Technologies for Safe & Efficient Transportation

THE NATIONAL USDOT UNIVERSITY TRANSPORTATION CENTER FOR SAFETY

Carnegie Mellon University | UNIVERSITY of PENNSYLVANIA

Bus-Turn Detection and Pedestrian Warning System

FINAL RESEARCH REPORT

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ESE Senior Design

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Direct Decibels

A Directed Audio Warning System for Visually Pedestrians at Crosswalks

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Advisor:

Dr. Daniel D. Lee

A) Executive Summary

Over the past two semesters, we designed and implemented a directed speaker to improve crosswalk safety for blind pedestrians. This report documents our design process, results, and outlook, in the following sections:

1. Overview of the Problem

We analyze current pedestrian warning speakers, and highlight safety concerns due to omnidirectional sound (sound that spreads evenly in all directions). We also study the livability concerns of current speakers that blare sound in all directions.

2. Method of Solution

We present our solution, which incorporates directed audio and face detection. We show how this simultaneously solves the problem of safety and noise pollution in current warning systems. Since directed audio is a novel technology, we present the physical theory behind how it works.

3. Design and Iteration

We discuss the nuts and bolts of our implementation of the directed speaker. We show how our design improved throughout the course of the semester, after evaluation and feedback.

4. Logistical Details

We present the budget, general minutes of our meetings with our advisors, and our progress report at different stages of the semester.

5. Conclusion

We discuss the impact that our solution achieves, and what we learned from the process. We present our outlook on future work that can be done for this project.

6. Appendix

We include PCB designs, and code listings to document the design process of our speaker.

B) Overview of the Problem

Intersections are dangerous places, especially for the visually impaired. Regular pedestrians take for granted that they rely on a set of visual markers in order to get across to the other side, such as the Walk Sign Indicator, and painted strips along the road, as seen in Figure 2.

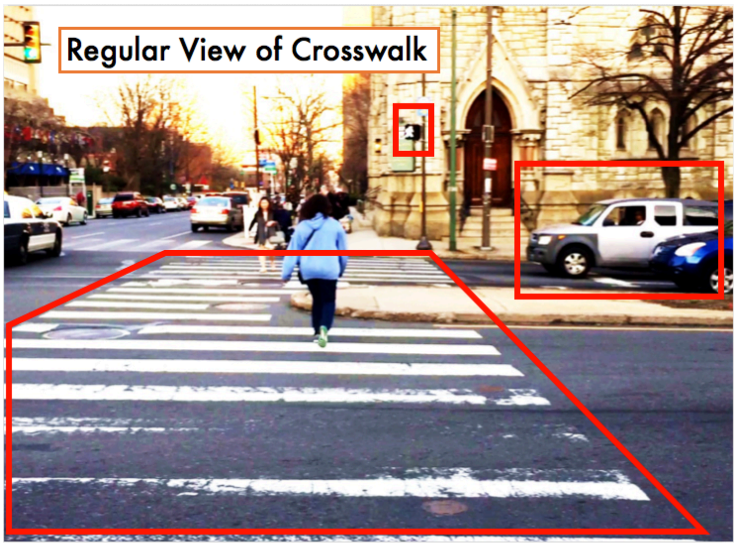

Figure 2: Visual markers to guide pedestrians across

For a blind pedestrian however, the visual markers do not help. The following image shows what a blind pedestrian with central vision loss my see:

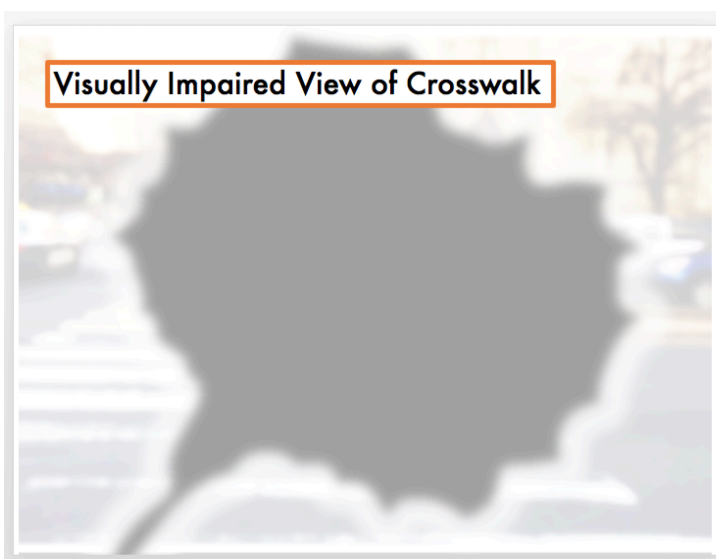

Figure 3: View of crosswalk with central vision loss

Without a sense of sight, they have difficulty answering a set of basic questions:

1. Where does the crosswalk begin?
2. When should I start walking?
3. Which direction should I walk in?
4. Are the cars turning toward me, or away from me?

There are current audio warning systems that emit a chirp or speech tone to guide to blind pedestrians across. A common button-press system with a speaker is shown in Figure 3:

Figure 3: Current audio warning system

However, these audio systems are not easily localized by the visually impaired, making it hard for them to walk safely toward the other side. A study[1] on crosswalk safety tests for blind pedestrians conducted by the ACB[2], AER[3] and SKERI[4] presented the following data:

1. On 34% of trials, blind pedestrians started crossing at the wrong time
2. On 52% of trials, blind pedestrians started crossing in the wrong direction

This clearly shows the need for a safer warning system.

Furthermore, these warning sounds blare out in all direction, creating a noise nuisance for surrounding residents. In cities already saturated with noise from construction and emergency vehicles, hearing a constant warning can be exasperating.

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[1] Barlow *et al.* “Accessible Pedestrian Signals: Synthesis and Guide to Best Practices”, National Cooperative Highway Research Program, May 2003.

[2] American Council for the Blind

[3] Association for the Education and Rehabilitation of the Blind and Visually Impaired

[4] Smith-Kettlewell Eye Research Institute

When SEPTA installed an additional audio warning for pedestrians on their buses, residents reacted negatively to the noise, as shown in the following blog post[5]:

SEPTA Buses Are About to Get Even Louder and More Annoying

Here's why.

BY VICTOR FIORILLO | MARCH 10, 2016 AT 4:27 PM

SHARE 173 TWEET 3 g+1 0 Pin it 0 EMAIL 2 18 COMMENTS

Photo by Jeff Fusco

Figure 4: Blog headline about installation of audio warnings on SEPTA buses

The summary of the problem with current audio warning systems, is that they are too soft for blind pedestrians, and too loud for surrounding residents.

[5] http://www.phillymag.com/news/2016/03/10/septa-bus-turn-warning/

C) Method of Solution

To solve the challenges in current audio warning systems, we wanted to design a safer and smarter pedestrian warning speaker. Over the course of the 2 semesters, we developed our solution that incorporates directed audio and face detection. Our solution consists of the following parts:

A) Directed Audio

Directed audio is sound that travels in a concentrated narrow beam. To achieve higher directivity, we designed our speaker to comprise several columns of multiple rows of ultrasonic transducers. The transducers used emitted an ultrasonic wave (~40 kHz) which feature lower wavelengths than conventional sound speakers. The shorter wavelengths of these transducers are what allowed our parametric speaker to produce the narrow sound beams. As these high frequencies in a narrow beam travel through air, nonlinearities in air pressure demodulate the frequencies back to the audible domain.

The explanation for how the frequencies get demodulated into the audible domain is as follows: Suppose the input audible frequency is 1 kHz. This signal is pulse-width-modulated at 40 kHz, producing the following frequency spectrum:

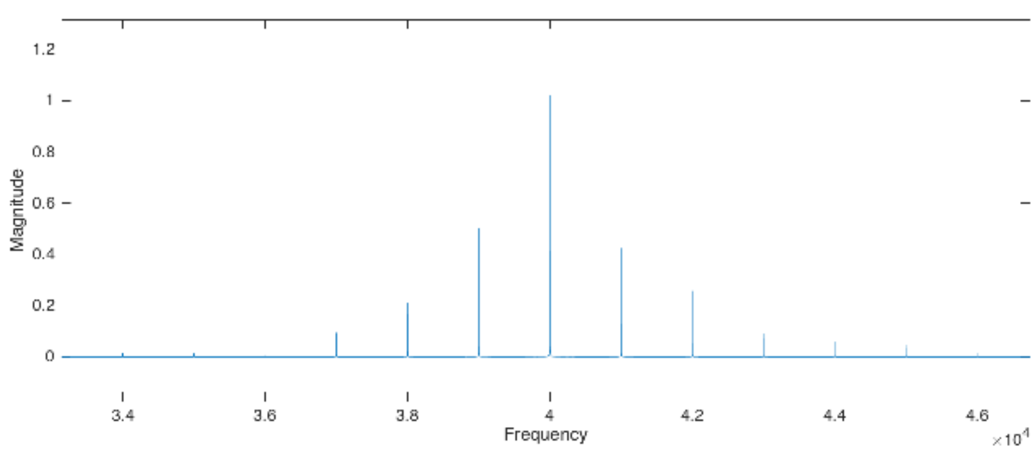


Figure 5: Frequency spectrum of modulated signal

As these frequencies travel through air, *difference frequencies* are produced, with the strongest frequency being 40 kHz – 39 kHz = 1 kHz. Thus, audible sound is produced, albeit not perfectly, but in a highly directional carrier beam.

B) Phased Array

In order to effectively target pedestrians attempting to cross, we implemented a phased array which is used to shift the direction of the beam of sound. This allowed for automated tracking of pedestrians before and while they are crossing the crosswalk.

The theory of a phased array is shown in the following diagram and explanation:

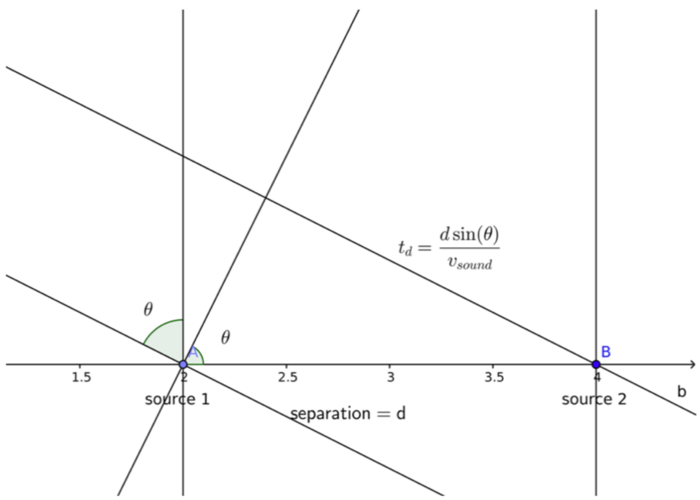


Figure 6: Geometric diagram of a phased array

Consider two sound sources placed at at separation *d* from each other. In order for the two sources two form a maximum at an angle θ from normal, one source needs to be delayed with a time t_d such that the the signal from the other source covers a little distance first. Then the waves from both sources would constructively interfere at an angle. The exact relation between the time delay and the angle, can be calculated from trigonometry, as shown in the diagram.

To implement the time delay, we programmed an FPGA to cascade many shift registers together. The time delay between each shift register is then the clock period of the FPGA.

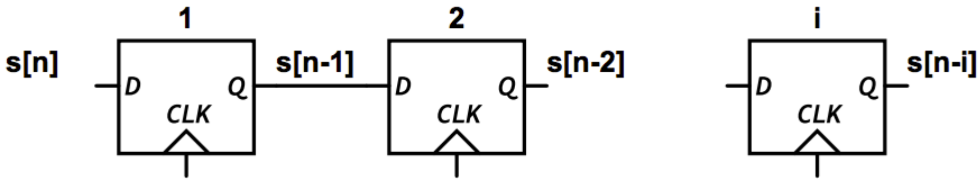


Figure 7: Delay implemented in the FPGA

The following is a sample calculation for the number of shift registers N_{SR} needed to achieve a beam angle of 30°, with the separation *d* at 1 cm, FPGA clock at 50 MHz:

$$t_d = \frac{d\sin(\theta)}{v_s} = \frac{0.01 \times \sin(30)}{340} = 1.47 \times 10^{-5}s$$
$$N_{sr} = t_d \times f_{clk} = 1.47 \times 10^{-5} \times 50 \times 10^6 \approx 735$$

C) *Face Detection*

We combined the phased array with face detection so that the sound beam would track a pedestrian's face. We utilized OpenCV's face detection libraries in our implementation. The library provided classifiers, which were trained over a database of faces to determine a set of features that would classify a face. We then applied to those classifiers to each video frame of a camera, and were locate faces in the frame. From the pixel coordinate of the pedestrian, we extracted the angle of the pedestrian relative to the camera, as shown in the following figure:

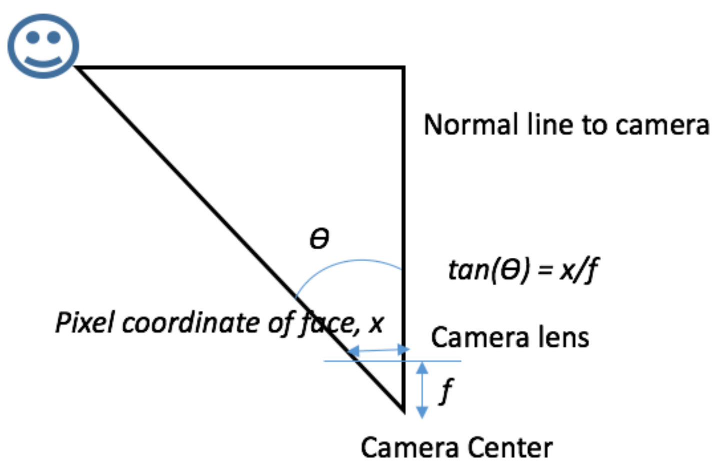


Figure 8: Extracting the angle from pixel coordinates

D) Amplifier Circuit

Each column was connected to its own individual amplifier to allow for each column receiving the sound waveform at a different phase which allowed for control of the direction of the beam of sound. This required a larger area for our amplifier circuit, but allowed for more control of the sound beam if we were to use an amplifier that powered all the columns of the speaker circuit. We designed the following amplifier that would be reproduced easily for all columns.

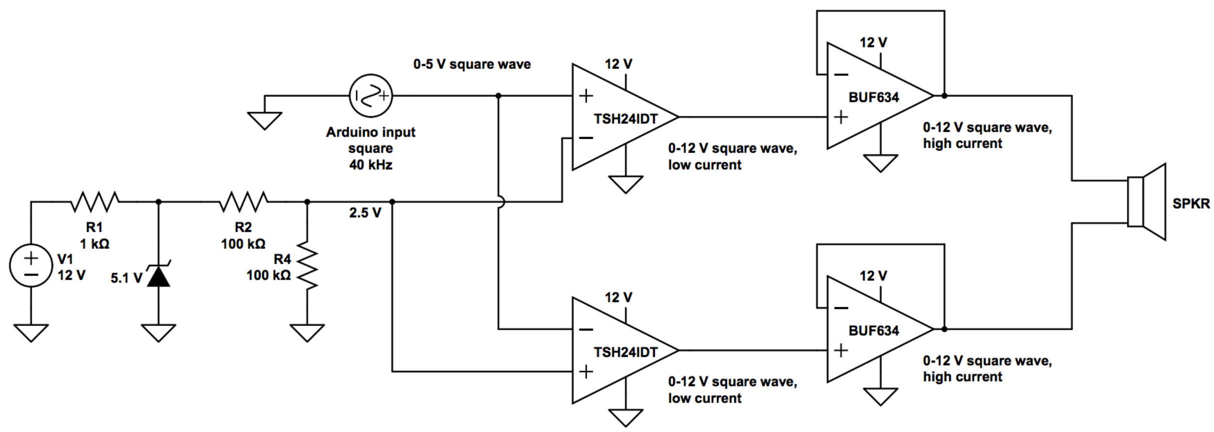


Figure 8: Schematic for amplifier circuit

To produce more compact and effective circuits, we utilized eagle software tool to design and create or own printed circuit boards for our amplifier and speaker circuits. The PCB circuits made our design cleaner, more efficient, and produced a greater quality of sound compared to the bread board circuits.

A summary of our signal processing blocks is shown in the diagram below:

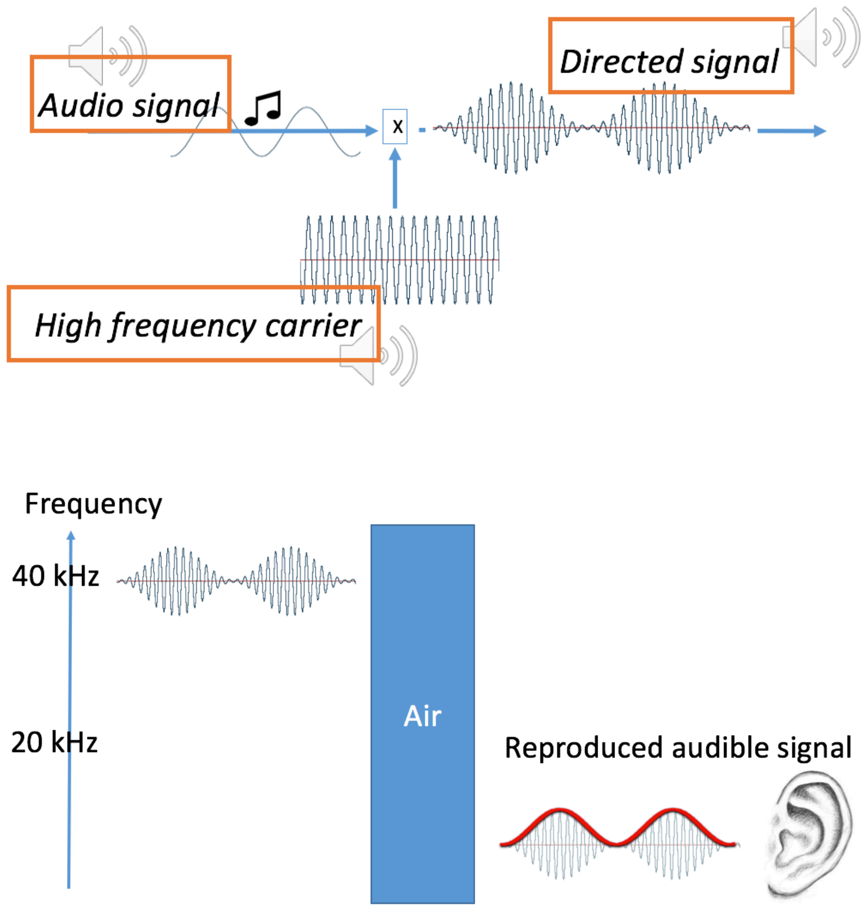


Figure 9: Signal Processing to produce directed audio

D) **Design and Iteration**

We implemented several design iterations throughout the year. After each iteration we gained feedback from our advisor and and evaluated it by testing it ourselves. A summary of our 4 major iterations is summarized below:

Protoype 0 (Early Fall 2015)

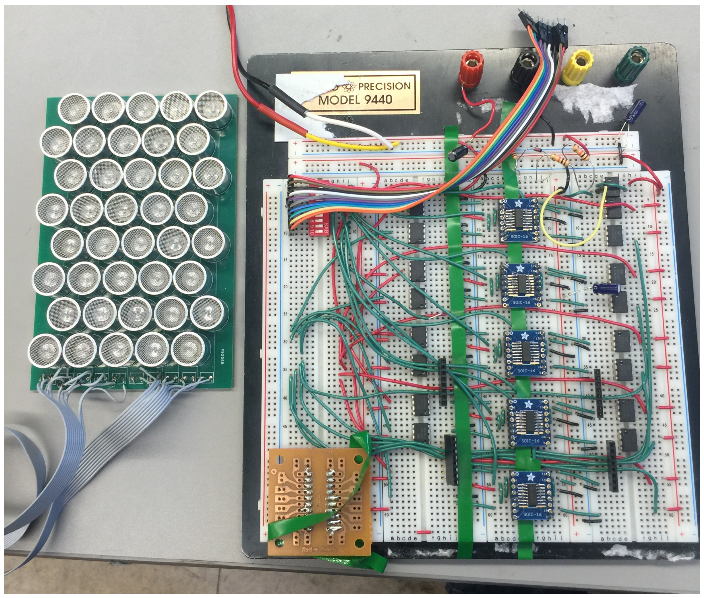


Figure 10: Protoype 0 looking wiry

Our first design was implemented on a bread board. We got the signal processing to work on an Arduino, and worked on improving the circuit design for higher power sound. The transducers are powered by square voltage pulses from 0V to 12V, but the output signal of the Arduino used to produce the waveform ranges from 0V to 5V. This requires the voltage signal to be amplified. The signal from the Arduino is fed to two comparators, with the plus pin on one set to 2.5V and the minus pin on the other also set to 2.5V. The Arduino output is fed to the remaining pin of each comparator, producing two square waveforms that are 180 degrees out of phase and with a voltage swing of 12V. The current output of these comparators was not high enough to produce a strong enough audio volume, however, so an additional stage with a unity voltage gain and strong current amplifier was needed to power the transducers. The circuit in Figure 8 was finally implemented.

Prototype 1 (Fall 2015 Demo Day)

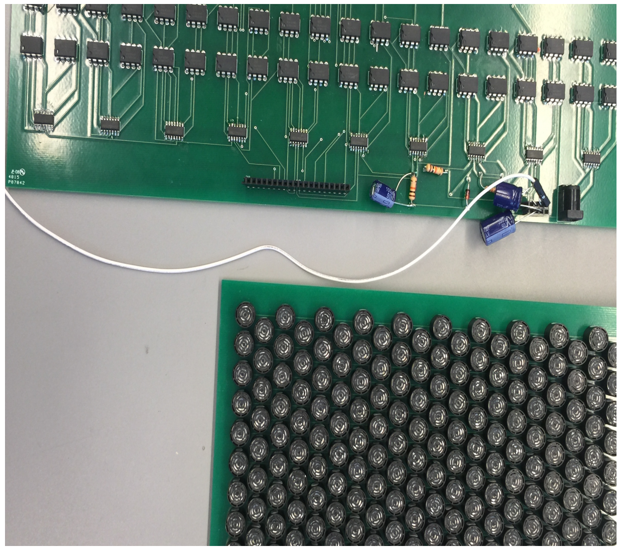


Figure 11: Prototype 1

We worked on getting new transducers that were smaller and more powerful, and laying everything out on a PCB. We also implemented the phased array delay on an FPGA, and laid out the amplifier on a PCB.

We tested out the phased array and collected data on the beam angle through the following experimental setup:

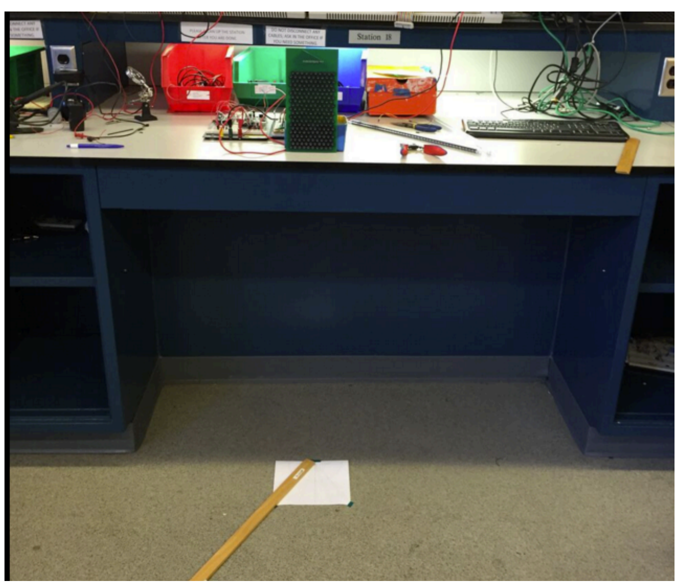
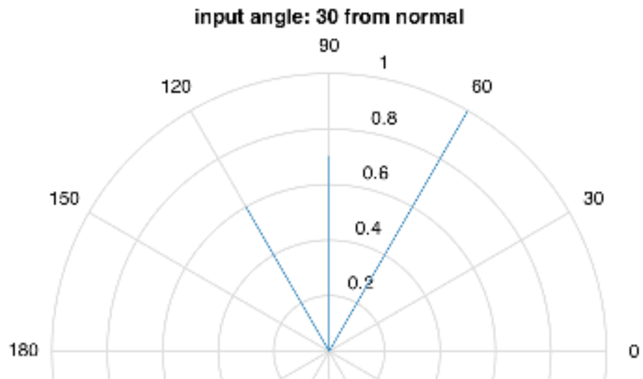
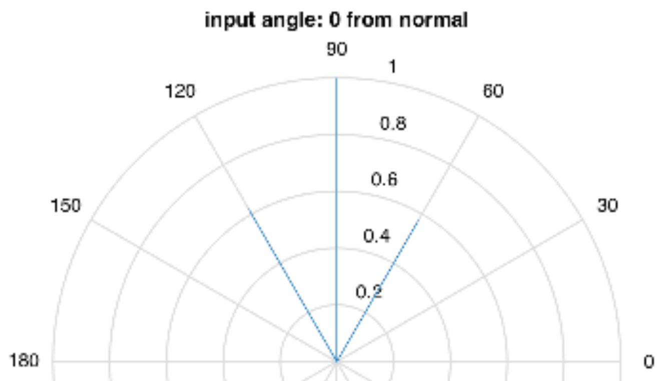


Figure 12: Experimental setup in the Detkin Lab

The table of dB readings are shown below, with their normalized polar plots:

Angle of Measurement	**dB Measurement (dB) at Input Angle**		
	-30°	**0°**	**30°**
-30°	106	67	63
0°	67	108	74
30°	74	62	105





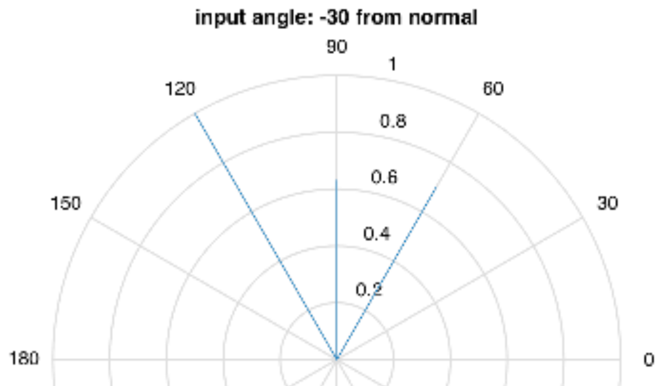


Figure 13: Data from testing of phased array

The results show the speaker was effective at producing highly directional sound.

We gathered feedback from our advisor Dr. Lee, and he was pleased with our progress on the phased array. He recommended that we next focus on designing an enclosure for the speaker, and making the wiring easy to set up.

Prototype 2 (Mid Spring 2016)

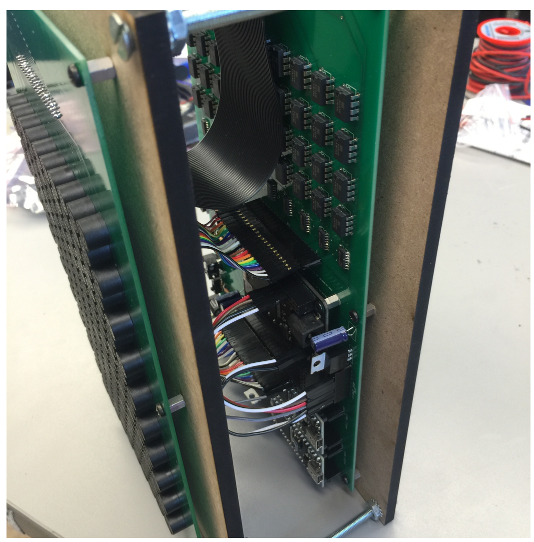


Figure 14: Enclosure for speaker

We thus designed an enclosure and improved the user design. We added intuitive input switches and an audio jack for easy configurability. We changed the microcontroller platform from the Arduino to MBED. We also worked on face detection, and got it to work by connecting a laptop to an on-board MBED.

Final Product (Spring Demo Day 2016)

Figure 15: Final Product

We designed a similar board as Protoype 2 with slight improvements to the layout of the circuit, for easier assembly. With this product, we were able to conduct testing outside and verify that the audio was loud enough even in traffic conditions to guide pedestrians across the street.

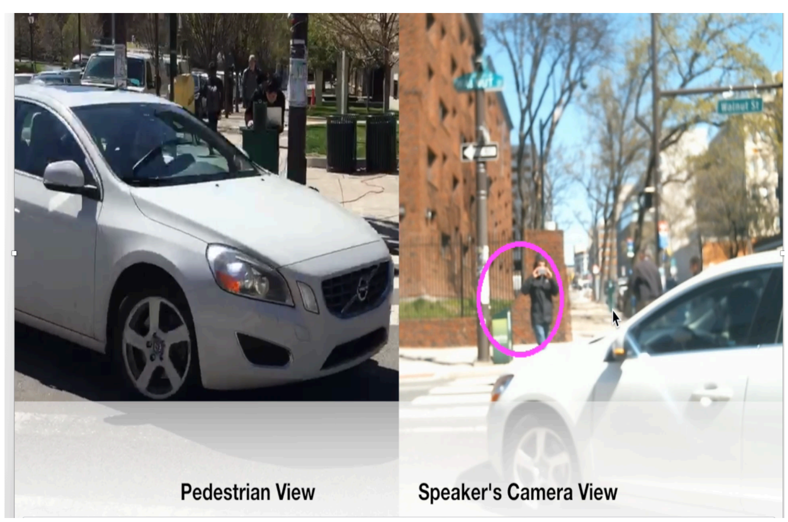


Figure 16: Outdoor testing

E) Summary of meetings

Dr. Lee, Alfred, and Marcus on Jan 19th

We discussed the direction of Direct Decibels for the new semester. Specifically, we went over designing a new enclosure of our system and implementing all our circuits and microcontrollers onto a single PCB to ease execution of any demos.

Siddharth Deliwala, Dwight Jaggard, Alfred, and Marcus on Jan 28th

During this meeting we discussed the present status of our project and what plans we had for the future. We presented our plan to use a camera and face detection to supplement our pedestrian warning system.

Dr. Lee, Alfred, and Marcus on Feb 16th

This was our second meeting with our advisor Dr. Lee. In this meeting we presented the latest prototype with the new circuit boards and enclosure and received advice on where to take the project next. Discussion about implementing face detection software with our product was held.

Dr. Lee, Alfred, and Marcus on March 15th

This marks our last meeting with our advisor Dr. Lee. During this meeting we gave a short demo of our project using face detection software to control the angle of our directed audio. Dr. Lee helped us plan out recording video footage of Direct Decibels being implemented in actual crosswalk.

Siddharth Deliwala, Alfred, and Marcus on April 19

After the ESE demo day, Marcus and Alfred met with Sid on April 19th to go over preparing for the SEAS wide senior design competition. During this meeting we discussed presenting Direct Decibels as a platform of software controlled directed audio that has universal applications in automated alert systems for automobiles and reducing public noise pollution.

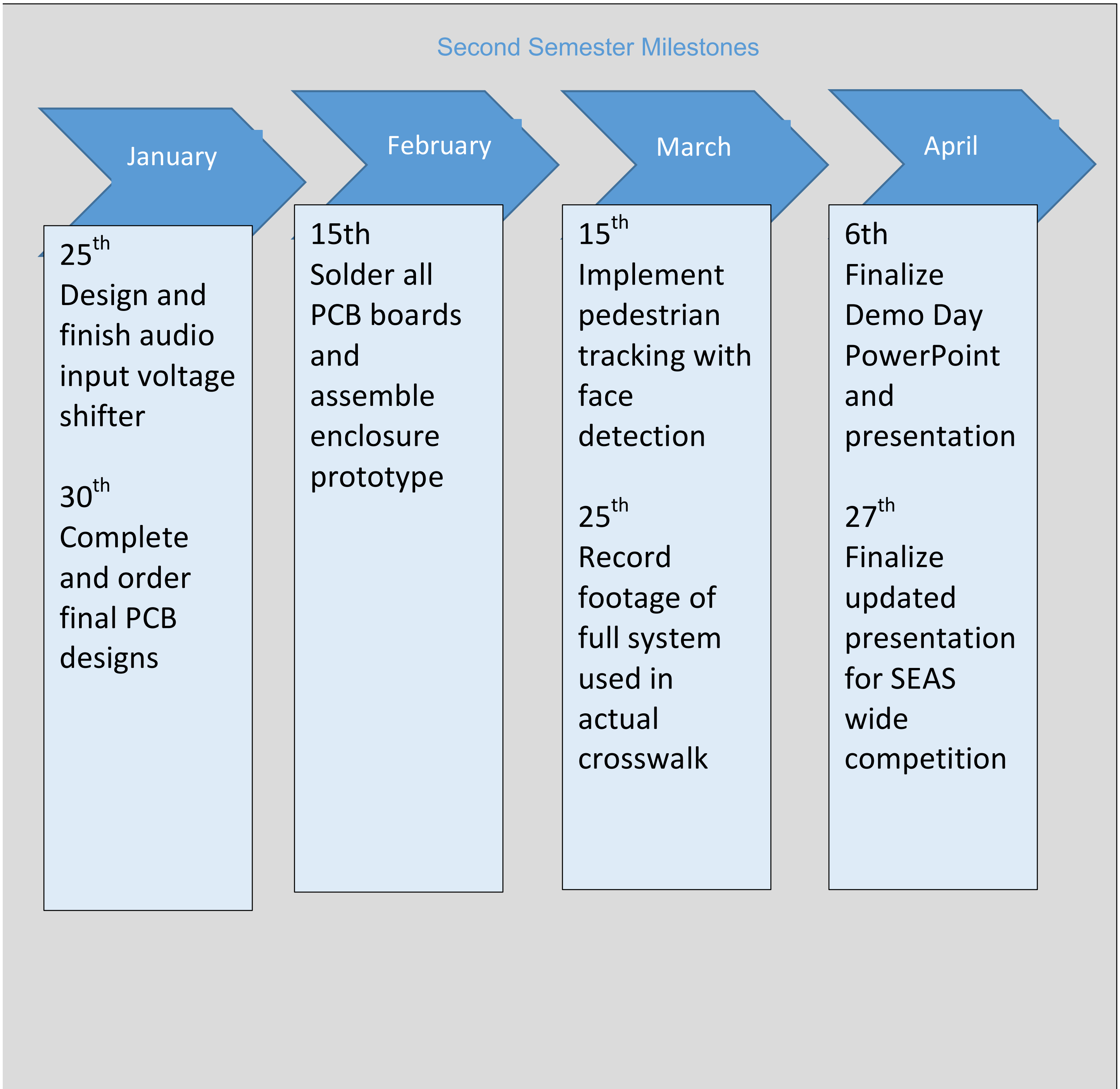
Siddharth Deliwala, Alfred, and Marcus on April 21st and 25th

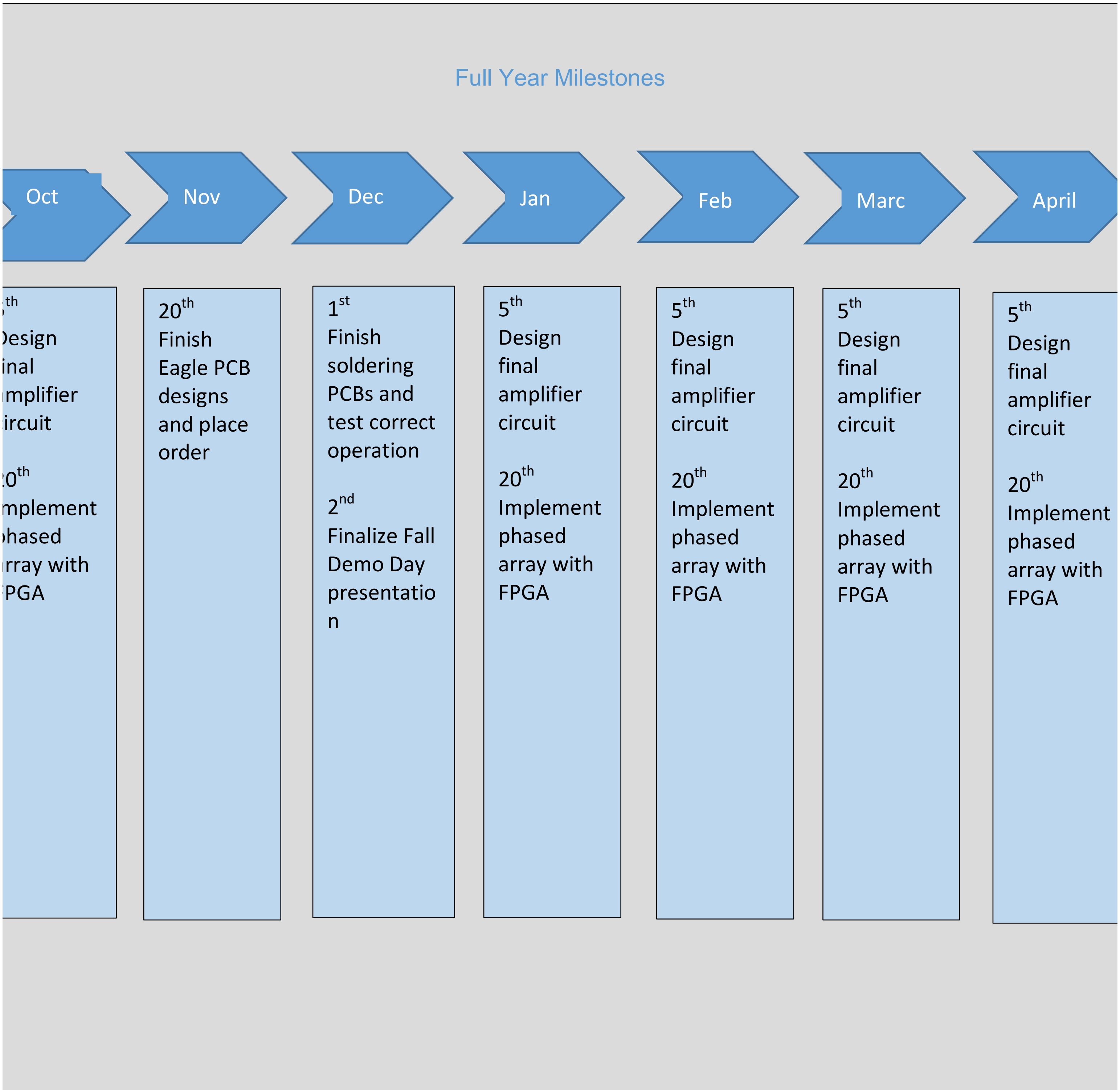
Our team met with Sid on April 21st and 25th to rehearse our presentation for the SEAS wide competition. We presented and received comments and tips on polishing up our presentation.

Alfredo Muniz, Sade Oba, Asura, Going Viral, Alfred, and Marcus April 23

On April 23rd our team, as well as the Going Viral and Asura, rehearsed with the TA's Sade Oba and Alfredo Muniz. During this rehearsal we each listen to the feedback given to each team to improve their presentations. A main point given after these rehearsals was to state the problem your project is trying to solve before introducing ourselves.

F) Milestones

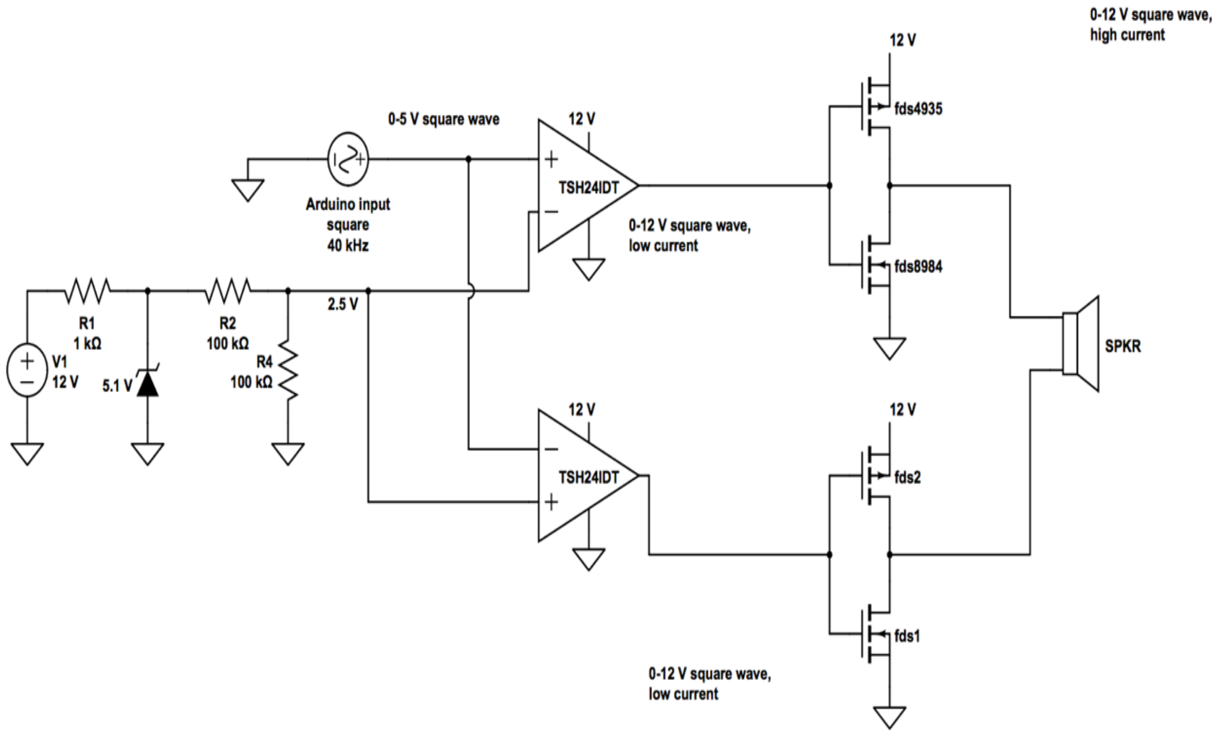



Full Year Milestones
Oct
Nov
Dec
Jan
Feb
Marc
April
esign inal mplifier ircuit
0th mplement hased rray with PGA
20th Finish Eagle PCB designs and place order
1st Finish soldering PCBs and test correct operation
2nd Finalize Fall Demo Day presentation
5th Design final amplifier circuit
20th Implement phased array with FPGA
5th Design final amplifier circuit
20th Implement phased array with FPGA
5th Design final amplifier circuit
20th Implement phased array with FPGA
5th Design final amplifier circuit
20th Implement phased array with FPGA

G) Budget

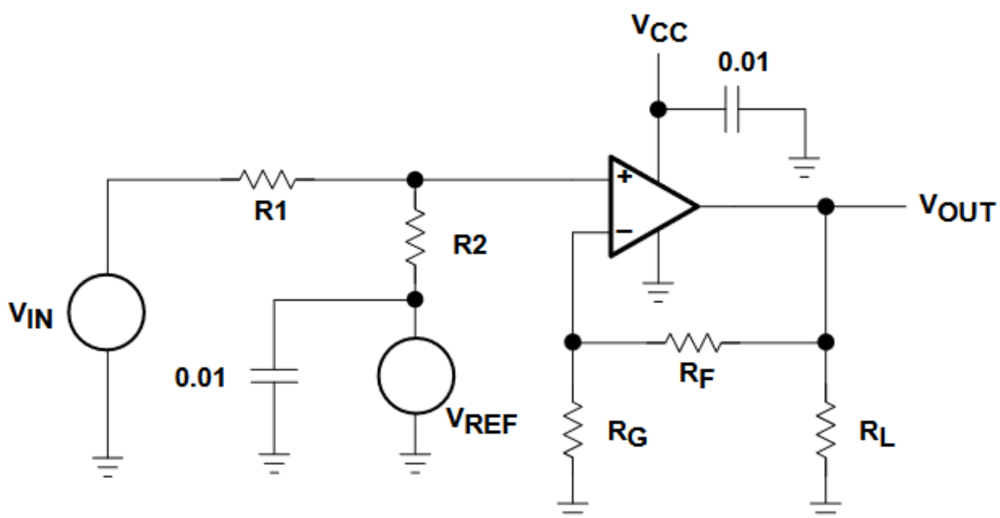
Item	Price
TSH24IDT Voltage Amplifiers (10 chips)	$10.00
BUF634 Current Amplifiers (40 chips)	$280.00
PCBS	$115.00
MBEDS (2)	$120.00
HD Camera	$80.00
Ultrasonic Speakers	$200.00
Total Budget	$805.00

An option we could take to lower the cost of our system would be to replace the expensive BUF634 current amplifiers with cheaper FDS4935 and FDS8984 transistors that would fill an identical role. The new, cheaper circuit is shown below.


0-12 V square wave,
high current
12 V
fds4935
0-5 V square wave
12 V
TSH24IDT
Arduino input
square
40 kHz
0-12 V square wave,
low current
fds8984
2.5 V
R1
1 kΩ
R2
100 kΩ
R4
100 kΩ
V1
12 V
5.1 V
SPKR
12 V
12 V
TSH24IDT
fds2
fds1
0-12 V square wave,
low current

H) Work in Second Semester

The beginning of the semester we met with our advisor on the 19th of January to discuss the direction of the project moving forward. To clean up our system and make it easier to demo and test, we needed to make a more compact and cleaner prototype. We used Eagle software to design more efficient PCB boards and made a new enclosure for the project with laser cut boards. We also designed and added a couple new circuits to our system. To play audio from external sources such as an iPhone, we needed to design a circuit to shift and amplify the audio sample to be sampled by the MBED. Typical audio from a smartphone produces and audio signal from around -.5V to .5V, and since our MBED only samples from 0 to 3V we used the circuit below to shift and amplify the signal.



Vout = Vin(R2/(R1 + R2))((Rf + Rg)/Rg) + Vref(R1/(R1 + R2))((Rf + Rg)/Rg)

This circuit shits the audio signal upwards out of the negative voltage region by adding a reference voltage to it as well as amplifies the original signal. Using this circuit, we were successfully able to sample external audio and play it with our directed audio ultrasonic transducers. Unfortunately, there is a noticeable distortion of the audio as the ultrasonic wave demodulates back into the audible range. While this distortion is undesirable if one is using the system to play music for entertainment, it has no significant consequence if the goal of the speaker is to simply produce a loud warning signal.

During the second meeting with Dr. Lee on February 16th, we presented our new prototype of Direct Decibels. This prototype combined the amplifier and speaker circuits all together in one enclosure. In addition, manual control of the audio angle was added to the system by using an adjustable potentiometer circuit that sent an analog signal to one of our MBEDs. The next step of our project at this point was getting a face detection algorithm to control the angle of our directed audio. We selected a digital camera that would be mounted onto the top of our speaker system that would send the video feed to a laptop. Throughout late February to the middle of March, we worked on using a face detection algorithm to control the angle of our speaker phased array. We programmed one of our MBEDs, that was connected to the laptop with the camera feed, to produce a digital select signal based on the position of the detected face in the camera feed. This digital select signal is an input to our FPGA which in turn implements the phased array angle by adding a distinct delay to each of the speaker columns depending on the signal.

On March 15th we met with Dr. Lee again to demonstrate the control of our audio beam using our new face detection software. Remaining work on our project after this was capturing footage of our system being used in an actual busy crosswalk. After testing our product outside, we realized we needed a better method to select a pedestrian to be tracked. In response that this, we added a functionality to click on a person in the camera feed. Once clicked on, the face detection would lock onto the pedestrian and stay on them until the camera loses track of that face. Using this added functionality, we were able to record a successful tracking of a pedestrian crossing the street with the audio constantly directed towards them throughout the crossing.

In the midst of preparing for our Final ESE Demo Day, we had the privilege of given a demo of our project at the Safety Summit in Washington D.C. on March 30. At this summit we got to see other engineers working on different ways to improve traffic and automobile safety. While discussing our project and hearing the input of the other engineers here, we gathered different ideas on how to expand the scope of our project. The trip was an invaluable experience that we took into the ESE demo day not long afterwards.

I) Conclusion

At the conclusion of second semester, we had an operational pedestrian warning system that can track a selected individual as they move across the street. Direct Decibels was effective of accomplishing our group goals of producing a louder, localized warning system compared to current systems while simultaneously reducing noise pollution into the surrounding areas. Despite these accomplishments, a few steps must be taken in order to successfully implement our system into an actual crosswalk. One problem that is left to be addressed is pinpointing a visually impaired pedestrian an ensuring the face detection remains locked on until they finish crossing the street. Currently, we have a few different proposals on how to accomplish this feat. One solution is having the pedestrian press a button on the other side of the street that will allow a camera system to track the individual that is right at the location where the button is placed. This button could be implemented right next to a pedestrian crossing button. An alternative solution would be having a visually impaired pedestrian in possession of some device that would be synced to the pedestrian tracking system. Once the pedestrian is near the crosswalk, they would activate the mobile device and allow the face detection program to pinpoint their position.

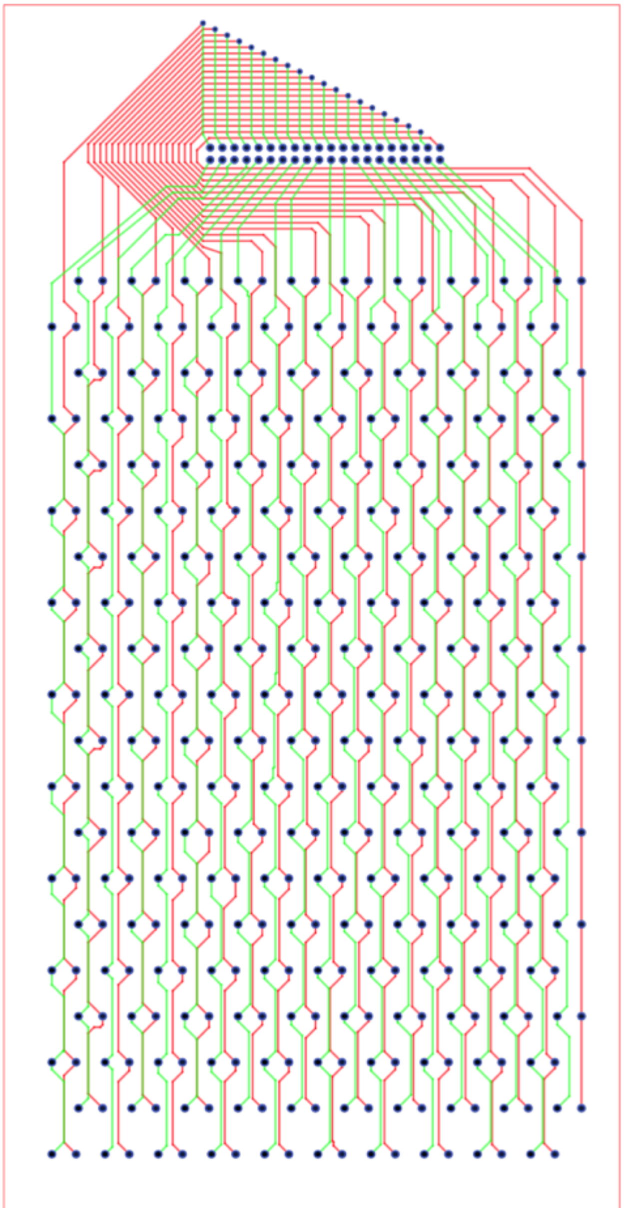
Direct Decibels is a pioneer product that combines directed audio with a software platform. The ability to change the direction of the directed audio electronically, and very quickly, allows for our warning system to be used in the field of automobile warning systems. Self-driving cars can use Direct Decibels in tandem with an onboard camera to send out warning signals to pedestrians and cars alike without adding unwanted noise pollution to the surrounding areas that do not need to hear it. In addition to less noise pollution, this application has the advantage that the warning's recipient hears a louder and more localized alert than if a conventional horn would be used.

In the fields outside of traffic warning systems, Direct Decibels has some potential in the market of home entertainment systems. A face recognition software can be used to lock onto a selected family member that wants to watch television, listen to music, or any other audio media outlet. Once locked on, our Direct Decibel system will take the place of a conventional audio player and direct the sound to the intended recipient without dispersing noise throughout the rest of the room and house. The major step to make this feature a reality with our current system would be implementing a digital signal processing program that counteracts the distortion caused by the demodulation of the ultrasonic waves back into the audible frequency domain.

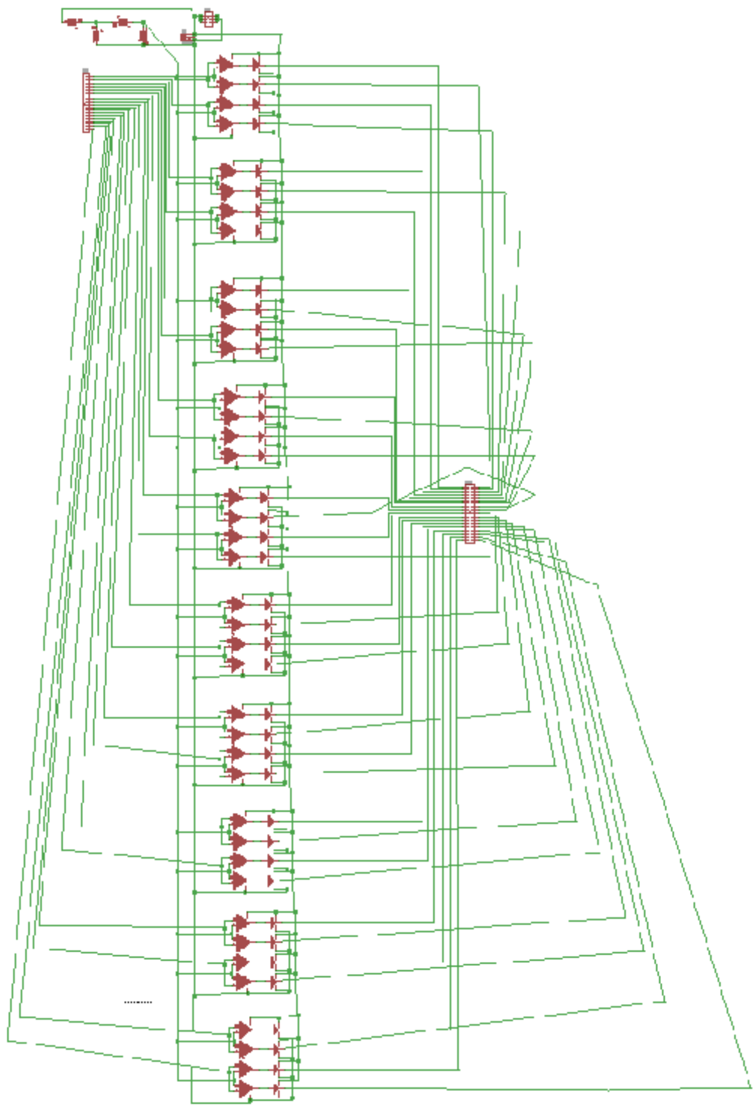
Overall, the Direct Decibels project was a successful entrepreneurship that offered a smart way to increase traffic safety while limiting noise pollution to a minimum. The far reaching implications of our platform extend past this clever application in crosswalk safety, however, and we are excited to see Direct Decibel systems expand into different industries.

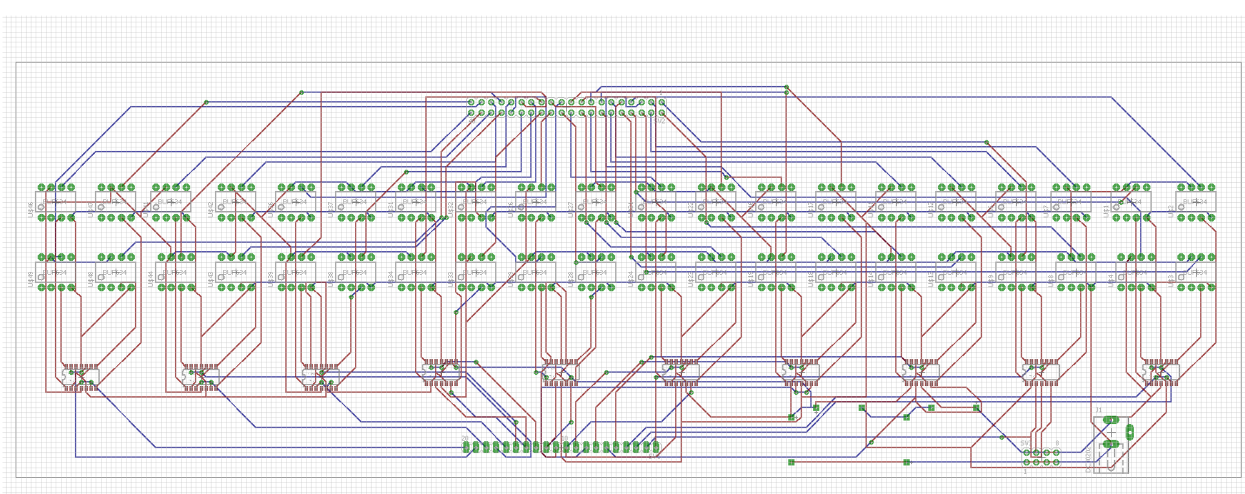
J) Appendix

PCB Design of transducer board:



PCB Design of Amplifier Circuit in Protoype 1





PCB Design of Signal Processing Board for Final Product