# Undergraduate Research Report

Jiamin Xie

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## I. Introduction

The report presented summarizes the research work that has done in the past semester. The subject of the research focuses on an acoustic system of target localization for an Autonomous Underwater Vehicle (AUV). The goal of the acoustic system is to listen to the sea ambient with an attention to the desired ship propeller noise. The circuitry will further amplify and digitally process the signal of interest to calculate a location information, i.e. AUV relative bearing to the ship. The system can be thought as like a hydrophone.

## II. Previous Work & Motivation

The previous work identified the frequency range of our interested ship propeller and propulsion machinery noise to be around 5Hz ~ 300Hz [1]. This motivated our design on a bandpass filter as a part of the acoustic system. We also studied ambient sea noise that is included in [2] to determine the necessary gain of the amplifier.

Prior to our study, there was another similar project that investigated an AUV towed array of hydrophones for localizing a sound source [3]. The method that was used before calculated the bearing angle based on the phase difference between the multiple acoustic signals that were received at the linear uniform sensors array [4]. Such method provided an idea of the front-end architecture of our system, however, the current design limits are different. For example, the maximum separation between sensors now is about 10 inches. This constrains the number of the sensors used, and challenges the precision and accuracy of our system output. With an effort in this semester, we have successfully built the first prototype of the system. We also obtained test data from examining the front-end sensors performance under different water conditions such as in a water tank and a shallow pond.

## III. System Overview

Our proposed system includes 5 circuit sections as sensory receiving, bandpass filtering, amplifying, digitizing, and processing the signal. The following photo (fig.1) shows the prototype board that was made in this semester. The circuit sections are located accordingly from the left to right of the board. The received signals from our two front-end sensors come into the board at the most left connectors.

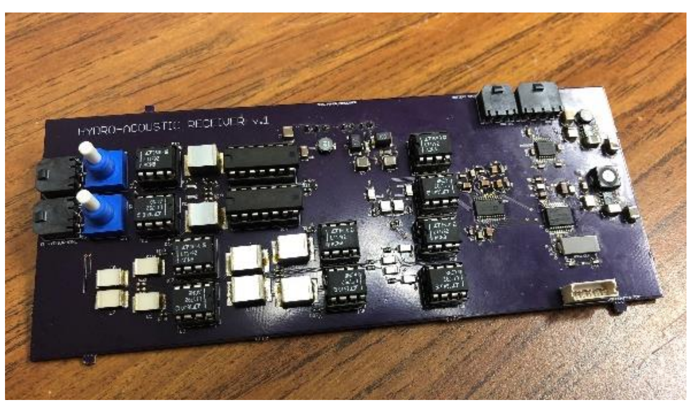


Figure 1 Hydro-acoustic Receiver Prototype Board

The connectors are used for interfacing the system with external resources. At the top right corner of the board, one connector on left is the battery input for the whole system. The one besides it is a communication port between RS232 (computer, external) and UART (microcontroller, internal). The bottom right connector allows the user to program the microcontroller (PIC32MM0064GPL020).

The board also equips power-electronic components like DC-DC converters for a power management of different integrated circuits. The printed circuit board has 4 layers to accommodate the powering planes required for Vcc battery (15~18V), $\pm$12V analog bipolar power for the ADC, +3.3V digital for the microcontroller, and +5 digital for quantization in the ADC. Note the ADC used is a 12-bit model with an input range of $\pm$5V or $\pm$12V that is programmable to select. This allows us to choose the optimal ADC resolution based on our estimation of the amplitude range of the test signal input.

## i) The board layout

A detailed EAGLE board layout is shown in figure 2. The board divides components into two categories – analog and digital. The ADC is shown beneath the vertical blue dashed lines (power plane borders) on the right to the middle of the board. The analog circuits are then assigned to the whole left area of the ADC, and the digital ones are located on the right. The purpose of such arrangement is to mitigate the noises that are injected to the analog traces by the high-frequency switching digital circuits.

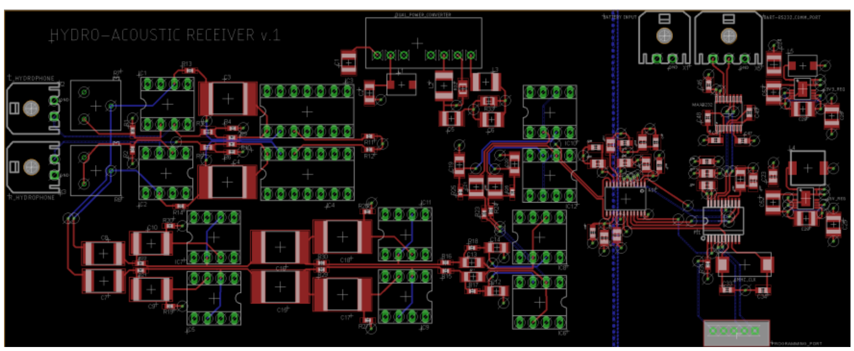


Figure 2 EAGLE layout of the prototype board

## ii) Front-end Sensors

Piezoelectric elements make a perfect match to our sensors design objectives. They also serve commonly as actuators in hydrophones. Figure 3 shows the cylindrical piezoelectric sensors that we used as a prototype in testing. The special shape offers a directivity in the front.

As we studied piezoelectric elements, with an appropriate attachment of electrodes on the elements' circular surfaces, one can measure the corresponding voltage from applying a pressure on the piezoelectric element. Since the incoming acoustic signal pressurizes the sensor surface when it arrives, the sensor converts the mechanical stress to a voltage difference between two opposite sensor surfaces. The characteristics of that acoustic waveform can be captured.

Figure 3 Cylindrical Piezoelectric Elements of 5mm thickness (Sensors)

Along with the study, sensitivity calculation becomes a key for us to choose the right sensor for our project. From one of the research article on hydrophone design in [5], the receiving sensitivity *(S)* of a piezoelectric element is found to be, $S = g_{ij} \cdot h$, where $g_{ij}$ *(i, j denotes pressure and voltage axis)* is the piezoelectric voltage coefficient, and *h is* the element thickness. For a proof of concept, the sensitivity of our element is chosen approximately same as what a common hydrophone design will use. The product found is a cylindrical Navy Type II piezoelectric element made from APC international, Ltd. with a surface diameter of 5 mm and thickness of 5 mm, using $g_{33}$ configuration. The sensitivity is then calculated to be $-198.132$ dBV/μPa in theory.

### iii) Waterproof Casing Material – Polyurethane

Since the sensors will be mounted at the AUV nose, we needed a casing material that will protect the piezo-elements, especially at the electrode surfaces, against the water. This material will need to have the acoustic properties close to that of water for the least energy reflected at the boundary of incidence. These properties include parameters such as material density, speed of sound through material, which the product of the two characterizes the acoustic impedance of material [6]. From our current research, we have found an available compound to be polyurethane RENCast 6410, which both meets the acoustic properties and the material rigidity. Figure 4 shows a cased piezo-sensor. Note the cure time of such casing material requires about 20 hours.

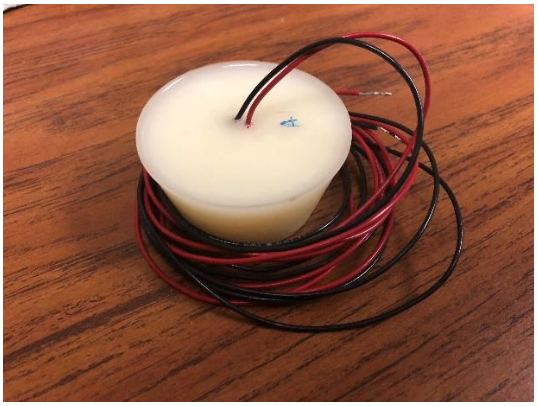

Figure 4 Cased Piezo-sensor

### iv) Amplifier and Filter Circuit

As we keep commercial hydrophone as a design reference, we followed a hydrophone amplifier configuration from Linear Technology, which utilizes an operation amplifier LT1792, as shown in the top half circuit in figure 2. Specifically, we replaced the proposed DC-Servo loop integrator with a lab-owned LM324 for simplicity.

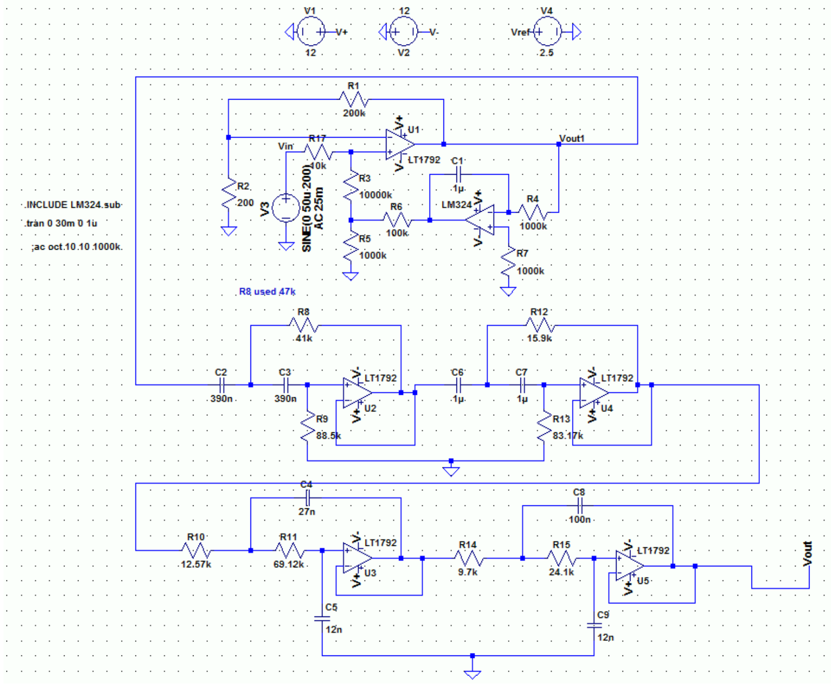


Figure 5 Amplifier and Bandpass Filter Circuits

The bottom half of figure 6 demonstrates a 4th order bandpass filter that we designed to acquire our signal of interest against other noises. The resistor and capacitor values are chosen in order to have the best approximation to have a gain cutoff at 60dB around the frequency of 300 Hz. They are also selected as common values that can be found from electronics distributors.

## IV. Testing Results

We have experimented with the sensors at different locations, such as the Claytor Lake nearby, a shallow pond on campus, and a water tank around the lab.

The experiments have a setup as following:

- Audio Transducer as a sound generator (Frequency ranges from 5Hz to 20kHz and up)
- Velleman Oscilloscope for waveform capture
- Our acoustic sensors compared to commercial hydrophones (no amplifier or filter)

In a test, components are loaded onto a steel skeleton that can be carried around and dropped underwater. The audio transducer generates a test tone, and is brought to a distance and an angle away from the receiving sensors. The distance, angle, and frequency of the transmitted signals are recorded. The sensed waveform and a MATLAB calculated phase angle information are compared to the known data.

### i) Sensors Tests

The goal of the sensors test is to check the performance of our front-end sensors, and thus to determine the influential factors. The resulted data also helped us to obtain a real-case input for the calculation of phase angle through the delay-and-sum algorithm that we coded in MATLAB.

One of the valuable tests on the impact of casing that we have run is at a water tank around the lab. An experiment overview is shown in figure 6 below. Note that we did not include any additional circuits at this point to have a pure observation on the sensors.

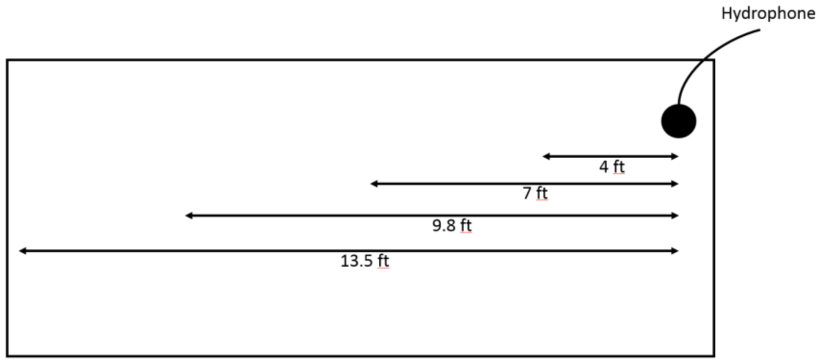


Figure 6 Water Tank Test

As seen in the figure 6, we placed our sensors at one end of the water tank and an acoustic transducer with a 7kHz tone at distances away. We have run the commercial hydrophones, 1cm self-made sensors, and 0.5 cm sensors for this test. Note the 1cm and 0.5cm thickness is referring to the separation between the casing outer surface to the piezo-element electrode surfaces. The resulted frequency representations of the received signals are shown below.

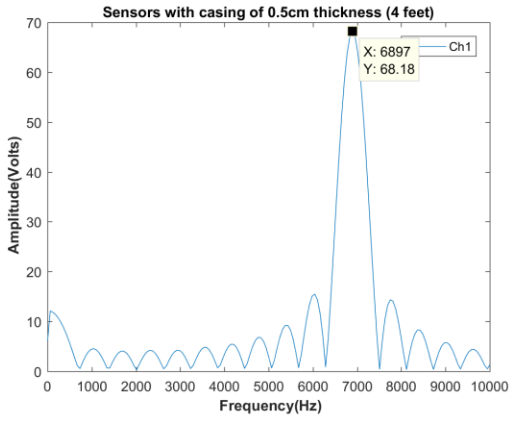


Figure 7 Sensors at 4 feet away (0.5 cm thickness)

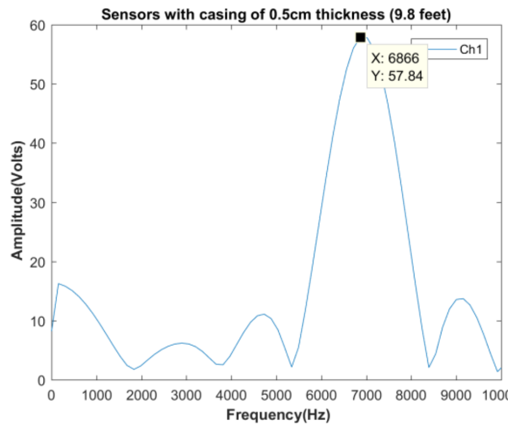


Figure 8 Sensors at 9.8 feet away (0.5 cm thickness)

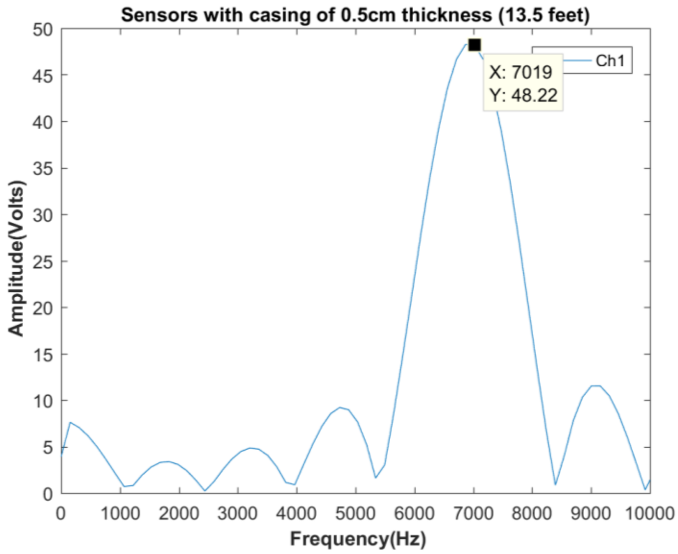


Figure 9 Sensors at 13.5 feet away (0.5 cm thickness)

The FFT plots shown in figure 7, 8 and 9 indicated a progressive trend of decreasing amplitude as the distance between sensors and the acoustic source increases from 4ft to 13.5ft. This follows the physics of energy inverse square law by the distances. Additionally, the highest peak around 7kHz captured the true 7kHz tone, which was the one generated by the transducer. These two factors together confirmed our design approach of a polyurethane casing and piezo-elements was correct. Note that the local maximum shown in the lower frequency was at 60Hz due to running the oscilloscope using laptop.

Next, we did a performance comparison between the different sensors within a fixed distance. Comparing figure 10, 11 and 8, we have seen the control sensor, i.e. the commercial hydrophone yielded the best response to the transmitting signal. This gave us a sense of our current prototype stage and a goal to achieve.

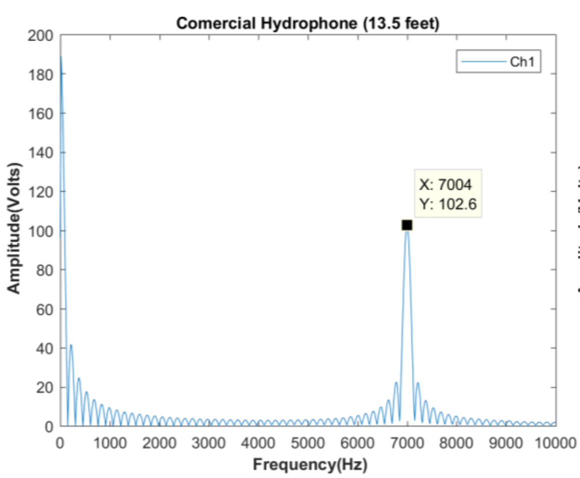


Figure 10 Commercial Hydrophone at 13.5 feet

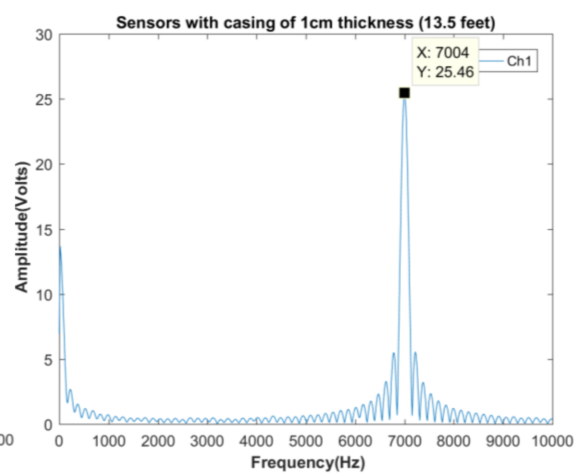


Figure 11 Sensors at 13.5 feet away (1 cm thickness)

On the other hand, comparing the self-made sensors with different casing thicknesses, as shown in figure 9 and 11, we found casing thickness is an important factor of the overall sensor sensitivity. The smaller separation between casing and piezo-element will have larger sensitivity because of the unavoidable acoustic losses in the polyurethane. Thus, following the observation in the tests, we further made a mode for a casing of 1mm thickness as shown in figure 12. This will be taken account into our future testing schedules.

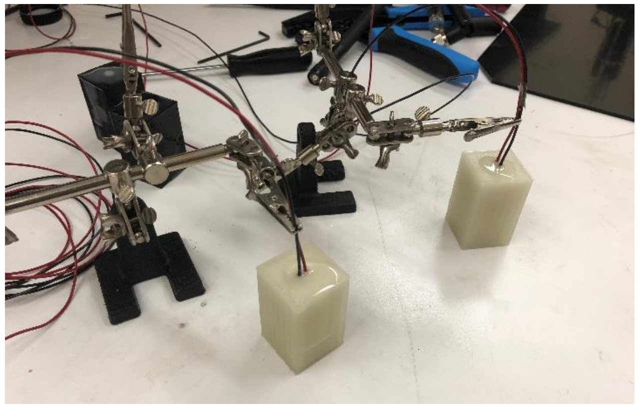

Figure 12 Sensors with casing of 1mm thickness in cure
(The outer rectangular shape is the mode)

At the end of the test, we also had the sensors surfaces faced at different angle to the target source. The peak amplitude in FFT occurred at when the *33* axis of the piezo-element was aligned with the incoming sound wave direction among all the angles that were being tested. This confirmed our study on the directivity of the cylindrical piezo-element that is previously illustrated at the **Front-end Sensors** section.

As mentioned before, we have conducted other tests at Claytor Lake and a shallow pond on campus. However, due to occasional incidents, those tests did not result in any significant data that could improve our study and knowledge on the project. Nevertheless, we have found that the Claytor Lake provides the largest separation and bearing angle between the sensor and transmitter. This can be the most stringent testing case for a late stage of project testing. The shallow pond is an extreme noisy condition that can also challenge our bandpass filter design. To effectively move on to those stages of testing, we would require more time spent on polishing the current design towards a better result at the water tank, i.e. approaching the commercial hydrophone.

### ii) The system board testing

In parallel with our tests at the front-end sensors, we also conducted few tests on the system printed circuit board. Since the tests started relatively late in the semester, one main achievement is the activation of the microcontroller. As shown in figure 13 and 14, a very simple code has been successfully loaded to the on-board microcontroller through the pickit-3 debugger. The pickit-3 debugger takes a power through USB in the laptop and supply a digital 3.25V to the PIC32. Thus, we have confirmed the microcontroller is working, and soon, we will implement our beamforming algorithm into the PIC32.

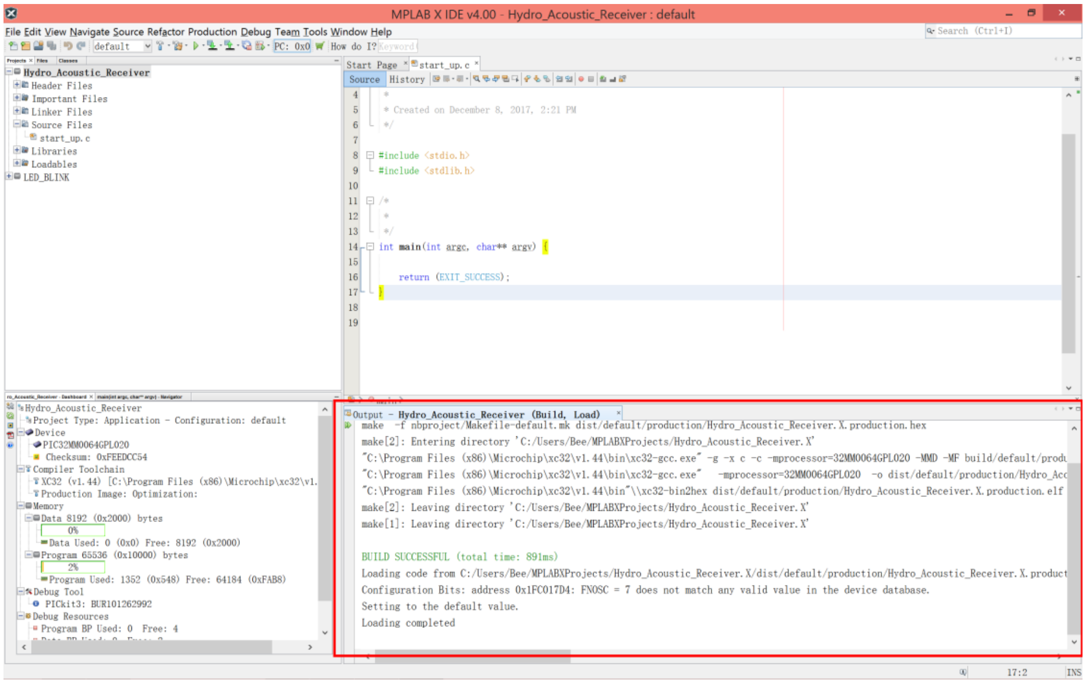


Figure 13 A Successful Loading of a Program onto the Microcontroller in the Board

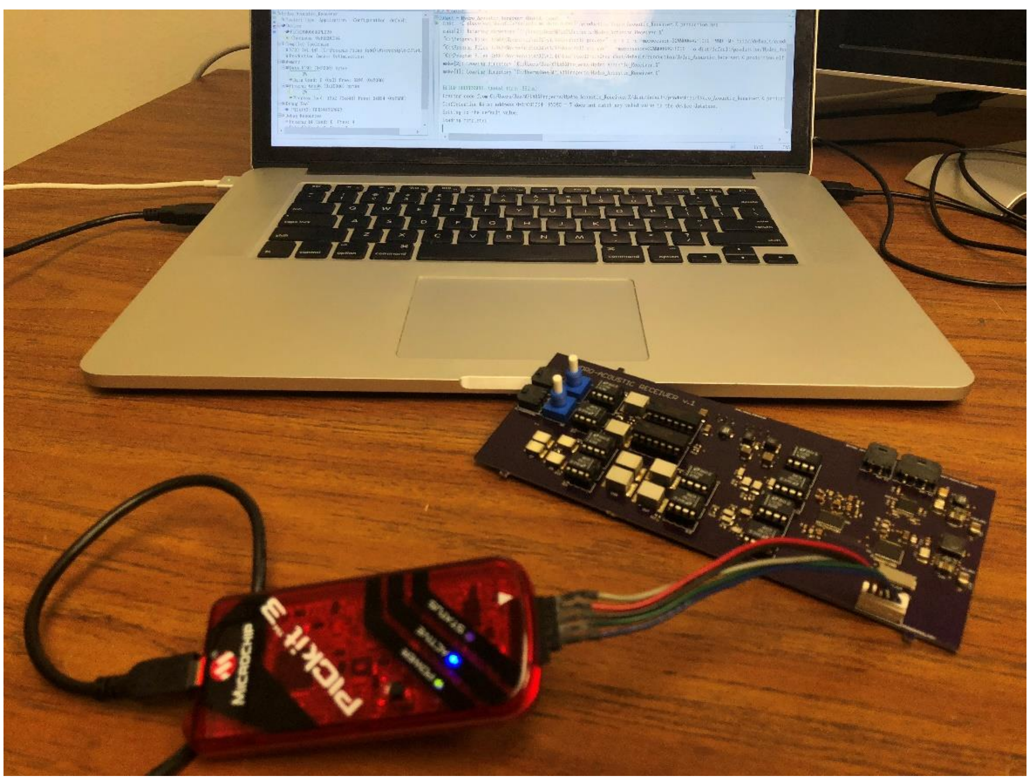


Figure 14 Microcontroller Activation Setup

## V. Conclusion

Overall, the work in this semester has moved forward the previous conceptual stage of the project to a first prototype. The testing results have been given a confirmation of our knowledge before. To progress toward the overall research goal, there is not only more things need to be done on testing the current design, but also preparations for a system design upgrade, such as a better quality and size of the piezo-element for a higher sensitivity, and low-tolerated circuit components for avoiding a system phase-lag to the two received signals. We are looking forward to accomplishing these through the winter break, and have a new stage of the project ready in the upcoming January.

## VI. Acknowledgement

**Special thanks to Dr. Stilwell for enrolling me into this interesting and valuable research.**

**Jorge for being a strong project partner and a helpful senior friend in life.**

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## VII. References

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