



An Improved TDoA Localization Algorithm Based on AUV for Underwater Acoustic Sensor Networks

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Abstract. Now localization is one of the major issues in underwater environment work. In terrestrial application, time different of arrival (TDoA) localization algorithm has been widely used. However, most localization systems rely on radio or optical signals while they cannot propagate well in water. Therefore, with complicated environment in underwater acoustic sensor networks (UASNs), traditional TDoA localization algorithm suffers various unstable factors, such as they can only work in a finite region or need clock synchronization. In this paper, we propose an improved TDoA localization algorithm (ITLA) based on AUV for UASNs. The mobile AUV first finds its own accurate three-dimensional coordinates in the surface with the help of GPS or other terrestrial location systems. Then we deployed AUV at predefined depth in underwater as reference nodes. AUV periodically sends packets with coordinates information to unlocalized nodes in different positions. After receiving data and a series of calculation, we quantify the conditions for unique localization and propose another condition to evaluate the reliability of results. This algorithm can achieve relatively higher accuracy with relatively smaller calculation and overcome some traditional localization drawbacks. We demonstrate the trade-offs between location coverage, the cost in placing reference nodes, and energy consumption.

Keywords: Underwater acoustic sensor networks (UASNs) ·
Time different of arrival (TDoA) · Autonomous underwater vehicles (AUVs) ·
AUV-aided localization

1 Introduction

Over the years, we have observed underwater wireless sensor networks are getting more attention [1]. They have been widely used in both military and civilian applications such as natural disaster warning system, oceanic navigate assistance, and biological environment monitoring, etc. To achieve these goals in complicated environment in underwater, the common method is to deploy some ordinary sensor nodes in networks.

For traditional devices, they collect data from their surroundings and need exchange information with the vessel on surface. However, these devices can be replaced by sensor nodes with relatively small in shape and less expensive in cost.

In underwater, sensor nodes continuously collect data, sense the environment and transmit to surface vessel or onshore stations. However, the traditional propagation medium such as radio and optical signals attenuate rapidly and scatter due to adverse environment in underwater [2]. Consequently, acoustic signals have been widely used in recent years as they attenuate less and travel far.

In reality, once sensor nodes have been deployed, recycling work will become very difficult. The position of sensor nodes will be greatly affected by the currents of water and the accurate position of sensor nodes will randomly change. Therefore, localization scheme now has been considered as a crucial mission in network composition, marking the collected messages, detecting the position of target and network routing protocol [3]. Range measurements in localization can be based on time of arrival (ToA) [4], time different of arrival (TDoA) [5], received signal strength (RSS) [6, 7], and direction of arrival (DoA) [8]. Most sensor nodes are equipped with pressure sensors to measure their depth. Hence, the coordinates of sensor nodes can be simplified into x-y coordinates.

The development of AUVs began to attract interest in the use of AUVs in localization [9]. AUVs are now being used in various tasks. The mobility of AUVs makes it possible to locate the position of sensor nodes in large scale. But some AUV-aided location methods also suffer time delay problem.

The structure of the paper is as follows: Sect. 2 introduces several related UASN localization techniques. Section 3 describes the improved localization algorithm based on the methods mentioned above in Sect. 2. We compare the ordinary localization algorithm in several aspects and the effects if we take AUVs to replace traditional anchor nodes in Sect. 4. Finally, we draw some conclusions and present the future research in Sect. 5.

2 Related Work

A lot of researches have been updated in localization algorithms in the past few years [1]. Many localization algorithms have been proposed to solve the unique situation of underwater acoustic environment for UASNs. In this section, we briefly provide a review of localization techniques that proposed in UASNs.

A silent positioning range-based system named Underwater Positioning System (UPS) has been proposed for UASNs in [10, 11] as is shown in Fig. 1. It is a basic

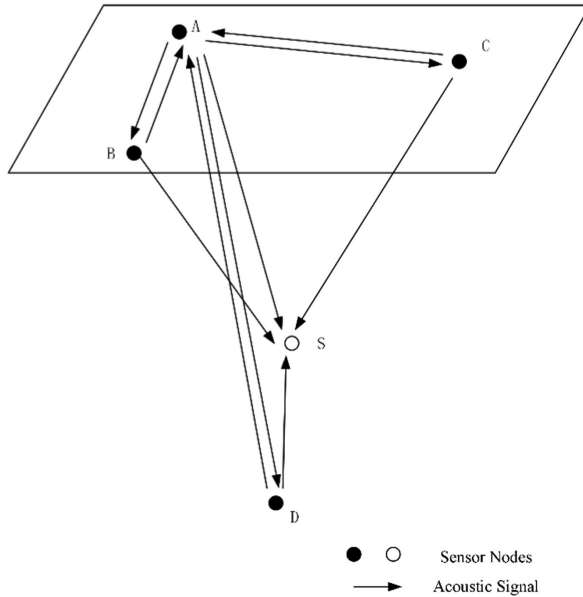


Fig. 1. Underwater Positioning System (UPS)

TDoA range-based measurement algorithm. By exchanging beaconing signals with reference nodes deployed on seabed, UPS estimates the location of a sensor node before localization schemes begin or surface buoys with GPS. However, using the method mentioned above, three-dimensional space will need at least four reference nodes and two-dimensional space will need at least three reference nodes to locate. It assumes the reference nodes cover the entire UASN area, therefore constrain the coverage area of interest. And the sensor nodes in underwater are moving freely with currents. Another drawback is the successful localization highly depends on the successful communication among fixed nodes. Time-delay is also a major issue to discuss.

To overcome the drawbacks mentioned above, like the limit of location area, in [12], the authors present more sensor nodes in localization schemes named Wide Coverage Positioning System (WPS). Four sensor nodes will be needed whenever four nodes attain unique localization, else five nodes will be needed in [13] (see in Fig. 2). But the cost of deploying sensor nodes in underwater is still too expensive. And the schemes still suffer time-delay error because of transmission error.

Hence at the first time, people prompted a method that using AUVs to replace traditional fixed sensor nodes in [14, 15]. This is an algorithm for a hybrid, three-dimensional UASN where AUVs moving in the same region with anchor nodes fixed nearby. AUVs will periodically send wake up messages to anchor nodes and calculate the range by receive response packets. The main drawback is that two-way ranging requires high synchronization which is hard to achieve in underwater environment. And too many AUVs also lead to high system cost [16].

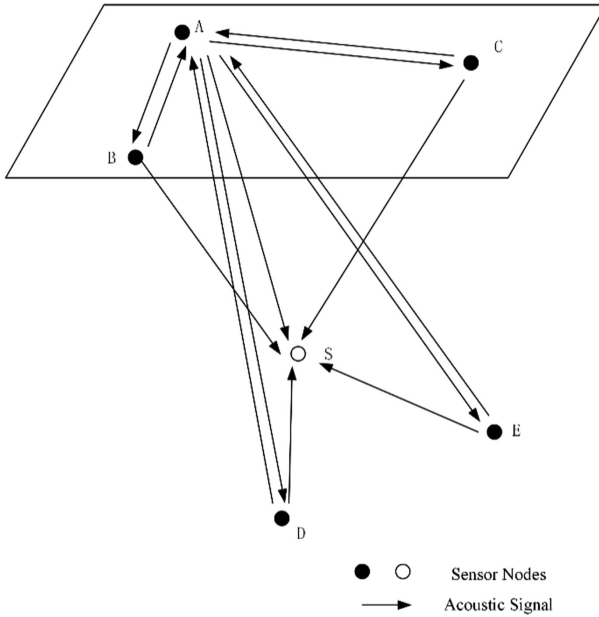


Fig. 2. Wide Coverage Positioning System (WPS)

3 An Improved TDoA Localization Algorithm

3.1 Main Innovations

Compared with classical TDOA algorithm, ITLA use AUVs as reference nodes which means a single AUV is used instead of too many anchor nodes in positioning scheme. This change solves the problems of high network cost and complexity of deployment. Besides, we add a result correction process in algorithm which improved the accuracy and at the same time, decreased the cost of deploying more sensor nodes. The movement of AUV also extend the location area.

3.2 Background and Assumptions

We assume a three-dimensional underwater sensor networks area. There are randomly deployed ordinary sensor nodes that without their positions only to sense the network. These sensor nodes are all capable to determine their depth and their transceivers can cover the entire interest space. AUVs are deployed from the surface and get their coordinates by GPS. We assume that AUVs periodically accelerate to predefined positions and send wake up messages to anchor node. There are at least four non-coplanar positions we predefined and no three of them are collinear. We propose an efficient localization algorithm by using mobile AUVs. To simplify the localization process, we present only one AUV to locate one anchor nodes that can extend to locate more anchor nodes with more AUVs. Network architecture we proposed is presented (see in Fig. 3).

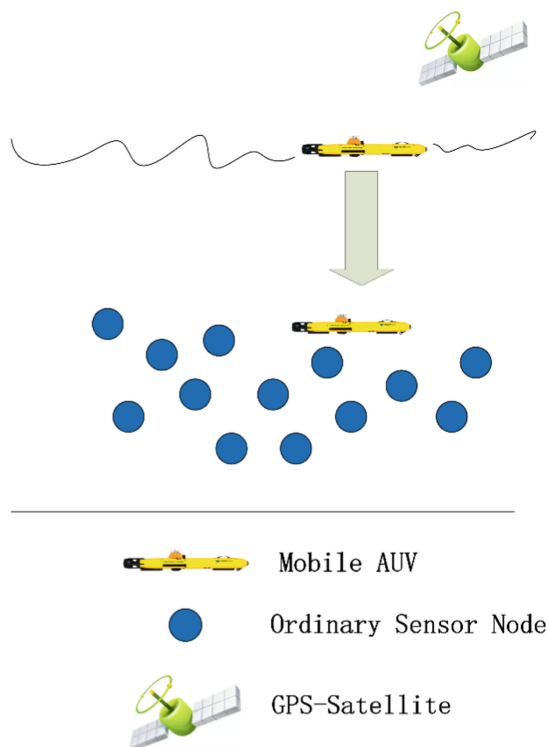


Fig. 3. Network architecture

Besides, the coordinates of AUV is got by GPS, the GPS positioning error may influence the accuracy of node location. But in our algorithm, to introduce ITLA better and clearly, we assume the errors in GPS positioning can be temporarily ignored.

3.3 Implementation

We assume every ordinary sensor node communicate with AUV and each other by acoustic waves. The mobile AUVs form a channel with GPS satellite via radio waves and use acoustic waves to communicate with underwater ordinary nodes. AUV will move to different position and send messages to anchor nodes.

3.4 Algorithm Operations

There are two main phases in our algorithm.

1. Localization message broadcasting and receiving
2. Location computation and results correction.

In the first phase, AUV dives into predefined depth and sends requesting message to anchor node S . If S receive the wake-up message, it will answer and send an answer

packet to AUV. AUV moves to next position during this packet transmitting. By analogy, the AUV moves to the next two positions and continues to send packets to *S*.

In the second phase, when *S* receives all the information sent by the AUV from various positions, it begins to calculate its own position. But the location of *S* might not be uniquely localized. Hence, we let *S* send a new request to allow AUV move to another new position. Then we continue to start the positioning process.

We assume the first location of AUV is $A(x_1, y_1, z_1)$. We have other positions of AUV can be expressed as $B(x_2, y_2, z_2)$, $C(x_3, y_3, z_3)$, $D(x_4, y_4, z_4)$. Let d_{ab} be the distance between *a* and *b*, where $a, b \in (1, 2, 3, 4, s)$.

We have

$$d_{s1} = \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} \tag{1}$$

The mathematical model we established is shown in Fig. 4.

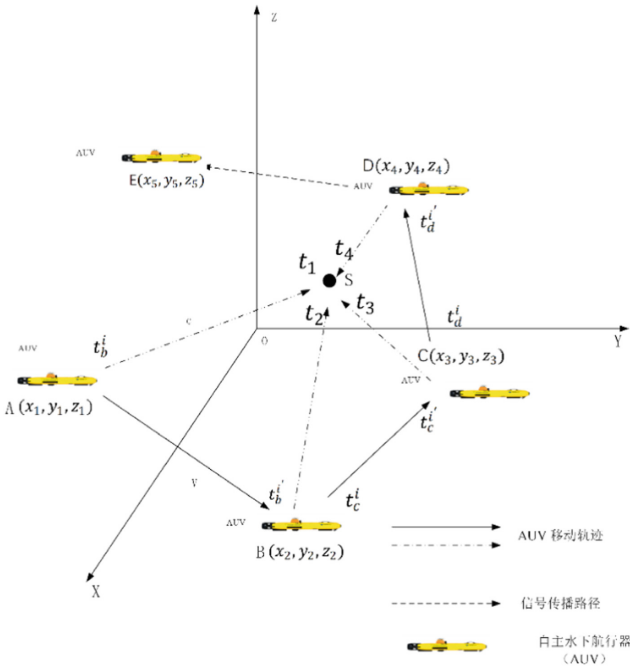


Fig. 4. Mathematical model

AUV sends wake-up messages to sensor node *S* from position *A* and initiates a localization cycle every *T* seconds. Each cycle begins when AUV transmits a signal from position *A*. *S* receives packets sent by AUV from position *A* in t_1^i .

We assume in t_b^i , AUV begins to move from position A to B and sends wake-up messages. The time of arrival at position B is t_b^i . We have the time difference of AUV arrival Δt_b^i is

$$\Delta t_b^i = t_b^i - t_b^i \tag{2}$$

We can get the velocity of AUV from the accelerometer, and assume v is the velocity and distance between A and B is:

$$d_{12} = \Delta t_b^i \times v \tag{3}$$

In the meantime, S receives packets sent by AUV from position B in t_2^i .

By analogy, AUV successively begins to move to next two positions $C(x_3, y_3, z_3)$, $D(x_4, y_4, z_4)$ at t_c^i, t_d^i and arrive at t_c^i, t_d^i . The same as mentioned above, we can get Δt_c^i and Δt_d^i .

During its moving, AUV continues to send packets to the $S(x, y, z)$ at these two positions. Then we can conclude that S receives packets at $t_j^i, i, j \in \{1, 2, 3, 4\}$, respectively. And clearly, based on triangle inequality,

$$t_1^i < t_2^i < t_3^i < t_4^i \tag{4}$$

We assume

$$\Delta t_1^i = t_2^i - t_1^i \tag{5}$$

$$\Delta t_2^i = t_3^i - t_1^i \tag{6}$$

$$\Delta t_3^i = t_4^i - t_1^i \tag{7}$$

Since the speed of ultrasound is c , we obtain

$$d_{12} + d_{s2} - d_{s1} + v \times \Delta t_b^i = c \times \Delta t_1^i \tag{8}$$

$$d_{13} + d_{s3} - d_{s1} + v \times \Delta t_c^i = c \times \Delta t_2^i \tag{9}$$

$$d_{14} + d_{s4} - d_{s1} + v \times \Delta t_d^i = c \times \Delta t_3^i \tag{10}$$

Which gives us

$$d_{s2} = d_{s1} + c \times \Delta t_1^i - d_{12} - d_{12} = d_{s1} + \emptyset_1^i \tag{11}$$

$$d_{s3} = d_{s1} + c \times \Delta t_2^i - d_{13} - d_{23} = d_{s1} + \emptyset_2^i \tag{12}$$

$$d_{s4} = d_{s1} + c \times \Delta t_3^i - d_{14} - d_{34} = d_{s1} + \emptyset_3^i \tag{13}$$

Where $d_{12}, d_{13}, d_{23}, d_{14},$ and $d_{34},$ are positive real numbers; and averaging $\emptyset_1^i, \emptyset_2^i$ and \emptyset_3^i over I intervals gives

$$\emptyset_1^i = \frac{c}{I} \times \sum_{i=1}^I \Delta t_1^i - 2d_{12} \tag{14}$$

$$\emptyset_2^i = \frac{c}{I} \times \sum_{i=1}^I \Delta t_2^i - (d_{13} + d_{23}) \tag{15}$$

$$\emptyset_3^i = \frac{c}{I} \times \sum_{i=1}^I \Delta t_3^i - (d_{34} + d_{14}) \tag{16}$$

In the next step, the algorithm applies trilateration with $\emptyset_1, \emptyset_2,$ and \emptyset_3 to calculate coordinates of S.

From (11)–(13) and (14)–(16), based on trilateration, we obtain four equations with four unknowns $x, y, z,$ and $d_{s1},$ where $d_{s1} > 0,$ like

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = d_{s1}^2 \tag{17}$$

$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = (d_{s1} + \emptyset_1)^2 \tag{18}$$

$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = (d_{s1} + \emptyset_2)^2 \tag{19}$$

$$(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2 = (d_{s1} + \emptyset_3)^2 \tag{20}$$

Solving these four equations, we have

$$d_{s1}^{(1)} = \frac{-B - \sqrt{B^2 - 4AC}}{2A} \tag{21}$$

$$d_{s1}^{(2)} = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \tag{22}$$

$$x = A_x d_{s1} + B_x \tag{23}$$

$$y = A_y d_{s1} + B_y \tag{24}$$

$$z = A_z d_{s1} + B_z \tag{25}$$

where

$$A = A_x^2 + A_y^2 + A_z^2 - 1 \tag{26}$$

$$B = 2(A_x B_x + A_y B_y + A_z B_z) \tag{27}$$

$$C = B_x^2 + B_y^2 + B_z^2 \tag{28}$$

$$A_x = -\frac{\emptyset_1}{x_2} \quad (29)$$

$$B_x = \frac{x_2^2 - \emptyset_1^2}{2x_2} \quad (30)$$

$$A_y = \frac{\emptyset_1 x_3}{x_2 y_3} - \frac{\emptyset_2}{y_3} \quad (31)$$

$$B_y = \frac{x_3^2 + y_3^2 - x_2 x_3 + \frac{x_3 \emptyset_1^2}{x_2} - \emptyset_2^2}{2y_3} \quad (32)$$

$$A_z = \frac{\emptyset_1 x_4}{x_2 z_4} - \frac{\emptyset_3}{z_4} - \frac{y_4 (\frac{\emptyset_1 x_3}{x_2} - \emptyset_2)}{y_3 z_4} \quad (33)$$

$$B_z = \frac{x_4^2 + y_4^2 + z_4^2 - x_2 x_4 + \frac{x_4 \emptyset_1^2}{x_2} - \emptyset_3^2 - \frac{y_4 x_3^2}{y_3}}{2z_4} + \frac{-y_3 y_4 + \frac{x_2 x_3 y_4}{y_3} - \frac{\emptyset_1^2 x_3 y_4}{x_2 y_3} + \frac{\emptyset_2^2 y_4}{y_3}}{2z_4} \quad (34)$$

The result is interesting that only when S is not close to or behind any position of AUV sending messages, (21) presents a unique feasible solution. Therefore, we add a result correction in the last step.

3.5 Result Correction

If we now substituting for x , y , z into (2), d_{s1} has to satisfy the following condition:

$$d_{s1}^2 A + 2Bd_{s1} + C = 0 \quad (35)$$

According to (26), we assume

$$\lambda_A - 1 = A_x^2 + A_y^2 + A_z^2 - 1 = A \quad (36)$$

The uniqueness of d_{s1} depends on the value of λ_A , as follows:

$$d_{s1}^{(1)} = d_{s1}^{(2)}, \lambda_A = 1; \quad (37)$$

$$d_{s1}^{(1)} \cdot d_{s1}^{(2)} < 0, \lambda_A < 1; \quad (38)$$

$$d_{s1}^{(1)} \cdot d_{s1}^{(2)} > 0, \lambda_A > 1; \quad (39)$$

If $\lambda_A > 1$, then there will be two solutions and we cannot uniquely localize the position of S. Then we ask AUV to move to position D(x_5, y_5, z_5).

We can get:

$$d_{s1}^2 A + 2(\lambda_{AB} - \emptyset_4) d_{s1} + \lambda_{BB} - \emptyset_4^2 = 0 \tag{40}$$

Where $B_{nn} = B_n - n_5, n \in \{x, y, z\}$, and

$$\lambda_{BB} = B_{xx}^2 + B_{yy}^2 + B_{zz}^2 \tag{41}$$

$$\lambda_{AB} = A_x B_{xx} + A_y B_{yy} + A_z B_{zz} \tag{42}$$

(35) and (40) have the same solutions under the following conditions:

$$\lambda_{AB} - \emptyset_4 = A_x B_x + A_y B_y + A_z B_z \tag{43}$$

$$\lambda_{BB} - \emptyset_4^2 = B_x^2 + B_y^2 + B_z^2 \tag{44}$$

These conditions can be transformed as follows:

$$A_x x_5 + A_y y_5 + A_z z_5 = \emptyset_4 \tag{45}$$

$$B_x x_5 + B_y y_5 + B_z z_5 = \frac{x_5^2 + y_5^2 + z_5^2 - \emptyset_4^2}{2} \tag{46}$$

We assume $\lambda_A > 1$, then S will be unique localization by adding position E and satisfy conditions in (46); else, the value of d_{s1} is determined by the solution of the following equation:

$$2d_{s1}(A_x^2 + A_y^2 + A_z^2 - 1 + \emptyset_4) + (d_{15}^2 - 2B_x x_5 - 2B_y y_5 - 2B_z z_5) + \emptyset_4^2 = 0 \tag{47}$$

Where d_{15}^2 can be measured by AUV. Then S can be uniquely localized. Pseudocode is shown below.

<pre> Improved TDoA Localization Algorithm: Pseudocode for S procedure ITLA 1: t=0 2: position = A 3: pkts = 0 4: Position of S = 0 5: Start localization beaconing sequence 6: while Position of S == 0 do 7: if (receive new beacon) then 8: pkts += 1 9: end if 10: if (pkts == 4 & $\lambda_a \leq 1$) (pkts == 5 & condition(46)= FALSE) then 11: Position of S =1 12: end if 13: end while end procedure </pre>
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4 Experiments and Discussions

4.1 Performance Metrics

In this section, we discuss the performance of ITLA and traditional TDoA localization algorithm like UPS and WPS in terms of localization time, localization error, and localization coverage. The complete positioning flow chart is shown in Fig. 5.

Besides, in many practical situations, the Doppler effect is also an important aspect to consider. When acoustic waves travel in shallow water, there are many factors that cause Doppler shifts, but there are two main factors:

The relative motions between signal reception and emission position cause a Doppler effect. We assume the frequency of a single acoustic signal is f_s , the moving speed of the transmitter is \bar{v}_s , and the moving speed of the receiver is \bar{v}_r , the frequency change of the received signal is expressed as follows:

$$f_r = f_s \cdot (c - \bar{v}_r) / (c - \bar{v}_s) \quad (48)$$

We assume the direction from transmitter to the receiver is the forward direction. \bar{v}_s and \bar{v}_r are vectors of unit m/s. The unit of f_s and f_r is Hz. c is the speed in water which could be considered as 1500 m/s.

When there is no relative motion between the receiver and the transmitter, the movement of the transmission medium will also cause Doppler effects such as waves and turbulence. These two factors are the main cause of the Doppler effect, which are closely related to the wind speed in surface. If the water wave is in the form of a sinusoid, the acoustic wave will be modulated by the forward scattering of the water wave during the propagation process, and the frequency of the acoustic wave received by the receiver will change. The Doppler effect caused by the waves can be given by the Carson rule.

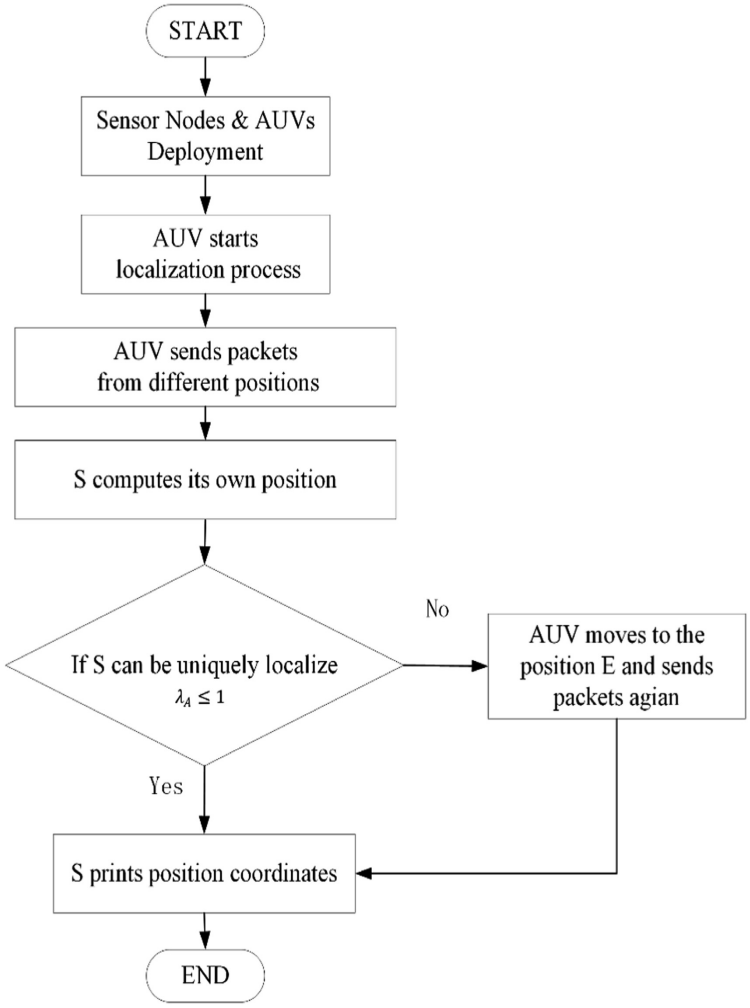


Fig. 5. Flow chart of complete localization process

$$f_d = 2f_w(1 + 2w \cos \theta_0 h_w / c) \tag{49}$$

Where f_w is the frequency of water wave, h_w is the mean square value of wave height, w is the wind speed (m/s), θ_0 is the nominal incident angle in the receiving end.

Certainly, the accuracy is affected by the Doppler effect caused by the motion of the transmission medium. Therefore, to improve the positioning accuracy, we need to do some frequency compensation, but the amount of compensation can be determined in advance, so in this paper, we temporarily ignore the Doppler shift caused by the motion of the transmission medium.

4.2 Simulation Environment and Discussion

We assume the mobility of AUV parameter varying from 2.0 m/s (≈ 3.887688 kn) to 5.0 m/s (≈ 9.71922 kn). The entire underwater area is 1000 m * 1000 m * 100 m water volume and filled with randomly deployed sensor nodes vary from 0 to 200. We use only one AUV to localize all sensor nodes.

The experiment results of different localization time are represented in Fig. 6. Due to the use of AUVs, the traditional localization algorithm cost much more time than ITLA. The extra time is mostly spent in the positioning process between different nodes. While AUV is used, the velocity of AUV movement in underwater also influences the speed of localization time. If AUV moves as fast as possible, then a positioning cycle ends sooner. AUV in 2.0 m/s cost nearly more 5 s than in 5.0 m/s in our simulation, but still better than UPS and WPS which the latter two spend more than 30 s in total. Besides, with more sensor nodes needs to be localized, the gap becomes bigger.

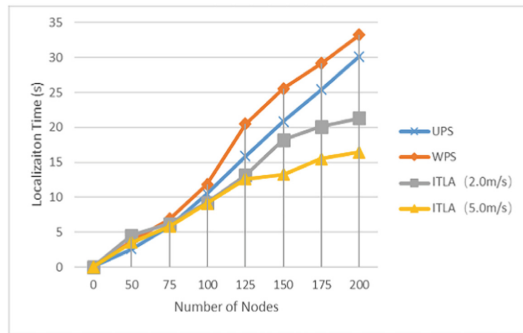


Fig. 6. Localization time

The localization error is represented in Fig. 7. With the distance between the unlocalized nodes and AUV and numbers of nodes increases in underwater, the error also increases. Owing to the efficient use of mobile AUV as the reference node, the localization error has been controlled into an acceptable situation. As is shown below, the accuracy of nodes coordinates improves nearly 1 m than traditional ways. This is mainly due to we add a result correction at last and the lateration of calculation. These differences are becoming more obvious with the increase of sensor nodes need to be localized.

The localization coverage is shown in Fig. 8. UPS only localized 66% of nodes while WPS reach to nearly 80% in the end. Due to AUV floating nearby, more sensor nodes can be localized by using ITLA. On the other hand, the localization coverage area is determined by the transmission range of nodes. As the transmission range of these nodes increases, more nodes get their accurate coordinates. Obviously, due to the wider range of AUV movement, the positioning coverage is larger than traditional ways and its coverage is nearly close to 90%. More unlocalized nodes will be in transmission range by the movement of AUV.

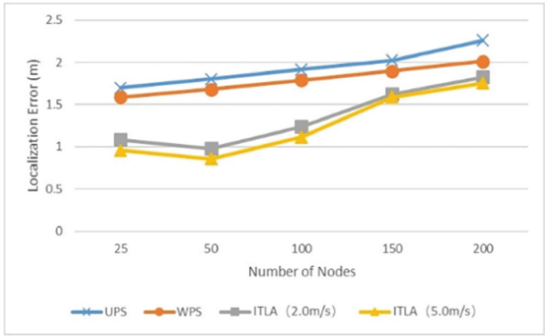


Fig. 7. Localization error

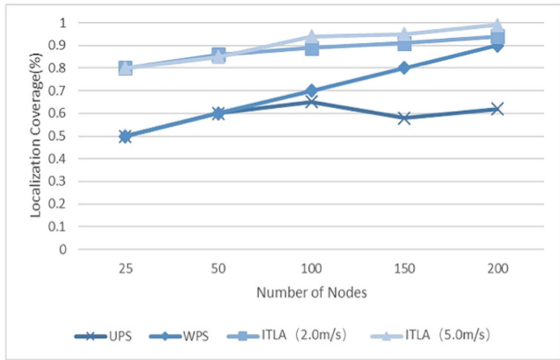


Fig. 8. Localization coverage

5 Conclusion

We propose an improved TDoA localization algorithm based on AUV. Comparing with traditional TDoA algorithm, we take AUV as reference nodes to locate the unlocalized anchor nodes. Our algorithm consists of two steps, localization message broadcasting and receiving and location computation and results correction. AUVs are deployed from the surface into underwater, it is equipped with accelerate and gyroscope to get their coordinates and direction by GPS and dive into predefined depth. Then AUV broadcast wake-up messages to unlocalized anchor nodes. After receiving position messages from AUV sent in different positions, anchor node computes its own coordinates by applying various mathematical techniques. And preliminary computation results will be corrected by results correction for more accurate positioning. Due to the use of mobile AUV in underwater, the localization coverage is improved, results in less localization error and localization time relatively shortened.

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