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Frogman Self-Navigation Method Based on Virtual Transponder Array and Dead Reckoning

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ABSTRACT Using single transponder ranging (STR) information to aid positioning satisfies the needs of frogman autonomous positioning in waters emergency rescue, where miniaturized and low-cost devices are preferred. On this basis, a frogman self-navigation method based on virtual transponder array (VTA) and dead reckoning (DR) is proposed in this article, to solve the problem that calculation results of DR still accumulate with time when STR information is taken as the external measurement. In the proposed method, firstly, by constructing the VTA with depth information constraint, frogman autonomous positioning under the condition of single transponder configuration is realized. Then, to combine the characteristics that DR positioning data is smooth and short-term stable, and that VTA positioning error is not cumulative, the DR navigation system is used to describe frogman's motion law, the frogman positioning coordinates that calculated by VTA are taken as external measurement and the Kalman filter is designed, which solves the problem of DR accumulated errors. Compared to traditional STR-DR method, the proposed VTA-DR method further improves the accuracy and stability of frogman navigation and positioning. Finally, based on the high-precision three-dimensional motion capture system, the semi-physical simulation experimental environment is built to verify the proposed method. The experimental results under different tracks indicate that the average total location error of VTA-DR method is 0.149m, which is reduced by 53.5% compared with STR-DR method. The proposed VTA-DR method can better suppress the accumulation of positioning errors and has better positioning accuracy and robustness.

INDEX TERMS Frogman self-navigation, integrated navigation, single transponder, underwater acoustic positioning, virtual transponder array.

I. INTRODUCTION

The emergency rescue in waters is an important task for all countries in the world, which concerns about the national economy and people's livelihood [1], [2]. Frogmen play important roles in water emergency rescue, and their safety and work efficiency are the guarantee for the successful completion of water emergency rescue missions [3], [4]. The limited gas cylinder capacity restricts frogmen's underwater working time, furthermore, the frogmen's perception errors of movement path and time will waste their effective time performing rescue tasks. In some critical situations, frogmen are even likely to lose their own direction and position, which seriously threatens frogmen's safety. Therefore, frogmen need to rely on navigation equipment to know their real-time navigation parameters, such as trajectory, position, speed, heading direction, attitude, etc., and this process is called frogman self-navigation [5], [6]. Self-navigation is an important technology that aids frogmen to swim to target in the best route, to perform a series of underwater missions, and to return in time according to the actual situation. Studying frogman self-navigation method can provide important basis

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for frogmen to make decisions on their own when they are operating in waters, which plays the key role of guaranteeing frogmen's safety.

In traditional field of underwater vehicle self-navigation, using the motion parameters measured by inertial navigation system (INS) and doppler velocity log (DVL) to perform inertial navigation or DR algorithm is a common method. This method is hardly disturbed by external environment, which has the characteristics of high autonomy, strong robustness, and continuous and stable output data. However, as a special kind of underwater vehicles, frogman puts forward strict requirements on the volume, weight and environmental adaptability of navigation system [7], so the high-precision INS with large volume and weight will no longer be applicable [8]. Therefore, it is urgent to explore new navigation equipment and corresponding self-navigation methods. In [9], RJE company from U.S.A, RTSYS company from France, and Sharkmarine company from Canada have studied the hand-held frogman self-navigation system and method based on the combination of inertial measurement unit (IMU), DVL, magnetic compass and depth-meter. By using this device, frogmen can easily get their navigation parameters through the screen. However, the precision of IMU mounted in this device is low, so its accumulated positioning errors are very big. In order to suppress the divergence of positioning errors caused by low-precision IMU in this hand-held device, it is required to introduce other positioning algorithm's result or other sensor's output data as the external measurement information. By designing integrated navigation scheme, frogmen's positioning accuracy can be improved [10]–[12].

In recent years, the acoustic ranging and positioning technology based on transponder is an important method for realizing high-precision navigation of underwater vehicles, which has been widely applied [13]–[15]. In this field, acoustic positioning system (LBL/SBL/USBL) based on the principle of multi-transponder positioning has been successfully applied to the positioning of large underwater vehicles [16]–[18] and the tracking of large surface ship to small underwater sub-vehicles [19], and it has also been used in frogman detection and the positioning and tracking of underwater frogmen by background task center [20], [21]. In this system, frogmen are in the status of being detected or being tracked, their position information that do not diverge can only be acquired by task center. However, frogmen cannot conduct self-navigation on their own. To realize frogman accurate self-navigation, [22] has used underwater acoustic networks (UANs) to perform the positioning of target divers based on multi-transponders. This method has taken the divers' position coordinates calculated by UANs as measurement information and has solved the problem of DR positioning error accumulation. However, this scheme requires the arrangement of multiple underwater acoustic transponders to constitute the transponder array in advance, which is complex and not convenient for the practical applications in small areas or under emergency conditions. To reduce the cost and to make positioning system more suitable for the miniaturized frogman application demands, introducing STR information as external measurement has become a research hotspot in the field of underwater positioning, which has been successfully applied in underwater vehicle navigation [23]–[25]. Reference [23] has proposed a range-only and single-beacon (ROSB) technology for the tracking and positioning of autonomous underwater vehicles (AUVs). Reference [24] has realized the tracking of AUVs by designing a filtering algorithm based on single beacon ranging. Reference [25] has proposed a single-beacon navigation method based on SIMO model to conduct the navigation and positioning of group AUVs. The methods in [23]–[25] use single beacon ranging information as the measurement and suppress the divergence speed of position errors by filtering. However, these methods have not solved the problem that positioning errors accumulate over time under the condition of single transponder configuration. If the frogman's position can be calculated by using the transponder ranging information and the calculated position can be directly used as the measurement, the positioning error can be better compensated. Reference [26] has proposed a localization method based on single-beacon. However, the acoustic ranging system may be disturbed by external environment, which causes the fluctuation error in single-beacon localization result. If the positioning result of single transponder can be integrated with the continuous and stable DR result, the accuracy and robustness of frogman self-navigation result can be further improved.

According to the above technical background, the limitations of navigation equipment's volume and weight under frogman operating environment, and the work demands under emergency situations, and based on the analysis of the characteristics of UANs and single transponder ranging (STR), in this article, we study the virtual transponder array (VTA) positioning method and the frogman self-navigation method based on VTA and DR (VTA-DR) combined system. In the proposed method, we construct VTA by translating several frogman's movement vectors in adjacent sampling periods under the condition of single transponder configuration, so that the frogman's positioning coordinates directly calculated by VTA can be taken as the external measurement. Therefore, by using the proposed VTA positioning method, the problem of DR accumulated errors when measurement is only provided by STR information is solved. Finally, we use 3D motion capture system as ground truth for the semi-physical simulation experiments. Experimental results show that the proposed VTA-DR frogman self-navigation method can effectively suppress the positioning errors' accumulation and realize accurate and stable tracking for frogman.

The paper is organized as follows. In Section II, the traditional integrated navigation method based on STR and DR (STR-DR) combined system is introduced. In Section III, the construction and positioning method of VTA is proposed. In Section IV, the frogman self-navigation method based on VTA-DR combined system is proposed. In Section V, the equipment, scheme, results and analysis of semi-physical experiment is shown. Finally, conclusions are given in Section VI.

II. THE INTEGRATED NAVIGATION METHOD BASED ON STR-DR

STR-DR is a common navigation and positioning method for small underwater vehicles at present [23]. In this method, the depth-meter is used for depth constraint, and the STR-DR combined system is used for horizontal two-dimensional positioning of underwater vehicles. In the combined system, DR navigation algorithm describes the carrier's motion law in x-y plane, which can be written as state equation [27]. Assuming that the underwater carrier's 2D position coordinate at the i-th moment is (x_i, y_i), the state vector is chosen as $\boldsymbol{X}_i = [x_i, \dot{x}_i, y_i, \dot{y}_i]^T$, then the state equation can be obtained as

$$\boldsymbol{X}_i = \boldsymbol{\Phi} \cdot \boldsymbol{X}_{i-1} + \boldsymbol{G} \cdot \boldsymbol{W}_{i-1}, \tag{1}$$

where $\boldsymbol{\Phi}$ is the state transition matrix, $\boldsymbol{G}$ is the noise driven matrix, $\boldsymbol{W}_{i-1} = [W_{x,i-1}, W_{y,i-1}]^T$ is the state noise matrix with zero mean and covariance matrix $\boldsymbol{Q}_{i-1} = diag([\sigma^2_{vx,i-1}, \sigma^2_{vy,i-1}])$, which is determined by the error of DR system. Assuming that the sampling period is Δt, then the matrix $\boldsymbol{\Phi}$ and $\boldsymbol{G}$ can be respectively expressed as

$$\boldsymbol{\Phi} = \begin{bmatrix} 1 & \Delta t & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & \Delta t \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \boldsymbol{G} = \begin{bmatrix} \frac{\Delta t^2}{2} & 0 \\ \Delta t & 0 \\ 0 & \frac{\Delta t^2}{2} \\ 0 & \Delta t \end{bmatrix}. \tag{2}$$

The relative distance between single transponder and underwater carrier in x-y plane at the i-th moment is chosen as the measurement $\boldsymbol{Z}_i$, then the measurement equation can be written as

$$\boldsymbol{Z}_i = \boldsymbol{h}(\boldsymbol{X}_i) + \boldsymbol{V}_i = \boldsymbol{H}_i \cdot \boldsymbol{X}_i + \boldsymbol{V}_i, \tag{3}$$

where $\boldsymbol{V}_i$ is the measurement noise matrix with zero mean and covariance matrix $\boldsymbol{R}_i = \sigma^2_{r,i}$, which is determined by the error of STR system. Assuming that the 2D position coordinate of single transponder is (x_S, y_S), then the expression $\boldsymbol{h}(\boldsymbol{X}_i)$ can be written as $\boldsymbol{h}(\boldsymbol{X}_i) = \sqrt{(x_i - x_S)^2 + (y_i - y_S)^2}$. Therefore, the Jacobian matrix $\boldsymbol{H}_i$ of $\boldsymbol{h}(\boldsymbol{X}_i)$ can be calculated as

$$\begin{aligned} \boldsymbol{H}_i &= \frac{\partial \boldsymbol{h}(\boldsymbol{X}_i)}{\partial \boldsymbol{X}^T} |_{\boldsymbol{X}_i} \\ &= \Bigg[\frac{x_i - x_S}{\sqrt{(x_i - x_S)^2 + (y_i - y_S)^2}}, 0, \\ &\quad \frac{y_i - y_S}{\sqrt{(x_i - x_S)^2 + (y_i - y_S)^2}}, 0 \Bigg]. \end{aligned} \tag{4}$$

The above STR-DR underwater integrated navigation system uses the acoustic ranging function of single transponder, and the STR information is taken as measurement for DR navigation and positioning result. However, this method cannot directly provide position information as the measurement, so the problem of positioning error accumulation cannot be solved fundamentally. Based on the depth-meter and STR, we construct the VTA in this article with the aid of IMU and DVL measurement information, so that the position coordinate of frogman can be directly calculated to provide position measurement for the integrated navigation system.

III. THE CONSTRUCTION AND POSITIONING METHOD OF VTA

To suppress the accumulation of positioning errors, we propose the construction and positioning method of VTA with depth information constraint. By constructing VTA, frogman's position coordinate can be calculated, which will provide measurement information for the VTA-DR integrated self-navigation system in Section IV. The flow diagram of this VTA method is shown as Fig. 1.

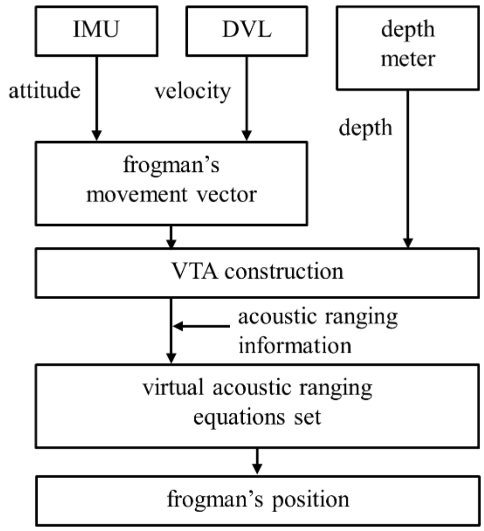

FIGURE 1. The flow diagram of VTA construction and VTA positioning method.

According to Fig. 1, VTA positioning method includes the following three steps:

a) Firstly, the complexity and dimension of underwater acoustic positioning algorithm are reduced by the constraint of depth information;
b) Then, frogman's movement vectors are calculated based on the information measured by IMU and DVL. By translating and superimposing the frogman's movement vectors in adjacent sampling periods, the VTA, which is composed of multiple virtual transponders, is constructed on the basis of actual single transponder;
c) Finally, aiding with the acoustic ranging information between interrogator (frogman) and each transponder in VTA, frogman's position coordinates can be calculated, so that the frogman self-navigation in local area under the condition of single transponder configuration can be realized.

A. THE UNDERWATER ACOUSTIC POSITIONING METHOD BASED ON MULTI-TRANSPONDER ARRAY WITH THE DEPTH INFORMATION CONSTRAINT

Acoustic ranging technology is an underwater wireless ranging method that uses the product of propagation delay of underwater acoustic signals and the sound velocity to calculate the relative distance between two points underwater [28]. Assuming that at the i-th sampling moment, the time required for the underwater acoustic signal to make a round trip between the transponder $\boldsymbol{X}_T$ and the interrogator $\boldsymbol{X}_R$ carried by frogman is Δt_i, and the sound velocity is known to be c, then the acoustic ranging information r_i between each transponder and the interrogator is shown as (5).

$$r_i = \|\boldsymbol{X}_R - \boldsymbol{X}_T\| = \sqrt{(x_R - x_T)^2 + (y_R - y_T)^2 + (z_R - z_T)^2} = \frac{1}{2}\Delta t_i \cdot c. \tag{5}$$

To ensure the uniqueness of three-dimensional positioning solution, at least four underwater transponder base stations with known locations are required. The relative distance information between the mobile underwater interrogator and the transponder base stations can be expressed as the underwater acoustic ranging equations set which is overdetermined, and the unique three-dimensional position coordinates of the underwater interrogator can be calculated by using the least square method to solve the overdetermined equations set. By introducing the depth information of the interrogator measured by the depth-meter, the dimension of underwater acoustic ranging equation set can be reduced from three dimensions to two dimensions. At this point, the two-dimensional space (x-y plane) position coordinates of the interrogator can be determined only by the underwater acoustic ranging information between three transponder base stations and the interrogator.

We assume that the depth value of the interrogator measured by the depth-meter at the i-th sampling moment is z_{Ri}, and that the position coordinates of the three underwater transponder base stations $\boldsymbol{X}_{T1} = (x_{T1}, y_{T1}, z_{T1})$, $\boldsymbol{X}_{T2} = (x_{T2}, y_{T2}, z_{T2})$, and $\boldsymbol{X}_{T3} = (x_{T3}, y_{T3}, z_{T3})$ are all known through prior calibration, then the underwater acoustic ranging equations set based on the depth information constraint at this time can be formulated as:

$$\begin{cases} (x_{Ri} - x_{T1})^2 + (y_{Ri} - y_{T1})^2 = r_{1i}^2 - (z_{Ri} - z_{T1})^2 \\ (x_{Ri} - x_{T2})^2 + (y_{Ri} - y_{T2})^2 = r_{2i}^2 - (z_{Ri} - z_{T2})^2 \\ (x_{Ri} - x_{T3})^2 + (y_{Ri} - y_{T3})^2 = r_{3i}^2 - (z_{Ri} - z_{T3})^2 \end{cases} \tag{6}$$

where r_{1i}, r_{2i} and r_{3i} are respectively the underwater acoustic ranging information between the three transponder base stations and the interrogator, and the unknown variables x_{Ri} and y_{Ri} in (2), which are the two-dimensional space position coordinates of the frogman, can be calculated by using the least square method.

Therefore, after introducing the depth information constraint, only three transponders are needed to realize the positioning of mobile interrogator.

B. THE CONSTRUCTION OF VTA AND THE CORRESPONDING UNDERWATER FROGMAN POSITIONING METHOD

1) OVERVIEW OF THE POSITIONING METHOD

According to the underwater positioning method based on multi-transponder array in section III. A, we should firstly lay at least three transponders, then calibrate the transponders' geographical positions before we start to locate the underwater frogman who carries the interrogator. This method will take a long time for making previous preparations, and it will also be difficult to arrange the complicated devices. Considering the strong emergency and high efficiency of frogman tasks, we propose the construction method of VTA based on IMU and DVL, and propose the corresponding underwater frogman positioning method.

In the proposed method, first we only throw one actual underwater transponder temporarily in the frogman's entry point to communicate with the interrogator carried by the frogman to obtain the acoustic ranging information between them. Then, according to the principle of DR navigation algorithm [29], the frogman's movement vectors can be calculated with the aid of the output data measured by the frogman-wearing IMU and DVL. And then, combined with the geometric relationship between the frogman's movement track and the actual single transponder, at least two virtual transponders will be constructed by translating the frogman's movement vectors. Those virtual transponders and the actual single transponder form the VTA together. Finally, by listing equations that satisfy the acoustic ranging information between the interrogator and the element transponders in VTA, we can get the virtual acoustic ranging equations set. Solving this equation set to obtain the frogman's position coordinates in x-y plane and placing the depth information measured by depth-meter into the third dimension, we can realize the frogman's three-dimensional positioning.

2) THE CONSTRUCTION OF VTA

Firstly, the frogman's entry point is assumed as the origin of navigation reference coordinate system. The right, forward and up directions of frogman's motion that are measured at the moment of entry by IMU are respectively specified as the x, y and z axes of navigation reference system, so that the navigation reference coordinate system is constructed. The VTA algorithm proposed in this section and the VTA-DR algorithm which will be proposed in Section IV are both carried out under this navigation reference system, and the frogman's position coordinates calculated through these two algorithms are the relative positioning results under this navigation reference system. Assuming that the frogman's three-dimensional position coordinate at the i-th sampling moment is (x_{wi}, y_{wi}, z_{wi}), in which z_{wi} is directly measured by the depth-meter, and the frogman's two-dimensional space position coordinate is $\boldsymbol{X}_{wi} = (x_{wi}, y_{wi})$. The actual single transponder is vertically thrown at the frogman's entry point, and the transponder's position coordinate under navigation reference system is expressed as $\boldsymbol{X}_s = (x_s, y_s, z_s)$. The two-dimensional space position coordinate of the first virtual transponder constructed at the i-th sampling moment is $\boldsymbol{X}_{iV1} = (x_{iV1}, y_{iV1})$, and the two-dimensional space position coordinate of the second virtual transponder constructed at the i-th sampling moment is $\boldsymbol{X}_{iV2} = (x_{iV2}, y_{iV2})$. The flow diagram for building VTA is shown as Fig. 2.

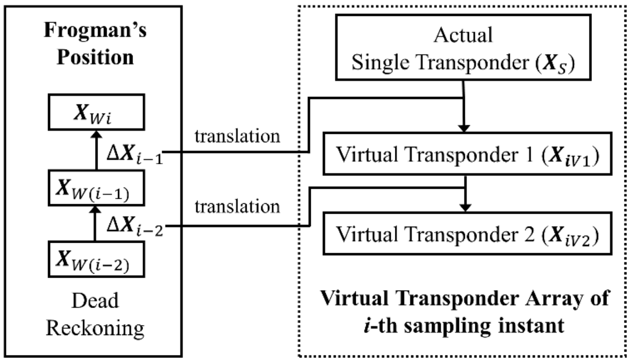

FIGURE 2. The flow diagram for building VTA.

In Fig. 2, $\Delta\boldsymbol{X}_{i-1}$ and $\Delta\boldsymbol{X}_{i-2}$ are respectively the frogman's movement vectors during the sampling period ΔT_{i-1} and ΔT_{i-2}, and the arithmetic expression of them is shown as

$$\begin{cases} \Delta\boldsymbol{X}_{i-1} = \boldsymbol{C}^n_{b(i-1)} \cdot \boldsymbol{V}_{b(i-1)} \cdot \Delta T_{i-1} \\ \Delta\boldsymbol{X}_{i-2} = \boldsymbol{C}^n_{b(i-2)} \cdot \boldsymbol{V}_{b(i-2)} \cdot \Delta T_{i-2} \end{cases} \tag{7}$$

where $\boldsymbol{C}^n_{b(i-1)}$ and $\boldsymbol{C}^n_{b(i-2)}$ are respectively the frogman's movement attitude transition matrices at the *(i-1)*-th sampling moment and the *(i-2)*-th sampling moment, and the matrices can be calculated by processing the output data from IMU [30]. $\boldsymbol{V}_{b(i-1)}$ and $\boldsymbol{V}_{b(i-2)}$ are respectively the frogman's movement velocity at the *(i-1)*-th sampling moment and the *(i-2)*-th sampling moment that can be measured by DVL. When the IMU and DVL are installed in a certain way and the IMU and DVL combined system is worn at the certain part of frogman's body, the movement vector of the frogman can be calculated according to (7).

On the basis of the definition of acoustic ranging information r_i shown in (5) in section III. A, the equations that satisfy the acoustic ranging information between the interrogator and the actual single transponder at the i-th, the i-1-th and the i-2-th sampling moment are:

$$\begin{cases} (x_{Wi} - x_S)^2 + (y_{Wi} - y_S)^2 = r_i^2 - (z_{Wi} - z_S)^2 \\ (x_{W(i-1)} - x_S)^2 + (y_{W(i-1)} - y_S)^2 \\ = r^2_{(i-1)} - (z_{W(i-1)} - z_S)^2 \\ (x_{W(i-2)} - x_S)^2 + (y_{W(i-2)} - y_S)^2 \\ = r^2_{(i-2)} - (z_{W(i-2)} - z_S)^2 \end{cases} \tag{8}$$

According to the principle of DR navigation algorithm, the relationship among the frogman's position $\boldsymbol{X}_{Wi}$, $\boldsymbol{X}_{W(i-1)}$, and $\boldsymbol{X}_{W(i-2)}$ at the i-th, the i-1-th and the i-2-th sampling moment can be expressed by introducing the frogman's movement vectors as shown in (9).

$$\begin{cases} \boldsymbol{X}_{Wi} = \boldsymbol{X}_{W(i-1)} + \Delta\boldsymbol{X}_{i-1} \\ \boldsymbol{X}_{W(i-1)} = \boldsymbol{X}_{W(i-2)} + \Delta\boldsymbol{X}_{i-2}. \end{cases} \tag{9}$$

By substituting (9) into (8), we obtain the equations set:

$$\begin{cases} (x_{Wi} - x_S)^2 + (y_{Wi} - y_S)^2 = r_i^2 - (z_{Wi} - z_S)^2 \\ [x_{Wi} - (x_S + \Delta x_{i-1})]^2 + [(y_{Wi} - (y_S + \Delta y_{i-1})]^2 \\ = r^2_{i-1} - (z_{W(i-1)} - z_S)^2 \\ [x_{Wi} - (x_S + \Delta x_{i-1} + \Delta x_{i-2})]^2 \\ + [(y_{Wi} - (y_S + \Delta y_{i-1} + y_{i-2})]^2 \\ = r^2_{i-1} - (z_{W(i-2)} - z_S)^2 \end{cases} \tag{10}$$

After comparing the forms of (10) and (6), we find that the arithmetic expressions $[(x_S + \Delta x_{i-1}), (y_S + \Delta y_{i-1})]$ and $[(x_S + \Delta x_{i-1} + \Delta x_{i-2}), (y_S + \Delta y_{i-1} + \Delta y_{i-2})]$ in (10) can respectively be the analogies of the actual transponders' two-dimensional space position coordinates (x_{T2}, y_{T2}) and (x_{T3}, y_{T3}) in (6), and they have played a role that is similar to the actual transponders in the processing of underwater frogman's positioning. Therefore, we define the arithmetic expressions $[(x_S + \Delta x_{i-1}), (y_S + \Delta y_{i-1})]$ and $[(x_S + \Delta x_{i-1} + \Delta x_{i-2}), (y_S + \Delta y_{i-1} + \Delta y_{i-2})]$ as the first and the second virtual transponder at the i-th sampling moment respectively, and their two-dimensional space position coordinates are respectively expressed as $\boldsymbol{X}_{iV1}$ and $\boldsymbol{X}_{iV2}$:

$$\boldsymbol{X}_{iV1} = \boldsymbol{X}_S + \Delta\boldsymbol{X}_{i-1} = [(x_S + \Delta x_{i-1}), (y_S + \Delta y_{i-1})], \tag{11}$$

$$\begin{aligned} \boldsymbol{X}_{iV2} &= \boldsymbol{X}_{iV1} + \Delta\boldsymbol{X}_{i-2} \\ &= [(x_S + \Delta x_{i-1} + \Delta x_{i-2}), (y_S + \Delta y_{i-1} + \Delta y_{i-2})]. \end{aligned} \tag{12}$$

According to (11), we can see that, the first virtual transponder $\boldsymbol{X}_{iV1}$ at the i-th sampling moment is constructed by translating and superimposing the movement vector $\Delta\boldsymbol{X}_{i-1}$ that frogman has made during the sampling period ΔT_{i-1} onto the actual single transponder $\boldsymbol{X}_S$. Similarly, according to (12), the second virtual transponder $\boldsymbol{X}_{iV2}$ at the i-th sampling moment is constructed by translating and superimposing the movement vector $\Delta\boldsymbol{X}_{i-2}$ that frogman has made during the sampling period ΔT_{i-2} onto the first virtual transponder $\boldsymbol{X}_{iV1}$. The construction process and result of VTA are shown as Fig. 3.

In Fig. 3, the actual transponder $\boldsymbol{X}_S$ and the virtual transponders $\boldsymbol{X}_{iV1}$, $\boldsymbol{X}_{iV2}$ together constitute the VTA at the i-th sampling moment. r_i, r_{i-1}, and r_{i-2} are respectively the ranging information between frogman and each transponder. Whether the single transponder is placed at bottom or on surface of water, frogman's motion parameters can be collected through the IMU and DVL that are worn on his own body, and the normal acoustic communication between transponder and interrogator is available. Therefore, the VTA positioning algorithm can be used normally both under the circumstance of bottom-of-water transponder and the circumstance of surface-of-water transponder.

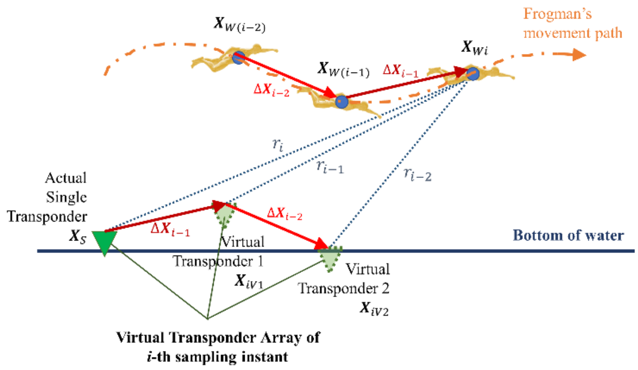

FIGURE 3. **The construction process and result of VTA.**

C. THE THREE-DIMENSIONAL POSITIONING METHOD BASED ON VTA

Based on the frogman's depth position z_{Wi} measured by depth-meter and position coordinates (x_{W1}, y_{W1}), (x_{W2}, y_{W2}) at $i = 1, 2$ sampling moment that have been calculated through the STR-DR algorithm in Section II, we can calculate the frogman's position coordinate (x_{Wi}, y_{Wi}) in x-y plane by adopting the VTA that has been built in section III. B and using the ranging information r_i, r_{i-1}, r_{i-2} between frogman and each transponder shown in Fig. 3. The specific calculation steps are as follows:

-- Firstly, according to the definition of virtual transponder and the geometric relationship shown in Fig. 3, we substitute (11) and (12) into (10):

$$\begin{cases} (x_{Wi} - x_S)^2 + (y_{Wi} - y_S)^2 = r_i^2 - (z_{Wi} - z_S)^2 \\ (x_{Wi} - x_{iV1})^2 + (y_{Wi} - y_{iV1})^2 \\ = r_{i-1}^2 - (z_{W(i-1)} - z_S)^2 \\ (x_{Wi} - x_{iV2})^2 + (y_{Wi} - y_{iV2})^2 \\ = r_{i-2}^2 - (z_{W(i-2)} - z_S)^2 \end{cases} \tag{13}$$

In (13), the first equation represents the relative distance between the projections of the actual single transponder and the interrogator in x-y plane, and the other two equations represent the relative distance between the projections of the virtual transponders and the interrogator in x-y plane. So that we define (13) as the virtual acoustic ranging equations set referring to the explanation of (6).

-- Secondly, by solving the virtual acoustic ranging equations set (13) with the least square method, the frogman's two-dimensional position coordinate (x_{Wi}, y_{Wi}) at the i-th sampling moment can be calculated.

-- Thirdly, by adding the depth information z_{Wi} measured by depth-meter as the third-dimension information, the frogman's three-dimensional position coordinate (x_{Wi}, y_{Wi}, z_{Wi}) at the i-th sampling moment can be obtained. Thus, we have realized the underwater frogman's three-dimensional positioning with the configuration of single transponder through the positioning method based on VTA with the constraint of depth information.

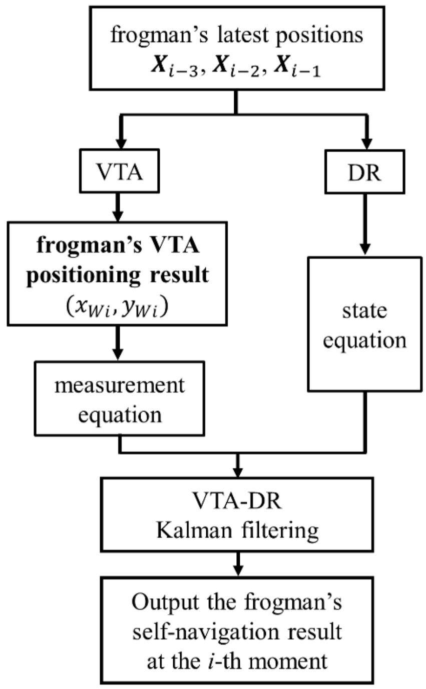

FIGURE 4. **The flow diagram of frogman self-navigation method based on VTA-DR integrated system (at the i-th moment).**

IV. THE FROGMAN SELF-NAVIGATION METHOD BASED ON VTA-DR

Using the VTA can directly calculate frogman's position and better suppress the error accumulation of DR navigation system. However, the error of acoustic ranging will cause the fluctuation error of VTA positioning, which is same as the error of wireless positioning. In order to give consideration to both the accuracy and robustness of positioning method, and to make the advantages of VTA and DR complementary to each other, we carry out the information fusion of these two algorithms and propose the frogman self-navigation method based on VTA-DR. In this method, DR accumulative errors are suppressed by introducing the VTA positioning results as external measurement information, at the same time, VTA fluctuation errors are suppressed by combining with the smooth and short-term stable DR positioning results, so that the frogman self-navigation with high-precision and strong-robustness can be realized. The flow diagram of VTA-DR self-navigation method is shown as Fig. 4.

The design scheme of Kalman filter shown in Fig. 4 is as follows.

The DR navigation system with depth constraint describes the frogman's motion law in x-y plane. Assuming that the underwater frogman's two-dimensional position coordinate is (x_i, y_i) at the i-th moment, the state vector is chosen as $\boldsymbol{X}_i = [x_i, \dot{x}_i, y_i, \dot{y}_i]^T$, then according to the principle of DR navigation, we can obtain the state equation as

$$\boldsymbol{X}_i = \boldsymbol{\Phi} \cdot \boldsymbol{X}_{i-1} + \boldsymbol{G} \cdot \boldsymbol{W}_{i-1}, \tag{14}$$

where the definitions of state transition matrix $\mathbf{\Phi}$, noise driven matrix $\boldsymbol{G}$, and state noise matrix $\boldsymbol{W}_{i-1}$ are same as that of the STR-DR integrated system in section II.

Combined with the three latest frogman's coordinates $\boldsymbol{X}_{i-3}$, $\boldsymbol{X}_{i-2}$ and $\boldsymbol{X}_{i-1}$ that have been calculated before the i-th sampling moment, we can calculate the frogman's two-dimensional position coordinate $\boldsymbol{Z}_i = [x_{Wi}, y_{Wi}]^T$ by using VTA method at the i-th moment, and choose $\boldsymbol{Z}_i$ as the measurement vector of VTA-DR integrated system, then the measurement equation can be expressed as

$$\boldsymbol{Z}_i = \boldsymbol{H}_i \cdot \boldsymbol{X}_i + \boldsymbol{V}_i, \tag{15}$$

where the measurement matrix $\boldsymbol{H}_i$ is

$$\boldsymbol{H}_i = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}. \tag{16}$$

The measurement noise matrix $\boldsymbol{V}_i$ with zero mean and covariance matrix $\boldsymbol{R}_i = \sigma_{w,i}^2$ in (15) is determined by the statistical error of VTA underwater positioning method. When the $i+1$-th moment arrives, the frogman's latest position coordinates that participate in VTA-DR calculation will be updated to $\boldsymbol{X}_{i-2}$, $\boldsymbol{X}_{i-1}$ and $\boldsymbol{X}_i$.

By using the result of VTA underwater positioning method as the position measurement information, we design the filter to correct frogman's DR navigation and positioning results. The VTA-DR integrated system can fully realize the complementary advantages of different navigation and positioning algorithms, better suppress the positioning error accumulated over time, and further improve the accuracy and autonomy of frogman self-navigation system.

V. EXPERIMENT

In order to verify the validity of the proposed self-navigation method, a semi-physical simulation experimental environment is built, which is based on IMU and high-precision three-dimensional motion capture system, and the semi-physical experiment is carried out. In the experiment, frogman's motion state is simulated by the up-and-down motion of experimenter's foot. By using the position and velocity data output by 3D motion capture system that is synchronized with the data output by IMU, the real value of depth-meter, DVL and STR can be calculated. Then, after adding the error data that is consistent with the corresponding sensor characteristics, the simulated value of sensors' output signals is generated. Finally, based on above simulated data and real IMU measurement data, the positioning performance of traditional STR-DR method and the proposed VTA-DR method is compared and analyzed.

A. EXPERIMENTAL EQUIPMENT AND SCHEME

1) EXPERIMENTAL EQUIPMENT

1) MTi-G-700 Inertial measurement unit

MTi-G-700 inertial measurement unit shown in Fig. 5 can output the data of 3D accelerometer and 3D gyroscope. The specs of MTi-G-700 IMU is shown in Table 1.

FIGURE 5. MTi-G-700 Inertial measurement unit.

TABLE 1. The specs of MTi-G-700 IMU.

Sensor	Measuring Range	Constant Drift	Random Error
Accelerometer	±5 g	10^{-3} g	5×10^{-4} g
Gyroscope	±450 °/s	0.2 °/s	0.01 °/s

In the experiment, MTi-G-700 IMU is worn on experimenter's foot to collect the foot's inertial movement information. By processing the measurement data of IMU gyroscope, experimenter foot's real movement attitude can be calculated and be directly used in the subsequent VTA-DR positioning algorithm.

2) Nokov 3D Optical motion capture system

Nokov 3D optical motion capture system can capture and output the accurate three-dimensional data of the object to be measured, which is mainly composed of infrared optical motion capture lens, operation, analysis and processing software and related accessories. The accuracy of system can reach sub-millimeter level, which meets the requirements of evaluating the positioning accuracy of the method we have proposed in this article. The Nokov 3D optical motion capture system is shown in Fig. 6. It is used as the recorder of experimenter's movement parameter, and the high-precision position, velocity and attitude information output by motion capture system will be the evaluation benchmark of the navigation results. In addition, part of the data will be processed to simulate the truth value of the output signals of underwater navigation subsystems such as DVL and single transponder acoustic ranging system. The specific simulation scheme will be described in detail in the next part of this section.

2) SCHEME OF THE SEMI-PHYSICAL SIMULATION EQUIPMENT

The scheme of semi-physical simulation experiment is composed of three parts: a) simulation of frogman's motion state; b) acquisition of frogman's movement parameters; c) processing of experimental data.

a) Simulation of frogman's motion state

It can be seen from [31] and [32] that the movement parameters of pedestrian's feet and frogman's body both show regular changes when walking and swimming respectively, and the similarity between these two motion models is high.

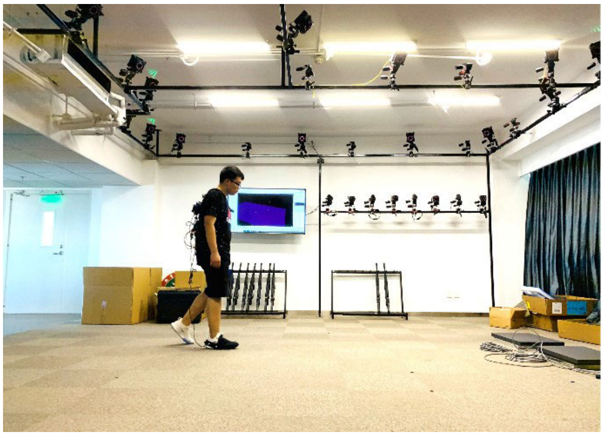

FIGURE 6. Nokov 3D Optical motion capture system.

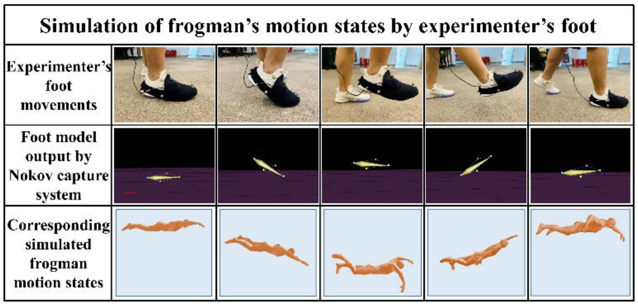

FIGURE 7. Simulation of frogman's motion states.

Therefore, we can use different foot movements of lifting and landing the foot, changing the heading direction of the toes, changing the inclination angle between the foot and the ground, etc., to simulate various possible motion states of the frogman during underwater swimming, such as the heaving and dipping of the body, the change of frogman's swimming direction and the swing from side to side, which is as the circumstance shown in Fig. 7.

In Fig. 7, the motion decomposition diagrams of experimenter's foot, the foot model diagrams output by Nokov capture system, and the corresponding diagrams of simulated frogman motion states are respectively presented. In the experiment, by controlling the foot attitude's changing frequency and the walking speed, we make it as consistent as possible with the frogman's body attitude and heaving-and-dipping frequency during swimming, so that frogman's motion states can be simulated effectively. Therefore, the error of navigation result under semi-physical simulation environment can reflect the navigation error characteristics of underwater frogman.

b) Acquisition of frogman's movement parameters

In the experiment, we use 3D motion capture system to obtain the position and velocity information that is synchronized with the IMU data. Then, we adopt the scheme shown in Fig. 8 to acquire frogman's movement parameters.

In the semi-physical simulation experiment,

-- We put the MTi-G-700 inertial measurement unit on the experimenter's foot to collect the inertial measurement

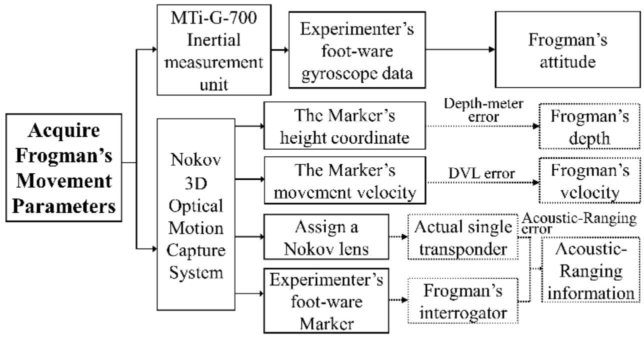

FIGURE 8. Schematic diagram of acquiring the frogman's movement parameters.

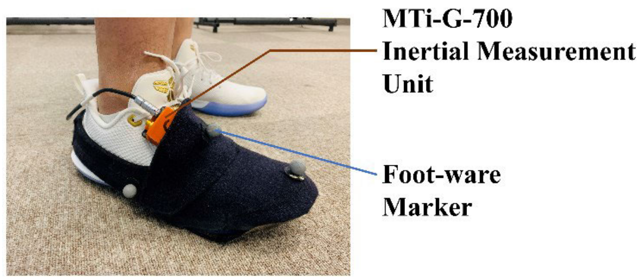

FIGURE 9. The detail picture of experimenter's foot-wearable device.

information during the simulated process of frogman movement. The detail of the experimenter's foot wearable device is shown in Fig. 9.

-- We stick the marker of Nokov 3D optical motion capture system onto the experimenter's foot to simulate the interrogator worn on the frogman's body, and assign a lens of the system to simulate the actual single transponder.

-- We respectively add the sensor errors of depth-meter and DVL onto the height coordinate and movement velocity of the marker stuck to the experimenter's foot that output by the optical motion capture system, simulating the frogman's depth information measured by depth-meter and the frogman's movement velocity measured by DVL.

-- We also add appropriate noises on the wireless ranging information between the marker stuck to experimenter's foot and the lens of Nokov 3D motion capture system for the simulation of the acoustic ranging information between the interrogator worn on frogman's body and the actual single transponder thrown to the bottom of water. The above data with sensor errors can accurately reflect the error characteristics of each sensor, so these data can be used as the output information of depth-meter, DVL and STR system for frogman positioning.

c) Processing of experimental data

Finally, we use both the traditional STR-DR algorithm introduced in Section II and the VTA-DR algorithm proposed in Section IV, to conduct the data processing of above frogman's movement parameters. Because Nokov 3D optical motion capture system can quickly and accurately track the position of the reflective marker, it is taken as the ground truth to evaluate the accuracy of our positioning method in the experiments of this article. By respectively calculating the errors between the ground truth and those two positioning methods, we analyze and compare the positioning performance of STR-DR and VTA-DR.

Through the above scheme of semi-physical simulation experiment, frogman's motion states during swimming can be simulated by the foot's periodic movements during walking. The measurement data of DVL and STR system are obtained by adding true error data of underwater sensors (extract from the previous experimental data accumulated by our research group) onto the truth values of velocity and ranging information that have output by the motion capture system. Therefore, after processing, the data obtained from our semi-physical simulation experiment have the same error characteristics as actual underwater sensors. This article studies the frogman's navigation and positioning method, which belongs to kinematics research and does not involve dynamics research, so the difference of air or underwater environment medium does not affect the effectiveness of the proposed self-navigation algorithm. Therefore, the semi-physical simulation experiment can be used to verify the effectiveness and performance of the VTA-DR method.

B. EXPERIMENTAL RESULTS AND ANALYSIS

We respectively carry out experiments on three different tracks (single-circle closed track, multi-circle closed track and non-closed track), and the availability and accuracy of the proposed positioning method will be verified through the analysis of experimental data under different movement time and various track shape.

1) EXPERIMENTAL RESULTS

After processing the experimental data according to the proposed method, the experimental results under three different tracks are obtained as shown in Fig. 10 to 12 respectively.

1) Experimental track 1
2) Experimental track 2
3) Experimental track 3

In Fig. 10 to 12, Δx_F and Δy_F are respectively the difference between the ground truth and the experimenter's location results calculated by STR-DR and VTA-DR algorithm in the x and y directions. Δ_F is the total difference between the ground truth and location results calculated by STR-DR and VTA-DR algorithm in x-y plane.

2) ANALYSIS OF THE EXPERIMENTAL RESULTS

We use the evaluation criterion that calculates the mean value μ and the standard deviation σ to describe the centralized location and the fluctuation of the positioning results shown in Fig. 10 to 12. Assuming that the number of sampling points is N, $\mu_{\Delta x_F}$ and $\mu_{\Delta y_F}$ are respectively the mean value of the location errors in x and y as shown in (17). $\sigma_{\Delta x_F}$ and $\sigma_{\Delta y_F}$ are respectively the standard deviation of the location errors in x and y as shown in (18). μ_{Δ_F} is the mean value of total location errors in x-y plane as shown in (19). σ_{Δ_F} is the standard deviation of total location errors in x-y plane as shown in (20).

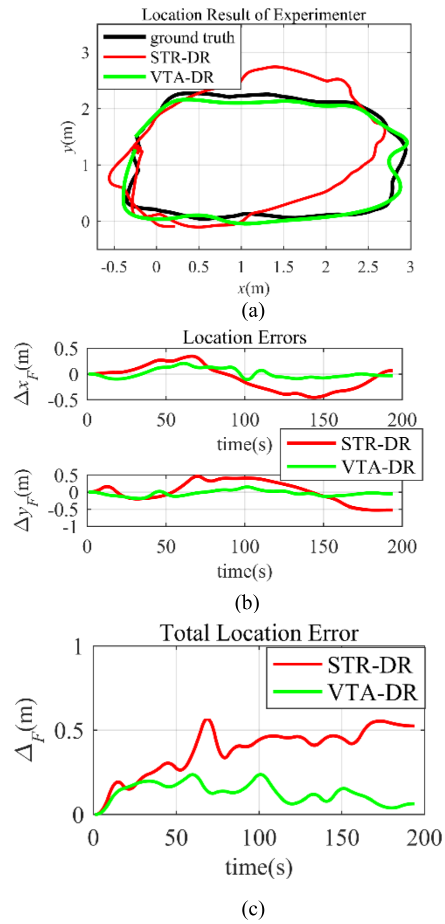

FIGURE 10. (a) Location result of the experimenter, (b) Location errors in x and y, (c) Total location error in x-y plane.

$$\mu_{\Delta x_F} = \frac{1}{N}\sum_{i=1}^{N} \Delta x_{Fi}, \quad \mu_{\Delta y_F} = \frac{1}{N}\sum_{i=1}^{N} \Delta y_{Fi}. \tag{17}$$

$$\sigma_{\Delta x_F} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (\Delta x_{Fi} - \mu_{\Delta x_F})^2},$$

$$\sigma_{\Delta y_F} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (\Delta y_{Fi} - \mu_{\Delta y_F})^2} \tag{18}$$

$$\mu_{\Delta_F} = \frac{1}{N}\sum_{i=1}^{N} \sqrt{(\Delta x_{Fi})^2 + (\Delta y_{Fi})^2}, \tag{19}$$

$$\sigma_{\Delta_F} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} [(\Delta x_{Fi})^2 + \left(\Delta y_{Fi}\right)^2 - \mu_{\Delta_F}]^2}. \tag{20}$$

According to above-mentioned principles, the data analysis of the experiments can be shown as Table 2.

To further analyze all the data obtained from experimental track 1 to 3 shown in Table 2, we calculate the average of the absolute mean value of location errors in x and y directions

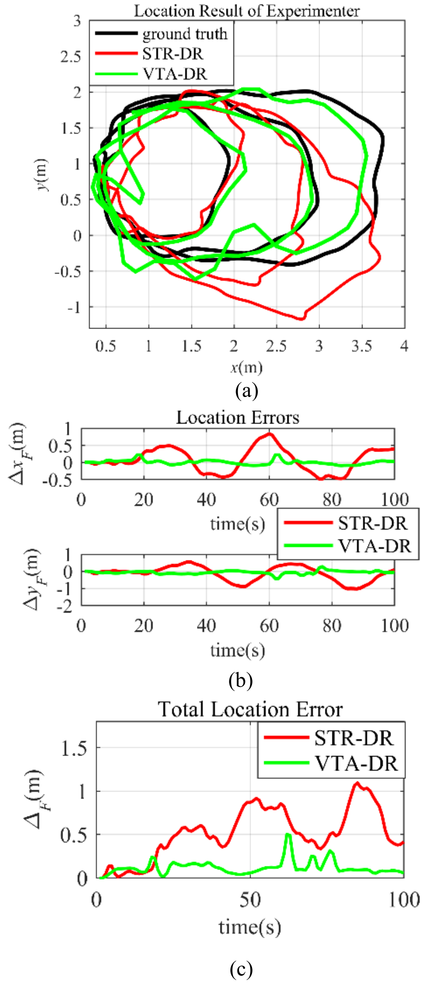

FIGURE 11. **(a) Location result of the experimenter, (b) Location errors in x and y, (c) Total location error in x-y plane.**

TABLE 2. **The analysis table of the experimental results under three different tracks.**

Track	Method	$\mu_{\Delta x_F}$ (m)	$\sigma_{\Delta x_F}$	$\mu_{\Delta y_F}$ (m)	$\sigma_{\Delta y_F}$	$\mu_{\Delta F}$ (m)	$\sigma_{\Delta F}$
1	STR-DR	-0.151	0.055	0.271	0.068	0.321	0.033
	VTA-DR	0.082	0.022	-0.104	0.019	0.165	0.014
2	STR-DR	0.221	0.051	-0.296	0.062	0.515	0.041
	VTA-DR	0.091	0.016	-0.185	0.027	0.238	0.025
3	STR-DR	-0.053	0.041	0.025	0.056	0.127	0.042
	VTA-DR	-0.036	0.031	0.026	0.033	0.045	0.036

that are expressed as $\overline{|\mu_{\Delta x_F}|}$ and $\overline{|\mu_{\Delta y_F}|}$, the average of the standard deviation of location errors in x and y directions that are expressed as $\overline{\sigma_{\Delta x_F}}$ and $\overline{\sigma_{\Delta y_F}}$, and the average of the mean value and standard deviation of total location errors in x-y plane that are expressed as $\overline{\mu_{\Delta F}}$ and $\overline{\sigma_{\Delta F}}$. The comparison of STR-DR and VTA-DR positioning performance is shown in Table 3.

Through the analysis of the positioning results of semi-physical simulation experiments under three different tracks, it can be seen that the average total location error of the proposed VTA-DR method is 0.149m. The positioning error of VTA-DR method is reduced by 53.5% compared with STR-DR method, so the positioning accuracy of VTA-DR

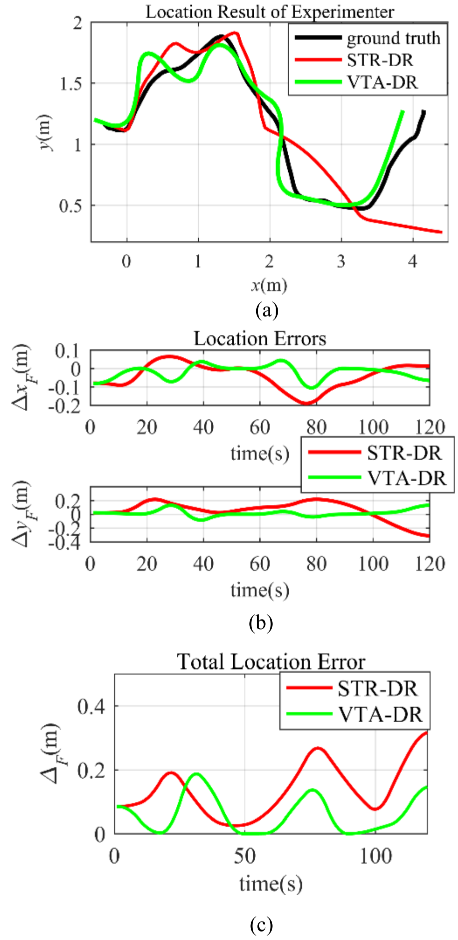

FIGURE 12. **(a) Location result of the experimenter, (b) Location errors in x and y, (c) Total location error in x-y plane.**

TABLE 3. **The comparison table of STR-DR and VTA-DR positioning results.**

Positioning Method	$\overline{\lvert\mu_{\Delta x_F}\rvert}$ (m)	$\overline{\sigma_{\Delta x_F}}$	$\overline{\lvert\mu_{\Delta y_F}\rvert}$ (m)	$\overline{\sigma_{\Delta y_F}}$	$\overline{\mu_{\Delta F}}$ (m)	$\overline{\sigma_{\Delta F}}$
STR-DR	0.142	0.049	0.197	0.062	0.321	0.039
VTA-DR	0.070	0.023	0.105	0.026	0.149	0.025

method is higher than STR-DR method. The total location error's average standard deviation of VTA-DR method is 0.025, which is reduced by 35.9% compared with STR-DR method, so the positioning robustness of VTA-DR method is stronger than STR-DR method. The above experimental results show that the VTA-DR positioning method we have proposed in this article can further improve the accuracy and robustness of positioning results under the condition of single transponder configuration, and realize high-precision tracking of the underwater frogman.

VI. CONCLUSION

In this article, we propose an underwater frogman self-navigation method based on DR-VTA. Using this method, the underwater frogman can be located reliably and accurately by means of constructing the VTA and adopting the information fusion of multiple sensors, which is under the condition of only throwing one actual transponder temporarily for the underwater acoustic ranging. Experimental results show that the average and standard deviation of total location errors of VTA-DR method is respectively reduced by 53.5% and 35.9% compared with traditional STR-DR method. Therefore, VTA-DR self-navigation method has the better positioning accuracy and robustness. This self-navigation method requires little preparation steps before the mission, and the device adopted for measurement is simple, light and easy to carry, so we think that it would have a good application prospect in emergency rescue of frogman or other special operation circumstances.

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