A USBL Position-assisted Information Calibration Method for DVL Measurement Error in Deep Water Environment

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Abstract. The primary problem with the SINS/DVL underwater integrated navigation system is to calibrate the installation relationship between SINS and DVL. The traditionally used method is GNSS velocity-assisted calibration. However, when it comes to a deep water environment, there is no GNSS signal, thus there is no effective external speed reference information underwater. Aiming at solving the problem, this paper proposes a USBL position-assisted DVL calibration method, taking advantage of position reference information provided by USBL underwater. The new method was deduced from GNSS velocity-assisted calibration method by integral operation. A sea trial experiment data was processed to validate the feasibility of the method. The results showed that the positioning error of SINS/DVL underwater integrated navigation after calibration by this method is reduced by nearly 50%. It can be concluded that this DVL calibration method can significantly improve the navigation and positioning accuracy of SINS/DVL underwater integrated navigation system in deep water.

Introduction

Doppler Velocity Log (DVL) is an instrument that measures the velocity of carrier in the water using the Doppler effect. It can measure the ground speed of the carrier in the bottom tracking mode and carrier speed relative to water in the water tracking mode. In the water tracking mode, it is necessary to know the water velocity to calculate the ground speed of the carrier. The effective range is an important indicator of DVL. Different models of DVL have different effective ranges. Generally speaking, the higher the speed measurement accuracy, the higher the DVL operating frequency, and the shorter the effective range. The relationship among the three important indicators is shown in Table 1 [1]. Therefore, when selecting the DVL, both accuracy and effective range should be considered according to the specific working conditions. Exceeding the effective range speed measurement accuracy will be seriously degraded, so the DVL speed measurement information is not reliable when diving to the working depth and floating up from the working depth [2].

Table 1. The relationship among the operating frequency, the measurement accuracy and the effective range of DVL.

<table>
<thead>
<tr>
<th>The operating frequency[kHz]</th>
<th>The measurement accuracy[mm/s]</th>
<th>The effective range[m]</th>
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<tbody>
<tr>
<td>150</td>
<td>0.5%V±2</td>
<td>425~500</td>
</tr>
<tr>
<td>300</td>
<td>0.4%V±2</td>
<td>200</td>
</tr>
<tr>
<td>600</td>
<td>0.2%V±2</td>
<td>90</td>
</tr>
<tr>
<td>1200</td>
<td>0.2%V±2</td>
<td>30</td>
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The main error sources of DVL in SINS/DVL underwater integrated navigation system include installation angle error and scale factor error. DVL measures the three-direction speed under the DVL measurement frame. In navigation solution, the speed of the DVL measurement frame should be transferred into the body frame:

\[ \mathbf{v}^b = C_b^a C_d^b \mathbf{v}_DVL^d \] (1)
This needs to know the exact value of $C_d^b$. If the DVL measurement frame is completely coincident with the body frame, the value of $C_d^b$ is $I_b$, but in practical, the installation relationship between Strapdown Inertial Navigation System (SINS) and DVL cannot be completely overlapped, and there is a constant installation angle error between them. Meanwhile, in actual measurement, system errors may occur due to problems such as formula simplification. The scale factor error is often introduced to describe such errors in practical engineering, and it also can be considered as a small amount constant [3].

The traditional method is GNSS velocity-assisted calibration, which is usually applied in shipborne water-surface integrated navigation system. It mainly depends on the external speed reference information provided by Global Navigation Satellite System (GNSS), taking advantage of the high precision of GNSS [4]. After the calibration result compensation is performed, the influence of installation error will not be considered in the subsequent navigation process. However, according to the DVL characteristics mentioned above, when it comes to a deep water environment, DVL cannot work normally on the water surface due to its limited effective range. It must be dived to the working depth for calibration, but GNSS cannot work underwater, thus there is no effective speed reference information underwater. But we can still find other reference information using a kind of underwater acoustic navigation instrument, that is Ultra Short Baseline Position System (USBL), which could provide precise position information of underwater carrier. A DVL calibration method using USBL position information will be proposed in the following content, aiming at completing DVL calibration in deep water environment instead of GNSS. And a sea trial experiment will be briefly introduced, whose data is used to test the feasibility of the new method.

**USBL Position-assisted DVL Calibration Method**

Multiply both sides of Eq. 1 by the matrix $C_n^b$ to get Eq. 2:

$$C_n^b v^n = C_d^b v_{DVL}^d$$

(2)

The DVL error calibration model is established below. Assuming that the DVL scale factor is $k$, and the installation angle error compensation value is $\eta = [\varepsilon_x, \varepsilon_y, \varepsilon_z]^T$, both of them can be considered as small amount constants. Thus, after error compensation and coordinate system conversion, the true value of DVL velocity under the body frame can be expressed as Eq. 3:

$$v_{true}^b = (I - \eta \times) k v_{DVL}^d$$

(3)

From Eq. 2 and Eq. 3, it can be observed that $C_d^b$ contains the DVL calibration parameters: the installation angle error compensation value and the scale factor. Since both of them can be regarded as constant values, the value of $C_d^b$ can also be considered as a constant.

Integrate the two sides of Eq. 2 to get Eq. 4:

$$\int C_n^b v^n dt = \int C_d^b v_{DVL}^d dt$$

(4)

Extract $C_d^b$ from the right side of Eq. 4, and the partial integration operation is performed on the left side of the above formula, which can reflect the position information in the formula, shown in Eq. 5 [5,6]:

$$C_n^b p^n - \int p^n \dot{C}_n^b dt = C_d^b \int v_{DVL}^d dt$$

(5)

In Eq. 5, $p^n$ can be provided by USBL, while $C_n^b$ and $\dot{C}_n^b$ can be provided by SINS, we can get two sequences on the timeline, and the conversion relationship between them is $C_d^b$, the value of $C_d^b$...
can be estimated by the least squares method. The discretization calculation process of USBL-assisted calibration is described in detail below:

i. SINS/USBL integrated navigation filter period is 1 second, which will be used as a unit of calculation to calculate the increment of each item per second in Eq. 5.

ii. The value of $b^n$ is from the output of the integrated navigation system per second, $p^n$ is the increment of the position per second (unit: m), the main items in Eq. 5 are updated as follows:

$$p^n = [R_n \Delta \text{Lati}, R_n \Delta \text{Longi}, 0]^T \quad (6)$$

$$\dot{C}^b_n = C^b_n \left[ \omega^n_{bn} \times \right] = C^b_n \left[ (\omega^n_m - \omega^n_{ib}) \times \right] = C^b_n \left[ (\omega^n_m - C^b_n \omega^n_{ib}) \times \right] \quad (7)$$

$$\int v^d_{DVL} dt = v^d_{DVL} \quad (8)$$

iii. Express Eq. 5 in component form as follows:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{bmatrix} = \begin{bmatrix} 1 & -\varepsilon_z & \varepsilon_y \\ \varepsilon_z & 1 & \varepsilon_x \\ -\varepsilon_y & -\varepsilon_x & 1 \end{bmatrix} \begin{bmatrix} \int v^d_{DVL,x} \\ \int v^d_{DVL,y} \\ \int v^d_{DVL,z} \end{bmatrix} = k \begin{bmatrix} \varepsilon_x \int v^d_{DVL,x} \\ \varepsilon_y \int v^d_{DVL,y} \\ \varepsilon_z \int v^d_{DVL,z} \end{bmatrix} \quad (9)$$

In Eq. 9, $C^b$ represents the three components of the left side of Eq. 5 projected under the body frame. The actual measured DVL data in this experiment only outputs the forward speed, and the speed output of the other two directions is 0. As a result, the form of DVL output data is $v^d_{DVL} = \begin{bmatrix} v^d_{DVL,x} \\ 0 \end{bmatrix}$, thus, the roll installation angle error could not be estimated.

### Experiment and Result

#### A Sea Trial Experiment

In November 2018, a sea trial experiment in South China Sea was carried out, the new proposed DVL calibration method was applied to evaluate its feasibility. SINS was provided by the laboratory ourselves. Its performance indicators are as follows: the accuracy of the gyros is better than $0.02^\circ/h$, the accuracy of the accelerometers is better than $50 \mu g$, and its sampling frequency is $200 Hz$. DVL is the type of HEU-150 of acoustic phase control from Harbin Engineering University, the measurement accuracy of which is $0.5% \pm 5 mm/s$, $V$ representing the ground speed of the carrier, and its sampling frequency is $1 Hz$. The maximum positioning error in a single direction of USBL is $7 m$, and its sampling frequency is $1 Hz$. The carrier cruised at a speed of 10 knots. The entire experiment took about 5 hours and the voyage was about $70 km$.

#### Result

Since the data processing is completed afterward in laboratory instead of in the field. The entire data is used to calibrate DVL to enhance the calibration accuracy, while in practical application, a voyage of 20km is enough. The whole calibration result is shown in Fig.1, and the final result is shown in Eq. 10. In general, it can be observed that the whole results are stable near the true values, apart from a peak at around $12000s$ in Fig1(a), it might be caused by DVL measurement outliers.

$$k = 0.9945, \ \eta = [0 \ 0.1374 \ -0.0042]^T \quad (10)$$
The calibration result of scale factor error

The calibration result of pitch installation angle error

The calibration result of yaw installation angle error

Figure 1. The DVL calibration result of USBL-assisted method.

The SINS/DVL integrated navigation results before and after DVL calibration using new proposed method are compared in Table 2 in detail. The USBL positioning results are used as reference standard. The results outside the brackets represent the maximum positioning error of SINS/DVL integrated navigation, while the results in brackets represent the final positioning error. It can be noticed from the below table that after USBL-assisted calibration of DVL measurement error, the positioning accuracy of the SINS/DVL integrated navigation system is significantly improved compared with that before calibration, and the maximum positioning error in the north direction is reduced by 30m, but the reduction is not notable. However, other positioning error indicators are all reduced by near 50%.

Table 2. The comparison of the SINS/DVL integrated navigation results before and after DVL calibration.

<table>
<thead>
<tr>
<th></th>
<th>North positioning error(m)</th>
<th>East positioning error(m)</th>
<th>Positioning error(m)</th>
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<tbody>
<tr>
<td>Before calibration</td>
<td>175(48)</td>
<td>250(50)</td>
<td>300(70)</td>
</tr>
<tr>
<td>After calibration</td>
<td>145(20)</td>
<td>115(23)</td>
<td>180(30)</td>
</tr>
<tr>
<td>Increment</td>
<td>30(28)</td>
<td>135(27)</td>
<td>120(40)</td>
</tr>
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</table>

Conclusion

A DVL calibration method using USBL position information has been proposed in this paper. First of all, the calibration model of USBL-assisted was established. Then, a sea trial experiment in South China Sea was introduced in brief, the experiment data was used to validate the feasibility of the method proposed above. The SINS/DVL integrated navigation results show that most of the positioning error indicators of integrated navigation are reduced significantly after DVL calibration, nearly by 50%. It can be concluded that the USBL position information can be used to assist the calibration of DVL in SINS/DVL integrated navigation in deep water environment, and the calibration result can effectively improve the navigation and positioning accuracy of the SINS/DVL underwater integrated navigation system.

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References


