TDOA DESIGN OF UNDERWATER ACOUSTIC SENSOR ARRAY

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BACKGROUND

The main motivation behind this independent study is to design a sensor array to complete a navigation task for Duke Robotics Club during RoboSub Competition. This submarine robot competition required robots from each team to complete a series of tasks, and some of the tasks need to be navigated by localizing an underwater pinger. This pinger locates at the bottom of the pool and periodically emits soundwave at certain frequencies (20kHz - 40kHz).

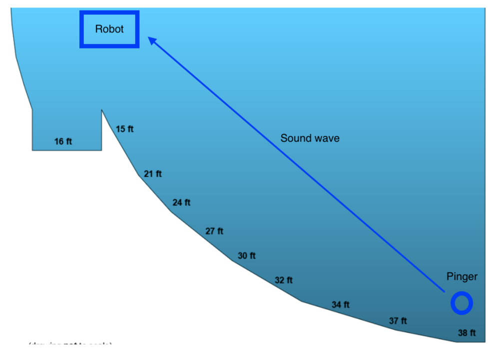

Figure 1: Cross-section of Competition Pool with Robot and Pinger

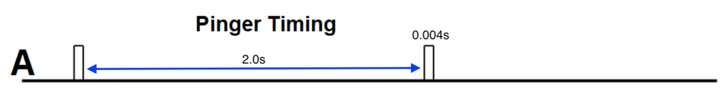

Figure 2: Pinger Timing

HARDWARE CONFIGURATION

The sensor array used is composed of four miniature omnidirectional hydrophones, which are small underwater microphones that can sense signals coming from all directions. The reason why four hydrophones are used is that they would generate three independent time differences, which would meet the minimal requirement to calculate the bearings in 3-D space. These four hydrophones are mounted at the corners of a square with a length of 18mm. The distance between the hydrophones are designed to be less than half wavelength of underwater soundwave at 40kHz to avoid spatial aliasing.

Figure 5: Mounted Hydrophone Array

INTRODUCTION

A sensor array is a group of sensors that are placed according to certain geometric pattern and measure data simultaneously. It is very useful in solving localization problem of unsynchronized signal source, like the pinger used in this independent study. The fixed distance between sensors allows the bearings of the signal source to be calculated based on the arrival time difference. This approach is called Time Difference of Arrival (TDOA). Unlike TOA (Time of Arrival), where two sensors can provide enough information to determine a point in 2-D space, TDOA needs three sensors to generate two time difference in order to locate a 2-D point.

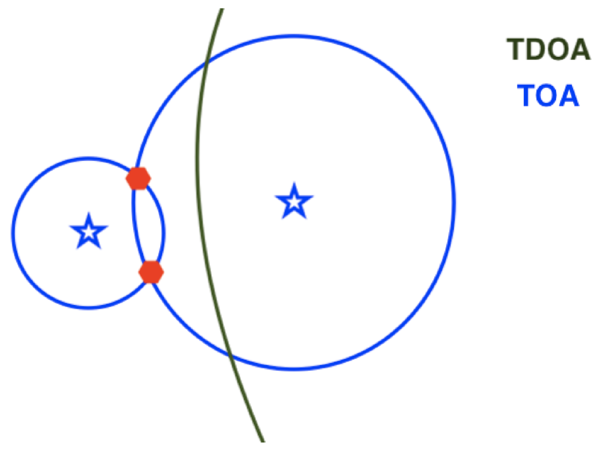

Figure 3: Comparison of TOA and TDOA with Two Sensors

CONCLUSION

With current hardware configuration and processing algorithm, including smallest variancein phase difference and TDOA, the hydrophone system is able to predict x-y direction bearing of the pinger sound source quite well even under small SNR condition. This shows that an unsynchronized sound source at certain frequency can be localized in 3-D space with four sensors using TDOA approach.

However, the lack of z-direction difference in current square geometric configuration resulted in the poor performance of z-direction estimation. Proved with MATLAB simulation data, a tetrahedron hardware configuration would greatly improve z-direction performance.

SOFTWARE SIMULATION & PROCESSING

To extract signals at the target frequency (20kHz-40kHz), the complex Fourier form at target frequency of the signal is calculated with a non-overlapping window. This transforms the acoustic signal into a series of complex numbers, each representing 125 samples. The magnitudes and phases of this complex number series are calculated. Within the window of maximum moving average of magnitude series, the phase differences across two hydrophones are calculated. An average phase difference is calculated from the window with the smallest variance.

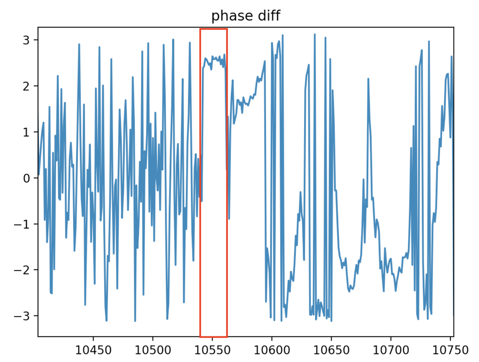

Figure 4: Phase Difference Plot from Wilson Pool Data

After three phase differences are calculated from four hydrophone signals, they are converted into distance difference between hydrophones and the pinger sound source. Since TDOA model generates a system of nonlinear equations, it cannot be solved by analytical approach. Therefore, a gradient descent based solver in Python SciPy package is used to calculate the location of the pinger from distance differences with an initial guess.

In order to speed up the testing cycle of the processing Python script, a MATLAB simulation is built to generate data with better controlled noise and ideal sinusoidal signal. The noise in MATLAB simulation is modeled to be Gaussian noise, and a 0.004s signal sinusoid is added to the noise to generate the final signal. The signal-to-noise ratio is controlled by adjusting the power ratio between the Gaussian noise and the signal sinusoid.

RESULT

The Python processing script is mainly tested with data from MATLAB simulation in this independent study, and there are two critical variables that affect the performance of the processing script: signal-to-noise ratio and gradient descent initial guess. Two 3-D plots are shown here: Figure 6 demonstrates the resulting bearings under different SNRs with perfect initial guess (blue dot); Figure 7 demonstrates the resulting bearings under a large SNR (SNR=4,000,000) with evenly distributed initial guesses.

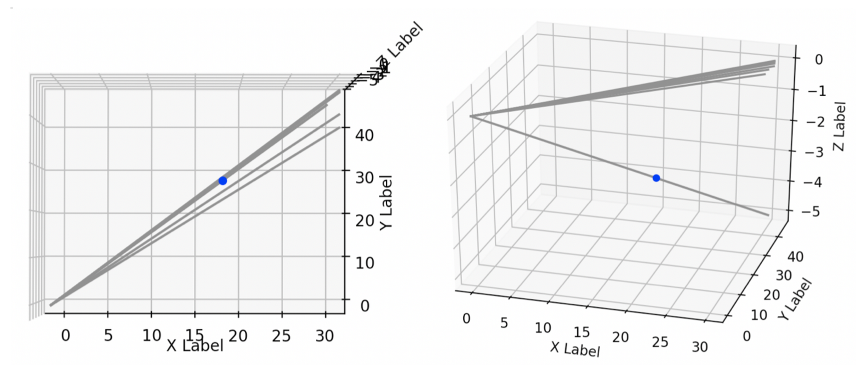

Figure 6: Resulting Bearings with Different SNRs

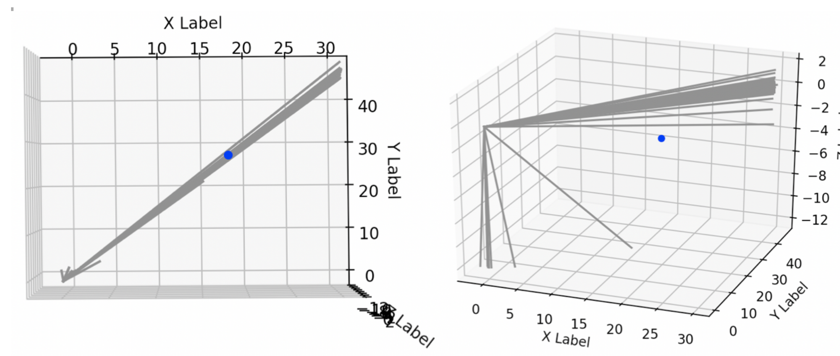

Figure 7: Resulting Bearings with Different Initial Guesses

As observed from the plots, most z-direction bearing estimations are clustered around $z = 0$ and $z = \infty$. This is due to the lack of z-direction difference in hydrophone placement. If the hydrophone array is designed to be a tetrahedron, a better performance in z-direction can be achieved.

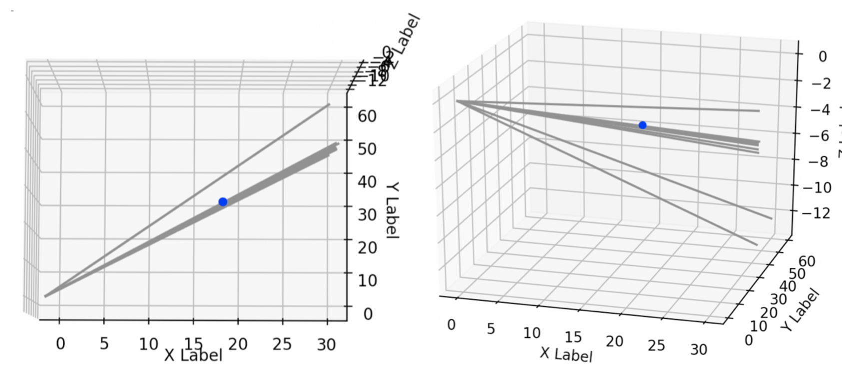

Figure 8: Resulting Bearings with Tetrahedron Configuration