

“Extended Reach” Echolocation Sensor

Senior Design Design Review

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TA: Lydia Majure

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1. Introduction

1.1 Project Statement

We have chosen to develop a way for a person to sense their surroundings using sonar by analyzing the reflected signals of ultrasonic chirps we send out and then outputting its characteristics. This project is a modular design, which works with our sister project the “Extended Reach” Haptic Array. We chose this project because it has the possibility to lead to some groundbreaking studies, and can be a prototype for an invisible cane for blind people. Not only will it aid people in way a variety of applications, it provides unique signal processing challenges as well as circuit design experience.

1.2 Objectives

The “Extended Reach” Echolocation Sensor will be able to send out a chirp at ultrasonic frequencies and receive ultrasonic signals reflected off objects in the vicinity of the device. The device will then be able to filter the signal and pull out characteristics of the signal that will be able to indicate distance, shape and other properties of objects that reflected the signals. These characteristics will then be exported so that they can be used by the “Extended Reach” Haptic Array project.

Benefits to the Customer

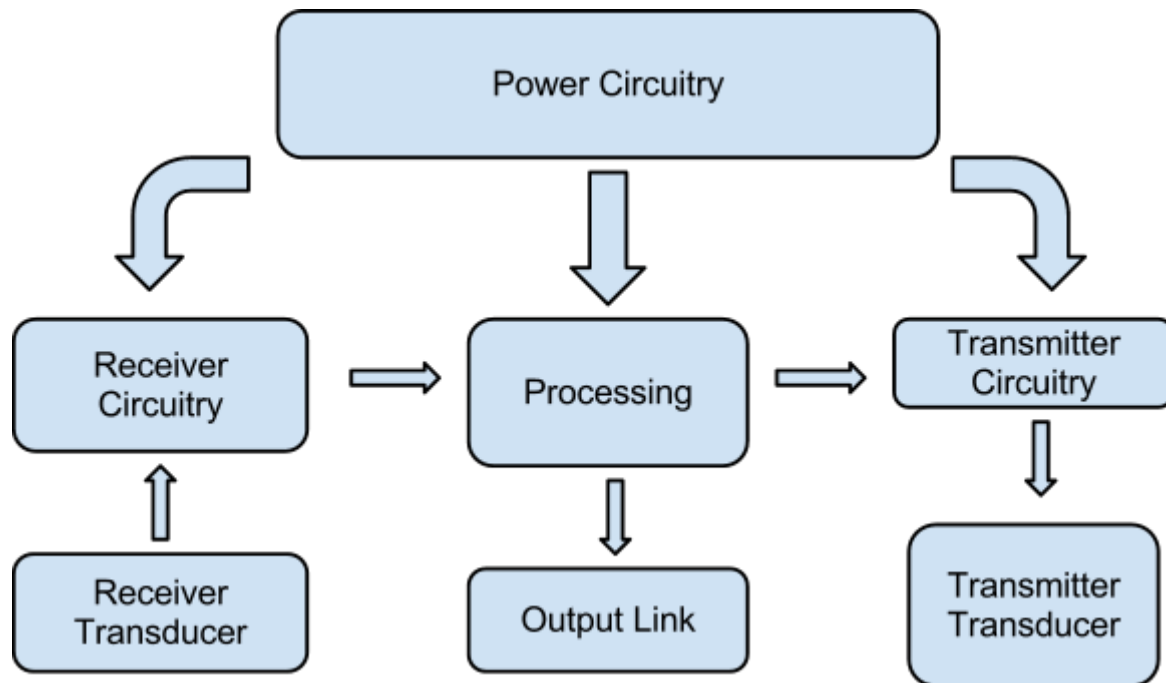
- It may be used to sense the surrounding environment without the need of light or without the use of sight.
- It will be a virtually weightless alternative to a cane
- Can be used in applications where people need to reach something that is out of eyesight
- Reasonably priced
- User friendly, and fun to learn

Product Features

- Ability to sense distance to an object within a maximum distance
- Ability to process multiple characteristics of reflected audio signal
- Ultrasonic frequency transmission from 22kHz – 40kHz
- Fast processing speed allowing continuous updates of sensing feedback
- Safe and reliable design

2. Design

2.1 Overall Block Diagram



2.2 Block Descriptions

Processing:

The processing block is the heart and soul of the echolocation sensor. For the sensor processing, we will be using an ST Discovery DSP board. The Discovery board will do three main things: send out the chirp waveform, process the incoming reflected signal, and output the signal characteristics to the output serial link. The chirp waveform will linear with a frequency bandwidth from around 22kHz to 40kHz. The incoming reflected signal will be analyzed using cross-correlation. The reflected signal will first be high-pass filtered in order to remove frequencies in the audible range. Then the signal will be cross-correlated with the outputted chirp waveform. Times (and therefore places) where the cross-correlation leads to larger values can be interpreted as important. We will utilize one of the programmable push-buttons on the Discovery board to yield two different output characteristic patterns. The first pattern will be in the time-domain, and the second pattern will be an FFT of the time-domain output pattern.

Transmitter Circuitry:

The transmitter circuitry will mainly handle amplification of the emitted chirp signal from the Discovery board. We want the signal to be amplified enough that the outgoing chirp will have a sound intensity of around 100-120dB (SPL). The reason for this is that this is the range that bats use in their echolocation and also the range that most ultrasonic rangefinders use.

Transmitter Transducer:

The transmitter transducer will send out the ultrasonic chirp. Since the chirp will have a bandwidth of about 22kHz to 40kHz, it would be nice if the transducer had a flat frequency response up to about 60kHz. We are trying not to use specially-built ultrasonic transducers because they can cost between \$100 and \$500. Cheaper ultrasonic transducers have too narrow of a bandwidth for our application. Instead we will be using audio transducers that have shown to have a flat response higher than their rated 20kHz. We have decided on using the Panasonic WM61A transducer.

Receiver Transducer:

The receiver transducer will receive the reflected ultrasonic signal. The specifications of the receiver transducer will be the same as the transmitter transducer.

Receiver Circuitry:

Once the emitted chirp is reflected and received by the receiver transducer, it needs to be modified for proper use with the Discovery board. Specifically, it needs to be lowpass filtered in order to prevent aliasing, and it needs to be biased and scaled in order to fit the specifications of the ADC on the Discovery board. The signal will go from being around 5V peak-to-peak to a 0-3.3V range.

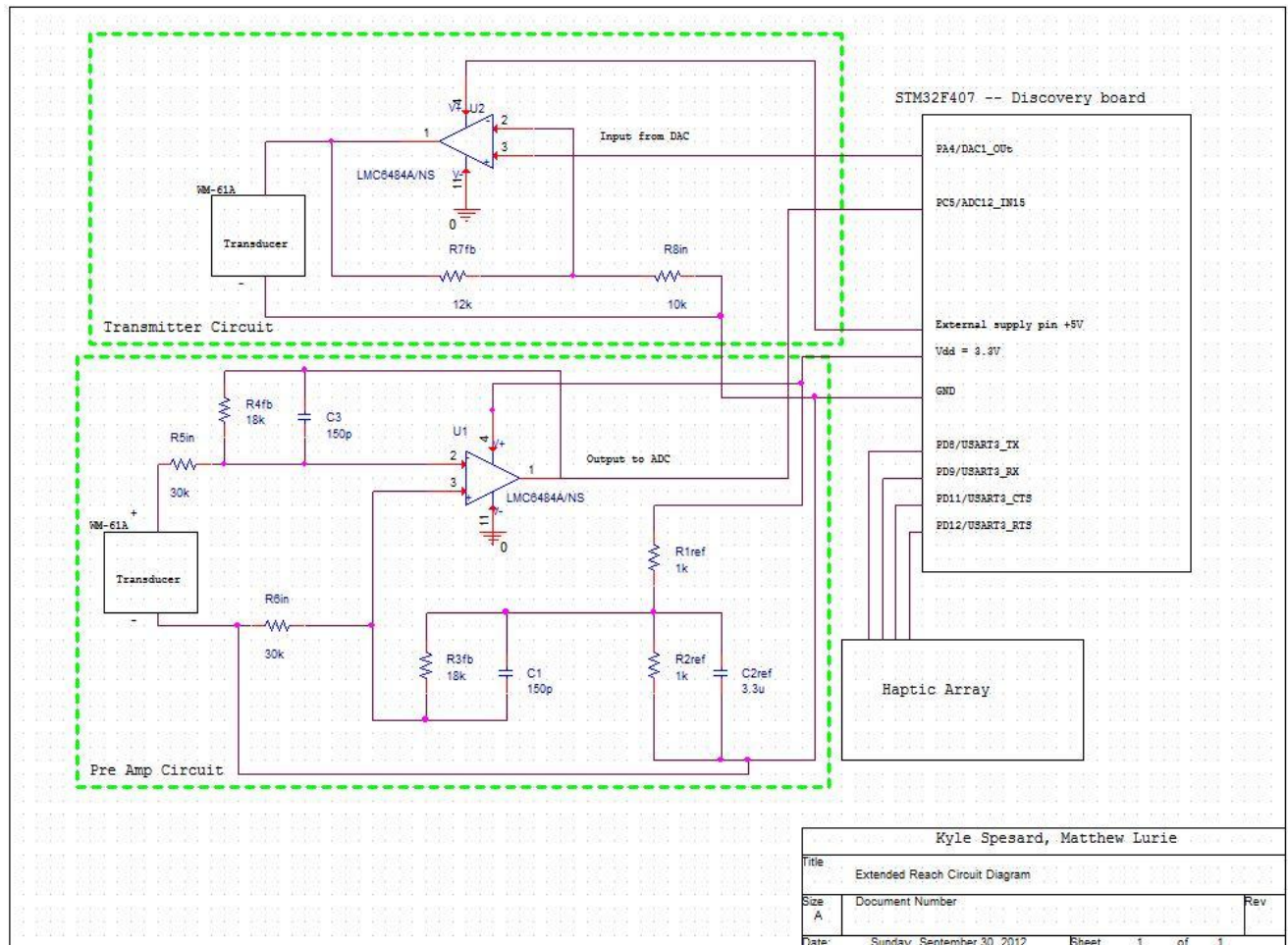
Output Link:

Packets of information regarding the characteristics of the room will be sent through USART. The Discovery board has pins that can be specially assigned for USART capabilities.

Power Circuitry:

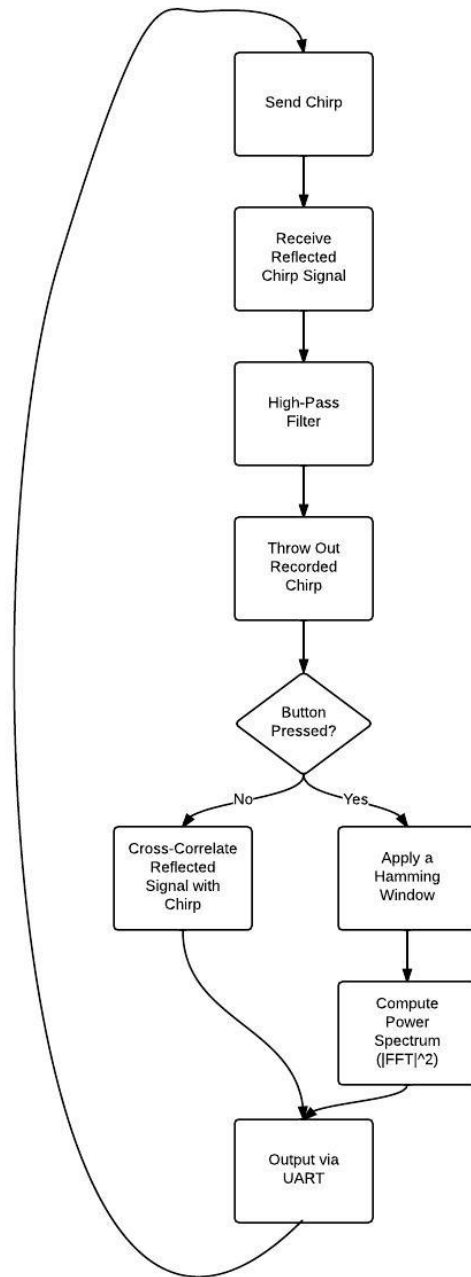
The power circuitry will supply power to the transmitter circuitry, the receiver circuitry, and the processing unit. Power will mainly come from a wall to mini-USB adapter. The mini-USB will power the ST Discovery board and the rest of the circuitry will draw power from the necessary pins on the board.

2.3 Hardware Schematics



Note: the LMC6484 op-amp was chosen because it can operate down to a supply rail voltage of 3Vdc and it can operate to within 100mV of its supply rail voltage on both input and output.

2.4 Software Flowchart



2.5 Calculations and Simulations

2.5.1 Hardware

Receiver Circuit

The receiver circuit can be broken into three functions: biasing, scaling, and filtering. Initially, we thought that this would necessitate three operational amplifiers (op-amps)--one per functions. It was later conceived that all three functions could be handled using only one op-amp using symmetry and a common ground. The common ground is achieved by applying a DC bias to the positive terminal of the op-amp. the 1.65V DC offset is produced from the 3.3V Vdd by use of a voltage divider circuit. The DC offset is given by the equation

$$V_{offset} = \frac{R_{ref1}}{R_{ref1} + R_{ref2}} V_{dd}$$

where Voffset is the DC offset in Volts, R1 and R2 are the same resistance given in Ohms, and Vdd is the positive reference voltage from the Discovery Board in volts. A differential op-amp circuit was selected as the basis of the design in order to allow for calculations of the DC offset to be independent of the circuit input gain. The input gain G is given by

$$G = -\frac{R_{fb}}{R_{in}}$$

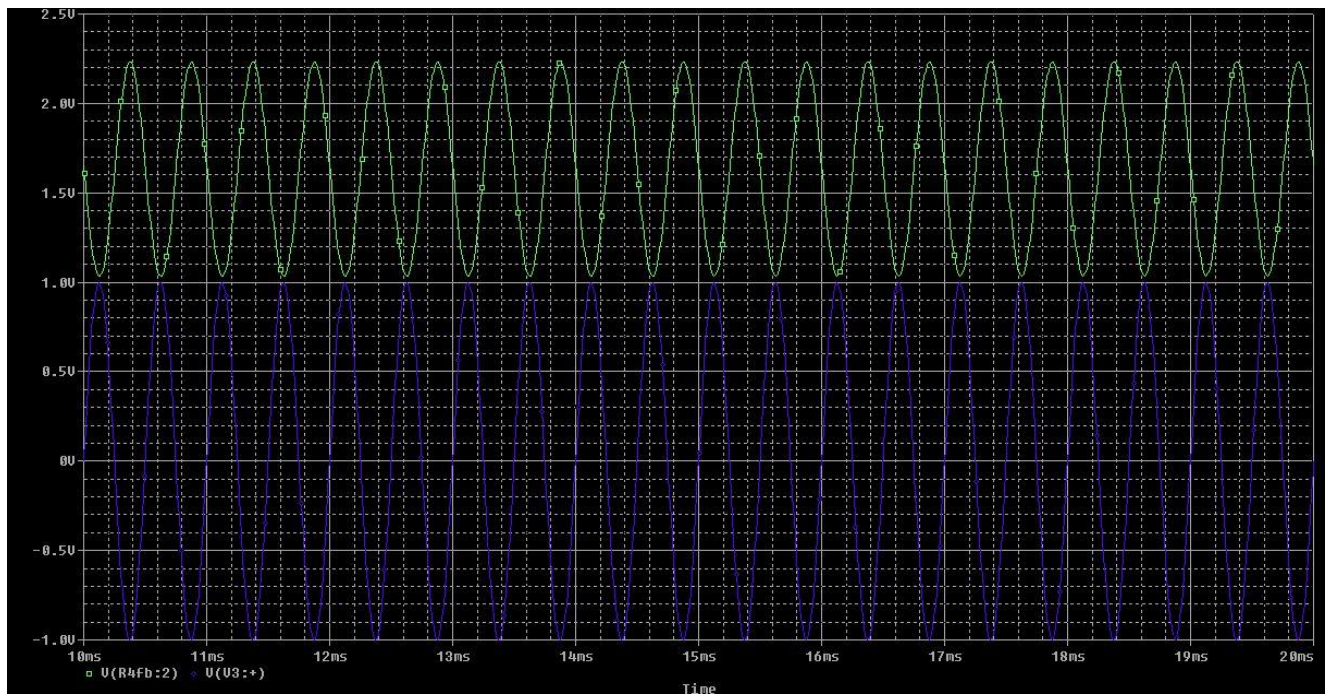
where G is in Volts/Volts and the resistors are measured in Ohms. The -3dB cutoff frequency is given by

$$f_c = \frac{1}{2\pi R_{fb} C_{fb}}$$

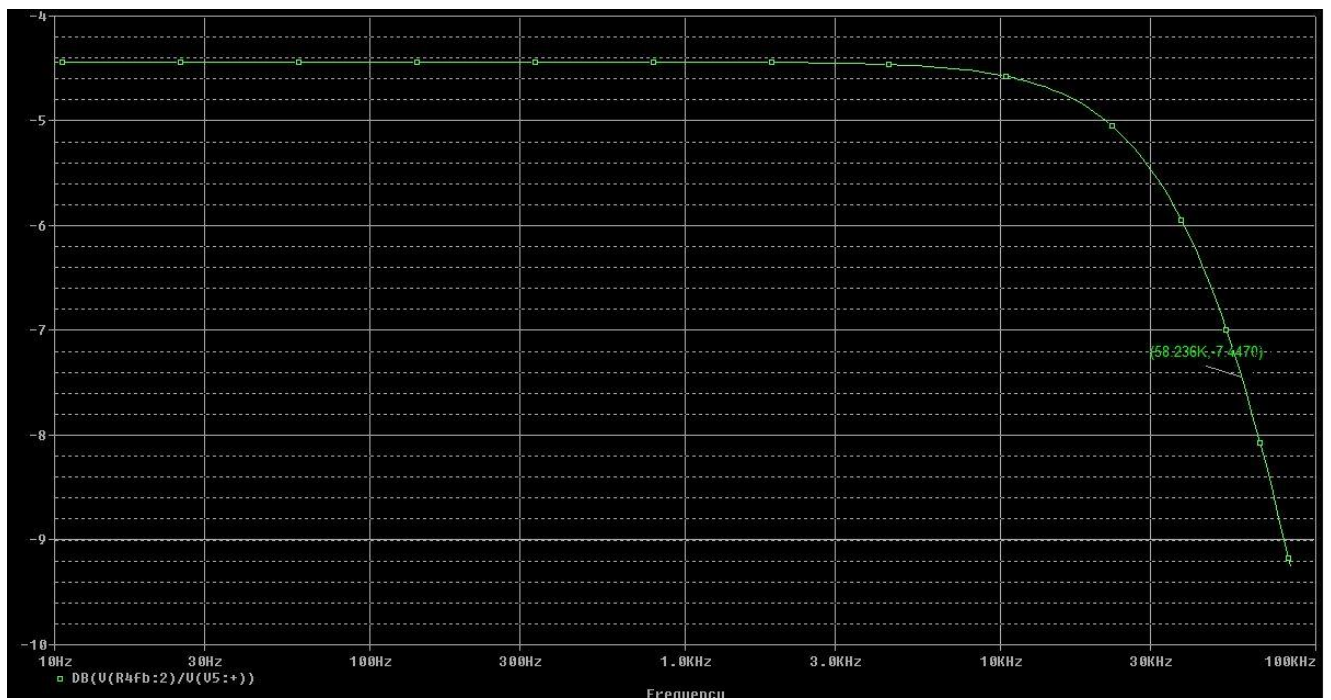
where f_c is the cutoff frequency measured in Hertz, Rfb is the feedback resistance in Ohms, and Cfb is the feedback capacitance in Farads. Putting this all together leads to an equation for the magnitude of the voltage outputted to the ADC pin of the Discovery Board. The equation is as follows

$$V_{ADC} = \frac{-\frac{R_{fb}}{R_{in}}}{\sqrt{1 + (\omega R_{fb} C_{fb})^2}} V_{in} + V_{offset}$$

where V_{ADC} is the voltage outputted to the ADC in Volts, V_{in} is the voltage from the receiver transducer measured in Volts, and ω is the frequency of the voltage from the receiver transducer measured in radians. The pspice plot shown below demonstrates the biasing and scaling feature of the circuit functioning properly.



The filtering aspect of the circuit was also demonstrated using pspice. The resulting simulation is shown below with the -3dB cutoff frequency labeled.

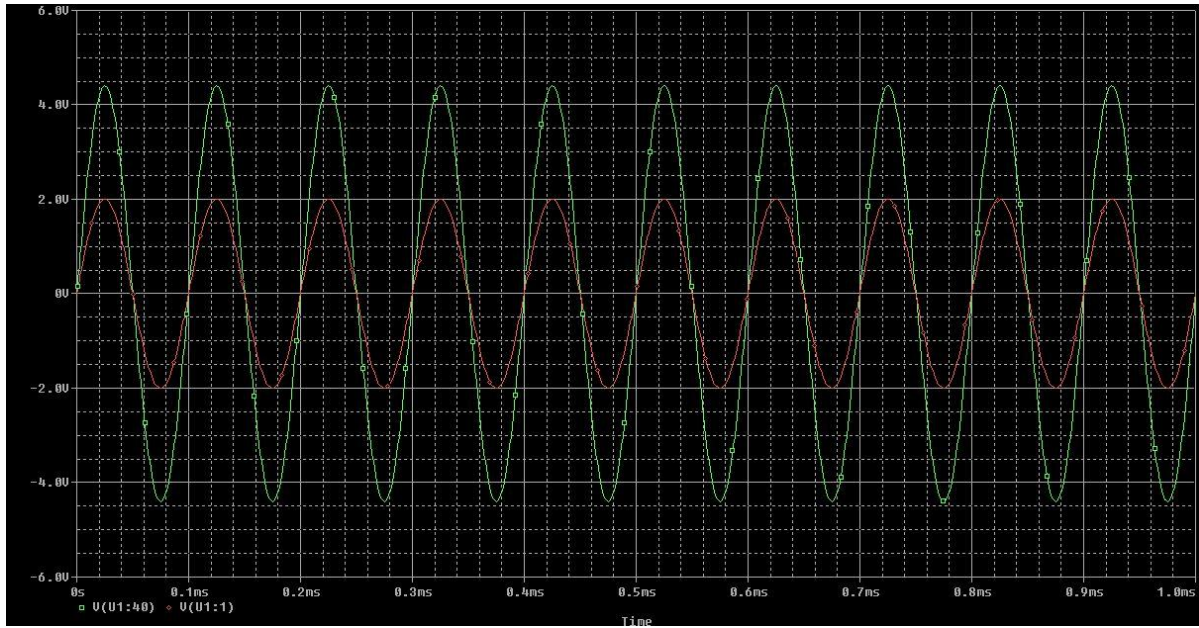


Transmitter Circuit

The transmitter circuit's primary function is to provide gain. A non-inverting op-amp circuit was chosen in order to preserve the shape of the transmitted chirp and because the non-inverting op-amp circuit has a high input impedance which will keep the experimental gain close to the calculated theoretical gain. The equation for the gain in this circuit is given simply by the following

$$V_{out} = (1 + \frac{R4}{R3}) V_{DAC}$$

where V_{out} is the voltage going out to the transmitter transducer measured in Volts, the resistors are measured in Ohms, and V_{DAC} is the voltage inputted to the circuit from the DAC pin on the Discovery Board. The plot in pspice shown below demonstrates the transmitter circuit operating properly.



2.5.2 Software

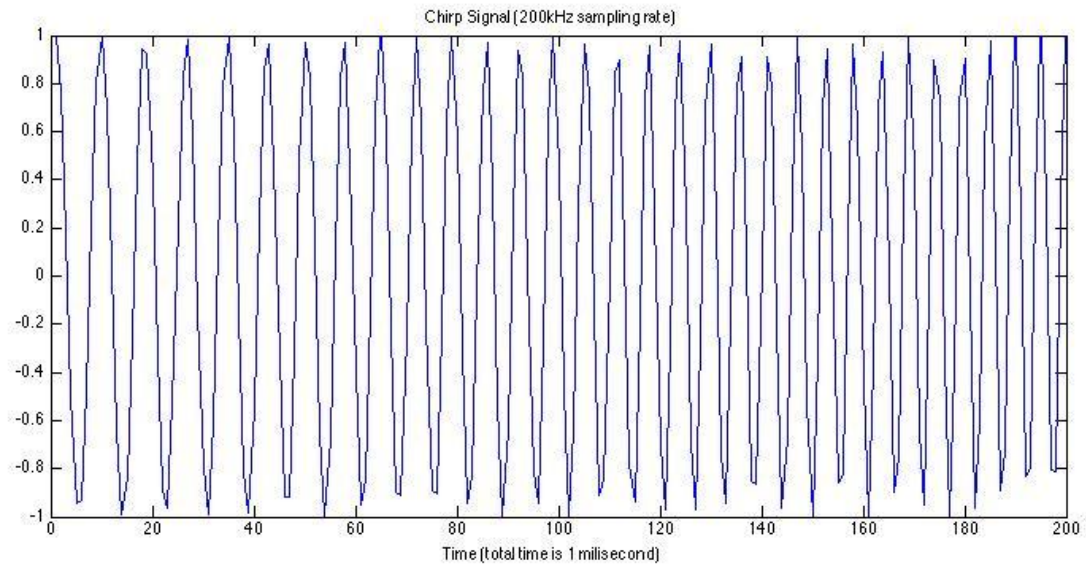
Chirp

The chirp is a linear frequency modulated waveform with an ultrasonic frequency range from 22kHz to 40kHz. A linear frequency modulated waveform is defined by:

$$x(t) = \cos(\pi \frac{\beta}{\tau} t^2) \quad 0 \leq t \leq \tau$$

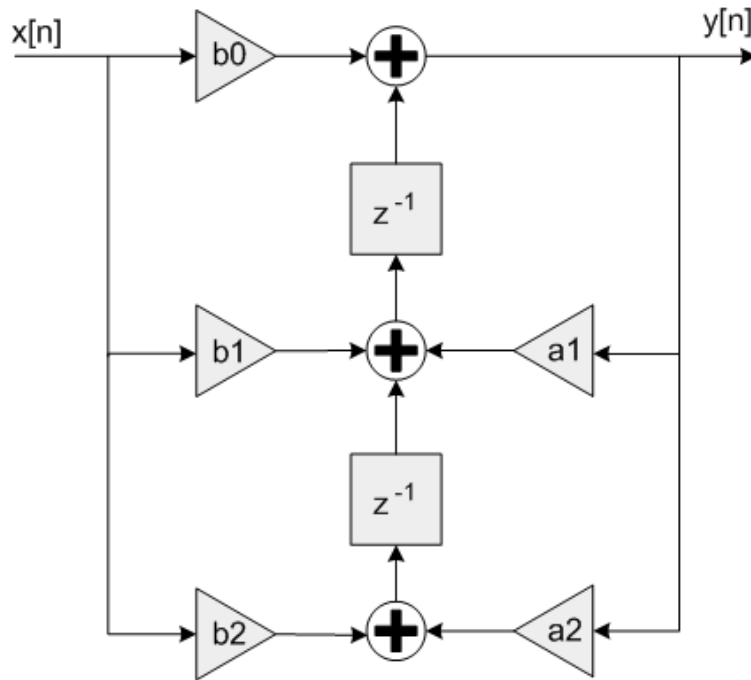
Thus the instantaneous frequency of this waveform sweeps linearly across a total bandwidth of β hertz during the τ -second pulse duration. A linear frequency modulated waveform was chosen over a simpler one-frequency sinusoidal pulse in order to increase the Rayleigh

resolution of the cross-correlated signal. The length of the pulse, τ , was chosen to be the time it takes sound to travel one foot. This effectively becomes the smallest distance that the sensor can detect objects at. The chirp was created using the (aptly named) MATLAB function `chirp` and using a sampling frequency of 200kHz. A plot of the chirp is shown below.

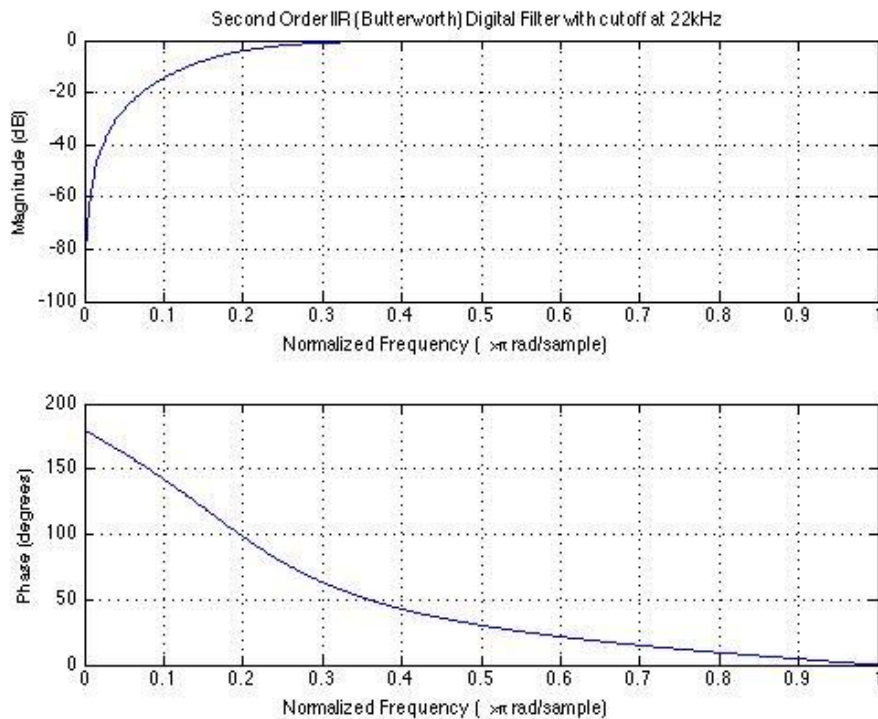


Digital High-Pass Filter

After the chirp is sent, the ultrasonic sound is reflected on the various surfaces in the room and sent back to the receiver transducer. Once the reflected signal is captured by the Discovery Board, the reflected signal is high-pass filtered in order to remove frequencies from the audible sound range. The high-pass filter being implemented is a second-order IIR digital butterworth filter using Direct Form 2 transpose structure. A diagram of the digital filter is shown below.



The filter coefficients were found through the MATLAB command `butter` and setting the -3dB cutoff at 22kHz. The frequency response of the designed filter is shown below.



The filter will be implemented on the Discovery Board by use of the Direct Form 2 IIR filter function in the CMSIS DSP Software Library.

Cross-Correlation/Waveform Matched Filtering

If the device is in the cross-correlation mode, the next step is to pick out the parts of the reflected signal where the chirp appears. This is done through waveform matched filtering. The reflected signal can be thought of as a collection of targets at various times plus noise. We would like a filter with an overall frequency response $H(\Omega)$ that will maximize the signal-to-noise ratio (SNR). To achieve this, consider that the spectrum of the desired output, $y(t)$, will be $Y(\Omega) = H(\Omega)X(\Omega)$, where $X(\Omega)$ is the received signal. We want to maximize the SNR at a specific time T_M . The power of the output at that instant is

$$|y(T_M)|^2 = \left| \frac{1}{2\pi} \int_{-\infty}^{\infty} X(\Omega)H(\Omega)e^{j\Omega T_M} d\Omega \right|^2$$

Now consider the case where the noise interference is white noise with a power spectral density of $N_o/2$ watts per hertz. The total output noise power is thus

$$n_p = \frac{1}{2\pi} \frac{N_o}{2} \int_{-\infty}^{\infty} |H(\Omega)|^2 d\Omega$$

and

The choice of $H(\Omega)$ that will maximize SNR can be determined via the Schwartz inequality under the form

with the equality if and only if $B(\Omega) = A^*(\Omega)$. Applying this equation to the numerator of the SNR equation gives

Thus SNR is maximized when $H(\Omega) = X^*(\Omega)e^{-j\Omega T_M}$ or $h(t) = x^*(T_M - t)$. This is called a matched filter because the waveform and the filter needed to maximize SNR are a “matched” pair. If one considers the waveform $x(t)$ and the target-plus-noise signal $x'(t)$, the output of the matched filter at time T_M would be the convolution

$$y(t) = \int_{-\infty}^{\infty} x'(s)h(t-s)ds \quad h(t) = x^*(T_M - t),$$

$$y(t) = \int_{-\infty}^{\infty} x'(s)x^*(s + T_M - t)ds$$

The second line is known as the cross-correlation of the target-plus-noise signal with the transmitted waveform. For our sensor, we will be cross-correlating the received signal with the transmitted chirp. Since our signals will be digital and therefore discrete, the discrete time-domain cross-correlation function becomes

$$y[n] = \sum_{m=-\infty}^{\infty} f[m]g[n+m]$$

where f is the chirp and g is the reflected signal. There is a frequency-domain method that utilizes the quick operation time of the Fast Fourier Transform (FFT). The equation for this is

$$Y[k] = F^*[k]G[k]$$

where $G[k]$ is the FFT of the reflected signal, $F^*[k]$ is the conjugate of the FFT of the chirp, and $Y[k]$ is the FFT of the cross-correlated output. The time domain output can be found by simply taking the Inverse Fast Fourier Transform.

Power Spectrum

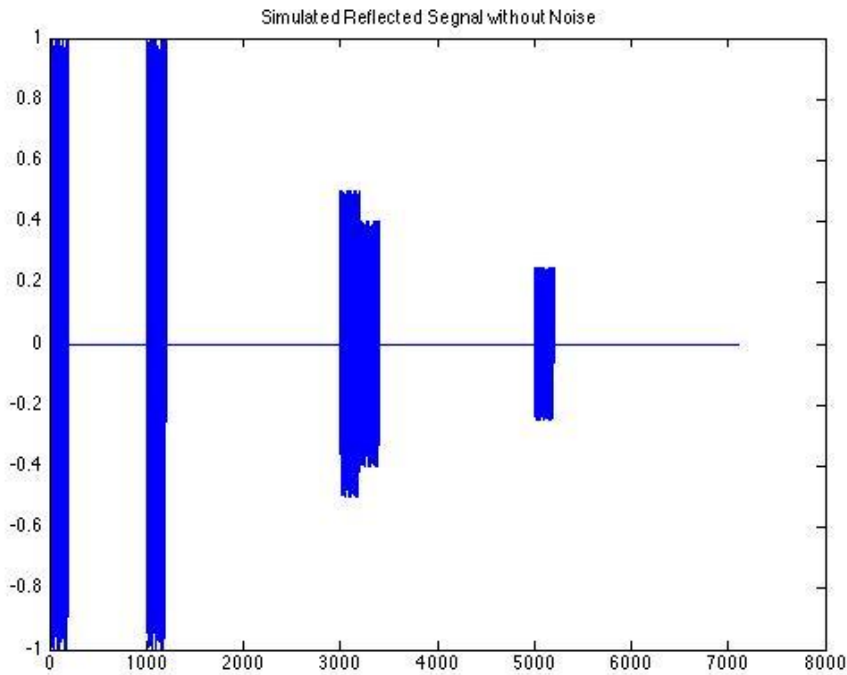
If the device is in power spectrum mode, the next step is to compute the power spectrum of the reflected signal. First, the reflected signal will be multiplied by a Hamming window in order to remove the effects of Gibb's Phenomenon. A Hamming window looks like the following

$$w[n] = 0.54 - 0.45 \cos\left(\frac{2\pi n}{N-1}\right) \quad 0 \leq n \leq N-1$$

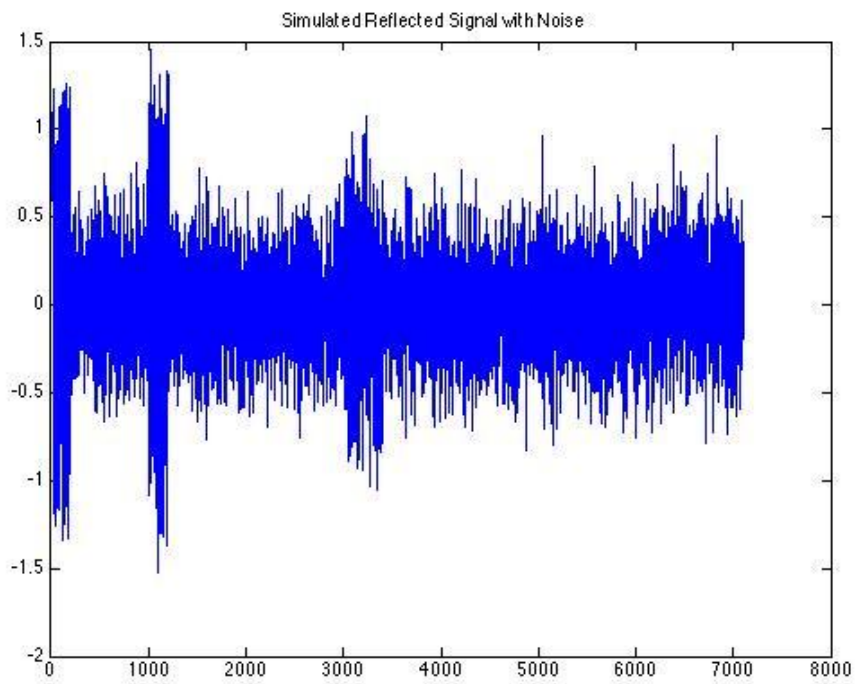
After the window is applied, the FFT of the signal is taken. The power spectrum is simply the square of the magnitude of the FFT, so after the FFT is taken, the magnitude of the FFT is computed and then squared.

Matlab Simulation Results

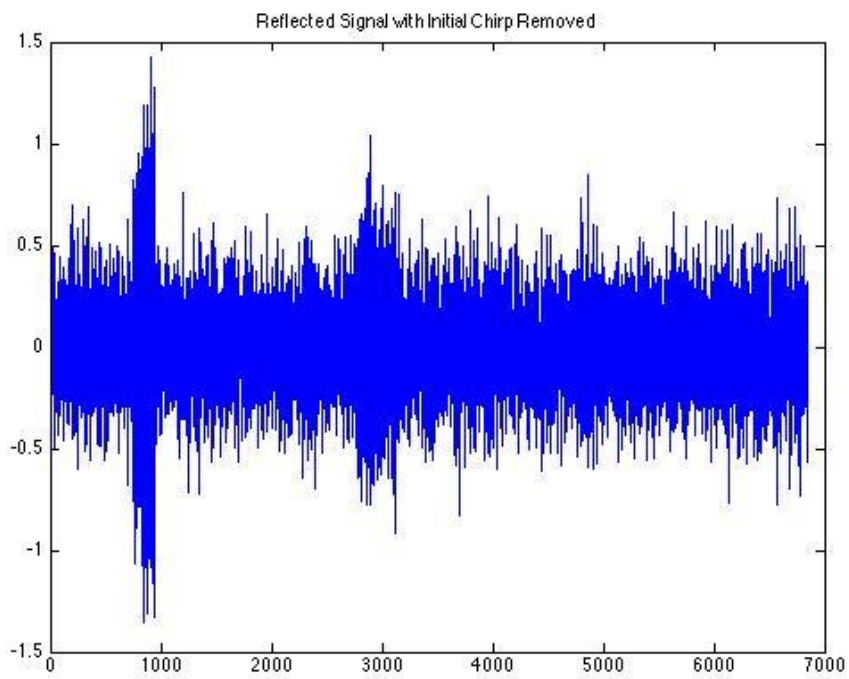
We created a MATLAB simulation in order to show the software algorithm in action. First, a reflected signal needs to be generated. This was done by first placing scaled versions of the chirp in an array at various points. The result was as follows



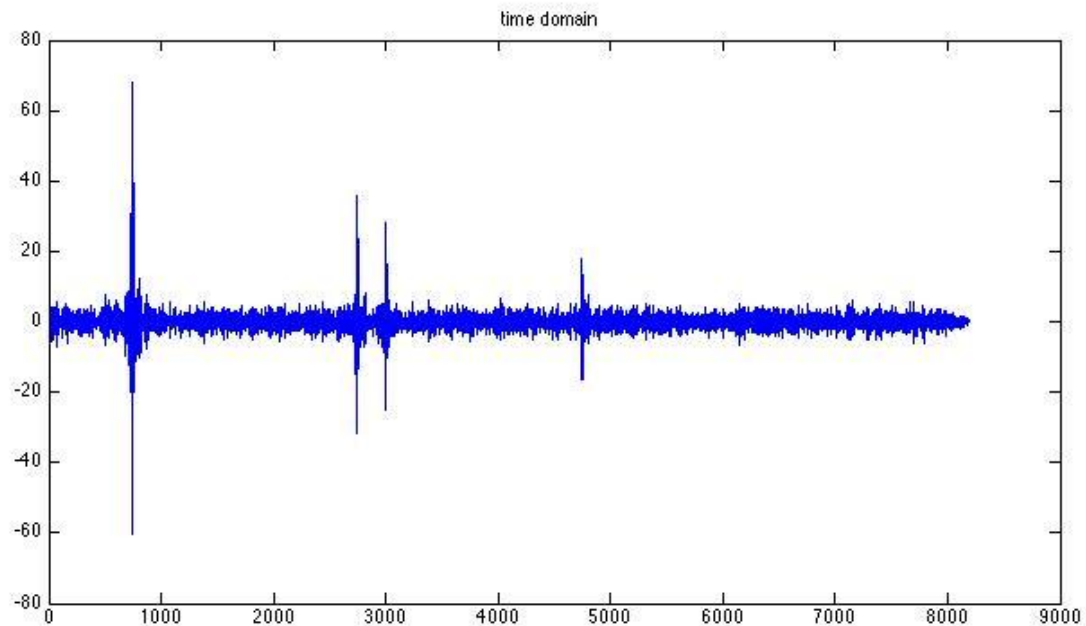
Next, noise was added to the reflected signal to properly model environmental conditions. The result was as follows



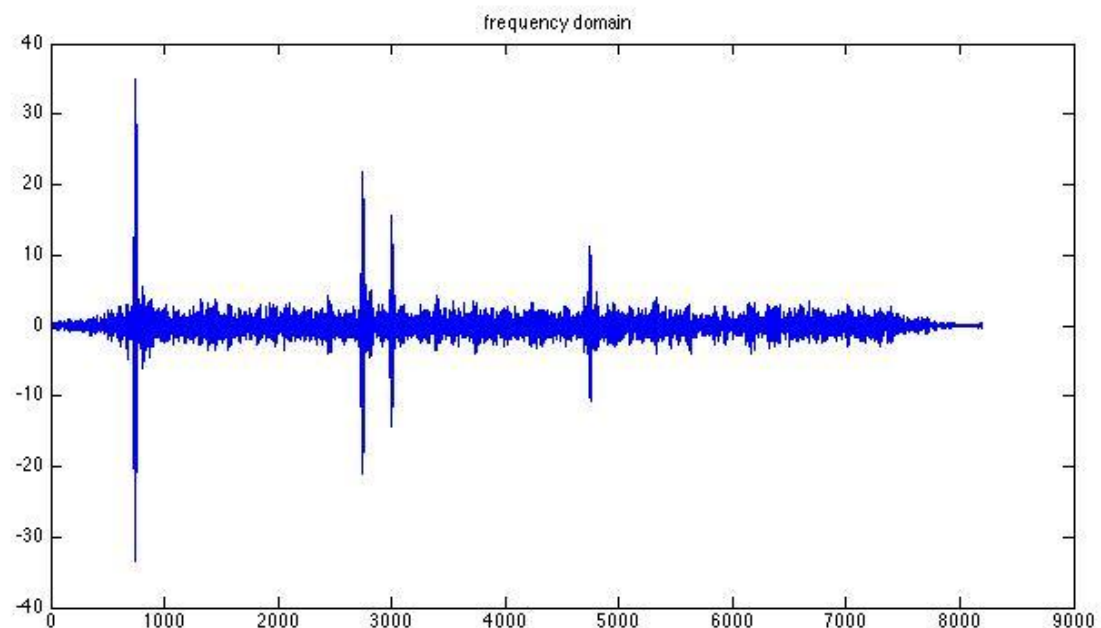
After the reflected signal was generated, it went through the high-pass filter and the initial chirp was removed. The result is as follows



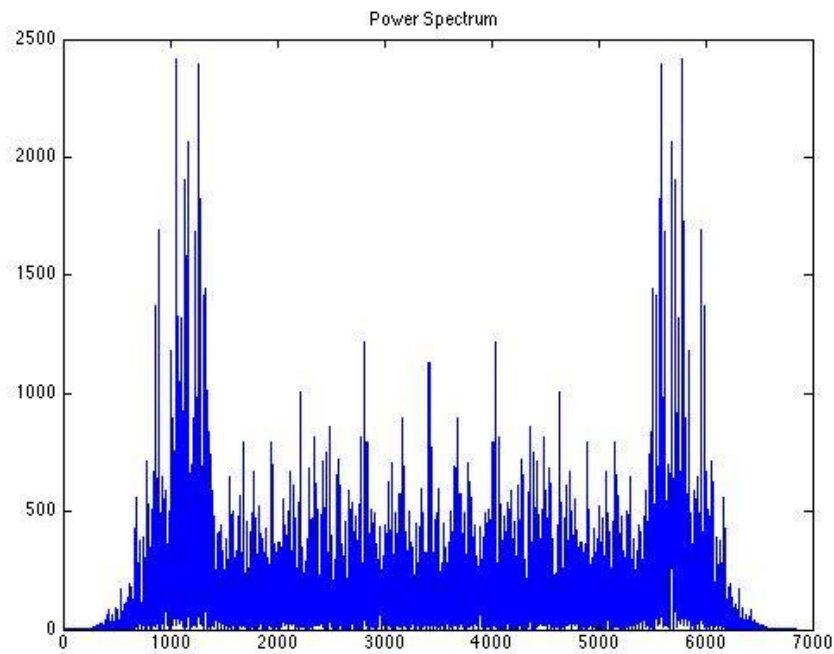
We then tested the cross-correlation using both time-domain and frequency-domain algorithms. The cross-correlation of the reflected signal with the chirp using the time-domain algorithm is shown below.



At this point, it is easy to see where in the reflected signal the chirps were actually reflected. For the frequency-domain algorithm, it was noted that the Discovery Board has a max FFT size of 2048 for the built-in optimized FFT function. Thus, the reflected signal was windowed with a 2048-point Hamming window and was done using 50% overlap in order to remove scaling issues due to the window. The resulting cross-correlation is shown below.



Comparing the two algorithms, one can see that both methods show where the chirp was reflected. Also, both outputs have very similar SNRs. After converting both algorithms into C code, we found that the frequency-domain algorithm completed twice as fast as the time-domain algorithm. For this reason, we will most likely use the frequency-domain method. We then simulated the power spectrum mode by applying a hamming window and taking the magnitude-squared of the FFT of the reflected signal. The result was as follows



3 Requirements and Verification

3.1 Testing Procedures

Requirement	Verification
1. Receiver Circuit a) Must apply correct amount of gain to map 5Vpp to 3.3V b) Must bias signal so that it becomes centered between 0 and 3.3V c) Must apply a low-pass filter with -3dB cutoff at 60kHz	1. Receiver circuit will be connected to a signal generator at the input and an oscilloscope at the output. We will use a voltage divider to supply power from the workbench. a) We will apply a 60Hz 5Vpp signal from the signal generator and make sure the output signal has a max of 3.3V.

	<p>b) We will also be able to use the 60Hz 5Vpp signal to make sure the output signal is between 0V and 3.3V.</p> <p>c) We will use the signal generator to send a frequency sweep and view the attenuation with the oscilloscope to make sure the cutoff is -3dB at 60kHz.</p>
<p>2. Transmitter Circuit</p> <p>a) Must apply correct amount of gain to map 2.2V to 4.8V</p>	<p>2. Transmitter circuit will be connected to a signal generator at the input and an oscilloscope at the output. We will use a voltage divider to supply power from the workbench.</p> <p>a) We will apply a 60Hz 2.2Vmax signal and make sure the output signal has a max of 4.8V.</p>
<p>3. Power</p> <p>a) Discovery Board must receive sufficient power from the USB source</p> <p>b) Discovery Board must supply sufficient power to power peripheral circuitry</p>	<p>3. We will be able to use a multimeter to measure the voltage and current supplied at the input of the USB power supply and the Vdd pins we are using to supply our Pre-Amp and transmitter circuits .</p> <p>a) The USB power adapter will be hooked up to line voltage through a wall socket, using a multimeter we will measure to see if it outputs at 5V.</p> <p>b) Then we will measure the Vdd ,which can be manually set in the code, using a multimeter off of the Vdd pins.</p>
<p>4. Transducers</p> <p>a) Transducers should have a flat or near flat frequency response from 22kHz to 40kHz</p> <p>b) Transducers should be able to output at around 100dB</p>	<p>4. We will drive the transducer using a signal generator and measure the voltage across the terminals using an oscilloscope. The data from the oscilloscope can be ported to MATLAB to calculate impedances.</p> <p>a) See Section 3.2 for more details</p> <p>b) We will drive the signal generator at 500Hz and 16Vpp. We will then measure the sounds pressure level using a sound level meter to verify that around 100dB are being produced.</p>
<p>5. Processing</p> <p>a) Input buffer must be able to obtain reflected signal from the ADC and then be able to send it to rest of code</p> <p>b) Output buffer must be able to obtain entire chirp signal and then be able to send it to the DAC</p> <p>c) The initial chirp in the reflected</p>	<p>5. The processing will be done on an STM32F4 Discovery Board using a Cortex-M4 DSP. Coding, compiling, and debugging of the DSP will be handled by the program Keil uVision which is pre-installed on the lab computers.</p> <p>a) We will connect a signal generator to the necessary ADC pin. The signal generator will send out a 0V-1V 30kHz signal. The input buffer is working when</p>

<p>signal must be removed before cross-correlation</p> <p>d) The reflected signal must be high-pass filtered with a cutoff of 22kHz</p> <p>e) In time-domain mode, the reflected signal must be properly cross-correlated with the chirp</p> <p>f) In frequency domain mode, the hamming window must be correctly applied</p> <p>g) In frequency domain mode, the power spectrum must be correctly calculated</p>	<p>the discretized signal shows up in the correct memory location using the Keil debugger.</p> <p>b) We will connect the pin for the necessary DAC to an oscilloscope. If the chirp is sent out correctly, it will show up on the oscilloscope.</p> <p>c) The reflected signal can be viewed in memory using the debugger. Checking to make sure the initial chirp was removed is just a matter of checking the memory to see if the values were shifted in their location correctly.</p> <p>d) We will connect a signal generator to the ADC pin and an oscilloscope to the DAC pin. We will send in a frequency sweep into the Discovery Board and show the filtered signal with the oscilloscope in order to verify a -3dB cutoff at 22kHz.</p> <p>e) We will send the cross-correlated signal to a second DAC. The second DAC is set up with the express purpose of being hooked to an oscilloscope which can then output data to MATLAB for analysis.</p> <p>f) We will apply the hamming window to the reflected signal and then it will be stored in memory. We can then analyze the data in memory using the Keil debugger to make sure it corresponds to the output we expected.</p> <p>g) We will send the power spectrum signal to a second DAC. The second DAC is set up with the express purpose of being hooked to an oscilloscope which can then output data to MATLAB for analysis.</p>
<p>6. Output Link</p> <p>a) Output pin must send information correctly using USART protocols</p>	<p>6. We will hook the designated USART pin on the Discovery Board to an oscilloscope.</p> <p>a) We will program USART to output an 8 bit word which we can read using an oscilloscope at the output pin. It will be working properly when the correct 8 bit word can be read on the oscilloscope.</p>

3.2 Tolerance Analysis

The functionality of this sensor is dependent on the transducers' abilities to send and receive signals accurately in the ultrasonic frequency range. If this device does not function properly, the chirps will not be sent out and received accurately, and the determined characteristics of the room might be false. The transducers need to be able to send and receive signals within the 22kHz to 40kHz bandwidth. We will test the frequency response of our chosen transducer at the limits of this bandwidth and make sure that has a relatively flat frequency response.

We will measure this by sending out a frequency sweep from a signal generator and measure the response using an oscilloscope, testing the desired frequency range of 22kHz to 40kHz. The data can then be imported into MATLAB for plotting and analysis on a log/log scale. The goal will be to determine an upper limit to the flat frequency response nature of the transducer.

3.3 Ethical Standards and Considerations

We will make sure to adhere to the following IEEE Code of Ethics standards in the following ways:

1. to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment;

Since our sensor will emit chirps at around 100dB in the ultrasonic frequency range, we will make sure not to activate our device around any animals that can hear in this frequency range. The chirps would be very irritating and possibly damaging to their hearing.

3. to be honest and realistic in stating claims or estimates based on available data;

We will be cautious and make sure the characteristics of the room we send out are the actual characteristics of the rooms and are not distorted in any way. We will not falsify any data received or transmitted by the sensor.

6. to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations;

This project will require skills and knowledge that we have developed after years of studying in and out of the classroom. It is possible that we will come across problems that test the boundaries of our knowledge. We will make great efforts to gain this knowledge and credit the sources whenever possible.

7. to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others;

Our project group consists of two people, so we will make sure to be critical of each other's work in order to prevent errors. We are also receiving guidance from two members of Dr. Doug Jones's DSP lab, Erik Johnson and David Jun. We will make sure to credit them for their contributions.

4. Costs and Schedule

4.1 Cost Analysis

Labor:

Employee	Labor Costs
Matthew Lurie	$\$35/\text{hr} * 15 \text{ hrs/week} * 12 \text{ weeks} * 2.5 = \$15,750$
Kyle Spesard	$\$35/\text{hr} * 15 \text{ hrs/week} * 12 \text{ weeks} * 2.5 = \$15,750$
Total	\$31,500

Parts:

Item	Part Number	Quantity	Cost Per Unit	Total Cost Per Item
STM32F4 Discovery Microcontroller	STM32F407	1	\$14.55	\$14.55
Ultrasonic Transducer	WM-61A	2	\$1.92	\$3.84
PCB		1	\$20.00	\$20.00
LMC6484 Op-Amp	LMC6484	1	\$3.31	\$3.31

1kohm Resistor	40T1807	2	\$.034	\$.034
10kohm Resistor	18R3504	1	\$.05	\$.05
12kohm Resistor	89M6846	1	\$.012	\$.012
18kohm Resistor	59M6955	2	\$.077	\$.154
30kohm Resistor	59M6981	2	\$.012	\$.024
150pF Capacitor	75-562R5GAT15	2	\$1.62	\$3.24
3.3uF Capacitor	DT-35	1	\$.17	\$.17
Female Header Pin Array (2x8)	11P4167	1	\$1.53	\$1.53
USB 2.0 A to mini-USB B connector		1	\$3.96	\$3.96
Wall to mini-USB power adapter		1	\$4.99	\$4.99
Total		19		\$55.86

Total cost: \$31,500 (Labor) + \$55.86 (parts) = **\$31,555.86**

4.2 Schedule

Week	Task	Person
9/16 <i>Proposal due 9/19, 4pm</i>	<ul style="list-style-type: none"> Finalize and submit proposal Research and order transducers Start researching power circuit requirements 	Matthew Lurie Matthew Lurie Kyle Spesard
9/23	<ul style="list-style-type: none"> Circuit design Coding simulation Start writing design review 	Kyle Spesard Matthew Lurie Kyle, Matt

9/30 <i>Design Review</i>	<ul style="list-style-type: none"> • Finalize design review • Start PCB design 	Matthew Lurie Kyle Spesard
10/7	<ul style="list-style-type: none"> • Finish and submit PCB order • Put together parts list • Program input output buffers 	Matthew Lurie Kyle Spesard Kyle Spesard
10/14	<ul style="list-style-type: none"> • Program highpass filter • Program cross-correlation 	Matthew Lurie Kyle Spesard
10/21 <i>Individual Progress Reports due 10/24, 4pm</i>	<ul style="list-style-type: none"> • Program frequency-domain mode • Create mock-up 	Matthew Lurie Kyle Spesard
10/28	<ul style="list-style-type: none"> • Tolerance analysis • Debugging 	Matthew Lurie Kyle Spesard
11/4 <i>Mock-up Demos</i>	<ul style="list-style-type: none"> • Get base features running • Debugging 	Kyle Spesard Matthew Lurie
11/11 <i>Mock-up Presentations</i>	<ul style="list-style-type: none"> • Start coordinating with Haptic Array group • Debugging 	Kyle Spesard Matthew Lurie
11/18 <i>Thanksgiving Break</i>	<ul style="list-style-type: none"> • Enjoy Thanksgiving! 	
11/25	<ul style="list-style-type: none"> • Verifications of specs • Debug with other project 	Matthew Lurie Kyle Spesard
12/2 <i>Demos/Presentations</i>	<ul style="list-style-type: none"> • Prepare presentation • Prepare demo • Final paper 	Matthew Lurie Matthew Lurie Kyle Spesard
12/9 <i>Presentations, Final Papers due, Lab Notebooks due, Checkout</i>	<ul style="list-style-type: none"> • Finalize final paper 	Kyle Spesard

References

1. "Cross-correlation." *Wikipedia*. Wikipedia, September 26, 2012. Web. 30 Sep 2012. <<http://en.wikipedia.org/wiki/Cross-correlation>>.
2. "IEEE Code of Ethics." *IEEE*. N.p., 2012. Web. 30 Sep 2012. <<http://www.ieee.org/about/corporate/governance/p7-8.html>>.
3. "LMC6484 Datasheet." *Texas Instruments*. N.p., n.d. Web. 30 Sep 2012. <<http://www.ti.com/lit/ds/symlink/lmc6484.pdf>>.
4. "Panasonic WM-61A Datasheet." *Panasonic*. N.p., n.d. Web. 30 Sep 2012. <http://www.panasonic.com/industrial/components/pdf/em06_wm61_a_b_dne.pdf>.
5. Richards, Mark A. *Fundamentals of Radar Signal Processing*. McGraw-Hill, 2005. Print.
6. "RM0090 Reference Manual." *ST*. N.p., n.d. Web. 30 Sep 2012. <http://www.st.com/stonline/stappl/st/com/TECHNICAL_RESOURCES/TECHNICAL_LITERATURE/REFERENCE_MANUAL/DM00031020.pdf>.
7. "STM32F407xx Datasheet." *ST*. N.p., n.d. Web. 30 Sep 2012. <http://www.st.com/internet/com/TECHNICAL_RESOURCES/TECHNICAL_LITERATURE/DATASHEET/DM00037051.pdf>.
8. "STM32F4 User Manual." *ST*. N.p., n.d. Web. 30 Sep 2012. <http://www.st.com/internet/com/TECHNICAL_RESOURCES/TECHNICAL_LITERATURE/USER_MANUAL/DM00039084.pdf>.