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Underwater Positioning Algorithm Based on SINS/LBL Integrated System

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ABSTRACT The interactive assistance of a strap-down inertial navigation system (SINS) and a long baseline (LBL) underwater positioning algorithm based on time of arrival is studied, and this algorithm mainly includes a solution algorithm of equivalent sound velocity, 3-D LBL underwater positioning algorithm with aided of SINS. The proposed method can quickly get the ideal equivalent sound velocity to calculate the distance from sound source to hydrophones, and effectively reduce the positioning errors caused by the uneven distribution of underwater sound velocity and sound ray bending, with high flexibility and adaptability. The results of simulation indicate that compared with the traditional algorithm, the improved can correct the cumulative error more directly and effectively, and extend the working hours of autonomous underwater vehicles.

INDEX TERMS Long baseline (LBL), TOA, underwater positioning, SINS

I. INTRODUCTION

As an autonomous navigation system, SINS (Strap–down Inertial Navigation System) can output the attitude, velocity and positioning navigation information of carries continuously [1]. SINS is often chosen as the primary navigation equipment, but the positioning error cumulates over time [2]. When AUV (Autonomous Underwater Vehicles) is working and moving to the effective regions of LBL (Long Baseline) underwater acoustic positioning system, the error can be calibrated [3]. However, LBL positioning system itself also has some defects. In LBL positioning system, the sound velocity and propagation path of sound ray may influence the measuring accuracy of slant range or slant range difference. Because the underwater sound velocity profile is nonlinear [4], the acoustic velocity cannot be regarded as a constant and is often difficult to determine. In addition, when measuring the slope distance or slope distance difference, the refraction, reflection and multipath phenomenon caused by underwater sound propagation may bring large measurement errors [5]. Aiming at these problems, average velocity method is often used to calibrate sound velocity in engineering, but the results in long–range acoustic positioning system often have big errors [6].

TOA (Time of Arrival) positioning method depends on the TOA value of LBL system, the distance between the sound velocity measuring carriers and hydrophones, and the spherical intersection model to position carriers [7]. In synchronous mode, the measuring accuracy of TOA value is normally associated with the working conditions of equipment, but the uneven distribution of underwater sound velocity and curved sound ray transmission make slant range result in big positioning errors, which need to be reduced by appropriate methods. A positioning algorithm of equivalent sound velocity based on interactive assistance of SINS is introduced in this paper, which takes on the following merits that simple calculation, the sensitivity in acquiring the suitable equivalent sound velocity implemented in calculating the slope distance, the futile necessity of establishing the forms according to surroundings, powerful flexibility and adaptability. Correcting the cumulative errors of SINS, the positioning results are well suitable for the AUV positioning navigation. The navigating system which embraces SINS and LBL positioning system can be only implemented in positioning assignment, nevertheless the errors of the SINS velocity and navigating orientation ought to be accumulated increasingly. In order to actualize the comprehensive navigating function, overall combination of remaining navigating techniques targeted at calibrating the navigating errors of SINS is required. Employing DVL (Doppler Velocity Logger) and MCP (Magnetic Compass Pilot) to calibrate the velocity and navigating orientation of carriers is a common method.

The structure of this paper is: firstly introduce the principle and structure of system, and the details of interactive assistance of SINS/LBL underwater positioning algorithm, then the SINS/DVL/MCP/LBL integrated navigation system. Finally it performs the simulation experiment.

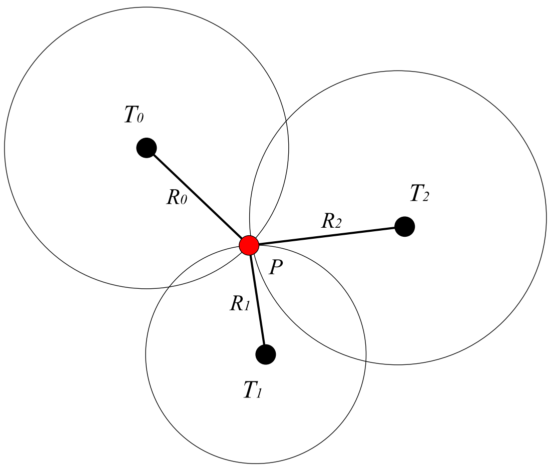

FIGURE 1. Schematic diagram of TOA positioning mode.

II. PRINCIPLE AND STRUCTURE OF THE SYSTEM

A. LBL UNDERWATER POSITIONING MODEL

TOA positioning method adopts the time delay and spherical intersection model to do positioning as shown in Fig. 1. T_0 (x_0, y_0, z_0), T_1 (x_1, y_1, z_1) and T_2 (x_2, y_2, z_2) are positions of three hydrophones; R_0, R_1 and R_2 are distances between three hydrophones and sound sources. Regarding the T_0, T_1, T_2 as the center and R_0, R_1 , R_2 as the radius, three spheres intersect at $P\,(x, y, z)$. From the geometric theory, P is the sound source, and sound velocity is known as c. The positions can be calculated by measuring TOA values t_0, t_1 and t_2. If there are N hydrophones, the positioning equation is as shown in Equation (1):

$$\sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2}=ct_i(i=0,1,\cdots,N-1) \tag{1}$$

If position coordinates of three hydrophones and distances from elements to sound source by TOA are known, according to Equation (1), the coordinate of sound source position P can be calculated. In three–dimensional space, it requires at least three hydrophones to calculate the positioning results. When there are more than four hydrophones, the optimal solutions can be obtained by the least square method.

B. WORKING PROCESS OF THE SYSTEM

TOA positioning algorithm depends on the TOA value of LBL system, distance between the sound velocity measuring carriers and hydrophones, and spherical intersection model to position carriers. In synchronous mode, the measuring accuracy of TOA value is normally associated with the working conditions of equipment, but the uneven distribution of underwater sound velocity and curved sound ray transmission make slant range result in big positioning errors, which need to be reduced by appropriate methods. A positioning algorithm of equivalent sound velocity based on interactive assistance of SINS is introduced in this paper, which takes on the following merits that simple calculation, the sensitivity in acquiring the suitable equivalent sound velocity implemented in calculating the slope distance, the futile necessity of establishing the forms according to surroundings, powerful flexibility and adaptability. In addition, the positioning results can calibrate cumulative errors of SINS.

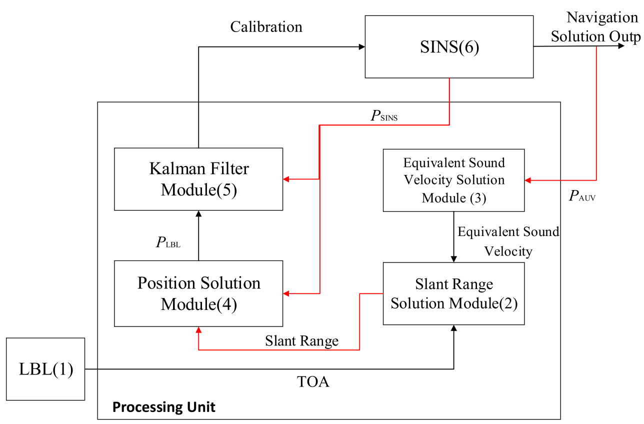

FIGURE 2. Principle block diagram based on TOA.

As shown in Fig. 2, the system consists of three parts: LBL positioning system, SINS and data processing unit. In addition, the data processing unit contains slant range solution module, equivalent sound velocity solution module, position solution module and Kalman filter module. Firstly, calculate slant range by TOA value of LBL system and equivalent sound velocity, which is calculated by the calibrating positioning information from previous position cycle provided by SINS. Then solve positioning results P_{LBL} according to spherical intersection model positioning algorithm, and input difference value of P_{LBL} and P_{SINS} as external observation information into Kalman filter which will calibrate errors of SINS. Special note is: when there are fuzzy solutions of AUV positions calculated by slant range from LBL system, the positioning information provided by SINS system can be used as the basis for choosing the right solution. Because SINS can assist LBL to calculate positions, and LBL can calibrate cumulative positioning errors of SINS, this system can be regarded as an AUV navigation system based on SINS/LBL interaction assisted.

III. PRINCIPLE OF INTERACTIVE ASSISTANCE POSITIONING ALGORITHM OF SINS/LBL

This section mainly describes the implementation principles of algorithms in Fig. 2, including the calculation of equivalent sound velocity and positions based on TOA.

A. CALCULATION OF EQUIVALENT SOUND VELOCITY BY TOA

When AUV is working underwater, between two adjacent positioning cycles, the environment of AUV and structure of sound ray change little, so the equivalent sound velocity doesn't change much. According to this point, the equivalent sound velocity from AUV to hydrophones can be calculated in the currently environment. The specific calculation is as following:

Suppose that there are N hydrophones in LBL underwater positioning system, of which position coordinates are expressed as $P_i(x_i, y_i, z_i)\,(i = 0, 1, \ldots, N-1)$ in rectangular coordinate system of earth. At time $k-1$, set the navigation positioning results as $P_{\mathrm{AUV}}(x_{\mathrm{AUV}}(k-1), y_{\mathrm{AUV}}(k-1), z_{\mathrm{AUV}}(k-1))$ to calculate the distance between hydrophones and AUV:

$$R_i'(k-1) = ((x_i - x_{\mathrm{AUV}}(k-1))^2 + (y_i - y_{\mathrm{AUV}}(k-1))^2 + (z_i - z_{\mathrm{AUV}}(k-1))^2)^{\frac{1}{2}} \quad (2)$$

Suppose the TOA value of LBL system from hydrophones to AUV at time $k-1$ as $t_i\,(k-1)$. Surrounding environment of AUV is not changed too much, and change of sound ray structure is little. Hence, the equivalent acoustic velocity $c_i\,(k)$ can be calculated by the ratio between slant range according to Equation (2) and TOA value of the last cycle, as Equation (3) showing:

$$c_i(k) = \frac{R_i'(k-1)}{t_i(k-1)} \quad (3)$$

When positioning at time k, the slant range can be calculated by equivalent sound velocity $c_i\,(k)$, which is gotten from the positioning information of the navigation system at time $k-1$, as Equation (4) showing:

$$R_i(k) = c_i(k)t_i(k) \quad (4)$$

Where $t_i\,(k)$ is the TOA value measured by LBL positioning system at time k.

B. TOA THREE-DIMENSIONAL POSITIONING ALGORITHM

Suppose that there are N hydrophones working in LBL positioning system, of which positions are $T_i\,(x_i, y_i, z_i)$ and slant ranges are $R_i\,(i = 0, 1, \ldots, N-1)$. The position coordinate of carries to be positioned is $P\,(x, y, z)$. The spherical intersection location equation is as Equation (5) showing:

$$R_i^2 = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2, \quad (i = 0, 1, \ldots, N-1) \quad (5)$$

Eliminate x^2, y^2 and z^2, the linear equation is as Equation (6) showing:

$$2\,(x_0 - x_{i+1})\,x + 2\,(y_0 - y_{i+1})\,y + 2\,(z_0 - z_{i+1})\,z = \left(R_{i+1}^2 - R_0^2\right) - \left(x_{i+1}^2 - x_0^2\right) - \left(y_{i+1}^2 - y_0^2\right) - \left(z_{i+1}^2 - z_0^2\right) \quad (6)$$

Where $i = 0, 1, \ldots, N-2$,

$$\begin{cases} A_i = 2\,(x_0 - x_{i+1}) \\ B_i = 2\,(y_0 - y_{i+1}) \\ C_i = 2\,(z_0 - z_{i+1}) \\ D_i = \left(R_{i+1}^2 - R_0^2\right) - \left(x_{i+1}^2 - x_0^2\right) - \left(y_{i+1}^2 - y_0^2\right) \\ \quad - \left(z_{i+1}^2 - z_0^2\right) \\ \quad (i = 0, 1, \cdots, N-2) \end{cases} \quad (7)$$

Then the Equation (6) can be simplified as:

$$A_i x + B_i y + C_i z = D_i\ (i = 0, 1, \cdots, N-2) \quad (8)$$

Written as matrix form:

$$A\mathbf{x} = B \quad (9)$$

Where

$$A = \begin{pmatrix} A_0 & B_0 & C_0 \\ \vdots & \vdots & \vdots \\ A_{N-2} & B_{N-2} & C_{N-2} \end{pmatrix}, \quad B = \begin{pmatrix} D_0 \\ \vdots \\ D_{N-2} \end{pmatrix}, \quad x = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad (10)$$

When N = 3, there are three unknowns and two equations in linear equations. Suppose that z is known, the x and y can be expressed by z:

$$\begin{cases} x = \dfrac{B_1 D_0 - B_0 D_1 + (B_0 C_1 - B_1 C_0)\,z}{A_0 B_1 - A_1 B_0} \\ y = -\dfrac{A_1 D_0 - A_0 D_1 + (A_0 C_1 - A_1 C_0)\,z}{A_1 B_2 - A_2 B_1} \end{cases} \quad (11)$$

Then substitute Equation (11) to (5), and quadratic equation of z can be gotten, which is substituted to Equation (11) to calculate x and y. There are two solutions in general, which need to be chosen by other information.

When $N = 4$, if A is reversible, there is unique solution:

$$\mathbf{x} = A^{-1}B \quad (12)$$

When $N > 4$, the least square solution is:

$$\mathbf{x} = \left(A^T A\right)^{-1}\left(A^T B\right) \quad (13)$$

According to the above positioning algorithm, three–dimensional positioning needs to calculate three–dimensional coordinate, and needs at least three hydrophones with known positions to provide distance information to positioning. When three hydrophones with known positions are used to positioning, there are fuzzy solutions needed to be determined by navigation information of the last cycle. When the number of hydrophones with known positions increases to four, there is unique solution. When the number is over four, the positioning results can be calculated by least square solution of equations.

IV. SINS/DVL/MCP/LBL INTEGRATED NAVIGATION SYSTEM

The above navigating system which embraces SINS and LBL positioning system can be only implemented in positioning assignment, nevertheless the errors of the SINS velocity and navigating orientation ought to be accumulated increasingly. In order to actualize the comprehensive navigating function, overall combination of remaining navigating techniques targeted at calibrating the navigating errors of SINS is required.

Employ the continuous and high accuracy velocity information from DVL to calibrate the velocity errors and suppress the positioning divergent of SIN. Because AUV volume is generally small, the gyrocompass isn't suitable for AUV, which is bulky, complex and high cost. MCP is used to calibrate attitude and course information of carriers, which is simple, reliable and low cost. It's should be noted that the high accuracy positioning information provided by LBL underwater positioning system can be calibrated intermittently within the effective scope of hydrophones. Running for a period of time, AUV can be calibrated and continue to run after reaching the effective scope of hydrophones. At the same time, SINS can provide some information for LBL system to calculate positions. Because of information distribution principle and decentralized structure, the federated filter with small amount of calculation, high flexibility and good tolerance of fault, is chosen as the basic algorithm by 'Public Kalman Filter' program of USAF fault tolerant navigation system [8],[9]. SINS/DVL/MCP/LBL integrated navigation systems designed by this paper adopt the federal Kalman filtering technique to fuse data of multiple sensors, which makes the system have better real–time and dynamic performance, and fault tolerance, as shown in Fig. 3.

Considering from the real–time and fault–tolerance of system, a filter with two stage data fusion is designed by this paper, which is a kind of NR (No–Reset Mode) federated filter, as V showing. The whole filter is composed of one main filter and SINS/LBL, SINS/DVL, SINS/MCP three sub–filters. The public reference system SINS is positioning matched with LBL, velocity matched with DVL, and course angle matched with MCP. Each sub–filter contains not only the public state XSINS, but also specific states, which is the standard Kalman filter. Running in parallel and filtering independently, the sub–filters send each filtering result to main filter to fuse at the same time. The main filter fuses and keeps the results until the next fusion time. Because the main filter doesn't feedback the fusion information to sub–filters, the sub–filter doesn't affect each other. The fault tolerance of system has been increased, which meets the high reliability requirements of the navigation system in AUV underwater operation. Finally in order to meet the long–endurance, long–range and high accuracy requirements of AUV, the feedback calibration mode is adopted in the filter. The final estimates of navigation parameters of the main filter feedback to the SINS system to calibrate and suppress the accumulated errors of the integrated navigation system in time.

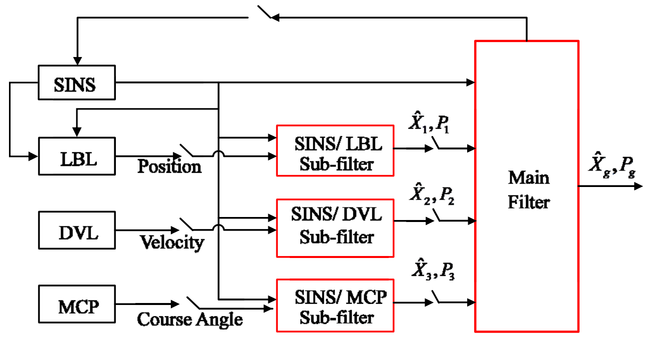

FIGURE 3. Federal Kalman filter structure of AUV.

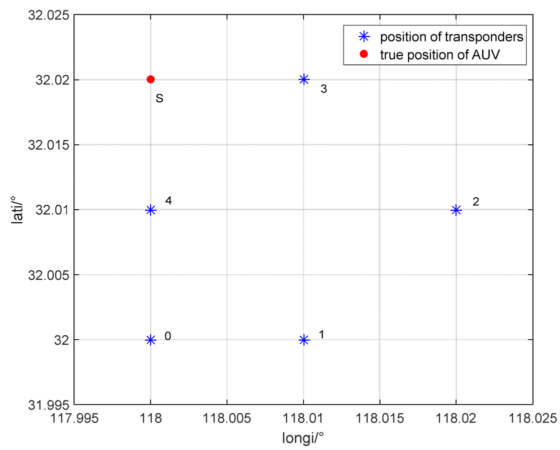

FIGURE 4. Layout of hydrophones and AUV.

V. SIMULATION AND EXPERIMENT

To validate the effectiveness of improved algorithm proposed in this paper for AUV positioning, the algorithm needs to be simulated in first.

A. SIMULATION OF STATIC POSITIONING SYSTEM

Static positioning simulation can well reflect the details of calculation, and preliminary verify the effectiveness and feasibility of algorithm. Set the position of hydrophones and AUV as Fig. 4 showing. Place $No.0 \sim 4$ hydrophones underwater, and their positions are expressed with longitude and latitude as $(118°, 32°)$, $(118.01°, 32°)$, $(118.02°, 32.01°)$, $(118.01°, 32.02°)$, $(118°, 32.01°)$, with the depth of $30m$. In addition, the real location of AUV is $(118°, 32.02°)$ with the depth of $10m$. By the experiment on this lake, the data of underwater acoustic velocity distribution is obtained. Simulate the acoustic signal propagation to calculate the position, which is compared with the real position of AUV.

When AUV and hydrophones are time synchronized, the system work in the synchronous mode and can positioning by TOA. According to the sound transmission path of

BELLHOP mode [10], [11], the propagation delay TOA value of sound signal from sound sources to hydrophones can be calculated as Table 1 showing:

TABLE 1. TOA value of simulation.

HYDROPHONE	TOA/S
0	1.5019
1	1.6352
2	1.4869
3	0.6408
4	0.7517

The traditional algorithm adopts the sound experience or equivalent velocity to calculate the distance between sound sources and hydrophones (set equivalent sound velocity c= 1481.9970m/s). The improved algorithm adopts the equivalent velocity of real–time calculation to calculate the distance. The results of two algorithms are as shown in Table 2, and error comparison is in Table 3.

From Table 2 and 3, the improved algorithm is closer to the truth value, which adopts real–time calculation and is closer to the situation of actual sound propagation and AUV environment. This can improve the positioning accuracy of TOA algorithm.

TABLE 2. Comparison of distance calculation results.

HYDROPHONE	TRADITIONAL ALGORITHM /M	IMPROVED ALGORITHM /M	TRUTH VALUE /M
0	2225.7645	2215.9810	2217.8234
1	2423.3960	2408.1577	2410.6922
2	2203.5236	2191.9454	2190.9781
3	949.6786	945.2929	944.9352
4	1114.0686	1107.5805	1109.0478

TABLE 3. Error comparison of distance calculation results.

HYDROPHONE	ERROR OF TRADITIONAL ALGORITHM /M	ERROR OF IMPROVED ALGORITHM /M
0	7.9411	2.0576
1	12.7038	-2.5344
2	12.5455	0.9673
3	4.7433	0.3577
4	5.0208	-1.4673

According to the result, the position of AUV can be calculated by TOA algorithm as Table 4 showing:

TABLE 4. Comparison of static positioning calculation results.

TRADITIONAL ALGORITHM	IMPROVED ALGORITHM	TRUTH VALUE
(117.9998551°,32.0201237°)	(118.0000030°,32.0199608°)	(118°,32.02°)

Fig. 5 indicates that: the accuracy of improved algorithm is superior to the traditional, and the results are closer to the actual position.RER (Radial Error Rate) can measure the positioning accuracy. Because the simulation is a single

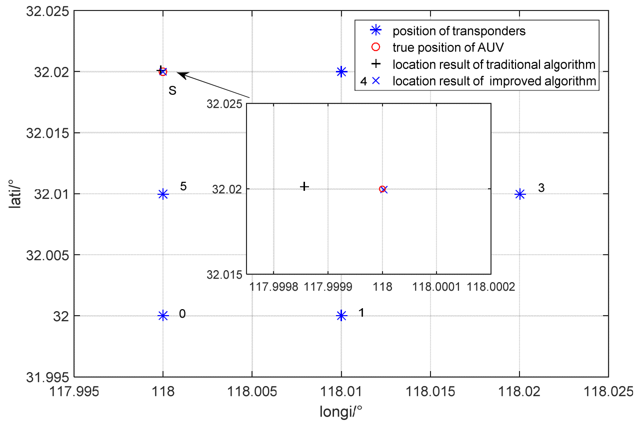

FIGURE 5. Comparison of TOA location results.

location, we can use RE (Radial Error) to compare directly. The calculation equation of RE is:

$$RE=([(L-L_0)\ (R_N+H_0)]^2+[(\lambda-\lambda_0)\ (R_E+H_0)\cos L_0]^2)^{\frac{1}{2}} \tag{14}$$

Where L and L_0 are the calculated value and truth value of latitude, λ and λ_0 are the calculated value and truth value of longitude, H_0 is the truth value of height, RN is the radius of curvature of the reference ellipsoid meridian plane, RE is the radius of curvature of the vertical meridian plane. The latitude and longitude value need to take the arc form, and height in the vicinity of the surface can be ignored. Substitute the location results in Fig. 5 into Equation (14) to calculate the comparison of RE of traditional and improved algorithms as Table 5 showing:

TABLE 5. Comparison of RE of positioning results.

TRADITIONAL ALGORITHM /M	IMPROVED ALGORITHM /M
19.3780	4.3552

It can be seen from Table 5 that: the RE of improved algorithm reduces greatly and improves the positioning accuracy of AUV effectively.

B. DYNAMIC SIMULATION OF NAVIGATION SYSTEM

Although the static simulation can verify the validity and feasibility of the algorithm, it is not able to eliminate the contingency of effective results. So the dynamic simulation of the algorithm is carried out to verify the dynamic effectiveness. SINS/DVL/MCP/LBL integrated navigation system is composed of the designed federated filters. The conditions and parameters of simulation are as follows:

1) The location of hydrophones: set five hydrophones underwater: Latitude and longitude: (118°, 32°), (118.01°, 32°), (118.02°, 32.01°), (118.01°, 32.02°), (118°, 32.01°);

Depth: 30m;

Suppose that: hydrophones are time synchronized.

2) Instrument performance: Gyro constant drifts: $0.04°/h$, gyro random drifts: $0.04°/h$;

Accelerometer bias: $50\mu g$, accelerometer random bias: $50\mu g$.

Velocity accuracy: $0.1m/s$;

Magnetic compass accuracy: 0.3°.

3) Initial navigation parameter settings Initial attitude angle: pitch angle is 0°, roll angle is 0°, course angle is 45°;

Initial attitude error: pitch angle is 0.005°, roll angle is 0.005°, course angle is 0.005°;

Initial velocity: $1m/s$;

Initial location: (117.995°, 32.025°);

Initial depth: $10m$.

The actual motion of AUV is impacted by the wave oscillation. In order to simulate the actual sea conditions, set AUV to do three axis swing motion. Swing parameters are shown in Table 6.

TABLE 6. Swing parameters.

	Pitch Angle	Roll Angle	Course Angle
Range(°)	9	12	10
Period(s)	8	10	6

According to the positioning modes of LBL system, carry out the dynamic simulation of TOA and TDOA interactive assisted integrated navigation system. The simulation time is 4000s.

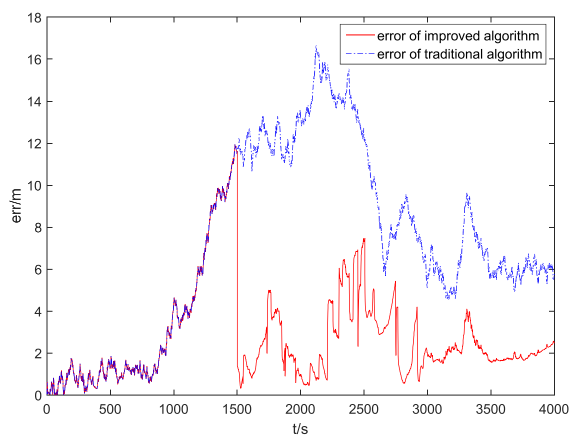

FIGURE 6. Error comparison of positioning results.

Fig. 6 is the comparison of the positioning error between the traditional and improved algorithms in TOA, and the positioning error is represented by the radial error. Fig. 7 is the comparison of the ideal and estimate track of two algorithms, and the location of hydrophones is as showing.

Analyze the positioning error data of the simulation period, and the mean error and root mean square error are shown in Table 7. The errors of improved algorithm are smaller than the traditional. The effectiveness of improved algorithm improving the AUV positioning performance has been verified.

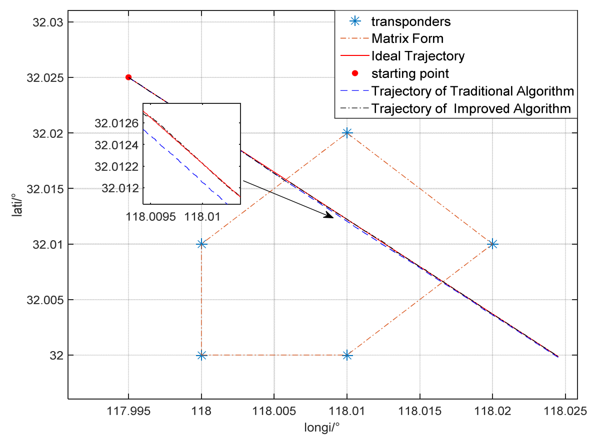

FIGURE 7. Comparison of positioning trajectories.

TABLE 7. The mean and root mean square of positioning error.

	Mean Error /m	Root Mean Square Error /m
Traditional Algorithm	7.0528	4.5342
Improved Algorithm	2.7147	2.3400

In Fig. 6, within 0∼1500s, the positioning errors of two algorithms enlarges gradually. Within the period, AUV is far away from the valid range of LBL hydrophones. Taking a long time for hydrophones to receive signal from sound source, it makes a great delay of positioning. Hence, LBL isn't used to calibrate within this period, instead, SINS/DVL/MCP integrated navigation system is doing positioning. When AUV approaches the valid range, namely after 1500s, LBL system begins to do calibration. Errors of traditional algorithm are so large that the effect of calibration isn't quite so obvious. While because of higher accuracy of positioning, the improved algorithm achieves a more obvious calibration effect and controls the location errors well. It can be seen from Fig. 7: when AUV is in the scope of hydrophones and LBL positioning system calibrates the positioning errors, compared with the traditional algorithm, the track estimated by the improved TOA algorithm is closer to the ideal track, and positioning errors are smaller. From the above analysis, we find that: in the actual dynamic operation, the improved TOA method can calculate the positioning when AUV is in the valid range of LBL hydrophones. The results can be used to calibrate the SINS/DVL/MCP integrated navigation system, and greatly improves the positioning accuracy of AUV.

VI. CONCLUSIONS

This paper, directing at the existing deficiencies of underwater positioning technology, proposes an improved system based on SINS and LBL interaction assisted. The whole system is made up of SINS/DVL/MCP integrated navigation system and LBL underwater acoustic positioning system. In addition, the latter adopts TOA positioning method based on SINS as well as positioning results provided by

SINS/DVL/MCP integrated navigation system, which assist in calculating equivalent sound velocity. In the meantime, the positioning results can also be used to screen the fuzzy solutions and correct the cumulative positioning errors of SINS.

Compared with the traditional, the final simulation results indicate that the proposed algorithm can greatly improve the positioning accuracy of AUV. When AUV approaches the valid range of LBL hydrophones, cumulative errors can be effectively reduced. Hence, this algorithm is practicable.

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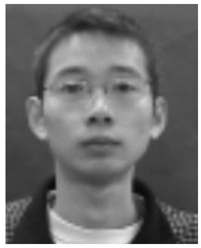

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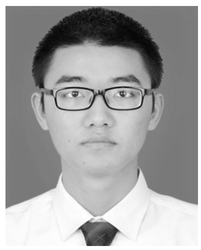

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