ROADSIDE SOUND METER

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Abstract

This paper documents an automatic system that monitors the noisy vehicles on the road, sends warnings to the drivers, and captures the license plates of the violating vehicles. Our system uses audio data collected by microphone arrays, processed by a localization algorithm, to determine the location of the source of the noise. We tested the functionality of our algorithm using pre-recorded audio data, and the results showed that the algorithm was able to detect the source of the noise. The hardware parts also function as desired, but the computational speed of the microprocessor used in the project was not enough for the localization algorithm to process real-time, which should be addressed in the future.

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1. Introduction

1.1 Purpose

Many states and municipalities within the United States have laws and regulations that limit the noise vehicles may produce in some areas. Whether the sound source is a noisy exhaust, loud engine revving, horns, or loud music, these noises can be distracting or possibly damaging to listen to. Currently, it is unrealistic to assign police officers to constantly monitor the noise, just as having an officer assigned to monitor speeding using up a valuable resource.

We propose a roadside system to warn drivers of their noisy vehicles, similar to speed radars. A pair of microphones is mounted to a pole on either side of the road allowing a phase-correction localization to be used to detect and track noise sources. A warning signal will then be turned on in the lane of the noisy vehicle to warn drivers of their noise level. In cases of excessive noise, a camera captures the license plate of the noisy vehicle as it passes through the system.

This report describes the building of this system. Chapter 2 talks about the design of various components of the project. Chapter 3 discusses the verification of the functionality of the components in the project. Chapter 4 sums up the cost of the project. Chapter 5 concludes the report and describe the work to be done in the future. Appendix A contains the Requirement and Verification Table.

1.2 Functionality

We have three high-level requirements for our project, which are:

1. The system must be able to use a pair of microphone arrays to track vehicles in up to four lanes of traffic, moving up to 40 miles per hour
2. Each unit should detect loud vehicles above 76 dBA and give loud vehicles at least 2 seconds of warning before passing the system.
3. Cameras should capture the license plate clearly so the characters can be read at least 80% of noise violation detections

The first requirement needs to be met for the warning and tracking to happen. We a put limitation on the vehicle's speed because the speed limit in residential areas is usually under 40 miles per hour [1]. The second requirement is needed since according to Illinois Vehicle Exhaust Noise Laws, the noise level is limited to under 76 dBA [1]. The two-second grace period is intended to encourage drivers to obey the law. The third requirement is necessary. The camera module would become useless if the photos are unreadable.

1.3 Subsystem Overview

Our system consists of two units placed on either side of a road with a set of modules included in each. The Sensing module handles the intake of audio from the two microphones, amplification of the audio, and conversion of the audio to a digital format that can be used in processing. This audio is then sent to the Processing module which uses a phase-correction localization between each pair of microphones to find peak sound sources. The Control module acts as the central microprocessor of the system and communicates between each module and the other unit's Control module as well. A set of four LEDs is included in the Warning module to allow for an observer to visually observe which lane is being detected and if a warning signal would have been sent. A system viewable to drivers was deemed outside the scope of this demonstration. The Camera module is able to capture a picture of the vehicle and license plate of the detected loud sound source. Lastly, the Power module handles converting a battery pack's voltage output to all the voltage levels required for powering each device and supplying phantom power to the microphones. The block diagram of the whole system is included in Figure 1. Figure 2 shows the placement of the units. Note that the two red dots represent the units. Figure 3 shows the modules assembled and connected within the physical unit.

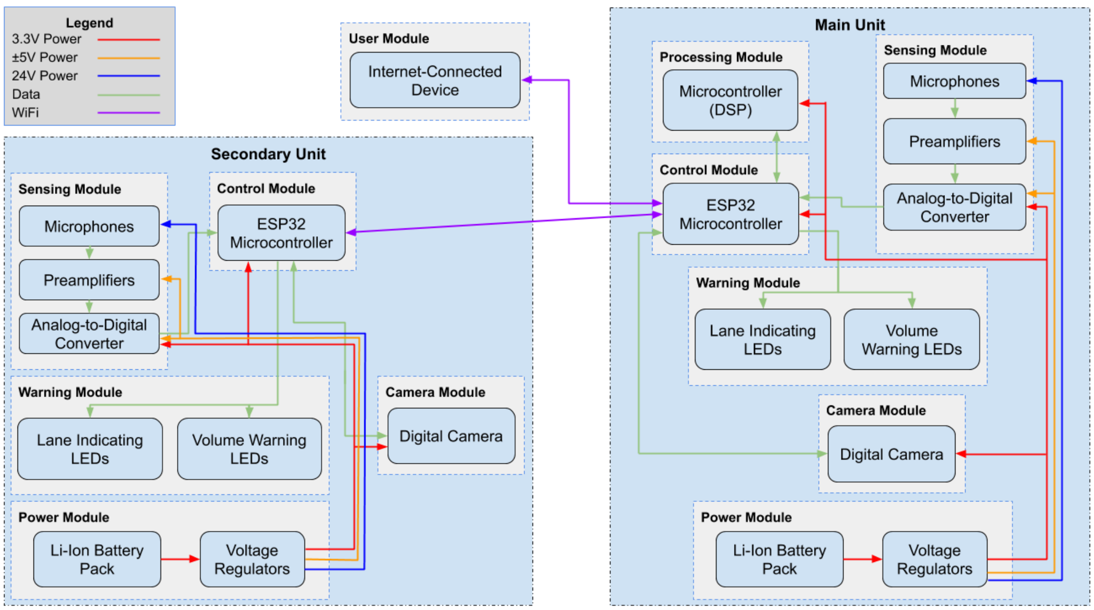


Figure 1. Block Diagram of Roadside Sound Meter

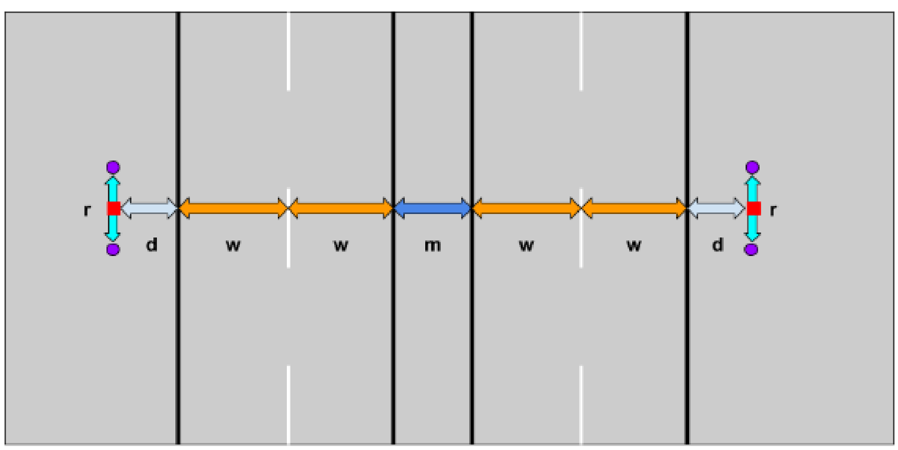


Figure 2. Unit Roadside Placement

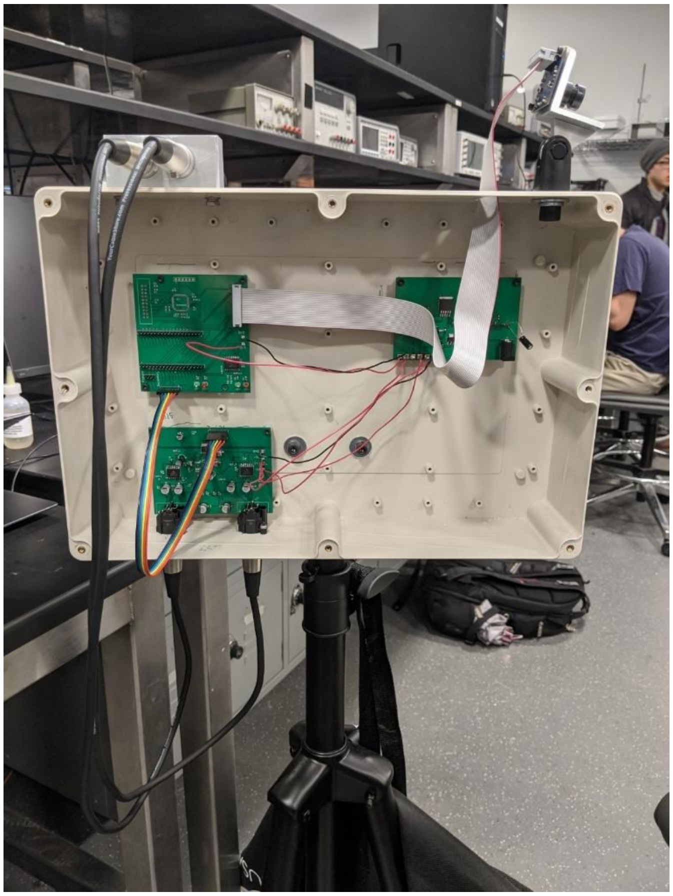


Figure 3. Unit Physical Design

2. Design

2.1 Sensing Module

The sensing modules receive audio input from microphones directed towards the road. The low output signals, which are in millivolts range [2], of the microphones are amplified by the pre-amplifiers and sent to the analog-to-digital converter (ADC). Finally, the ADC samples the analog signal and converts it into digital format before sending it to the control module. Note that there are two microphones and two preamplifiers in one sensing module, acting as the left and right channel of the audio signal. The two microphones in one unit form an array, which is required by the localization algorithm.

2.1.1 Microphones

The microphones operate in arrays and are directed towards the road to collect audio data for tracking sources of noise. We, therefore, chose to use Behringer ECM8000. This model of microphone has a generally flat response [3] in the human hearing range, which is 20 – 20000 Hz [4], as shown in Figure 4. The flat response ensures that the collected audio data is not distorted, as required by the localization algorithm. Behringer ECM8000 also has an omnidirectional response [3], which is favorable for array operation. Behringer ECM8000 is a condenser microphone, and its 15-48 V phantom power can be easily supplied.

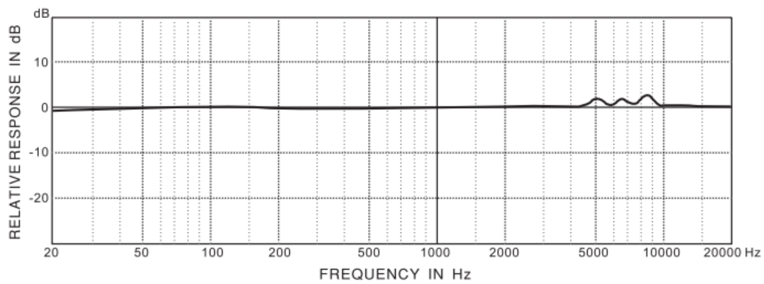


Figure 4. Relative Response of Behringer ECM8000 Microphone [3]

2.1.2 Preamplifier

The preamplifier takes in the low outputs from the microphone, which are typically in the millivolt range, and boost them to around 3 V without significant distortion, which is the recommended input voltage level for our analog-to-digital converter [5]. Based on these conditions, we chose to use Texas Instruments INA217, which has a flat frequency response in the human hearing range, as shown in Figure 5 [6].

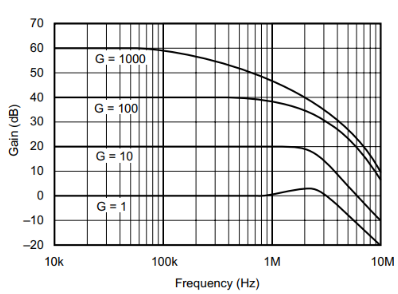


Figure 5. Frequency Response of INA217 [6]

Typical passenger vehicles moving at 30 – 39 MPH have a road noise range of 60-74 dBA[7]. The sensitivity of our microphone is 11 mV/Pa [8]. For our purposes, we assume a maximum limit of sound pressure to be 100 dB SPL. The maximum output of the preamplifier would be 3V at the maximum input volume, which is the recommended nominal analog input voltage level to the ADC [5]. We arbitrarily set the minimum output voltage to 750 mV to calculate the minimum gain. We, therefore, can calculate the gain limits of the preamplifier:

$$100\ [dB\ SPL] = 20\log_{10}(\frac{P}{2.0 \times 10^{-5}[Pa]}), P = 2\ [Pa] \quad (1)$$

$$V_{in} = 2\ [Pa]\ \times 11\ \left[\frac{mV}{Pa}\right] = 22\ [mV] \quad (2)$$

$$G_{max} = V_{max} \div V_{in} = 3\ [V] \div 22\ [mV] = 136.4\ [\frac{V}{V}]\ or\ 42.7\ [dB] \quad (3)$$

$$G_{min} = V_{min} \div V_{in} = 750\ [mV] \div 22[mV] = 34.1\ \left[\frac{V}{V}\right] or\ 30.7[dB] \quad (4)$$

We arbitrarily set the gain of the preamplifier to 40 dB, which is equivalent to 100 V/V. The gain of INA217 is set by an exterior resistor across terminal RG_1 and RG_2, as indicated by Figure 6 [6].

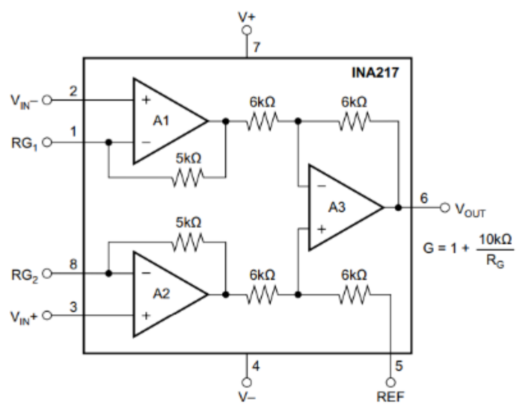


Figure 6. INA217 Functional Block Diagram [6]

We, therefore, are able to calculate

$$R_G = \frac{10k}{100 - 1} = 101[\Omega] \quad (5)$$

The full schematic of the INA217 preamplifier with supporting components is shown in Figure 7. Note that the gain resistor, R5, is set to 100 Ω, which is easier to acquire. We also included a special circuit at the input of the preamplifier to provide 24 V phantom power for the microphones. Resistors R6 and R7 provide current path for the phantom power. Capacitors C4 and C5 filter out the DC component of the input signal, so that the phantom power is only supplied to the XLR connector. The +5 V and -5 V bias voltages and 24 V are all provided by the power module. The output is connected to the analog-to-digital converter.

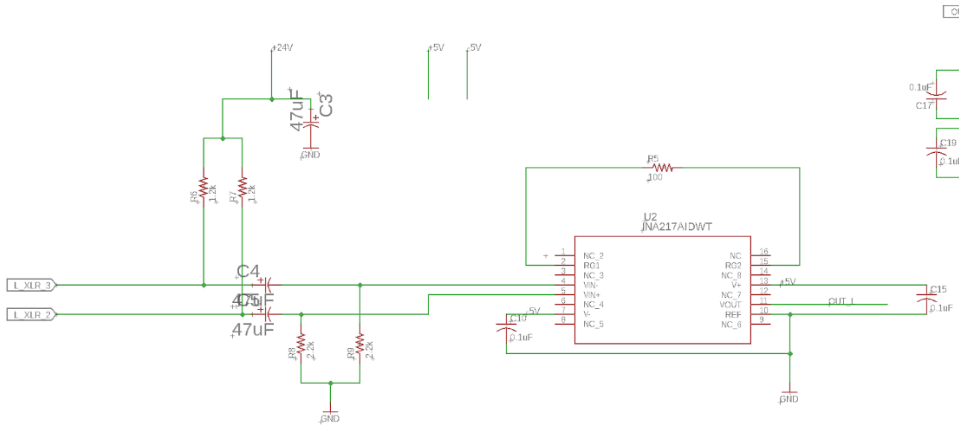


Figure 7. Preamplifier Circuit

2.1.3 Analog to Digital Converter (ADC)

The amplified signals from the two preamplifiers are fed into the left and right analog input channels of the analog-to-digital converter, which is supposed to convert the analog signal into digital format and supply it to the control module. There are many reasons that we chose to use Texas Instrument PCB1803A as our ADC. First off, it has two analog inputs [5], which satisfies our localization algorithm's need of two-channel audio inputs. Secondly, it is capable of outputting I^2S digital signals [5] usable by the ESP32 control module. Finally, it has configurable sampling rate with a maximum of 96 kHz [5].

In order for the analog-to-digital converter to function correctly, there are several digital control signals that we have to set, as shown in Figure 8 [5]. The digital high is provided by the 3.3V output on the power board, while the digital low is connected to the digital ground. Note that the digital ground and the analog ground are separated for better noise separation, which can be seen in Figure 9. The digital control signals are Power Down, LCF Bypass, Mode[1:0], Format[1:0], and Oversampling. Power Down is set to HIGH, as it is only used when the other control signals are changed in use [5]. LCF Bypass has been set to LOW to reject the DC component in the input. Oversampling is set to LOW, so that the oversampling ratio is x64. Mode[1:0] has been set to 10 in our case, which enables the ADC to provide the timing of the serial audio data communications between the ADC and the ESP32 control module. Format[1:0] is set to 01, so that the output is 24-bit I^2S signal.

The Data Out pin is connected to the ESP32 control module. There are also three clock signals that we have to take care of. The system clock is supplied by the ESP32 control module. Since the MODE pins configure the ADC to operate in Master mode, the BCK and LRCK signals are supplied by the ADC to the control module [5].

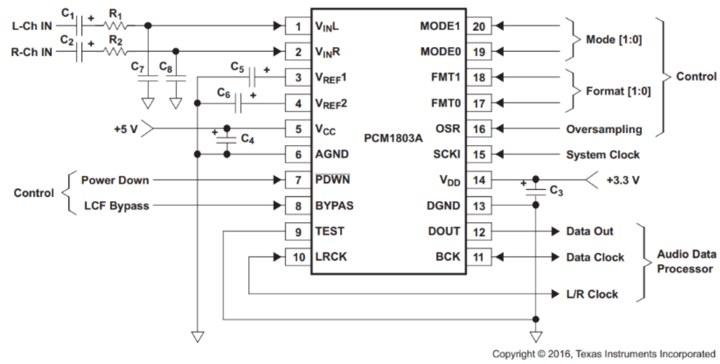


Figure 8. Typical Application of PCM1803A [5]

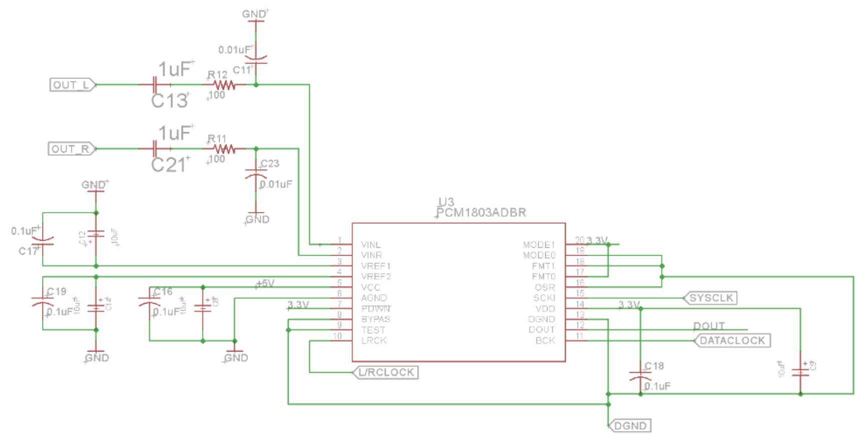


Figure 9. Schematic of the Analog-to-Digital Converter

2.2 Control Module

The control module is comprised of two ESP32 microcontrollers which are capable of Wifi communications [9]. Both ESP32 microcontrollers are located on the main and the secondary unit respectively and are controlling the sensing module, warning module, and the camera module. The ESP32 microcontroller on the main unit is responsible for taking the inputs from the sensing module on both main and secondary unit and pass them to the processing module. Additionally, it acts as a web server to render images or videos from the camera module.

2.3 Processing Module

In order to convert the audio from the sensing module into sound source locations along the road, a localization algorithm is run on a microprocessor. The audio inputs are converted to frequency-domain using a Fast Fourier Transform (FFT). This algorithm uses a series of complex phase delays covering each angle and frequency multiplied with the frequency-domain version of each microphone input. The now phase-adjusted inputs are summed and have the magnitude of each frequency added together. These magnitudes are compared over each angle checked and the peaks represent an angle where a sound source is located. Two angles, one from each array, are then converted into a physical location as shown in Figure 10.

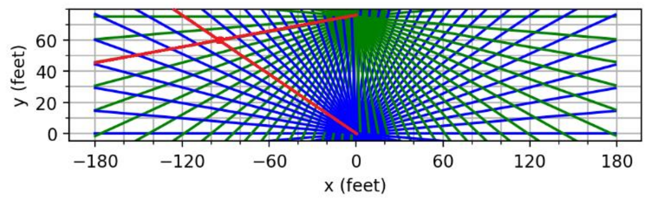


Figure 10. Diagram of Possible Angles (Blue and Green) and Detected Angles (Red)

Since the localization algorithm has a lot of steps to run through and requires complex arithmetic, we selected the STM32F446 for its ARM Cortex M4 core. This processing core has support for the ARM CMSIS library which contains optimized single-precision float and complex number operations. This processor also supports SPI which can be used to communicate with the Control Module [10]. Figure 11 shows how we connected power, SPI, UART, and JTAG to the microprocessor.

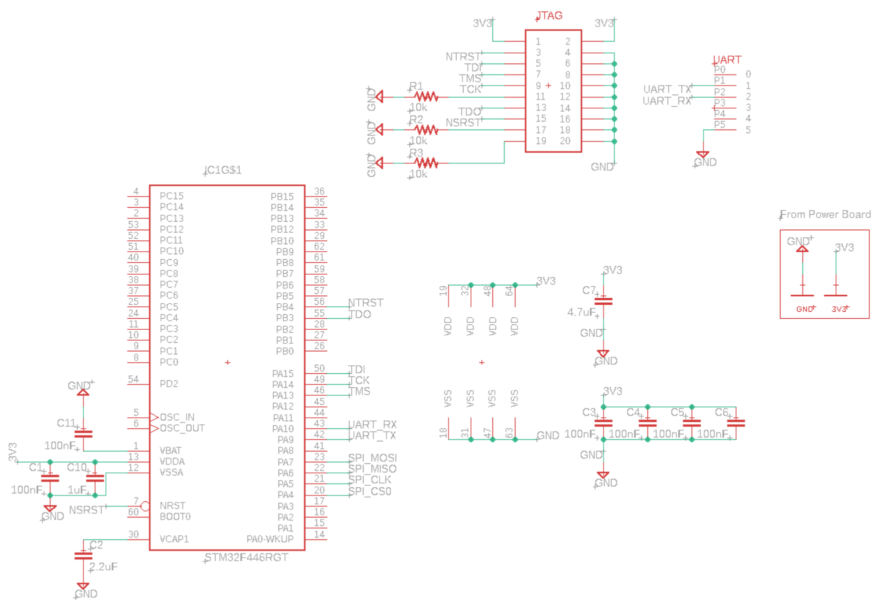


Figure 11. Schematic of Microprocessor, JTAG, and UART Ports

2.3.1 Localization Algorithm

The complex phase delays that are required in this algorithm can be generated using Equation 6. This Equation uses the distance between each microphone *r*, the number of angles being used *N*, the size of the FFT *D*, the number of microphones *M*, the sampling rate *f*, and the speed of sound *c*.

$$< v(n,m,k) = -\frac{(m-1)\times r\times \cos\big(n\pi \div (N-1)\big)\times 2\pi f k}{cD} \qquad (6)$$

$$n \in [0, N-1], m \in [0, M], k \in [0, \frac{D}{2}]$$

We determined the minimum number of angles that need to be used in the localization process by considering how far apart the 2-dimensional spacing would be between each pair of angles. The minimum spacing *d* is determined in Equation 7 by the location update speed *U*, 200 ms, and the maximum vehicle speed, 40 MPH, as listed in section 1.2.

$$d\ [ft] = \frac{5280}{3600} \times V\ [MPH] \times U\ [seconds] \tag{7}$$

Using the values above, this would give a maximum *d* of about 11.7 ft. Figure 12 shows a representation of the angles for a setup with a spacing of 75 feet between the two units and a total of 360 feet along the direction of travel, equivalent to about 3 seconds before and after the array at 40 MPH.

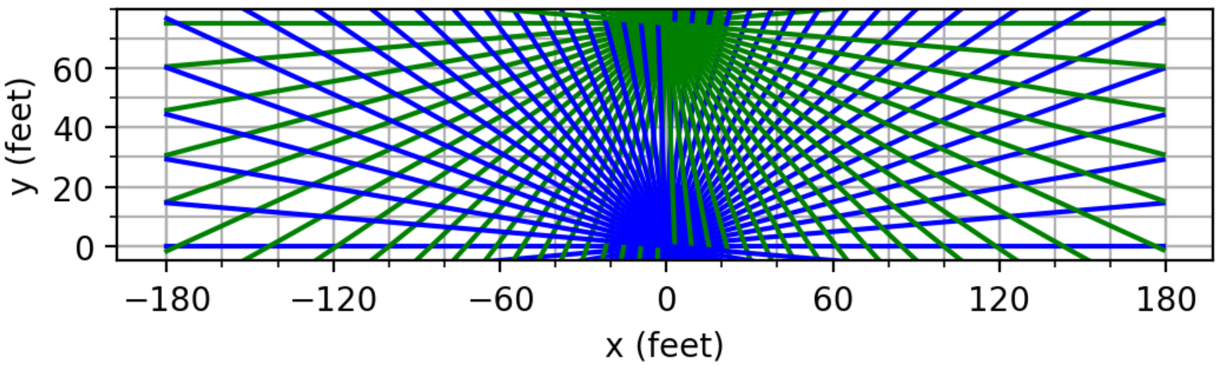


Figure 12. Diagram of Angle and Point Separation at *N* = 40 Angles

The vertical spacing between each point increases at greater road widths, so a width of 75 feet will be used in the minimum angle calculations. For the horizontal spacing, we have to consider that the drivers need a minimum warning time of two seconds. At 40 MPH, this gives a minimum width to consider of about 235 feet. This calculation will focus around up to 150 feet before and after the set of arrays. The actual horizontal spacing between localization points can be calculated using Equation 8.

$$x = y \times \tan(\theta_1) = 75 + y \times \tan(\theta_2) \tag{8}$$

<u>For N = 100 angles:</u>

$\theta_1 = \frac{\pi}{99}\ rad,\ \theta_{2a} = \frac{85\pi}{99}, \theta_{2a} = \frac{84\pi}{99}$

$x_1 = 147.7\ ft, x = 137.04\ ft, \Delta x = 10.67\ ft$

<u>For N = 90 angles:</u> (9)

$\theta_1 = \frac{\pi}{99}\ rad,\ \theta_{2a} = \frac{85\pi}{99}, \theta_{2a} = \frac{84\pi}{99}$

$x_1 = 141.68\ ft, x_2 = 130.64\ ft, \Delta \text{x} = 11.03\ ft$

Based on these calculations, a minimum number of angles *N* of 90 should be used. This gives a maximum spacing less than the *d* of 11,7 ft calculated earlier.

2.4 Warning Module

Each warning module contains two pairs of LEDs, one pair for each possible lane on each unit's side of the road. The green LED indicates the detection of a car in that lane. The red LED indicates the detected car's volume is above a designated threshold. These are for demo purposes and only need to be visible to an observer near each unit. With all the connections in the control module, there were not enough GPIO pins left to directly control each LED. We instead added a GPIO expander. This expander communicated over the SPI connection already implemented and added eight more digital GPIO lines [12].

2.5 Camera Module

Each camera module is consisted of an OV7670 camera without FIFO mounted. This module will be triggered by the control module through I2C [11]. OV7670 camera should be pointed at the back of cars to capture their license plate as they pass the system. The pictures are then sent to the control module by a parallel connection.

2.6 Power Module

The power module supplies voltages for various components in our project. A 12V battery pack is used as the voltage source, which is connected to the board using a barrel connector. Two linear regulators convert the 12V DC to 3.3V DC and 5V DC respectively. A switching regulator and a boost converter convert the 5V DC to -5V DC and 24V DC. The schematic of the power module is shown in Figure 13.

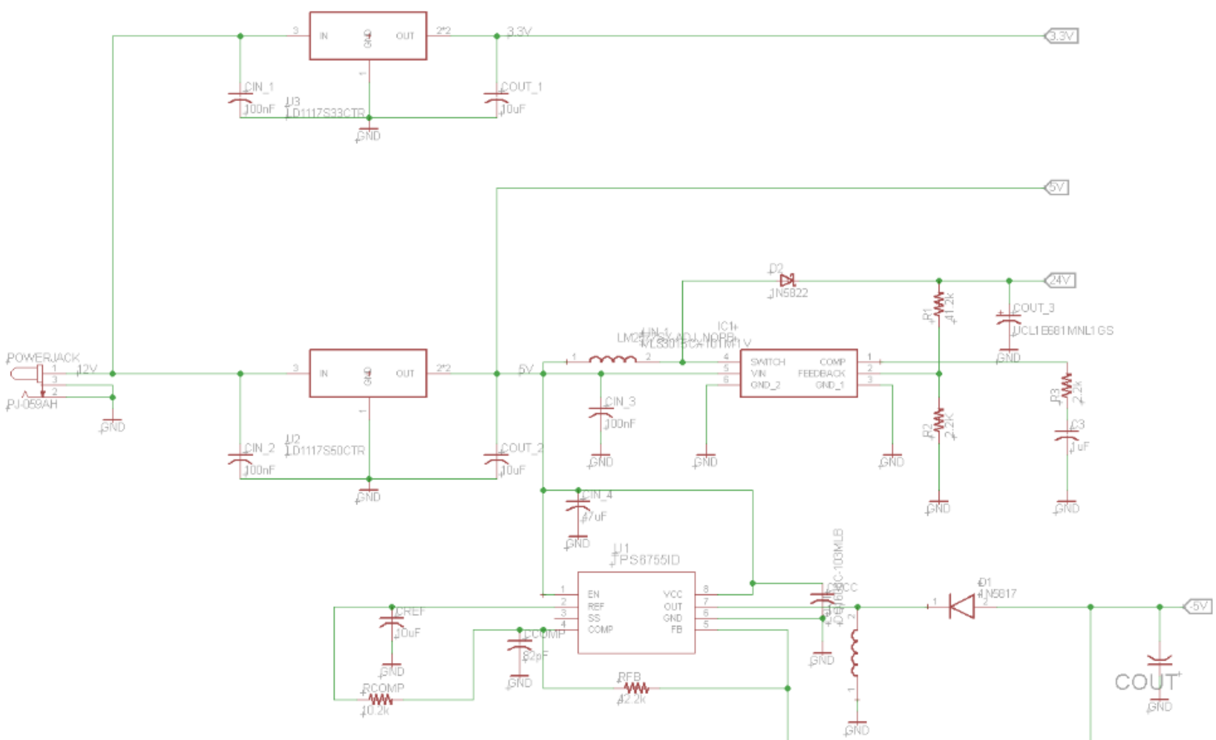


Figure 13. Schematic of the Power Module

2.6.1 Battery Pack

Originally, we wanted to have a battery pack that charges from a solar panel on each unit, since it is more practical for our product to be used in a real-life situation. However, we later determined that it is unnecessary for demonstrating the main purpose of our system. We instead decided to use Talentcell Rechargeable 6000 mAh Li-Ion Battery Pack, since it is cost-effective. Its output is only connected to the two linear regulators, so the current would not be an issue [13].

2.6.2 Linear Regulators

Two versions of LD1117 low-dropout regulators are used, which are providing 3.3V and 5V DC. They are chosen because of that they are cost-effective and require very few supporting components [13]. The 3.3V DC powers the ESP32 in the control module, the STM32 in the processing module, and also the ADC in the sensing module. Additionally, the 3.3V DC is also the digital high signal for the ADC. The 5V DC is the analog power supply of the ADC and the positive bias of the preamplifier. It also provides the input for the switching converter and the boost converter.

2.6.3 Switching Converter

To provide the negative bias for the preamplifier, we need use an inverting converter to invert the 5V DC. TPS6755 was chosen because of its input ranges from 2.7V to 9V [14], which fits our project, and its output is -5V [14].

2.6.4 Boost Converter

The condenser microphones in our project require 24V phantom power. We chose to use LM2577 because of its wide input voltage range and its adjustable output voltage [15]. To set the gain, we have to calculate the values of the external resistors in the feedback loop [15], as shown in Figure 14. The input is 5V DC, and the output needs to be 24V DC. Setting R_2 to 2000Ω, we are able to calculate

$$R_1 = 2000\left(\frac{24}{1.23} - 1\right) = 37000\Omega \tag{10}$$

Note that in Figure 14, we used R_1 = 41.2kΩ and R_2 = 2.2kΩ, since we have other resistors that have the value of 2.2kΩ.

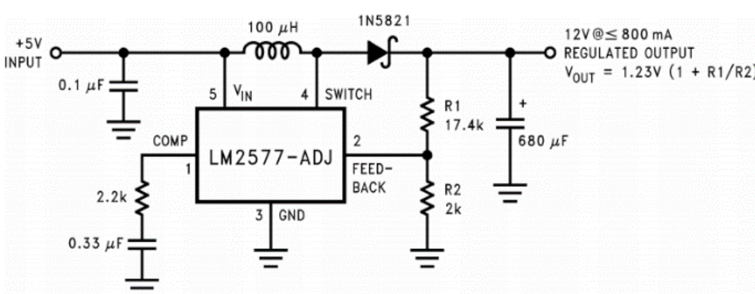


Figure 14. LM2577 Schematic [15]

3. Design Verification

Since our project is a large and highly complicated system, we decided to modularly test and verify each subsystem, instead of testing everything at once. Despite that our project was not able to track real-time signals due to the computational power of our DSP processor, the other components are all working as expected.

3.1 Sensing Module

3.1.1 Microphones

The microphones could not be verified because the lab was too noisy to test inputs to the system. In order to test properly, we would have needed to make sure the sine wave sound source was significantly louder at the microphone than the background noise, even at the full 250 feet distance used in our requirements. We could not find a time in the lab when no one else was around talking or working on other projects. Testing would need to be done either outside with a portable oscilloscope or in another quiet room.

3.1.2 Preamplifier

We require the preamplifier to have linear gain and linear phase delay over human hearing range, which 20 – 20000 Hz. The gain needs to be 40 dB or 100 V/V. In order to verify the functionality of the preamplifier, we put testing probes on the board of the sensing board, as shown in Figure 15. VIN- is the negative input to the preamplifier, VIN+ is the positive input, and OUT is the output of the preamplifier. A waveform generator in the lab was used to generate the input signal to the preamplifier.

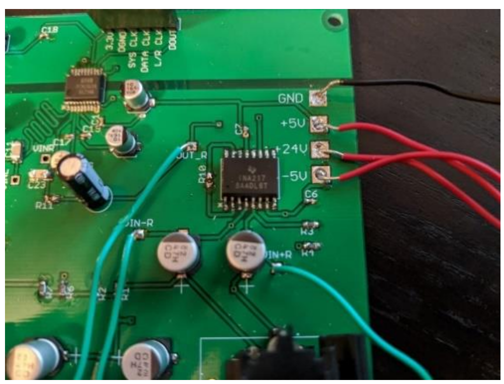


Figure 15. Sensing Module

The positive input is supplied with a sine wave, while the negative input is supplied with a same wave but with a phase delay of 180 degrees, shown in Figure 16 and Figure 17. After turning on the power module, we are able to measure the output of the preamplifier while varying the frequency of the input waves. The results are shown in Figures 18-21.

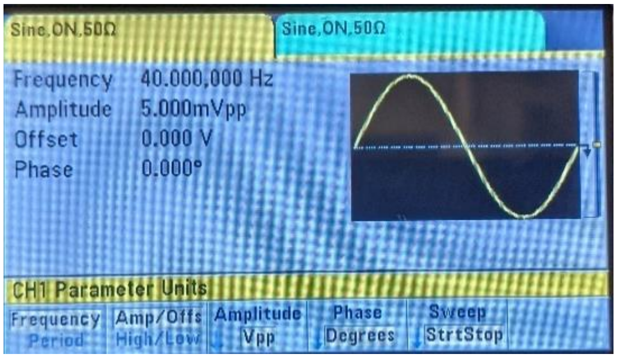


Figure 16. Positive Input

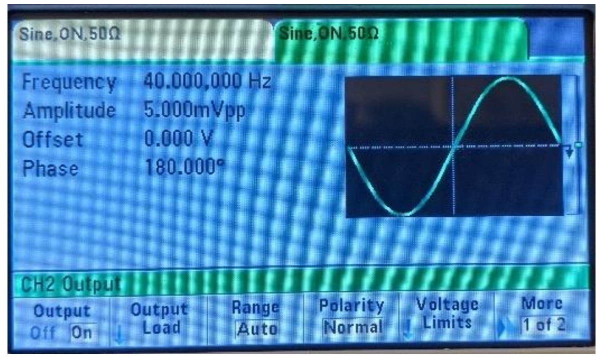


Figure 17. Negative Input

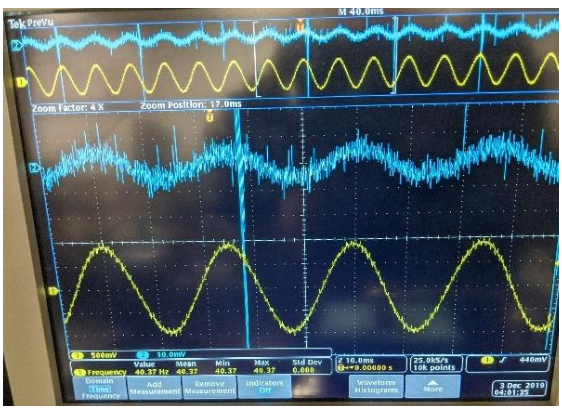


Figure 18. Output at 40 Hz

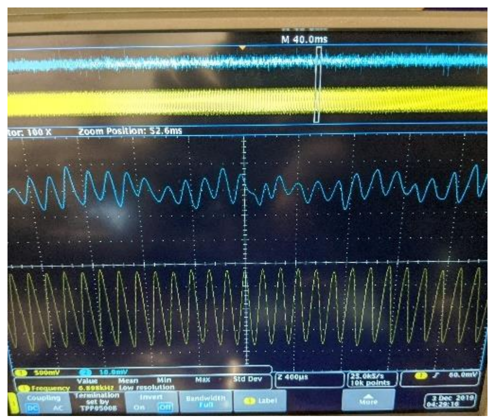


Figure 19. Output at 6.898 kHz

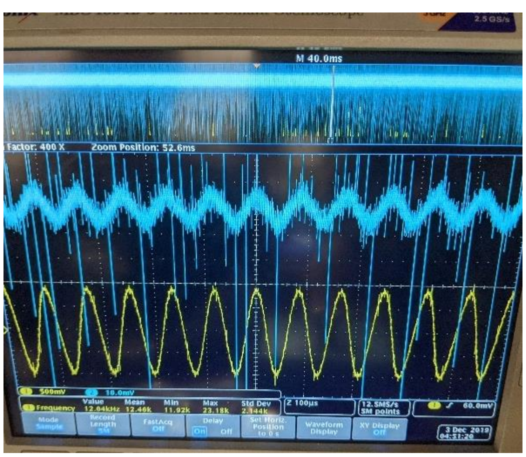


Figure 20. Output at 12.04 kHz

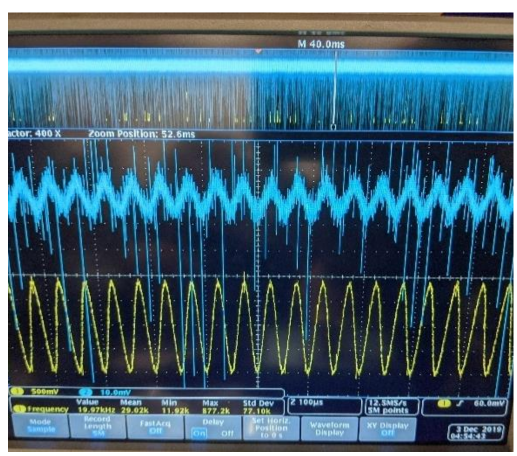
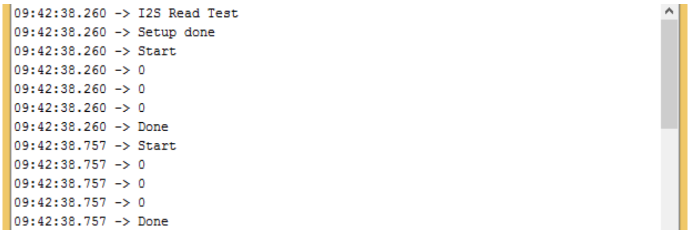


Figure 21. Output at 19.97 kHz

We can observe that the peaks of the input waveform and the output are matched, indicating zero phase delay. We are also able to verify that the gain is constant over the frequency range. Note that we measure a 10 mV peak-to-peak input voltage for each input pin, while the output is 2V peak-to-peak. The reason is that the preamplifier converted the differential signal to ground-referenced signal, and the sum of the input signals is 20 mV. Therefore, we are able to verify that the gain of the preamplifier is 100 V/V.

3.1.3 Analog-to-Digital Converter

To verify the operation of the analog-to-digital converter, we configured the control module to supply the system clock signal to the analog-to-digital converter and wrote a program to receive the signal. An example is shown in Figure 22. This serial output displays 'Start' when the program begins receiving data. After receiving, the first three bytes received, representing the three bytes of the first sample, are displayed then 'Done' is printed. Note that zero values are shown because we didn't supply signals to the preamplifier when we took the screenshot. We have verified that the clocks generated by the ADC are correct and data is output in the correct format.



```
09:42:38.260 -> I2S Read Test
09:42:38.260 -> Setup done
09:42:38.260 -> Start
09:42:38.260 -> 0
09:42:38.260 -> 0
09:42:38.260 -> 0
09:42:38.260 -> Done
09:42:38.757 -> Start
09:42:38.757 -> 0
09:42:38.757 -> 0
09:42:38.757 -> 0
09:42:38.757 -> Done
```

Figure 22. Verification of ADC

3.2 Control Module

To test the range of transmission distance of the control module, we connected each of the ESP32 to the same 2.4GHz Wifi which could reach up to 150 feet indoors and 300 feet outdoor. The picture from the camera module on the second control module was successfully sent to the first control module while the ESP32 are separated at least 100 feet away

3.3 Processing Module

To test the speed of the localization process, the localization program was configured to take a test recording and run through the rest of the process. The test recording had sound sources at 60° and 110°. The phase delays were generated before starting a timer when the first cycle started since these would not change most of the time. Eleven cycles were completed in each run and outputs were checked each time for accuracy. The output angles were at 62 and 112 degrees and could have been corrected for with an added calibration step in a real-world setup. The results of each run are shown in Table 1.

Table 1. Processing Speed Test Results

Test #	1	2	3
Average Time per Cycle	554 ms	570 ms	563 ms

As shown in Table 1, the processing speed was almost three times too slow, even without time to receive inputs and send outputs. This could be improved by removing some interior angles near 90° as the physical spacing between localization points is more precise than necessary. Additionally, testing could be done to see if using a smaller FFT size, possibly 256 or 128 samples, would give the same accuracy. Upgrading the microprocessor to an ARM Cortex M7 or A5 core would improve speed as well.

3.4 Warning Module

The LEDs were plugged into a breadboard and connected to a 120Ω resistor to limit the current to about 10 mA. As seen in Figures 23 and 24, the LEDs are bright enough to view from 10 feet away when supplied with 3.3V.

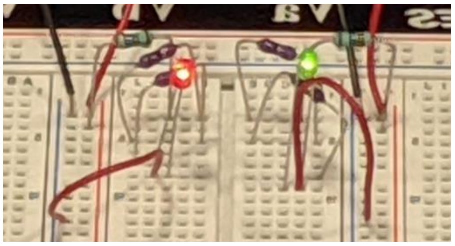


Figure 23. LEDs On

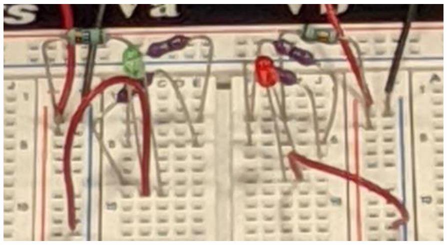


Figure 24. LEDs Off

3.5 Camera Module

We tested out the camera module by focusing at 150 feet away. However, due to limited memory storage on the control module, the camera module was unable to show a clear picture at that distance. In the end, we tested it could only focus at around 5 feet away with a minimum resolution of 320 * 240 pixels.

3.6 Power Module

To test the power module, we connected the battery pack to the DC connector on the board and measured the voltages on the output pins.

3.6.1 Linear Regulators

The verifications of the two linear regulators can be seen in Figure 25 and Figure 26. Although the requirements for them are 3.0-3.6 V and 4.8-5.5V, respectively, their actual performance exceeded our expectations.

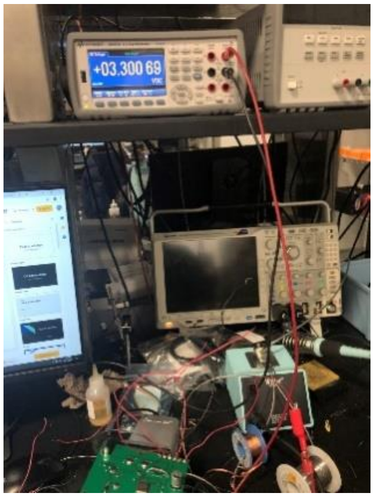


Figure 25. 3.3V Regulator

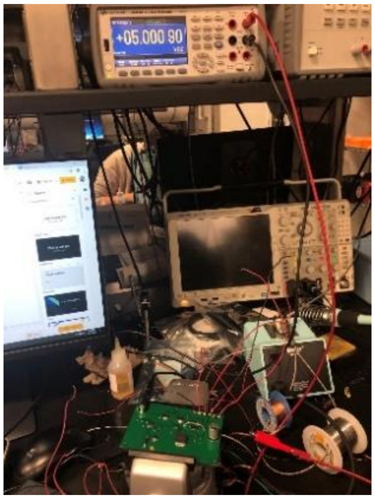


Figure 26. 5V Regulator

3.6.2 Switching Converter

The requirement for the switching regulator is an output in the range of -4.8 to -5.5 V. As shown by Figure 27, the requirement has been met.

3.6.3 Boost Converter

The requirement for the switching regulator is an output in the range of 23.5 to 24.5 V. The result in Figure 28 verifies the functionality.

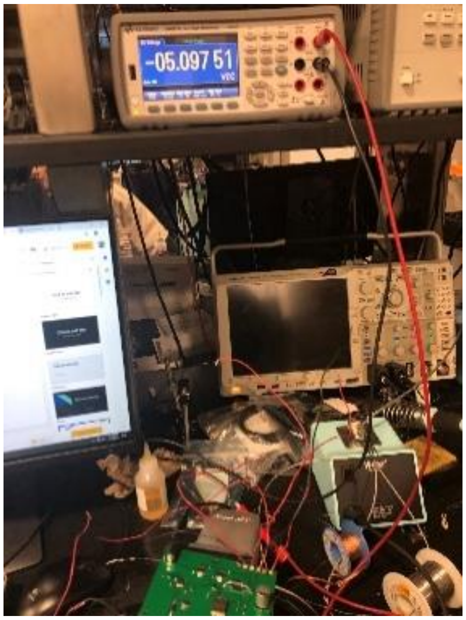


Figure 27. Switching Converter

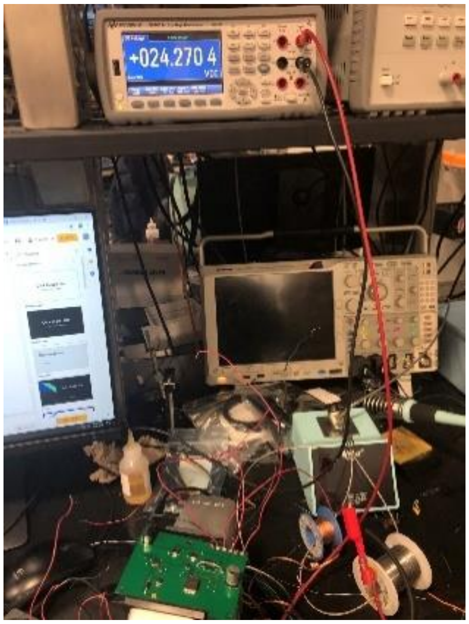


Figure 28. Boost Converter

4. Cost and Schedule

4.1 Cost

Table 2: Parts Cost

Part	Manufacturer	Unit Cost ($)	Quantity	Actual Cost ($)
XLR Cable	Your Cable Store	6.69	4	26.76
XLR Connector	Neutrik	1.64	4	6.56
ECM8000 Microphone	Behringer	59.99	4	239.96
INA217 Preamplifier	Texas Instruments	6.95	4	27.80
PCM1803A ADC	Texas Instruments	3.87	2	7.74
Male Pins (6)	Sullins	0.18	4	0.72
Jumper Wires	SparkFun	0.95	2	1.90
ESP32	Espressif	10.00	2	20.00
Male Pins (19)	Sullins	0.42	4	1.68
Male Pins (3)	Sullins	0.09	2	0.18
Jumper	Sullins	0.13	2	0.26
GPIO Expander	Microchip	1.10	2	2.20
STM32	STMicroelectronics	7.75	1	7.75
JTAG Header	Sullins	0.46	1	0.46
UART Header	Sullins	0.53	1	0.53
Red LED	Lite-On	0.36	4	1.44
Green LED	Lite-On	0.36	4	1.44
OV7670	Omnivision	2.20	2	0 (Free in the lab)
Ribbon Cable Connector	Assmann WSW Components	1.48	2	2.96
Header	Amphenol ICC	0.74	2	1.48
12V DC Battery Pack	TalentCell	29.99	2	59.98
LD1117-3.3	STMicroelectronics	0.42	2	0.84
LD1117-5	STMicroelectronics	0.43	2	0.86
TPS6755ID	Texas Instruments	4.31	2	8.62
LM2577	Texas Instruments	6.10	2	12.20
DC Power Connector	CUI	0.89	2	1.78
Various Resistors, Inductors, Capacitors, and Diodes	Various			35.36
Total				**471.46**

Table 3: Labor Cost

Team Member	Hourly Wage	Weekly Hours	Number of Weeks	Cost per Member
Charlie Yang	$25.00	10	10	$2500
Jordan Rodier	$25.00	10	10	$2500
Wentao Jiang	$25.00	10	10	$2500
Total				**$7500**

4.2 Schedule

Table 4: Schedule

Week	Jordan Rodier	Charlie Yang	Wentao Jiang
9/30/2019	Order Parts	Design schematics	Design schematics
10/7/2019	Design Main PCB	Design schematics	Design PCBs
10/14/2019	Finalize Main PCB	Set up ESP32 communication and test range	Finalize and order PCBs. Order parts
10/21/2019	Meet with Machine Shop	Set up ESP32 communication and test range	Wait for PCBs
10/28/2019	Program Localization Program; Assemble main PCB	Set up Camera module and Control Module	Assemble and test power module and sensing module
11/4/2019	Program Localization Program	Integrate Camera module and User module	Debug sensing module
11/11/2019	Test Control Module	Set up a server for User module	Debug sensing module
11/18/2019	Test Processing Module; Design Sensing Board Version 2	Debug User module and Control Module	Order Sensing Board Version 2
11/25/2019	Debug Processing and Control Module	Debug Camera module and Control Module	Assemble and test Sensing Board Version 2
12/2/2019	Final assembly, testing, and demonstration	Final assembly, testing, and demonstration	Final assembly, testing, and demonstration
12/9/2019	Final Presentation and Final Report	Final Presentation and Final Report	Final Presentation and Final Report

5. Conclusion

5.1 Accomplishments

Our project is a success in each submodule. Our sensing module can amplify the signals and convert them to digital format. Our processing module can track the sound movement and detect noises. Our power module can supply 3.3V, 5V, and 12V from a 12V battery pack. Our warning module can light up the LED and the camera module can take a picture once a signal is sent from the control module. And our control module can send signals to other modules independently. And the user module can show pictures and videos on any connected devices.

5.2 Uncertainties

We overestimate the processing power of our Control module and it is loaded with tasks from various modules. The control module can handle transmitting signals between each module individually, but it might not work properly due to excessive amount of work with receiving camera data as well. Because the ADC has not been verified to output correct data, we are also uncertain if there is any noise in the Sensing module that could interfere with the accuracy of the localization process.

5.3 Ethical considerations

We have based our ethical considerations on the IEEE Code of Ethics [16]. Since our device will be used outside and most likely near combustible trees and grassland, the battery pack in the power module of our project, if misused, can be a hazard to the environment, the public property, and nearby people. Damaging the casing and the connections of the battery can have detrimental effects [17], so we will take care to make a visible sign to ensure that people do not accidentally damage the device.

There is also a privacy issue since there are cameras and the microphones constantly operating. In the United States, photographing and videotaping in public places, such as roads, streets, and sidewalks, are legal [18]. However, to avoid misuse of the system in residential areas, we will ensure that the cameras and microphones only monitor the vehicles on the road. we should avoid filming the inside of houses through the windows. Therefore, the cameras should be placed so that only the image of the road is captured. They should be kept as low as possible if the license plates of the vehicles can be captured. In previous sections, we mentioned that the microphones should be able to reject sound behind them. They should also be placed and directed toward the road so that the conversation of people nearby is not recorded, as the laws of the U.S. require at least one-party consent for recording conversations [19]. The recorded audio signal should only be used in the tracking of the noisy vehicles, and it will not be sent to the user module. Additionally, there should be signs nearby warning people of the recording device, which adheres to #2 of IEEE Code of Ethics [16].

5.4 Future work

To continue this project, since each individual module is working properly, we will first integrate all of them together and test with real audio data. Another improvement we will make is that we can replace with higher quality units such as a faster processor for the processing module and a camera with memory. We would also enhance our user module by adding a user-interface to see violated vehicles’ license plate and tune various parameters for processing module. Finally, we would seal all the components in a resistant, waterproof box which will be planted along the roads to conduct testing on real vehicles.

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Appendix A Requirement and Verification Table

Table 5: Requirement and Verification Table

Module Name	Requirement	Verification	Status
Microphone	1. Flat response from 40-20000 Hz.	1a. Measure voltage output on a multimeter in response to a constant volume sound source playing tones from 40-20000 Hz from five feet away. 1b. Check output voltages differ by only ±3 dB.	Not Tested
	2. Output voltage follows directly inversely to distance over 5-250 feet.	2a. Use constant volume sound source at multiple distances on axis from the microphone. 2b. Measure the output voltages on a multimeter, ensuring the voltage stays within 5% of the median voltage after accounting for loss over a distance.	
Preamplifier	1. Linear gain of 30-40 dB over 20-20000 Hz.	1a. Set gain to within range. 1b. Using a signal generator, input a constant magnitude sine wave into the input of the preamplifier circuit and adjust over the whole range. 1c. Measure the output voltage on a multimeter, ensuring the voltage stays within 5% of the set amplified voltage.	Y
	2. Linear phase delay over 20-20000 Hz.	2a. Connect the input of the preamplifier to a signal generator, and the output to a vector network analyzer. 2b. Configure the signal generator to send a constant magnitude sine wave into the preamplifier and adjust the frequency over the whole range. 2c. Record the phase delay of each frequency and make sure that the phase delay is within 5% of the linear approximation line.	
Control Module	1. Transmit and receive data over at least 100 feet using 2.4 GHz WiFi.	1a. Power each ESP32 module separately with 3.3 V.	Y

		1b. Transmit data from one to another from at least 100 feet away. 1c. Ensure identical data is received on the second unit by outputting to a computer over UART.	
	2. Communication delay less than 100 ms at 100 feet.	2a. Turn on an LED on one unit to signal the beginning of data transmission and begin a timer. 2b. Transmit data from one unit to another from 100 feet away. 2c. Turn on an LED on second unit when first bit of data is received and stop timer. 2d. Ensure identical data is received on the second unit by outputting to a computer over UART.	
Processing Module	Can process data fast enough to output angle results every 200 ms.	1a. Supply 100 ms of audio recorded at 44.1 kHz sampling frequency from two microphones. 1b. Raise an output pin to HIGH to show start of computation. 1c. Localize the input using an FFT frame size of 512 samples and 90 evenly spaced localization angles. The speed of sound should be set according to the air temperature during the audio recordings. 1d. Process this input twice, simulating processing time for two arrays, and lower an output pin to LOW to show computation is finished. 1e. Measure time output pin is high on an oscilloscope and check accuracy of output angles over UART connection to computer.	N
Warning Module	Each LED must be visible 10 feet away with a drive current of 10 mA.	1a. Connect LED through a 120 Ω resistance to a power supply set to 3.3 V. 1b. Measure current of circuit	Y

		on a multimeter to ensure near 10 mA. 1c. Point LED directly at the viewer and observe from 10 feet away. 1d. Ensure LED is easily visible.	
Camera Module	Can focus at 150 feet away.	1a. Program the camera for VGA output (640 x 480) 1b. Set focal length at maximum range 1c. Stand 150 feet away with a license plate or another object of similar size with lettering 1d. Take pictures at varying focal lengths until picture is in focus and license plate is readable	N
Linear Regulators	1. The 3.3 V linear regulator takes in 12 V output convert it down to 3.0-3.6 V. 2. The 5 V linear regulator takes in 12 V output convert it down to 4.8-5.5 V.	1a. Connect the input of the linear regulator to a power supply, and the output to a multimeter. 1b. Observe the output voltage on the multimeter and make sure that it stays within the range. 2a. Connect the input of the linear regulator to a power supply, and the output to a multimeter. 2b. Observe the output voltage on the multimeter and make sure that it stays within the range.	Y
Switching Regulator	The switching regulator takes in +5 V and convert it down to -4.8 to -5.5 V.	1a. Connect the input of the switching regulator to a +5 V power supply, and the output to a multimeter. 1b. Observe the output voltage on the multimeter and make sure that it stays within the range.	Y
Boost Converter	Supplies at least 50 mA at 23.5-24.5V output.	1a. Assemble the complete boost converter circuit. 1b. Attach a DC electronic load to the output of the circuit and increase current up to 50 mA. 1c. Measure output voltage	Y

		and check stability within 23.5-24.5V.	
User Module	Transmit and receive data over Raspberry Pi from ESP32 using 2.4 GHz WiFi.	1a. Power each ESP32 module separately with 3.3V and power Raspberry Pi with 5V. 1b. Transmit data from ESP32 to Raspberry Pi from at least 10 feet away. 1c. Ensure data is received on the Raspberry Pi.	Y