soldered to a four-layer PCB. The team does not anticipate any thermal management issues with this circuit.

H. Battery Considerations

Li-Ion batteries offer superb performance and high energy density, but require special attention to safety. Under normal circumstances the LTC4162-L will monitor battery voltage and avoid overcharging. A NTC thermistor will allow the LTC4162 to monitor local charging temperatures and limit current in accordance with JEIDA recommendations.

For safety reasons, the team requires stricter battery specifications than originally planned. While our charger's thermistor can limit charging current in response to ambient temperature extremes, it cannot monitor individual cells–particularly if the battery pack is intended to be modular. While it can recognize and respond to abnormal battery voltages or short conditions, it cannot automatically determine maximum safe charging current. Any battery pack used must have a maximum charge current greater than the maximum current delivery of the charger. Battery packs must also meet UL1642 and IEC61960 standards and contain internal protection circuitry to limit charge and discharge currents and protect against thermal runaway.

The LTC4162 can deliver a maximum of 3.2 amps and has an efficiency of up to 95%. Assuming optimal efficiency and 26 W output from the wireless receiver, the charging voltage must be at least $frac25W3.2A$ = 7.8 V in order to fully utilize the available power. Since the voltage of a typical Li-Ion cell is 3.7 V and the charging voltage is 4.2 V, the target battery pack should consist of two or more cells in series. The LTC4162 supports 1 to 8 cell series arrangements provided the input voltage is adequate. Optimal arrangements would include a 7.4V pack rated for 3.2 A charging, a 11.1 V pack rated for 2.2 A charging, or a 14.8 V pack rated for 1.7 A charging. The number of cells is set by selection pins and may be configured by a DIP switch or jumpers. It is not necessary to specify a specific number of cells for suitable battery packs, provided that they meet UL1642 and IEC61960 standards. The optimal balance of safe charging rates and performance will likely be found with packs utilizing six to eight 18650 cells or the equivalent. The power delivery estimates above are optimistic and actual power delivery from the charger may not reach these levels. As prototyping progresses, it will be possible to refine battery recommendations and expected charging times.

Ideally, up to 25 W will be delivered to the battery pack, making the battery the largest potential source of heat in our system. Since the battery pack is intended to be a modular, removable component with flexible specifications, it will not necessary for it to be enclosed with the wireless receiver PCB and receiving coil. It will be connected by an appropriate low-loss cable and connector, and exact placement will be determined by the user application. For this reason, the team has specified that only battery packs with internal temperature monitoring and protection circuitry should be used with this charger.

Our original specifications suggested that the charging subsystem would be capable of detailed monitoring of battery health and charge state. The team has learned that this type of information must be obtained at the individual cell level by a specialized controller which is usually integrated into the battery pack itself. Our charge subsystem can only recognize an approaching low-battery condition by a drop in voltage, and cannot estimate battery capacity except by calculation using charging voltage, charge times and currents, and such data would be of limited use considering battery aging and user-replaceability. It will be possible to notify the user and target device of a drop in battery voltage, but more detailed fuel gauge and battery health information will require an SMBus enabled smart battery. An I2C line on the MSP430FR5994 will be reserved for communication with an optional SMBus capable smart battery pack. If feasible, optional battery pack telemetry may be polled by firmware and reported to the user along with the data already available from the LTC4162.

All the parts and design resources needed to complete the charging and power subsystem are readily available. Constructing this subsystem within the projected time-frame is feasible.

Table 5: Final Design's Charging Subsystem Specifications

DC-DC stage from wireless receiver to V_{in}	May not be necessary, pending further determination of wireless receiver output voltage
DC-DC stage from V_{out}	5V at 100mA; 3.3V at 100 mA
Battery Requirements	UL1642 and IEC61960 compliant Li-Ion packs with 7.4-15 V_{DC} nominal output voltage
Maximum Charging Current	3.2A (7.4V); 2.2A (11.1V); 1.7A (14.8V)
Provision for optional smart battery health and fuel gauge monitoring	Reserved I2C line from MSP430FR5994 with buffering

I. Microcontroller Considerations

The MSP430FR5994 has a body size that ranges from 6mm by 6mm to 12mm by 12mm depending on the package the group purchases, 8KB RAM, 68 GPIO pins, 4 I²C, 4 UART, up to four serial communication ports, and 20 ADC channels. The MSP430 series include limitations that range from safety to performance [2].

Relevant limitations to the project include:

1. ESD (Electrostatic discharge) ratings. For a human-body model, safe discharge ratings are around 500 V to 1000 V, while for a charged-device model, safe discharge ratings are around 250 V. These regulations are taken from JEDEC JS-001 and JESD22-C101 respectively [2].

2. Absolute maximum ratings: voltage applied to any pin must be within -0.3 V to 4.1 V, voltage difference between DVCC and AVCC pins must stay within -0.3 V to 0.3 V (if not, writing errors could occur to RAM and FRAM), and current at any device pin must have a maximum of -2 to 2 mA [2].

3. Supply voltage applied should be within 1.8 V to 3.6 V, maximum ACLK frequency should be 50 kHz, and maximum SMCLK frequency should be 16 MHz [2].

4. For the eUSCI I²C, eUSCI (enhanced universal serial communication interface) input clock frequency should not exceed 16 MHz, SCL clock frequency should not exceed 400 kHz [2].

J. Firmware Requirements: Transmitter

The Wireless Power Transmission Stage (Transmitter) will be controlled by an MSP430FR5994 running custom firmware. The firmware must meet the following requirements:

1.) Activate or deactivate wireless transmitter.

2.) Respond to commands received from a Bluetooth link with the Wireless Power Receiver Stage (Receiver), which may include requests for power delivery measurements or instructions to initiate or cease charging.

3.) Continuously monitor wireless power transmitter current and voltage and calculate delivered power.

4.) Automatically cease power transmission when the Receiver requests a shutdown or if severe interference is detected.

5.) Communicate operating status to the Receiver via Bluetooth, and directly to the user via fault LED's or an installed LCD.

K.   Firmware Requirements: Receiver

The Wireless Power Receiver Stage (Receiver) will be controlled by an MSP430FR5994 running custom firmware. The firmware must meet the following requirements:

1.) Link to the Transmitter over Bluetooth.

2.) Link to user GUI device over Bluetooth.

3.) Link to an optional UART connection with the target device.

4.) Respond to queries or instructions from the Bluetooth connection to the user GUI or from the optional UART connection.

5.) Monitor charging state and battery status though I2C connection with LTC4162 and optional SMBus link with smart battery.

6.) Recognize low voltage state or optional low capacity battery warning and notify the user and target device.

7.) Signal the Transmitter via Bluetooth to initiate charging when instructed by the user or target device.

8.) Continuously monitor wireless power receiver current and voltage and calculate delivered power.

9.) Monitor reported power transmission from the Transmitter, compare it with received power, and recognize excessive power losses that could indicate unsafe interference conditions

10.) In the event of excessive transmission losses, instruct the Transmitter to cease power transmission. Notify the user and target device of the error condition.

The Transmitter and Receiver firmware will be developed with Texas Instruments Code Composer Studio. The team has suitable Launchpad development boards and access to all necessary documentation and libraries are available. The team is composed of multiple experienced programmers in our group. The firmware requirements are limited and well-defined and completing it within our scheduled time-frame is feasible.

L. *Software Requirements: GUI*

The GUI will be operated on multiple platforms and rely upon QT5 to operate. The software must fulfill the following requirements:

1.) Provide connection to transmitter and receiver for the product's user that grants sufficient control over the product's hardware

2.) Serve as a platform for custom messages to and from the user's device connected to the receiver.

3.) Provide alert system via push notifications and continuous monitoring of the transmitter and receiver.

M. *Coil Considerations*

Table 6: Final Design's Coil Tubing Specifications

Material	122 Copper
Tube Size	$\frac{1}{8}$ [in]
Outter Diameter (OD)	$\frac{1}{4}$ [in]
Wall Thickness	0.049 [in]
Inner Diameter (ID)	0.152 [in]
Fabrication	Seamless
Bending Method	By hand
Temper Rating	Soft
Compatible Tube Fittings	Compression, Solder Connect
Specifications met	ASTM B75 RoHS 3(2015/863/EU) Compliant
Resistivity	1.68 x 10^{-8} [Ω/m]
Conductivity	5.96 x 10^7 [S/m]

This tubing has good corrosion resistance and excellent heat transfer qualities. All tubing meets international standards for copper tubing. Important to note: Tube size is an accepted industry designation, not an actual size [1].

Table 7: Final Design's Receiver Coil Specifications

Outside Diameter of Coils (Do)	90 mm
Number of Turns	4
Length	729.6 mm
Spacing	4.81 mm
Width of Tubing	3.175 mm
Inner Diameter (Di)	26.12 mm
Winding Radius	29.03 mm
Radial Depth	31.94 mm
Inductance	909.66 nH.
Capacitance	150.55 pF
Frequency	13.6 MHz
Resistance (Dc)	1.5462 mΩ
Total Resistance	69.46 mΩ
Quality Factor	1119.09

N. Specification Summary

Table 8: Final Design's Receiver Specifications

Charge time(4Ah Battery Pack)	5 Hours Max
Battery pack voltage	User Selectable: 7.4V-14.2 V
Coupling Efficiency Transmitter to Receiver	90%
AC-DC Conversion Efficiency	80%
Charging Controller DC-DC Converter	85%
Overall Receiver Conversion Efficiency	61.2%
Battery Requirements:	UL1642 and IEC61960 compliant Li-ion packs.
Maximum Battery Charging Current	3.2A (7.4V); 2.2A (11.1V); 1.7A (14.8V)
Charger Subsystem Charge Protocol	Constant Current Constant Voltage (Li-Ion Battery)
Battery Type	UL1642 and IEC61960 compliant Li-Ion packs; 7.4-15 VDC nominal output voltage.
Power Negotiation	Using Bluetooth 5 LE
Deliverables	Wireless resonant charger with approximately 30W power transmission capability. Stretch Goal: a mobile device to demonstrate autonomous charging.
Telemetry	Report State to GUI Device
LCD display	Diagnostic Data Character String Display

Table 9: Final Design's Transmitter Specifications

Operating Frequency	13.56 MHz
RF Power Output	30 W
Max. Charging Distance	30 cm
DC Power supply	48V 1.25A min.
Conversion Efficiency DC-AC	80%
Telemetry	Report State to Receiver

Table 10: Final Design's Communication Link Specifications

Communication Medium	Bluetooth 5 LE
Protocols	GUI: Host Controller Interface (HCI) Receiver- transmitter: Synchronous Connection-Oriented (SCO) link

Table 11: Final Design's GUI Specifications

OS	WinOS, IOS, Linux, & Android
License	LGPL 3.0
Software Architecture	Model-Controller-View (MCV) Architecture
Delivery Model	Open Source Free App Download

Table 12: Ethical and Professional Considerations

Public Health	· Medical Equipment RF Exposure · Electrical Shock · Chemical Exposure
Safety and Wellness	· RF Bandwidth Jamming · Electrical Shock · Chemical Exposure
Global Factors	· International Governing Bodies · Sourcing Restrictions · Inter-Market Penetrability
Societal Factors	· Open-Source Capitalization · STEM Educational Resources · Professional Organizations · Customer Privacy & Security
Environmental Factors	· Chemical Pollution · User Environmental Awareness · Emergency Shut Off Cases
Economic Factors	· Open-Source Capitalization · Specialty Clientele · Rapid Agile-Deployment · Light-Weight Production

IV.   REFERENCES

SOFTWARE REFERENCES

Block diagrams were rendered in Windows Visio Standard 2019.
Multisim circuits simulated in NI Multisim V.14.2 2019.

DESIGN REFERENCES

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