Research on the real-time positioning method of vector buoys in deep sea

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Abstract. Buoys are generally difficult to anchor in Deep-sea environment, at the same, due to the influence of long-term in the ocean environment, the location relationship between each other buoys will change, which may cause the traditional predicted method of buoy system trapped in losing efficacy. This paper researched on the problem of the buoy baseline length vary positioning method applicability, on the basis of this study, focused on the theoretical analysis and simulation of applicability to different positioning method. Following this, a real-time positioning method based on vector buoys system in deep sea is presented. Covered the applicability shortage of traditional underwater acoustic passive positioning, used multiple vector buoys to locate the target jointly, and provide a theory basis for real-time positioning function of vector buoys in engineering. The simulation results show that this method is feasible and effective.

1. Introduction

The occurrence time and moving situation of passive target are unknown information. Usually, the layout of buoys will refer to the positioning method adopted. However, in the long-term underwater environment, the floating of deep mass buoys caused by the influence of current will change the buoy baseline length. Assuming the flow velocity of 3 mile/h, the buoys’ following range will reach nearly 1km in 10 minutes. However, when buoys can acquire high SNR data, the horizontal range between the buoys may be affected by the current, which will produce a large offset compared with the deployment. Therefore, we should fully consider the applicability of the positioning method caused by the change of buoys baseline length, so as to avoid the situation that the buoy floats calculated invalid real-time position data of passive target. Aiming at the problems existing in the positioning of deep-sea buoys, based on the analysis of principle of buoy positioning method, the positioning performance of conventional methods is compared, and the error is analyzed. A-real-time positioning method based on TDOA and bearing-only TMA of deep-sea vector buoy is proposed to realize joint positioning under the condition of random distribution of buoys [1].

The position information of the target includes azimuth and distance. The vibration velocity information of the buoy through the vector channel can measure the angle of the target relative to the X+ axis of the vector coordinate system. Since the buoy system is floating in the marine environment, the measurement angle needs to be corrected by the compass information installed on the buoy itself. The corrected angle is the angle relative to the north direction, that is, the buoy coordinate system is transformed into geodetic coordinate system. The communication system combines with the buoy acquisition and processing module, uses the geodetic coordinates of different buoys to solve the
position relationship between them. Based on the position relationship as the criterion, bearing-only TMA or TDOA method is selected to process the target position information. Finally, the target position relationship is transmitted back in real time through the communication satellites [2][3].

2. Real-time positioning method of random vector buoys in deep sea

The position parameter of the target includes azimuth and distance. The vector buoy can measure the angle of the target relative to X+ axis through the vibration velocity data of the vector channel. Because the buoy is floating in the marine environment, the target angle needs to be corrected by the compass installed on the buoy itself. The correct angle is the angle relative to the north direction, therefore, the vector coordinate system is converted to the geodetic coordinate. The communication system combines with the buoy acquisition and processing system, using the geodetic coordinates of different buoys to calculate the position relationship between buoys, then selecting TDOA or bearing-only TMA method to process the position of target based on the buoys’ position relationship. Finally vector buoy transmits the real-time position of target back through the communication system.

TDOA method uses the time delay difference between the arriving signal of each buoys to calculate the azimuth and distance of target relative to buoys, so the accuracy of delay is the key. Cross-correlation method is a typical time delay estimator. In order to calculate the time delay by cross-correlation method, the spatiotemporal correlation of the channel should be considered first. Taking a point noise source as an example, two receiver hydrophones are placed far away from the sound source, the baseline length between them is \(d\), and the cross-correlation function of two hydrophones signal \(Z_1(t)\) and \(Z_2(t)\)

\[
R_{12}(\tau, d) = \frac{Z_1(t, x)Z_2(t + \tau, x + d)}{Z_1^2(t, x)}
\]  \hspace{1cm} (1)

\(R_{12}(\tau, d)\) is called the spatiotemporal correlation function of point source. The spatial correlation radius is defined as \(d\) when the peak value of normalized correlation \((d = 0)\) decreases to half of the peak value. The baseline length of two vector buoys should be greater than the spatial correlation radius \([4]\). If \(\lambda\) is the wavelength, the spatial correlation radius is about \(300 - 500\lambda\). When \(f = 2\text{kHz}\), the wavelength \(\lambda\) is about 0.75m, and the spatial correlation radius is about 225m - 375m. That is, when the frequency of target continuous spectrum noise is up to 2kHz, the longest baseline length of two buoys should not exceed 375m. With the decrease of the center frequency of the target continuous spectrum noise signal, the spatiotemporal correlation radius also increases.

The deep sea is different from shallow water, because of the serious irregularity of the seabed topography and the influence of internal waves, the spatial correlation radius will be reduced. The time delay calculated by correlation is affected by multipath, which will lead to the increase of positioning error. With the low environment noise and small influence of multipath in deep sea, the positioning error of time delay is reduced by correlation method at the same time.

bearing-only TMA method uses the radiated broadband noise generated by the target navigation to obtain the azimuth parameters of moving target through signal processing, and then to realize the purpose of passive ranging indirectly. The azimuth is obtained by the vibration velocity sensor of the vector hydrophone. The horizontal range between two vector buoys affect the accuracy of bearing-only TMA method.

According to the figure 1, in the underwater environment, the horizontal range between the buoys may be changed by the current, so we should fully consider the applicability of the positioning method, TDOA or bearing-only TMA is selected to locate the target according to the horizontal range between buoys, so as to avoid the situation that the buoy floats causes the invalid real-time passive target positioning.
Figure 1. A scene diagram of real-time positioning of target based on vector buoy in deep sea.

The traditional TDOA passive positioning method adopts three or more linear units, but linear buoy layout model is hard to lay out due to the underwater environment. In view of this, this TDOA method adopts random three vector buoys to locate target passively. Assumed that propagation mode conforms to spherical wave spreading under deep-sea environment, vector buoy 0, 1, 2 and target are in the same plane, vector buoy 0 is the origin of coordinates, the link line of vector buoy 2 and vector buoy 0 is defined as polar axis, Geometric sketch is shown as figure 2. According to geometrical relationship and mathematical derivation, the exact localization formula is obtained as follows [5].

\[
\cos \theta = \frac{(A-B) \times (C+D \cos \alpha) - D \sin \alpha \times \sqrt{E-(A-B)^2}}{E}
\]

Figure 2. The aerial view of sea scene with the baseline length between buoys suitable for TDOA.

When the target is in the region \([\alpha, 180^\circ]\)
When the target is in the region $[180^\circ, \alpha + 360^\circ]$:

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

$$r = \frac{d_1^2d_2 + d_2^2d_1 - c^2(d_2\tau_{01}^2 + d_1\tau_{20}^2)}{2c(d_1\tau_{20} - d_2\tau_{10}) + 2d_1d_2(2\sin \frac{\tau_{01}}{2}\cos(\beta - \alpha) + \sin \alpha \sin(\theta - \alpha))}$$ (3)

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

![Figure 3](image_url)

Figure 3. Aerial view of sea scene with the baseline length between buoys suitable for bearing-only TMA.

bearing-only TMA passive positioning method adopts two units at least, according to the figure 3, 1 and 2 are vector buoys, vector buoy 0, 1, 2 and target are in the same plane, the direction $\beta_1, \beta_2$ of target to 1 and 2 is calculated by the vector azimuth estimation algorithm, the communication working signal is transmitted by the communication module of every vector buoy, after receiving the communication working signal, buoy 1 can calculate the azimuth of 2 relative to 1 and set it as $\gamma$. at the same time, the length of 1 and 2 can be measured by GPS, which is set as $d$. target and two vector buoys are from triangle relationship, and the angles of points 1 and 2 of the triangle are $\alpha_1$ and $\alpha_2$.

$$\alpha_1 = \pi/2 - \beta_1 - \gamma_1$$

$$\alpha_2 = \pi/2 - \beta_2 + \gamma_2$$ (6) (7)

Assuming that coordinate of the target is $(x, y)$ in the two-dimensional rectangular coordinate system, the equations are established through 1T and 2T lines.

$$\tan \alpha_1 = \frac{y}{x}$$

$$\tan(\pi - \alpha_2) = \frac{y}{x - d}$$ (8) (9)

Then
the target position can be figured out.

Using three vector buoys, three positioning results of the target can be obtained. Compared with two vector buoys, the average processing of three results can reduce the positioning error and improve the positioning accuracy [6].

3. Applicability analysis of positioning method

In this section, two kinds of deep-sea buoy positioning method are simulated and analyzed, the TDOA method uses three buoys to locate the target, calculates the target position through the time delay difference between the buoys, and calculates the time delay value of buoys 1 and 0, 2 and 0 by cross-correlation, the simulation results is shown in the figure 4.6.8. The simulation results of TDOA positioning performance are shown in the figure 5.7.9, when the vector buoys baseline length is 80m, 160m and 250m. In bearing-only TMA method, the orientation ability of the vector buoy is used to calculate the target direction, and two vector buoys are combined to calculate the position information of the target. The direction finding error of vector hydrophone based on average sound intensity are shown in figure 10.11. The simulation results of bearing-only TMA positioning performance are shown in the figure 12-15, when the vector buoys baseline length is 80m, 160m, 600m and 500m.

\[
x = \frac{d \cos \alpha_1 \sin \alpha_2}{\sin \theta} \quad (10)
\]
\[
y = \frac{d \sin \alpha_1 \sin \alpha_2}{\sin \theta} \quad (11)
\]

Figure 4. Time delay of a position calculated by cross correlation method, baseline length is 80m(4m+4m).

Figure 5. The TDOA positioning accuracy when the baseline length is 80m(40m+40m).

Figure 6. Time delay of a position calculated by cross correlation method, baseline length is 160m (80m+80m).

Figure 7. The TDOA positioning accuracy when the baseline length is 160m (80m+80m).
Figure 8. Time delay of a position calculated by cross correlation method, baseline length is 250m (125m+125m).

Figure 9. The TDOA positioning accuracy when the baseline length is 250m (125m+125m).

It can be seen from the figure4-9 that time delay between adjacent buoys is obtained by cross correlate, and the target position information is calculated by TDOA method. Within the correlation radius, the positioning accuracy will increase with the increase of baseline length.

Figure 10. Direction finding error of vector hydrophone based on average sound intensity SNR=3dB.

Figure 11. Direction finding error of vector hydrophone based on average sound intensity SNR=-3dB.

It can be seen from the figure10-11 that the direction finding performance of the vector buoy improves with the increase of the SNR. According to the simulation results, when the SNR is greater than 3dB, the direction finding accuracy can meet the requirements of bearing-only TMA method.
Figure 12. The bearing-only TMA positioning accuracy when the baseline length is 80m.

Figure 13. The bearing-only TMA positioning accuracy when the baseline length is 160m.

Figure 14. The bearing-only TMA positioning accuracy when the baseline length is 250m.

Figure 15. The bearing-only TMA positioning accuracy when the baseline length is 500m.

It can be seen from the figure 12-15 that with the increase of baseline length, the positioning performance of the bearing-only TMA method gradually improves. The positioning performance of the two positioning methods under different baseline length conditions is compared, which is summarized in the following table.

Table 1. The positioning performance of bearing-only TMA and TDOA methods under different baseline length conditions.

| Baseline Length | Bearing-only TMA Positioning Error | TDOA Positioning Error | Bearing-only TMA Positioning Error | TDOA Positioning Error |
|-----------------|----------------------------------|------------------------|----------------------------------|------------------------|
| 40m             | 43.67%                           | 63.47%                 | 79.33%                           | 86.75%                 |
| 80m             | 57.23%                           | 78.64%                 | 91.85%                           | 93.92%                 |
| 160m            | 79.26%                           | 91.15%                 | 93.92%                           | 93.92%                 |
| 250m            | 88.87%                           | 94.45%                 | 95.32%                           | 96.09%                 |
| 500m            | 96.19%                           | 98.12%                 |                                  |                        |
| 1000m           | 97.74%                           | 98.83%                 |                                  |                        |
It can be seen from table 1 that the positioning performance of TDOA method is affected by the buoy baseline length. With the baseline length becomes larger, the positioning error accuracy becomes better, when the buoy baseline length reaches 250m, the positioning accuracy of TDOA method is obviously better than that of bearing-only TMA method. However, in the actual underwater environment, the larger buoy baseline length will reduce the signal correlation, at the same time, the time delay accuracy of TDOA method is reduced due to the influence of marine environment noise and multipath. Therefore, bearing-only TMA method can be selected for positioning when buoy baseline length is larger. The positioning performance of bearing-only TMA method is affected by the direction finding accuracy and buoy baseline length. Compared with the figure 12-15 and table 1, bearing-only TMA positioning error accuracy becomes better with the baseline length larger, and the positioning performance reaches to the best when buoy baseline length is 1000m.

4. Conclusion
Based on the theoretical analysis and simulation comparison of TDOA and bearing-only TMA, which are two kinds of buoys positioning method, a joint positioning method for buoy deep-sea positioning is proposed, which makes up for the shortcomings of two methods in the actual underwater environment, makes the buoy positioning performance is not affected by the change of buoy baseline length which caused by the current floating, and enhances the robustness of vector buoys locating method. At the same time, it provides the method basis for the real-time location and location data returning back.

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