Accurate and Rapid Localization of an AUV in an Absolute Reference Frame using the Iterative Resection

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***Abstract*- Because of the advantage of acoustic signal traveling in the water, most techniques of precisely locating AUVs adopt GPS and acoustic measurements. The development of modern GNSS techniques, attitude measuring techniques and precise underwater ranging techniques make GPS-acoustic technology possible for accurate localization of an AUV. Because the transmit angles are unknown for transducers, it is complicated for us to solve the coordinates of the AUV. In order to rapidly and accurately obtain the positions of AUV at each epoch, in this paper, an algorithm for locating an AUV in an absolute reference frame is presented. It uses three surface buoys or vessels to range and adopts the iterative resection to solve the position of the AUVs. Acoustic ranges are calculated using the equivalent sound speed profile and travel times of sound rays. This simple equivalent SSP is usually adopted to have a constant gradient in the total water column. Under some approximate conditions, the initial Snell constant can be deduced so that the linear geometric distances can be obtained through ray trace after the Snell constant is iteratively solved. Finally, the precise position of the AUV at each epoch is calculated using the precise geometric distances. It is proved by simulation that this method is capable of real-time positioning of the AUV with an accuracy of ±20cm in the inner cover area of three transducers at a depth of 500m supposing the error of sound speed is 0.1m/s. The precision can be improved further if kalman filter is adopted.**

***Index Terms*- Localization, AUV, Resection, Equivalent sound speed profile**

I. INTRODUCTION

Autonomous underwater vehicles (AUVs) provide a wide range of applications in ocean engineering, ocean researching, oceanic rights and interests protecting, etc [1]-[3]. However, in order to exploit these capabilities, AUVs navigation must approach the meter-level and localization to the decimeter-level. Because of the advantage of acoustic signal traveling in the water, most of the techniques of precisely locating AUVs adopt GPS and acoustic measurements [2]-[16]. Most GPS/acoustic techniques mainly include four similar procedures: (i) to determine the position of GPS antennas on the ship in real time; (ii) to determine the position of the transducer using the attitude of the carrier and the relative displacement between the antennas and the transducer; (iii) to obtain the range between the transducer and underwater transponders by measuring the travel time and SSP. and (iv) to calculate the absolute three-dimensional position of a underwater object using the triangulation. As the development of modern GNSS technique, we can use precise processing methods to locate surface platforms (ships, buoys) with sub-decimeter accuracy for a distance up to a few thousands km from shore-based reference sites [17]. Regarding acoustic positioning, the classic positioning modes are ultra short baseline (USBL) system and long baseline (LBL) system. The former needs measure range and transmit angle. The range is calculated using the travel time of an acoustic signal and sound speed profile (SSP) in water. Limited by the error of angle, USBL can not provide very high precision of positioning, and is usually about 1% of the depth. The positions of transponders in the latter need be settled on the seafloor and located at first, which is complicated and time-consuming due to the requirement of pre-surveying a grid of acoustic transponders on the sea-floor and recovery of transponders after the mission [18]. Besides the acoustic positioning techniques, dead reckoning and the aid navigation based on geophysics are also mainly methods. The former consists of inertial measurement unit (IMU) and a Doppler velocity log (DVL) [19]. However, position errors accumulate with distance traveled at a rate dependent on the quality of the devices. Although more precise sensors can be used to reduce the rate of accumulated error, this approach may not be satisfactory due to practical, power or financial limitations [16], [18]. The latter mainly includes terrain navigation [20], magnetic navigation, and gravity navigation. This kind of methods doesn't accumulate position errors, but they can only provide low accuracy of positioning. At present, multi-sensor integrated navigation technology can improve the precision of position and is widely used in underwater dynamic object localization [21]-[24]. But it is expensive and complicated. Other methods, such as computer vision [25]-[27], sonar image [28], are only suitable for positioning in small scenes. Therefore, in order to serve ocean engineering, ocean researching, etc., we should find a simple method to provide accurate and rapid localization of an AUV in an absolute reference frame.

Modern GNSS techniques and attitude measuring techniques can locate the transducer at the level of centimeters. Precise underwater ranging is based on precise sound travel time measurement. The precision of travel time can achieve at the level of a few microseconds. Modern transponder is able to control the systematic range error due to the time delay within the transponder to the level of millimeters. The random

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ranging error is reported to be at the order of one centimeter. These technologies have created good prerequisites for accurate localization of an AUV in an absolute reference frame. The most damaging factor in underwater positioning is the errors induced by the inaccurate SSP, which can reach some hundreds of ppm [11]. A typical measured SSP may have a bias error of 2m/s. Based on these conditions, in this paper, an algorithm of the iterative resection for locating an AUV in an absolute reference frame is presented. Acoustic ranges are calculated according to the equivalent sound speed profile. The more accurate ranges can be obtained using resection and least squares. It uses three surface buoys or vessels to range and adopts the iterative resection to solve the position of the AUVs. It calculates range differences between curved ray and linear geometric distances based on the theory of equivalent sound speed profile (SSP) [29]. Thus a simple and equivalent SSP can be obtained to replace the actual complicated SSP. This simple SSP is usually used to have a constant gradient in each layer. The zone of survey during positioning is in a small area. Because the sound speed mainly varies with the depth, and varies little along horizontal direction in such a small area and short time, it is reasonable to assume that the sound speed only varies with the depth during positioning. Then the precise range differences can be obtained through ray trace after transmit angles are iteratively solved.

In this paper, an algorithm for locating an AUV in an absolute reference frame is presented. It uses three surface buoys or vessels to range and adopts the iterative resection to solve the position of the AUVs. Acoustic ranges are calculated using the equivalent sound speed profile and travel times of sound rays. Under some approximate conditions, the initial Snell constant can be deduced so that the linear geometric distances can be obtained through ray trace after the Snell constant is iteratively solved. Finally, the precise position of the AUV at each epoch is calculated using the precise geometric distances. This paper comprises four sections. After this introduction, Section II describes the principles and data processing methods. Section III details the simulated results. The conclusion is presented in Section IV.

II. THE POSITIONGING PRINCIPLES AND DATA PROCESSING METHODS

The ESS is the sound speed which when multiplied by its travelling time between two underwater points, yields the geometric or slant range between them [6]. The equivalent SSP is introduced as follows. Assuming a sound ray is traced respectively in two different SSPs with the same speed at the surface, the calculated position of this beam footprint will also be the same using the same travel time and initial launch angle if the area between the ray and depth axis is the same, i.e., the area of the polygon O-c_0-c_1-c_2-c_3-z_3-O and that of O-c_0-z-z_3-O in Fig. 1). Thus a simple SSP (or called equivalent SSP) can be obtained to replace the actual and complicated one. A SSP with a constant gradient in each layer is usually used [30].

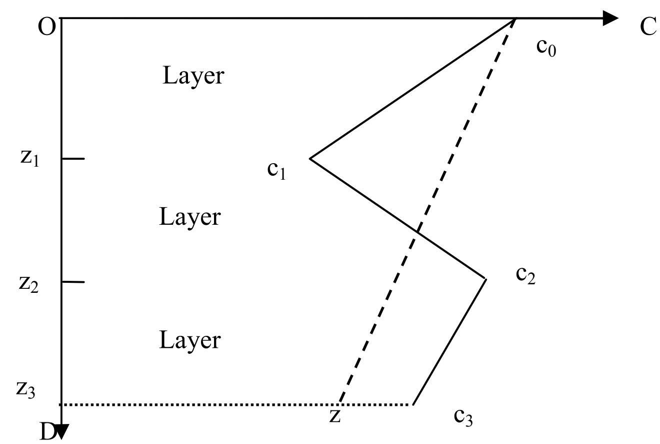

Fig. 1 The illustration of equivalent SSP

The travel of sound in water follows the Snell's Law as:

$$\frac{\sin\theta_0}{C_0} = \frac{\sin\theta_1}{C_1} = \cdots = \frac{\sin\theta_i}{C_i} = \cdots = \frac{\sin\theta_n}{C_n} = p \quad (1)$$

where θ_i is the incidence angle in water layer *i*, C_i is the sound speed in water layer *i*. *i*=0,1,…,n, and *p* is a constant. In each layer, the actual track of ray is an arc if the sound speed has a constant gradient. The radius *R* of the arc is [31]

$$R = -1/(pg_i) \quad (2)$$

where g_i is the sound speed gradient in layer *i*.

The horizontal distance D_i in layer *i* is calculated by[31]:

$$D_i = \frac{(1-(pC_i)^2)^{1/2} - [1-p(C_i + g_i\Delta z_i)^2]^{1/2}}{pg_i} \quad (3)$$

where C_i is the sound speed at the initial position of the layer and Δz_i is the depth of the layer. Then the geometric distance ρ_i is computed by:

$$\rho_j = \sqrt{D_j^2 + \Delta z_j^2} = \sqrt{(x - x_{sj})^2 + (y - y_{sj})^2 + (z - z_{sj})^2} \quad (4)$$

where the subscript *j* denotes the transducer *j*, *j*=1,2,3. (*x,y,z*) are the coordinates of the AUV. (x_{sj}, y_{sj}, z_{sj}) are the coordinates of the transducer *j*.

The length of the arc is obtained by [31], [32]:

$$S_i = R_i(\theta_i - \theta_{i+1}) \quad (5)$$

where θ_i is the incidence angle, and θ_{i+1} is the departure angle. Thus the equation of the travelling time is:

$$t_i = \frac{S_i}{C_H} = \frac{\arcsin[p(C_i + g_i\Delta z_i)] - \arcsin(pC_i)}{pg_i^2\Delta z_i}\ln[1 + \frac{g_i\Delta z_i}{C_i}] \quad (6)$$

where C_H is the harmonic sound speed, which is the ratio of the total distance traveled to the total time of travel.

In this paper we assume that there is a SSP for a working area, which is reasonable for positioning an underwater object. The equivalent SSP can take a simple form of one layer (Fig. 1), which involves three parameters, i.e. the surface sound speed c_0, the depth *z* and a constant gradient *g*. c_0 is the observed value, *z* is related to *g* with a certain SSP.

Three buoys or ships are used as the known points. The coordinates of transducers under the buoys or ships can be calculated according to [12]. During a localization of an AUV, the traveling time of sound ray is the observed quantity. The precise ρ_i is a required quantity to execute resection. p, g_i , D_i , Δz_i are the known parameters. The initial coordinates of the AUV can be calculated if the uniform water layer is assumed. The initial g_i can be calculated using the area A between the ray and depth axis and initial depth, as Equation (7).

$$g_i^0 = \frac{2(A - C_0 \cdot \Delta z_i^0)}{\Delta z_i^0 \cdot t_i} \tag{7}$$

where the superscript 0 denotes the initial value. Then the initial p can be achieved according to Equation (6) using an iterative calculation. And then the horizontal distance D_j will be obtained. Therefore (x,y,z) will be updated according to equation (4) using resection. These calculations will be iterative until the coordinates of (x,y,z) change within a small scope. The final (x,y,z) is just the precise coordinates of the AUV. The precision is expected to be improved further if kalman filter is adopted. For the dynamic system model, the state estimation can be expressed as:

$$X_{k+1} = \Phi_k X_k + W_k \tag{8}$$

and

$$Z_k = H \cdot X_k + V_k \tag{9}$$

for the measurement model where the subscript k denotes the value at time step t_k. X is the vector of coordinate component of the AUV including the position, velocity and acceleration. ϕ is the state transition matrix. H is the observed matrix, and Z is the measurement matrix. W is the system noise, and V is the measurement noise.

ϕ, H can be respectively expressed as

$$\Phi_k = \begin{bmatrix} 1 & t & t^2 \\ 0 & 1 & t \\ 0 & 0 & 1 \end{bmatrix} \tag{10}$$

and

$$H = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \tag{11}$$

For each component of (x,y,z), the operating process of kalman filter is the same.

III. THE SIMULATED EXMPLES AND RESULTS

We simulated an AUV over the seafloor with a depth of 500m (Fig.2). The depth is the most interesting from the point of view of AUV applications [33]. The detail movements of the AUV and GPS antennas on sea surface are showed as Fig.3. A sound speed structure was adopted in an area of South China Sea (Fig.4). The sound speed and water temperature were measured at different depths. The equivalent sound speed gradient g can be calculated if sound speed structure is simplified by one constant gradient layer. The equivalent sound speed was assumed with an accuracy of ±0.1m/s. The mean square error of travel time was 10us. The period and amplitude of tide are respectively 12h and 5m. The period of wave is 10s, and amplitude is 1m. The transducer was indirectly positioned by GPS antennas according to [12]. The RMS of the plane position of the transducer in each coordinate component is 2cm, and 3 cm in vertical direction. We calculated the position of the AUV in each epoch with a 0.1m/s error of ESS according to Section II. The errors of positioning are showed in Fig.5. After kalman filter was executed, the results of positioning had some improvement (Fig.6). Fig.7 shows the relation between the horizontal distances from the AUV to geometrical center of buoys and errors of positioning. Fig.8 illuminates the real-time positioning results with a 1m/s error of ESS. It shows the influences of errors of sound speed on the results of dynamic positioning.

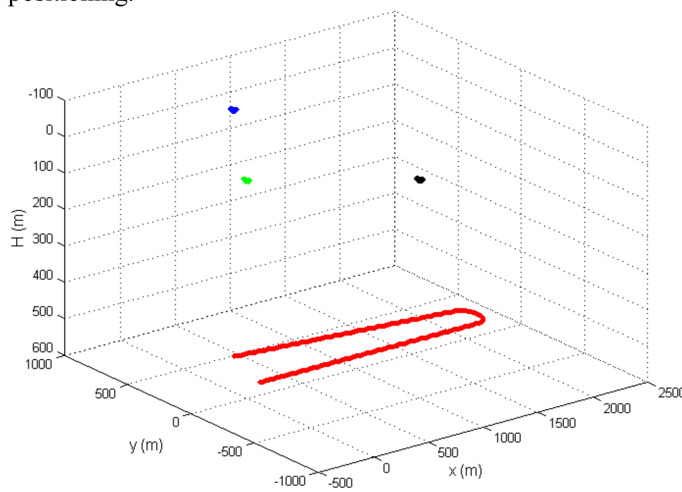

Fig.2 The space structure of locating an AUV

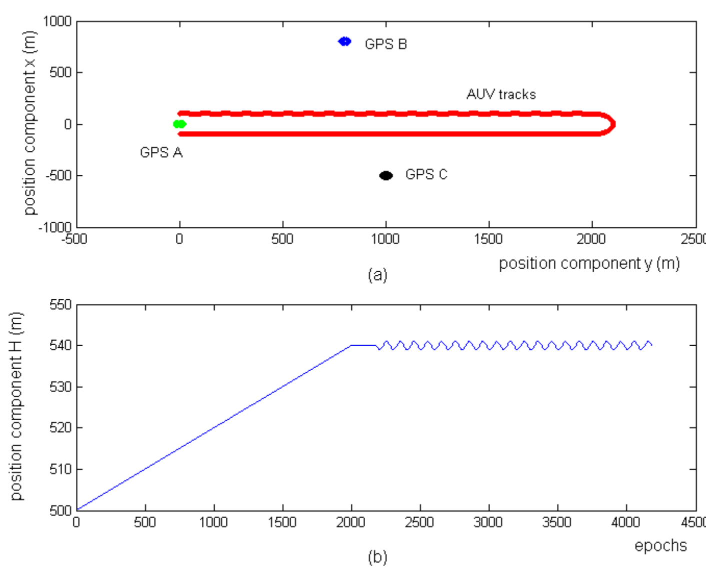

Fig.3 The plane structure of locating an AUV (a) the simulated positions of GPS antennas, i.e. transducers and the AUV; (b) the simulated depth of the AUV varies as time

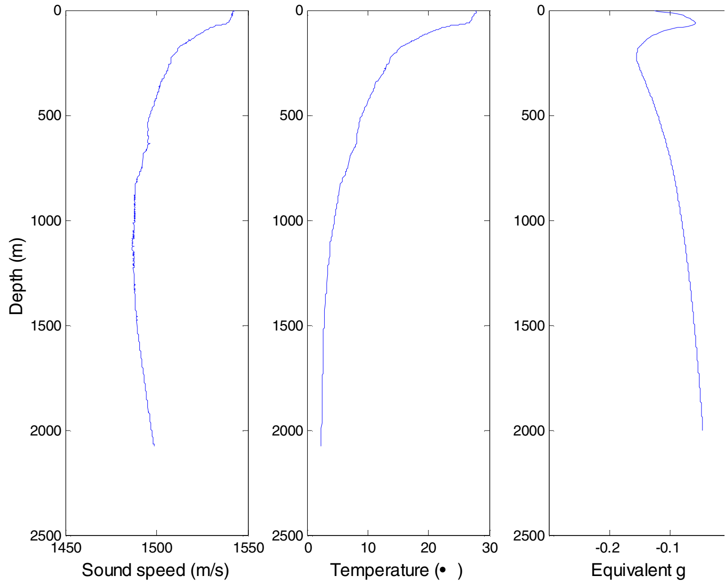

Fig.4 The example of characteristic of sound speed and temperature in South China Sea

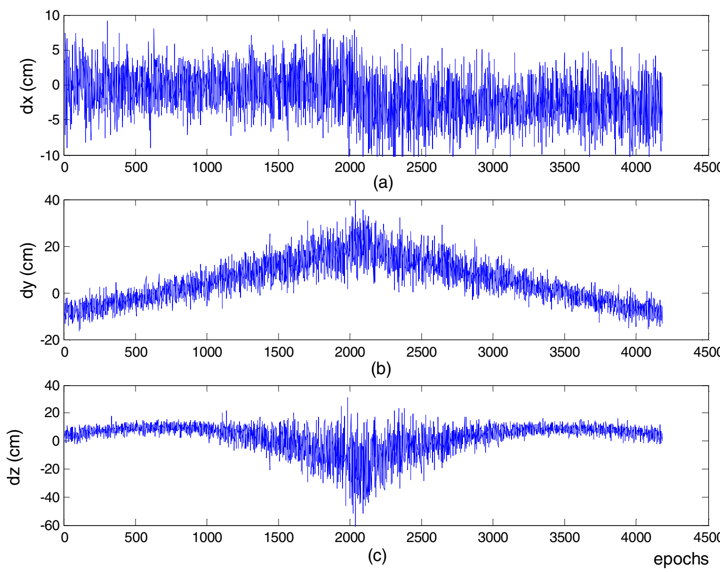

Fig.5 The real-time positioning results with a 0.1m/s error of ESS (a)the errors of the AUV coordinates in north component; (b)the errors of east component; (a)the errors of depth component

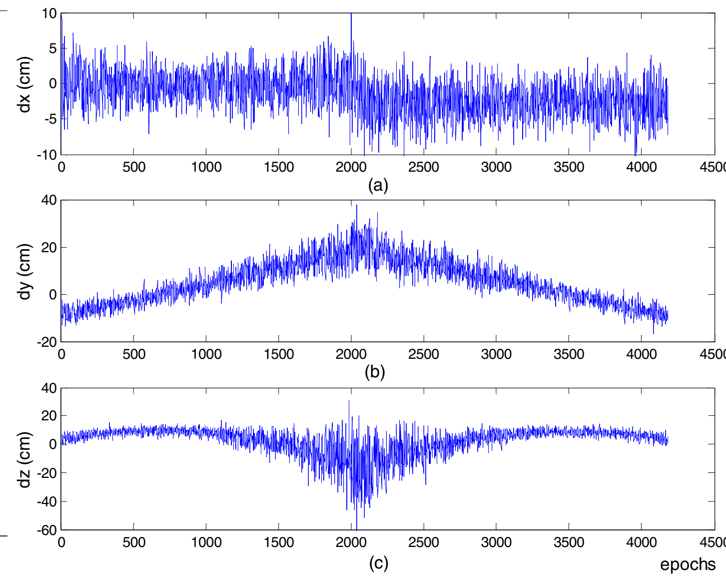

Fig.6 The results of kalman filter for data in Fig.5

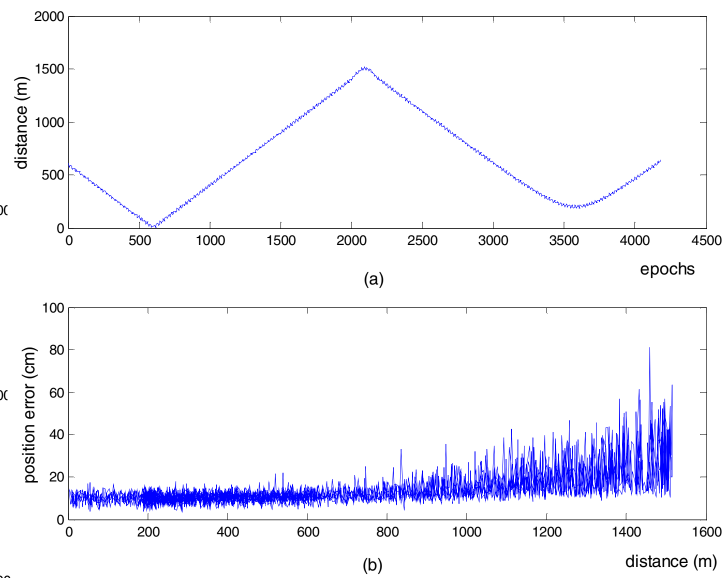

Fig.7 The relation between the horizontal distances from the AUV to geometrical center of buoys and errors of positioning (a) the distance of each epoch; (b) the relation between the distances and errors

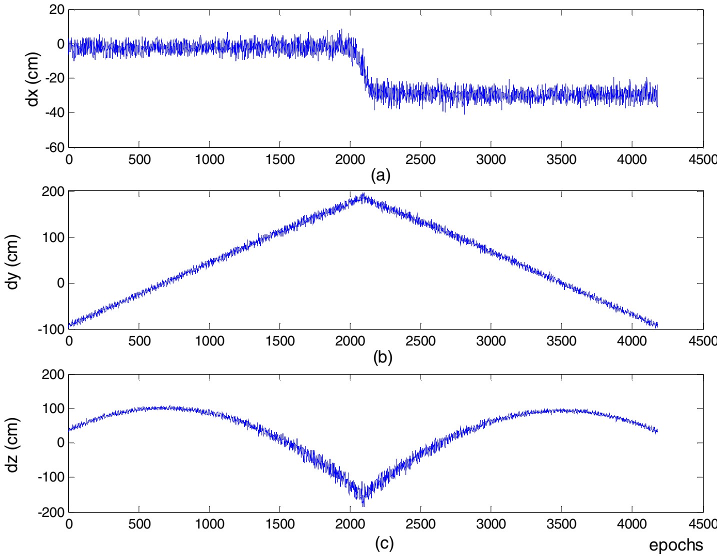

Fig.8 The real-time positioning results with a 1m/s error of ESS

The results illustrated by Fig.5, Fig.7 and Fig. 8 show that the positioning errors are related to the horizontal distances from the AUV to geometrical center of buoys, and the error of sound speed profile. The longer the distance is, the lower the positioning precision will be. The bigger the error of sound speed profile is, the lower the positioning precision will also be. The errors of sound speed profile include the measured error and the variance between assumed invariable SSP and real situation. Because the absolute value of the equivalent sound speed gradient *g* is generally smaller than 0.2 when water depth is bigger than 100m, the different constant g only has a small influence on positioning precision. We can obtain the three-dimensional position of an AUV with an accuracy of ±20cm in the inner cover area of three transducers at the water depth of 500m, and the corresponding precision of ESS is about ±0.1m/s. The positioning precision will be degraded to ±1m in this cover area if the error of ESS drops to ±1m/s. The positioning errors will increase as the depth of an object increases with a fixed ESS error. In order to improve the positioning precision, the feasible ways are to precisely measure sound speed profile, or to make the plane position of the AUV close to the center of three transducers. Modern sound speed sensors can control measured error below ±0.1m/s. It is exciting for us to precisely positioning and navigating underwater dynamic objects. In order to make the AUV close to the plane center of transducers at all times, we can adopt a way of moving acoustic network [34]-[37]. From the results of Fig.5 and Fig. 6, the precision of positioning can be improved further if kalman filter is adopted. Because the velocity of the AUV isn't measured, the effect of improvement can not be too much.

IV. CONCLUSIONS

This paper has proposed a method of accurate and rapid localization of an AUV in an absolute reference frame using the iterative resection. Three surface buoys or vessels were used to obtain the position of the AUVs. Acoustic ranges were calculated using the equivalent sound speed profile and travel times of sound rays. And the linear geometric distances can be obtained through ray tracing. The precise position of the AUV in each epoch can be calculated using the precise geometric distances and the algorithm of space resection. The precision of positioning is related to the horizontal distances from the AUV to geometrical center of buoys and the error of sound speed profile. Therefore the feasible ways of improving precision are to precisely measure sound speed profile, or to make the plane position of the AUV close to the center of three transducers. This precision of sound speed has attained at least 0.1m/s for common sound speed sensors. The simulation results show that this method is capable of real-time determining the three-dimensional position of the AUV with an accuracy of ±20cm in the inner cover area of three transducers at a depth of 500m when the error of sound speed is 0.1m/s. The precision can be improved further if kalman filter is adopted. It is recommended that moving acoustic network is adopted in order to make the AUV close to the plane center of transducers at all times and improve the precision of positioning. Future work will include field tests on the method and how to debase the influence of error of sound speed when positioning in deep water.

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