Research on the Path Plan for Searching Acoustic Beacon of Black Box based on AUV

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Abstract —Acoustic source searching is a key technique in underwater defense, and can be applied to locate the missing automatic underwater vehicle (AUV), the submarine in distress, and the black box for ship or plane. This paper addresses the path plan scheme for acoustic source searching based on AUV. The planed path is composed of three steps. In Step 1, the AUV uses the comb path to search the target's signal, and the comb interval is discussed to guarantee both high detection probability and high searching efficient. In Step 2, to approach the target, an elliptical arc path is proposed, which achieves a trade-off between the approaching distance and the localization precision. In Step 3, the circular path is introduced to precisely locate the target. The optimal radius of the circle is calculated based on horizontal dilution of precision (HDOP) analysis to improve the localization precision, and a result fusion algorithm is presented to avoid the blind area for the direction of arrival (DOA) based localization method or the time difference of arrival (TDOA) based localization method. Simulation results validate the effectiveness of the proposed path plan method.

1 Introduction

Acoustic source searching is a technique, which has an extensive value in use [1]. In the military application, it can be used to detect the underwater weapons, such as the submarine, the automatic underwater vehicle (AUV), and the torpedo. In the civilian application, it can be applied to find and locate the black box for the missing airplane or ship. Therefore, acoustic source searching has attracted researcher's attentions in recent years, and their work can be divided into two parts.

The first part is the nonsynchronous localization method, including the direction of arrival (DOA) based method [2]-[3] and the time difference of arrival (TDOA) based method [4]. Generally speaking, the DOA based method has a higher localization precision in near distance, while the TDOA based method has a larger effective range.

The second part is the path plan. The existing acoustic source searching usually use the comb path, and the comb interval is decided mainly on experience [5]. Actually, the detection probability and the searching efficient have a close relationship with the comb interval, and the localization precision is dramatically affected by the path.

In this paper, we address the path plan problem, and the designed path is composed of three steps. In the first step, a comb path is used to search the signals. The comb interval is discussed to guarantee both high detection probability and high searching efficient. In the second step, an elliptical arc path is proposed to guide the AUV approaching the target. The proposed elliptical arc path can achieve a tradeoff between the approaching distance and the localization precision. In the third step, a circular path is utilized to localize the target with a high localization precision. The optimal radius is calculated based on the horizontal dilution of precision (HDOP) analysis considering both DOA based localization method and TDOA based localization method.

2 Path Plan for the Acoustic Source Searching Based on AUV

In this section, we propose the path plan method for acoustic source searching based on AUV. The proposed method is composed of three steps as follows.

2.1 First Step: Target Searching Using the Comb Path

The main task of the first step is to search the target. We use comb path in the first step since the comb path has the highest searching efficient.

Fig. 1 shows a typical comb path for searching the acoustic target, where, R_{range} is the effective detection range of the sonar on AUV, R_{shu} is the comb interval, h_{sea} is the depth of the sea, and h_v is the depth of the AUV.

From Fig. 1 it is obvious that the comb interval should be:

$$R_{\text{shu}} = 2\sqrt{R_{\text{range}}^2 - (h_{\text{v}} - h_{\text{sea}})^2} \quad (1)$$

In real situation, the bottom of the sea is fluctuant. The effective detection range is also a variable due to the time-varying signal channel. Hence, allowances should be given to avoid target undetected when calculate the comb interval. Considering the allowances, the improved comb interval is given as:

$$R_{\text{shu}} = 2\sqrt{(R_{range} - R_{al})^2 - (h_{\text{v}} - h_{\text{sea}} - h_{al})^2} \tag{2}$$

where, R_{al} and h_{al} are the effective detection range allowance and the detection range allowance, respectively.

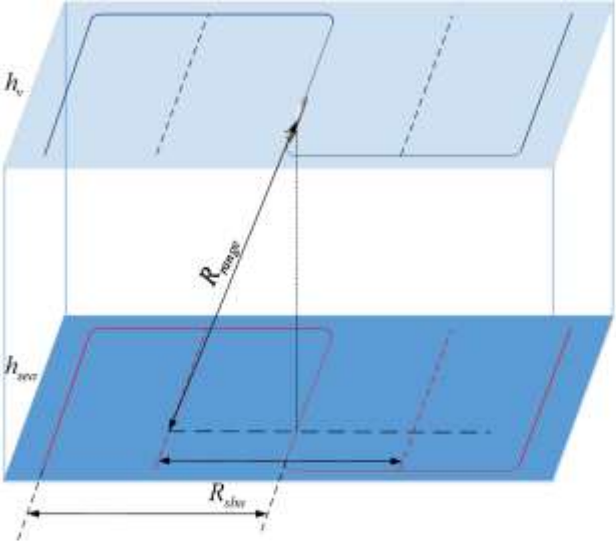


Figure 1. Typical comb path for searching the acoustic target.

2.2 Second Step: Target Approaching Using the Elliptical Arc Path

When the distance between the target and the AUV is less than the effective detection range, the AUV detect the target. In this case, the system come to the second step.

For the second step, the main task is to approach the target. There is a significant contradiction between the approaching distance and the localization precision. The path along the line of sight (LOS) has the shortest approaching distance. However, the localization precision is low for both the DOA based method (since the target are in the end-fire direction) and the TDOA based method. On the opposite, the path vertical to the LOS obtains the highest localization precision, while the approaching distance is the longest.

In this case, we use a controllable coefficient to achieve a trade-off between the approaching distance and the localization precision. The direction along the LOS is denoted as $\boldsymbol{v}_l$ and the direction vertical to the LOS is denoted as $\boldsymbol{v}_v$. Then, the approaching direction is presented as:

$$\boldsymbol{v} = k\boldsymbol{v}_l + (1-k)\boldsymbol{v}_v \tag{3}$$

In (3), $0 \le k \le 1$ is the controllable coefficient, which is used to adjust the contradiction between the approaching distance and the localization precision. A larger *k* indicates a shorter approaching distance and a lower localization precision, while a smaller *k* has a longer approaching distance and a higher localization precision.

For example, Fig. 2 shows the approaching path for different *k*, and the corresponding performance is given in Table 1. It is obvious that the approaching distance is contradicted with the localization precision, and a trade-off between the approaching distance and the localization precision is controlled by *k*.

Table 1. Approaching distance and localization precision for different *k*.

k	0.7	0.5	0.3	0
Approaching distance	4460m	5990m	10120m	-
Localization precision	37.3m	15.8m	7.4m	-

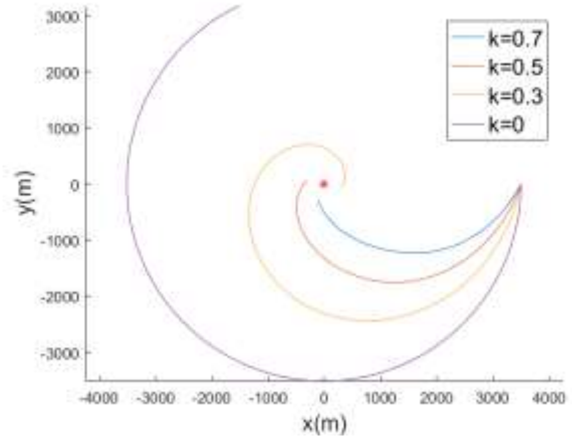


Figure 2. Elliptical Arc path for different *k*.

2.3 Third Step: Precisely Localization Using the Circular Path

When the distance between the target and the AUV equals to a certain value (optimal radius), the AUV stop the elliptical arc path, and the third step begins.

For the third step, the main task is to precisely localize the target. The circular path is utilized in this step, and the optimal radius of the circle is designed to improve the localization precision. But before that, we should discuss the localization precision based on HDOP analysis.

The HDOP for the TDOA based localization method can be calculated as:

$$\begin{aligned}\mathbf{H}_{TDOA} = \mathbf{M}_x^{-1} \cdot (&\mathbf{M}_t \cdot \mathbf{D}_t \cdot \mathbf{M}_t^T + \mathbf{M}_0 \cdot \mathbf{D}_0 \cdot \mathbf{M}_0^T + \mathbf{M}_1 \cdot \mathbf{D}_1 \cdot \mathbf{M}_1^T \\ &+ \mathbf{M}_2 \cdot \mathbf{D}_2 \cdot \mathbf{M}_2^T + \mathbf{M}_c \cdot \mathbf{D}_c \cdot \mathbf{M}_c^T) \cdot \mathbf{M}_x^{-1\text{T}}\end{aligned} \tag{4}$$

where, $\mathbf{M}_x, \mathbf{M}_t, \mathbf{M}_0, \mathbf{M}_1, \mathbf{M}_2, \mathbf{M}_c$ are the partial differential matrices for the target's coordinate ($\mathbf{M}_x$), the TDOA ($\mathbf{M}_t$), the AUV's coordinate ($\mathbf{M}_0, \mathbf{M}_1, \mathbf{M}_2$), and the sound speed ($\mathbf{M}_c$), $\mathbf{D}_t, \mathbf{D}_0, \mathbf{D}_1, \mathbf{D}_2, \mathbf{D}_c$ are the corresponding covariance matrix.

Similar to (4), the HDOP for the DOA based localization method can be obtained by:

$$\mathbf{H}_{DOA} = \mathbf{M}_a \cdot \mathbf{D}_a \cdot \mathbf{M}_a^T + \mathbf{M}_b \cdot \mathbf{D}_b \cdot \mathbf{M}_b^T + \mathbf{M}_L \cdot \mathbf{D}_L \cdot \mathbf{M}_L^T \tag{5}$$

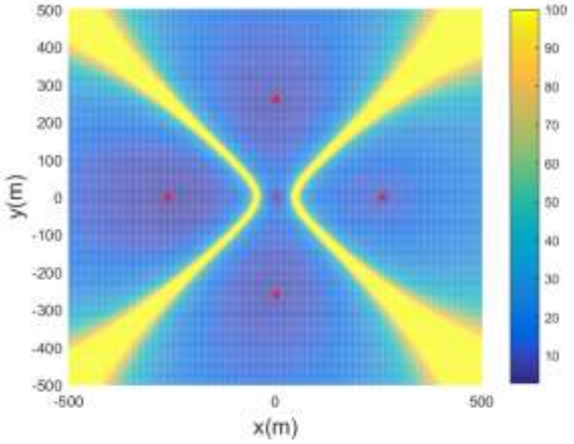
where, $\mathbf{M}_a, \mathbf{M}_b, \mathbf{M}_L$ are the partial differential matrices for the DOA ($\mathbf{M}_a, \mathbf{M}_b$) and the internal navigation system ($\mathbf{M}_L$), $\mathbf{D}_a, \mathbf{D}_b, \mathbf{D}_L$ are the corresponding covariance matrix.

From the HDOP, the localization precision is given as:

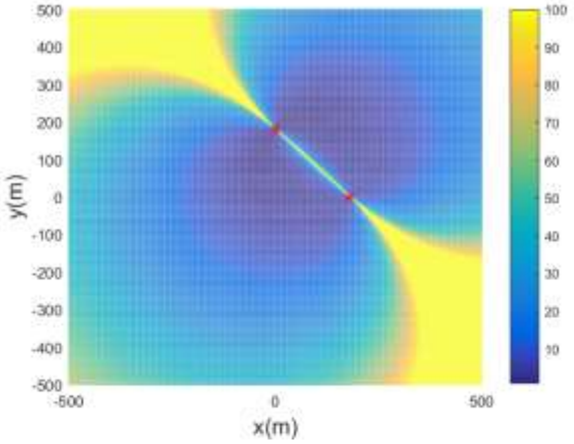
$$\sigma_l = \sqrt{\mathrm{tr}(\mathbf{H})} \tag{6}$$

where, $\mathrm{tr}(*)$ means the trace of matrix.

Fig. 3 shows the distribution of localization precision for TDOA based method and DOA based method, respectively.



(a) TDOA based method



(b) DOA based method

Figure 3. Localization precision distribution.

From Fig. 3, it is obvious that:

(1) The TDOA based method has a larger effective range, while the DOA based method has a higher localization precision in near field.

(2) Each method generates a blind area (the yellow colour in the figures).

In this case, we use a data fusion algorithm which combines the localization results obtained from TDOA based method and TOA based method. The data fusion algorithm can avoid the blind area, and increase the localization precision.

Supposing the localization precision for TDOA based method and DOA based method are σ_{TDOA} and σ_{DOA}, the fused localization result is given as:

$$\boldsymbol{x}_f = \frac{\sigma_{TDOA}^2}{\sigma_{TDOA}^2 + \sigma_{DOA}^2} \boldsymbol{x}_{TDOA} + \frac{\sigma_{DOA}^2}{\sigma_{TDOA}^2 + \sigma_{DOA}^2} \boldsymbol{x}_{DOA} \tag{7}$$

where, $\mathbf{M}_a, \mathbf{M}_b, \mathbf{M}_L$ are the partial differential matrices for the DOA ($\mathbf{M}_a, \mathbf{M}_b$) and the internal navigation system ($\mathbf{M}_L$), $\mathbf{D}_a, \mathbf{D}_b, \mathbf{D}_L$ are the corresponding covariance matrix.

The localization distribution is affected by the position of the AUV (red point in Fig. 3), and the position of the AUV is related with the optimal radius. Therefore, the optimal radius influence the localization precision, and we design the optimal radius to minimize the localization precision, that is:

$$\begin{aligned} r_{op} &= \mathop{\arg\min}_{r_{op}=r} \sigma_f^2(r) \\ &= \mathop{\arg\min}_{r_{op}=r} \frac{2\sigma_{TDOA}^2(r)\sigma_{DOA}^2(r)}{\sigma_{TDOA}^2(r) + \sigma_{DOA}^2(r)} \\ &= \mathop{\arg\min}_{r_{op}=r} \frac{2\,\mathrm{tr}[\mathbf{H}_{TDOA}(r)]\,\mathrm{tr}[\mathbf{H}_{DOA}(r)]}{\mathrm{tr}[\mathbf{H}_{TDOA}(r)] + \mathrm{tr}[\mathbf{H}_{DOA}(r)]} \end{aligned} \tag{8}$$

where, $\sigma_f^2(r)$ is the fused localization precision and r is the radius of the path circle.

As an example, Fig. 4 shows the localization precision for different radius. From the figure, it is obvious that after data fusion, the localization precision is improved. Compared with the TDOA based method, although the precision of the fused method has a slightly deterioration, the blind area for the TDOA method is eliminated. The optimal radius should be 400 m, and the best localization precision is 2.90 m.

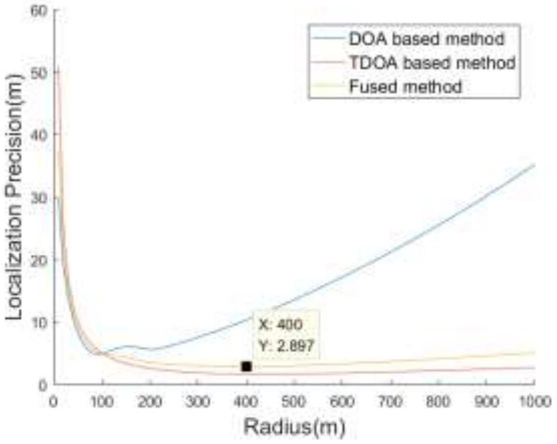


Figure 4. Localization precision for different radius.

3 Simulation

In this section, a simulation is presented to prove the effectiveness of the proposed method. The simulation parameters are as follows. The depth of the sea is 1500 m (fluctuating 50 m), the depth of the AUV is 1200 m. The effective detection range of the sonar is 3500 m (fluctuating 100 m). The target's coordinate is [0, 0] m, the AUV searching the target from the coordinate of [28000, -20000] m. The error parameters are as follows. The estimation error of the target's direction is 1 degree at 1 km, 2 degrees at 2 km, and 4 degrees at 3 km. The estimation error of the signal's delay is 0.3 ms at 1 km, 0.5 ms at 2 km, and 0.8 ms at 3 km. The depth estimation error is 1 m. Sound speed estimation error is 1.5 m/s. The inertial navigation system (INS) is 0.2%.

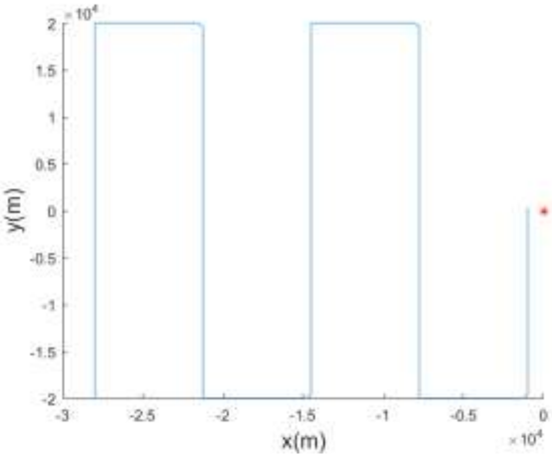
3.1 First Step

Based on the simulation parameters, the comb interval is calculated as 6753 m from (2), and the planed comb path is given in Fig. 5(a).

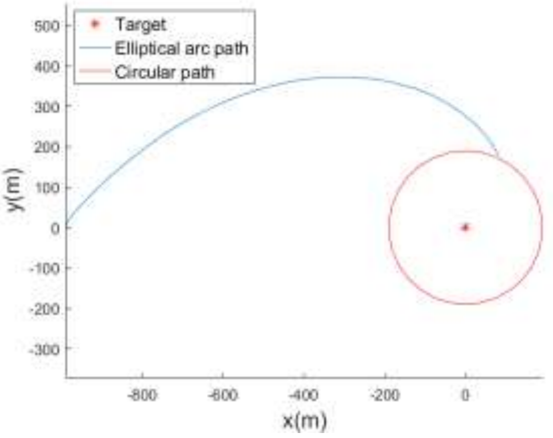
3.2 Second Step and Third Step

Before design the elliptical arc path, we should calculate the optimal radius for the circular path. Hence, the separation between the second step and the third step is clear. From (8), the optimal radius is calculated as 210 m with a minimum localization precision 3.04 m. Fully considering both the approaching distance and the localization precision, the controllable coefficient *k* is set as 0.5 in step 2. Then, the planed path for the second step and the third step is shown in Fig. 5(b).

Utilizing the planed path, the target's localization is estimated as [2.71, 1.66] m, which has a 3.23 m error compared with its real position. Simulation results validate the effectiveness of the planed path.



(a) Step 1: comb path



(b) Step 2: elliptical arc path and Step 3: circular path

Fig. 5. Planed path for the simulation.

4 Conclusions

This paper addresses the path plan for acoustic source searching based on AUV. The designed path is composed of three steps. In the first step, a comb path is used to search the target's signal. The comb interval is calculated by the environmental parameters to guarantee high detection probability and high searching efficient. In the second step, an elliptical arc path is used to approach the target. There is a contradiction between the approaching distance and the localization precision, and a controllable coefficient is established to achieve a trade-off between them. In the third step, a circular path is used to locate the target at a high localization precision. The optimal radius of the circle is calculated based on HDOP analysis. Besides, a result fusion algorithm is presented to avoid the blind area utilizing the result obtained from TDOA based method and DOA based method. Finally, simulation is implemented to test the proposed method, and the result shows that a high localization precision can be obtained via the designed path.

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Speaker Biography

Sun Sibo was born in Harbin, China, in 1987. He received B.E. and Ph.D. degrees from Harbin Institute of Technology in 2010 and 2017, respectively, and has been studied in National University of Singapore in 2014. Now, he is an assistant professor in Harbin Engineering University. His research interests include sonar localization and detection.