A research on blind area of random layout units for localization

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Abstract. Acquisition distance information of the underwater target is very important to evaluate the target noise level, so it is necessary to do some research on the passive localization method for the underwater target. In this paper, the multi-hydrophone units model is used to passively achieve target localization information in the underwater environment; the accurate DOA estimation and ranging calculation method are presented. The localization blind area problem with different units models is discussed. The blind area problem caused by traditional passive localization model (three units) is solved by the method with four random units, which can locate the underwater unpredictable target in arbitrary direction.

1. Introduction
In the acquisition and analysis target radiated noise in underwater environment, distance information of target is very important. TDOA (Time Delay of Arrival), MFP (matched-field processing) and BOL (bearing only location) are mainstream passive localization method in underwater environment at present, and TDOA can achieve passive localization of target under the condition of that the complex underwater environment parameters can not be acquired or long baseline [1-3], but the localization blind area is TDOA’s defect [4, 5]. The layout of hydrophone units is the key to the effective passive localization of targets by TDOA. This paper introduces the localization theory based on random four hydrophone units. The model of random layout model overcomes the defect that four hydrophone units must be in line [4], as well as the localization method has no blind area problem. The localization blind area of different layout model is analyzed and compared quantitatively. When the distance between the units and the target is 1km away from the target and the units spacing is 16 m-20 m, the localization blind area range is more than 25% using the traditional three units layout localization method. The localization method with four random hydrophone units can locate the passive target without blind area in the underwater environment.

2. Localization theory of random three hydrophone units
The traditional passive localization method adopts three or more linear units, but linear unit layout model is hard to lay out due to the complex underwater environment. In view of this, this section adopts random three hydrophone units to locate target passively. Assumed that S is the target (sound source) and conforms to spherical wave spreading, hydrophone unit 1,2,3 and S are in the same plane, unit 0 is the origin of coordinates, the link line of unit 2 and unit 0 is defined as polar axis, Geometric sketch is shown as Figure 1. According geometrical relationship and mathematical derivation, the exact localization formula is obtained as follows.
When the target $S$ is in the region $[\alpha, 180^\circ]$.

$$\cos \theta = \frac{(A-B)x+(C+D\cos \alpha)-D\sin \alpha \sqrt{E-(A-B)^2}}{r}$$

$$r = \frac{d_2^2d_1+d_1^2-d_2^2}{2c(d_1\tau_{20}-d_2\tau_{01})+2d_1d_2(2\sin^2\theta \cos(\theta-\alpha)+\sin \sin(\theta-\alpha))}$$

When the target $S$ is in the region $[180^\circ, \alpha + 360^\circ]$.

$$\cos \theta = \frac{(A-B)x+(C+D\cos \alpha)-D\sin \alpha \sqrt{E-(A-B)^2}}{r}$$

$$r = \frac{d_2^2d_1+d_1^2-d_2^2}{2c(d_1\tau_{02}-d_2\tau_{10})+2d_1d_2(2\sin^2\theta \cos(\theta-\alpha)+\sin \sin(\theta-\alpha))}$$

**Figure 1.** Geometric sketch with three random units model.

Where $\tau_{01}$ is the time delay between source signal arrives unit 0 and unit 1, $\tau_{20}$ is the time delay between source signal arrives unit 2 and unit 0, $r$ is defined as the distance between the target and unit 0, $\theta$ is defined as target azimuth, $d_1$ is the distance between unit 0 and unit 1, $d_2$ is the distance between unit 0 and unit 2, $\alpha$ is used to represented the deviation of nonlinear laying. $A = ct_{01}(c^2\tau_{20}^2 - d_1^2)$, $B = -ct_{20}(c^2\tau_{01}^2 - d_2^2)$, $C = d_1(c^2\tau_{20}^2 - d_2^2)$, $D = d_2(c^2\tau_{01}^2 - d_1^2)$, $E = C^2 + 2CD\cos \alpha + D^2$, $c$ is underwater acoustic velocity.

3. The discussion on localization blind area generated by units layout

Taking the random three units as an example, the unit layout model is shown in Figure 2. The whole plane area is divided into two parts. The area $[\alpha, 180^\circ]$ is S1, the area $[180^\circ, \alpha + 360^\circ]$ is S2. L is center line of the angle $\varphi$, $\beta$ presents the deviation of $L$.

Simulation condition: $d_1=16$ m, $d_2=20$ m; target source noise is limited white gaussian noise with broadband of 1 kHz-10 kHz; SNR=10 dB; underwater environmental noise is not relevant; sampling frequency is 100 kHz; acoustic velocity is 1500 m/s. Using cross correlation method to solve the time-delay. In this paper, localization error is defined as the distance difference of target position and the TDOA position divided by target actual distance. Localization blind area is defined as the section that localization error is more than 10%.

When $\alpha$ is $30^\circ$, the units layout model is shown in Figure 3.

Figure 3 presents the target position estimation based on TDOA method, where the blue points show the localization of the three hydrophone units, the red + presents the actual position and the black circles presents the estimated position of the target for Section S1 and Section 2. According to Figure 2, when the target appears in the area nearby the $\varphi$ angular bisector, localization error value is the minimum, localization error increases with the increase of $\beta$, localization blind area will appears when the target closes to the $d_1$ and $d_2$. 

![Figure 1](image1.png)

![Figure 2](image2.png)
4. Units layout model without blind area problem
Four hydrophone units model is used to solve the localization blind area problem in the random layout of three units. Unit 1, 2, 3 are Scalar hydrophones and unit 0 is vector hydrophone, they can be randomly laying as shown in Figure 4. The flat area is divided into 6 sections \((S_1, S'_1, S_2, S'_2, S_3, S'_3)\). First vector hydrophone unit 0 is used to estimate the target direction \([6]\), when the target appears in \(S_1\) and \(S'_1\), adopting unit 0, 2, 3 to locate the target’s position, when the target appears in \(S_2\) and \(S'_2\), adopting unit 1, 0, 3 to locate the target’s position, when the target appears in \(S_3\) and \(S'_3\), adopting unit 1, 0, 2 to locate the target’s position. According to the different area, selecting three correct units from four random units model to locate the target’s position, so as to achieve the all-directional passive localization in underwater environment.
5. Simulation study

In this section, localization performances are analyzed and compared for the different units models, related simulation as follows.

Simulation condition: source noise is limited white gaussian noise with broadband of 1 kHz-10 kHz; SNR=10 dB; sampling frequency is 100 kHz; acoustic velocity is 1500 m/s. Using cross correlation method to solve the time-delay.

Considering the case that three equidistance units are in line, d1=20 m, d2=20 m, the target is moving from 0-360 in a circle with the middle unit as the center with the radium of 1 km. Figure 5 shows the target position estimation performance based on TDOA method, where the blue points show the localization of the three hydrophone units, the red + presents the target actual position and the black circles presents the estimated position of the target. The Figure 5(c) presents localization error value by calculation.

According to the Figure 5, while closing to the endfire of line between two units, the localization effect is becoming worse. By calculation, the region that localization error value is more than 10% accounted 25% DOA (direction of arrival), and the region that localization error value is less than 10% accounted 75%.

Considering the case that three units are in line, d1=20 m, d2=10 m, the distance between central unit and target is 1km. For different direction, the localization result is shown in the Figure 6.

By calculation, the region that localization error value is more than 10% accounted 37.78% DOA, and the region that localization error value is less than 10% accounted 62.22%, the results have worsened.

When three units is random, d1=20 m, d2=10 m, α=30°, the distance between central unit and target is 1km. For different direction, the localization result is shown in the Figure 7.

By calculation, the region that localization error value is more than 10% accounted 43.61% DOA, and the region that localization error value is less than 10% accounted 56.39%.

However, when four units are considered, d1=16 m, d2=20 m, d3=18 m, α1=60°, α2=330° the distance between central unit and target is 1km. For different direction, the localization result is shown in the Figure 8.
By calculation, the region that localization error value is more than 10% accounted 0% DOA, and the region that localization error value is less than 10% accounted 100%.

The proportion of the localization blind area of representative layout model is summarized in Table 1. When the target is 1 km away from the unit 0, expanding the units spacing can reduce the localization blind area. To the same units spacing, when it is in a straight line, the localization blind area range is the smallest, and the blind area range increases with the increase of $\alpha$. Adopting four random units model to locate target passively, the localization blind area is 0. Otherwise, such as SNR, the distance between unit and target, are characteristics which affect localization accuracy. Under the condition of high SNR, increasing the units distance will expand the effective localization area up to several kilometers, but in the actual underwater environment, the spatial correlation radius is about 300-500$\lambda$, and the excessively large distance between the units will affect the correlation of received signals. Owing to focusing on blind area problem and target DOA, other factors are not discussed in detail in this paper.

Figure 5. (a) Units layout model, (b) localization performance, (c) localization error value.
Figure 6. (a) Units layout model, (b) localization performance, (c) localization error value.

Table 1. Localization blind area of different units layout model.

| Unit quantity | Layout model       | Layout unit parameter | Localization blind area percentage |
|---------------|--------------------|-----------------------|-----------------------------------|
| 3             | Equidistance linear| d1=d2=20m             | 25%                               |
| 3             | Equidistance linear| d1=d2=10m             | 54.4%                             |
| 3             | Nonuniform linear  | d1=20m d2=10m         | 37.78%                            |
| 3             | Nonuniform linear  | d1=20m d2=18m         | 26.6%                             |
| 3             | random             | d1=20m d2=10mα=30°    | 43.61%                            |
| 3             | random             | d1=18m d2=20mα=30°    | 33.33%                            |
| 3             | random             | d1=18m d2=20mα=90°    | 60.27%                            |
| 4             | random             | d1=16m d2=20m d3=18m  | 0                                 |
|               |                    | α1=60° α2=330°        |                                    |
Figure 7. (a) Units layout model, (b) localization performance, (c) localization error value.
Figure 8. (a) Units layout model, (b) localization performance, (c) localization error value.

6. Conclusions
Traditional three equidistance linear model must be the straight line, or it will produce a large localization error, which puts forward very high requirements for the layout of units model. In addition, no matter how, it still has localization blind areas problem. The method of four random units model proposed in this paper is adopted to overcome the defect that the traditional layout model needs to be in a straight line; and solve the inherent localization blind area problem at the same time. In the practical application of underwater environment, four random hydrophone units can be quickly deployed with acoustic synchronous positioning beacon in the seabed where the targets pass. The positional relation of the units model and the synchronization of real time clock are determined by the beacon. Finally, location information of the underwater unpredictable target in arbitrary direction is estimated.

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