ECE 445 Design Document - Spring 2024

Wireless Drone Charging Station

Project # 29

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1. Introduction

1.1. Problem

Drone technology is becoming more vital for our modern society because it improves productivity and precision for several applications. Despite this, the operation time continues to be a key technological challenge because of the drone's battery life limitations. As a result, our project aims to address this issue by implementing an automated drone charging system that extends the drone's flight time without human intervention.

1.2. Solution

Our group aims to use resonant inductive coupling to develop a wireless drone charging station that allows the drone to land and charge its battery within an acceptable distance from the transmitter. The combination of the coils on the drone and on the charging pad will essentially act as an air gap transformer. Circuitry leading up to the coil on the charging pad side will consist of a power source, full bridge synchronous rectifier, and resonant tank. Circuitry after the transformer on the drone side will include an AC-DC converter followed by a synchronous buck converter and ending with a BMS. Our system should start power transfer only when the drone lands in close proximity to the coil on the pad. An MCU will be used to provide PWM to the gate driver that drives MOSFETs used throughout the project based on inputs from a proximity sensor.

1.3. Visual Aid

Figure 1: Visual Aid

1.4. High Level Requirements

1. The system is able to supply 3.7V± 3% V DC to 1S LiPO battery, when supplied with 24V DC power from the power supply.
2. The charging pad is able to charge the drone to at least 90% of the maximum battery capacity without human interference with an efficiency of at least 50% only after the coils are within the set proximity of 5 cm.
3. The system should be able to operate upto a resonant frequency of 125kHz.

4. The system should operate within the 0.97dB range(Power produced by the resonant tank is between Pmax and 0.8*Pmax).

2. Design

2.1. Block Diagram

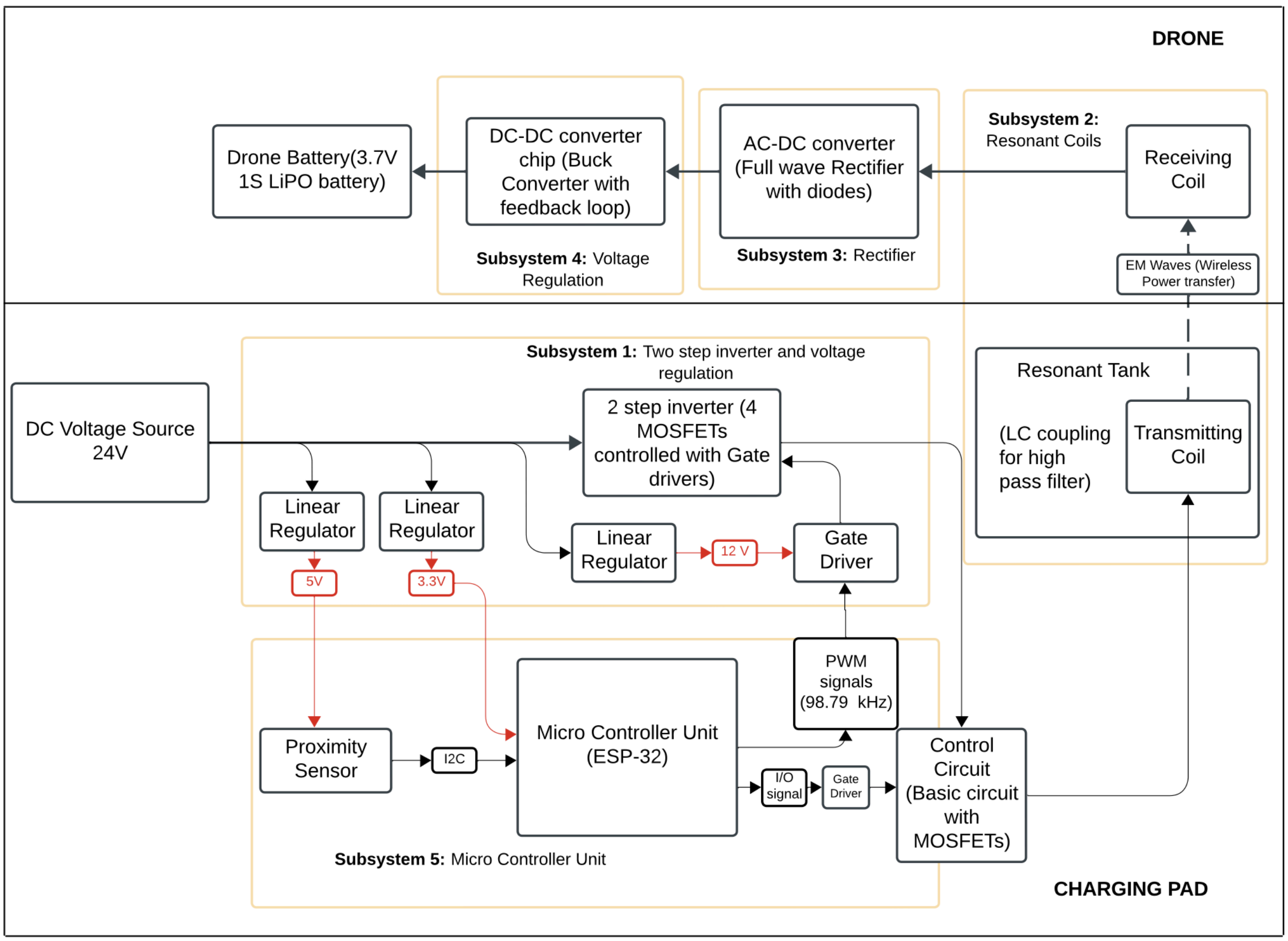


Figure 2: Block Diagram

2.2. Physical Design

The Wireless Charging pad will be a box of the following dimensions - 7.62 x 4.62 x 2.25 in / 194 x 117 x 57 mm / 0.68 lbs

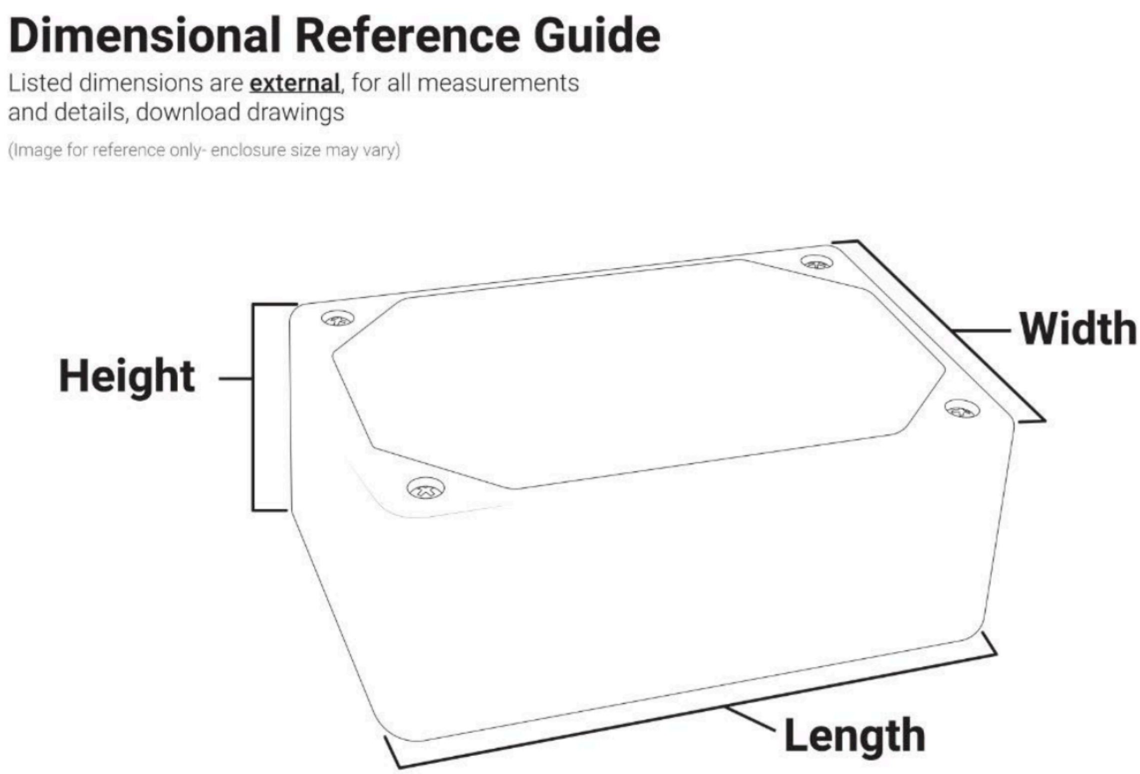


Figure 3: Box Ordered from Polycase[15]

The next sections explain the subsystems mentioned in the block diagram. The requirements and verifications for all the subsystems are mentioned after the explanation of the subsystems.

2.3. Subsystem 1: Two Step Inverter and Voltage Regulation

This subsystem consists of a 24V DC power supply and a full bridge inverter circuit. We also provide power to the transmitter of the proximity sensor as a part of this subsystem.

Inverter Circuit:

Our inverter circuit consists of four MOSFETs as seen in the figure. The circuit takes input from a 24V DC Power Supply and it outputs a square wave. This is a 2 step inverter meaning the output will only have two voltage values 0V and 24V. The inverter circuit will be based on the following topology.

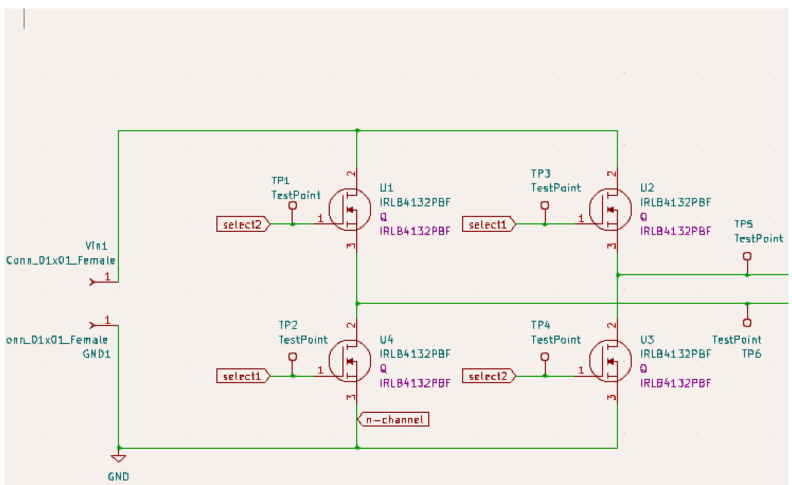


Figure 4: Full Bridge inverter

The MOSFETs will be controlled by complementary PWM signals (98.794 kHz frequency) which will be generated by gate driver ICs. The output of this subsystem is going to be a square wave with voltages 24V and -24V.

This subsystem also consists of three linear regulators, which take in 24V from the DC power source and output 3.3V, 3.3V and 12V. The two 3.3V outputs are used to power devices in subsystem 5(proximity sensor and MCU) while the 12 V is used to power the gate driver used to amplify the PWM signals to the MOSFETs. The circuit for the gate driver is as follows:

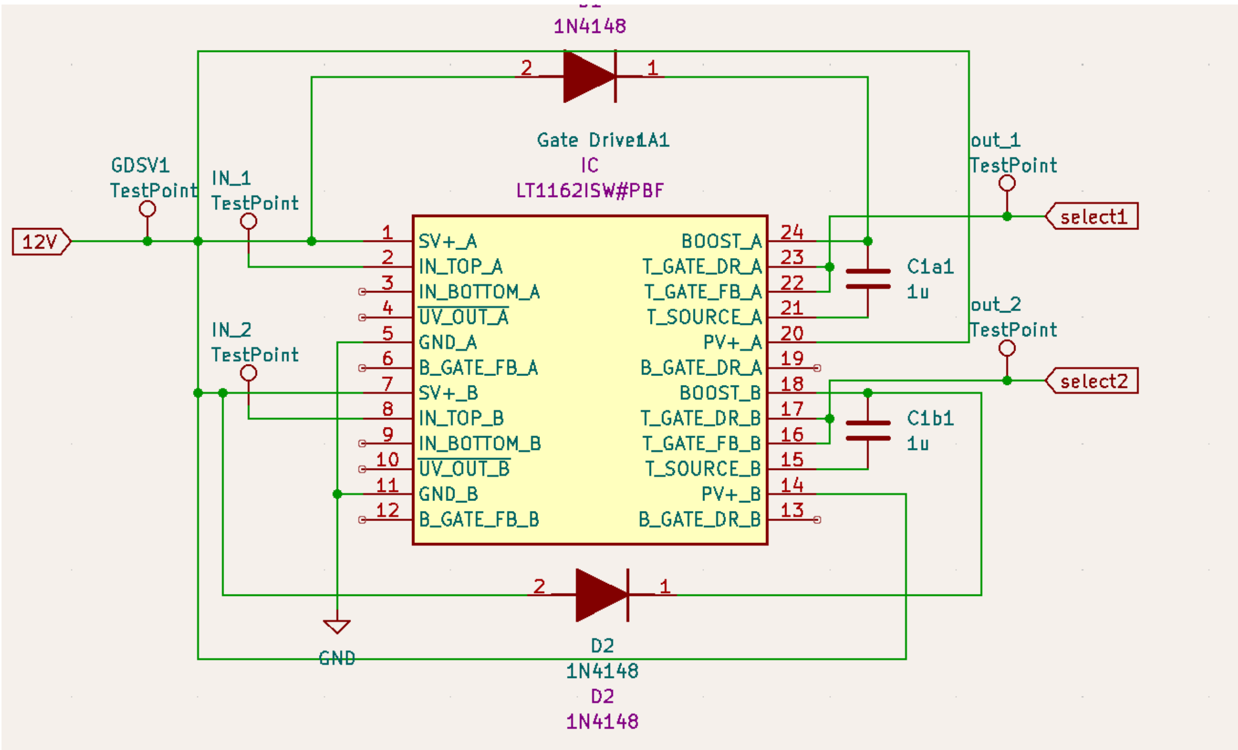


Figure 5: Gate Driver circuit

Select1 and select2 are complementary PWM signals (98.794 kHz) which are then driving 2 MOSFETs each as shown in Figure 4. The input for the gate driver is coming from the ESP-32. A gate driver is used to amplify the voltage levels of the PWM signals so that they can effectively trigger the MOSFETs. This implementation of the gate driver is inspired by the application circuit provided in the datasheet for the Gate Driver [16].

Requirements	**Verification**
The output of the circuit is a square wave with voltages -24V and 24V	Input 24V DC and use an oscilloscope to check the waveform of the output
The voltage supplied by the linear regulators match the specified value	Input 24V DC and check the output of the linear regulators with the help of an oscilloscope
All four MOSFETs in the full bridge inverter are driven at the correct	This would be tested using the test points for select 1 and select 2 to

switching frequency of 98.794 kHz .	make sure they are receiving the signal and that the signal is of a correct frequency. This is verifiable using an oscilloscope.
Gate driver works properly and amplifies the input signals	This would be tested using an oscilloscope and checking the input and output waveforms.

2.4. Subsystem 2: Resonant Coils

This system consists of the LC Resonant tank and the transmitting and the receiving coils. The LC coupling will be used as a band pass filter for the incoming square wave. The Inductance over here will be the inductance of the transmitting coil. We will be designing the circuit to output only AC with 125kHz. This frequency was selected since the coils we were able to get have an operating frequency of 125kHz. The schematic for this subsystem will be similar to the following figure:

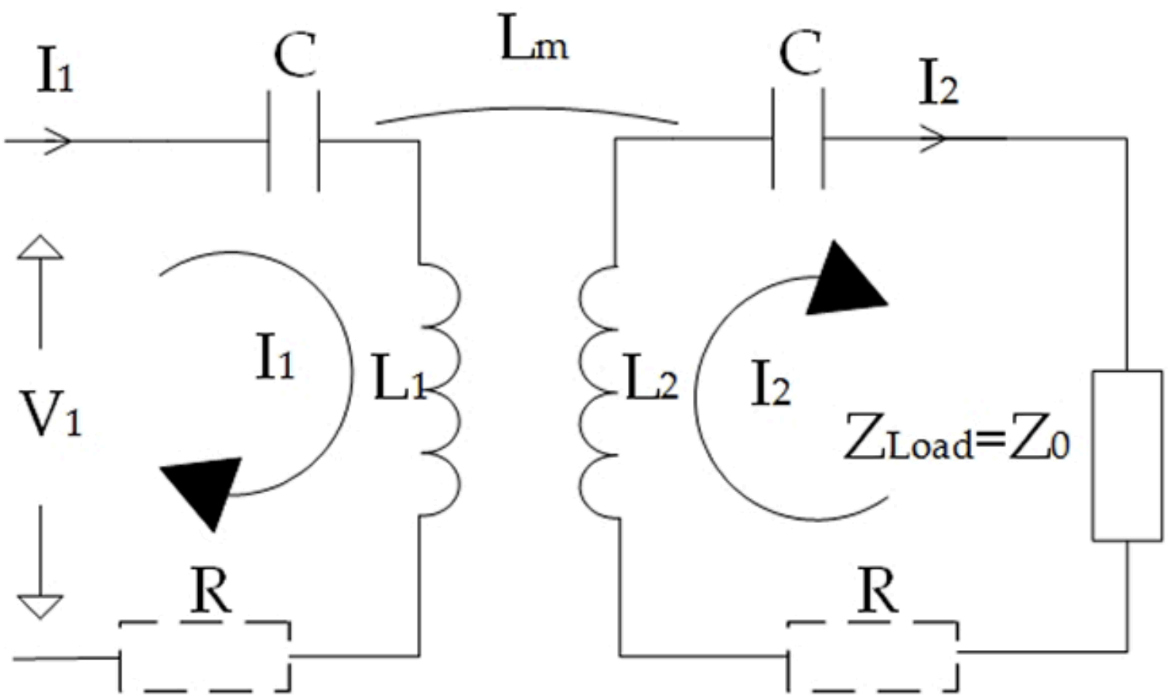


Figure 6: Coil Network with LC Resonant Tank

The left side will be the transmitting side. The input to the transmitting side will be the square wave. L1 represents the inductance of the transmitting coil. The capacitor will be chosen in such a way that the resonant frequency of the circuit is equal to 125kHz. For our design, we won't be including the capacitor on the receiving side(right side). The resistances indicate the resistances of the wires and L2 indicates the inductance of the receiving coil. Lm is the mutual inductance.

The main thing in this subsystem is to keep the quality factor of the LC circuit high to ensure that the waveform for wireless power transmission is of high frequency.

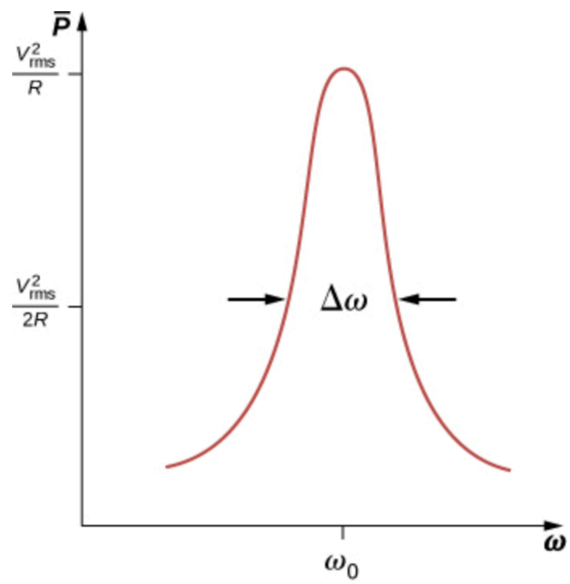


Figure 7: Bode Plot

To ensure high efficiency the peak of this plot should be as narrow as possible. The quality factor is a function of L,C, and R and all of them will have to be tuned appropriately to get a high quality factor.

We are aiming for a frequency within the 0.96dB range. This would mean that the power outputted by the Resonant tank would be within Pmax and 0.8*Pmax (Pmax being the maximum power output at 125kHz).

Another factor to consider here is the coupling coefficient of the coils. The coupling coefficient depends on the individual inductances of the coils and the mutual inductance.

Requirements	**Verification**
The efficiency of the wireless power transmission should be more than 50%	Given an input AC, the input power on the transmission side and output power on the receiving side will be measured with the help of watt meters. The output power should be greater than 50% of the input power.
The LC circuit on the transmission side should be operating within the 0.97 dB of the resonance frequency i.e. 125kHz.	We will check this by using a network analyzer. A network analyzer can determine the frequency response of the transmitting coil, ensuring it operates within the desired frequency range for efficient

	power transfer.
The distance between the coils should be less than 5cm	Checked physically with the help of a tape measure/ruler.

2.5. Subsystem 3: Full Bridge Rectifier

This subsystem includes a full bridge rectifier with a filter, which is responsible for converting AC voltage from receiving coil to 10V DC. Our target AC voltage from the receiving coil is 12± 3% V AC, but this may vary depending on the electrical characteristics of the coils, especially the coupling factor. Our capacitive filter would be flexible enough to account for unexpected variations. The filter would include a capacitor tank to allow for more flexibility. The rectifier would utilize four 1N4007-T diodes, hence communication with ESP32 microcontroller is not required.

The figure below shows a typical full bridge rectifier circuit [9]:

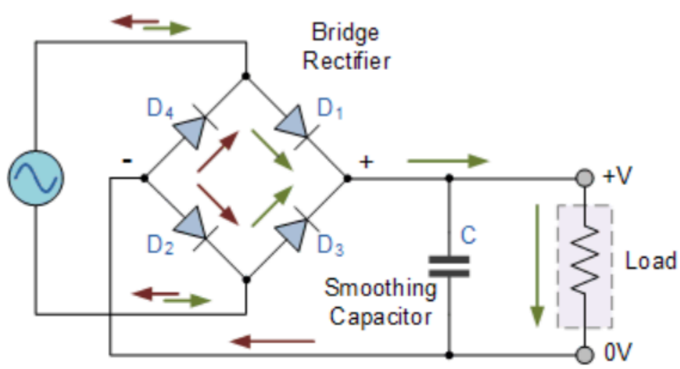


Figure 8: Full Bridge Rectifier

Requirements	Verification
The full bridge rectifier must be able to convert 12± 3% V AC from the WPF system to 10 ± 3% V DC.	We will use the variac, wattmeter, and oscilloscope in the lab to confirm this AC-DC conversion.

2.6. Subsystem 4: Synchronous Buck Converter with Voltage Regulation

This subsystem includes a TPS54335ADDAR (TI) synchronous buck converter chip responsible for converting 10 ± 3% V DC to 3.8 ± 3% V DC for the drone's battery. We will rely on the current mode control capabilities of the chip to perform output voltage dynamic regulation. It is vital to ensure effective and safe charging of the drone's battery in all scenarios, thus ensuring system stability. This would be achieved by controlling the duty ratio of the converter chip.

The figure below shows a schematic for the synchronous buck converter chip:

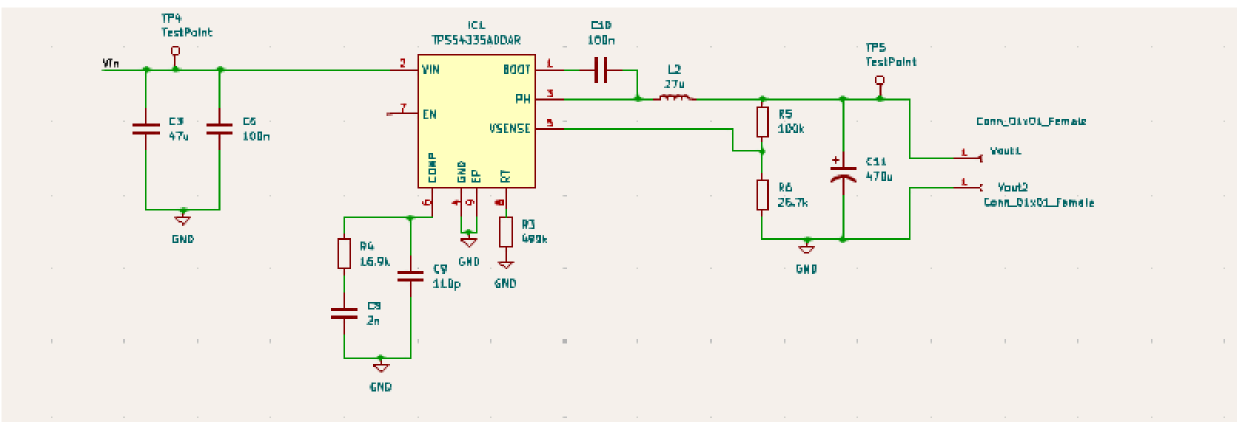


Figure 9: Synchronous Buck Converter

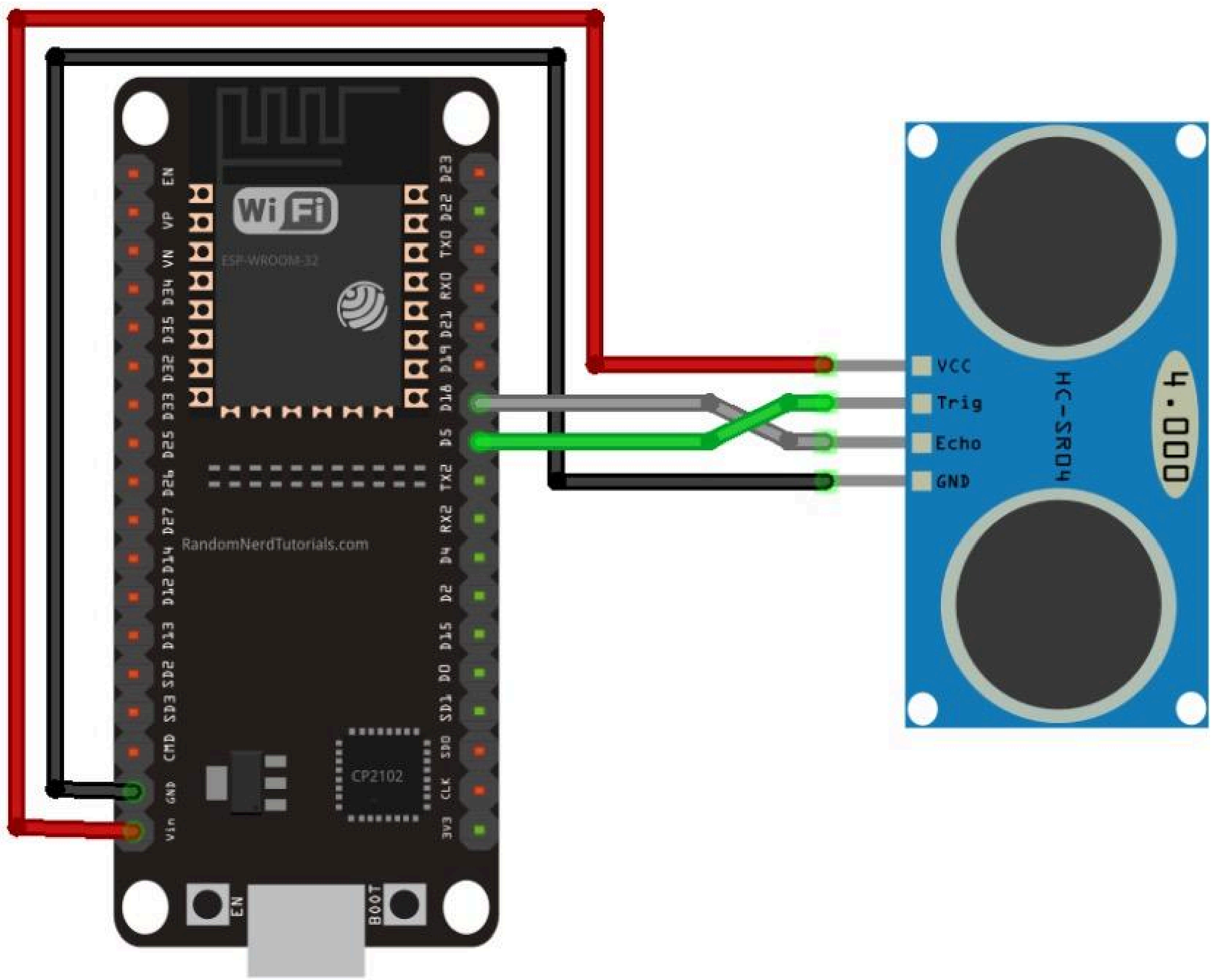
Requirement	**Verification**
The TI buck converter should be able to convert 10 ± 3% V DC to regulated 3.8 ± 3% V DC.	This DC-DC conversion would be confirmed using a testbench DC power supply and oscilloscope.
The synchronous buck converter chip operates at 98.794 kHz switching frequency.	This would be confirmed using an oscilloscope.
Maximum output current of 2A	This would be confirmed using current probes.

Successful dynamic regulation of output voltage.	We will use the testbench DC power supply to send low input voltages into the converter chip to verify that the chip is able to control the duty ratio in order to maintain output voltage.

2.7. Subsystem 5: Micro Controller Unit

This subsystem would include the ESP32 microcontroller responsible for sending PWM(98.794kHz) signals to all MOSFET switches, successful communication with the proximity sensor, and driving the control circuit to allow for charging only when the drone is detected by the proximity sensor. If time permits, this unit would also be responsible for communicating with LED displays to visually convey the charging status of the drone's battery. The control circuit is essentially a MOSFET which is controlled by the MCU and allows charging only when the drone is detected. The output signals from the MCU are amplified with a gate drive so that it can effectively control the MOSFET.

The figure below shows a layout connection for the ESP32 and proximity sensor[17]:



Requirement	**Verification**
Successful communication between proximity sensor and ESP32 microcontroller.	Confirmation that the proximity sensor distance data is being read through the use of serial printing onto the monitor.
Successful communication with the gate driver and the PWM(98.794kHz) signal is 98.794kHz.	Validated via serial printing onto the monitor.
Successful control of the transmitting circuit with I/O signal. Allow charging only when the drone is detected	Confirmed by observing the output of the MCU and the control circuit via an oscilloscope.

2.8. Tolerance Analysis:

The frequency of the LC circuit should be within 0.97db of the resonant frequency i.e. 125kHz.
The capacitors we are using have a tolerance of ±10% and the inductance of the transmitting coil will also have a general tolerance of ±10%.
Thus the frequency of the LC circuit would be between 100kHz and 150kHz.
This can be explained as follows :

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

The formula for the resonant frequency is:
If we take the worst case values of L and C, i.e. 1.1*L and 1.1*C, we will get a new frequency of 113.63kHz. If we take the values of L and C on the other spectrum, we get a frequency of 138.9kHz.

Now, let's calculate our 0.96dB frequency range. It is the frequency when the power output of the system is half of the maximum power output of the system.
The lower cutoff frequency is given by the formula -

$$\omega_L = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

Whereas the upper cutoff frequency is given by the formula-

$$\omega_H = +\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

The transmitting coil we are using for the circuits has a resistance value of 55 m-ohm. The inductance of the transmitting coil is 10uH and the capacitance at resonance is 0.16u The 0.96 dB bandwidth of the circuit is given by

$$BW = \frac{f_r}{Q}, \quad f_H - f_L, \quad \frac{R}{L} \text{ (rads)} \quad \text{or} \quad \frac{R}{2\pi L} \text{ (Hz)}$$

For our case, the worst case bandwidth is 50kHz. Based on the inductor we will be using, this bandwidth range is easily achievable and we will be able to operate our circuit properly with the real components.

3. Cost and Schedule

3.1. Cost Analysis

Our total cost comes out at $36619.00. This takes into account our parts and labor. The following table shows how we came to that number, with a quick explanation of labor costs below.

3.1.1. Parts List

Part (Part Number)	**Manufacturer (Website)**	**Quantity (Spare)**	**Cost**	**Link**
Diodes (1N4007-T)	Diodes Incorporated (DigiKey)	10 (6)	$0.20 each	Diode
ESP32 (ESP32-DEVKITC-VIE)	Espressif Systems	1 (0)	Free	Borrowed
Mini RC Drone with 3 batteries	Holy Stone (Amazon)	1 (0)	$36.99	Drone
110pF capacitor (GRM1555C1H111GA01D)	MuRata (DigiKey)	3 (2)	$0.17 each	110pF cap
47uF capacitor (GRM32ER61C476KE15L)	MuRata (DigiKey)	2 (1)	$1.10 each	47uF cap
470uF capacitor (APXF6R3ARA471MH80G)	Chemi-Con (DigiKey)	4 (2)	$1.01 each	470uF cap
TI Buck Chip (TPS54335ADDAR)	Texas Instruments (DigiKey)	2 (1)	$0.64 each	Buck_Drone
1k Ohm resistor (RC0402JR-071KL)	Yageo (DigiKey)	10 (9)	$0.018 each	1k_Ohm
27uH inductor (744774127)	Würth Elektronik (DigiKey)	1 (0)	$1.88	L
26.7k Ohm resistor	Vishay Dale (DigiKey)	10 (9)	$0.026 each	26.7k_R

(CRCW040226K7 FKED)				
16.9k Ohm resistor (CRCW040216K9F KED)	Vishay-Dale (DigiKey)	10 (9)	$0.026 each	16.9k_R
100k Ohm resistor (CRCW0402100K FKED)	Vishay-Dale (DigiKey)	10 (9)	$0.026 each	100k_R
499k Ohm resistor (CRCW0402499K FKED)	Vishay-Dale (DigiKey)	10 (9)	$0.026 each	499k_R
100nF capacitor (C0805C104M5RA CTU)	Kemet (DigiKey)	10 (9)	$0.056 each	100nF cap
2.0nF capacitor (C0805C202J3GA CTU)	Kemet (Mouser)	2 (1)	$0.48 each	2.0nF
Transmitter Coil (76030810312)	Wurth Elektronic (DigiKey)	1 (0)	$14.91	Transmitter Coil
Receiver Coil (760308103109)	Wurth Elektronic (Digikey)	1 (0)	$14.83	Receiver Coil
MOSFETs (IRLB4132PBF)	Infineon Technologies (Mouser)	10 (6)	$0.80 each	MOSFETs
Gate Driver (LT1162ISW)	Analog Devices (Mouser)	1 (0)	$15.52	Gate Driver
0.33uF Capacitor (KAM31NR81H334 KU)	KYOCERA AVX (Mouser)	10 (8)	$2.75	0.33uF Capacitor
3.3 V Linear Regulator (UA78M33CDCYR)	Texas Instruments (Mouser)	5 (3)	$2.95	3.3V Linear Regulator
12 V Linear Regulator (L7812ABV-DG)	STMicroelectronics (Mouser)	5 (4)	$4.45	12 V Linear Regulator

Proximity Sensor (SEN-15569)	SparkFun (Mouser)	1 (0)	$3.95	Proximity Sensor
1uF Capacitor		8 (4)	Free	ECE
0.1uF Capacitor		4 (2)	Free	ECE
Diodes (1N4148)		4 (2)	Free	ECE
Machine Shop	University of Illinois at Urbana-Champaign	Box for the charging pad and the stand for testing.	$500	10 hours
Labor		3 people (team members)	$36000	360 hours in total

3.1.2. Labor Cost Analysis

With the assumption that each group member will do about 12 hours of work per week on average, the total amount will come out to 12 * 10 weeks * 3 = 360 hours to complete the project. Assuming an average UIUC graduate salary of $40 per hour, the total labor cost can be calculated at $40 * 2.5 * 360 = $36000.

The machine shop has given us the quote of 10 hours to complete the mechanical part of the project. If we assume a cost of $50 per hour for machine shop work, the total machine shop cost can be calculated at $50 * 10 = $500.

3.2. Schedule

The tasks for each group member during the week will be discussed in the weekly check-in meeting based on availability during the week and skill in that area. We will all be working together on different parts of the project but each person will be taking the lead on certain tasks. We have mentioned the person against the task.

Week Num ber	**Dates**	**Main Person Working on the task**	**Tasks**
6	February 19 - February 25	Samuel	- Design for full bridge rectifier and synchronous buck converter -Research feedback loop control for dynamic voltage regulation - Find components for receiving side
		Pranshu	- Design the transmitting side of the circuit
		Jason	- Find values and parts for transmitting side - Cost analysis and ethics
		All	- Finalize proposal resubmission and design document
7	February 26 - March 3	Samuel	- Continuing looking for parts for receiving side - Looking into transformer characterization, especially coupling factors. Needed for full bridge rectifier simulation
		Pranshu	- Finalizing a new design for the gate drivers and the MOSFETs
		Jason	- Continue finding parts after feedback - Look into ESP-32 and Ki-Cad

		All	- Design review with Professor Schuh - Make adjustments to project based on feedback
8	March 4 - March 10	Samuel	-Work on PCB for receiving side -Formulate testing plan for transformer characterization -Continue looking for parts
		Pranshu	- Work on the schematic and PCB design for the transmitting side
		Jason	- Work on PCB for transmitting side - Set up updated test plan for transmitting side - Continue looking into parts
		All	- First round PCBway Orders - Teamwork Evaluation I
9	March 11 - March 17	All	- Spring Break - Catch up on anything from above that has not been completed
10	March 18 - March 24	Samuel	- Finalize design for drone's PCB -Look into TI buck chips, focusing on chips that have current mode capabilities
		Pranshu	- Finalize the second schematic and come up with a testing plan for the coils.
		Jason	- Order first round of parts - Finish second iteration of transmitter PCB - Look into proximity sensor
		All	- Second Round PCBway Orders
11	March 25 - March 31	Samuel	- Perform characterization tests for the transmitting and receiving coils - Submit PCB for receiving side

			- Formulate testing plan for drone's PCB (on breadboard and on PCB) - Resimulate full bridge rectifier with results from characterization test
		Pranshu	- Third PCB pass and start work on the tolerance analysis and new dB frequency.
		Jason	- Order second round of parts - Write code for the ESP-32
		All	- Third Round PCBway Orders - Individual Progress Report - Testing of the coils
12	April 1 - April 7	Samuel	- Test subsystems 3 and 4 on a breadboard with spare parts before soldering and testing PCB. - Perform unit and integration tests for subsystems 3 and 4.
		Pranshu	- Start soldering the boards and test subsystems 1 and 2 on the PCBs. Perform unit and integration tests.
		Jason	- Testing transmitter side components - Finalize ESP-32 Code
		All	- Fourth Round PCBWay Orders
13	April 8 - April 14	Samuel	- Solder components onto the drone's PCB. Help out for other boards. -Test PCB with soldered components if
		Pranshu	- Solder the components onto the transmitting board and set up the entire electronics in the box received from the machine shop.

		Jason	- Solder the components onto the transmitting boards - Test components after soldered on PCB
		All	- Fifth Round PCBWay Orders - Testing
14	April 15 - April 21	All	- Mock demo with Matthew - Continue debugging as necessary -Full functionality test
15	April 22 - April 28	All	- Final Demo - Mock Presentation
16	April 29 - May 2	All	- Final Presentation - Final Papers

4. Ethics and safety

Most ethical concerns to do with this project are more so about the drones and their enhanced capabilities when used with our wireless charger than the actual wireless charger itself. The biggest ethical concern to do with drones is privacy because they have the capability to record people without their knowledge or permission. Another ethical concern is the potential weaponization of drones. Drones are already used in combat, and cutting out the need for them to get plugged in in order to charge could make them more useful in this area. Our project is not intended to be used in either of these ways. It is, however, intended to be used for research purposes. This would create environmental ethical concerns such as noise and congestion issues. We would hope that the drones would be used in moderation to limit these concerns. The last potential ethical issue would be the loss of jobs as this technology would take over the need for people to charge the drone. We do not really foresee this becoming an issue.

There are a few safety issues to consider with both the drone and charger components of the project. The biggest potential issue would be the drone colliding with people or objects. This could be caused by control malfunction or, more related to our project, the battery runs out. There are also risks related to cybersecurity and drones getting hacked. The drone we will use will follow IEEE 1936.1-2021 for drone applications[1].

The charger safety issues include shock risks along with overheating leading to fire. The shock risk is our main concern in this project since we anticipate having exposed coils with live voltage running through them. We will make sure to follow appropriate standards to mitigate all risks involved with our project. This includes, but is not limited to, the “Interface definitions” (IEC PAS 63095-1: 2017) standard and the SAE J2954: 2020 which regulates wireless power charging[2].

The charger will be charging a 3.7 V lithium ion battery which also comes with some safety concerns. These include battery failure due to aging, thermal abuse, and electrical abuse[6]. Our group is aware of the possible risks and will abide by ISO 26262[7]. We have also signed off on the batteries training documentation provided by course staff. We are aware of the dangers of using a lithium battery and have selected a charging IC made for batteries to help mitigate some of the risk. We also are aware of the procedure in the event that something goes wrong while testing the battery.

5. Citations

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