**University of Victoria**

**Faculty of Engineering**

**Summer 2022 ENGR 446 Final Report (Modified for AUVIC)**

**Underwater Acoustic Target Localization**

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**July 22nd, 2022**

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# Abstract

This report details the engineering analysis of an acoustic localization subsystem for use on an autonomous underwater vehicle (AUV). Although this subsystem was designed for the *Trident* AUV developed by UVic’s Autonomous Underwater Vehicle Interdisciplinary Club (AUVIC), the system can easily be adapted to support different AUV’s in different environments.

The embedded system detailed in this analysis is designed for use in the RoboSub competition. It aids the AUV by providing locational data of several acoustic beacons placed around an underwater arena. These beacons are markers for various tasks that must be completed by the AUV. Each beacon placed around the arena emits sinusoidal “pings” at periodic intervals, and each beacon transmits at a unique frequency. Lastly, only one beacon will transmit at a time.

Two potential solutions were constructed based on the following problem statement. The system must triangulate the source of an acoustic, momentary, single frequency, pressure wave, and communicate this information to the main board of the *Trident* AUV. This information must be communicated within reasonable accuracy and time to guarantee the data is both relevant, and beneficial for the system.

Solution one uses a single hydrophone and an inertial measurement unit (IMU) to calculate the location of the beacon. At its core, this solution works by comparing the change in signal amplitude over time. Based on this change, the system can calculate the expected location of the beacon. Solution two uses a hydrophone array to calculate the beacon location. This solution uses the time difference of arrival between each pair of hydrophones in the array to calculate the expected location of the target. Due to several requirements of solution one, such as logging relative position and needing the AUV to be moving, solution two was carried forward for the full engineering analysis.

The conclusion of the report suggests firmware algorithms and hardware that will result in a reliable system. The hardware is a bandpass filter that was simulated using LTspice resulting in a desirable cutoff frequency, and the firmware was based on a cross correlation algorithm simulated in MATLAB. Although this system met its design goals in simulation, it was recommended that the system, specifically the MATLAB simulation, be further developed to better analyze the system in its entirety to help evaluate its overall accuracy.

\*READ ME\*

This report was completed as the technical report for ENGR 446, it was later modified for use as an internal document for AUVIC. The new sections were tacked on at the end of the report so excuse the somewhat awkward report structure. See section 6.0 onward for the added material.

# Glossary

**Amplifier:** (AMP) An amplifier is a fundamental circuit that scales the input signal by some factor, ideally without affecting its phase.

**Analog to Digital Converter:** (ADC) An electrical circuit that converts an analog signal to a discrete signal that can be processed within a digital system.

**Controller Area Network:** (CAN) A serial communication protocol that allows multiple nodes to communicate over a single bus.

**Digital Correlation:** (DC) Methodology used to correlate the time shift between two arrays of data.

**Discrete Fourier Transform:** (DFT) Transform used to derive the frequency components of a discrete system.

**Gain Product Bandwidth:** (GPBW) Product of open loop voltage gain over the device’s frequency range.

**Hydrophone**: Transducer that converts pressure changes to a weak electric signal, typically via piezoelectric material.

**Low Pass Filter:** (LPF) A low pass filter attenuates signals above its cutoff frequency, so that only the lower frequencies are passed.

**LTspice:** Circuit simulation software used to simulate the time and frequency domain response of a system based on defined test signals.

**Microcontroller:** (MCU) A microcontroller is an integrated circuit that includes a processor, input/output, peripherals, and memory that help control an electrical system.

**Operational Amplifier:** (Op-Amp) Fundamental electrical component used to amplifier the potential difference between its two inputs.

**STM32:** Family of 32-bit processors from STMicroelectronics.

# 1.0 Introduction

The University of Victoria’s Autonomous Underwater Vehicle Interdisciplinary Club (AUVIC) competes in a yearly RoboSub competition using its updated autonomous underwater vehicle (AUV). AUVIC’s *Trident* AUV is an unmanned autonomous submarine that includes various subsystems needed to compete at the RoboSub competition. Some of these subsystems include optical cameras, robotic arms, thrusters, and a dummy torpedo launcher. To navigate between competition tasks the AUV needs to follow several acoustic beacons placed around an aquatic course. Therefore, the AUV needs a method to locate these beacons. An illustration of AUVIC’s previous *Polaris* AUV is shown in Figure 1 [1].

Diagram

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Figure 1. AUVIC Polaris AUV

Locating objects in 3D space is a useful feature employed by various systems. For example, navigation, augmented reality, and collision detection all need some method of spatial awareness to varying degrees. Consider technologies such as LiDAR used in augmented reality [2], computer vision in aircraft navigation [3], and sonar in marine navigation and modeling [4]. Sonar is the appropriate technology for use with submerged devices since sound can travel much further than light through water due to differences in absorption [5].

This report will detail the engineering analysis of an underwater acoustic localization subsystem for use on AUVIC’s *Trident* AUV. The system must triangulate the source of an acoustic, momentary, single frequency, pressure wave, and communicate this information to the main processor of the *Trident* AUV. This information must be communicated within reasonable accuracy and time to guarantee the data is both relevant, and beneficial for the system. In this report, two solutions will initially be evaluated in a preliminary analysis, afterwards a full engineering analysis (EA) will be conducted, resulting in a final recommendation and conclusion.

# 2.0 Potential Solutions

Two potential solutions were considered for the original target localization system. These solutions include solution one; a hydrophone and inertial measurement unit (IMU) based solution, and solution two; a hydrophone array. These solutions will be discussed in detail in section 2.1 and section 2.2. A preliminary analysis of these two solutions will then be conducted in section 2.3, to compare the feasibility, performance, accuracy, and complexity of each system. The final solution must meet the following design goals to be considered feasible for AUVIC’s purposes. Note that directional accuracy refers to the direction the AUV is instructed to follow, not the absolute position of the target.

1. Directional accuracy < 20⁰
2. Processing time < 2 seconds

Before either system can be discussed, it is important to note the limitations of this analysis, and therefore the scope of either solution. Properly accounting for the effects of multiple emitters, signal reflection, and signal diffraction would significantly bloat the overall scope of the project. As such, the design will be limited to a noise free environment, with a single emitting target. This limitation should not affect its usability in the RoboSub competition since it is hosted in a controlled arena with non-overlapping acoustic beacons.

## 2.1 Solution One

Solution one uses a single hydrophone and an IMU to calculate the location of an acoustic target. This system functions by observing the change in signal amplitude over time. For example, if a stream of data is collected at and again at then the change in magnitude of a periodic signal will be proportional to the change in propagation length from the emitter to the hydrophone for any two data points. Consider a hydrophone attached to an AUV traveling on a 2D plane, shown in Figure 2. Due to the symmetry of the system, there will be an extraneous solution. To eliminate the extraneous solution, the AUV would need to test one of the points by deviating in either direction. In 3D, each axis would need to be tested to eliminate all extraneous solutions in an ideal system.

Diagram

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Figure 2. Solution One Illustration

## 2.2 Solution Two

Using a four-hydrophone array it is possible to calculate the position of an acoustic emitter based on the phase shift of the signal between each hydrophone, or based on the signals’ time difference of arrival. This assumes the hydrophones’ locations are known, and the speed of sound in water can be reasonably approximated. Using this method, its possible to calculate the location of a target from a single frame of data, where a frame of data would be considered multiple samples across each hydrophone as shown in Figure 3.

Diagram

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Figure 3. Solution Two Illustration

In 3D, the targets position can be calculated with a minimum of four hydrophones. Similar to solution one, having only two hydrophones leads to an extraneous solution in the 2D illustration of Figure 3. In 3D the first pair of hydrophones results in a solution space that resembles the shell of a 3D cone. Three hydrophones reduce the solution space to two points symmetric about a parabola, and lastly 4 hydrophones result in a single solution. See Figure 4 for a MATLAB simulation illustrating the solution space for a hydrophone array with 3 transducers.

Graphical user interface, chart

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Figure 4. Three Hydrophone Array Solution Space

## 2.3 Comparison of Solutions

It was not feasible to perform a full engineering analysis on both solutions due to the limited scope of this technical report. To accommodate this, one solution will be selected based on a preliminary analysis of either solutions performance.

A verbose explanation for the algorithm for solution one is listed below. Several complications need to be considered based on this solution. Firstly, the AUV must be moving to collect the various datapoints , otherwise there is no change in amplitude that can be measured. Furthermore, the accuracy of the system is proportional to the distance between samples; meaning, if the AUV is moving slowly it may not be feasible to meet both the processing time, and accuracy goals listed in section 2.0 simultaneously.

1. Initialize IMU
2. Initialize position at
3. Collect a frame of samples at position
4. Monitor IMU for changing acceleration
5. Increment position based on AUV acceleration
6. Collect a frame of samples at position
7. Process frames and
   1. Calculate amplitude of received signals
   2. Calculate difference in propagation based on signal attenuation
   3. Calculate position of the target using the distance between samples , , and the previously calculated propagation difference
8. Store calculated location in memory
9. Repeat step 4 to 7 for datapoints and and compare to previously calculated location

Next consider the explanation of solution two’s algorithm, listed below. Although it has less steps than solution one, there is notable complexity accompanied with each step. For example, step 2a will require the analysis of two vectors of data. Furthermore, calculating the phase shift of these samples is not entirely trivial. Methods for deriving the phase shift of two discrete signals include digital cross correlation (DC), and the discrete Fourier transform (DFT) [6]. After deriving the phase-shift between the signals, calculating the position of the target will follow a similar algorithm to solution one.

1. Sample ADCs to collect frame of data
2. Process frame
3. Calculate difference in propagation based on phase shift
4. Calculate position of the target using the distance between hydrophones, and the previously calculated propagation
5. Repeat for each pair of hydrophones
6. Store calculated location in memory
7. Repeat steps 1 to 3

Due to the need to track position using an IMU, and requirement that the AUV be moving, solution one was deemed undesirable when compared to solution two. Although the computational complexity of solution two is greater than that of solution one, due to the necessity of vector calculus, the overall versatility of this solution is preferred. A more rigorous EA will be conducted to evaluate solution two’s feasibility and expected performance in section 3.0.

# 3.0 Engineering Analysis

Based on the preliminary analysis presented in prior section, the preferred solution is the passive hydrophone array. In this section the passive hydrophone array will be discussed in detail; such that its theory of operation and hardware implementation are clearly conveyed. Lastly, to help reduce the complexity of this analysis, the system will only be considered in two dimensions.

To understand the theory of operation, consider a small hydrophone array consisting of two hydrophones separated by a known distance (*d*), shown in Figure 3. These hydrophones receive acoustic pressure waves from an un-identified target and convert them to weak electrical signals via a piezoelectric transducer [7]. Depending on the position of the target, the signals received by the hydrophones will be identical, although phase shifted, copies of one another. If the acoustic propagation constant is known, then this phase shifts can be directly related to the angle of arrival of the incoming plane wave.

There are several assumptions that need to be considered when implementing this model. Foremost, this model assumes the propagation speed is known and constant; however, this parameter depends on the water temperature, water depth, and water salinity [8]. Additionally, the angle of arrival assumption requires a plane wave. For this assumption to be appropriate, the distance from the target to the hydrophone must be much greater than the distance (d) between the hydrophones.

Implementing the solution on hardware is feasible based on existing systems used on various AUV’s [9]. There are several methods to implement this system on hardware, so only a generalized overview will be provided. The block diagram is shown in Figure 5 and consists of an analog front end for filtering and amplification of the incoming signal, an analog to digital converter (ADC) to discretize the waveform, and a microprocessor to interpret the results.

Diagram

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Figure 5. Hydrophone Hardware Overview

## 3.1 MATLAB Simulation

The MATLAB simulation will model the fundamental aspects of the hydrophone array solution. This simulation must model the acoustic propagation, analog signal conditioning, signal discretization, and the microprocessor algorithm. Using this model, the true target location can be compared to the decoded location, allowing for an analysis of system accuracy, noise tolerance, and computation time. Furthermore, this simulation will provide a clear path for firmware development and finalizes the technical feasibility of the design.

When in water, sound waves travel at a variable speed described by equation 3.1 [8]. This equation depends on the water temperature in Celsius (T), water salinity in parts per thousand (S), and the depth below the surface in meters (D).

(3.1)

Although the speed of sound is variable, it would help simplify both hardware and firmware design if it could be assumed constant. To gauge the effect of this assumption, equation 3.1 was tested over the range of feasible inputs. When temperature is varied from 0 to 30°C, depth 0 to 50m, and salinity 0 to 35 ppm. The resulting maximum and minimum speeds are meters per second, and meters per second, shown in Table 1.

Table I. Speed of Sound in Water Approximate Variability

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Temperature (°C) | Salinity (ppm) | Depth (m) | Speed of Sound in Water (m/s) |
| Max | 30 | 35 | 50 | 1657.5 |
| Min | 0 | 0 | 0 | 1400.6 |

Assuming the transducers are separated by 30 millimeters, which is the case for AUVIC’s hydrophone enclosure, the largest propagation delay would result when the target is 90 degrees, or perpendicular, to the AUV’s direction of travel. In this case the time difference of arrivals between the two signals would be at maximum 7.1 microseconds, and at minimum 6.1 microseconds shown in equation 3.2 and 3.3; where (d), is the distance between hydrophones, and (C), is the speed of sound in water.

(3.2)

(3.3)

Assuming the ADC samples the signal at 100 thousand samples per second (KSPS), this variability will marginally affect the overall accuracy of the system. Furthermore, regardless of the overall accuracy of measurements, the algorithm will naturally approach the true location based on the AUV’s movement. For example, assume that every decoded trajectory has an error of 25 percent. After each course adjustment, the AUV comes closer to the target, hence the overall accuracy becomes less and less of a concern. Eventually the AUV will be close enough to the target for the AUV’s optics to take over. For these reasons, the speed of sound in water will be treated as a constant of 1500 meters per second for all subsequent analyses.

Next consider the phase difference, or alternatively the time shift (), between the received signals. The formula to convert this time difference to the angle of arrival () is presented in equation 3.4. This formula is derived from the illustration in Figure 3; where (), is the direction to the target or angle of arrival (), is the time difference of arrival between the two received signals or the time shift, and (C), is the speed of sound on water.

(3.4)

Next consider an acoustic wave traveling on a 2D plane as described by equation 3.5 [10]. This formula relates the amplitude of a signal over position and time, where () is the sending end amplitude, () is the attenuation constant, () is the frequency, () is the time, () is the wavelength, () is the distance from the emitter to the receiver, and is the initial phase shift of the signal. For the purposes of this report the equation was modified to incorporate the cartesian coordinate system by making the substitution . The modified equation is shown in equation 3.6.

(3.5)

(3.6)

Equation 3.6 was then translated to MATLAB, and two hydrophones were placed on arbitrary points on the waveforms surface. The hydrophones are represented by the red and blue dots in the leftmost image of Figure 6. As seen in Figure 6 the signals received by the hydrophones (rightmost image) are phase shifted copies of one another. This first simulation was only a test of the calculus discussed thus far, both the frequency of the source, and the placement of the hydrophones is not reflective of the final system.

Chart, surface chart

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Figure 6. MATLAB Propagation Simulation Testing

Two functions were then created, *Analog\_System* and *ADC\_System,* to manage the simulation and discretization. Analog\_System simulates the continuous time system, it contains the propagating acoustic wave, and received hydrophone signals. This function can produce a simulation similar to Figure 6, shown in Figure 7, as well as a bird’s eye view to better illustrate the placement of the hydrophones, shown in Figure 8. The purpose of the ADC\_System is to discretize the incoming continuous time samples by reducing them to the desired number of bits. For detail on *Analog\_System* and *ADC\_System,* refer to Appendix A and Appendix B respectively.

Diagram

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Figure 7. MATALB Propagation Simulation

Graphical user interface

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Figure 8. MATLAB Propagation Simulation Bird's Eye

Lastly, an algorithm needs to develop to correlate the sampled signals to a time shift. An example of the ADC samples that need to be correlated is shown in Figure 9, this is the same system shown in Figure 7 and Figure 8. The time shift is needed to calculate the angle of arrival in equation 3.4. As mentioned prior, there are two methods that could be employed. These methods include digital cross correlation, or the discrete Fourier transform [6].

Digital cross correlation finds the maximum correlation in a dataset by shifting the data in one array and comparing it against the other. Consider Figure 9, from observation, hydrophone two leads hydrophone one by three samples. Therefore, applying a time shift of three samples should result in maximum correlation.

Chart

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Figure 9. MATLAB Simulation ADC Quantization

Computing the discrete Fourier transform would be possible, given many MCU’s have provided DSP libraries [11]. Computing the FFT would allow the system to determine the frequency of the incoming signal and calculate the phase of both signals. Finding the difference in phase would reveal the phase shift, which would then be scaled by the fundamental signal period to determine the time shift.

Due to the simplicity of DC, this method was selected for further analysis. One final container script was written that implements both *Digital\_System* and *ADC\_System* to test the correlation algorithm, shown in Appendix C. In this test the hydrophone pair was placed 30 meters away from the target, 5 meters above the x-axis, and the hydrophones were separated by 3 cm. The expected angle of arrival is approximately , shown in equation 3.7. Whereas the calculated angle of arrival from the simulation was . This error is well within the tolerances defined in section 2.0.

(3.7)

Various hydrophone positions were next tested to validate the overall accuracy of the system. The result for this test is shown in Table 2. The script shown in Appendix C was used to evaluate each datapoint. In table 2, the target is placed at the origin (0,0), and the hydrophone at “Position X” and “Position Y”.

Table II. MATLAB Derived Angle of Arrival

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Position X [m] | Position Y [m] | Expected AOA | Calculated AOA | Error |
| 30 | 30 |  |  |  |
| 30 | 25 |  |  |  |
| 30 | 20 |  |  |  |
| 30 | 15 |  |  |  |
| 30 | 10 |  |  |  |
| 30 | 0 |  |  |  |

Lastly, stm32f4 processors include efficient implementations of instructions for DSP, and are capable of real time DFT. For example, even a relatively slower stm32f0 is capable of producing DFT results in tens of milliseconds [11]. A simpler algorithm such as DC can be expected to be at least this responsive. Exact numerical analysis would require porting this algorithm to the desired microcontroller.

Based on the presented engineering analysis, a system using DC is capable of deriving the location of an acoustic emitter, with an error of less than 20 degrees, and with a processing delay well below two seconds. The simulation results have continued to support the feasibility of this design and have helped to outline the initial firmware of the project.

## 3.2 Hardware Analysis

To properly assess the system, a brief hardware analysis needs to be conducted. This analysis will ensure that the design is feasible given the desired hardware, and will support further quantitative analysis if deemed necessary. For example, once feasible hardware is selected, the ADC sample rate will be known which can then be applied to the simulation presented in section 3.1 to help quantify the system accuracy.

Consider the illustration shown in Figure 5. The signal conditioning section, or analog front end, will consist of a buffer, filter, and amplifier, which will be referred to as the hydrophone preamplifier, or preamp. The preamp circuit will be placed between the hydrophone and the ADC. Existing documentation for hydrophone preamplifiers is limited due to the propriety nature of most equipment, as a result a typical microphone amplifier will be used as a basis for this analysis. This is possible since both microphones and hydrophones use piezoelectric material [7].

One possible buffer stage is shown in Figure 10. Note that only a single ended signal is used from the hydrophone. A differential buffer would be feasible but would require additional circuitry.

Diagram, schematic

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Figure 10. Hydrophone Amp Stage One

The now buffered signal can then be amplified by an inverting amplifier with active filtering. Due to the gain product bandwidth (GPBW) of the device, it is preferrable to cascade multiple amplifiers to help maintain the overall bandwidth of the circuit. The resulting cascaded inverting amplifier is shown in Figure 11.

Diagram, schematic

Description automatically generated

Figure 11. Hydrophone Amp Stage Two/Three

The last component of the preamp is a stable reference voltage for the various amplifier stages. This reference voltage, which was labeled GND in Figure 10 and Figure 11, will be produced by a voltage divider and buffer pair, shown in Figure 12.

Diagram, schematic

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Figure 12. Hydrophone Amp GND Reference

According to the RoboSub manual [12] the maximum frequency of the incoming signal is 40kHz. Based on this the appropriate op-amp for the preamplifier will have a bandwidth greater then 200kHz and will have minimum offset voltage to help maintain the signal to noise ratio at the input. A device that meets these requires is the LME49721MAX [13].

The preamplifier was next ported to LTspice, shown in Figure 13, using an LME49721MAX spice model provided through the manufacture’s website [14]. Note that an extra amplifier stage was added to the circuit, due to the package type of the LME49721MAX. The resulting bandwidth of the cascaded amplifier is approximately 250kHz as shown in bode plot of Figure 14.

A picture containing scatter chart

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Figure 13. Hydrophone Amplifier Schematic LTspice

A screenshot of a computer

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Figure 14. Hydrophone Amplifier Bode Plot LTspice

In the future, this spice model can be used to simulate the performance of various analog front ends. The resulting bode plot shown in Figure 14, can be ported to MATLAB to implement a more realistic simulation.

# 4.0 Conclusion

In this report, the feasibility of an acoustic localization subsystem for use on AUVIC’s AUV was investigated through an engineering analysis. The conclusion of this analysis is that the subsystem should use a discrete cross correlation algorithm to derive the angle of arrival of the acoustic signal. This process was proven to be sufficiently accurate, and provided the design uses an adequate microcontroller, such as a stm32f4, the processing delay is expected to be well below the threshold outlined in section 2.0.

# 5.0 Recommendation

Based on the results of this engineering analysis it was concluded that the acoustic localization subsystem using discrete cross correlation to derive the location of targets will meet the design goals outlined in section 2.0. However, due to the scope of this engineering analysis, there are several limitations that need to be highlighted. Ideally, the engineering analysis would continue developing the presented MATLAB code, to further quantify the performance of the overall system.

Now that the MATLAB framework has been developed, shown in Appendix A and Appendix B, the system can be modified to simulate the selected hardware presented in section 3.2. Much of the engineering analysis assumed ideal noise free components, when in reality they will introduce errors into the system that will worsen the overall accuracy of the derived angle of arrival. Due to this fact, it is recommended that the MATLAB script be further developed to incorporate a more realistic model. Modules for amplifier frequency response, system noise, and component tolerances should be introduced.

# 6.0 Schematic Capture

This section covers the main modules of the hardware design. Note that this board was designed as a steppingstone for later development. As such the layout was kept basic to ease testability. The top-level schematic is shown in Figure 15; note the design was separate into four sheets consisting of the power, analog, microcontroller, and communication circuits.

A picture containing chart

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Figure . System Top-Level Schematic

The power schematic is shown in Figure 16. This board is powered from an external 5V supply *+5V\_EXT*. During debug, the 5V power can be rerouted to *+5V\_Debug* by using the jumper *JP1*. The regulated 3.3V is used by all ICs on the board. Note that the analog power has been further filtered by an LC pi-network. Furthermore, the analog and digital ground are separated by net *NT2*.

Diagram

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Figure . System Power Schematic

The microcontroller schematic is shown in Figure 17. An IMU is included since this design supports either solution discussed in earlier section of this report. There are five debug related I/O in this design. This includes three debug LEDs and two debug selection jumpers. These are helpful for firmware development.

Diagram, schematic

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Figure . System Control Schematic

The communication schematic is shown in Figure 18. This board supports communication via CAN to the main AUV. The board also includes a header for programming and debugging. For programming, connect the st-link to *SWDIO*, *SWCLK*, and *GND*. 3V3 can either be supplied by the st-link or from the LDO. If this device is a terminating node of the CAN network populate *R29*.

Diagram, schematic

Description automatically generated

Figure . System Communication Schematic

The analog circuit was split into two separate schematics, one top-level (Figure 19), and one amplifier block (Figure 20). The hydrophone amplifier consists of a buffer stage followed by three inverting amplifiers. Since the exact hydrophone was somewhat unknown, the gain can be configured from 10x to 1000x. Beware of depreciated bandwidth at higher gain settings.

Chart

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Figure . System Analog Top-Level Schematic

Diagram

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Figure . System Analog Schematic

# 7.0 PCB Layout

For a top-level discussion of the PCB layout consider the 3D model in Figure 21. The analog circuitry (left) is physically separated from the digital section (right). First the incoming signal is received at either the BNC connector or the male headers. This signal is then amplified by one of four hydrophone amplifiers. Each amplifier has three potentiometers labeled for either offset or gain adjustment. There are three jumpers on the board, two of which (JP6/JP5) are for debugging, and the third labeled PWR is for selecting the 5V supply.

A picture containing text, electronics, circuit

Description automatically generated

Figure . PCB 3D Model

Due to time constraints, and personal bandwidth limitations, this board uses a 4-layer stack up. This board arguably could (and probably should), use a 2-layer board. In the existing design the extra layers help separate analog and digital power delivery, as well as route reference signals to the amplifier stages. In the current design the analog and digital ground is separated by net *NT2*. Looking back on this decision, more attention should have been paid to the return signals. In the current revision all the signals in the analog front do not have an adjacent reference plane, instead the analog ground is separated by a ground plane. Meaning signals on L1 are referencing a plane on L3, which is separated by both a ground plane on L2 and the core of the PCB. As a result, the fields coupling L1 to L3 will be blocked by L2. I suspect the board will both radiate noise to nearby circuits, and pickup noise relatively easily. Hopefully, since the circuit is low frequency, this will be tolerable… but none the less I’m surprised I didn’t notice this during my design (I blame my ECE 499 project taking up all my bandwidth).

# References

[1] “Vehicles – AUVIC,” Autonomous Underwater Vehicle Interdisciplinary Club. [Online]. Available: https://onlineacademiccommunity.uvic.ca/auvic/vehicles/. [Accessed: 22-Jul-2022].

[2] T. Brookes, “Your iphone pro has lidar,” How-To Geek, 13-Oct-2021. [Online]. Available: https://www.howtogeek.com/759121/your-iphone-pro-has-lidar-7-cool-things-you-can-do-with-it/. [Accessed: 10-Jun-2022].

[3] J. Tang, W. Zhu, and Y. Bi, “A Computer Vision-Based Navigation and Localization Method for Station-Moving Aircraft Transport Platform with Dual Cameras,” Sensors (Basel, Switzerland), vol. 20, no. 1, p. , Jan. 2020.

[4] K. Herkül, A. Peterson and S. Paekivi, "Applying multibeam sonar and mathematical modeling for mapping seabed substrate and biota of offshore shallows," Estuarine, Coastal and Shelf Science, vol. 192, pp. 57-71, 2017.

[5] J. WRIGHT and A. COLLING, "chapter 5 - light and sound in seawater," in Seawater: Its Composition, Properties and Behaviour, Second ed.Anonymous Elsevier Ltd, 1995, pp. 61-84.

[6] Z. Yuan, Y. Gu, X. Xing, and L. Chen, “Phase Difference Measurement of Under-Sampled Sinusoidal Signals for InSAR System Phase Error Calibration,” Sensors (Basel, Switzerland), vol. 19, no. 23, p. 5328–, 2019, doi: 10.3390/s19235328.

[7] J. L. Butler and C. H. Sherman, Transducers and Arrays for Underwater Sound, 2nd ed. 2016. Cham: Springer International Publishing, 2016. doi: 10.1007/978-3-319-39044-4.

[8] A. Collins, “Underwater Sound Propagation,” *Underwater Acoustics*. [Online]. Available: https://www.arc.id.au/UWAcoustics.html. [Accessed: 03-Jul-2022].

[9] Liu, Z., Yang, T., Xu, W., Yu, J., McFarland, D.M. and Lu, H., Underwater acoustic positioning with a single beacon and a varied baseline for a multi-jointed AUV in the deep ocean. IET Radar Sonar Navig., 2020. doi: 10.1049/iet-rsn.2019.0330

[10] F. T. Ulaby and U. Ravailoli, Fundamentals of Applied Electromagnetics, 7th ed. Boston, Massachusetts: Pearson, 2015, pp. 28-29

[11] “AN4841 application note,” Digital signal processing for STM32 microcontrollers using CMSIS, Feb-2018. [Online]. Available: https://www.st.com/resource/en/application\_note/dm00273990-digital-signal-processing-for-stm32-microcontrollers-using-cmsis-stmicroelectronics.pdf. [Accessed: 22-Jul-2022].

[12] RoboSub, “24th Annual International RoboSub Competition,” 2021. [Online]. Available: https://robonation.org/app/uploads/sites/4/2021/03/RoboSub-2021-Mission-and-Rules\_V1.pdf. [Accessed: 03-Jul-2022].

[13] Texas Instruments, “High-Fidelity Rail-to-Rail Input/Output Audio Operational Amplifier,” LME49721 datasheet, Apr. 2013 [Accessed: 03-Jul-2022].

[14] “LME49721: 2-channel, 20-MHz, RRIO, audio op amp,” LME49721 data sheet, product information. [Online]. Available: https://www.ti.com/product/LME49721. [Accessed: 22-Jul-2022].

# Appendix A – MATLAB Code Analog\_System

Text, letter

Description automatically generated

Text

Description automatically generated

# Appendix B – MATLAB Code ADC\_System

Graphical user interface, text, application

Description automatically generated

# Appendix C – MATLAB Script Testing

Graphical user interface, text, application

Description automatically generated