Relative acoustic localization with USBL (Ultra-Short Baseline)

Paula A. Graça* José C. Alves† Bruno M Ferreira‡

***Abstract*—The present article focuses on the study of mechanisms that lead to a flexibility and precision improvement of an experimental USBL system to be used in an AUV with small dimensions, intended to operate for short and long range. Firstly, a study is conducted on possible methods for evaluating sensor configuration performance Lastly, the adaptive configuration selection method is presented, which serves as a tool that reconfigures the set of active hydrophones, from a discrete group in fixed known positions, depending on the estimated transmitter location. This method intends to achieve a higher localization precision and rectify issues that arise from classic USBL systems.**

After implementation, all developed mechanism were subjected to comprehensive simulated tests that demonstrate promising results in controlled conditions. Additionally, preliminary tests were performed in laboratory environment.

***Index Terms*—Fisher Information Matrix, Position estimation, Optimization, Ultra-Short Baseline, Underwater acoustic localization**

I. INTRODUCTION

The concept of using AUVs as "mules" for data transport appeared as a way to anticipate the access to collected data during autonomous missions of long duration. For such application, USBL (Ultra-Short Baseline) systems prove to have several advantages comparatively to other localization methods, such as optical, radio and inertial based techniques. The main advantages are the achievable range, limited error and lower sensibility to environment conditions, such as salinity and turbidity. For that reason, in this scenario a USBL system is used to receive the transmitted signals and calculate the angle of arrival of the acoustic signal, thus the direction that the mule AUV should navigate. Additionally, using a synchronization mechanism, the mule is also able to determine the distance to the acoustic source and thus the vehicles' relative positions.

In such scenario, since the acoustic source can be located anywhere, it is essential that the estimation is accurate for both short and long range distances. Additionally, the system needs to have line of sight in any direction, which is compromised from the start by deploying the sensors on an AUV. Therefore, this dissertation intends to develop a method that improves relative localization of AUVs using reconfigurable USBL systems.

This research work falls under the scope of activities developed by the Center of Robotics and Autonomous Systems of INESC TEC. It is integrated in the GROW project which focuses on exploring the use of AUVs as data mules for long duration missions.

*paula.graca@fe.up.pt
†jca@fe.u.pt
‡bm.ferreira@fe.up.pt

II. STATE OF THE ART

A. Underwater Acoustic Localization

Underwater localization is a key element in most underwater communication applications. An extensive survey on available algorithms and techniques is presented in [1], highlighting their features, advantages, drawbacks and applications.

B. Time Difference of Arrival

The Time Difference of Arrival (TDoA) is a technique that compares the time of arrival of a signal to different hydrophones in order to estimate the angle of arrival of the acoustic signal [1]. The array of reception hydrophones have known relative positions among them so that is is possible to compare the different times of arrival or phase differences.

C. Optimization of Sensor Configurations

This section is dedicated to explore some commonly employed methodologies which evaluate the performance of sensor layouts considering determined parameters.

1) Crámer-Rao Lower Bound: The Crámer-Rao lower bound (CRLB) is a tool which analyzes the variance of a sensor configuration and determines the minimum bound it can achieve independently from an efficient and unbiased estimator [2]. THE CRLB uses the Fisher Information matrix, $I(d)$, expressed as (1), where $\nabla_d t(d)$ is the gradient matrix of the observations vector regarding d_i, whereas Σ is the covariance matrix, in which the diagonal contains the standard deviation of the components of each noise vector, construed as $(\sigma_1^2, \sigma_2^2, ..., \sigma_N^2)$.

$$I(d) = \nabla_d t(d)^T \; \Sigma^{-1} \; \nabla_d t(d) \quad (1)$$

III. CONFIGURATION PERFORMANCE EVALUATION

Three different methods are presented to evaluate the performance of sensor configurations. Considering that r_i is defined as the vector that connects the origin of the axis to hydrophone i and rr_i defines the vector that connects hydrophone i to the acoustic source, then $r_i = r + rr_i$ allows to obtain r which corresponds to the position of the acoustic source in relation to the origin of the axis.

A. Assumptions

This research work relies on a set of premises that were considered throughout the development of the proposed system:

a) Number of sensor: The system uses multilateration to perform 3D localization, therefore a minimum of 4 hydrophones are needed.

b) Synchronism: The system integrates a synchronization mechanism that allows to know the time of emission of an acoustic signal, hence it is possible to compute the signal's ToA which indicates the range of communication.

c) Noise characteristics: The system assumes an injected error e_i added to the time differences of arrival, Δt_{ij}, that follows a Gaussian distribution with $e_i \sim \mathcal{N}(0, \sigma^2)$. For this project, a deviation of 5° in phase difference estimation was considered to be reasonable for an underwater navigation scenario, which results in a time differences of arrival equal to $0.5\mu s$.

B. Evaluation Methods

Three methods were implemented and analyzed as potential tools to be used. The first two methods are based on the estimates dispersion given by Monte Carlo simulations of a position estimator, namely a geometry based estimator (GBE) and an estimator that assumes a plane wavefront (PWE) [3], while the third is the CRLB based on the Fisher Information Matrix (FIM).

From the simulation results, it is expected that for short range estimation, the GBE presents estimates that are more approximated to the real value than the PWE, since it uses the geometric relations between the hydrophone and the transmitter in order to estimate the position. Contrarily, for long range estimations, distances higher than a few meters, the PWE is expected to achieve lower estimation errors than the GBE, since it is a linear system and the approximation it considers does not affect the estimation.

Lastly, as the FIM reflects the quantity of information that a configuration is capable of acquiring in relation to a specific position, then it can be directly related to the accuracy of the estimation. The Crámer-Rao lower bound, which is intrinsically linked to the FIM, assumes the use of any unbiased and efficient estimator, which makes it a more generic tool. Consequently, it is widely used in literature for sensor configuration's performance analysis and it is considered the most efficient for this application.

IV. Adaptive Configuration Selection Method

The proposed method serves as a tool that selects a set of four hydrophones, from a discrete group in fixed positions, depending on the perceived transmitter position in order to assure line of sight to it, increasing the localization precision. This approach uses a Monte Carlo method which is useful to solve problems that are deterministic in nature through repetition and application of random parameters. It considers a total of nine hydrophones is considered, whose positions are illustrated in Figure 1. Hydrophone 1 is always integrated in order to assure that all configurations are non coplanar.

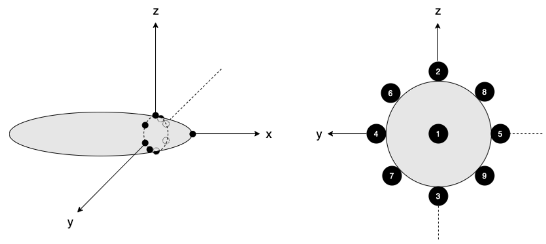

Figure 1: Hydrophone positions for the implementation using 9 hydrophones

Then the algorithm is described as follows: for each hydrophone configuration defined, the estimation is repeated 1000 times, so that averaged errors can be deduced for the estimate. This process is repeated 10 times for each configuration, resulting in average error deviations for each configuration. Then only the sets of four hydrophones that have line of sight to the transmitter compared to extract which is the one which leads to the higher localization precision.

A. Simulation Results

The simulation results for the above mentioned configurations were successful, as the configuration that achieved lower error was always selected. Then, as further investigation, the illustrated positions for hydrophones 1 to 9 are replicated two times with spacing of $20cm$ between them, originating 1512 configurations. These were analyzed in terms of range based performance of the acoustic transmitter instead of analyzing the angle of arrival of each individual considered position. Accordingly, recalling previous conclusions, the results obtained for the FIM using E-optimality [4] reveal that there are distinct configurations that on average perform better for short and long range. Additionally, the configuration that achieves the average best results for both short and long range estimation, using the GBE it is expected an approximated maximum expected deviation for azimuth is $2°$, elevation is $0.6°$ and norm is $6m$.

V. Conclusion

Overall it is possible to conclude that using a USBL system that reconfigures the hydrophone selection leads to an improvement on the underwater localization precision, allowing to always have a set of four active hydrophones with line of sight to the transmitter and makes it suitable for both short and long range estimation.

References

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