Bat Migration Monitor Design Document

ECE 445

Spring 2024
Senior Design

Team #35

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Spring 2024

1. Introduction

1.1 Problem

The population of bats, whose presence provides pest control, pollination, and seed dispersal has been on decline due to various reasons such as WNS, habit destruction, and wind turbines(>400,00 hoary bats are killed by wind turbines annually). Due to the unawareness of their migratory path, minimum support has been provided in order to protect them. At the moment, there are VHF & Untraceable GNSS tags currently available in the market, however, they both have their own downsides. The VHF tags are very labor intensive and only are beneficial when the bat is stationary. Untraceable GNSS tags are unable to be retrieved which creates a lot of data loss of the paths. Additionally, both tags have a pricey dollar tag attached to both. In order to aid in bat conservation efforts, we need to learn more about the bats' migration habits, which calls for the need of a new low-cost tracking product, such that it can improve the devices that are currently in the market in order to preserve the current population of bats.

1.2 Solution

Our design is aimed to have low-cost VHF & GNSS technology that can store the bat's movement as well as send a signal for tracking data. This information will help us gather data for the bats' winter-summer migration paths, and use it to prevent the further increase in bats' casualties.

For our design from a high level perspective, it is essential to construct a device that incorporates a GNSS tag integrated with VHF tracking capabilities to resolve issues that current devices have in the market. The construction of the device must ensure a weight below 1.5g and have an approximately 21x13x5 mm dimensions, such that the device would have no interference with the flight capabilities of bats.

1.3 Visual Aid

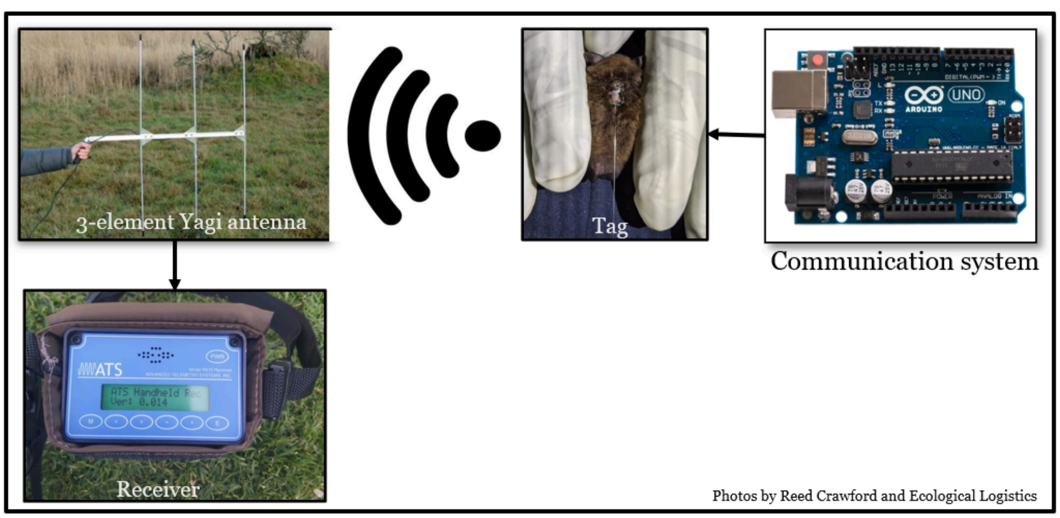

Figure 1- Visual Aid

1.4 High Level Requirements List

- Our design will need a GNSS module that will monitor the daily paths of a bat, which will provide insights of the movement patterns bat take throughout the day. Our device should be able to collect data every 5-10 minute intervals over a span of 6 hours each day, over a period of 3 consecutive days.
- In order to retrieve the device we have constructed, we require a tracking system such that we would be able to pinpoint the exact location of the device and be capable of collecting the data that was provided by the GNSS module. Thus, our device will utilize a VHF transmitter in the 148-152 MHz band, this band matches the receiver already in use by the lab. The transmitter should be able to be detected if it is within a 1 km range.
- We must be able to integrate the GNSS and VHS modules such that it would not interfere with the bats normal functionalities. Therefore, the weight of the device should be approximately less than 1.5 grams and have a maximum dimension of 21x13x5 mm.

2. Design

2.1 Block Diagram

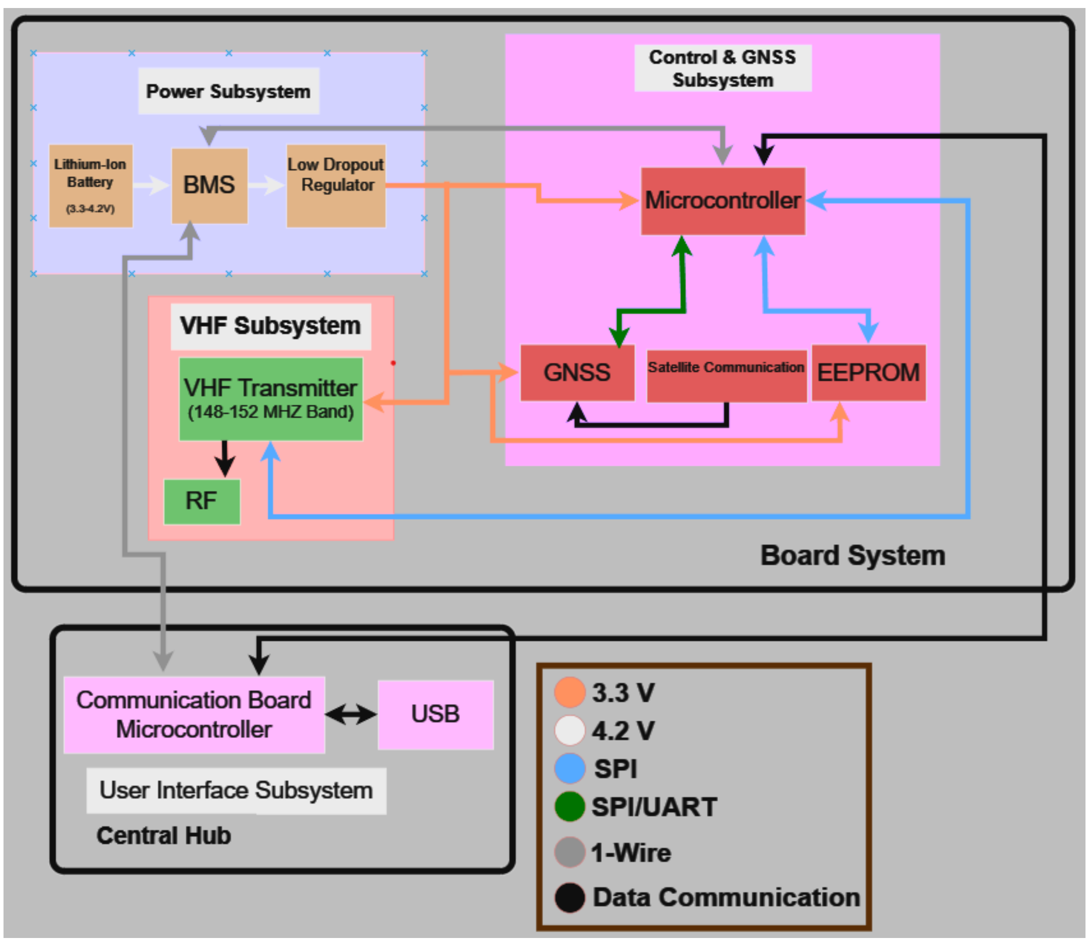

Figure 2 - Block Diagram

2.2 Subsystem Overview

2.2.1 Power Subsystem

The power subsystem needs to consist of a portable voltage supply such that it can supply the different modules that are a part of the constructed device that will be attached to the bat. The LOD regulator has the primary function of regulating the voltage from the battery source to the GNSS and VHF systems. The design will require the reduction of voltage from the battery to the GNSS and VHF systems in order for them to properly function. Overall, The power subsystem will be connected to the VHF, GNSS, and the microcontroller subsystems so that the modules receive the necessary voltage in order to function properly.

The power subsystem will require a rechargeable battery voltage supply of 4.2-3.7V. The Low Dropout Regulator to bring the voltage down to 3.3V +/- 0.1 V as well as providing a max output current of 30mA +/- 1mA for the supply to the GNSS, VHF, EEPROM, and the Microcontroller. The BMS must manage a single cell battery in the 4.2-3.7V range.

Requirements	Verification
• Provide 3.3V +/- 0.1V from a 3.7V source	• Connect the subsystem output to an oscilloscope to ensure that the output voltage stays within 0.1V of 3.3V
• Operating current for standby and max operating current requirements, that is, 110uA and 24mA+/- 1 mA	• Connect the LDO output to a variable load and measure the current and voltage using an oscilloscope to ensure the minimum current and the max current requirement is met while staying within 0.1V of 3.3V
• The battery charging circuit must be able recharge the battery at its specific current and voltage rates	• The battery has a standard charge of 0.2C and a rapid charge of 0.5C. The battery should charge until current declines to <= 0.02C. We can verify this by setting up the circuit separately before the final assembly. The charging circuit and the battery will be connected via banana wires and pins on different PCBs, this is to be able to use a current probe in such a small circuit. Once the circuit is tested, the final product will have the components in one PCB. • For the voltage, we will use a similar procedure where the components are

	placed separately. In this case, we can use the oscilloscope or a multimeter to measure the voltage, which should be able to charge at 4.2V.
● Battery Protection for depletion. Discharge cutoff voltage of 3.0V	● To ensure the battery safety, we can discharge the battery by connecting the LDO output to a load, and let it discharge for around 2 hours(it'd require a load drawing a current of 0.5C). We need to continuously monitor the voltage on the battery using a multimeter or an oscilloscope to ensure the battery protection is doing its job. As an extra feature, we can connect a current probe to the load to measure the current and ensure the battery stopped providing power.

Table l - Power Subsystem Requirement

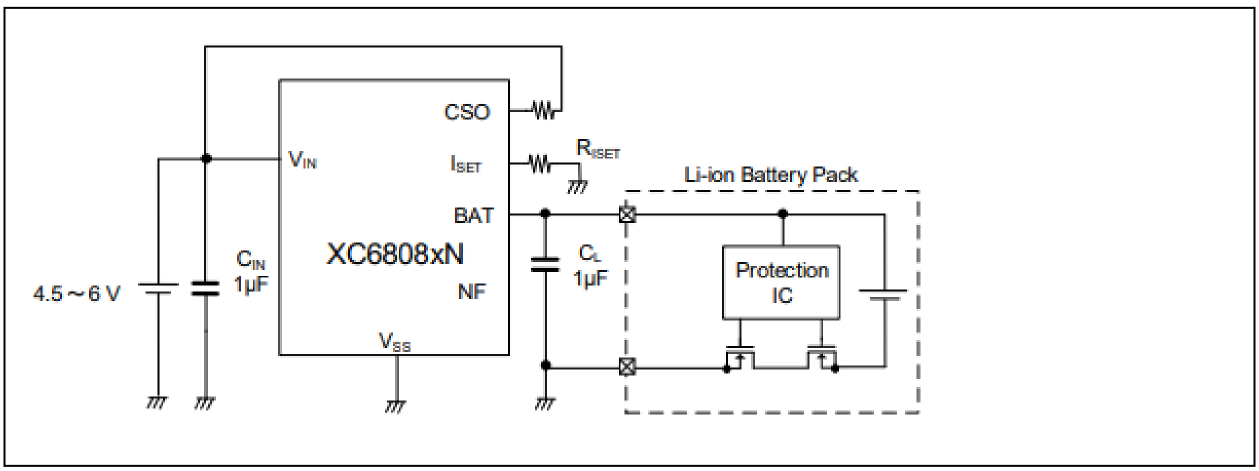

Figure 3 - Charger Circuit

2.2.2 Control & GNSS Subsystem

For our project it is essential to have a device that is able to provide accurate position data of the bat in the measurement of longitude and latitude in order to track the migration path that the bat takes throughout the day. The GNSS section will need to communicate with the microcontroller and EEPROM such that the data can be transferred and stored until the device is retrieved from the bat. In order to store the location data of the bats migration path, the microcontroller and EEPROM is essential for our design. The overall subsystem will be required to be connected to the power subsystem in order to obtain the necessary power to function properly.

The GNSS subsystem must run from a 3.3 +/- 0.1 V supply, have an accuracy range of at least 10m, with an ON current of 10 mA or less and standby current of less than 100uA. The time to fix from standby must be 30 seconds or less. The GPS must have an OFF current of 100nA or less. The microcontroller must be capable of communicating using 1-wire, SPI, and UART. It must run off 3.3V +/- 0.1v and have an ON current of 8 mA or less and a standby current of less than 10uA. The EEPROM chip must work off 3.3V +/- 0.1v and store at least 16KBytes of data.

The GNSS module will be connected to a resonant quarter-wavelength antenna of 4.76cm. As shown by simulations in HFSS, this provides very good radiation resistance and around 70 ohms, the inefficiency caused by the impedance mismatch is negligible.

	Freq [GHz]	re(ActiveZ(1:1)) Setup1 : LastAdaptive	mag(ActiveZ(1:1)) Setup1 : LastAdaptive	im(ActiveZ(1:1)) Setup1 : LastAdaptive
1	1.575420	31.151052	76.581630	-69.959689

Figure 4 - Estimated Frequency

Requirements	**Verification**
• The GNSS, Microcontroller, and external EEPROM chips should be supplied by a 3.3 +/- 0.1 V voltage supply.	• To ensure the correct amount of voltage is being supplied from the power subsystem, we can utilize an oscilloscope to confirm the voltage being supplied to the GNSS chip is approximately 3.3 +/- 0.1 V.
• The resonant quarter-wavelength antenna must accumulate precise location data by ensuring an effective connectivity with satellites. After the location data is collected, the GNSS chip must be able to transfer the data to the microcontroller via I2C.	• In order to validate the connections between the GNSS, antenna, and the microcontroller, an oscilloscope could be used to monitor voltage readings during specific intervals where there should be an expectation of an alternation of the voltage. This ensures that certain connections between the chips and the antenna are connected in a proper manner. • To verify that the I2C lines between the GNSS and microcontroller are

	properly connected, a test script can be programmed to the microcontroller to ensure that the necessary data is being received. Along with verifying the I2C connection, this verification procedure also ensures that the communication with the satellite and our antenna is accurate.
• The GNSS unit should collect data every 5-10 minutes during a 6 hours interval for 3 consecutive days. This provides energy conservation and allows an efficient way to monitor a bats movement trends/patterns.	• To ensure the GNSS chip is on standby mode when data is not needed to be collected, an oscilloscope could be used to measure the voltage readings of the connections with the GNSS chip.
• The external EEPROM must be able to store ~18 kbytes worth of data that is exported from the microcontroller via I2C.	• A test script can be programmed to the microcontroller to transfer the locational data obtained by the GNSS chip to the external EEPROM.

Table 2 - Control and GNSS Requirements

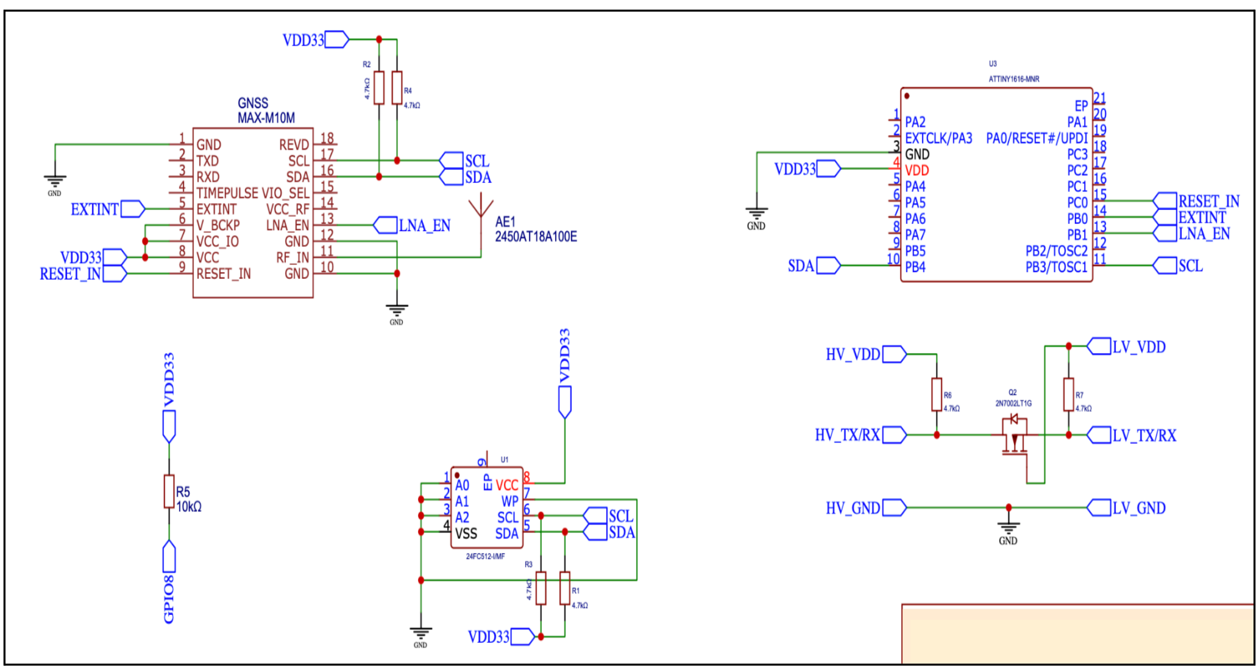

Figure 5 - Control and GNSS Circuit Design

2.2.3 VHF Subsystem

In order to access the data generated and stored by our constructed device, it is necessary to establish a tracking system that can find the device's location. For the tracking system for this project, a VHF transmitter system will be used. The system will be capable of transmitting frequency signals which will be captured by an external VHF receiver. This module may be provided initial programming by the microcontroller through SPI, as well as receiving power from the 3.3v supply.

The VHF transmitter system will be in the 148-152MHz band and needs to have a range of at least 1 km. The receiver used by the lab has a minimal detectable limit of -150dBm and -133dBm with the DSP using a 3-pole Yagi antenna with a gain of 7.7 dBi. Given the Wavelength of 2-meters and the incredibly small form factor requirements and omnidirectional need the antenna will be electrically small giving a predicted gain around 1.76 dBi. This means the transmitter will need to output at atleast 13 dBm to be detected by the receiver and overcome inefficiencies in the antenna. The modulation scheme is a simple pulse of width 12ms and fundamental frequency of 1.0 - 0.1 Hz. Table 1 summarizes our goals for our VHF system.

Requirement	Verification
• The input voltage needs to be maintained at 3.3+-.1 volt	This is handled by the Power subsystem and the verification of such will be covered in that section.
• Peak Input current needs to be lower than 30 mA when operating at 13 dBm.	Connect a current probe to measure the input current to the chip and program the chip to 13dBm.
• The Frequency Range needs to operate between 148-152 mHz	Connect Class E output match circuit to a vector analyzer to ensure correct filtering.
• The Modulation type of OOK with a pulse length of 12 ms and a off time of 5-10 seconds	This can be verified using an oscilloscope E-field probe used around the antenna, or an oscilloscope at the Transmitter driver.
• At least 1km transmission range.	Put the antenna in Anechoic chamber with a known testing antenna, determine antenna realized gain. Use that realized gain to calculate max distance knowing -150 dBm reception limit. Cheaper option is to just walk 1km away from the receiver and see if it can pick up a signal from the tag.

Table 3: VHF Data

VHF Subsystem Design:
Antenna:
The antenna is the one system on the device that may exceed the physical size dimensions given by the requirements, but must be discrete, low weight, and have low directivity given the use case. Given this the antenna type is essentially shoehorned into being an electrically small antenna. Decent antenna efficiency is possible however with impedance matching. The antenna design we are going with is a 4.76 cm antenna modeled 1 mm above the PCB ground plane (13x21x.035mm). Given the physical orientation of the PCB plane to the antenna can loosely be approximated using small dipole calculations, but HFSS was used to simulate and get a better sense of antenna efficiency, radiation pattern, and input reactance. The results of calculations and HFSS simulations show a quite decent radiation efficiency and a large capacitive reactance, as predicted by calculations. This capacitive reactance can be mitigated by a 2.01uH inductor, which is combined with the last filter inductor, making it a 2.06uH inductor, bringing the load impedance to the desired impedance of 50 ohms.

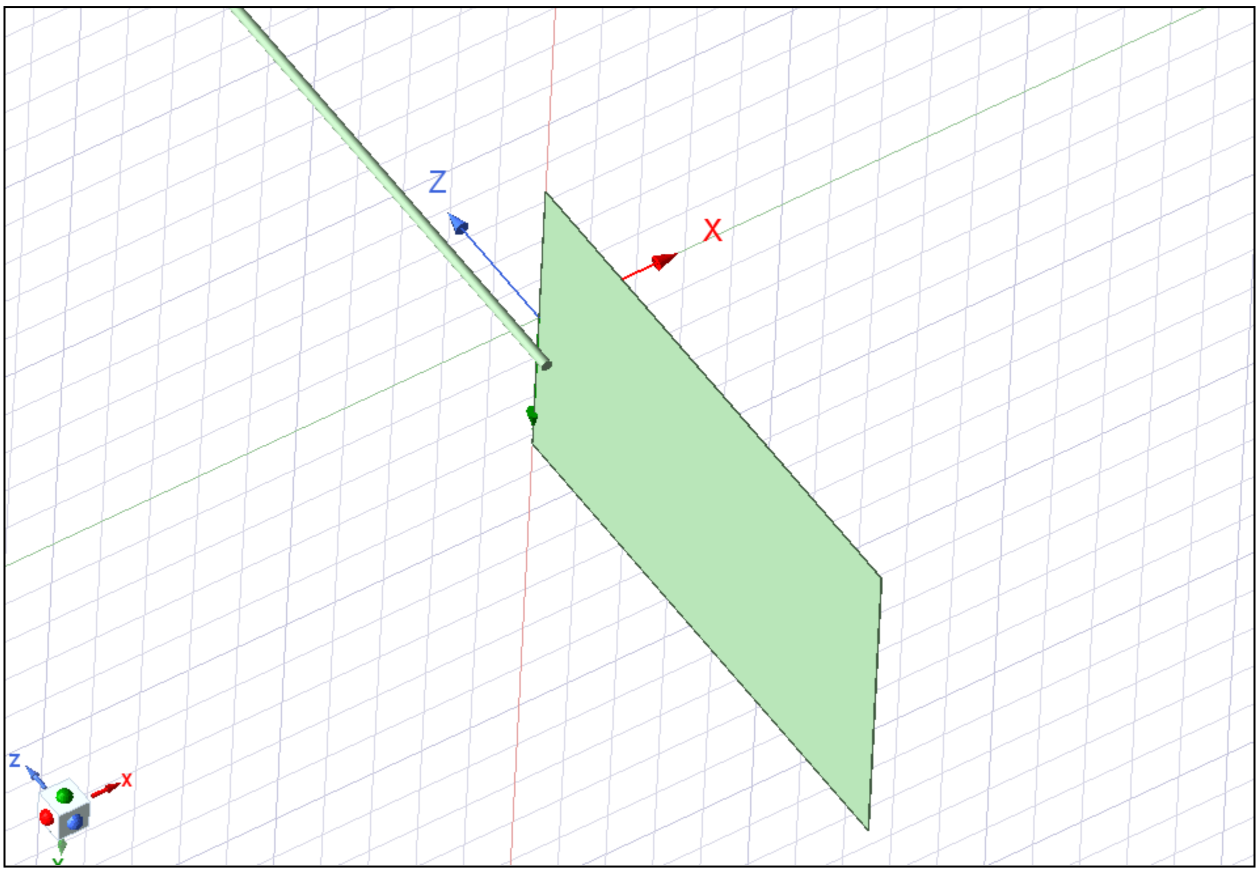

Figure 6 - HFSS antenna model

	Freq [MHz]	re(ActiveZ(2:1)) Setup1 : LastAdaptive	mag(ActiveZ(2:1)) Setup1 : LastAdaptive	im(ActiveZ(2:1)) Setup1 : LastAdaptive
1	150.000000	0.618404	1944.295398	-1944.295300

Figure 7 - VHF antenna impedance characteristics.

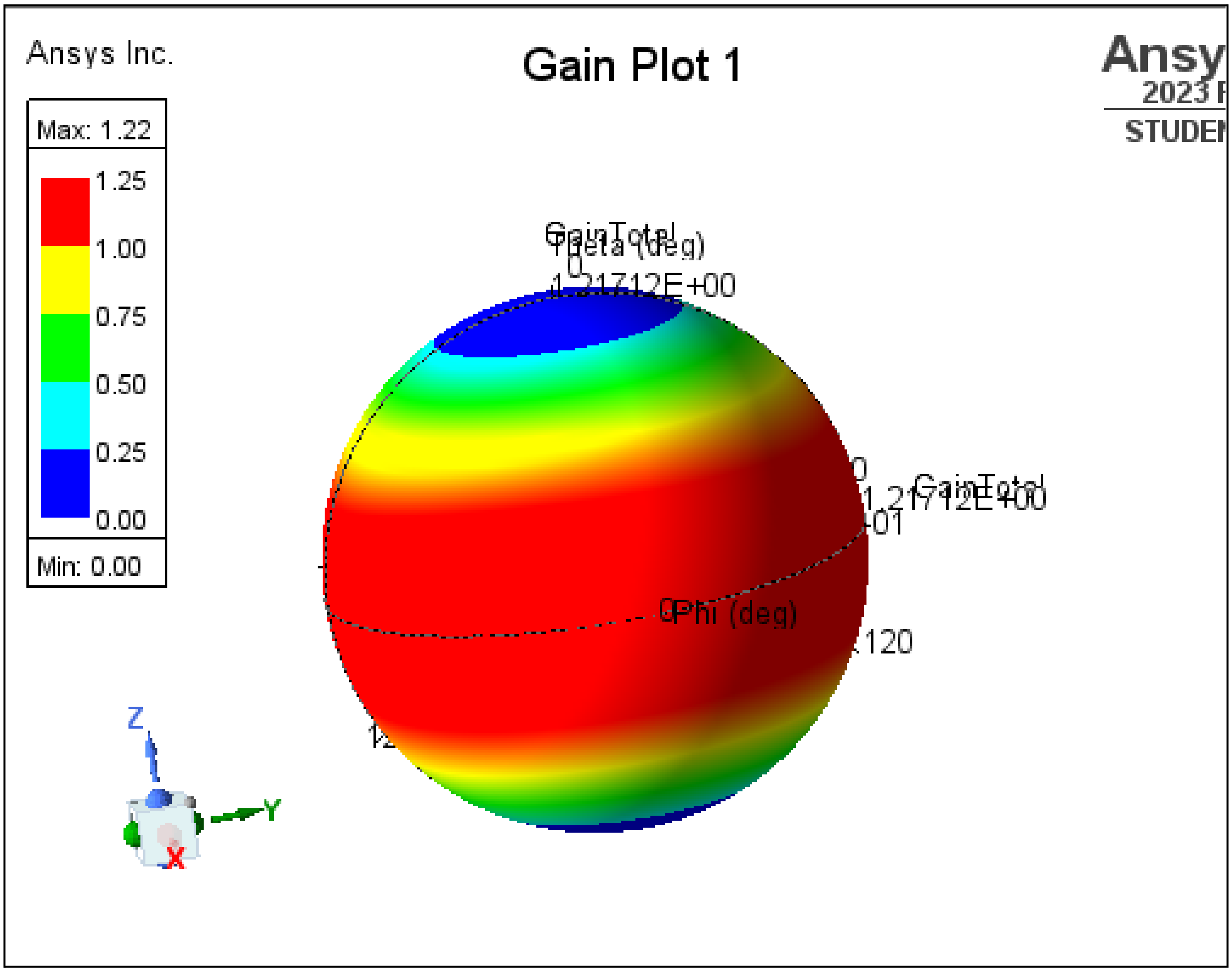

Figure 8 - VHF antenna gain

Transmitter:

Calculations

To achieve the transmitter requirements there were many different options to choose from, but the constraints are as given: Thermal stability given the unknown exposed environment; Low radiation resistance of the antenna due to physical requirements, high efficiency to meet power requirement; reconfigurability over frequency band of 148-152 MHZ. These design variables cause a class E amplifier being the best choice. A class E amplifier is a type of switching amplifier that uses a square wave driven resonant tank circuit filtered by a low pass filter to drive the antenna. This amplifier will be controlled by the on board microcontroller using the Si4063 rf transmitter chip. The power delivered by an ideal class E is given from the PA matching document and is as follows:

$$P_{OUT} = \pi\omega_o C_{SHUNT} V_{DD}^{\ 2}$$

Figure 9 - Formula For Power delivered

This is highly valuable, as the ideal power output has no dependence on load impedance. In practice for the Si4063 this is limited by mainly the electrical limitations of the transistors used in the amplifier. Using the PA matching guide for the Si4063, however given the desire 13dBm out for the transmitter, the circuit can be better matched as max VDD voltage at that power rating is only 4.12 volts, meaning the voltage spike across Voltage drain is far away from the ~6 volt recommended limit is a nonissue. A picture of the sample circuit is provided below, as well as the simulation results from the calculated values using the HFSS modeled antenna values.

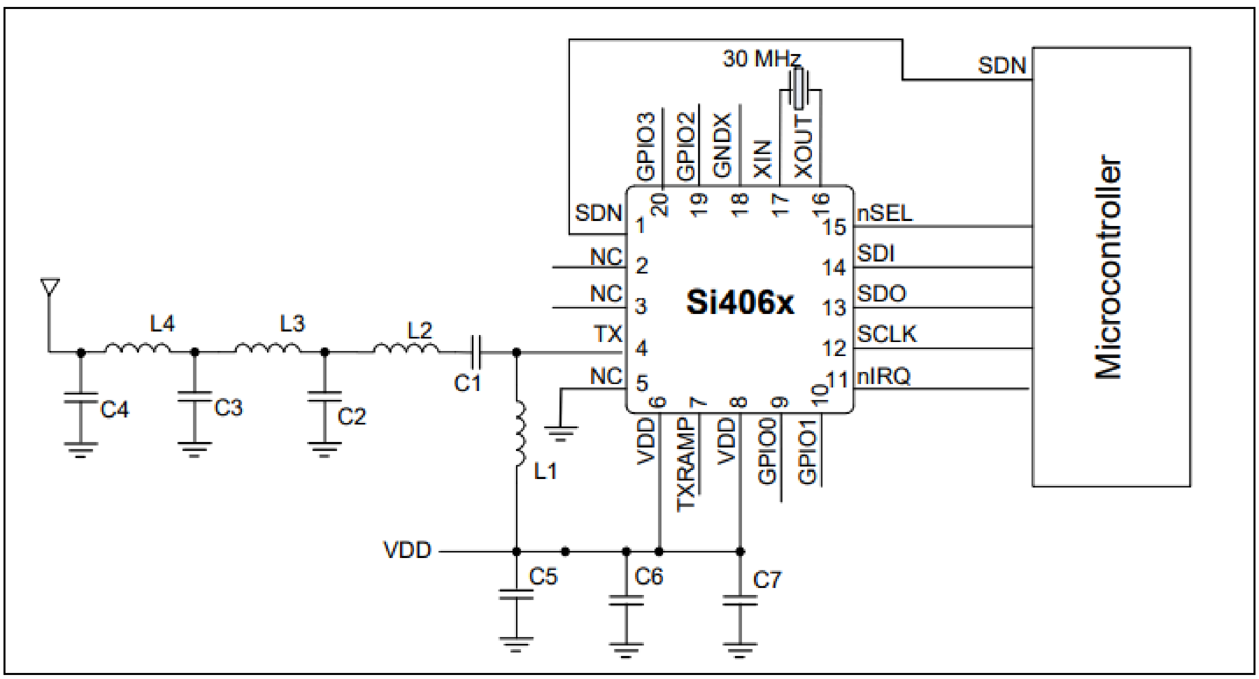

Figure 10 - Si406x Application Example

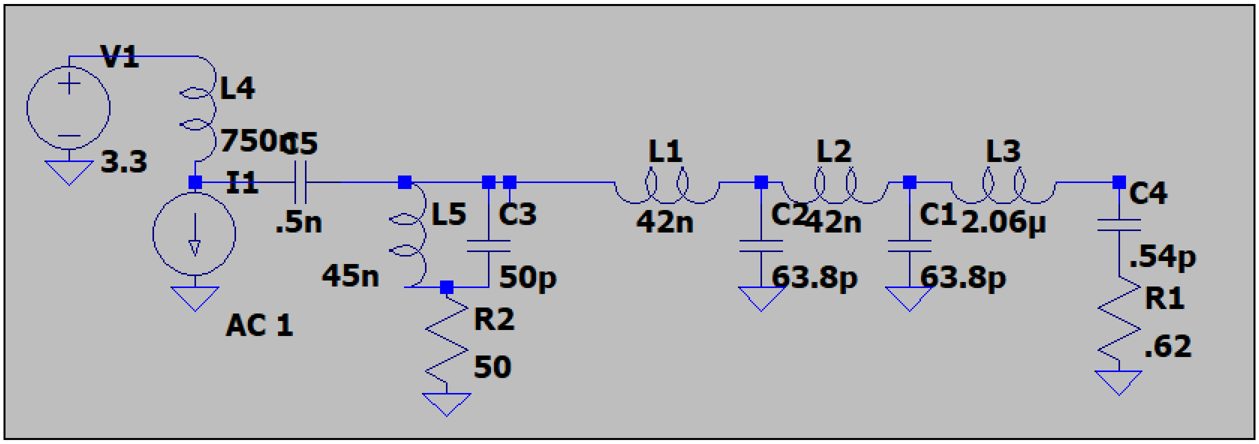

Figure 11 - Class E amplifier Matched load

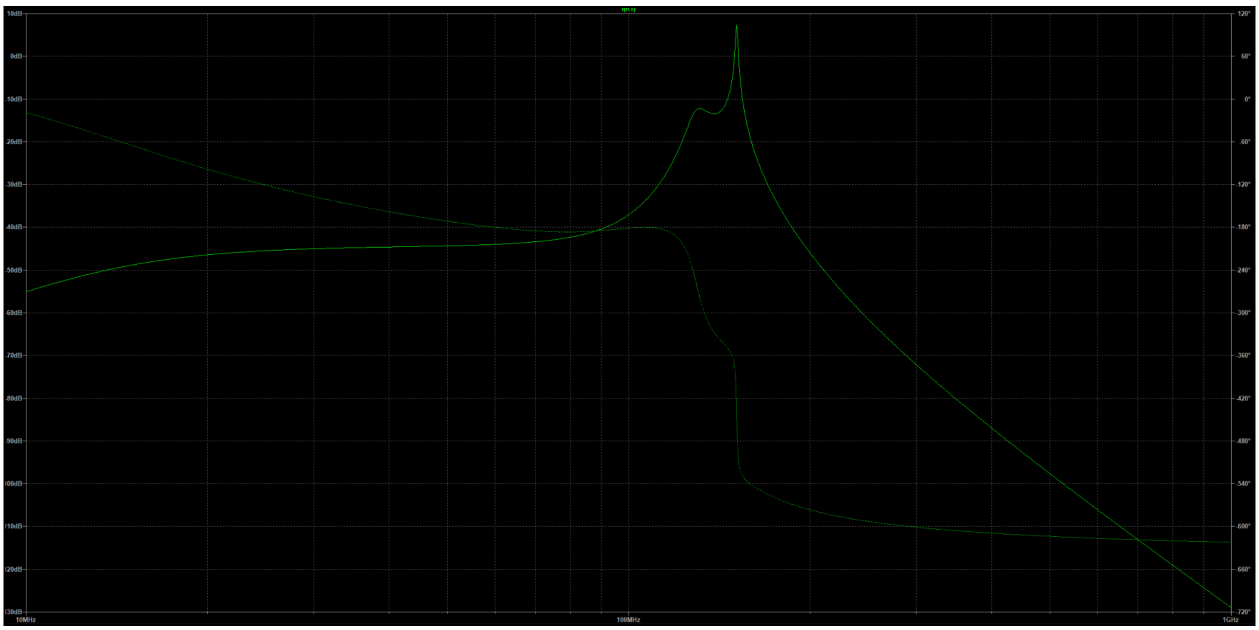

Figure 12 - Class E amplifier matched load bode plot

2.2.4 User Interface Subsystem

This system is contained on a separate board and will not be placed on the bat. After retrieving the device off of the bat with the help of the VHF subsystem, the user interface subsystem will allow the user to obtain the location data off of the device to help determine the migration path that the bat followed throughout the day while charging the battery. The communication will be done using 1-wire protocol. The reason for this choice is simple, once complete the tag will be very small and encased in a water proof resin. Therefore we need minimal external connections that must handle unreliable signal integrity, as those connections will be used after being exposed to nature and water for long periods of time.

Requirements	Verification
• Input Voltage must be between 5+/- 0.25v	• Hook up an oscilloscope to the output of the 5 volt LDO and
• Must be capable of communicating with other microcontroller	• Setup test transactions and monitor using an oscilloscope to verify communication accuracy of one-wire.

Table 4 - Interface Requirements

The microcontroller must run off a 5.0 +/- 0.1 V supply and be capable of communicating over 1-wire to the tag microcontroller and usb to a host computer. We are going to be using a 5 volt capable FTDI cable for programming and communicating to the board, so this is not verified by us.

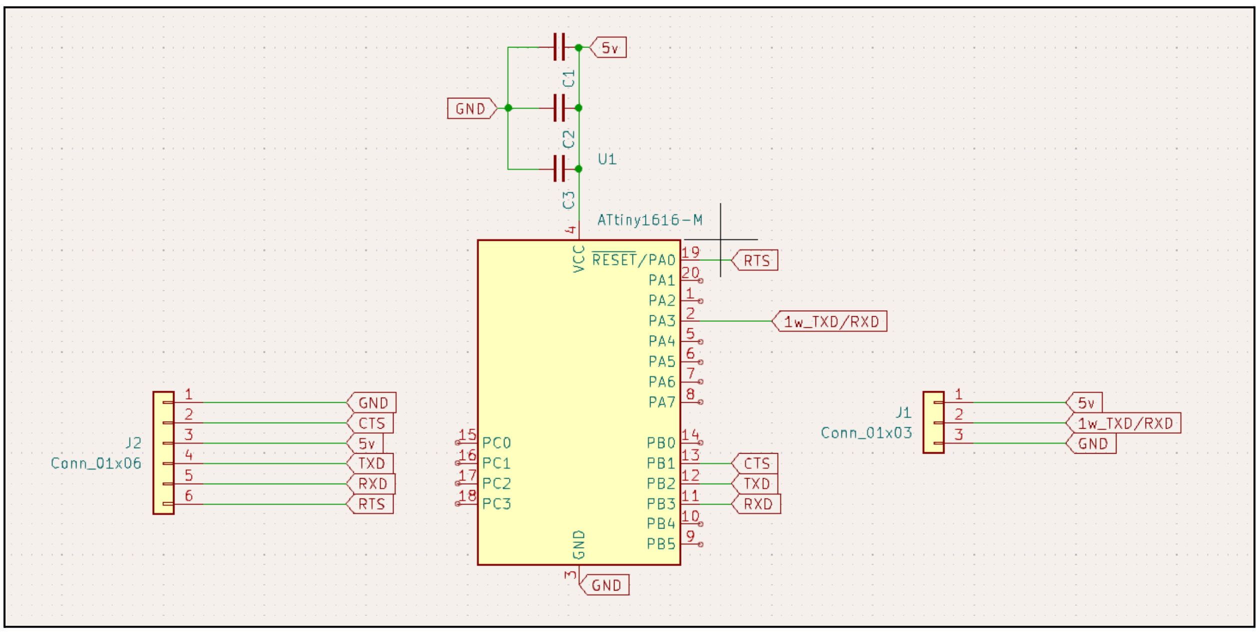

Figure 13 - Microcontroller and control schematics

2.3 Tolerance Analysis

The system has two independent boards, the tag board and User interface board. The tag board has modularity, but is governed by the following equation to meet specifications:

$$Q_{batt} \geq i_{GPS,\, avg\, on} * (18\, hours) + i_{VHF,\, avg\, on} * (168\, hours)$$

There are two great risks to our project not being usable by the lab, those are weight and charge usage. These are not independent issues and need to be at the forethought of any decisions we make on the tag board. Currently we are confident enough to move forward, but it's close. The GNSS module weighs about 0.6 grams, and while still not fully decided we predict the battery will be at most the same weight given a 25 mAh battery is 0.62 grams. This gives the rest of the GNSS and VHF a ~0.3 gram weight limit(worst case scenario). Unfortunately, It is not possible to figure out any information about chip and component weights as they aren't included in the data sheets, so this is something we will have to determine after physically having a working system. However we can mitigate this unknown through Charge analysis, as battery weight can be lowered if our charge consumption is lessened. Currently, given the component we are planning to purchase and using the limit of the electrical spec range we get, our average charge use per system can be calculated as follows:

$$Q_{tot} = \int_{T_{experiment}} i(t)dt$$

$$Q_{batt} \geq i_{GPS,\, avg\, on} * (18\, hours) + i_{GPS,\, avg\, off} * (150\, hours) + i_{VHF,\, avg\, on} * (168\, hours)$$

$$i_{GPS,\, avg\, on} \leq \frac{1}{600\, sec}\left(\int_{0}^{30} (18ma)\, dt + \int_{30}^{600} (110uA)\, dt\right) \leq 0.93876\, mA$$

$$i_{VHF,\, avg\, on} \leq \frac{1}{600\, sec}\left(\int_{0}^{.012} (30ma)\, dt + \int_{.012}^{600} (100nA)\, dt\right) \leq 36uA$$

$$i_{GPS,\, avg\, off} \leq 100nA$$

$$Q_{batt} \geq .93876\, mA * (18\, hours) + 100\, nA * (150\, hours) + 36uA * (168\, hours)$$

$$Q_{batt} \geq 22.9\text{ mAh}$$

These numbers were calculated using the upper threshold of current draw (least efficient system) and the lower threshold for specifications. This analysis means that even if we have the worst implementation of our system, we are predicted to make weight given what we currently know. The VHF receiver used by the lab has a minimal detectable limit of -150dBm and -133dBm with the DSP using a 3-pole Yagi antenna with a gain of 7.7 dBi. Given the Wavelength of 2 meters and the incredibly small form factor requirements and omnidirectional need the antenna will be electrically small giving a predicted gain worse case of 1.76 dBi. Using the antenna power formula we can see that even with a very inefficient antenna we can still be detected, using a 0.1% efficient antenna, which given an electrically small antenna isn't improbable, we get -83 dBm which still well exceeds the receiver reception at 1km.

$$Pr = \frac{Pt*(Gr*.001)*Gt*\lambda^2}{(4\pi r)^2} = -83.5\, dBm$$

3. Cost and Schedule

3.1 Cost Analysis

Quantity	Component	ManufactureR	Total Cost	Link
1	GNSS	u-blox	$21.00	LINK
2	Microcontroller	Microchip	$1.80	LINK
1	EEPROM	Microchip	$2.04	LINK
1	RF Transmitter IC	Silicon Labs	$6.87	LINK
3	10uF Capacitor	Murata Electronics	$0.10	LINK
4	1uF Capacitor	Taiyo Yuden	$0.10	LINK
3	100nF Capacitor	Samsung Electro-Mechanics	$0.10	LINK
2	43nH inductor	Murata Electronics	$0.10	LINK
1	750nH inductor	Murata Electronics	$0.23	LINK
1	22nH inductor	Johanson Technology Inc.	$0.10	LINK
1	23nH inductor	Murata Electronics	$0.15	LINK
1	2uH inductor	Murata Electronics	$1.48	LINK
1	.5nH capacitor	YAGEO	$0.11	LINK
1	50pF capacitor	YAGEO	$0.10	LINK
2	62pF capacitor	KYOCERA AVX	$0.14	LINK
1	6 Pin connector	JST Sales America Inc.	$0.30	LINK
1	3 Pin connector	JST Sales America Inc.	$0.19 $0.10	LINK LINK
1	Charging IC	Torex Semiconductor Ltd	$1.27	LINK
1	3.3v LDO	Microchip	$0.18	LINK

		Technology		
1	Stainless steel wire	Remington Industries	$15.55	LINK
1	Magnetic Wire	Remington Industries	$11.20	LINK
1	Crystal	EPSON	$3.44	LINK

Table 5 - Itemized list of Components and Costs

Labor Cost:

Average UIUC graduate starting salary: $87,276 -> $45 per hour (Really rough estimate)

Total hours worked by group: 30 hours per week * 15 weeks -> $20,000

3.2 Schedule

Week	Task
02/18-02/24	Lily: Finalize VHF circuit Gary: Finalize the search for a battery Romin: Research and finalize on MCU, EEPROM, and GNSS chips. Start designing schematic for the Control & GNSS subsystem. Everyone: Revise design proposal & complete design document
02/25-03/02	Lily: PCB and components order Gary: Finalize the individual schematics Romin: Finalize circuit diagram of the Control & GNSS subsystem. Everyone: Present design review & attend peer review.
03/03-03/09	Lily: VHF Software package programming Gary: Have a Final Schematic with every component connected Romin: Construct circuit design with all subsystems Everyone: Complete teamwork evaluation

	& first round of PCB orders
03/10-03/16	SPRING BREAK
03/17-03/23	Lily: VHF Software package programming and hardware debugging Gary: Solder pieces to PCB Romin: Assist with software programming MCU & GNSS subsystem Everyone: second round of PCB orders
03/24-03/30	Lily: VHF Software package programming and hardware debugging Gary: Finalize hardware debugging Romin: Assist in software & hardware debugging Everyone: third round of PCB orders & complete individual progress report
03/31-04/06	Lily: Finalized VHF to be transferred to the combined PCB Gary: Finalize assembly for all individual components Romin: Testing compact final design Everyone: fourth round of PCB orders
04/07-04/13	Everyone: Integrate
04/14-04/20	Lily: Debugging Gary: Debugging Romin: Debugging Everyone: Mock demo & complete team fulfillment contract
04/21-04/27	Everyone: Final demo/mock presentation
04/28-05/04	Everyone: Final presentation, complete final paper, turn in lab notebooks

Table 6: Team Schedule

4. Ethics & Safety

We recognize the importance, and commit ourselves, to the highest ethical and professional conduct that surrounds our profession. We understand the IEEE Code of Ethics[1] and recognize that the technology we create may impact our profession, our fellow teammates, and the communities we serve. We acknowledge there's another project that will attempt the same problem, and we will not tolerate a violation of privacy towards either group.

One major ethical concern our group faces is relating to the conflict between the desire of this course and the desires of the lab to whom the idea belongs. This conflict is due to the necessity of the weight limit imposed by the lab compared to the electrically focused nature of the course. To be blunt, there may be a point in which our group is faced with a decision to choose making a more useful product for the lab at the expense of our grade in the course due to not meeting a proposed electrical specification to instead hit the weight spec.

A particular issue our team faces in this project is that we are making a tracking monitor for animal research, and unfortunately that type of device could also be used to track and monitor people. Given this is a pitched project and open source, there is very little we can do to combat potentially nefarious actors from reproducing this tag.

References

[1] IEEE, "IEEE Code of Ethics," *ieee.org*, Jun. 2020. https://www.ieee.org/about/corporate/governance/p7-8.html

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