Hands-Free support for the Visually-Impaired

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1 Introduction

1. 1 Objective

We propose to make daily life easier for the visually impaired by creating a device that enables them to sense their environment via ultrasonic sensors. In order to make the project appropriate for ECE 445, we think that it should be hands-free, allow 360 degree obstacle detection, and be as non-invasive as possible. In the event that our subsystem PCB design is not sufficient for ECE 445, we will use an off-the-shelf development board for testing, but design our own peripherals and solder the microcontroller chip onto it after we are certain that the microcontroller meets our requirements.

This device will be secured onto a vest, allowing friendly use. The user will then be able to know which direction the nearest object is through an audio subsystem feedback. This requires using a pair of open-ear headphones and circuitry that will be able to create a tone that gives meaningful information to the user regarding how far he or she is from objects and people, as well as the elevation.

1.2 Background

According to the World Health Organization there are roughly 253 million people in the world who are visually impaired, of which 36 million are blind [1]. The most commonly used aid is the walking cane, but it has its limitations. The cane keeps one arm engaged and has a limited range. It can also be tiring to carry and may not provide extensive information about the objects in the user's path. The cane only signals the user that an object, usually near the ground, is present. But it does not provide information about objects above ground or people behind the user. Previously people have come up with solutions to this problem in this class.

Our proposed solution is to use ultrasonic sensors mounted on a vest to allow a blind person to detect objects nearby and ground elevation. Since we are placing the sensors on the front side and back side of the vest, the sensing range will not be quite 360 degrees. The device will, however, alert the user of the presence of objects in front and behind the user. The feedback mechanism we are pursuing is open-ear headphones. We will create the circuitry necessary to create the audio tones with an intuitive protocol indicating to the user how far objects are. Currently we are thinking that if we encode information about distance onto the amplitude of the audio signal (louder tone as people get closer/user moves closer to objects and vice versa). We must make the audio directional in order for the audio controller to perform its job correctly. We must design an audio controller that receives sensor echo data from the microcontroller (through a DAC) and amplify it, filter it, and implement a stereo sound such that what the user hears the sound it gives him or her a sense of direction of the obstacle.

Our project combines some of the most notable features of the previously designed solutions. Specifically the idea of using an audio circuit in project “Blind Eye” and the idea of using ultrasonic sensors and a vest from “Ultrasonic Spatial Awareness Device for the Visually Impaired”. This gives us the chance of reducing the weight and size of the vest by using audio circuits and microcontrollers instead of haptic feedback.

1.3 High-level requirements

If successful, the device should enable the user to maneuver around objects in any direction without the need and use of sight. At the moment we are planning to detect objects within a 1-2 meter radius of the user. Our high level requirements for this project are as follows:

1. The device should detect objects around the user, effectively covering front and back views (*120 degrees* horizontal on each side).
2. The device must be able to detect objects within a *1-2 meters* range in order to give the user ample time to react to the auditory feedback information
3. For the specified detection range, the overall error in distance measurements should be less than *5 inches* to make sure that the system remains as accurate as possible.

2 Design

2.1 Block Diagram

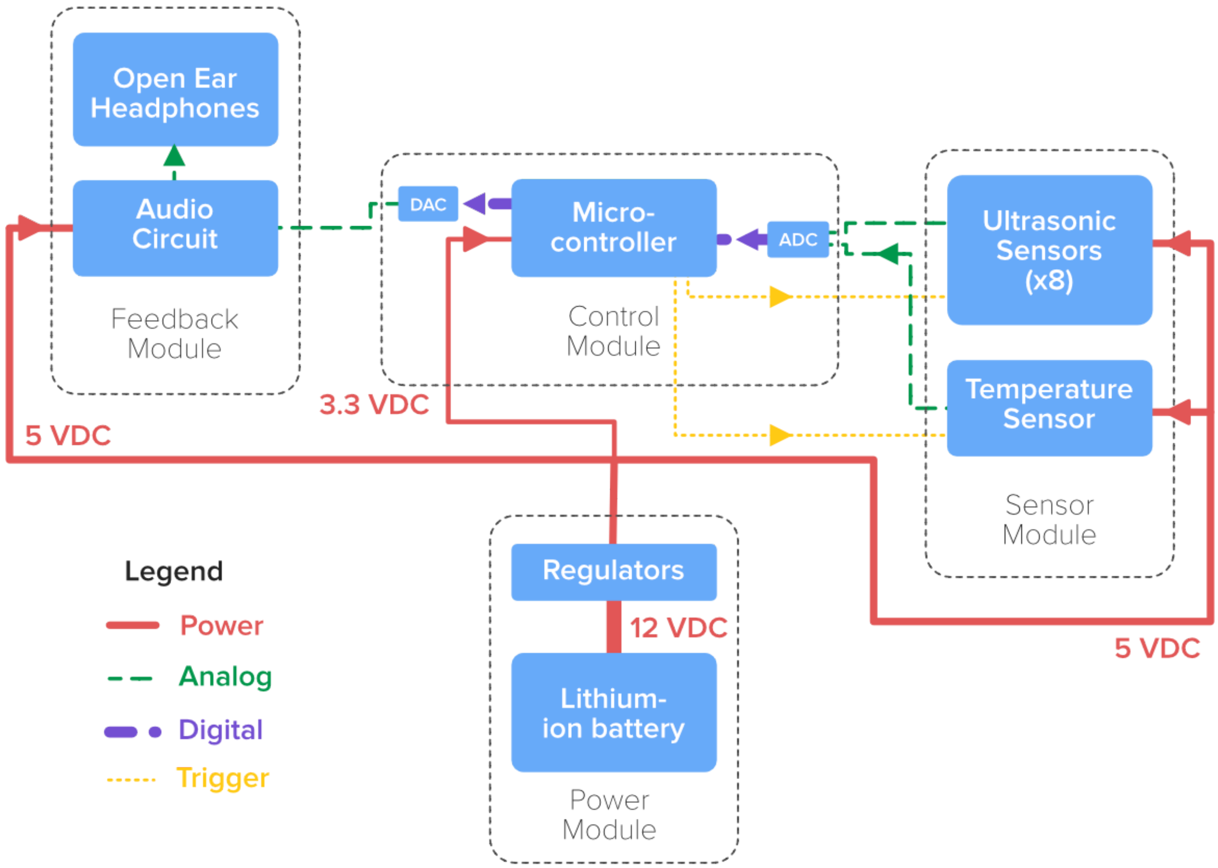

Figure 1: Block Diagram of the Project

To satisfy requirement #3, the sensors must be calibrated upon turning the device on. Using an Atmega328P-PU microcontroller chip (initially onboard an Arduino Uno for development) we will program a boot-up sequence where a few seconds are used up for calibration purposes. This step is also essential because our algorithm for generating directional tones for feedback relies on time differences between echo arrivals across the vest and the person wearing the vest could have a smaller or larger torso than us. To satisfy requirement #1, there will be four ultrasonic sensors on the front side of the vest and four of them on the backside. Each sensor should measure accurately at least 25 degrees - 30 degrees azimuthally. As a stretch goal, we will include a ninth sensor to detect elevation changes. To satisfy requirement #2, we will design an ultrasonic transmitter as well as an ultrasonic receiver. The transmitter will produce 4-8 cycle bursts of ultrasonic rectangular pulses. The receiver will take in the transducer voltage and amplify it with roughly 30 dB of gain. These design choices will help us achieve our goal of allowing the user to sense objects ultrasonically in a 1-2 meter range.

2.2 Physical Design

The device would be laid out on a vest as shown in the figure above. The user will wear this like any other vest thus making the process intuitive. The ultrasonic sensors will be mounted on a harness structure. There will be four sensors facing each direction - front and back to provide roughly a 360° view. There will be a sensor pointing downwards to monitor change in terrain. The power subsystem and the audio subsystem would be installed on the back of the vest. The feedback will be provided through a pair of open-ear headphones.

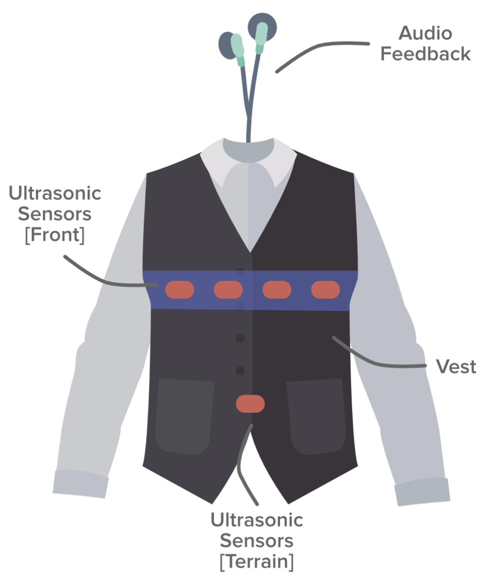

Figure 2: Front view of the vest

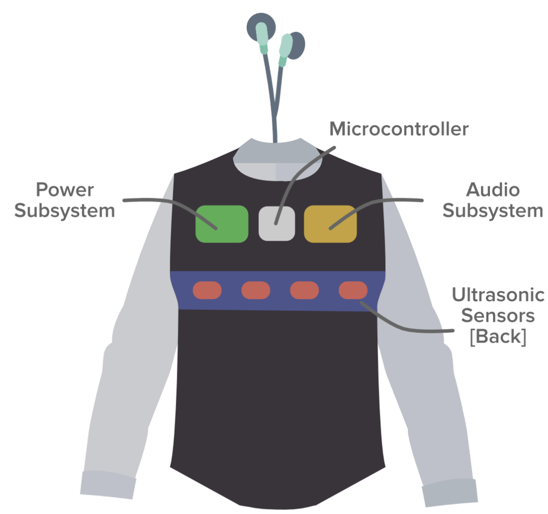

Figure 3: Back view of the vest

As clearly visible in the top view figure shown below in figure 4, each sensor mounted on the vest would have an azimuthal sensing angle of 30°, sweeping a range of 240° - front and back included. The range of object detection would lie within a 1 to 2 meter radius of the user. Since we want our device to be non-invasive we would want to test extensively on various distances to strike the current balance between providing feedback which is just enough to navigate safely and discrete enough so that the user doesn't get disturbed continuously by the audio through the headphones.

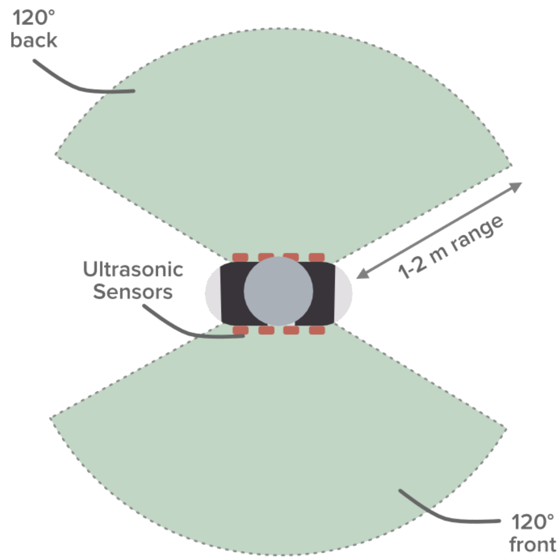

Figure 4: Top view of the device

2.3 Block Design

2.3.1 Sensor Module

Functional Overview

Ultrasonic Sensors

The ultrasonic sensors are key to our project. We will use a total of eight to achieve our main goal of sensing objects azimuthally in the 1-2 meters range. As a stretch goal, we will add a ninth sensors to detect ground level changes. The sensors are a necessary component for all of our high level requirements.

Ultrasonic Transmitter

In order to generate rectangular ultrasonic pulses, we plan to use the famous 555 timer chip as our oscillator [2]. We will trigger this chip using the microcontroller in order to generate waves that would be transmitted through the ultrasonic transducer. The minimum spacing between the trigger pulses from the microcontroller to the receiver should be 11.76 ms, as will be justified in the "supporting material" section for this module. A 2N2222 common emitter amplifier will be used to drive the transducer.

Ultrasonic Receiver

The ultrasonic receiver circuit uses an ultrasonic transducer to capture the echo sent by the transmitter circuit. Currently in the circuit simulations we are including an additional stage for amplification. Realistically however, we may need to get rid of the amplification stage since our application requires us to distinguish between different amplitude levels of the received echos. It is a possibility that including the amplifier will saturate the output (since the detection range is limited to only 1-2 meters and the signal amplitudes may not get attenuated enough to require amplification).

In the event that the output of the receiver is saturated and we can not clearly distinguish between the echo peaks to perform our calculations in the microcontroller, we will get rid of the amplification stage. Not only will this be necessary in that case, but it will also simplify the circuit design, reduce component cost, and reduce power usage.

Temperature Sensor

Since we want our device to perform as accurately as possible, we need to account for the fact that the speed of sound depends on the temperature of the medium of propagation which in our case is air. The temperature sensor would need to accurately perform within the range of habitable environments.

Requirements and Verifications Table

Requirements	Verification
Ultrasonic sensors 1. Must have an effectual angle of at least 12.5°. 2. Must be able to detect objects in the 1-2 meters range with an accuracy of $\pm 5\ inches$	1. Sensing angle a. Power up and trigger the sensors for at least $10\ \mu s$ for transmission and reception b. Connect another ultrasonic sensor to a signal generator and generate a 40 kHz pulse c. Rotate the device under test and find out at what angle the

	received power is halved. This would be the half-power bandwidth d. Multiply the measured angle by two to obtain the full azimuthal range 2. Range a. Measure out a distance of 2 meters to a wall, use the ultrasonic sensors to transmit and receive a pulse to the wall 3. Measure the time difference between the sent and received signals and multiply by the speed of sound to obtain the object distance 4. Calculate the error between the two different measurements (ruler Vs. sensors)
Transmitter Circuit 1. Transmit 4-8 consecutive pulses at 40 kHz 2. The spacing between each pulse sequence should be at least $11.76\ ms$ to account for the maximum delay between each sensor transmission and reception cycle	1. Pulse transmission a. Trigger the 555 chip on the transmitter using a signal generator oscillating between ⅓ to ⅔ of the supply voltage, at 40 kHz b. Measure the output voltage using an oscilloscope to ensure proper functionality c. Connect the microcontroller trigger signal to the transmitter and measure the output using an oscilloscope d. Check if 4-8 pulses are generated at the transmitter output 2. Pulse spacing a. Connect the microcontroller trigger signal to the transmitter's 555 timer chip b. Send the trigger signals to the transmitter and use an oscilloscope to measure the time difference between the end of the first pulse and the beginning of the next pulse
Receiver Circuit	1. Amplification

1. Must be able to receive a rectangular pulse sequence in the 100 mV - 1V range at its input and amplify it to 6-12V at its output	a. Use a signal generator to generate a 100 mV rectangular waveform at the receiver's input b. Verify that the receiver can amplify 100 mV signals up to at least 6V
Temperature sensor 1. Must sense temperature with an accuracy of 5°C 2. Must be able to function within the range of -10°C and 35°C	1. Compare readings of the temperature sensor against a known source. a. Find spaces where the temperature is known - for eg. inside of a refrigerator or an ice bath. b. Take multiple readings using both the sensor and an accurate mercury thermometer. c. Verify the sensor reading within 5°C of thermometer reading.

Supporting Material

Ultrasonic sensors

We will be using the HC-SR04 ultrasonic range finders. We plan to desolder the sensors and the sensors, design our own PCB for each sensor set, and finally solder them onto the PCB for the testing stage.

Transmitter

Since the maximum range required to meet our high level requirements is 2 meters, the transmitter should allow enough time for each pulse to be transmitted and echoed back at a maximum distance of 2 meters. This means that the spacing between each pulse should be at least:

$$\frac{2*2m}{340m/s} = 11.76\ ms$$

The frequency of the 555 timer is primarily set by resistors R_1, R_2 and capacitor C_2. The equations below show our chosen component values to set the oscillation frequency to roughly 40 kHz, and as a result set the duty cycle to 54.78 %. The circuit design was found at [3]. One can see that there is a trade-off between choosing the frequency accurately and maintaining a 50% duty cycle since R_1 and R_2 control both the frequency of oscillation and the duty cycle. Although C_2 also plays a role in setting the oscillation frequency, it may not be wise to use it as a tuning parameter since it would be hard to measure and change its value once it is soldered onto a PCB. Even if a variable capacitor is used, it would not be practical to manually change its capacitance once it is integrated into the system and sown/mounted onto the vest.

$$f = \frac{1.38}{(R_1+2R_2)C_2} = \frac{1.38}{(1k\Omega+9.45k\Omega)(3.3\ nF)} = 40.01\ kHz$$

$$Duty\ cycle\ = \frac{R_1+R_2}{R_1+2R_2} = \frac{5.725\ k\Omega}{10.45\ k\Omega} = 54.78\ \%$$

Figure 5 shows the schematic representation of our transmitter. As mentioned before, $R_1,\ R_2,\ and\ C_2$ are responsible for determining the oscillation frequency and the duty cycle of the output waveform. Figure 6 shows a transient simulation we performed on the transmitter. Although the trigger voltage closely resembles a sawtooth waveform, it is not necessary for it to be such. The key take-away from the trigger signal is that it must oscillate between ⅓ and ⅔ of the supply voltage in order for the transmitter to work correctly and transmit the desired rectangular pulses.

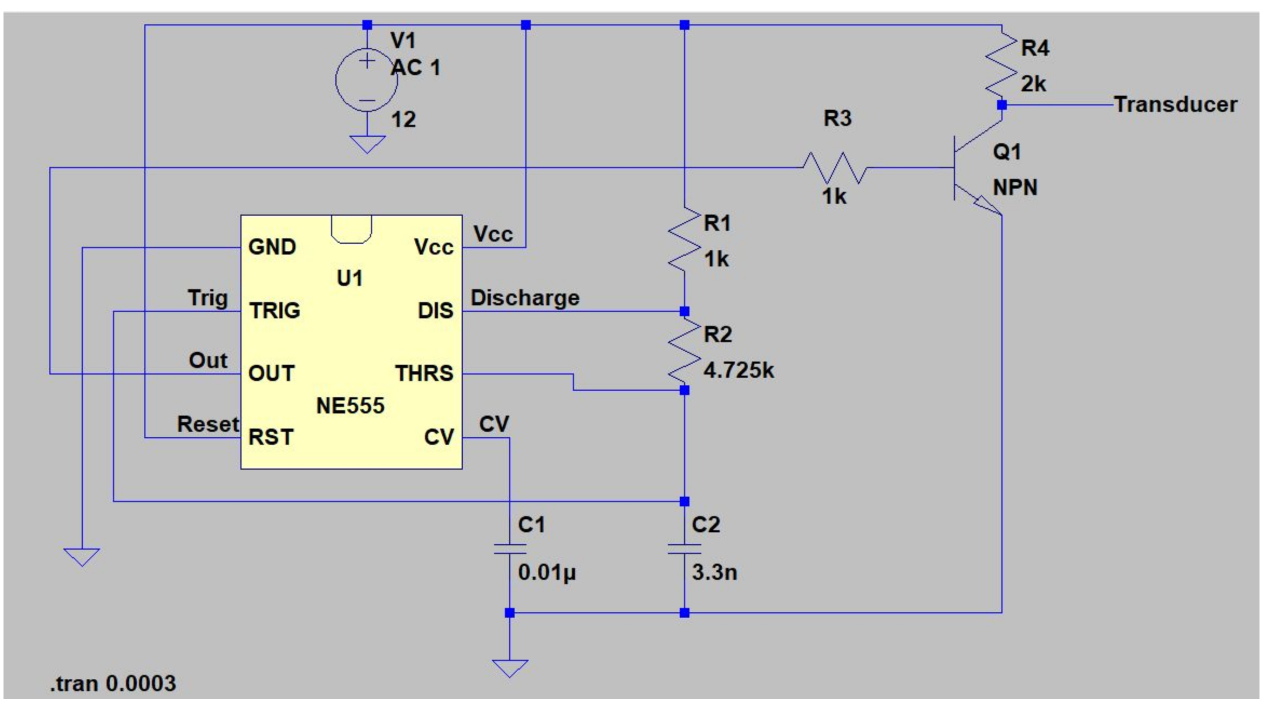

Figure 5: LTspice schematic of the 555 timer used to transmit ultrasonic pulses

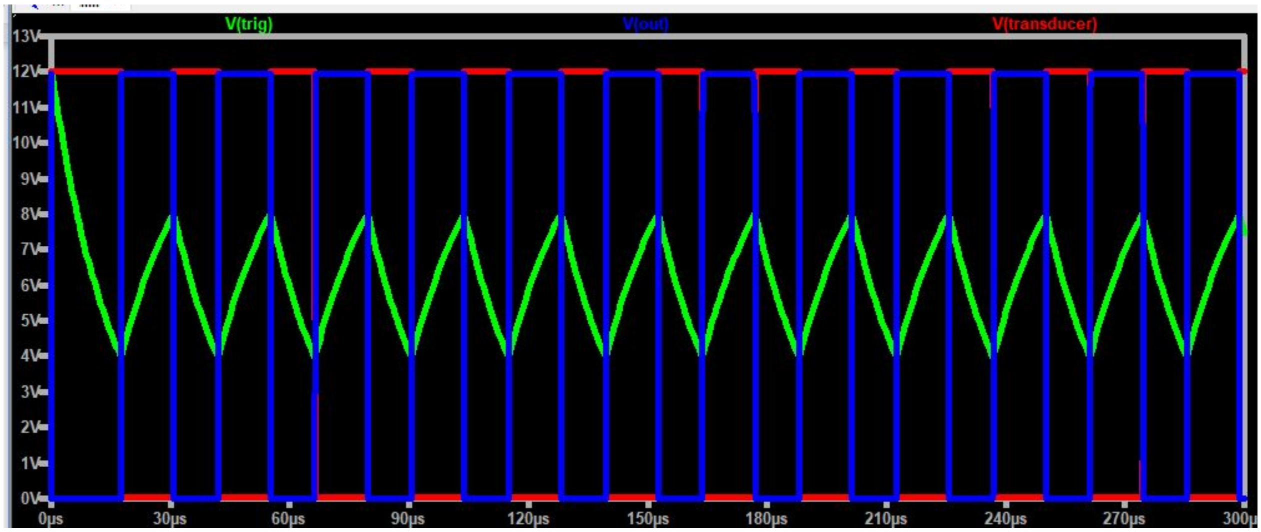

Figure 6: Transient simulation of the 555 timer used to transmit ultrasonic pulses

Receiver

The ultrasonic receiver circuit will detect the ultrasonic echoes produced by the transmitter as a voltage at the transducer terminals. It is then passed to the second stage where it is amplified further and sent to the ADC such that the data can be sampled and used by the microcontroller for processing. The design idea for this circuit along with its component values were taken from [4]. Figure 7 is a schematic of the receiver while figure 8 shows a simulation of the receiver circuit when a small signal of 100 mV is detected at the transducer terminals. The slight unevenness in the period of the output is due to the custom rise and fall times chosen for the transient simulation ($10\ \mu s$).

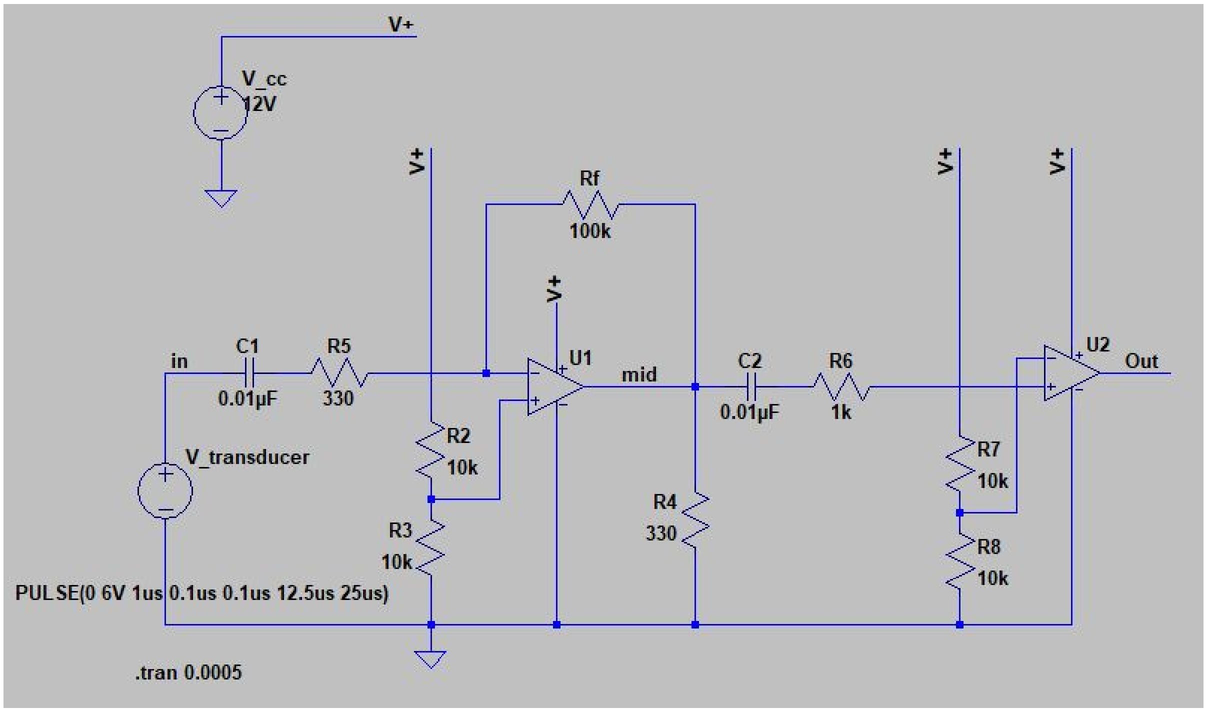

Figure 7: Our multi-stage ultrasonic receiver circuit

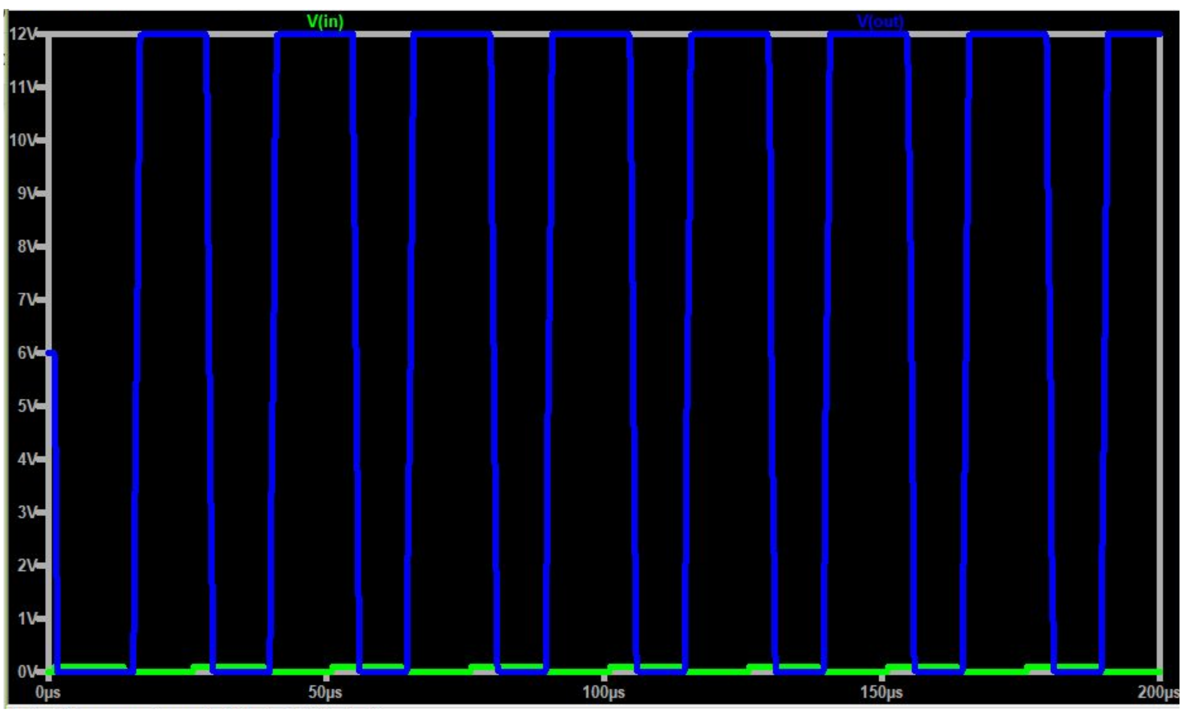

Figure 8: Transient analysis of the receiver circuit with low transducer input voltage (100 mV) simulating low SNR echos

2.3.2 Control Module

Functional Overview

Microcontroller Unit

The microcontroller will be the interface between the sensor controller module and audio controller module. Using 2 bit select lines, the MCU will be able to transmit to and receive data from the correct sensor, storing any received data into the corresponding buffer. Since all data processing will occur in this module, the speed of reading, writing, transferring, and using algorithm(s) will need to be fast enough to output audio data correctly to the audio controller. The system clock from the development board will be used to control a slow clock that controls the cycles of our system. The data processing from the sensors happens here as well as for the output audio signal. The microcontroller will need to operate at 4.5-5.5V at 20 MHz.

ADC

To process the ultrasonic signals obtained by the receiver, the ADC must first convert the received waveforms to digital data via sampling. The maximum output voltage of the ultrasonic receiver circuit is 12V. We may not need more than a 250 mV resolution for the ADC. This means we need $12V/0.25 = 48$ levels to be represented by the comparators inside the ADC. This means that we need at least $\lceil log_2(48) \rceil = 6$ bits. For more resolution, we could use 100 mV increments, which means we should have 12V/0.1V = 120 levels, and a corresponding $\lceil log_2(120) \rceil = 7$ bits to represents those voltage levels.

Since the bandwidth of the ultrasonic echos will be centered around $40\ kHz$, we will need the sampling frequency of the ADC to be at least $2 * 40\ \ kHz = 80\ kHz$ in order to satisfy Nyquist's criterion for sampling.

This component relates to all three of our requirements, but specifically requirements #2 and #3. It relates to requirement #2 because in order to create any form of feedback information to the user, we must first acquire a signal from objects to be sensed and process them with the microcontroller and finally use the calculated information to trigger the audio controller and send useful auditory feedback to the user. These steps require an ADC in order for the analog waveforms to be processed digitally. This component also relates to requirement #3 because in order to test the accuracy of the device, we must first obtain samples of the received ultrasonic echo and calculate a distance to compare with physical measurements with a meter stick to ensure that requirement #3 is met.

DAC

To use the data generated by the microcontroller as a result of processing the ultrasonic echo, we must convert the microcontroller's output to analog waveforms. The audio controller would then use these waveforms to correctly output a stereo sound to the user. Since 20 kHz is the maximum frequency a human can hear, using 44.1 kHz for sampling rate would work well for the audio output.

4 to 1 MUX

This MUX will be placed between the sensors and the ADC. Using a control signal from the microcontroller, the MUX will be able to output the correct signal based on the given inputs from the 4 ultrasonic sensors. The power supply must be at 3.3V +10%. Power supply current should be at .004 pA. The switching speed should be fast enough below 10 ps.

1 to 4 MUX

This MUX will be placed between the transmitter circuit, sensors, and microcontroller. Using a control signal from the microcontroller, the MUX will be able to select the desired output signal line to the corresponding ultrasonic sensor. The power supply must be at 3.3V +10%. Power supply current should be at .04 pA. The switching speed should be fast enough below 10 ps.

Requirements and Verifications Table

Requirements	Verification
ADC Chip 1. Successfully sample the analog signals at a minimum of 80 KSPS	1. Check the sampling rate a. Connect an oscilloscope to the output of the ADC b. Use to oscilloscope to see the frequency of sampling against the rated version
DAC Chip 1. Successfully convert the digital signal	1. Check the conversion rate a. Sweep the DAC from 0 to its

back to analog at a minimum frequency of 44.1 KHz	maximum output step using a function generator b. Compare the response to what it should be at every output step c. Use the oscilloscope to see the digital data signal frequency at 44.1 kHz
Microcontroller 1. Operates at 4.5-5V and 0.2mA	1. The power supply must provide a voltage in the range of 4.5-5.5V for a current load up to 0.2mA 2. Use test programs to verify that needed I/O pins provide correct output. a. Connect all digital input pins to corresponding lines b. Load the test program to print digital input data in a terminal c. Send a trigger signal to the transmitter circuit d. The terminal screen should display live digital data from the sensors e. The data buffer should be populated if any echo received f. Repeat for each sensor
4:1 MUX 1. Successfully switch one of the four input lines through to a single, common line by using a control signal 2. Max pulse switch current is 100 mA	1. Check switching mechanism a. Connect four different input signal lines and the desired select lines input (2-bit control signal) to the MUX b. Power the MUX and use a simulation to verify the correct input line is selected against the control signal bits at the right time 2. Pulse switch current is at 1ms with 10% duty cycle
1:4 MUX 1. Successfully select one of the four output lines from a control signal (2 bits)	1. Check switching mechanism a. Connect four different output signal lines and the desired select lines input (2-bit control signal) to the MUX b. Power the MUX and use a

	simulation to verify the correct output line is selected against the control signal bits at the right time

Supporting Material

Microcontroller

If we divide the maximum detection range of 2 meters by the average human running speed, we find our maximum allowed latency from the very first procedure to the very last. This means that the minimum latency and the maximum latency should be calculated as follows:

Minimum latency $(2m)/(12.52m/s) = 0.159\ s\ =\ 159\ ms$

Maximum latency $(2m)/(1.4m/s) = 1.428\ seconds$

Where the maximum latency was found by noting that the average human walking speed is roughly 1.4 m/s. These results imply that the latency of our device should be in the 159 ms - 1428 ms range.

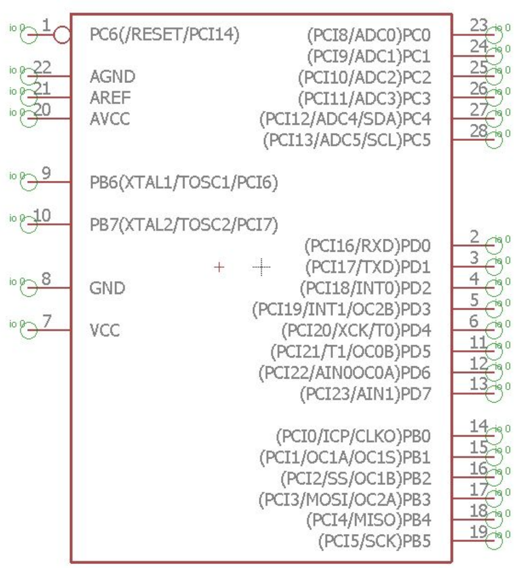

Figure 9: Microcontroller Chip Schematic (ATMEGA328P) [5]

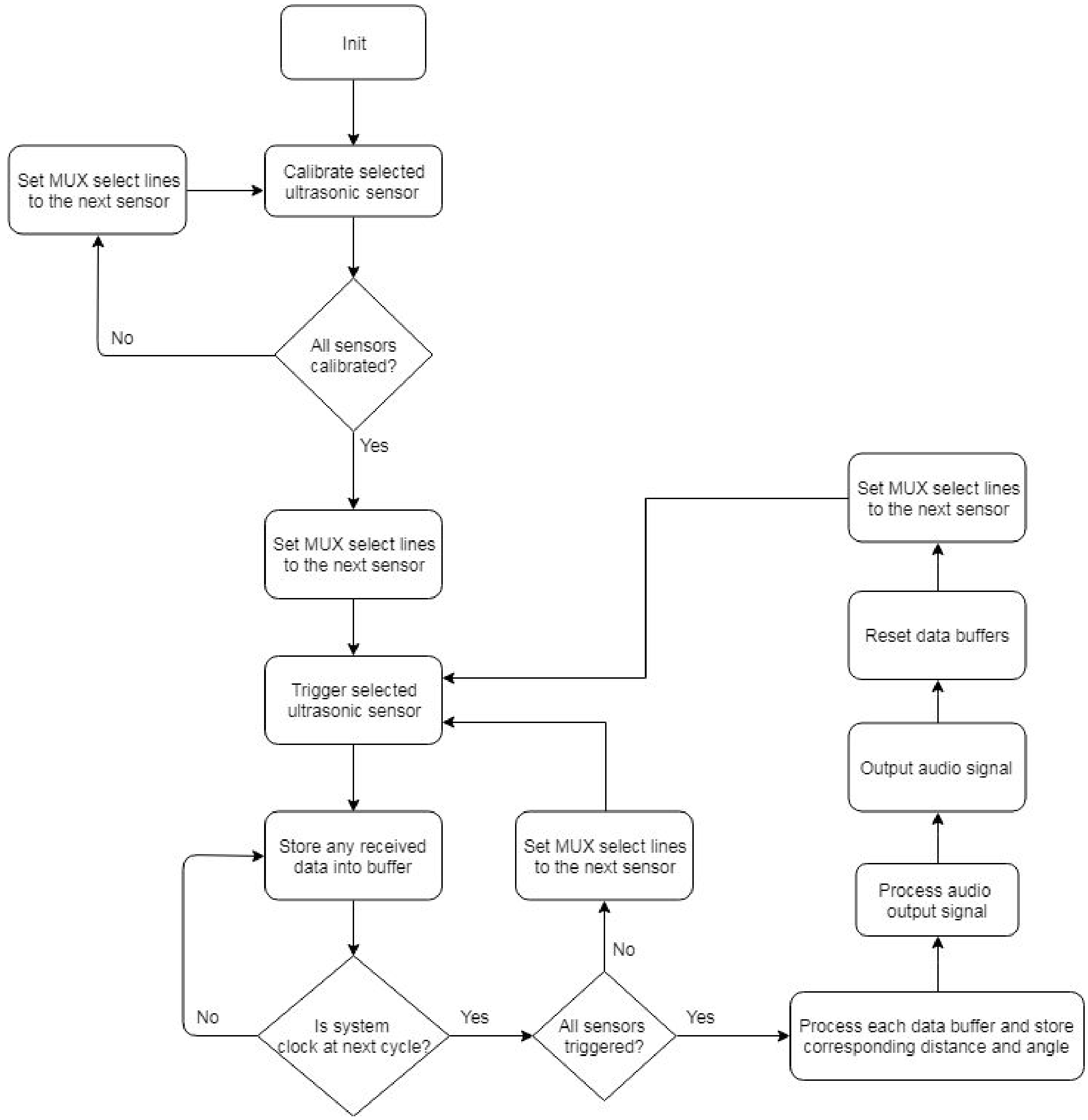

Figure 10: System logic flow chart

This chart represents the high level logic flow of our system. The calibration sequence will be ran on bootup and the user can enter this sequence again at any time after using a button. The temperature sensor will continuously send analog data to the MCU and the processing step can take this value into account.

ADC

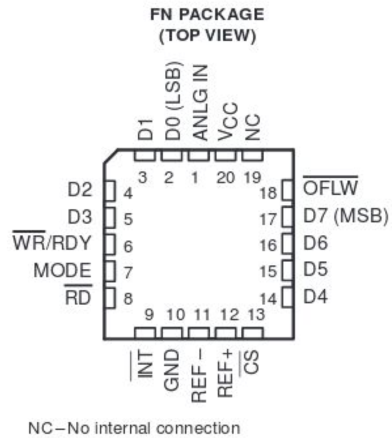

Figure 11: TLC0820A Chip [6]

The on chip track and hold circuit has a 100 ns sample window which allows this device to convert continuous analog signals with a rate of 100 mV/ps. So the switching rate is fast enough for our design. It is 8-bit and outputs 392 kSPS which is higher and faster than what we need. The chip operates at 5V and 7.5mA supply voltage and current.

4 to 1 MUX

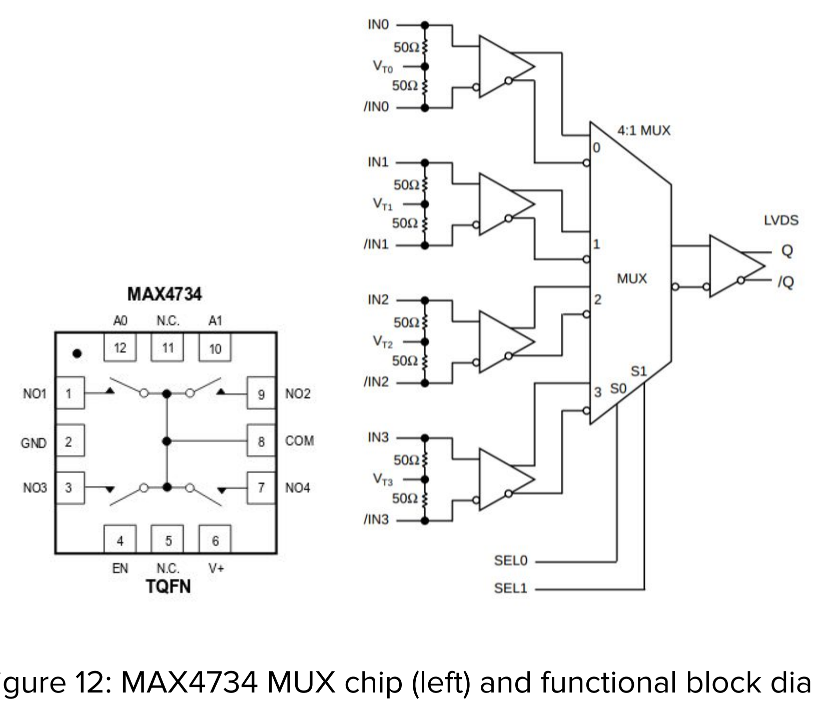

Figure 12: MAX4734 MUX chip (left) and functional block diagram (right) [7]

Shown below is the how the 4 to 1 MUX will be used in order to selected the desired ultrasonic sensor to receive data from. The select signals are set by the microcontroller unit and the chip operates at 3.3V. The analog input to the MUX will be from the output of the each ultrasonic sensor. The analog output of the MUX will be translated by the ADC as an input before reaching the microcontroller unit.

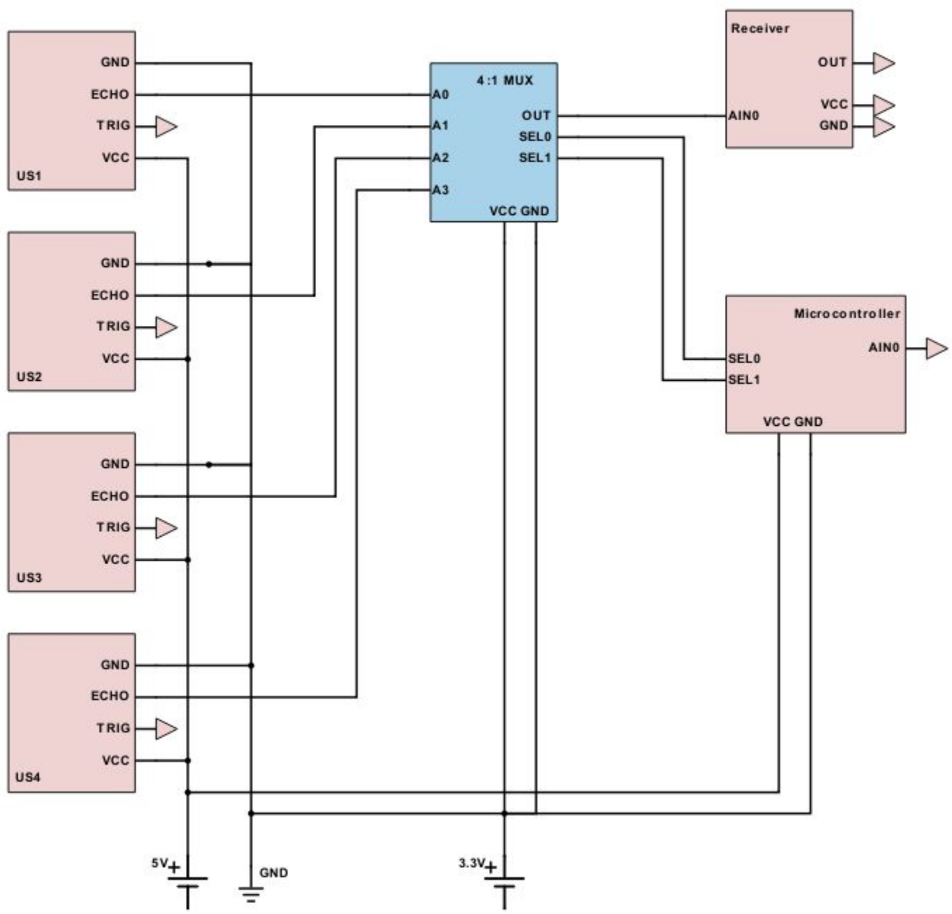

Figure 13: 4:1 Multiplexer Schematic (one side of sensors only)

1 to 4 MUX

Shown below is the how the 1 to 4 MUX will be used in order to selected the desired ultrasonic sensor to trigger. The select signals are set by the microcontroller unit and the chip operates at 3.3V. The input to the MUX will be from the output of the transmitter circuit, supplying a generated pulse waveform for triggering the sensor. The analog outputs of the MUX are connected to the trigger line of the sensor respectively.

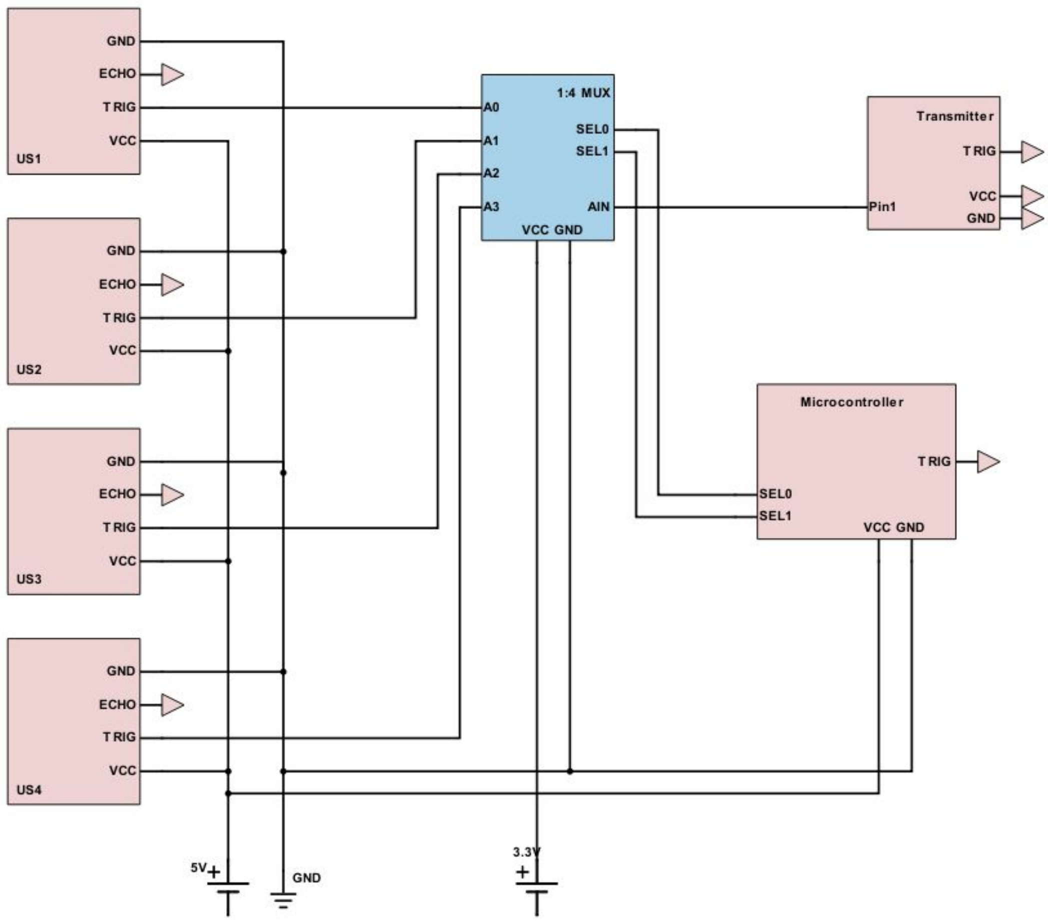

Figure 14: 1:4 Multiplexer Schematic (one side of sensors only) [8]

DAC

The MCP4901 [9] is an 8 bit voltage output digital to analog converter chip with SPI interface. It operates from a 2.7V to 5V supply and provides high accuracy and low noise performance for situations where calibration or compensation of signals are required.

2.3.3 Power Module

Functional Overview

Since our application uses batteries, it would be ideal to minimize unnecessary power loss. We think that using DC-DC switching type regulators would be best for our application. Although they would introduce a lot more noise than linear regulators, they would be more efficient in terms of power conversion [10]. With that being said, using DC-DC switching regulators would require the use of a control signal, itself triggered by a voltage source or a counter driven by the clock. For this reason, we will use standard LDOs for our project.

12V Lithium-Ion Battery

In order to energize all of the modules in this system, we need to supply X Watts of power to it. To do this, we will use a 12V Lithium ion battery. We will need to design an enclosure for the battery and mount it on the vest, as close to the other modules as possible. This module is absolutely essential in satisfying all three of our high level requirements.

Linear voltage regulators

To be able to use the sensor, control, and feedback modules, we will need to supply 12V and roughly 130 mA to the transmitter circuit, 12V and 80 mA to the receiver, as well as 3.3V-5V to the control module, sensor module

Requirements and Verifications

Requirements	Verifications
12V Lithium-ion battery 1. Must be able to provide 400 mW - 450 mW of power 2. Must supply 35 mA - 45 mA of current	1. Power delivery a. Connect the battery to a resistor rated for at least four times the supplied power (1.8W rating or more) b. Ensure that the resistor and battery are connected properly c. Measure the current through the resistor using an

	ammeter d. Measure the voltage drop across the resistor (ideally 12V) and multiply that value by the measured current
Linear voltage regulators 1. Must be able to generate a steady voltage in the 3.3V-5V range 2. Must deliver an output current of 100 mA - 150 mA	1. Voltage a. Connect a reference voltage of 12V from the Li-ion battery to the input of the regulator b. Measure the output voltage of the regulator using an oscilloscope 2. Current a. Connect the output of the LDO to a standard load of $50\Omega - 100\Omega$ and insert an ammeter in the circuit to measure the current flowing through the loop

Supporting Material

<u>Transmitter power consumption (theoretical)</u>

Our LTspice circuit simulation indicates that with a 12V supply voltage and a roughly 50% duty cycle, square pulse shaped current with a peak magnitude of 22 mA, the average power consumption o the transmitter circuit would be:

$$P_{Tx-average} = 12\ V * 0.5 * 22\ mA = 132\ mW$$

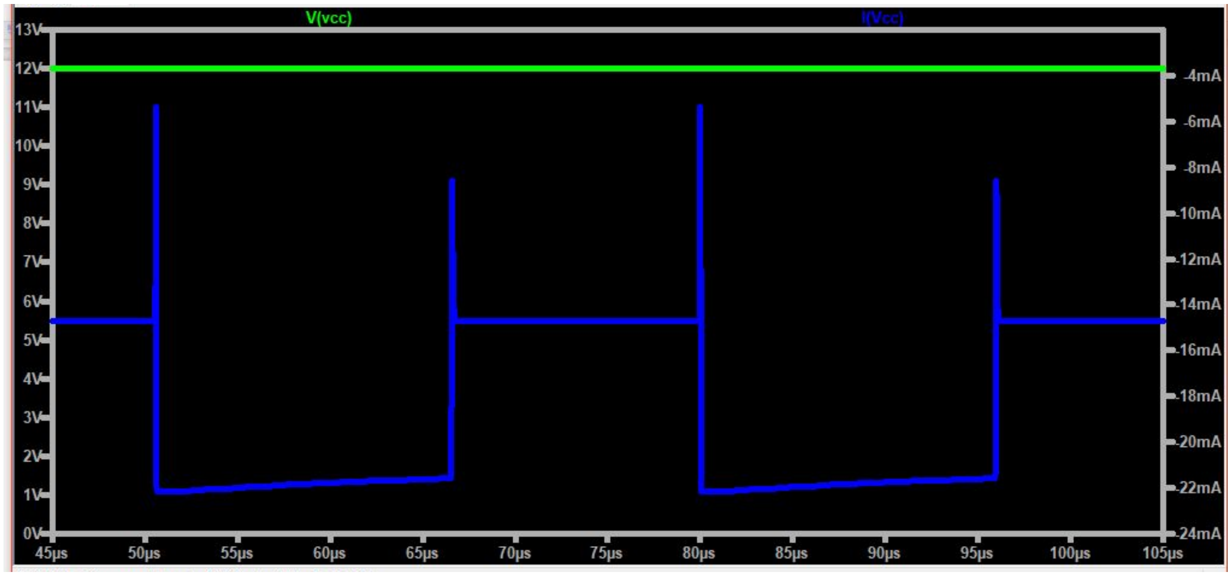

Figure 15: Instantaneous transmitter supply voltage and current

<u>Receiver power consumption (theoretical)</u>

Using an ideal model in our circuit simulation for the receiver, we can see in figure 16 that the supply current has a frequency of:

$$f_{supply} = \frac{1}{(259.66326 - 234.67695)\mu s} = 40.022\ kHz$$

We will approximate the function representing the supply current as roughly a cosine. Since this is purely a back of the envelope estimation, we can treat the cosine as one that is half-wave rectified. The current function would then be:

$$I_{supply} \simeq \frac{1}{2} * 20.672mA * cos(2\pi * 40.022kHz * t) = \sqrt{\frac{1}{4} * 427.33168 * cos^2(2\pi * 40.022kHz * t)}$$

$$I_{supply-average} = \sqrt{\frac{1}{4} * \frac{1}{2} * 427.33168} = 7.309\ mA$$

$$P_{Rx-average} = 12\ V * 7.309\ mA = 87.704\ mW$$

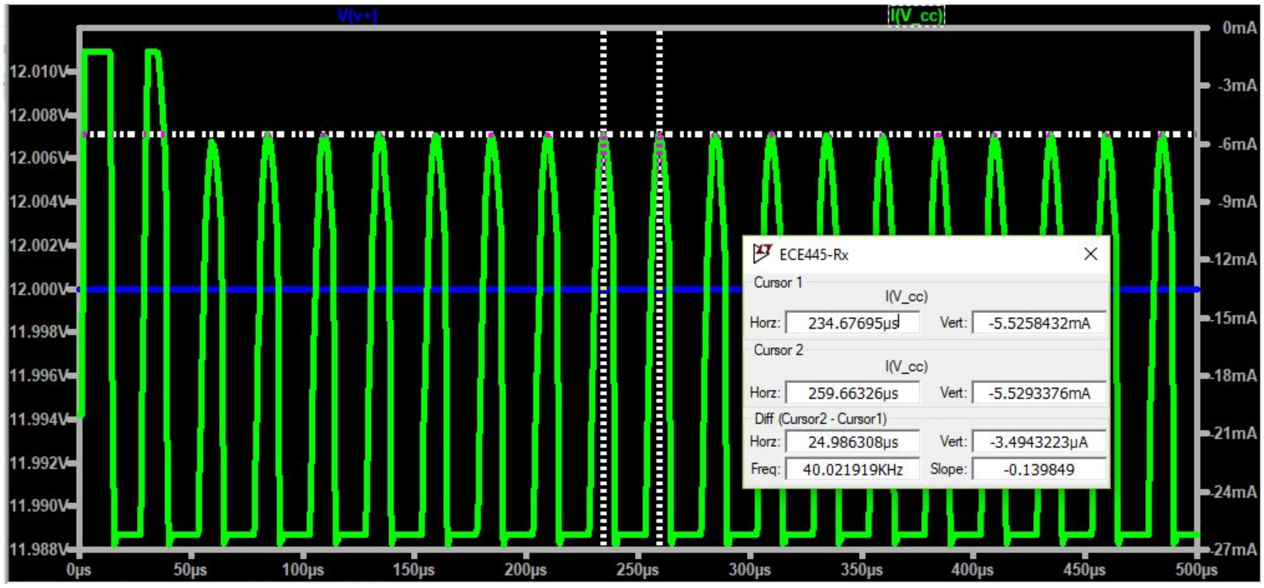

Figure 16: Instantaneous supply voltage and current in the receiver circuit

Microcontroller power consumption (theoretical)

The maximum operating voltage of the microcontroller at 20 MHz is found on the datasheet to be 5.5V. The active mode current is 0.2 mA. This means that the microcontroller's power consumption would be:

$$P_{micro-average} = 5.5V * 0.2\ mA = 1.1\ mW$$

Ultrasonic sensor power consumption (theoretical)

There are eight total sensors operating at 5V and 2.5 mA. Although they will each be on only a portion of the time, we will take the worst case scenario and assume they are on all the time. In that case, the total power consumption of all the ultrasonic sensors would be:

$$P_{sensors} = 8 * 5V * 2.5\ mA = 100\ mA$$

Temperature sensor power consumption (theoretical)

The nominal voltage for the temperature sensor would be 4.5V and the current would be roughly $100\ \mu A$. The power consumption would be roughly:

$$P_{temp-average} = 4.5V * 100\ \mu A = 0.45\ mW$$

<u>Audio controller power consumption (theoretical)</u>

We estimate the audio controller will consume 5V and roughly 20mA of current, in which case we would need to supply it with:

$$P_{audio-average} = 5V * 20mA = 100\ mW$$

In conclusion, the estimated power consumption of the essential components would be:

$$P_{average} = P_{Tx-average} + P_{Rx-average} + P_{micro-average} + P_{sensors} + P_{temp-average} + P_{audio-average} = 421.3\ mW$$

The requirement for the lithium ion battery supply current is therefore:

$$I_{ion-supply} = P_{average}/V_{supply} = 35.1\ mA$$

2.3.4 Feedback Module

Functional Overview

Audio Controller

This module is necessary for satisfying our number one requirement, which is to detect objects around a user and alert him or her about the azimuthal direction of the object through auditory feedback. We will use the concept of interaural time differences (ITD) and head related transfer functions (HRTF) to create the illusion of directional tones for the user.

The idea behind ITD is to create the illusion of directionality by generating tones based on the difference in arrival times from the left ear to the right ear. The difference here is that the signals are ultrasonic and will not be directly perceived through the person's ears. What this implies is that what would normally include a measurement of the average person's head diameter, should actually include the diameter of the torso because the ultrasonic sensors will act as ears. Once we develop the algorithm that determines which sensor is directly pointed in the direction of the object, we will additionally calculate the time difference between echo arrival times to determine the direction in which the echo is coming from. With this technique, we will send a series of encoded trigger pulses to the audio controller to indicate which direction the tone should appear to come from.

The three sources of error for generating directional tones are outlined in [11]. They are reversal error (front-back confusion), elevation error, and in-head localization. The main error that we will try to mitigate is reversal error which would be important for our design since the user would wrongly perceive a signal to be heard 180 degrees away from where it is meant to be heard.

Requirements and Verifications

Requirements	Verifications
Audio controller 1. Take an encoded bit stream from the microcontroller that indicates what directional tone to play 2. Filter the output audio signal before transmitting to ensure that it is in the audible hearing range for humans	1. Bit stream a. Use a logic analyzer to probe the output of the microcontroller to the audio controller. Ensure that the bit sequence corresponds to the correct obstacle direction 2. Filtering a. Use an oscilloscope to measure the output of the audio controller before the filter and after the filter b. Take the FFT on the oscilloscope to view the spectrum and detect noise in the filter input, and significantly reduced noise in the filter output
Open-ear headphones 1. Must use the output from the audio controller to generate clearly	1. Audability a. Confirm that the headphones produce sound by testing it

audible sounds corresponding to different directions	using an audiofile on a phone. b. Test sound output at different volumes to make sure that even it low settings, it is clearly audible.

Supporting Material

To be able to generate directional tones for the user in order to help them navigate through obstacles, we must essentially apply head related transfer function (HRTF) models and sound localization techniques at ultrasonic frequencies where the wavelengths are on the order of millimeters. This can become tough since most of the literature we have found deals with frequencies less than 2 kHz.

In our project, the user's torso replaces the traditional head used for modeling HRTF, and the eight ultrasonic sensors will act as ears. The "cone of confusion" is a region where all of the echoes will have the same interaural time differences, which means the object could be anywhere within the cone of confusion. After reading some of the literature we have noticed that generating directional tones accurately in the azimuth as well as zenith angles is actually a very challenging problem as the human body, orientation of the head, and many other factors can affect the direction in which the sound is perceived by the user. For this reason, we will focus primarily on localizing the sound in the azimuth plane. Localizing the objects in zenith will be a problem beyond the scope of this course since more theoretical understanding would be needed, and our time is limited to a semester.

At auditory millimeter waves frequencies, certain curve-fit approximations - such as that proposed by Lord Rayleigh - fail. The wavenumber at this frequency would be:

Wavenumber $k = \frac{2\pi f}{v} = \frac{2\pi(40\ kHz)}{340\ m/s} = 739.2\ radians/meter$

One advantageous consequence of this result is that the far-field would be much closer to the user than 1 meter. This means that we can neglect acoustic phase changes starting from a few inches to the user all the way out to two meters and beyond. Figure 17 shows the left and right filters that would normally give us the ability to generate directional tones, had the acoustic frequency been roughly 2 kHz. We will need more research to combat this difficulty and determine how other teams have used HRTF models at ultrasonic frequencies.

we have been able to get a good low-frequency fit to Rayleigh's solution with the following simpler model:

$$H_R(\omega, \theta) = \frac{1 + j2\alpha\omega\tau}{1 + j\omega\tau} e^{-j\omega T_R}$$

$$H_L(\omega, \theta) = \frac{1 + j2(1-\alpha)\omega\tau}{1 + j\omega\tau} e^{-j\omega T_L}$$

where $\alpha = \frac{1}{2}(1 + \sin\theta), \tau = \frac{1}{2}(a/c), T_R = (1-\alpha)\tau$ and $T_L = \alpha\tau$. This model fits Rayleigh's solution well for frequencies below 2 kHz. When one listens to synthetic binaural sounds produced by this filter, the apparent location moves smoothly from the left ear to the right ear as θ is varied from $-90°$ to $90°$ [5]. However, this model does not provide any elevation dependence, and the apparent location is not externalized, but appears to be inside the head.

Figure 17: Rayleigh model for head-related transfer function [12]

As a submodule in the audio controller, we simulated a first order RC low pass filter. The values were chosen by noting that:

$$\omega_{-3dB} = \frac{1}{RC}$$

$$\omega_{-3dB} = 2\pi(20kHz) = 40,000\pi$$

Since we know the what the 3 dB bandwidth is, we calculated the RC time constant to be roughly $7.9577 * 10^{-6}$. We chose the easy-to-implement values of $R_1 = 1.5\ k\Omega$ and $C_1 = 5\ nH$ out of all the possible combinations that would yield $RC = 7.9577 * 10^{-6}$.

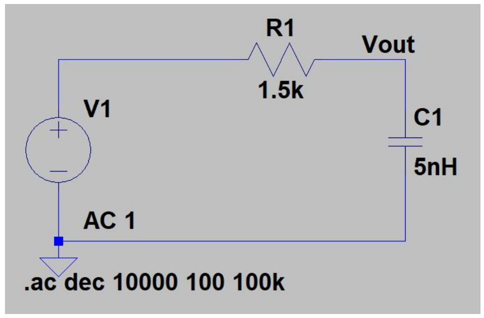

Figure 18: Simple low pass filter design

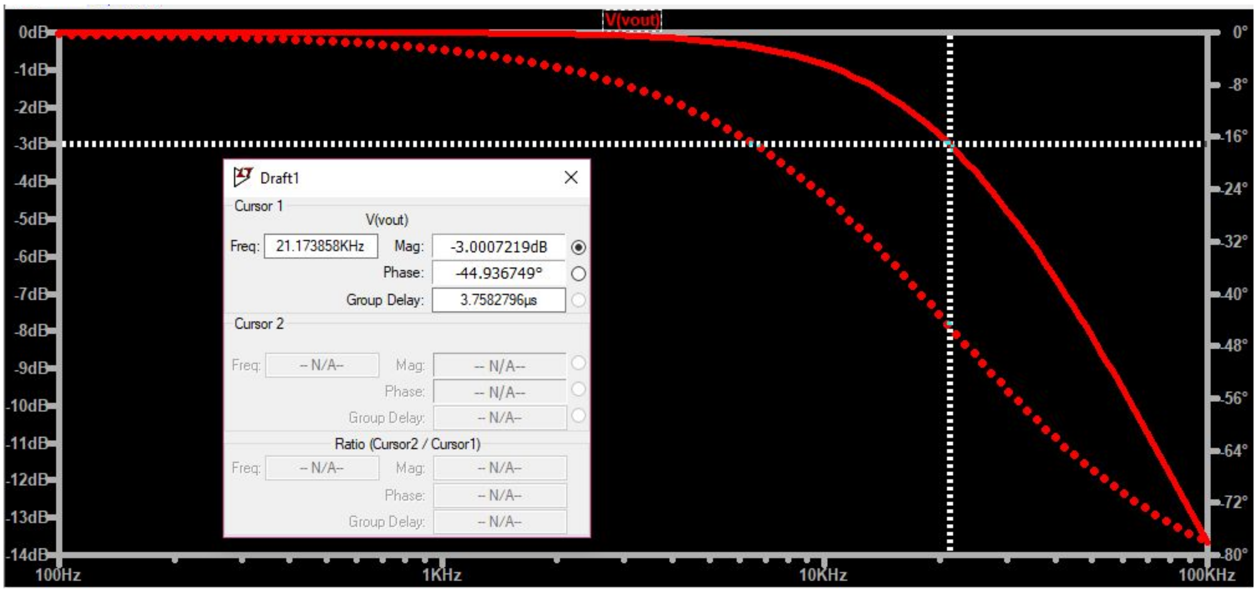

Figure 19: Bode plot of our simple RC low pass filter. Simulated $f_{-3dB} = 21.17\ kHz$

2.4 Tolerance Analysis

Since we have chosen every module and component based on the assumption that the ultrasonic transmitter sends pulses at 40 kHz, it is critical for our transmitter to have an error in output frequency that sits within $\pm 10\ kHz$. One example to illustrate why this is critical is the following:

The ADC was chosen such that it samples analog waveforms at $2 * 40\ kHz = 80\ kHz$ in order to satisfy Nyquist sampling criterion. If the transmitter's frequency shifts to $50\ kHz$, then $f_{sampling} = 80\ kHz\ <\ 100\ kHz$. This means that aliasing would occur and the microcontroller would not be able to reconstruct the signal correctly. Assuming a 10% tolerance for $R_1, R_2, and\ C_2$, we would have $R_1 = 1\ k\Omega\ \pm 100\Omega$, $R_2 = 4.725\ k\Omega\ \pm 473\Omega$ and $C_2 = 3.3\ nF\ \pm 0.33\ nF$. The extreme values of each component would then be:

$$R_{1-min} = 900\ \Omega \qquad R_{1-max} = 1.1\ k\Omega$$

$$R_{2-min} = 4.252\ k\Omega \qquad R_{2-max} = 5.198\ k\Omega$$

$$C_{2-min} = 2.97\ nF \qquad C_{2-max} = 3.63\ nF$$

$$f_{min} = \frac{1.38}{(R_{1-max}+2R_{2-max})C_{2-max}} = \frac{1.38}{(11.496\ k\Omega)(3.63\ nF)} = 33.069\ kHz$$

$$D_{min} = \frac{R_{1-min}+R_{2-min}}{R_{1-min}+2R_{2-min}} = 51.78\ \%$$

$$f_{max} = \frac{1.38}{(R_{1-min}+2R_{2-min})C_{2-min}} = \frac{1.38}{(9.404\ k\Omega)(2.97\ nF)} = 49.409\ kHz$$

$$D_{max} = \frac{R_{1-max}+R_{2-max}}{R_{1-max}+2R_{2-max}} = 54.78\ \%$$

Simulating the transmitter with the critical components at their minimum values gave us the results shown in figure X. The simulation dictates that the frequency would shift to $f_{max} = \frac{1}{(104.3379-84.474)\ \mu s} = 50.344\ kHz$. Evaluating the critical components at their maximum tolerance values gave us the results shown in figure Y. In this case $f_{min} = \frac{1}{(109.40439-80.250784)\ \mu s} = 34.301\ kHz$. In conclusion, due to the sensitivity of the transmitter to some of the component values, we need to ensure that the ADC samples the echo signal at a minimum sampling rate of 2*50 kHz = 100 ksps, which would take care of the upper bound error caused by the capacitor and resistor tolerances in the transmitter.

Figure 20: Tolerance analysis of the transmitter's output frequency when the critical components are at their minimum tolerance values. $f_{max} = 50.344\ kHz$

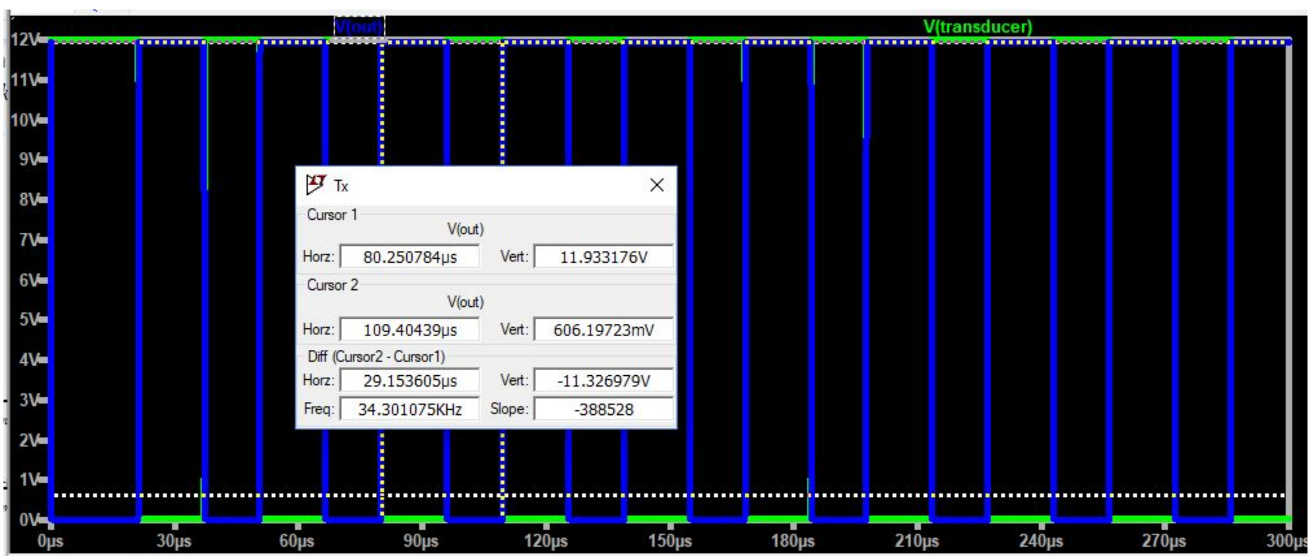

Figure 21: Tolerance analysis of the transmitter's output frequency when the critical components are at their maximum tolerance values. $f_{min} = 34.301\ kHz$.

2.4 Risk Analysis

The potential error introduced by the ultrasonic sensors causes the greatest risk. If the error is a few feet, then the user can accidentally walk into objects and harm him or herself. Handling the data through the microcontroller will not be as great of a risk since signal propagation occurs at electronic speeds. The reliability of the ultrasonic sensor data, however, will depend mainly on air temperature and wind speeds, both of which are outside of our control. One way to mitigate this risk would be to use a temperature sensor and re-calculate the speed of sound using the microcontroller.

3 Cost and Schedule

3.1 Cost Analysis

Labor

	Hourly Rate	Hours Invested	Cost
Arrian Movahedi	$30.00	240	$7200.00
Napat Sutthasinwong	$30.00	240	$7200.00
Yash Agrawal	$30.00	240	$7200.00
Unadjusted Total		720	$21,600.00
Adjusted Total (2.5x)			$54,000

Parts

Description	Part Number	Quantity	Cost/Part	Total Cost
Ultrasonic Range Finder	HC-SR04	10	$3.29	$32.9
Temperature Sensor	AD22100KTZ-ND	1	$4.74	$4.74
Microcontroller	ATmega328P-PU	1	$2.15	$2.15
Quadruple Norton Op Amps	LM3900	3	$0.48	$1.44

LDO	TLV704	3	$0.83	$2.49
ADC	TLC0820ACDBR	2	$4.52	$9.04
DAC	TLC5602CDW	2	$4.64	$9.28
4:1 MUX	MAX4734EGC	1	$1.95	$1.95
1:4 MUX	CD4555BE	1	$0.46	$0.46
			Total:	$64.45

Grand total = $54,000 + $64.45 = $54,064.45

3.2 Schedule

Week	Team	Arrian	Napat	Yash
9/17	Proposals	Finalize Proposal	Mock Design Review Prep	Determine ultrasonic sensors to use
9/24	Mock Design Review Sign-up	Sign up for Mock Design Review Finish Eagle Assignment	Finish Eagle Assignment Find microcontroller	Finish Eagle Assignment
10/01	Mock Design Review	Simulate Tx, Rx and audio circuits in LTspice Research Audio subsystem	Finish Design Document Find ADC, DAC, MUXES	Complete Mock Design Review Finish Design Document
10/08	Design Review	Participate in the Design Review Soldering Assignment	Participate in the Design Review Soldering Assignment	Participate in the Design Review Soldering Assignment
10/15		Determine audio	Assemble sensor	Assemble sensor

		feedback subsystem Determine control module	module Determine control module	module Determine control module
10/22		Verify sensor module	Assemble control module	Begin PCB layout
10/29		Verify control module Assemble audio feedback module	Finish PCB layout Complete backlog	Verify control module Complete backlog
11/05		Reorder PCB if required	Assemble all modules	Mount device on the vest
11/12		Verify all modules Complete backlog	Verify all modules Complete backlog	Verify all modules Complete backlog
11/19	Fall Break			
11/26	Mock Demo	Revise requirements and verification table if necessary	Work on feedback received	Commence working on the final paper
12/03	Presentation	Prepare for final presentation Complete Final paper	Prepare for final presentation Complete Final paper	Prepare for final presentation Ensure requirements on par for final paper
12/10	Final Paper	Proofread Final Paper Lab checkout	Proofread Final Paper Lab checkout	Proofread Final Paper Lab checkout

4 Ethics and Safety

4.1 Ethics

According to the IEEE Code of Ethics we need to be honest and realistic in stating claims [13]. Our project aims to provide easy and hands-free navigation to the visually impaired and while it is an ethically sound idea, the safety of the user is paramount. Given the short 16 week duration of the project, it is not recommended that the device at this stage be used as a primary means of navigation by the visually impaired. Upon further work and extensive testing this device could potentially help navigation without the need of sight.

In addition, there are notable risks involved with wearable electronic devices that we need to acknowledge. In accordance with the IEEE Code of Ethics we must promptly disclose factors that might endanger the public [14]. Malfunctions of the power subsystem would arguably be biggest risk involved in our project. To make sure that there are no potentially hazardous issues with the power subsystem we will provide liquid Ingress Protection level 3 against spraying water.

4.2 Safety

Given the nature of the project certain precautionary measures need to be taken in order to be safe. We plan to use a lithium based battery to power our circuit and in general any device that stores energy carries the risk of exploding or overheating. We will make sure to properly test our power system.

We want our device to be as non-invasive as possible so that a user can go about their day to day life without any issues but since there's an audio subsystem at play, we must make sure that the directional tone isn't irritating to the user and the volume is just high enough so that the feedback is heard but low enough that it doesn't cause any distraction. Finally, we need to minimize the latency from the sensors to the feedback so as to make this device as safe to use as possible.

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