Research on Error Correction methods for the Integrated Navigation System of Deep-sea Human Occupied Vehicles

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***Abstract*—Because electromagnetic wave attenuates fast in water, some land navigation equipment cannot be used underwater, so Long Base Line, Doppler Velocity Log and Motion sensor become the main mean of navigation and positioning for HOV. This paper puts forward the corresponding errors compensation methods for the instruments and system that mainly used underwater in order to improve the navigation and positioning accuracy. In this paper, UKF is selected as filtering algorithm to fuse the data after compensation. At last, the numerical experiments showed that the propose approach here is applicable and effective.**

Keywords—HOV (Human Occupied Vehicle); Integrated Navigation System; LBL (Long Base Line); Motion Sensors; DVL (Doppler Velocity Log); UKF (Unscented Kalman Filter).

I. Introduction

As an important tool for human to explore and exploit ocean, Human Occupied Vehicles(HOV) have been widely used in many fields. High precision navigation and positioning is not only a necessary condition for Human Occupied Vehicles to work well and effectively underwater, but also related to the safety of the vehicles. Jiao-long HOV, which is studied and developed in China has been successfully dived to 7000m depth underwater successfully in 2012[1]. Although the develop of Jiao-long has achieved many technical breakthroughs, several techniques still need to be improved. Among them, the improvement of the accuracy of navigation and positioning system is an urgent one.

Because electromagnetic waves attenuate fast in water, some onshore navigation techniques (such as GPS) cannot be used underwater. Navigation instruments and systems that are used underwater mainly include Long Base Line acoustic positioning system, Doppler Velocity Log, Motion Sensors and Depth Gauge.

This paper focuses on the error correction of Long Base Line acoustic positioning system, Motion Sensors and Doppler Velocity Log. Effective method has been adopted to fuse the data of Long Base Line acoustic positioning system, Motion Sensors and Doppler Velocity Log. At the same time this paper puts a validation technique based on statistics theory to test the result between the data before and after compensation. And this paper selects And Unscented Kalman Filter(UKF) [2] is selected as filtering algorithm to fuse the data after compensation.

The error correction algorithms can not only apply to deep-sea HOV, but also to other underwater robots which use LBL, Motion Sensors and DVL as navigation systems.

II. RESSEARCH ON ERROR CORRECTION MENTHODS

A. Research on Error Correction methods of LBL

The navigation and positioning system for HOV mainly depends on measuring propagation time of sound velocity in the seawater [3]. Randomness and no uniformity of seawater have effect on sound velocity and the track of sound propagation. But in the traditional acoustic ranging in the sea, we often think sound velocity is constant and the track of sound propagation is a straight line, these estimations cause errors of navigation and positioning for HOV [4]. So these error need to be compensated.

First, the sea is divided into many layers, then the paper uses constant gradient sound velocity profile and constant sound velocity profile to Instead of the real sound velocity profile respectively, acquires the following horizontal positioning equation:

$$R_i = -\frac{1}{kg_i} \tag{1}$$

$$x_i = R_i(\sin\alpha_i - \sin\alpha_{i-1}) = \left|\frac{C_0}{\cos\alpha_0 g_i}(\sin\alpha_i - \sin\alpha_{i-1})\right| \tag{2}$$

Sponsor: The National High-Tech Research and Development Program of China (2009AA093302).

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978-0-933957-43-5 ©2015 MTS

This is constant gradient sound velocity profile horizontal positioning equation. g_i is gradient value. α_i is grazing angle of each layer. R_i is radius of curvature.

$$x_s = \Delta z_i \cot a_i = \frac{kC_i \Delta z_i}{\left(1-(kC_i)^2\right)^{1/2}} \tag{3}$$

Here this paper introduces the difference of relative area.

$$\varepsilon_s = \frac{\Delta s}{s} = \frac{C_i - C_{i-1}}{2C_{i-1}} \tag{4}$$

The relative positioning error is:

$$\varepsilon_x = \frac{x_s - x_t}{x_t} = \frac{x_s}{x_t} - 1 \tag{5}$$

Put (2), (3) and (4) into (5), we can get the equation:

$$\begin{aligned}\varepsilon &= \frac{x_s - x_t}{x_t} \\ &= \left\{ \frac{\left\{ \cos\alpha_{i-1} \big/ 2\varepsilon_s \ln\left[(1+2\varepsilon_s)(1+\sin\alpha_{i-1}) \big/ \left(1+\sqrt{1-(1+2\varepsilon_s)^2\cos^2\alpha_{i-1}}\right) \right] \right\} \big/}{\sqrt{1-(1+2\varepsilon_s)^2\cos^2\alpha_{i-1}} - \tan\alpha_{i-1} - (1+2\varepsilon_s)\cos\alpha_{i-1}} \right\} - 1\end{aligned} \tag{6}$$

From the equation, the following conclusion can be obtained: if two sound velocity profiles have the same grazing angle and difference of relative area, we think they have the same positioning result. So we use the constant gradient sound velocity profile to instead of the real sound velocity profile to reduce the computing complexity calculated amount. Then we use spherical localization [5-7] algorithm to calculate, and set a threshold value for selecting the best solution from multiple solutions. We use someday sea trial data to validation the method that we put forward above. The 2D and 3D contrast figures of before and after compensation can be seen in figure 1 to figure 2.

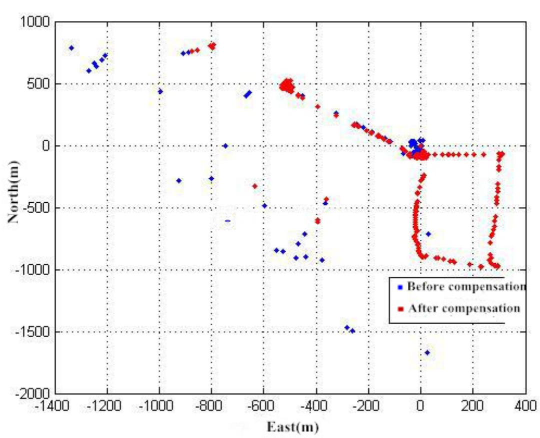

Fig. 1. 2D contrast figure after compensation

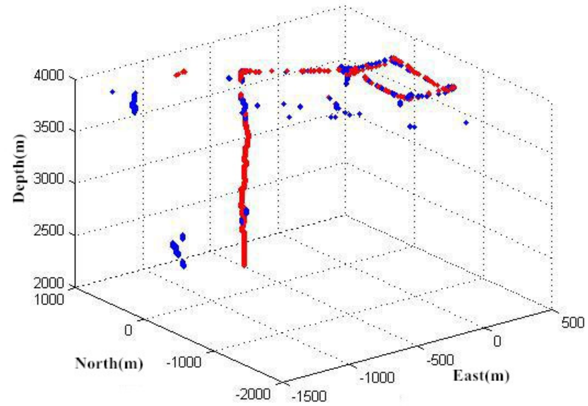

Fig. 2. 3D contrast figure after compensation

From the figure above, we find that outlier of after compensation is less than that before compensation. But because the limitation of objective factors, we cannot get the real value of the HOV's positioning underwater. So in this paper we put up with a new method which based on statistical principle to compare the positioning accuracy of before and after compensation. Now we introduce this method: the measuring points of before and after compensation distribution in the area of the circle with center point of the real positioning value with different radius. The whole track of HOV can be seen as a curve that consist of many tiny straight lines, we select a straight line named AI of them to explain. According to statistical principle the positioning points of before compensation (the yellow points) and the points after compensation (the red ones) distribute the both sides of the real positioning track (the black line), and if the accuracy of after compensation better than the before, then we can draw such a conclusion $P(\|\overline{AB}\| > \|\overline{ab}\|) > 0.5$. This conclusion is extended to the whole track of HOV: accuracy after compensation is better than the one before compensation is a necessary and sufficient condition with measuring voyage of after compensation is longer than the one before compensation. So if we want to compare the accuracy before and after compensation, we can finish it through comparing the measuring voyage. Now, we compare the measuring voyage of the sea trial data that we use just now, and then we obtain comparative result below.

Table 1 LONG BASE LINE DATA CONTRAST BEFORE AND AFTER COMPENSATION

Data amount	After	Before	Difference
2000	1407.6	1523.0	-115.38
4000	1614.6	1874.2	-259.6
6000	4208.8	4612.7	-403.82
8000	4349.9	4840.3	-490.35
10000	4553.8	5188.3	-634.58
12000	6337.3	7116.1	-778.8
14000	6899.4	7822.4	-923.02
16000	7228.5	8324.5	-1096.1
18000	9494.0	10731.0	-1236.8
20000	10007.0	11359.0	-1352.2

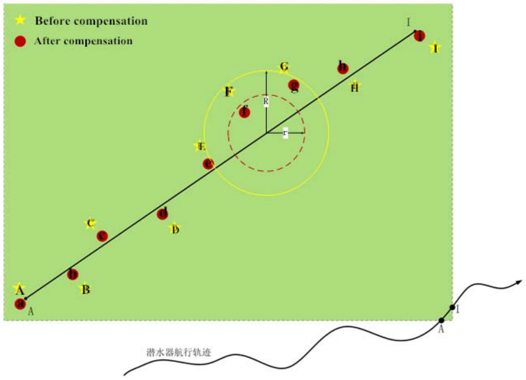

Fig. 3. Track piecewise linearization of HOV

From the table above, we can see the measuring voyage of after compensation is longer than the one before compensation obviously, then, we can see that the accuracy after the compensation is apparently better than the one before compensation.

B. Research on Error Correction methods of Motion Sensors and DVL Integrated Navigation System

According to the navigation and positioning work characteristics of HOV, Motion Sensors in a dead-reckoning navigation as the main navigation equipment, at the same time it need other equipment: DVL, Electronic Compass and so on, for data fusion to form the water integrated navigation system. Here focuses on error compensation method of DVL and Motion Sensor integrated navigation system.

In engineering practice, we describe HOV's location information with latitude and longitude on the earth's surface, thus use the differential equations for the carrier's location:

$$\dot{L} = \frac{V_N}{R_e + h} \tag{7}$$

$$\dot{\lambda} = \frac{V_E \sec L}{R_e + h} \tag{8}$$

$$\dot{h} = V_U \tag{9}$$

L, λ, h respectively is HOV's latitude and longitude and the vertical depth; V_E, V_N respectively is east and north to velocity of HOV in real time and R_e is radius of the earth.

In the navigation system HOV's underwater speed error is:

$$\delta V^n = \tilde{V}^n - V^n = \phi \times V^n + \delta K V^n \tag{10}$$

We put speed error equation into positioning error equation at the same time introduce the Motion Sensor attitude angle error and ignore the vertical speed, get these equations blow:

$$\delta\dot{L} = \frac{\phi_U}{R_M} V_E^n + \frac{\delta K}{R_M} V_N^n \tag{11}$$

$$\begin{aligned} \delta\dot{\lambda} = & -\frac{\phi_U \sec L}{R_N} V_N^n + \frac{\delta K \tan L \sec L}{R_N} V_E^n \\ & + \frac{\delta K \sec L}{R_N} V_E^n \end{aligned} \tag{12}$$

$$\begin{aligned} \dot{\phi}_E = & \phi_N \left(w_{ie} \sin L + \frac{V_E^n}{R_N} \tan L \right) \\ & - \phi_U \left(w_{ie} \cos L + \frac{V_E^n}{R_N} \right) - \frac{\phi_U V_E^n + \delta K \cdot V_N^n}{R_M} \end{aligned} \tag{13}$$

$$\begin{aligned} \dot{\phi}_N = & -\phi_E \left(w_{ie} \sin L + \frac{V_E^n}{R_N} \tan L \right) - \phi_U \frac{V_N^n}{R_M} \\ & - \delta L w_{ie} \sin L + \frac{\delta K \cdot V_E - \phi_U V_N^n}{R_N} \end{aligned} \tag{14}$$

$$\begin{aligned} \dot{\phi}_U = & \phi_E \left(w_{ie} \cos L + \frac{V_E^n}{R_N} \right) \\ & + \phi_N \frac{V_N^n}{R_M} + \delta L \left(w_{ie} \cos L + \frac{V_E^n}{R_N} \sec^2 L \right) \\ & + \frac{\delta K \cdot V_E^n - \phi_U V_N^n}{R_N} \tan L \end{aligned} \tag{15}$$

By the type, we can see that the dead-reckoning positioning error of the integrated navigation system is mainly due to the heading angle error ϕ_U and DVL scale factor δK .In order to ensure the accuracy of dead-reckoning we shall compensate for errors.

First of all, we calculate error of displacement in t_i.

$$\delta S_i^n = \tilde{S}_i^n - S_i^n = (\phi \times + \delta K I) S_i^n \tag{16}$$

In the type $\tilde{S}_i^n$ is the distance of dead-reckoning and S_i^n is real track; If attitude $\phi \times = 0$, we get DVL scale factor error:

$$\delta K = \left| \frac{\delta S_i^n}{S_i^n} \right| = \left| \frac{\tilde{S}_i^n}{S_i^n} \right| - 1 \tag{17}$$

Using geometrical relationship we can get heading angle error:

$$\delta\phi = \arccos\left(\frac{\left|\tilde{S}_i^n\right|^2 + \left|S_i^n\right|^2 - \left|\delta S_i^n\right|^2}{2 \tilde{S}_i^n S_i^n} \right) \tag{18}$$

With the sea trial data, we use computed scale factor error and heading angle error compensation can get the positioning east and north error of before and after compensation.

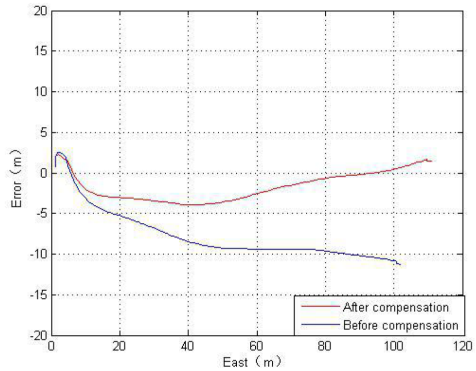

Fig. 4. East error

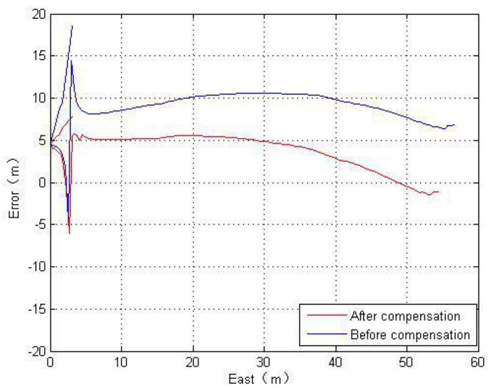

Fig. 5 North error

From the figures above, we can find that the error has reduce significantly after compensation, and the error after compensation can to meet the need of the engineering sufficiently.

C. Fusion Algorithm

In order to further overcome the cumulative error of dead-reckoning method and multiple outliers and low frequency problem and provide a more accurate and timely navigation and positioning information for the HOV, we use the UKF as the data fusion algorithm to fuse the LBL and Motion Sensors and DVL Integrated Navigation System data that has been compensated in the former two section. Then we use this data that has been fused to compare with the data that only be fused but don't be compensated and analysis the result of the comparison result. We can get the figures blow.

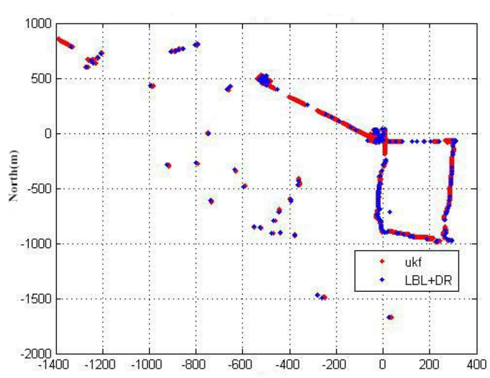

Fig. 6. 2D map view of fusion before compensation

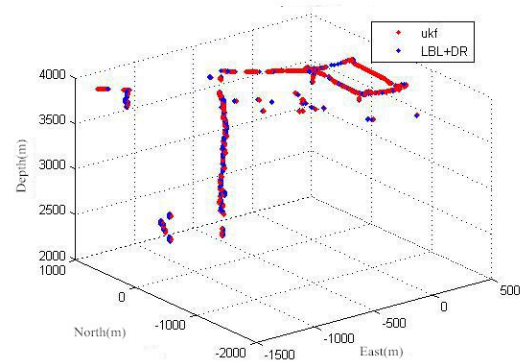

Fig. 7. 3D map view of fusion before compensation

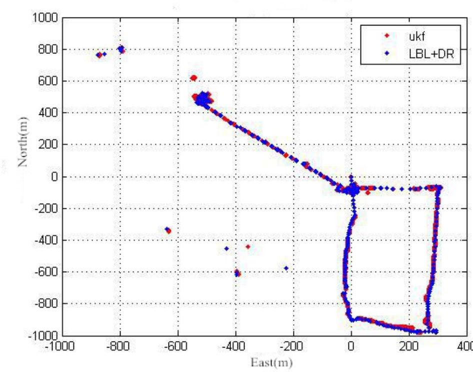

Fig 8. 2D map view of data fusion after Compensation

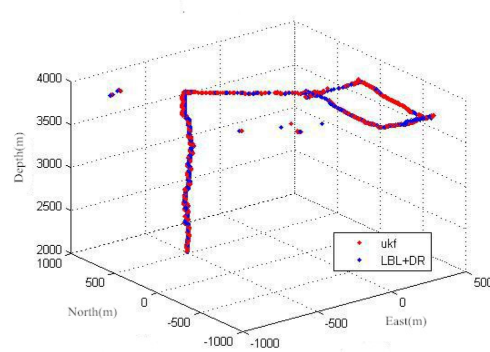

Fig 9. 3D map view of data fusion after compensation

From the figures above, we find that the outliers points of the data that through compensating and fusing is less than the one that only be fused but don't be compensated, and the continuity is better than the one that be fused but don't be compensated. In order to further compare the accuracy of the data between that we mentioned above. We use the statistical methods that used in the first section. Then we obtain comparative result below.

Table 2 DATA CONTRAST BETWEEN BEFORE AND AFTER FILTER

Data amount	After	Before	Difference
2000	321.36	407.22	-85.861
4000	652.87	824.61	-143.34
6000	866.28	1181.1	-314.85
8000	1146.2	1575.8	-429.62
10000	1429.2	1973.5	-544.26

12000	4919.5	5578.5	-659.01
14000	5432.4	6176.2	-743.77
16000	6171.0	7057.6	-886.58
18000	8041.6	9035.0	-993.46
20000	10534.0	10534.0	-1165.6
22000	9825.2	11077.0	-1251.5
24000	10255.0	11621.0	-1366.3
26000	10509.0	11990.0	-1480.9
28000	10693.0	12260.0	-1567.1
30000	11177.0	12859.0	-1682.0
32000	11360.0	13129.0	-1768.3

From the table above we can see the measuring voyage of after fusion and compensation is longer than the one be fused but don't be compensated. we can draw such a conclusion that the accuracy the former is better than the latter.

III. III CONCLUSION AND FUTURE RESEARCH

This paper proposes error compensation method for LBL and Motion Sensors and DVL Integrated Navigation System, and uses UKF fusion algorithm to fuse the data that has been compensated, and compares with the data that be fused but are not compensated. We find that the accuracy and continuity of the former is better than the one of the latter obviously, and the outliers of the former is obviously less than the latter one. The positioning and navigation data through fusion and compensation can make HOV navigate and operate better. The next step job is to reduce the amount of calculation and optimize the calculating method.

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