Key Techniques of SINS/DVL Integrated Navigation System

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Abstract. Doppler Velocity Log (DVL) aided Strapdown Inertial Navigation System (SINS) is commonly used for the applications of Autonomous Underwater Vehicles (AUVs). In lack of other aiding sensors, how to maintain precise integrated navigation is still a challenge issue. In this paper, the structure and basic principles of the SINS is presented. Alignment calibration of SINS and DVL, fast in-motion alignment and data fusion are key factors which has great influence on the navigation accuracy. Research efforts taken in these fields in recent years are surveyed. This paper may provide a firm foundation for the researchers in related areas.

Keywords: SINS; DVL; Alignment; Calibration.

1. Introduction
Covering with water nearly three quarters of its surface, the earth appears as a “blue planet”. With increasing demand for energy and resources, people concentrate sight on exploiting marine resources by using various underwater vehicles. Among these, AUVs which has dependent navigation system perform well for underwater applications. Those functions, such as positioning, path tracing and control, cannot be realized with continuous navigation parameters. Compared with land and air navigation, there are few information sources for underwater navigation. The main navigation techniques for underwater vehicles includes: acoustic navigation, geophysical navigation and inertial navigation. SINS is able to obtain continuous three-dimensional position, velocity and attitude. However, due to its inherent gyroscope biases and accelerometer biases, its navigation errors accumulate with time. External aiding sensors are usually needed to limit the error growth. The main acoustic navigation systems includes: Long Baseline (LBL), Short Baseline (SBL), and Ultra Short Baseline (USBL). It is implemented by measuring the range from acoustic beacons by acoustic signals. Therefore, acoustic navigation techniques have a limit range and are not suitable for long term missions. Geophysical navigation utilizes external environmental features including terrain, geomagnetic or gravity for localization. While using these methods, prior information is usually required. For example, geomagnetic navigation is implemented by matching the magnetic obtained from magnetic sensors with magnetic field maps. However, magnetic field maps are incredibly difficult to gain.

SINS/DVL is a good choice for AUV's navigation. DVL is operated based on Doppler Effect. It can obtain a vehicle’s speed over seafloor accurately. In order to operate reliably, a DVL has to hear it signals returning from the seabed. The DVL’s bottom tracking (BT) range and accuracy is mainly determined by its acoustic emission frequency. Operating at a higher emission frequency, a DVL can achieve higher accuracy in the cost of smaller bottom-locked range. However, even with DVL aiding, the navigation solutions of SINS/DVL will diverge inevitably[1]. Figure 1 is a typical underwater navigation system. With additional navigation information such as Global Navigation Satellite System
GNSS or LBL, position observations can be obtained. It is able to improve the accuracy of positioning once these signals are available. However, there are many limitations for real application. For example, underwater vehicles should rise to get GNSS signals. It is very inconvenient for practical use. INS/DVL integration is the main operation mode of the underwater navigation.

![Figure 1. A typical underwater navigation system structure.](image)

In SINS/DVL integration, aiding information for the SINS is very limited. Only the DVL’s velocity is employed. There are still problems to be solved for precise integrated navigation, such as:

1. Alignment calibration of SINS and DVL. The install misalignments between SINS and DVL, DVL’s scale factor, should be calibrated before conducting a mission.
2. Fast initial alignment of the SINS. Fast initial alignment without any local level frame measurements is still a tough problem which has no well-established solutions.
3. Data fusion of SINS/DVL. Linear filtering and nonlinear filtering methods are usually utilized in data fusion. As DVL may fail during the missions, the integration navigation approach to deal with DVL malfunction should also be considered.

2. System Description

SINS is a dead reckoning (DR) system. It consists of three accelerometers and three gyroscopes which are installed orthogonally. Based on Newton’s laws of mechanics, accelerometers and gyroscopes measure acceleration vectors and angular velocity vectors in the inertial reference frame. By integration and translation of these vectors, navigation solutions can be obtained continuously. It can provide navigation parameters at a high update rate and have a high short-term accuracy. However, its navigation errors increase with time.

For underwater applications, a DVL is usually employed to assist the SINS. A Doppler transducer unit should have at least three downward-looking beam transducers. The transducers measure the velocity along each beam. Then these measurements are converted to three-dimensional velocity vectors which are in the Doppler instrumental frame. The accuracy of the DVL is affected by sound speed accuracy, time stamp accuracy, and geometric effect of turn rate. Both sound speed error and time stamp error with caused a DVL scale factor error. The sound speed error will cause a scale factor error of:
\[ k = \frac{\delta v_s}{v_s} \]  

(1)

Where \( k \) is the scale factor error, \( v_s \) is the sound speed, \( \delta v_s \) is the sound speed error. The time stamp error and geometric effect of turn rate will also cause a velocity error which present as a scale factor error.

Figure 2. Loosely coupled SINS/DVL integration structure.

Figure 3. Tightly coupled SINS/DVL integration structure.

Figure 2 shows a typical structure of SINS/DVL integration. It is commonly known as loosely coupled integration. By using the SINS’s attitude, the DVL’s velocity is converted to navigation frame. With the SINS error model and the DVL measurement model, the data from the SINS and DVL can be fused by data fusion techniques. To deal the cases in which some beam measurements are unavailable, a tightly coupled integrated navigation structure is proposed. As can be seen from Figure 3, beam measurements of the DVL are directly employed for data fusion. With this method, navigation solutions can be obtained even when malfunctions of some beams occur. In addition, the accuracy can also be improved. Dynamic model of the vehicle is also employed for the data fusion. And it is defined as model-aided navigation techniques[2]. With this method, the kinetic model is derived to establish the state equations. Then the estimation of the navigation parameters can also be obtained by data fusion techniques.
3. Key Techniques

3.1. Alignment Calibration

The SINS and DVL are often installed in different locations of an AUV. Therefore, it has to calibrate the misalignments before a navigation mission. In addition, scale factor error of the DVL should also be calibrated. The DVL measurements $\tilde{v}_d$ are usually modelled as:

$$\tilde{v}_d = \left(1 + k\right)v_d + \delta v_d$$  \hspace{1cm} (2)

Where $d$ is the Doppler instrumental frame, $v_d$ is the DVL’s velocity in $d$ frame, $\tilde{v}_d$ is the DVL measurements in $d$ frame, $k$ is the scale factor error, $\delta v_d$ is the measurement noise which is often regarded as Gaussian white noise. The measurements of the DVL are converted transformed to $b$ frame by:

$$\tilde{v}_b = C^b_d \tilde{v}_d$$  \hspace{1cm} (3)

Where $C^b_d$ is the alignment matrix between $d$ frame and $b$ frame, $\tilde{v}_b$ is the DVL measurement in $b$ frame. The so called alignment calibration is often addressed as calibrating the transformation parameters including alignment matrix $C^b_d$ and scale factor error $k$.

The methodology for alignment calibration can be classified to two categories: online calibration and offline calibration. By using offline calibration techniques, external aiding navigation systems, such as GNSS, LBL, are usually employed. These systems are able to provide measurements including position, velocity, which can be utilized as the benchmark of the calibration. In [3], by using the measurements from LBL, the calibration is implemented by calculating the transform matrix between two observation point sets. The estimation theories such as Wahbar’s problem, least squares estimation are utilized. Quaternions-based estimation methods are also applied for the calibration. In [4], the solutions from INS/GPS are used in estimation model. It is scheme is shown in Figure 4. It is able to obtain the DVL’s scale factor error and the misalignments simultaneously.

![Figure 4. GPS assisted calibration scheme.](image)

Considering the calibration techniques which require external signals are inconvenient for practical use, online calibration has aroused great attention. In [5], the authors proposed a simple calibration method which aims at improving the convenience of the real application. With this method, only one additional position is required. In addition, a backtracking algorithm is proposed to improve INS/DVL integration accuracy and hence improve the accuracy of the calibration. Acceleration-based calibration method is also proposed. The advantage of this methodology is that no external navigation beacon is required, which is very convenient for AUV’s applications. However, it requires complex motions. Online estimation is another way to solve this problem. The misalignments and the scale factor error...
are estimated by estimation techniques online. In [6], it is shown by analysis that the misalignments and the scale factor is observable under some special motions. Therefore, the calibration can be conducted without any additional sensors.

3.2. Initial Alignment of SINS
SINS Initial alignment is the process whereby the initial attitude of the SINS is determined. Poor initial alignment may lead to poor navigation accuracy. In addition, the accuracy and rapidity are the most important specifications.

According to different criteria, initial alignment can be classified to many sorts. Normally, it is often divided into two phases: coarse alignment and fine alignment[7]. During coarse alignment, the initial attitude is estimated roughly. In fine alignment, the small misalignments are further estimated.

Various coarse alignment techniques have been reported. Under static conditions, the accelerometers and gyros measure the gravity and Earth’s rotation rate in SINS frame. Compare with the known gravity and Earth’s rotation rate in the local level frame, it is able to calculate the initial attitude. However, these techniques are not suitable for underwater vehicles. In underwater environments, the motions of the vehicle will be added in the measurement values of accelerometers and gyros. It will greatly reduce the initial alignment accuracy. In order to deal with this problem, a coarse alignment method which is defined as inertial reference frame based alignment technique is proposed. It is further developed as an optimization-based alignment (OBA) algorithm. With the velocity vectors in the inertial body frame and inertial navigation frame, the attitude matrix can be estimated. The estimation can be implemented by the solutions of Wahbar’s problem[8]. This technique has aroused great attention. Much work has been done to improve its performance. External aiding information which is able to provide additional observations such as GPS measurement can also be employed and hence improve the estimation accuracy. Furthermore, by averaging and interleaving methods, the accuracy can be further improved. In [8], DVL measurements are utilized. This technique is further adjusted for the application of the underwater vehicles.

With SINS error model and the observations from DVL, the fine alignment is usually implemented by using Kalman filters (KF). With DVL aiding, slow convergence of the heading error is an inevitable problem. Much work has been done to speed up the alignment process. Kalman filters may have good performance in dealing with linear estimation problems. However, it is unable to deal with nonlinear filtering problems. By using the nonlinear INS error model and the nonlinear filtering method such as Unscented Kalman filter (UKF), it is able to speed up the initial alignment. In [9], a quaternion-based nonlinear filter model is proposed. And an Unscented Quaternion Estimator (USQUE) is utilized. It performs well which faced with nonlinear estimation problems. Therefore, it is able to rapidity and accuracy of the alignment. In [7], a backtracking alignment scheme aiming at speed up the alignment is proposed. With this scheme, the fine alignment executes with the measurements logged during coarse alignment. It is equivalent to extend the coarse and fine alignment. Therefore, the accuracy of the alignment can be improved.

3.3. Data Fusion
By using data fusion techniques, optimal estimation of the navigation parameters can be got by fusing the information from the SINS and DVL. It is often implemented by using Kalman Filters. KF is a linear filter which is able to deal with linear estimation problem. It could get good filtering performance if system is linear and noise is Gaussian White noise. However, real systems are usually nonlinear systems with non-Gaussian White noises, so is the SINS/DVL. With only DVL aiding, slow convergence of the navigation parameters is a difficult problem for underwater applications. Various nonlinear filters are adopted for the SINS/DVL integrated navigation, which aim at improving its performance and speeding up the convergence of the navigation parameters. The performance of Extend Kalman filter (EKF) and UKF on estimating the position of AUV by SINS/DVL is also compared by the researchers. It is shown by the experiments that the EKF performs better. Nonlinear filter methods include: Particle filter (PF), Cubature Kalman filter (CKF), etc. are also utilized for the integrated navigation. Adaptive Kalman filter (AKF) is another way to
improve the performance of the navigation. The main idea of the adaptive Kalman filtering methods is to estimate the system noises or adjust the Kalman filter gain adaptively real time. The motion of the vehicle also affects the accuracy of the navigation. It is found that the velocity error of the DVL can become observable when the vehicle is manoeuvring. The SINS/DVL performs better on across track than along track. In [1], the authors investigate the observability of the states under different kinds of vehicle dynamics. The results show that rotation motions are able to improve the observability of the system. However, the motions especially the attitude change of the vehicle also affect the accuracy of the DVL measurements. A correction should be done when data fuses[10,11]. In some cases, the DVL may not be able to obtain bottom-lock velocity measurements. For example, the vehicle sails across sea creatures. In addition, a DVL also has a maximum operation range. It may provide water-track velocity measurements or partial measurement. When facing with DVL watertack problem, the water current velocity should be estimated first. And then the bottom-track velocity can be obtained. Much work has also been done to deal with DVL malfunction. By using the current and past velocities of SINS, a hybrid based approach is developed to predict the DVL measurements if malfunctions happen[12]. In [13], a neural network model is utilized to predict DVL measurements. With the predicted mearements, the SINS/DVL can maintain short-term accuracy. To deal with the case of only partial DVL measurements are available, the authors proposed an extended loosely coupled (ELC) approach [14]. With partial raw data of the DVL, it is able to predict vehicle velocity. As we known, kinematic constraints are usually used in land vehicle navigation. It is also adjusted for underwater vehicles improve the robustness of the system.

4. Conclusions
SINS/DVL is a common autonomous underwater navigation approach for AUVs. We summarized some key techniques in SINS/DVL integrated navigation. A comprehensive summary and analysis of the current status of research into alignment calibration, SINS initial alignment and data fusion is presented. In recent years, there have been technological and theoretical advances in these research areas. However, there are still challenge issues:
(1) Without positioning measurements, the position error of the SINS/DVL will diverge inevitably. Works has to be done to limit its error growth.
(2) The accuracy and rapidity of the initial alignment needs to be further improved.
(3) In dealing with DVL malfunctions problems, there are no well-established solutions. The performance of the existing methods is limited.

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