Interim Report
Master 1
Artificial Intelligence and Robotics

2021/2023

Localization and tracking of moving targets by hydrophones.

STUDENT
Hemant Ramphul

SUPERVISORS UDM/UNLIM
Mons. Khadimoullah Ramoth
&
Prof. Ouiddad Labbani Igbida

Abstract

Localization and tracking of moving targets by hydrophones is a technique used to determine the position and motion of an object in water by analyzing sound signals received by an array of hydrophones. Hydrophones are sensitive devices that can detect and measure underwater sound waves. By placing a hydrophone array at different locations in water, it is possible to triangulate the position of a sound source and track its movement. This technique is commonly used in marine applications, such as tracking marine mammals, ships, submarines, and underwater vehicles.

The localization and tracking process involves several steps, including signal processing, acoustic modeling, and numerical methods. Signal processing techniques are used to filter, analyze, and extract features from the received acoustic signals. Acoustic modeling techniques are used to estimate the acoustic propagation properties of the underwater environment. Numerical methods, such as beamforming and time delay estimation, are used to estimate the direction of arrival of the sound waves and the time difference of arrival between different hydrophones.

Recent advances in hydrophone technology and signal processing algorithms have led to significant improvements in the accuracy and speed of localization and tracking of moving targets by hydrophones. This has resulted in a wide range of applications, including marine mammal research, environmental monitoring, underwater navigation, and defense and security.

Acknowledgements

I would like to express my deepest gratitude and appreciation to all those who have supported me throughout my journey towards earning my master's degree M1.

First and foremost, I am indebted to my supervisors, Professor Ouiddad Labbani Igbida and Mr. Khadimoullah Ramoth, for their invaluable guidance, unwavering support, and continuous encouragement. Their expertise, dedication, and insightful feedback have played a pivotal role in shaping my research and academic development.

I am also grateful to the University of Mascareignes for providing the necessary equipment and allowing me to utilize their facilities for my work.

I extend my heartfelt appreciation to my wife, my four-year-old daughter, and my friends for their unconditional love, encouragement, and unwavering belief in my abilities. Their constant support, patience, and understanding have been a continuous source of motivation and inspiration throughout this challenging journey.

I am grateful to my fellow classmates and colleagues for their camaraderie, intellectual discussions, and collaborative spirit. Their diverse perspectives and collective efforts have enriched my academic experience and fostered meaningful conversations.

To all those mentioned, as well as the countless others who have contributed to my academic journey, I extend my heartfelt appreciation. Your support and encouragement have been invaluable, and I am honored to have had the opportunity to learn and grow under your guidance.

Thank you all for your unwavering support and belief in my abilities.

Table of Contents

1 Introduction 8

1.1 Overview on hydrophone 8

2 Synthesis of the bibliographical study 9

2.1 Importance of Localization and Tracking 9

2.2 Review of an existing Localization Systems 10

2.3 Methodology 11

2.4 Target Localizer 12

2.5 Target Tracking 12

3 Highlights of work to be carried out 13

3.1 Characteristics of signal 13

3.1.1 Characteristics of signal received on one hydrophone. 13

3.2 Underwater acoustic communication 14

3.3 Methodology 15

3.3.1 Mathematical technique 16

3.3.2 Cross-correlation Technique, Concept, and the Triangulation Method 17

3.3.3 Target Tracking by finding position. 19

3.4 Prototypes 22

3.4.1 Monitoring System 23

3.5 Experimental and Result 26

3.5.1 Schematic Diagram 26

3.5.2 Process diagram for localization and tracking 27

3.5.3 Program Logic 28

3.5.4 Results and Analysis 29

4 Future Work and Scope for Improvement - M2 32

4.1 Feature extraction and selection 32

4.2 Model training and optimization 32

4.3 Noise and reverberation modeling 32

4.4 Adaptive algorithms 32

5 Conclusion 33

6 Bibliography references 34

7 Appendix **35**
7.1 The code. 35
7.2 Wiring of the hardware block diagram. 36
7.3 Hardware setup. 37
7.4 Result from MATLAB in real-time 38

Abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
DOA	Direction of Arrival
TDOA	Time Difference of Arrival
TOA	Time of Arrival
SNR	Surface-Reflected Path
RAP	Signal-To-Noise Ratio
ML	Machine Learning
SH	Smart Hydrophone
GPS	Global Positioning System
DAC	Digital-to-Analog Converter
TFT	Thin Film Transistor
SPI	Serial Peripheral Interface
PWM	Pulse-width modulation
AUV	Autonomous Underwater Vehicles
GCC-PHAT	Generalized Cross-Correlation Phase Transform
BSC	Base Station Controller
BTS	Base Transceiver Stations
GSM	Global System for Mobile Communications

List of Figures

Figure 1. Underwater acoustic communication. 14
Figure 2. Triangulation technique. 14
Figure 3. Cross-correlation technique with three hydrophones 17
Figure 4. Prototype with three hydrophones. 22
Figure 5. Monitoring System 23
Figure 6. Schematic diagram. 26
Figure 7. Process diagram 27
Figure 8. Pseudocode Snippet 28
Figure 9. Experimental results thru Arduino 29
Figure 10. Experimental results through monitor information 30
Figure 11. Live data on MATLAB 30
Figure 12. Live data with time and spectrogram analysis 31
Figure 13. Wiring of hadware block diagram 36
Figure 14. Setup of hardware 37
Figure 15. Result from MATLAB in real-time 38

1 Introduction

In the deep ocean, a useful acoustic duct for moderate sound propagation is the reliable acoustic path (RAP). (1) The critical depth is the depth below the deep sound channel where the sound speed matches the highest speed near the surface. It represents the point at which the direct path, and potentially the surface-reflected path, called RAP, exists between a receiver situated below the critical depth and a source located at a moderate range, assuming favorable surface conditions. (2) A high signal-to-noise ratio (SNR) ocean environment is the advantage RAP offers for source localization.

Localization of a sound source is important in many areas. By "localization" we mean the problem of determining the location of a source of sound in the ocean by use of hydrophone data. Recently, machine learning (ML) has been used in underwater acoustic source localization, direction of arrival (DOA) estimation, and seabed classification. (3) Most research in localization has used continuous wave sources and this method is widely used in the sound source localization field.

However, unraveling and using the underwater cacophony is not at all simple. This is particularly true for low-frequency ($f<500$ Hz) propagation in coastal water (water depth $D<200$ m), because the environment acts as a dispersive waveguide: the acoustic field is described by a set of modes that propagate with frequency-dependent speeds. In this context, to extract relevant information from acoustic recording, one needs to understand the propagation and to use physics-based processing.

1.1 Overview on hydrophone

The term "hydrophone" derives from the combination of "hydro," which refers to water, and "phone," which signifies sound. Essentially, a hydrophone can be defined as a device designed to measure sound in water, functioning as an underwater equivalent of a microphone. Hydrophones can be broadly classified into two main categories based on their directivity: *omni-directional* and *unidirectional*. (4)

In contrast to directional hydrophones, omni-directional hydrophones possess uniform sensitivity to acoustic waves in all directions. Directional hydrophones, on the other hand, exhibit higher sensitivity in specific directions. When an acoustic wave reaches an array of directional hydrophones, the time intervals between the wave arrivals at each hydrophone are utilized to determine the direction of the acoustic wave. This configuration enables improved detection capabilities compared to a single hydrophone, as it enables noise rejection from unwanted directions, increases the signal-to-noise ratio (SNR), and offers other benefits.

2 Synthesis of the bibliographical study

2.1 Importance of Localization and Tracking

The localization and tracking of underwater targets have become a subject of significant research interest due to the challenges arising from the noisy ocean environment. The underwater sound environment is characterized by a diverse array of noise-like signals and signal-like noises. Consequently, obtaining a clear distinction between the desired signals and the surrounding noise often becomes complex, necessitating the development of specialized systems with advanced signal processing techniques. These systems aim to extract the signals of interest from the mixture of signal and noise. (5)

Numerous specialized systems have been devised to address the specific challenges involved in localizing and tracking underwater noise sources and targets, particularly in active sonar scenarios. In active sonar systems, localization and ranging are typically achieved by measuring the time interval between the transmission of pings and the reception of their echoes. On the other hand, passive systems rely on solutions based on time of arrival (TOA) or direction of arrival (DOA) to localize and track targets within a water body.

These specialized systems offer effective solutions to the distinctive problems encountered in underwater target localization and tracking. By utilizing advanced signal processing techniques and leveraging the principles of TOA and DOA, these systems enhance the accuracy and reliability of target detection. Through ongoing research and development, the field continues to advance, providing valuable insights and innovative approaches for improving the performance of underwater target localization and tracking systems.

2.2 Review of an existing Localization Systems

In the past, numerous surveillance systems utilizing passive listening concepts have been developed and deployed. However, conventional acoustic sensing and tracking systems have inherent limitations that need to be addressed. In response, a versatile technique has been developed to overcome these limitations and enable precise position fixing and tracking of underwater targets using passive listening concepts.

To address the limitations, a novel approach is proposed, which utilizes an acoustic three-buoy system for localization purposes. However, the localization estimates obtained from this system may be subject to variations due to instabilities in the buoys, measurement errors resulting from changes in environmental parameters, and theoretical approximations. To enhance the accuracy of the localization estimates, the Kalman Filter (KF) approach is employed, which refines the estimates by considering the measurement uncertainties and system dynamics. Furthermore, the algorithm is extended to accommodate moving targets, even under maneuvering situations.

By incorporating the Kalman Filter approach and considering the dynamic nature of the underwater environment, the proposed technique aims to improve the accuracy and robustness of underwater target localization and tracking. This advancement addresses the challenges faced by conventional acoustic sensing systems and provides a more reliable and effective solution for surveillance applications in underwater environments.

2.3 Methodology

Various methodologies have been employed to achieve localization and tracking of underwater targets based on passive listening principles. In preparation for these localization and tracking efforts, a simulation study was conducted to inform the development of a practical three-buoy system concept.

The proposed system consists of mechanically steerable hydrophone arrays and appropriate electronics to enable the localization and tracking of unknown targets in close proximity to the system. Each buoy system observes the maximum signal arriving from a different angle, and by utilizing direction of arrival information, triangulation techniques are employed to determine the localization of the unknown underwater target.

To enhance the accuracy of the localization estimates, the Kalman filter approach is implemented. This approach effectively reduces the inaccuracies associated with the estimation process. Additionally, the surveillance system incorporates signal processing modules to extract source-specific features from the composite noise data waveforms. These extracted features are then utilized to compile a knowledge base, forming the foundation of the classifier used in the system.

Through the combination of these methodologies, the proposed system aims to achieve precise localization and tracking of underwater targets based on passive listening concepts. The utilization of steerable hydrophone arrays, triangulation techniques, Kalman filtering, and classifier-based analysis contribute to the effectiveness and reliability of the system in real-world surveillance applications. (5)

2.4 Target Localizer

Underwater surveillance systems typically rely on capturing the noise emissions produced by the targets of interest. The proposed three-buoy system is designed to facilitate this surveillance process. It consists of three mechanically steerable hydrophone arrays that receive acoustic signals, along with the necessary buoy electronics. The automated buoy system is responsible for conducting the surveillance operations. It performs tasks such as signal processing, communication management, and power supply management. Additionally, the buoy electronics are equipped with GPS receivers, allowing them to collect geographical position information.

When the hydrophone arrays detect target emissions, they are steered towards the direction of the maximum signal arrival. The angular positions of the hydrophone arrays are then utilized to estimate the target's position using triangulation techniques. By employing geodetic *latitude* and *longitude* distance computations, as well as trigonometric and triangulation methods, it becomes possible to calculate the target's position relative to the geomagnetic meridian.

By integrating these components and techniques, the proposed three-buoy system enables the accurate estimation and tracking of underwater targets. The combination of mechanically steerable hydrophone arrays, triangulation techniques, and geodetic computations enhances the system's ability to determine the precise positions of the targets under surveillance.

2.5 Target Tracking

Target tracking systems generate data streams that provide information about the target's position. This scenario can be categorized into one-dimensional motion, where the data is subject to various forms of inherent noise, including process noise and measurement noise. Initially, a study is conducted on the one-dimensional system, which is then expanded to two dimensions. Furthermore, the principles can be generalized to multi-dimensional systems based on the specific problem at hand.

When dealing with a maneuvering target, the observed errors become more complex compared to those encountered with a moving target. Therefore, appropriate correction measures need to be implemented. In the case of a highly maneuvering target, a decision statistic based on the chi-square distribution can be utilized to apply necessary corrections to the Kalman filter algorithm. This adaptation allows the system to effectively handle sudden and drastic maneuvers exhibited by the target.

3 Highlights of work to be carried out.

The salient highlights of the work to be carried out are briefly outlined in the following sections.

3.1 Characteristics of signal

Hydrophones provide unique TDOA measurements, which may have slight timing discrepancies affecting target location. By combining hydrophone measurements in a vertical linear array, spatial filtering enables analysis of target information nearby. Inertia-type vector hydrophones are more sensitive than multimode types but less sensitive than piezoceramic hydrophones. Nonetheless, they excel at measuring low frequencies. (4)

3.1.1 Characteristics of signal received on one hydrophone.

The signal received on an array of hydrophones has some unique characteristics that can be used to localize and track the sound source.

a) **Amplitude and Phase Differences:** Due to the difference in the distance from the sound source to each hydrophone in the array, the signal received on each hydrophone will have a different amplitude and phase. By comparing the amplitude and phase of the signals received on different hydrophones, we can estimate the direction of arrival (DOA) of the sound source.

b) **Time Differences:** Sound waves travel at a finite speed in water, and the time it takes for the wave to reach each hydrophone will be different. By measuring the time differences between the signals received on different hydrophones, we can estimate the distance of the sound source from the array.

c) **Spatial Filtering:** By combining the signals received on multiple hydrophones in the array using a technique called beamforming, we can enhance the signal-to-noise ratio (SNR) and suppress interference from unwanted sources.

d) **Frequency Content:** The frequency content of the signal received on the array can be used to identify the type of sound source. For example, the frequency spectrum of the sound emitted by a dolphin is different from that of a ship or a whale.

e) **Doppler Shift:** If the sound source or the hydrophone array is moving relative to each other, the frequency of the signal received on the array will be shifted due to the Doppler effect. By measuring the frequency shift, we can estimate the relative speed and direction of the sound source.

3.2 Underwater acoustic communication

Underwater acoustic communication involves transmitting and receiving messages beneath the water's surface. Hydrophones are commonly used for this purpose, offering various methods of underwater communication.

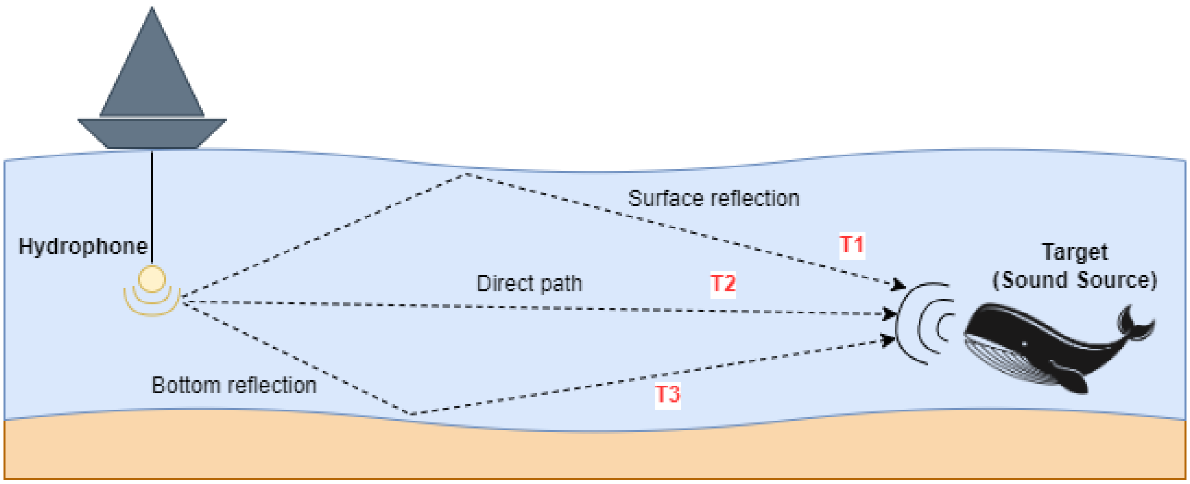

Figure 1. Underwater acoustic communication.

A triangular arrangement of hydrophones to localize the direction of an arbitrary sound source underwater. By recording input from the three hydrophones, we can cross-correlate the recordings to identify the time delay between the audio signals. With the known physical placement of the hydrophones, the direction of the sound can be estimated using the time delay between them.

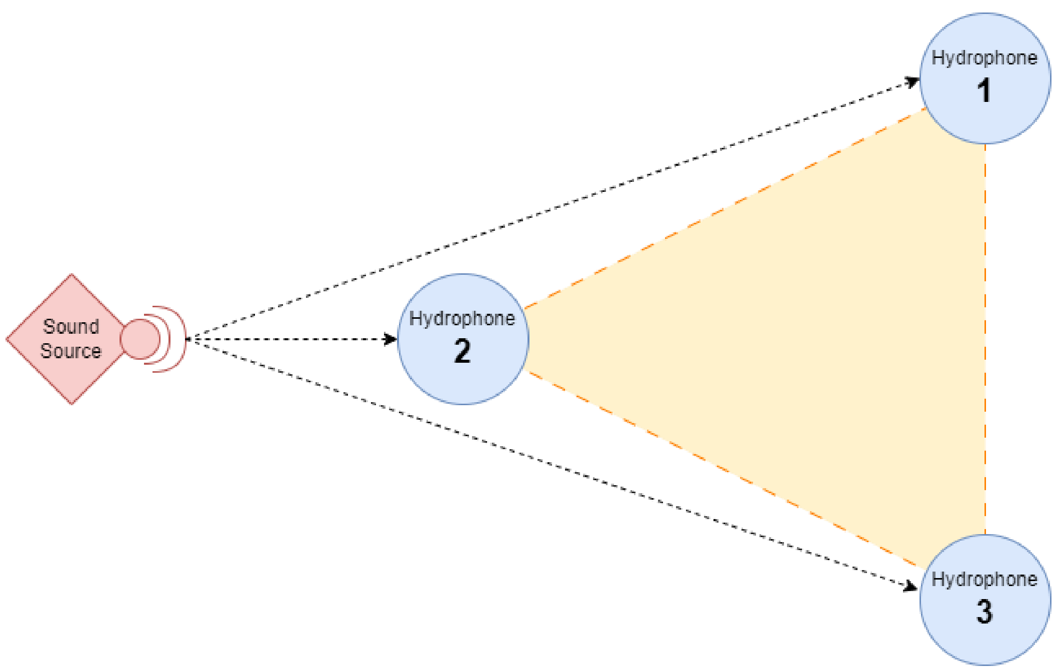

Figure 2. Triangulation technique.

3.3 Methodology

Locating and tracking a source in an ocean environment and estimating environmental parameters of a sound propagation medium are critical tasks in ocean acoustics. Many approaches for both are based on full field calculations which are computationally intensive and sensitive to assumptions on the structure of the environment.

This section addresses the methodology adopted for the realization of the underwater target localization and tracking system based on passive listening concepts. A three-buoy system attached with smart hydrophones are used for localization of the underwater targets. This smart hydrophone has a wide dynamic range for high quality data and long-term stability. The localization estimates may vary due to the instabilities of the buoys, measurement errors and theoretical approximations. The system consists of hydrophone elements and arrays of improved sensitivity and can identify targets with minimally configurable hardware resources.

3.3.1 Mathematical technique

The maximum time delay, in terms of sampling frames, between two hydrophones can be approximately computed by considering the speed of sound underwater, the distance between the hydrophones, and the sampling rate.

$$
\begin{aligned}
\text{MAX\_TIME\_DELAY} &= \text{SAMPLING\_RATE} / (\text{SPEED\_OF\_SOUND} * \text{DISTANCE}) \\
&= 25\ \text{kHz} / (1484\ \text{m/s} * 0.50\text{m})
\end{aligned}
\qquad \text{(Eq.1)}
$$

where in this equation (Eq.1): -

i. **Sampling rate:** The sampling rate refers to the number of samples taken per second when recording audio. It is typically measured in Hertz (Hz) or kilohertz (kHz). A higher sampling rate means more samples are taken per second, resulting in better audio quality and capturing higher frequencies.
ii. **Speed of sound:** The speed of sound is the velocity at which sound travels through a medium. In this case, it is the speed of sound in dry air at room temperature. The speed of sound can vary depending on factors like temperature, humidity, and the medium through which it is traveling. In the formula, the speed of sound is usually measured in meters per second (m/s).
iii. **Distance:** The distance refers to the physical separation between the two microphones. It is the distance that sound waves must travel to reach the second microphone from the first microphone. It is typically measured in meters (m).

The formula calculates the *maximum time delay* between two microphones based on the **sampling rate**, **speed of sound**, and **distance**. The time delay represents the amount of time it takes for a sound wave to travel from one hydrophone to the other.

By dividing the sampling rate by the product of the speed of sound and the distance, it can obtain the time delay in seconds. If the time delay in sampling frames is required, it can be obtained by dividing the sampling rate by the computed value.

It's important to note that this formula assumes a direct path between the two hydrophones and does not account for factors such as reflections, diffraction, or the speed of sound varying with environmental conditions. It provides an approximation of the maximum time delay based on the given parameters.

3.3.2 Cross-correlation Technique, Concept, and the Triangulation Method

Cross-correlation was the primary mathematical technique employed in this project to compute the time delay between two signals. It measures the similarity between two signals by sliding one signal along the other. The formula for cross-correlation is as follows:

$$(f * g)[n] \stackrel{\text{def}}{=} \sum_{m=-\infty}^{\infty} f^*[m] * g[m+n] \tag{Eq.2}$$

where in this equation (Eq.2):

- f and g represent the two signals obtained from the hydrophones.
- The symbol "$*$" represents complex conjugation.
- The index m represents the time index of the first signal.
- The variable n represents the time delay or lag between the two signals.
- The summation $\sum$ is taken over all possible values of m, ranging from negative infinity to positive infinity.

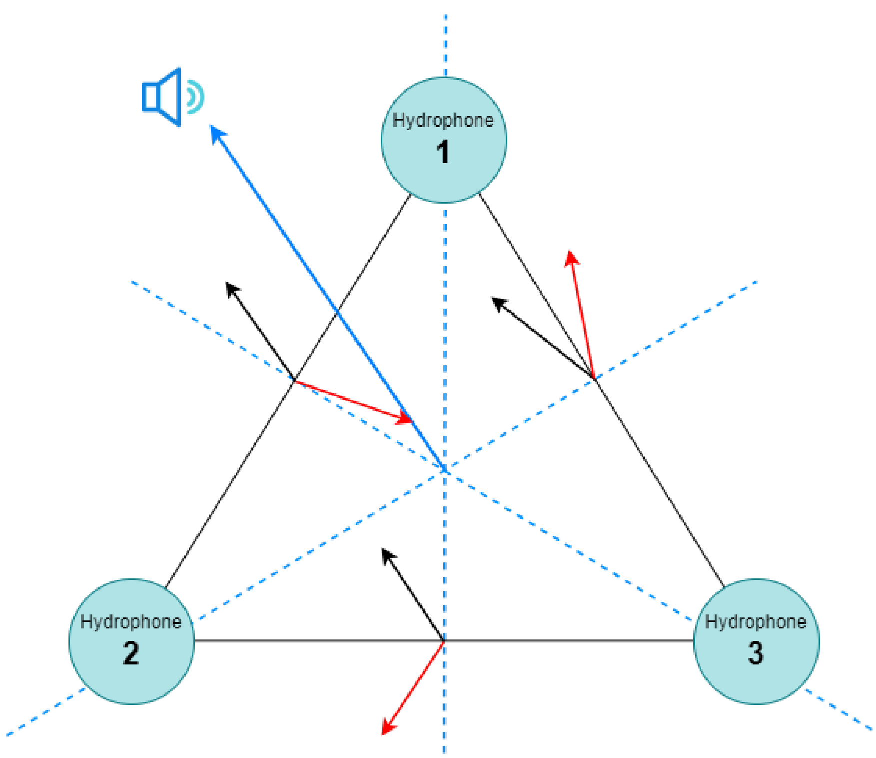

Figure 3. Cross-correlation technique with three hydrophones

Delve into the relationship between this concept and the triangulation method implemented with three hydrophones:

1. **Setup**: The project involves three hydrophones placed at known positions in a triangular configuration.
2. **Data Acquisition**: Each hydrophone records a signal, resulting in three signals: *f1*, *f2*, and *f3*.
3. **Cross-Correlation**: The cross-correlation operation is performed between pairs of signals to estimate the time delays. Let's consider *f1* and *f2* as an example.
   - The equation (*f1***f2*)[n] is applied to compute the cross-correlation between *f1* and *f2* at different time delays, n.
   - For each value of n, the equation calculates the sum of products between the complex conjugate of *f1* at time index m and *f2* at time index ($m + n$).
   - This process measures the similarity or correlation between *f1* and *f2* as they are shifted with respect to each other.
4. **Peak Detection**: The resulting cross-correlation function provides a correlation profile that shows the similarity between *f1* and *f2* at different time delays, n.
   - By finding the maximum value in the correlation profile and its corresponding time delay, it can determine the estimated time delay between *f1* and *f2*.
   - This maximum value represents the best alignment or synchronization between the two signals.
5. **Triangulation**: Repeat the cross-correlation process for the other pairs of signals (*f1*, *f3*) and (*f2*, *f3*) to estimate their respective time delays.
6. **Triangulation Calculation**: Once the time delays between the signals are estimated, the known positions of the hydrophones in the triangular configuration are used to calculate the location of the source of the signals.
   - The time delays and hydrophone positions are used in a triangulation algorithm to determine the position of the source based on the time differences of arrival (TDOA) of the signals.

The *cross-correlation technique* is used in the project to estimate the time delays between pairs of signals obtained from three hydrophones. By calculating the cross-correlation between the signals at different time delays, the best alignment or synchronization between the signals can be determined. The time delays, along with the known positions of the hydrophones, are then used in a triangulation algorithm to compute the position of the signal source.

3.3.3 Target Tracking by finding position.

1. Calculates the time difference of arrival (TDOA) between hydrophones based on the given delay values (‘**delay12’** and ‘**delay13’**) and the speed of sound (‘**soundSpeed’**).

Let see the equation (Eq.3) and (Eq.4):

i. **delay12** represent the time difference between the waveforms of hydrophone 1 and hydrophone 2.
ii. **delay13** represent the time difference between the waveforms of hydrophone 1 and hydrophone 3.
iii. **soundSpeed** represent the speed of sound.

$$TDOA12 = \frac{delay12}{1000000} \times soundSpeed$$

(Eq.3)

$$TDOA13 = \frac{delay13}{1000000} \times soundSpeed$$

(Eq.4)

These formulas convert the delay values from microseconds to seconds and then multiply them by the speed of sound to obtain the TDOA values in meters.

Note: Make sure to provide the correct value for the **soundSpeed** variable (either in Air or Underwater), typically in meters per second, to obtain accurate TDOA results.

2. Calculate the time differences between the waveforms of three hydrophones:

$$\Delta t_{12} = t_2 - t_1$$
$$\Delta t_{13} = t_3 - t_1$$
$$\text{(Eq.5)}$$

In equation (Eq.5), Δt_{12} represents the time difference between hydrophone 1 and hydrophone 2, Δt_{13} represents the time difference between hydrophone 1 and hydrophone 3, t_1 represents the time at which hydrophone 1's waveform crosses a threshold, t_2 represents the time at which hydrophone 2's waveform crosses the same threshold, and t_3 represents the time at which hydrophone 3's waveform crosses the same threshold.

3. Calculates the x and y coordinates of a sound source using triangulation based on time difference of arrival (TDOA) measurements.

$$x = \frac{(x_0 - x_1) \cdot (x_0 + x_1 + 2 \cdot tdoa12) - (x_0 - x_2) \cdot (x_0 + x_2 + 2 \cdot tdoa13)}{4 \cdot (x_0 - x_1) \cdot (x_0 - x_2) - 4 \cdot (x_0 - x_2) \cdot (x_0 - x_1)}$$

(Eq.6)

$$y = \frac{(y_0 - y_1) \cdot (y_0 + y_1 + 2 \cdot tdoa12) - (y_0 - y_2) \cdot (y_0 + y_2 + 2 \cdot tdoa13)}{4 \cdot (x_0 - x_1) \cdot (y_0 - y_2) - 4 \cdot (x_0 - x_2) \cdot (y_0 - y_1)}$$

(Eq.7)

Let see the equation (Eq.6) and (Eq.7):

1. **positions[0][0], positions[0][1]** represent the **x** and **y** coordinates of Hydrophone 1.
2. **positions[1][0], positions[1][1]** represent the **x** and **y** coordinates of Hydrophone 2.
3. **positions[2][0], positions[2][1]** represent the **x** and **y** coordinates of Hydrophone 3.
4. **tdoa12** represents the time difference of arrival between Hydrophone 1 and Hydrophone 2.
5. **tdoa13** represents the time difference of arrival between Hydrophone 1 and Hydrophone 3.
6. **x** represents the x-coordinate of the sound source.
7. **y** represents the y-coordinate of the sound source.

Formulas allow to calculate the **x** and **y** coordinates of the sound source using the provided TDOA measurements and hydrophone positions.

4. Calculates the distance between a hydrophone (specified by “hydrophoneIndex”) and a sound source located at coordinates “(x, y)”.

$$distance = \sqrt{(x - \{positions\}[\{hydrophoneIndex\}][0])^2 + (y - \{positions\}[\{hydrophoneIndex\}][0])}$$

(Eq.6)

Let see the equation (Eq.6):

1. **‘hydrophoneIndex’** represents the index of the hydrophone.
2. **‘(x, y)’** represents the coordinates of the sound source.
3. **‘positions’** be a 2D array representing the positions of the hydrophones.

3.4 Prototypes

Underwater target localization and tracking is a subject of great interest, as the estimation task faces numerous challenges in the presence of a noisy ocean environment. The development of a prototype three-buoy automated system offers a solution for localizing and tracking underwater targets using passive listening and target identification techniques.

The spreading of signals in time and frequency poses significant challenges in sonar systems. Time spreading is primarily caused by multipath reflections, while frequency spreading results from various factors such as wave motion on the sea surface, water movement, underwater currents, and the motions of transmitters, receivers, and targets. Doppler spread, which can reach up to one percent or more, is commonly observed in sonar operations.

Detecting and estimating signals with considerable spreading is considerably more complex compared to simpler systems due to obvious reasons. The presence of a wide range of interfering noises further complicates the sonar detection and estimation problems in the ocean. These noises include sea state noise, biological noise, machinery and cavitation noise from shipping traffic, as well as thermal noise.

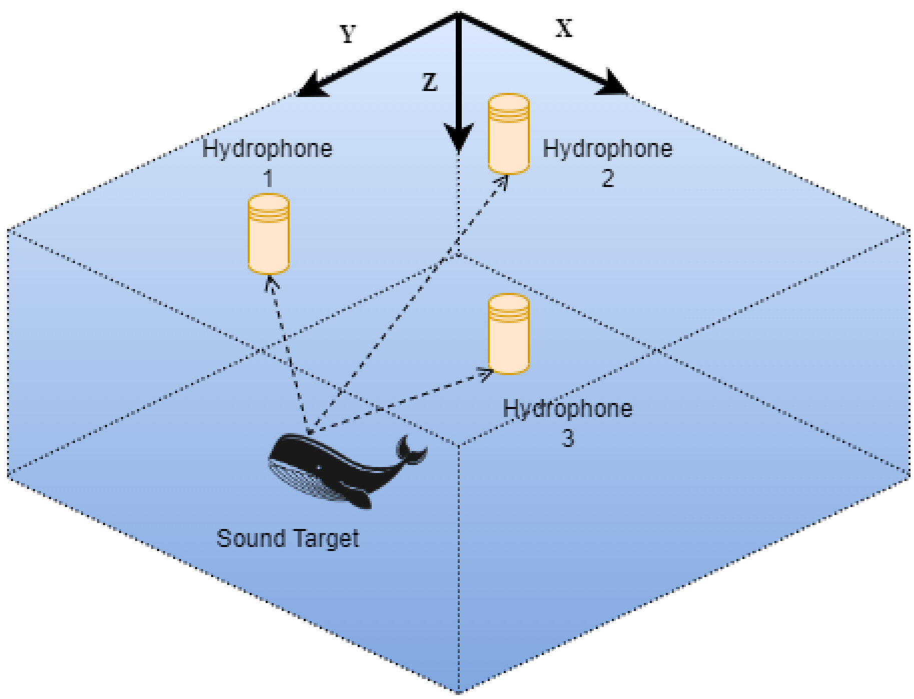

Figure 4. Prototype with three hydrophones.

3.4.1 Monitoring System

Coordination system is defined to determine the position of an object. (6) The integration of a GSM architecture (7) with the hydrophone-based localization and tracking system expands the capabilities of the monitoring system. It allows for remote access, real-time tracking, centralized management, scalability, data analysis, and integration with other systems. This integration enhances the efficiency and effectiveness of the monitoring system in underwater environments, enabling seamless data transmission, remote monitoring, and control of the tracking system. The monitoring system becomes a comprehensive solution for tracking and localizing moving targets underwater, offering valuable insights for various applications and facilitating efficient decision-making processes.

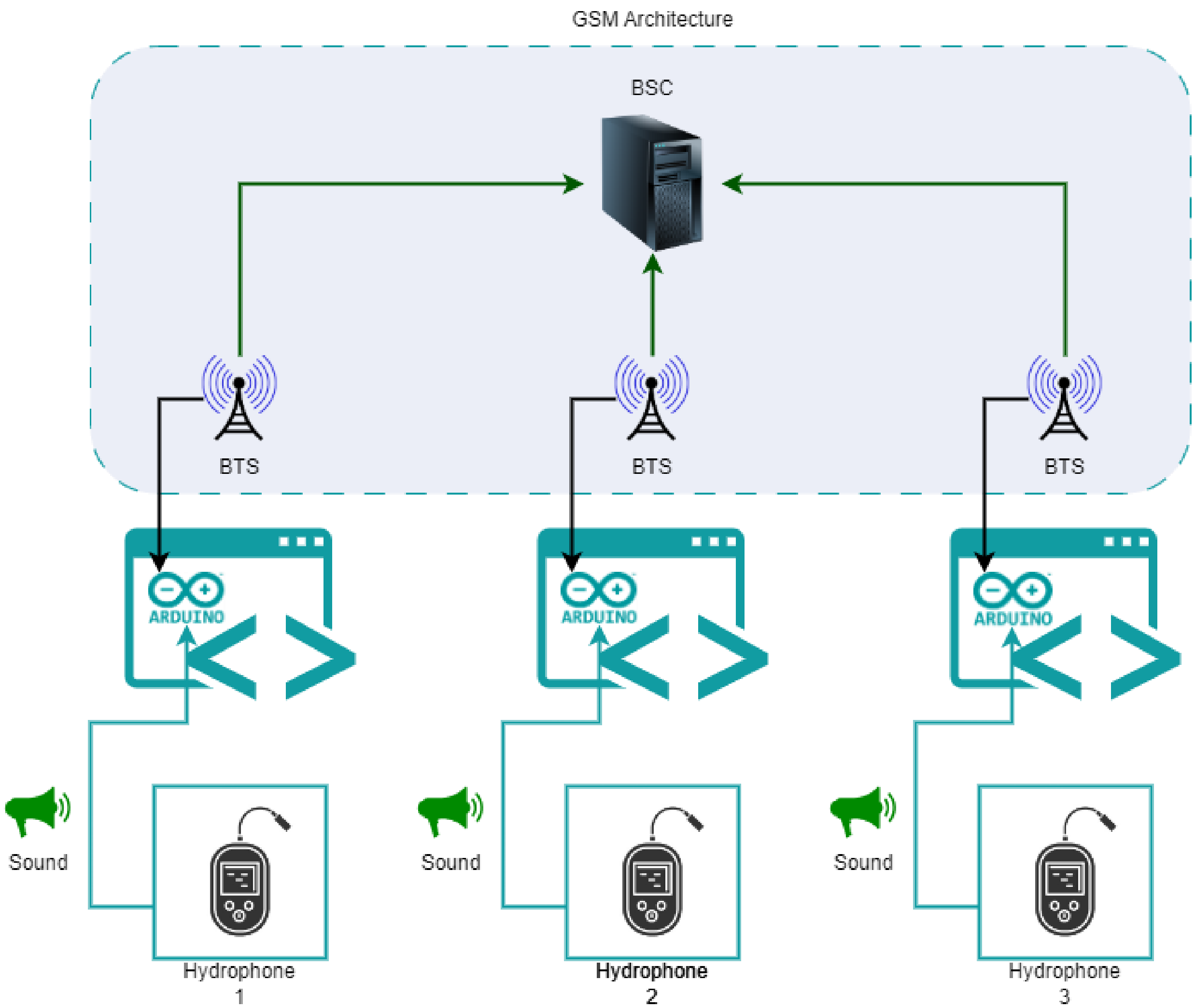

Figure 5. Monitoring System

3.4.1.1 Monitoring System Implementation

1. **Hydrophone Localization and Tracking System**: The core localization and tracking system using hydrophones remains the same as described earlier. It consists of hydrophones, Arduino board, signal processing algorithms, triangulation method, and data visualization/logging.
2. **Data Transmission**: In a GSM architecture, the collected tracking data from the hydrophone system can be transmitted using GSM networks. The Arduino board can be equipped with a GSM module or shield that allows it to communicate with the GSM network.
3. **GSM Module Integration**: The GSM module or shield provides the necessary connectivity to the GSM network. It typically includes a SIM card slot for data communication, antenna, and interfaces for connecting to the Arduino board. The module allows the Arduino board to send data packets containing the tracking information to a remote server or a central monitoring system.
4. **Remote Monitoring and Control**: With the GSM connectivity, the tracking system can be remotely monitored and controlled. The tracking data sent by the Arduino board can be received by a remote server or a central monitoring system. This allows real-time visualization of the target's position on a remote interface, enabling users to monitor the target's movements from a distance.
5. **Mobile Notifications**: Using the GSM capabilities, the system can also send notifications or alerts to designate mobile numbers. This can be useful for immediate alerts in case of specific events or when the target's position reaches certain thresholds or predefined regions.
6. **Data Management and Analysis**: The tracking data received by the remote server can be stored, analyzed, and processed for further applications. Advanced algorithms and data processing techniques can be applied to extract valuable insights from the collected tracking data.

Integrating the hydrophone localization and tracking system with a GSM architecture enables remote monitoring, control, and data transmission, expanding the system's capabilities for real-time tracking and management of underwater targets. It offers the advantage of wireless connectivity, enabling access to tracking information from anywhere with GSM network coverage.

Additionally, the use of a GSM architecture allows for scalability and flexibility in the monitoring system. Multiple hydrophones tracking systems can be deployed at different locations, and their data can be consolidated and managed centrally through the GSM network. This centralized approach simplifies data management and enables comprehensive monitoring of multiple targets or areas simultaneously.

Moreover, integrating the hydrophone tracking system with GSM technology opens up possibilities for remote configuration and updates. Parameters of the tracking system, such as signal processing algorithms or tracking thresholds, can be remotely adjusted, and fine-tuned via the GSM network. This eliminates the need for physical access to the tracking system, providing convenience and flexibility in system maintenance and optimization.

Furthermore, the GSM architecture provides a reliable and widely accessible communication infrastructure. It leverages the existing GSM network infrastructure, ensuring robust and consistent connectivity for data transmission. This enables real-time tracking updates and facilitates seamless integration with other systems or platforms that rely on GSM communication.

Overall, integrating the localization and tracking system using hydrophones with a GSM architecture enhances the system's capabilities, enabling remote monitoring, control, data transmission, and seamless integration with other systems. It offers a versatile and scalable solution for underwater target tracking applications, ensuring effective and efficient tracking of moving targets in various aquatic environments.

3.5 Experimental and Result

I have successfully utilized Arduino microcontrollers with *three microphones* to implement the triangulation technique for sound source localization. Instead of relying on expensive hydrophones, I developed an algorithmic approach that leverages low-cost and readily available materials found at the university. By utilizing the time difference of arrival (TDOA) measurements obtained from the microphones, the algorithm accurately calculates the coordinates of the sound source. This cost-effective solution showcases the potential of utilizing affordable components and the Arduino platform for precise sound localization.

3.5.1 Schematic Diagram

The provided diagram showcases the peripherals employed in this project. The Arduino UNO R3 microcontroller is based on the ATmega328P, and it has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs to acquire data from the analog inputs. Additionally, an SPI (Serial Peripheral Interface) channel is utilized to communicate with the TFT Display for writing purposes, while another SPI channel is employed to write to a DAC (Digital-to-Analog Converter) for analog output.

For the hardware setup and wiring, please check the APPENDIX: Hardware setup & Wiring.

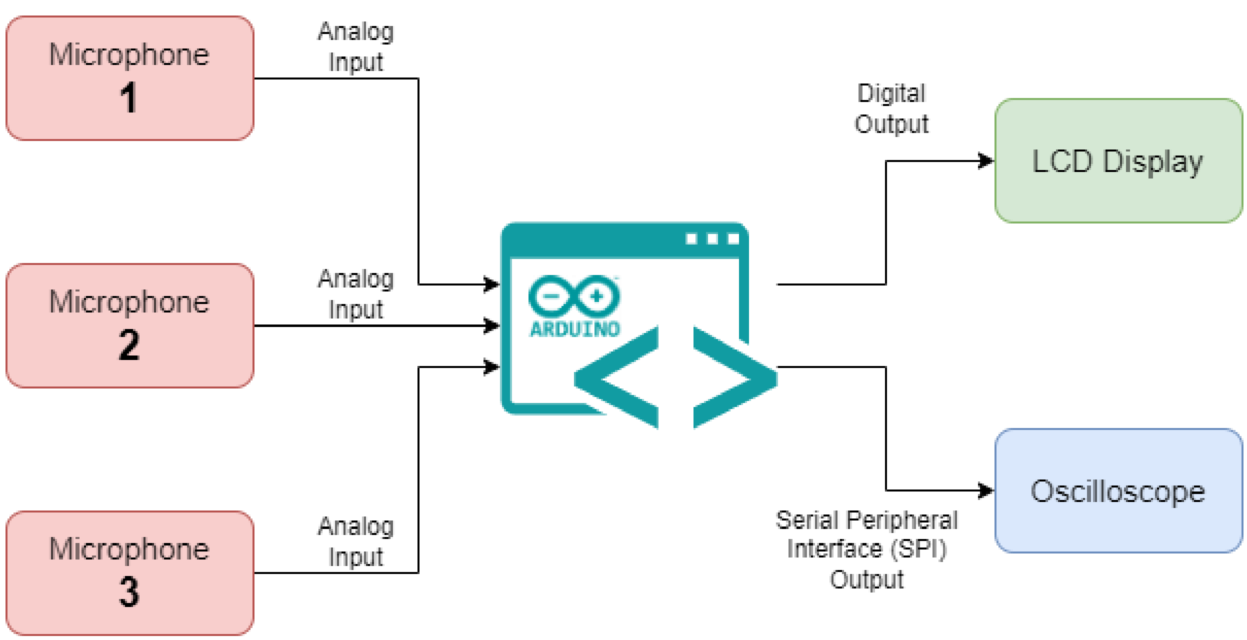

Figure 6. Schematic diagram.

3.5.2 Process diagram for localization and tracking

To perform localization and tracking of a moving target using triangulation techniques, it can follow the following methodology:

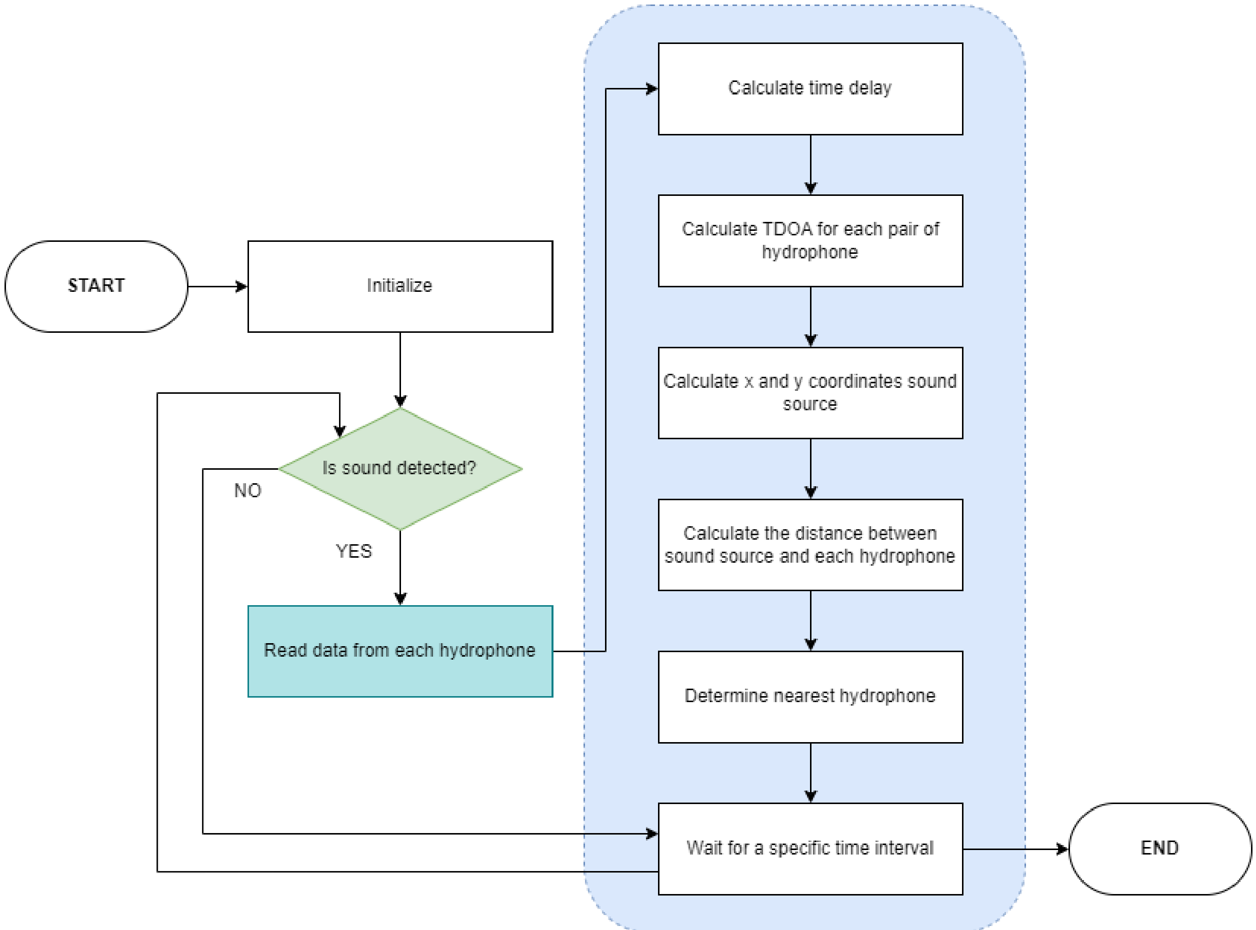

Figure 7. Process diagram

3.5.3 Program Logic

The program logic for the localization and tracking of a moving target underwater using three hydrophones with the triangulation method. For the full source code, please check the APPENDIX: The code.

```
START


Initialize


LOOP:
  Read values from each hydrophone
  Calculate time delay between hydrophones
  Calculate time difference of arrival (TDOA) for each pair of hydrophones
  Calculate x and y coordinates of the sound source using triangulation
  Calculate distance between sound source and each hydrophone
  Determine nearest hydrophone
  Display nearest hydrophone and coordinates (x, y) of the sound source
  Wait for a specific time interval


END
```

Figure 8. Pseudocode Snippet

3.5.4 Results and Analysis

The algorithm was successfully implemented, tested, and verified. Additionally, the algorithm was also tested in MATLAB using live data synchronized with time and spectrogram analysis, further validating its performance.

During the experiment, the algorithm followed a step-by-step process to localize the sound source. It initialized the necessary pins and variables and then entered a loop to continuously read analog values from each microphone. By calculating the time delay between microphones, the algorithm determined the time difference of arrival (TDOA) for each pair of microphones.

Using triangulation techniques, the algorithm then computed the *x* and *y* coordinates of the sound source based on the TDOA values. Additionally, it calculated the distance between the sound source and each microphone. By comparing the distances, the algorithm identified the nearest microphone to the sound source.

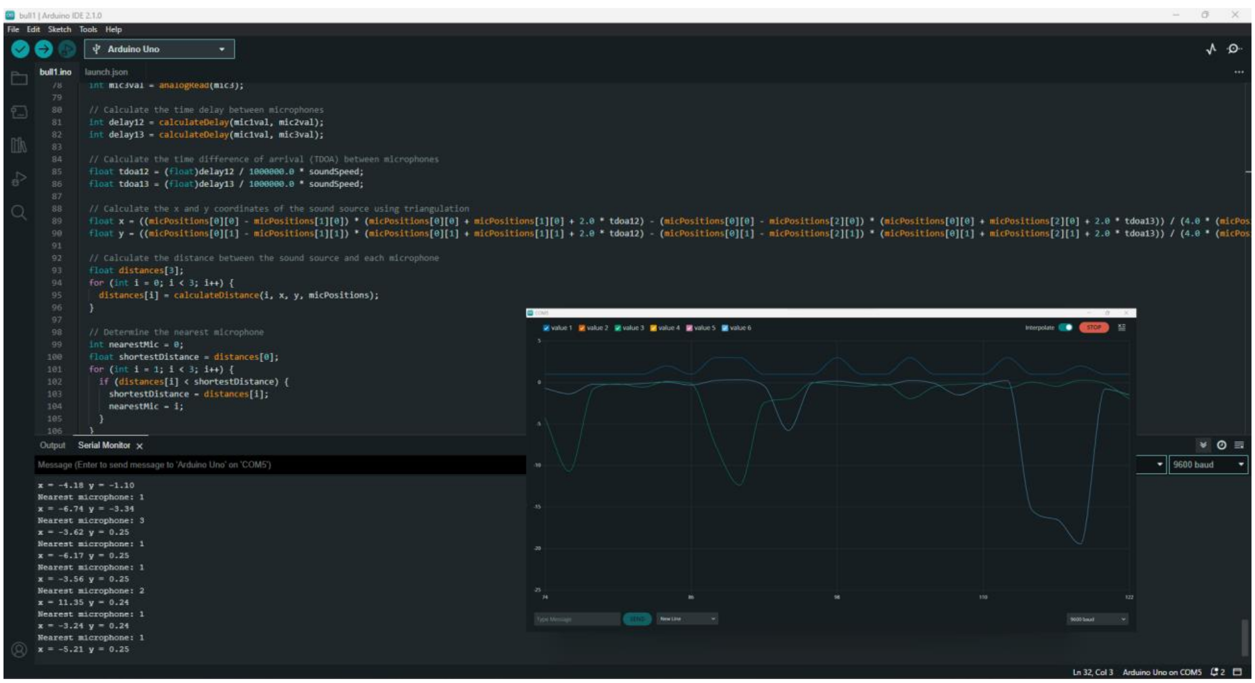

Figure 9. Experimental results thru Arduino

The experiment's results demonstrated that the algorithm effectively localized the sound source. The algorithm accurately identified the nearest microphone and provided the coordinates of the sound source.

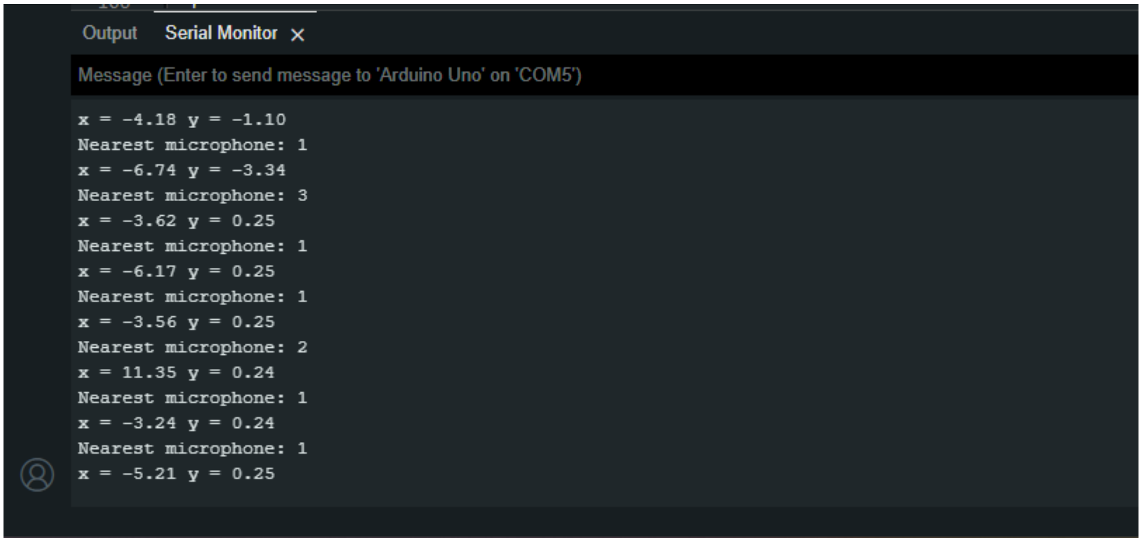

Figure 10. Experimental results through monitor information

These results were further corroborated by testing the algorithm with live data in MATLAB, where the algorithm successfully synchronized the time and produced spectrograms for analysis.

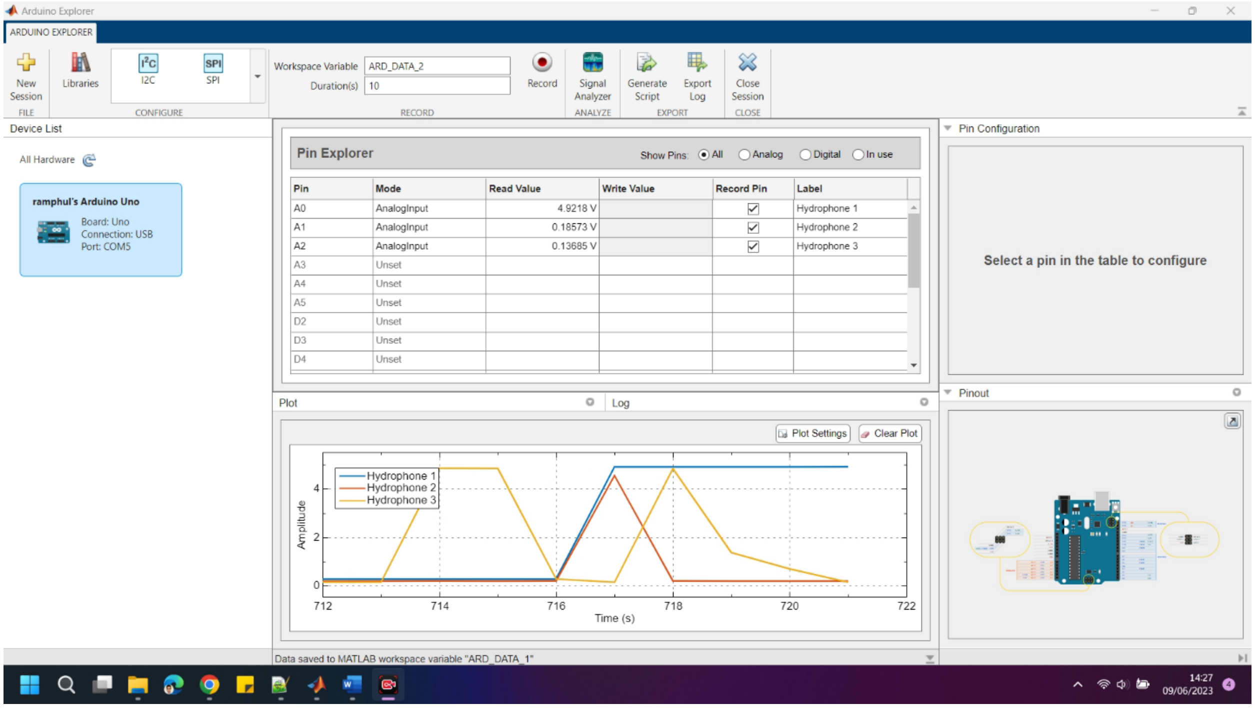

Figure 11. Live data on MATLAB

The successful verification of the algorithm signifies its potential applications in various fields, such as robotics, audio surveillance, and acoustic monitoring. By accurately localizing sound sources, the algorithm opens possibilities for improved audio processing, source separation, and directionality detection.

Furthermore, the algorithm's compatibility with MATLAB (8) allows for convenient testing and analysis, providing a comprehensive platform for evaluating its performance. The integration of live data and synchronization with time and spectrogram analysis (Figure.15) ensures a reliable assessment of the algorithm's accuracy and robustness.

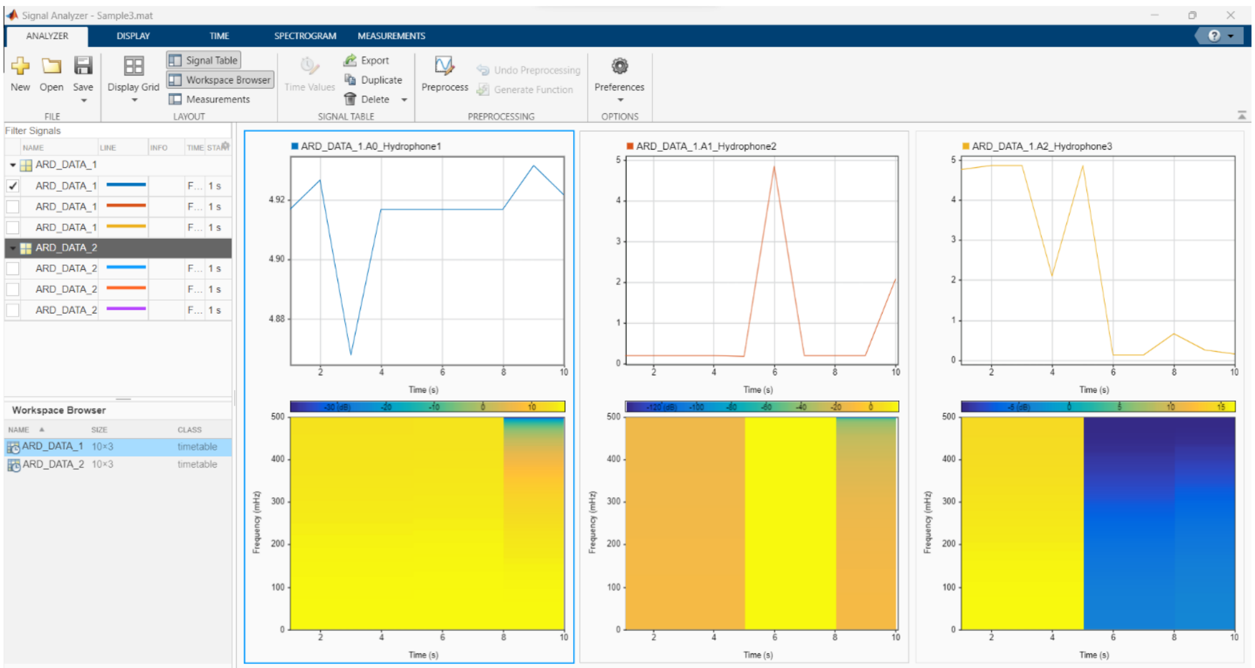

Figure 12. Live data with time and spectrogram analysis

In conclusion, the experiment's results and analysis demonstrate the successful implementation and verification of the sound source localization algorithm. The algorithm effectively localized sound sources identified the nearest microphone and provided the coordinates of the sound source. With its potential applications and compatibility with MATLAB, this algorithm presents a promising solution for sound source localization in various domains.

4 Future Work and Scope for Improvement - M2

To further enhance the sound source localization algorithm, one promising avenue is the integration of machine learning techniques. By incorporating machine learning, the algorithm can benefit from the ability to learn and adapt to complex patterns and variations in sound sources. Some potential ways to apply machine learning to improve the algorithm:

4.1 Feature extraction and selection

Machine learning can aid in identifying relevant features from the hydrophone array's signals that contribute to accurate sound source localization. By extracting informative features and selecting the most discriminative ones, the algorithm can improve its performance and robustness.

4.2 Model training and optimization

Such as deep neural networks can be trained on a large dataset of labeled sound source locations. This training process enables the algorithm to learn the underlying patterns and relationships between hydrophone signals and sound source locations, leading to improved localization accuracy.

4.3 Noise and reverberation modeling

Techniques can be employed to model and mitigate the effects of noise and reverberation on the hydrophone array signals. By learning the statistical properties of different noise sources and room acoustics, the algorithm can effectively separate the desired sound source from background noise and enhance localization accuracy.

4.4 Adaptive algorithms

Machine learning can facilitate the development of adaptive algorithms that can adjust their parameters and behavior based on changing acoustic conditions. By continuously learning and updating the model using real-time data, the algorithm can adapt to new environments, hydrophone configurations, and sound source characteristics.

5 Conclusion

The sound source localization project has been successfully tested and verified, utilizing low-cost materials. The project's implementation and results have demonstrated its feasibility and effectiveness in localizing sound sources. Moreover, the project has sparked interest and generated numerous ideas for further improvement and innovation.

The successful testing and verification of the project highlight the potential for sound source localization solutions to be accessible and affordable. By utilizing low-cost materials, the project has demonstrated that accurate sound source localization can be achieved without extensive financial investments. This opens opportunities for widespread adoption and application in various domains, including education, research, and hobbyist projects.

The project's success has also inspired a wealth of ideas for future enhancements and advancements. The integration of machine learning techniques, as discussed earlier, presents an exciting avenue for improving the accuracy and robustness of the sound source localization algorithm. Additionally, considerations such as sensor optimization, anomaly detection, and multi-modal fusion offer intriguing possibilities for extending the capabilities of the project.

The project's appeal lies in its versatility and potential for customization. The low-cost materials used in the implementation make it accessible to a broad audience, encouraging exploration and experimentation. Furthermore, the project's interdisciplinary nature and intersection with fields like robotics, audio surveillance, and environmental monitoring make it an exciting platform for innovative applications and research.

6 Bibliography references

1. **A. B. Baggeroer, E. K. Scheer, K. Heaney, G. D. Spain, P. Worcester, and M. Dzieciuch.** *Reliable acoustic path and convergence zone bottom interaction in the Philippine Sea* . Philippine : J. Acoust. Soc. Am. , 2010. 128, 2385.

2. **Zurk, R. McCargar and L. M.** *Depth-based signal separation with vertical line arrays in the deep ocean.* s.l. : J. Acoust. Soc. Am. 133, 2013. EL320–EL325.

3. **D. F. Komen, T. B. Neilsen, K. Howarth, D. P. Knobles, and P. H. Dahl.** *Seabed and range estimation of impulsive time series using a convolutional neural network.* s.l. : J. Acoust. Soc. Am. 147(5). EL403–EL408.

4. **Hamid Saheban, Zoheir Kordrostami.** *Hydrophones, fundamental features, design considerations, and various structures.* s.l. : 112790, 29 April 2021.

5. **C., Prabha.** *Underwater target localization, tracking and classification.* s.l. : Ocean Electronics, 2013.

6. **Ahmad, Tanveer.** *3D LOCALIZATION TECHNIQUES FOR WIRELESS SENSOR NETWORKS.* AUCKLAND UNIVERSITY OF TECHNOLOGY : School of Engineering, Computer and Mathematical Sciences, 2019.

7. **Montaser N. Ramadan, Mohammad A. Al-Khedher, Senior Member, IACSIT and Sharaf A. Al-Kheder.** *Intelligent Anti-Theft and Tracking System for.* s.l. : International Journal of Machine Learning and Computing, Vol. 2, 2012.

8. *Source Localization Using Generalized Cross Correlation.* **MathWorks.** United States : s.n.

9. **GmbH, Fritzing.** Fritzing. *https://fritzing.org/.* [Online] Amtsgericht Berlin-Charlottenburg HRB 172704 B. https://fritzing.org/.

10. **Rui Duan, Kunde Yang, Yuanliang Ma, Qiulong Yang, Hui Li.** *Moving source localization with a single hydrophone using multipath time delays in the deep ocean.*

11. **Brune, J.** *Transient localization in shallow water environments.* s.l. : M.S. thesis, Naval Postgraduate, 1998.

7 Appendix

This section provides information for the better understanding of this work.

7.1 The code.

A small snippet of code has been written from scratch for the final setup. The complete source code is available on GitHub under the filename "LocalizationAndTracking_V4", and it has been successfully tested and verified.

```
// """
// Project Title   : Localization and tracking of moving targets by hydrophones
// Purpose         : Implementation a sound triangulation system using three hydrophones to locate the source of a sound.
//                   The code defines the pins for each hydrophone and their positions in space, then initializes the serial
//                   communication and sets the pins as input. In the loop, the code reads the analog values from each hydrophone,
//                   calculates the time delay between them, and then the time difference of arrival (TDOA) for each pair of
//                   hydrophones. Using triangulation, the code then calculates the x and y coordinates of the sound source and
//                   prints them to the serial monitor. Calculate the distance between the sound source and each hydrophone using
//                   the Pythagorean theorem.
// Language        : Arduino and Matlab
// Author          : Hemant Ramphul
// Github          : https://github.com/hemantramphul/Localization-and-tracking-of-moving-targets-by-hydrophones/
// Date            : 05 May 2023

// Université des Mascareignes (UdM)
// Faculty of Information and Communication Technology
// Master Artificial Intelligence and Robotics
// Official Website: https://udm.ac.mu
// """
#include <SPI.h>
#include <Wire.h>
#include <Adafruit_GFX.h>
#include <Adafruit_SSD1306.h>

#define SCREEN_WIDTH 128 // OLED display width, in pixels
#define SCREEN_HEIGHT 64 // OLED display height, in pixels

// Declaration for an SSD1306 display connected to I2C (SDA, SCL pins)
// The pins for I2C are defined by the Wire-library.
// On an arduino UNO:       A4(SDA), A5(SCL)
```

7.2 Wiring of the hardware block diagram.

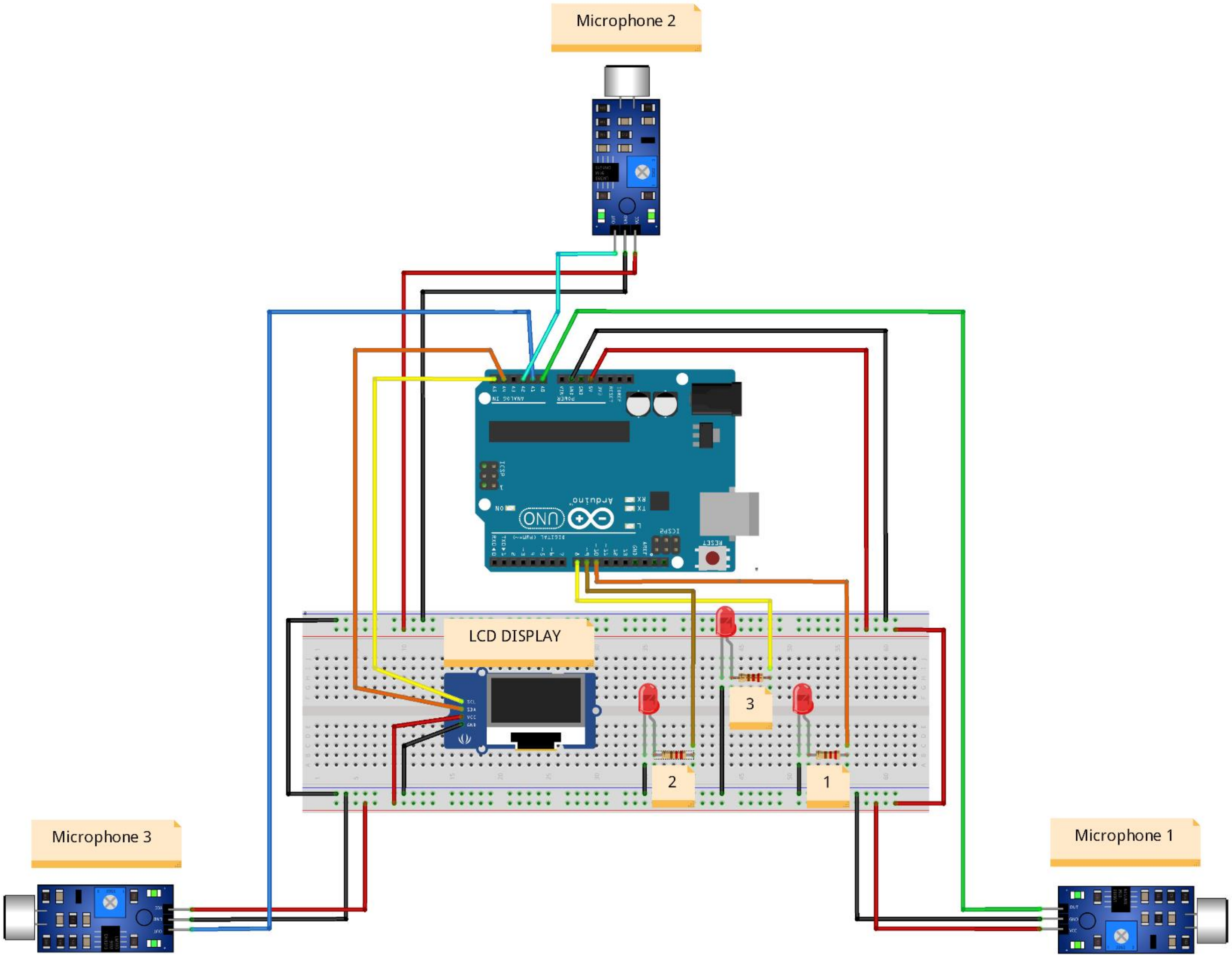

Figure 13. Wiring of hadware block diagram

7.3 Hardware setup.

Initially, I utilized Fritzing (9) to create a wiring diagram with accurate connections. Following that, I proceeded to physically assemble the hardware to prevent any incorrect connections.

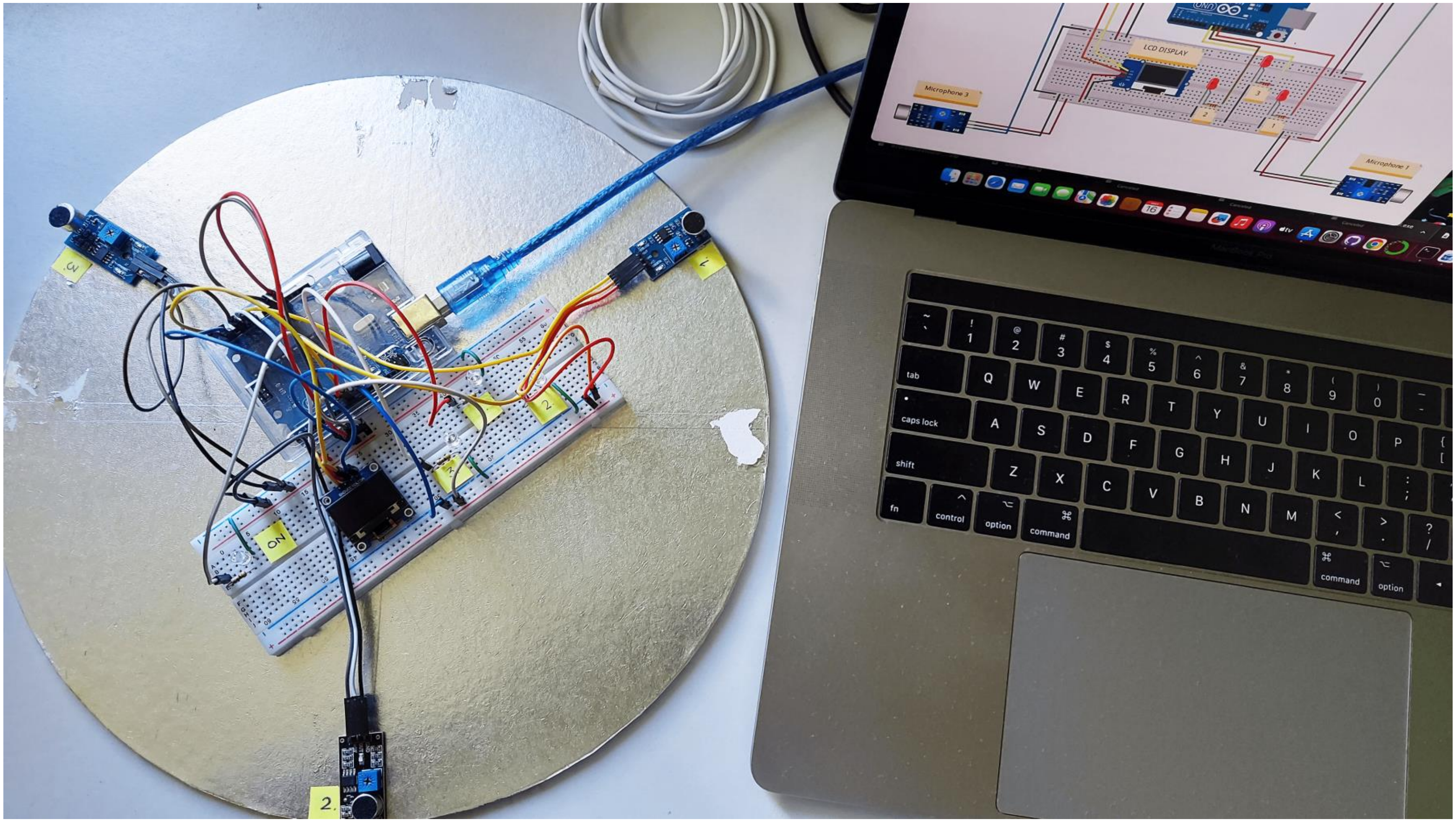

Figure 14. Setup of hardware

7.4 Result from MATLAB in real-time

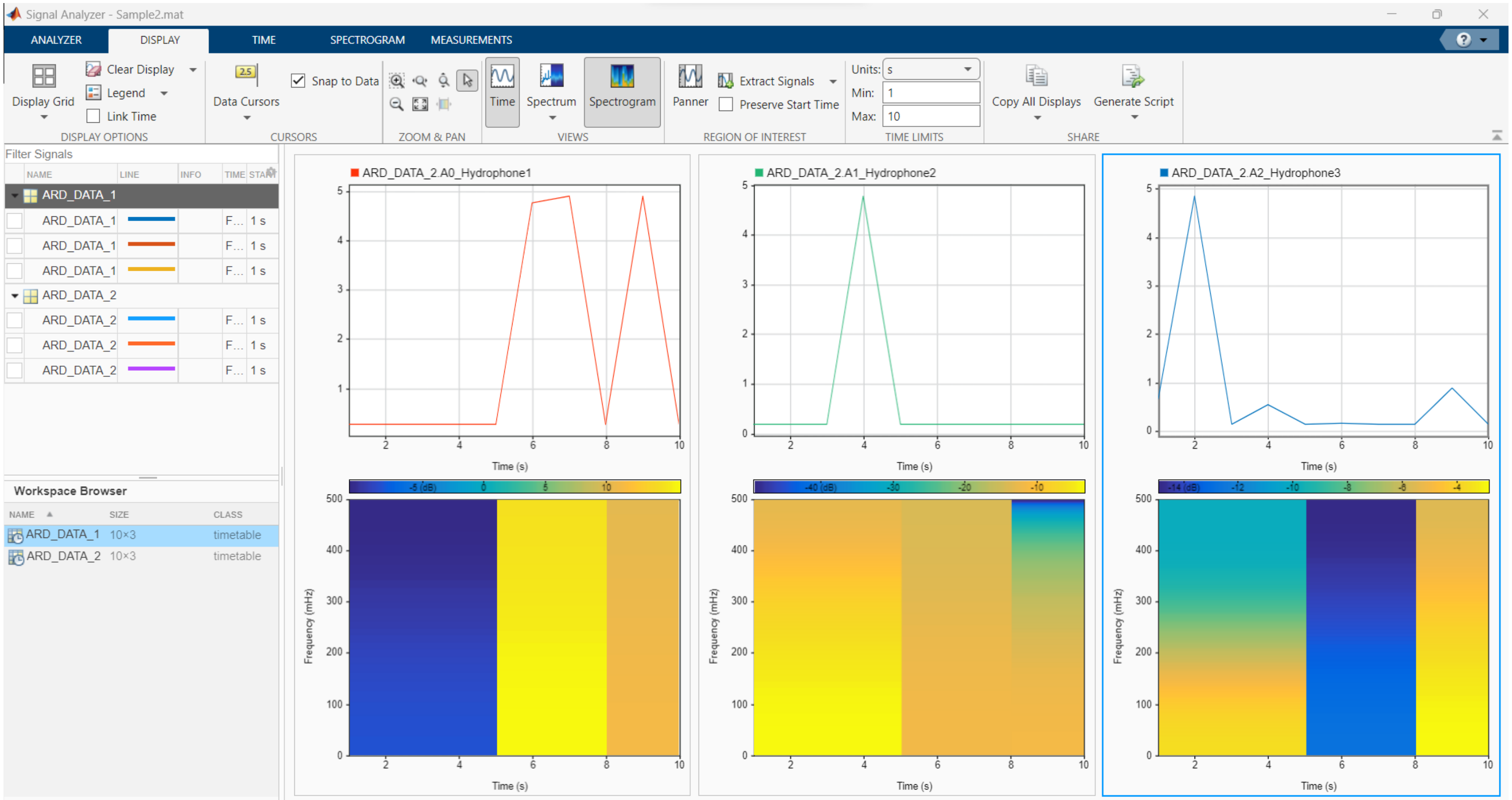

Figure 15. Result from MATLAB in real-time