Ultrasonic Transponder

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Abstract: Ultrasonic transponders are a method of wireless communication that uses sound waves rather than electromagnetic waves to send signals through the air. This style of communication is usually used for tracking and locating objects. The Ultrasonic Transponder senior design project goal is to implement one of these devices. This system is composed of an interrogator and transponder in a master-slave configuration respectively. The interrogator contains a transponder and a central computing core which is able to calculate distance of individual transponders as well as sending commands to each device. The transponder is responsible for receiving signals, decoding commands from the interrogator, and transmitting return messages. To capture and produce the ultrasonic waves each device has a transducer, this device can convert pressure waves to electrical waves and vice versa. This paper discusses the implementation, experimentation, and improvements made to each of the electronic circuits, micro controller firmware, and PCB design of the ongoing ultrasonic transponder project.

Keywords:
Ultrasonic,Receiver,Transmitter,
UART,PCB,Transducer,Interrogator,
Transponder,ATmega2560,Microcontrollers

I. Introduction

The Ultrasonic Transponder project has been a multi-year attempt to implement a system in which an interrogator and transponder can communicate wirelessly through ultrasonic waves. The system relies on an interrogator which will send a wave through a transducer device to the interrogator which will return the distance between devices by adjusting the wave. The interrogator performs the calculations from the data received at a central hub while we can have many other transponders it communicates with as shown in Fig. 1. The project will need to meet a few specifications before we can call it complete; an eventual triangulation system that will increase accuracy and extend distance calculations, a minimum communication distance of 40 feet, and an accuracy above 99.8% in communication.

This semester's group has focused on increasing accuracy and stability of transmission by utilizing three sub teams; PCB, Electronics, and Arduino. The PCB team has worked on soldering multiple receiver and transmitter boards which should help with accuracy by having identical systems. The electronics team has improved the design of certain stages in the receiver circuit to have a more stable signal and proper gain control. Finally, the Arduino team has been performing tests to finalize their distance calculation code and making sure we achieve proper accuracy within communication. They have also worked on code to have back and forth communication with a receiver and transmitter circuit side by side.

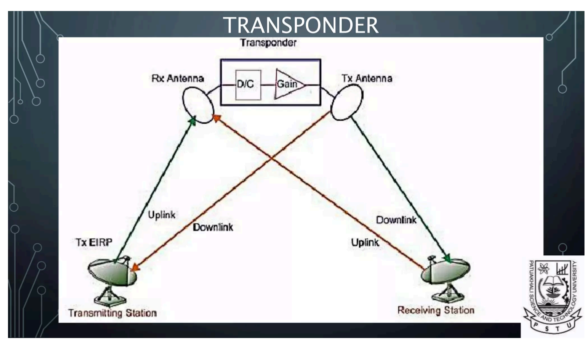

Fig. 1. Interrogator & Transponder System

II. Experimental and Simulation Transmitter

The first step in communication is the transmission of a signal. For this, we use a transmitter that combines a high-frequency carrier signal and a low-frequency modulation signal which shapes the carrier wave to transmit data. The schematic for this circuit is shown in Fig. 2. As shown in the schematic diagram we are using a 40.3kHz square carrier signal with a 500 Hz pulse signal with a width of 1ms. Both of these signals are offset by +2.25V with an amplitude of 5V peak to peak.

In previous semesters we had a constant carrier wave being transmitted, we found this caused interference once we moved to two-way communication. To solve this issue we generated the carrier signal from our ATmega2560 microcontroller, this allowed us to stop the carrier once transmission was complete. Due to the limitations of the microcontroller we have moved both amplitudes of carrier and modulation signal up from 4.5V in Fall 2023, to our current amplitude of 5V.

Building off the progress of previous semesters we deployed our PCB Transmitter as shown in Fig. 3 for experimentation. This circuit has been tested and verified to be functional in previous semesters but with our new amplitude voltage, we circled back to fully test this circuit again.

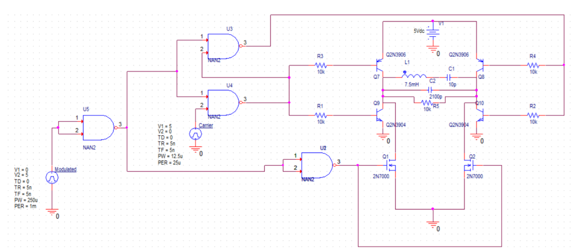

Fig. 2. Transmitter Schematic

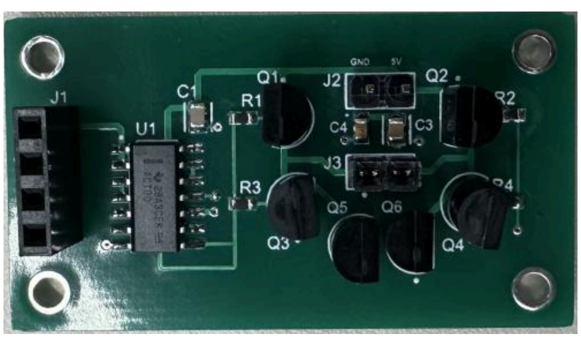

Fig. 3. Transmitter PCB

With the changes made to both carrier and modulated signal our transmission wave has retained its structure and functions correctly. Fig. 4 shows the signal obtained in Fall 2023, comparing that to Fig. 5 obtained in Spring 2024 we see no major differences.

In testing, we found there were no major improvements or detriments to our signal with the changes stated earlier. With this matter sorted the team shifted focus on improving the stability and reliability of the receiver circuit.

III. Experimental and Simulation Receiver

The second half of the transponder is the receiver circuit which captures our transmitted signal and separates the modulated signal from the carrier wave while also amplifying it. After several steps of signal processing the envelope detector functions as an ADC which transforms the analog signal into a digital one.

The receiver circuit contains 7 stages starting with preliminary amplification, then the Automatic Gain Control (AGC), a buffer stage, amplification with low gain, a bandpass filter, a high gain amplifier, and finally our envelope detector. The first six stages intend to transform the signal after energy is lost through transmission over air. Fig. 6 shows the analog signal in pink after all filtering and amplification stages. After the envelope detector, we expect a digital signal (shown in yellow) with an amplitude of 5V and a period of around 1ms shown in both Fig. 6 and Fig. 7. This signal is then sent to the ATmega2560 for digital signal processing and then turned into an ASCII message.

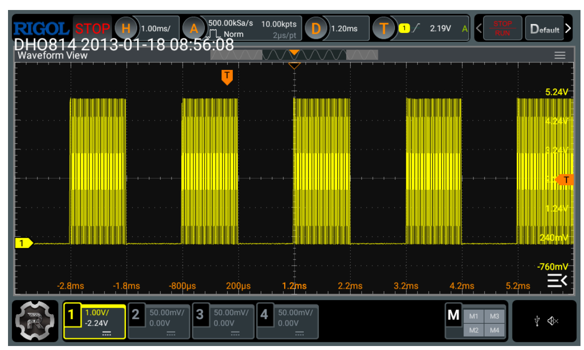

Fig 4. Fall 2023 Transmitter Signal

Fig. 5. Spring 2024 Transmitter Signal

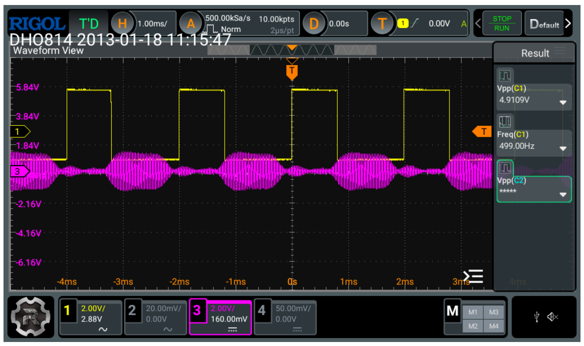

Fig. 6. Receiver Analog and Digital Signal

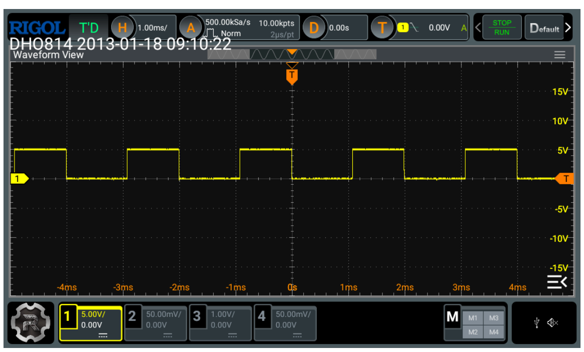

Fig. 7. 5V Peak to Peak Data Transmission

With a confirmed working circuit the PCB team designed and procured a PCB last semester. Building off the work of last semester we soldered the new receiver PCB and began testing. With this, we found that the results did not match what we were expecting from our working breadboard circuit. We found that some values in the schematic were changed on the breadboard to tune it more precisely. Along with this, there were a few design issues with the Automatic Gain Control. The main issue was related to the capacitors in the Sallen-Key band-pass filter. The capacitor values were affecting the band-pass frequency we were attempting to capture. The differing values caused it to be shifted away from the center frequency of 40.3 kHz. After solving this discrepancy in component value we came across another issue dealing with the AGC. By probing each stage in the receiver we were able to find issues after R1(10kΩ) in Fig. 8 where the signal would become distorted in the envelope detector, close to the feedback line of the AGC, which was causing our problems. The initial feedback for our AGC is taken from the output of the diode (D2) in Fig. 8, it is then fed into a reverse-biased diode which leaves only the negative half of the signal. This signal is then used to control a set of transistors which will regulate the current allowed through the differential amplifier. Using this method we can increase or decrease the gain based on the current regulated by our feedback line.

Much of our time was spent adjusting the values of resistors in the AGC, Fig. 9. We found that swapping R39(220Ω) to a 1.5kΩ and R33(1kΩ) to 220Ω helped with clipping when our transmitter was too close to the receiver. Adjusting the value of R41(100kΩ) to 47kΩ and R35(510Ω) to 1kΩ and finally increasing C17(1uF) to 2uF increased the AGC's ability to hold onto a signal with fluctuating amplitude. With these changes, we were able to achieve the gain desired through our analog section and improved the stability of our signal to a greater degree than in previous semesters.

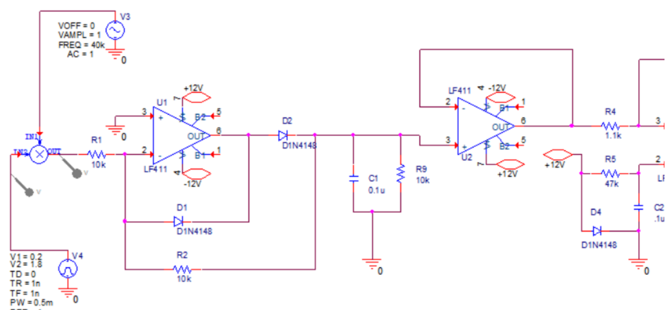

Fig. 8. Envelope Detector

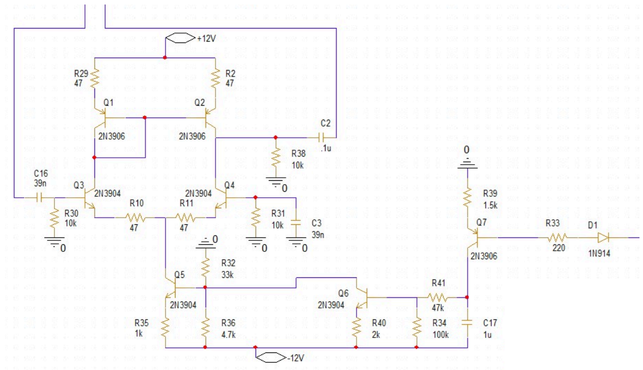

Fig. 9. AGC Schematic

IV. ATMEGA2560 MICROCONTROLLER

The main goal of the embedded software (Arduino) subteam was to implement proper software that would handle digital signal processing and thus meet integration requirements of the whole project. For the purpose of this project, signal processing has been implemented using the Arduino microcontroller platform. Specific modification of the Arduino is the Arduino Mega 2560, powered by ATmega2560 chip. The necessity of such a high end Arduino modification is due to the specification of the system for the possible simultaneous reception and transmission of the digital signal. Thus, at least 2 Serial ports are required for a proper integration of the system. Three available Serial ports of Arduino Mega 2560 provided the necessary Serial debugging port and two serial ports for simultaneously-available (non shared serial buffer) digital RX and TX signals.

This semester's focus was on full codebase refactoring and transition from a test-like code into the final production-level code that would actually be running on the microcontroller and allow constant communication between Interrogator and Transponder without any manual interference.

The general idea behind code refactoring was to compress Interrogator and Transponder code bases into a single code base, the compiled version of which can run on both interrogator and transponder devices. Since a lot of internal code logic for both sides uses the same functions, putting the code together simplified the debugging process and further code development. As code is compiled and uploaded onto a microcontroller, the code logic has to differentiate between which device it is currently running on, either Interrogator or Transponder. For that purpose, one of the GPIO pins of the Arduino is used to differentiate between the devices. If the pin is grounded, the device is considered to be a Transponder by the internal code logic. Otherwise, the device is considered to be an Interrogator. This way, once the compiled code is uploaded onto the microcontroller, one of the input pins can determine how the Arduino should treat the analog circuit to which it is connected without having to recompile and reupload the code every time there is a need to change Arduino's purpose.

Major improvements were made to the code logic that moved the software closer to its final working version where no manual input is required to send commands. With the improved codebase, the Interrogator code is now constantly polling the Transponder, while Transponder is constantly waiting for a message. Importantly, there is no manual interference, all systems start functioning once the microcontroller is powered. Arduino's timers have been used to add timeout logic to restart the system if there is no communication happening for a long time. Moreover, brand new logic was added in order for interrogators to be able to poll multiple transponders at the same time. This way the interrogator, as it constantly polls the transponders, always knows its distance to every transponder, given stable ultrasonic wave transmission.

Another big improvement to the whole system was done by the Arduino team by producing a 40.3 kHz modulation signal (needed by analog transmitter circuit in order to shape the carrier wave in order to transmit data) using the microcontroller. Such a signal was produced by using timer interrupts with a frequency that would generate a modulation signal with desired period. Such an improvement allowed us to stop using external signal generators and move the project closer to the desired system mobility.

A big milestone for our project is that as of recent testing, we were able to get pretty accurate measurements of distance between Interrogator and Transponder for multiple transponders. Fig. 10 below shows a live serial output from the Interrogator during one of our recent testings, indicating the time in milliseconds that it takes to poll the transponder and get the message back from it. During this test we confirmed that we can poll two Transponders simultaneously and get consistent distance calculations. As electronics and PCB teams are moving closer to the mobility of the system solution, the next step for the Arduino team would be to start designing software solutions to the triangulation problem that would allow the Interrogator to locate its coordinates within a 3-D space defined by Transponder locations.

V. PRINTED CIRCUIT BOARD DESIGN

For Spring 2024, the Printed Circuit Board (PCB) team continues to use Altium Designer as its main program as it persits to be one of the industries-leading programs for PCB design. Along with its PCB documentation, its cloud-based workspace, and the ability to modify and restore past revisions, this program helps transition new members into the program and the PCB team.

At the beginning of the semester, our priority was to make sure new ECE 492 members were caught up with the past semester's work. To achieve this, a workshop was conducted with the goal to familiarize students with Altium

Designer and included the design process which included a summary of how the receiver was made starting from a schematic up to the manufacture of the PCB Fig.11. This semester was mostly focused on soldering components and testing them, which was why only the fundamentals of Altium Design were discussed.

Once all new ECE 492 members were caught up, we moved on to our next goal of soldering the components into our PBC. Expanding on the PCB, it includes a receiver circuit and an envelope detector as shown in Fig. 12. In the assembly process, we utilized the ChipQuik SMD291AX soldering paste to facilitate precise and efficient soldering of most components onto the PCB. This high-quality soldering paste ensured that we produced a strong solder joint. All capacitors and resistors were mounted onto the board using this paste along with specific components that did not require solder strips or wires. Our circuit design featured a complexity that demanded careful attention to detail for all its components. In total, this circuit featured a total of 105 components.

```
14:17:31.662 -> S1
14:17:31.662 -> Turnaround time: 122
14:17:31.883 -> S2
14:17:31.883 -> Turnaround time: 91
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Fig. 10. Polling Two Transponders Through One Interrogator

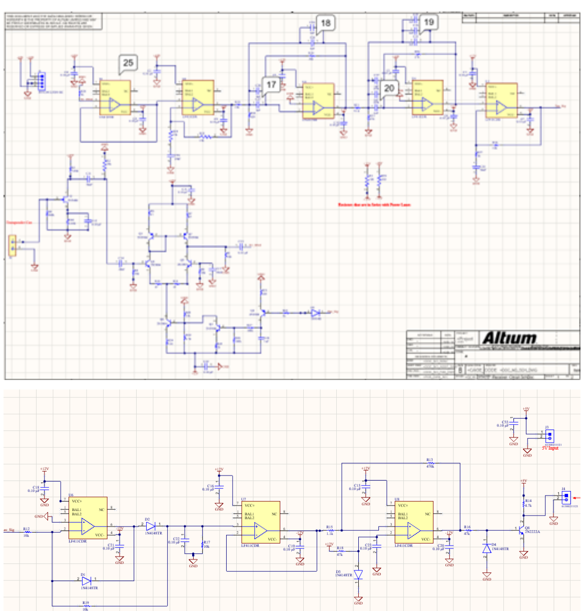

Fig. 11. Receiver (Top) and Envelope Detector (Bottom) PCB Schematics

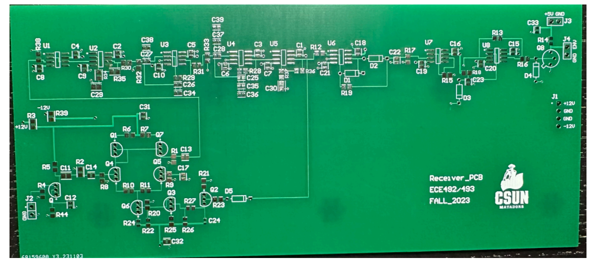

Fig 12. Manufactured Receiver/Envelope PCB

As we started to solder on components, it is important to mention one change that we made as we designed the receiver PCB. This change entailed using only 0805 surface mount components for resistors and capacitors as opposed to 0603 surface mounts which were used on our transmitter. During the assembly process of our PCB, we started by soldering the passive components such as resistors and capacitors, making sure of precise placement and solder joints for optimal connections. Then, we proceeded to mount the integrated circuits, to prioritize alignment and secure soldering. Finally, we integrated the active components including transistors and diodes to guarantee reliable performance and stability. During this process, we employed WYCTIN 60-40 Tin Lead Rosin Core Solder Wire to ensure reliable solder joints, facilitating efficient electrical connections across the PCB components.

Throughout this semester, two PCB boards were made, each presenting distinct challenges. Our first board, being the team's first-time soldering, entailed a significant learning curve which included mastering soldering techniques, placement, and use of equipment. During the first process of soldering over 105 components we encountered gaps in the soldering joints such as in the diodes and transistors. Another recurring challenge was solder bridging, an occurrence where the transistors experienced connectivity issues due to excessive solder application, resulting in the connections of multiple legs. Additionally, we frequently encountered component shifting, particularly during the application of heat using the hot air gun. This often led to displacement of our 0805 and 0603 footprint components from their original position. Following the completion of the initial board, the team was not satisfied with the results and decided to work on a second one during spring break. After much struggles with the first PCB, the team dedicated more time to mastering the process of soldering to better facilitate work. We were fortunate enough to receive assistance from other senior design teams who had previous soldering experience. Our team was grateful for the experience and humbled by the intricate detail required of soldering.

Despite encountering initial challenges, our second board demonstrated notable improvement, with noticeable cleaner assembly and fewer operational issues than our first board. Apart from coming out cleaner, it was significantly easier to troubleshoot this board for testing. During the spring break our team took advantage of the free time and completed the second PCB, which was executed with enhanced efficiency and assembled faster compared to its predecessor. After completing the second PCB, we ran tests and immediately noticed crucial problems with our design. Among these issues were multiple parallel capacitors in U3 and U4, which are integral to a 4th order butterworth filter whose purpose is to limit the frequencies that pass through analog signal processing.

Our desired frequency range is a high of 45.8kHz and a low of 34.5kHz, yet we were receiving 17.2kHz and 15.2kHz, respectively. In contrast to the PCB, the breadboard prototype featured only a single capacitor in this configuration. After finding the correct tuning capacitance with multiple parallel capacitors on the breadboard, the Electronics team had changed this to a single capacitor. This modification failed to be reflected on the PCB. This was due to a miscommunication between both the PCB and Electronics team. The additional capacitors shifted the bandpass of our butterworth filter and because of this the receiver was not able to receive any incoming signal from the transmitter.

$$f_{Low} = \left(\frac{1}{2\pi * 1nF}\right) * \sqrt{\frac{12k+620}{12k*36k*620}} = 34.5kHz \tag{1}$$

$$f_{High} = \left(\frac{1}{2\pi * 1nF}\right) * \sqrt{\frac{9.1k+470}{9.1k*27k*470}} = 45.8kHz \tag{2}$$

$$f_{Low} = \left(\frac{1}{2\pi * 3nF}\right) * \sqrt{\frac{12k+620}{12k*36k*620}} = 15.2kHz \tag{3}$$

$$f_{High} = \left(\frac{1}{2\pi * 3nF}\right) * \sqrt{\frac{12k+620}{12k*36k*620}} = 17.2kHz \tag{4}$$

Our desired frequency range is a high of 45.8kHz and a low of 34.5kHz, yet we were receiving 17.2kHz and 15.2kHz, respectively. In contrast to the PCB, the breadboard prototype featured only a single capacitor in this configuration. After finding the correct tuning capacitance with multiple parallel capacitors on the breadboard, the Electronics team had changed this to a single capacitor. This modification failed to be reflected on the PCB. This was due to a miscommunication between both the PCB and Electronics team. The additional capacitors shifted the bandpass of our butterworth filter and because of this the receiver was not able to receive any incoming signal from the transmitter.

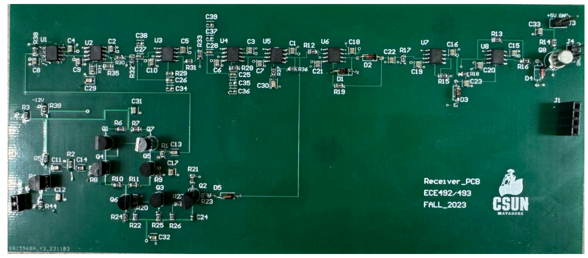

Fig 14.1. Second Receiver PCB With All Components Soldered (Front)

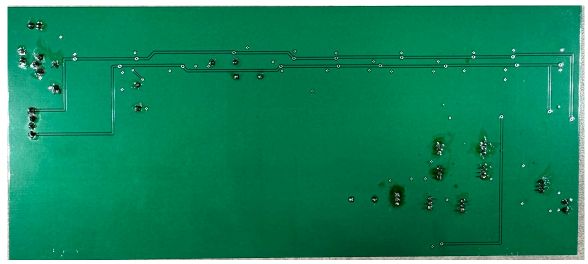

Fig 14.2. Second Receiver PCB With All Components Soldered (Back)

During the troubleshooting procedures we noticed the first two stages would have a voltage of 300 mV and after the output of the third and fourth stage the voltage would drop to 15 mV peak to peak. Meanwhile our current receiver breadboard is receiving at least 2V peak to peak at the third and fourth stage. Upon identifying the issue, all parallel capacitors were removed and replaced with the correct value. Despite this change both envelope detector and AGC had struggled to maintain the consistent signal that we expected. Through troubleshooting conducted by the electronics team, new resistors were soldered onto the PCB. Specifically, resistors R21, R23, R27, and R35 (as silkscreened on the PCB) were modified in order to make the PCB produce a strong signal. Moreover, an additional 1uF capacitance was added into the AGC circuit, for a total capacitance of 2uF. This modification was achieved by stacking a 1uF capacitor on top of the existing one thus making a parallel connection, as depicted in Fig. 15. Finally, after completing all the modifications with the PCB we were able to produce a strong stable signal.

The future plans for next semester's PCB team is to conduct comprehensive tests to assess the possibility of eliminating "U1", one of the buffers from the original circuit design. Depending on the evaluation, and assuming that the elimination of this component does not compromise the functionality of the system, the PCB team will proceed to update the Altium Designer Schematic. This would include adjusting footprints, power lines, and other relevant parameters. Additionally, any modifications will necessitate

Fig. 15: Two 1uF Capacitors Stacked On Top of Each Other

the generation of a new Bill of Materials for component ordering, fabrication of the revised PCB, and soldering work to integrate the updated components. Learning from our previous mistakes, the future PCB team will not have to replace all the new resistors on the AGC and remove the capacitors that are in parallel on the receiver side. Future plans also include discussions regarding the consolidation of the transmitter and receiver into a single PCB. This integration aims to enhance overall performance while also achieving our goal of rending the project mobile.

VI. Experimental & Simulation Power

In order to reach the goal of bringing mobility to the project, it was necessary to begin implementing a simple yet effective power supply design. Therefore a Power Supply subteam was created within the project to begin tackling the task.

Measurements of the power draw of the PCB Transmitter circuit and the breadboard Receiver circuit were taken to determine the parameters the power supply design will need to meet. The measured power draws can be seen in Table I and Table II.

A. Power Supply Design Approach

With known power demands of the respective circuits in the transponder system, the receiver module's power supply design took priority due to its greater complexity, especially with varying input voltage levels.

The receiver circuit requires a 12V dual power rail capable of providing positive and negative potentials, alongside an input voltage range of 6-20V to drive the Arduino Mega

To meet these requirements, we opted for four 9V Duracell battery cells as the primary voltage source. These were wired in series pairs to create two +18V sources. By connecting the +18V series pairs in parallel with respect to ground, an 18V dual power rail with positive and negative potentials was achieved.

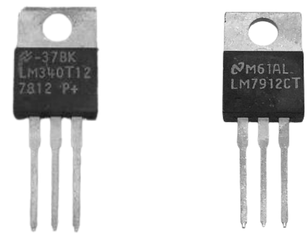

Fig. 16. Positive (Left) and Negative (Right) 12V Linear Voltage Regulator IC's

To step-down the 18V dual power rail down to the required 12V level, we connected the +/-18V outputs to 12V voltage regulator integrated circuits (ICs). Specifically, the LM340T12 7812 P+ positive voltage regulator and its negative counterpart LM7912CT seen in Fig. 1, were selected for their wide input voltage range of 12-27V and ability to produce regulated low-noise outputs.

TABLE I

Transmitter (PCB) Power Draw Measurements

	Idle	**Active**
Current (mA)	86.024	102.987
Voltage (V)	9	9
Power (mW)	774.22	926.88
20% Safety Factor (mW)	154.84	185.38
Total Power Draw (mW)	929.06	1112.26

TABLE II

Receiver (Breadboard) Power Draw Measurements

	Idle	**Active**
Current (mA)	126.50	126.50
Voltage (V)	12	12
Power (mW)	1517.99	1517.99
20% Safety Factor (mW)	303.58	303.58
Total Power Draw (mW)	1821.48	1821.48

The choice of LM340T12 7812 P+ positive voltage regulator and LM7912CT negative voltage regulator was made with careful consideration of the critical need to maintain a stable power rail within the transponder system. Stable power rails are essential for preventing noisy or interrupted communication between components. The wide input voltage range and regulated low-noise outputs of these voltage regulators ensure consistent and reliable operation of the receiver module, contributing to the overall effectiveness of the communication system.

To power the Arduino Mega microcontroller, we utilized the on-board voltage regulator of the Arduino. With an input voltage range of 6-20V, the on-board regulator handles the voltage step-down to the required voltage for the microcontroller.

Given the wide input voltage range of the Arduino Mega, two potential locations within the receiver power supply circuit emerged for supplying the Arduino's input voltage: either from the regulated +12V or the unregulated +18V power rail. To preserve the integrity of the regulated +12V rail, the Arduino's input voltage was connected and supplied by the unregulated +18V power rail.

One drawback of selecting the +18V rail to supply the input voltage is that it pushes the upper limit of the Arduino Mega's input voltage range specification, posing a slight risk of overheating the microcontroller's on-board voltage regulator. However, in our application and bench testing, we observed no noticeable impact on the performance of the Arduino Mega with an +18V input, which mitigates the need for further investigation into this risk. Furthermore, it's worth noting that as the battery voltage level decreases with use, the risk associated with overheating the voltage regulator diminishes.

B. Receiver Power Supply Schematic and Simulation

Shown in Fig. 17 is the PSPICE schematic representing our receiver power supply design. This schematic mirrors the approach outlined in the preceding sections, demonstrating the incorporation of the 18V dual power rail and the utilization of LM340T12 7812 P+ positive voltage regulator and LM7912CT negative voltage regulator for voltage regulation. Through simulation in PSPICE, the functionality and performance of our receiver power supply design was verified, with physical circuit function as expected per the simulation.

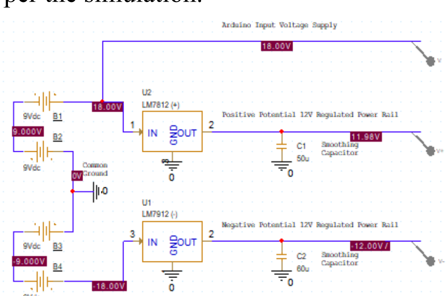

Fig. 17. Receiver Power Supply PSPICE Schematic

C. Future Improvements

One avenue for future improvement involves reducing the number of batteries by identifying two optimal 18V batteries with dimensions that are more conscientious of the required space.This optimization aims to keep the size of the module small while maintaining the necessary power supply capacity.

Coordination with the Arduino team will be essential to implement a power rail voltage monitoring program. This program will introduce a flag when the voltage falls below a specific level. Given that the Arduino is connected to the unregulated +18V power rail straight from the batteries, this monitoring system can provide accurate voltage readings and enable proactive measures to address low voltage situations.

Due to circuit complications, smoothing capacitors were not incorporated into the current design of the Spring 24' team. Future work will focus on finding the ideal smoothing capacitor values to further reduce noise and enhance power rail steadiness. This enhancement will contribute to improved performance and reliability of the power supply system.

VII. Discussion And Conclusion

Many improvements have been made towards the overall success of this project this semester. With the reliability improvements to the circuity, refactoring of codebase, and implementation of 2 PCB receivers many of the preliminary goals we wished to achieve have been met and exceeded. Though much of the development of the circuitry and PCB has been through troubleshooting issues, the improvements made have significantly improved the overall design.

With substantial improvements to signal retention the receiver is now in a state in which two-way communication can be easily established and repeated. With two PCB receivers, two transmitters, a restructured codebase, and a preliminary power supply design the Ultrasonic Transponder project is in a great position for subsequent semesters. With goals such as active battery monitoring, triangulation software, and full mobility, there is much work to be done and great improvements to be made in the future of the Ultrasonic Transponder project.

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