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A Novel Dual-Hydrophone Localization Method in Underwater Sensor Networks

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***Abstract*—In this paper, we propose a novel dual-hydrophone localization method, termed DHL, in underwater sensor networks. The objective is to reduce the impact of the serious disturbance of noise, poor link quality, long latency, limited bandwidth and low data rate. For underwater localization problems, DHL uses dual-hydrophone nodes to convert the localization problem into half-plane intersection issues. In particular, DHL adopts the sign of TDOA (Time difference of arrival) from the acoustic source to the pairwise hydrophones as the binary measurement information, in order to narrow the feasible region of the acoustic source. To test the performance of DHL, we evaluate it with extensive simulations. The simulation results demonstrate that DHL achieves higher robustness than the TDOA-based method when location and angle errors of nodes exist. Consequently, DHL is a promising scheme for underwater localization in adverse conditions.**

Keywords—Underwater Sensor Networks; Dual-hydrophone; Localization

I. INTRODUCTION

In the underwater environment, radio signals attenuate rapidly, hence they can only travel short distances, whilst in fact optical signals also scatter and cannot travel far in adverse conditions [1]. On the other hand, acoustic signals attenuate less, and they can travel further distances than radio signals and optical signals. Consequently, acoustic communication emerges as a convenient choice for underwater communications. However, it has several challenges, because the bandwidth of the acoustic channel is low, and hence the data rates are lower than they are in terrestrial wireless sensor networks (WSNs). Data rates can be increased by using short range communications which means more nodes are required to attain a certain level of connectivity and coverage. In this case, large-scale underwater acoustic sensor networks (UASNs) bare many additional challenges for acoustic communication and networking protocols. Moreover, the acoustic channel has low link quality [2], which is mostly due to the multi-path propagation and time-variability of the medium. Furthermore, the speed of sound is slow (approximately 1500m/s), yielding large propagation delay. In addition to these issues, in mobile UASNs the relative motion of the transmitter or the receiver may create the Doppler effect. Furthermore, in addition to these challenges associated with communication channel, UASNs are also energy limited similar to other WSNs.

Although there exists various localization algorithms for terrestrial WSNs, the unique properties of UASN have necessitated an innovative re-examination of problems which are related to localization. Some localization schemes based on RSS (Radio signal strength) [3], TOA (Time of arrival) [4] or TDOA (Time difference of arrival) [5] cannot directly extended to underwater sensor networks [6]. Indeed, long propagation delays, limited bandwidth, Doppler shift, and multi-path interference render many previously proposed solutions inaccurate or simply not infeasible [7]. Furthermore, 3D localization becomes even more challenging due to the economically-driven sparseness of USN deployments [8]. A TDOA-based silent positioning algorithm was proposed for the underwater sensor network [9]. An algebraic solution using TDOA and frequency differences of arrival of a signal received at a number of receivers has been proposed for locating a moving source [10].

In order to overcome the above challenges, we explore a novel dual-hydrophone localization method in order to locate a single acoustic source in USNs. This paper offers the following intellectual contributions. Firstly, in the underwater environment, there exists a long latency in communication, so there is a high requirement on time synchronization, and the synchronized dual-hydrophone on each node we used in DHL can reduce the time-synchronized requirement. Secondly, the poor link quality of UASNs results in retransmission of packages, and the bandwidth is limited, so each node in DHL passes or retransmits only one bit binary information to the server. Thirdly, we simulate DHL under the impact of different errors, and the simulation evaluation results show that DHL has high robustness, and it can reduce impact of the location error and angle error of nodes. To the best of our knowledge, this is the first work to leverage dual-hydrophone nodes in order to solve acoustic source localization problems in underwater sensor networks.

The rest of this paper is organized as follows. Section II presents the preliminary system overview. Section III details the system design. The simulation of the system is evaluated in Section IV. Finally, Section V summarizes the conclusion and future works.

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II. SYSTEM OVERVIEW

Fig. 1 shows a layout of an underwater sensor network with an acoustic source S and some dual-hydrophone nodes, the distance between the dual-hydrophone is fixed. Each node is attached to a surface buoy by a cable, which can transmit data between the node and the surface buoy. When the sensed data is received by the buoy, it is transmitted to the central station by wireless communication, then the server analyzes the data to estimate the location of the acoustic source. These buoys can obtain their absolute location from the equipped common GPS. Nodes obtain their absolute positions from the GPS on the surface buoys and get their direction information from IMU (Inertial Measurement Unit). The goal of our work is to locate an unknown source in the complex underwater environment.

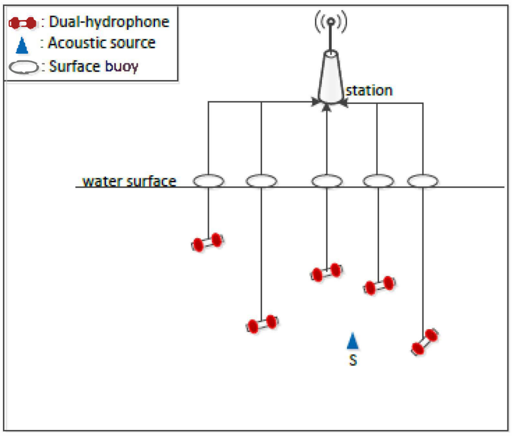


Fig. 1. System overview. A three-dimension UASNs formed by randomly deployed dual-hydrophone nodes, which can be used to locate the acoustic source. Each node floats with a buoy.

Without using accurate range-based information, we propose a range-free localization method. Assume there exists an acoustic source S, and that the source emits a beep. The acoustic signal propagates along the cable, and nodes would receive the signal when the sound is within their sensing range. After receiving the signal, each node computes TDOA from S to its dual-hydrophone through the GCC (Generalized Cross-Correlation) algorithm. For the *i*-th node, we draw a perpendicular plane to divide the whole localization area into two regions. The node can use the sign of TDOA to judge the source, as to whether it is at the left or right side of the perpendicular plane, and it marks the responding region with binary code 0 or 1. After all nodes pass their binary information to the server, the server analyzes the information of all nodes, and we can narrow the feasible region of the acoustic source. Finally, we obtain a polyhedron containing the acoustic source, and the centre of the polyhedron is the estimated location of the acoustic source.

III. DESIGN

The top-level idea of DHL is to use the binary information based on the sign of TDOA in order to narrow the feasible region by half-plane intersection, and to obtain the final region of the acoustic source. DHL includes two phases. Nodes with time synchronized dual-hydrophone compute binary information based on the sign of TDOAs, and pass the binary information, containing their positions and directions to the server during Phase I. In Phase II, the server realizes the process of binary cutting through half-plane intersection in order to obtain the final region of the acoustic source, and it estimates the location of the acoustic source.

A. Phase I – Nodes Processing

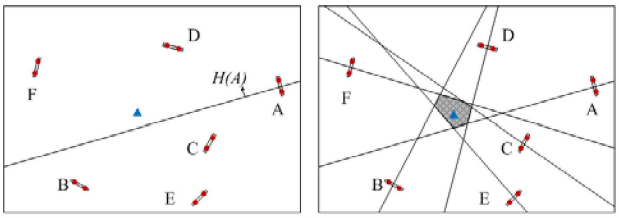
After all nodes are deployed, each node reports through the buoy to the server its directions, and the locations of the pairwise hydrophones. Once the acoustic source emits a signal, if the signal is in the sensing range of the *i*-th node, the node uses the GCC algorithm to compute the value of TDOA from the source to the two hydrophones on the node. The sequence *BinSequence* can be generated by the sign of TDOAs, and can be defined as

$$BinSequence(i) = \begin{cases} 1 & TDOA(i) > 0 \\ 0 & TDOA(i) < 0 \end{cases} \tag{1}$$

Where $1 \le i \le N$, N is the total number of nodes, *TDOA(i)* is the value of TDOA for the acoustic source to the *i*-th node. According to (1), if the value of TDOA from the source to the node's dual-hydrophone is positive, we can mark the corresponding region with binary code 1, and then the opposite region can be marked with 0. Each node sends its direction, location and binary information to the server.

B. Phase II – Server Processing

After receiving the direction, location and binary information from all nodes, the server analyzes the information and estimates the localization of the acoustic source. To make it easy to understand, we use a 2D case to describe the process of DHL. As shown in Fig. 2(a), there are six nodes in the localization space. The whole space can be divided into two half-planes by the perpendicular bisector of node A's dual-hydrophone, and *H(A)* represents the half-plane which contains the source by processing the binary information of node A. After processing every bit of the binary sequence, the whole space can be divided into many half-planes, and we can narrow the area of the acoustic source by using the half-plane intersection. As is shown in Fig. 2(b), the deep shadow is the final region of the source.



(a) Using the binary information of A to get the two half-planes

(b) Using the binary sequence to get the half-plane intersection

Fig. 2. Example ofDHL using half-plane intersection to locate the source.

The core idea of DHL is to use the sign of all TDOAs from the acoustic source to each dual-hydrophone node in order to

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obtain many half-planes, and narrow the feasible region by half-plane intersection. The final region of the acoustic source can be represented by H_f, which can be calculated as:

$$H_f = \bigcap_{i=1}^{N} H(i) \tag{2}$$

In the practical localization system, node location error and node direction error inevitably affect the localization results. Node location error, angle error and measurement error can result in H_f to be an empty set, which then leads to localization failure. In order to reduce the impact of errors (location error and angle error of dual-hydrophone) in the localization result, DHL adds an empty set detection process. In DHL, after using a node to cut the space, if the feasible region is an empty set, we regard the information provided by the node as being invalid. We do not use the invalid node to cut the space in this iteration, and we then simply handle the information of the next bit. After using all nodes to cut the space, we can narrow the final region of the acoustic source.

To summarize, DHL is presented in Algorithm 1 as shown in Fig. 3. The inputs are the location coordinates and directions of nodes, and the binary information for all the nodes along with the space size R. The output is the estimated location of the acoustic source. Line 1 is the initialization step, in which we set the initial feasible region H_f with the whole space. From line 2 to 13 defines a half-plane intersection function to narrow the range of the acoustic source by processing the binary sequence. Finally, DHL takes the centre of the final region as the coordinates of the acoustic source shown in line 14.

Algorithm 1: The DHL Algorithm

Input: The location coordinates of nodes
The direction of nodes
The space size R
Measurement information: $BinSequence$

Output: Estimated location: $[x, y, z]$

1 Set the feasible region: $H_f \leftarrow R$;
2 **for** *node* $i \leftarrow 1$ *to* N **do**
3 Using i's direction and location to get $TDOA(i)$;
4 Judging the sign of $TDOA(i)$ to get i's binary information: $BinSequence(i)$;
5 Using $BinSequence(i)$ to get the half-plane including the source: $H(i)$;
6 Narrow the acoustic source's feasible region:
7 **if** $H_f \cap H(i) == \emptyset$ **then**
8 continue;
9 **end**
10 **else**
11 $H_f \leftarrow H_f \cap H(i)$;
12 **end**
13 **end**
14 $[x, y, z]$=*Coordinate* (H_f);
15 **return** the estimated position: $[x, y, z]$.

Fig. 3. Pseudo code of DHL.

IV. SIMULATION RESULTS

In this section, we evaluate the performance of DHL with the traditional hyperbolic intersection based TDOA method. We also simulate DHL with the impact of different numbers of nodes, node location and node angle errors, using MATLAB.

In the simulation settings, 100 nodes are randomly distributed in a 100 × 100 × 100m area. The location and angle of all nodes are assumed to be known in advance. The distance between the two hydrophones on each node is 0.5m. All the statistics are running 500 times for high confidence, and are reported by CDF figure.

Comparison with TDOA: In this experiment, we compare DHL with a traditional hyperbola-based TDOA method by adding a zero-mean with 0.5m^2 variance node location error, and a zero-mean with 10° variance node angle error. The TDOA-based method uses any group of four nodes to estimate the acoustic source position in a 3D scenario. In the simulation, we sort the RMSE (root mean square error) results of TDOA-based method by ascend, and choose the mean of the first 20% localization results in comparison with DHL. As shown in Fig. 4, with nearly 98% of the localization error below 7m for DHL, DHL performs better than TDOA, because TDOA is very sensitive to the errors added to the nodes.

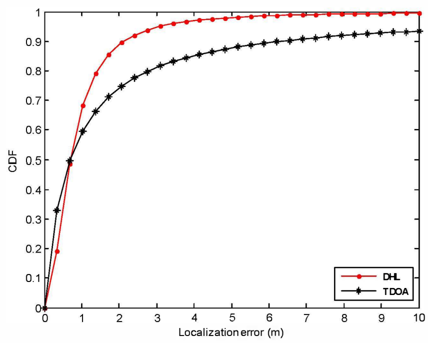

Fig. 4. Compared with TDOA-based method.

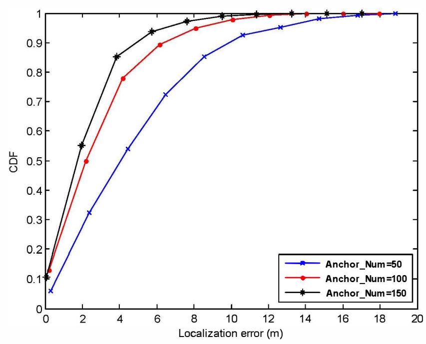

Fig. 5. Impact of node number.

Impact of node number: In this simulation, we investigate localization error with different numbers of nodes, from 0 to 200 with steps of 10. We add a zero-mean with a 0.5m^2 variance node location error, and a zero-mean with 10° variance node angle error. Since DHL aims to narrow the range of the acoustic source by processing binary sequence, the whole area can be divided into more parts as the number of nodes increases, and so the localization results are more accurate. Fig. 5 shows the CDF and localization error with 50, 100, 150 nodes for DHL. Fig. 5 demonstrates that nearly 90% of localization errors are below 10m for the three curves. During the server processing phase, once the feasible region is an empty set, we discard the information provided by the node, and simply then handle the information of the next bit.

Impact of location error: In this experiment, we evaluate DHL using the location error of nodes from zero-mean with 0m to 3.0m variance in steps of 0.25m, and the other parameters remain as default. We choose node location errors as 0.5m, 1.0m and 1.5m in order to show the positioning performance for DHL as shown in Fig. 6. It indicates that the location error of nodes can affect the localization results. As demonstrated in Fig. 6, about 98% of the localization error is within a 7m localization error for each 0.5m location error.

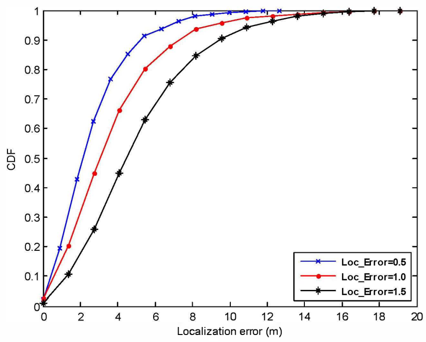

Fig. 6. Impact of location error of nodes.

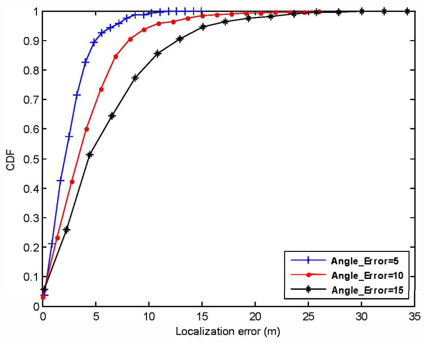

Fig. 7. Impact of angle error of nodes.

Impact of angle error: In the experiment, we perform the simulation with different angle error of nodes, ranging from 0° to 180° in steps of 5° for DHL. As the direction of the nodes is uncertain, we assume the angle error of node may influence the localization accuracy. As shown in Fig. 7, we choose angle error with 5°, 10°, 15° for DHL, and the localization error for DHL increases as the node angle errors enlarge. The CDF can reach about 95% within a 10m localization error for 10° node angle error.

V. CONCLUSIONS

This paper presents DHL as a novel underwater acoustic source localization method that uses dual-hydrophone nodes to locate an unknown acoustic source. By using dual-hydrophone sensors, we can convert the localization problem into half-plane intersection issues by using binary information to locate the acoustic source. Simulation evaluation results demonstrate that DHL achieves a robust localization result in the presence of location and angle error of nodes. As ongoing and future work, we will conduct experiment in a swimming pool in order to implement DHL, and try to locate multiple acoustic sources.

ACKNOWLEDGMENTS

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