

# Three-dimensional positioning based on TOA combining acoustic signal and optical signal

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**Abstract:** In recent decades, the massive depletion of the earth's terrestrial resources has turned people's attention to the ocean, so many underwater technologies have emerged and developed rapidly with the comprehensive progress of human science. Since the TOA positioning algorithm only needs a synchronous time source, the application of the TOA positioning algorithm by the traditional underwater wireless sensor system network is very common. Underwater positioning technology uses underwater sensor network (UWSN) to locate unknown nodes, which can be divided into underwater acoustic communication positioning and water optical communication positioning according to different transmission channels. The characteristics of underwater acoustic communication and water optical communication determine that the former has better accuracy in long-distance transmission, and the latter has better accuracy in short-range positioning. In this paper, the weight coefficients of sound and light are set separately to obtain the distance cut-off values of sound and light channels. The distance demarcation value can be changed according to the actual environment and needs. We will set the threshold of the impact factor of the underwater environment to ensure that the accuracy error caused by environmental losses is minimized. The reasonable arrangement of UWSN's anchor nodes will maximize energy savings. Simulation results show that the proposed method makes reasonable use of the advantages of acoustic signal and optical signal, and obtains more accurate positioning results after setting the threshold.

**Keywords:** UWSN; TOA; LOS; Acoustic signal; Optical signal; Anchor node arrangement.

## 1. Introduction

Underwater wireless localization has been drawing much attention for many years because of the security of ocean environment and the popularity of wireless smart sensor networks (WSSN). Due to the localization accuracy plays a key role in underwater wireless localization, so many practical localization methods was put forward, such as Time of Arrival (TOA), Time Difference of Arrival (TDOA), Received Signal Strength (RSS), Angle of Arrival (AOA), and hybrid localization.

In an outdoor environment, the unknown node (UN) can be located with highly accuracy from the Global Positioning System (GPS), or from BeiDou Navigation Satellite System. In the underwater environment, GPS cannot be applied to these land-based devices due to the shadow effect of water. Therefore, underwater wireless sensor networks can be well used for locating unknown nodes.

The specific positioning method needs to be based on the hardware facilities and positioning environment of the wireless sensor network, for example, using the angle of arrival AOA method, the node needs to be equipped with a special antenna array; The arrival time TOA or arrival time difference TDOA method only requires the node to be equipped with a clock system with a certain accuracy. This will help improve the positioning accuracy of unknown nodes. In this paper, we will study the underwater positioning of TOA, and the main innovations are as follows:

1) Set a threshold for the dynamic factors of the underwater environment, the anchor node is detected, and when the environmental impact factor is greater than this threshold, the positioning process is not carried out.

2) Take advantage of the advantages and disadvantages of acoustic signals and optical signals, complement them, and obtain higher accuracy beyond this distance value.

3) According to the nature of underwater influencing factors, reasonably set the position of the anchor node.

## 2. Problem overview

In this section, we propose a problem to improve the positioning accuracy of the TOA positioning algorithm combining acoustic and optical signals in underwater wireless sensor networks, and to rationally arrange nodes in the underwater environment where LOS dynamically changes. Given that existing wireless sensor network (WSN) localization methods will be based on the TOA method, the following discussion will first focus on TOA optimization, and then will discuss localization in LOS environments.

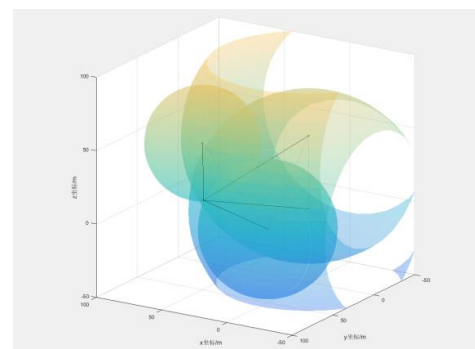


Fig.1 Schematic diagram of spatial positioning

First, given four non-coplanar anchor nodes in three-dimensional space, an unknown node to be located. Use a matrix to calculate the coordinates of unknown nodes.

Supposing that four points A, B, C and D are known in the space, and their coordinates are  $(X_1, Y_1, Z_1)$ ,  $(X_2, Y_2, Z_2)$ ,  $(X_3, Y_3, Z_3)$ ,  $(X_4, Y_4, Z_4)$ . The coordinates of unknown node P are:  $(X, Y, Z)$ , and the distances from P to the four points are  $d_1, d_2, d_3, d_4$ , as shown in figure 1. According to the distance

formula, the following equations can be obtained:

$$\begin{cases} (X1 - X)2 + (Y1 - Y)2 + (Z1 - Z)2 = d12 \\ (X2 - X)2 + (Y2 - Y)2 + (Z2 - Z)2 = d22 \\ (X3 - X)2 + (Y3 - Y)2 + (Z3 - Z)2 = d32 \\ (X4 - X)2 + (Y4 - Y)2 + (Z4 - Z)2 = d42 \end{cases} \quad (1)$$

Arranging (1) and can get:

$$\begin{cases} X2 - 2X1 * X + Y2 - 2Y1 * Y + Z2 - 2Z1 * Z = d12 - X12 - Y12 - Z12 \\ X2 - 2X2 * X + Y2 - 2Y2 * Y + Z2 - 2Z2 * Z = d22 - X22 - Y22 - Z22 \\ X2 - 2X3 * X + Y2 - 2Y3 * Y + Z2 - 2Z3 * Z = d32 - X32 - Y32 - Z32 \\ X2 - 2X4 * X + Y2 - 2Y4 * Y + Z2 - 2Z4 * Z = d42 - X42 - Y42 - Z42 \end{cases} \quad (2)$$

The third-order difference of the equation is used to eliminate the higher-order term to obtain the following first-order equation:

$$\begin{cases} 2X(X2 - X1) + 2Y(Y2 - Y1) + 2Z(Z2 - Z1) = d12 - d22 + X22 - X12 + Y22 - Y12 + Z22 - Z12 \\ 2X(X3 - X1) + 2Y(Y3 - Y1) + 2Z(Z3 - Z1) = d12 - d32 + X32 - X12 + Y32 - Y12 + Z32 - Z12 \\ 2X(X4 - X1) + 2Y(Y4 - Y1) + 2Z(Z4 - Z1) = d12 - d42 + X42 - X12 + Y42 - Y12 + Z42 - Z12 \end{cases} \quad (3)$$

The equation is expressed in matrix form: AC=B

$$A = \begin{bmatrix} 2(X2 - X1) & 2(Y2 - Y1) & 2(Z2 - Z1) \\ 2(X3 - X1) & 2(Y3 - Y1) & 2(Z3 - Z1) \\ 2(X4 - X1) & 2(Y4 - Y1) & 2(Z4 - Z1) \end{bmatrix} \quad (4)$$

$$C = \begin{matrix} X \\ Y \\ Z \end{matrix} \quad (5)$$

$$B = \begin{matrix} d12 - d22 + X22 - X12 + Y22 - Y12 + Z22 - Z12 \\ d12 - d32 + X32 - X12 + Y32 - Y12 + Z32 - Z12 \\ d12 - d42 + X42 - X12 + Y42 - Y12 + Z42 - Z12 \end{matrix} \quad (6)$$

The equation can be written as:

$$C = A^{-1}B \quad (7)$$

### 3. TOA Based Distance Measurements

TOA(time-of-arrival) positioning is a distance-based positioning method, which can be used to locate unknown nodes by multiplying the arrival time of the signal by the propagation speed to obtain the distance. Without considering the error, only four non-coplanar anchor nodes are needed in the three-dimensional space to calculate the target position.

Without losing generality, it is assumed that the start time of each source ranging is 0, and the time signal from the *i*th anchor node is received at time *t<sub>i</sub>*, which means that *t<sub>i</sub>* is a TOA measurement. The relationship between distance and time is as follows:-

$$d_i = t_i * c, i=1,2,3,\dots,n \quad (8)$$

Where *t<sub>i</sub>* is the time of the signal from the anchor node to the UN, *d<sub>i</sub>* is the calculated distance from the UN to the *i*th anchor node, *c* is the speed of the signal under water. The calculation process of UN coordinates is shown in step A.

## 4. Acoustic And Optical Hybrid Based Distance Measurements

### 4.1. Acoustic

We set the received signal of the underwater acoustic channel as:

$$x_{ri}(t) = A \sin(2\pi f A c t + \phi_i + \phi_{wi} + \phi_0) + w_i(t) \quad (9)$$

Where *i* represents four non coplanar anchor nodes that have been successfully positioned, *A* represents the amplitude of the received signal,  $\phi_i$  represents the phase shift due to interference noise,  $\phi_{wi}$  represents the phase uncertainty, and  $w_i(t)$  is a Gaussian zero mean random noise.

The attenuation of underwater acoustic signal strength is related to various factors, which will affect the amplitude and

frequency of the acoustic signal. The acoustic signal strength is written as:

$$10 \log_{10} \left( \frac{A_0}{A} \right)^2 = k \cdot 10 \log_{10} d + d \cdot 10 \log_{10} \alpha \quad (10)$$

Where *k* represents the geometric diffusion factor, which is usually between 1 and 2, *d* represents the distance between the anchor node and the UN,  $\alpha$  represents the underwater acoustic absorption coefficient, and the value of  $\alpha$  is usually calculated by Thorp's formula, :

$$10 \log_{10} \alpha = \frac{0.1 f A c^2}{1 + f A c^2} + \frac{40 f A c^2}{4100 + f A c^2} + 2.75 \times 10^{-4} \times f A c^2 + 0.003 \quad (11)$$

### 4.2. Optical

Underwater optical communication systems employ directly detectable intensity modulation (IM/DD), which uses an ON-OFF keying (OOK) in the physical layer. The initial simulations will be done in the LOS environment, which will save us from having to talk about light in the presence of obstacles. The radiant intensity of light underwater can be expressed as,:

$$I_s(d, \varphi) = P \frac{m+1}{2\pi d^2} \cos m \varphi \quad (12)$$

Where *d* is the angle between the optical path direction of the anchor node and the vertical direction, *d* is the distance between the anchor node and the UN, *m* is the Lambert's modulus of the beam effect of the anchor node, *p* is the average optical power, where *m* is expressed as,:

$$m = \frac{-\ln 2}{\ln(\cos \varphi / 2)} \quad (13)$$

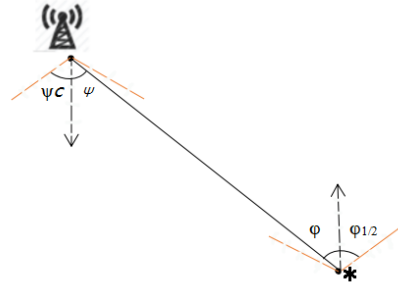


Fig.2 Main parameters of the optical link model

Let *A<sub>eff</sub>* be the effective area of the UN receiving the incident light radiation, and which is expressed as:

$$A_{eff}(\psi) = f(\psi) A_r \cos \psi, |\psi| \leq \psi_c \quad (14)$$

where *A<sub>r</sub>* is the UN area,  $\psi$  is the incident angle and *f*( $\psi$ ) is the light concentrator gain given by:

$$f(\psi) = \begin{cases} \frac{n^2}{\sin^2 \psi_c}, & \text{if } |\psi| \leq \psi_c \\ 0, & \text{if } |\psi| > \psi_c \end{cases} \quad (15)$$

Where  $\psi_c$  is the half-angle Field of View (FOV) of the optical detector, and *n* is the refractive index of the seawater.

Since the attenuation of light underwater is mainly absorption, in order to accurately determine the position of the UN, we set the absorption coefficient as:

$$Lch = \exp(-Kad) \quad (16)$$

where *K<sub>a</sub>* is the diffuse attenuation coefficient.

Using (15), (17), and (19), the received optical signal strength in dB at the UN side can be calculated as:

$$POW = 10 \log_{10}(I_s A_{eff} Lch) + \xi \quad (17)$$

Where  $\xi$  is the average value of noise (in dB) generated by natural light underwater.

### 5. Improvement of toa

In underwater UN positioning, acoustic positioning is often used due to the limitations of the scale of the simulated

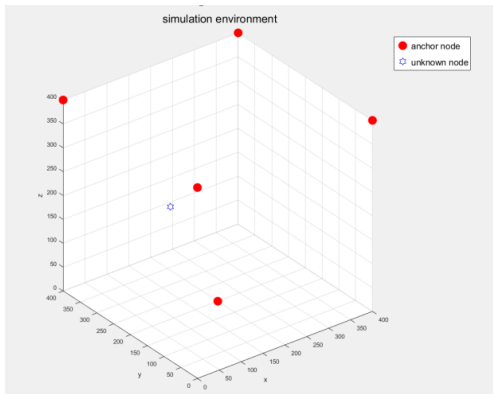
environment and energy saving. However, considering the advantages of underwater optical communication such as high speed, high bandwidth, and high security, its advantages in short-range communication are very significant. Therefore, considering the underwater situation of sound and light, we evaluate the advantages of sound and light in distance  $d$ , that is, when the positioning distance  $d$  is greater than  $d_d$ , the redundant sound part  $d - d_d$  uses acoustic communication data, and the range from 0 to  $d_d$  uses optical communication data, and combined with sound and light to locate unknown nodes. In the following simulation, we will carry out the process of obtaining  $d_d$  by this method several times, and extend the data to the general case, that is, save the  $d_d$  data obtained by each anchor node using optical communication, which greatly saves energy consumption.

**Table 1.** Hybrid Acoustic/Optical Algorithm

1: Locate an UN and use optical communication first
2: <b>If</b> localization distance $d \leq d_d$
3: Notify that the acoustic communication does not need positioning, obtain the optical communication distance $d$ , and the positioning of the anchor node is completed
4: <b>end if</b>
5: <b>If</b> $d > d_d$
6: Notification acoustic communication positioning, then $d = d_d + d_{acoustic}$ ;
7: <b>end if</b>

## 6. Simulation

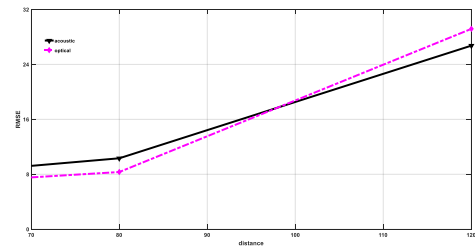
In this section, we will simulate the underwater positioning algorithm on the Matlab platform and simulate the localization problem of the TOA algorithm in the underwater LOS environment, as shown in Figure 3:



**Fig.3** LOS simulation environment

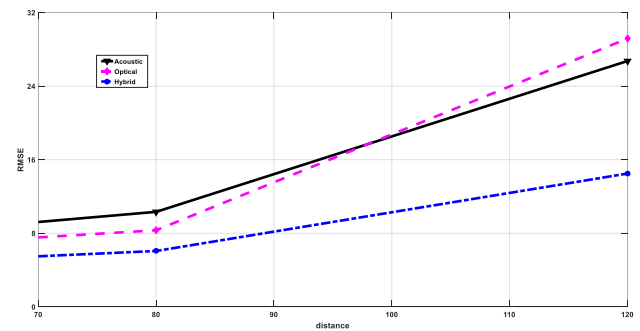
Figure 3 shows the anchor node arrangement in an underwater LOS environment. Place four anchor nodes at the four corners of the water surface in three-dimensional space, and one anchor node in the center of the bottom. Such a sensor network system arrangement will effectively overcome the characteristics of underwater environment loss, that is, the underwater environment due to salinity, temperature and other factors, the deeper the loss of the signal, the greater the loss. Therefore, such an anchor node arrangement will also be a major innovation in this paper.

First, we will simulate the distance critical values of acoustic and optical signals during positioning, and the simulation results are shown in Figure 4:



**Fig.4** Determination of acousto-optic distance

We believe that the opposite properties of underwater sound and light will create a distance equilibrium point. We believe that the cost and benefit of acousto-optic positioning are almost the same in the distance balance point after the judgment is completed, and this balance point will also be regarded as the critical point of acousto-optic combination. As can be seen in the simulation results shown in Figure 4, the simulation result obtained is 98m, and this distance value can be changed according to the actual environmental requirements. Taking advantage of the combination of acoustic signal and optical signal, the positioning simulation of TOA algorithm is carried out, and the results are shown in Figure 5:



**Fig.5** Hybrid acoustic/optical localization

It can be seen from Figure 5 that the positioning accuracy of the TOA positioning algorithm after the combined acousto-optic signal is higher than that of a single communication channel after the obtained distance value.

## 7. Conclusion

Underwater wireless sensor network positioning system using TOA positioning algorithm mostly uses acoustic signals for signal transmission, and acoustic and optical signals have their own disadvantages, so the advantages and disadvantages of the two complement each other, and better positioning accuracy can be obtained than a single signal. At the same time, in the setting of the underwater environment, this paper also considers the influence factor of the underwater environment, that is, if the impact factor is too large, the signal loss is large, which will seriously affect the positioning accuracy, and such influence parameters need to be monitored. We have made reasonable settings for the positioning system in three-dimensional space, which greatly reduces the use of anchor nodes and energy consumption. Simulation proves that the proposed algorithm has good positioning accuracy. In the future, we will consider anchor node placement and simulation in the NLOS environment.

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