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A novel backtracking navigation scheme for Autonomous Underwater Vehicles

Wanli Li [a,b,*], Wenqi Wu [a], Jinling Wang [b], Meiping Wu [a]

[a] College of Mechatronic Engineering and Automation, National University of Defense Technology, China
[b] School of Civil and Environmental Engineering, University of New South Wales, Australia

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ABSTRACT

A high quality Inertial Navigation System (INS) combined with a Doppler Velocity Log (DVL) is a common approach for Autonomous Underwater Vehicle (AUV) navigation. In this paper, a novel backtracking navigation scheme is employed. In the case of only when an initial position and the velocity of DVL are available, a precise current position can be obtained when finishing the backtracking. Therefore, AUV can be launched without waiting for the completeness of the alignment. In addition, a newly derived INS error model is employed to reduce the volume of the data that has to be recorded for the backtracking and to estimate the INS biases. With the proposed method, INS/DVL integration is able to reach the accuracy of within 0.3% of the distance travelled.

1. Introduction

Currently, few techniques exist for reliable 3-D position sensing for Autonomous Underwater Vehicles (AUVs) [1]. The Global Positioning System (GPS) provides superior 3-D navigation for both surface and air vehicles, however, the GPS radio frequency signals rapidly attenuate in water and deeply submerged vehicles could not directly receive it [2]. Long baseline (LBL) acoustic navigation system is able to obtain sub-centimeter precise position. Unfortunately, due to the rapid attenuation of higher frequency sound in water, high frequency LBL systems typically have a very limited maximum range [3].

Inertial Navigation System (INS) is a good choice for autonomous navigation of an AUV. However, due to inherent errors in the gyros and accelerometers, the INS solutions will have an unbounded drift inevitably [4]. Therefore, an aided framework is needed to limit or reduce the error growth. The development of DVL that provides bottom velocity measurements with a precision of 0.3% or less and update rates up to 5 Hz has enabled the development of a wide variety of Doppler-based navigation techniques [5]. INS/DVL integration is regarded as one of the most potential autonomous navigation approach [6].

The DVL provides accurate velocity measurements that are independent of running time in the Doppler instrumental frame. However, alignment and navigation without geodetic frame observations is still a challenge issue, which has to be addressed [7,8]. It is an essential task to achieve high INS alignment accuracy within a short period [9–11]. The traditional alignment techniques consisting of coarse and fine alignment are not suitable for fast in-motion alignment [12]. It should be noted here that both the coarse and fine alignments occupy a part of the alignment time. Therefore, we proposed a backtracking scheme in that the fine alignment runs with the data recorded during the process of the coarse alignment and thus will not take extra time [13]. Furthermore, a novel INS error model was derived for reducing the volume of the data that has to be recorded, thus making this scheme possible for real time applications. It is able to reach the alignment accuracy of 0.08 degree in heading and

* Corresponding author. Address: Lab 313, Department of Automatic Control, College of Mechatronic Engineering and Automation, National University of Defense Technology, Changsha 410073, China. Tel.: +86 13574835140; fax: +86 731 84576305x8212.

E-mail address: liwanli1201@hotmail.com (W. Li).

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0.007 degree in leveling by using a navigational grade INS and a 1 Hz bottom-lock Doppler within 600 s [13].

The main concern of this paper is to extend the backtracking alignment scheme to the navigation. With this technique, there is no need to wait for the alignment when the AUVs start a mission. Continuous positioning information can be obtained in the case of only the initial position and the velocity of DVL are available. By using the traditional alignment scheme, there will be an unacceptable position error due to the large misalignment errors in the process of the coarse alignment. However, with the proposed method, a precise current position can be obtained when finishing the backtracking. The resulting position can be used for the subsequent navigation. This is very important for the INS applications on an AUV platform where the geographic position is usually unavailable unless the AUV rises. In [13], we proposed a novel INS error model derived in the inertial reference frame to reduce the volume of the data that has to be recorded for the backtracking. As it is well known, however, when the INS error model is switched to the traditional local level frame error model in the stage of the navigation, there may be an overshoot caused by the tuning of the Kalman filter [14–17], which could result in position errors. It is expected that this error model could be employed in the subsequent navigation. However, it does not include the major INS sensor biases (accelerometer bias and gyro bias) which are important factors limiting the accuracy of INS/DVL integration [18]. Therefore, this recently developed INS error model is further improved here by considering the un-modeled INS biases. In the implementation of the Kalman filter, the attitude and the velocity errors are feed back through each Kalman filtering cycle, while the open loop framework is employed to estimate the INS biases. Therefore, no extra data needs to be recorded by using the backtracking scheme. The ship-mounted experimental data was collected to evaluate the performance of the proposed algorithm. It is clearly shown that the INS biases can be estimated reliably by the proposed method and hence improved the performance of the INS navigation. With the proposed navigation scheme, a navigation grade INS and a bottom-lock Doppler is able to obtain relative navigation error of within 0.3% of distance traveled.

The rest part of this paper is organized as follows. In Section 2, the algorithmic principle for INS computation in the inertial reference frame is presented. Section 3 is devoted to the derivation of the proposed novel INS error model. Section 4 discusses the implementation of the INS/DVL integration. Section 5 presents the experimental results. Conclusions are drawn in Section 6.

2. INS update in the inertial reference frame

2.1. Attitude computation

The attitude matrix $\boldsymbol{C}_b^n$, which relates the INS body frame b to the navigation frame n (local-level frame and its orientation is north-up-east (NUE)), can be decomposed as follows [13,19]:

$$\boldsymbol{C}_b^n = \boldsymbol{C}_{n_0}^n \boldsymbol{C}_{i_{n_0}}^{n_0} \boldsymbol{C}_{i_{b_0}}^{i_{n_0}} \boldsymbol{C}_b^{i_{b_0}} \tag{1}$$

where n_0 is the n frame at the start-up; i is the Earth-centered initially fixed (ECIF) orthogonal reference frame; i_{b_0} and i_{n_0} denote the inertial reference frames, they are formed by fixing the b frame and the n frame at the start-up in the inertial space respectively. The rotation matrix $\boldsymbol{C}_b^{i_{b_0}}$ which represents the orientation of the b frame relative to its initial at start-up is firstly initialized as a 3×3 identity matrix and updated by the gyro output $\boldsymbol{\omega}_{ib}^b$:

$$\dot{\boldsymbol{C}}_b^{i_{b_0}} = \boldsymbol{C}_b^{i_{b_0}} [\boldsymbol{\omega}_{ib}^b \times] \tag{2}$$

$\boldsymbol{C}_{i_{n_0}}^{n_0}$ is slowly changing due to the Earth's rotation. It is given by:

$$\boldsymbol{C}_{i_{n_0}}^{n_0} = \boldsymbol{C}_e^{n_0} \boldsymbol{C}_{i_{e_0}}^{e} \boldsymbol{C}_{i_{n_0}}^{i_{e_0}} \tag{3}$$

where e denotes the Earth-centered Earth-fixed (ECEF) orthogonal reference frame, another newly defined inertial reference frame i_{e_0} is formed by fixing the e frame at the start-up in the inertial space. There exists:

$$\boldsymbol{C}_e^{n_0} = \begin{bmatrix} -\sin L_0 \cos \lambda_0 & -\sin L_0 \sin \lambda_0 & \cos L_0 \\ \cos L_0 \cos \lambda_0 & \cos L_0 \sin \lambda_0 & \sin L_0 \\ -\sin \lambda_0 & \cos \lambda_0 & 0 \end{bmatrix} \tag{4}$$

$$\boldsymbol{C}_{i_{n_0}}^{i_{e_0}} = (\boldsymbol{C}_e^{n_0})^T \tag{5}$$

$$\boldsymbol{C}_{i_{e_0}}^{e} = \begin{bmatrix} \cos(\omega_{ie}(t-t_0)) & \sin(\omega_{ie}(t-t_0)) & 0 \\ -\sin(\omega_{ie}(t-t_0)) & \cos(\omega_{ie}(t-t_0)) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{6}$$

L_0 and λ_0 are the geographic latitude and longitude of the initial position. $\boldsymbol{C}_{n_0}^n$ is slowly changing with the movement of the vehicle, which can be obtained by:

$$\boldsymbol{C}_{n_{k+1}}^{n_0} \approx \boldsymbol{C}_{n_k}^{n_0} \boldsymbol{C}_{n_{k+1}}^{n_k} \tag{7}$$

$$\boldsymbol{C}_{n_{k+1}}^{n_k} \approx \boldsymbol{I} + \begin{bmatrix} 0 & \frac{d_{\Delta N}^{n_k}(t_k)}{r_N} & \frac{d_{\Delta E}^{n_k}(t_k)\tan L(t_k)}{r_N} \\ \frac{-d_{\Delta N}^{n_k}(t_k)}{r_N} & 0 & \frac{-d_{\Delta E}^{n_k}(t_k)}{r_E} \\ \frac{-d_{\Delta E}^{n_k}(t_k)\tan L(t_k)}{r_N} & \frac{d_{\Delta E}^{n_k}(t_k)}{r_E} & 0 \end{bmatrix} \tag{8}$$

where r_N and r_E are the meridian and transverse radius of the Earth respectively; $d_{\Delta N}^{n_k}$ and $d_{\Delta E}^{n_k}$ denote the incremental distance of the vehicle in the North and East direction at each time epoch, it can be obtained by dead reckoning (DR) shown in Section 4. Since both the i_{n_0} frame and the i_{b_0} frame are fixed with respect to the inertial reference frame at the start-up, $\boldsymbol{C}_{i_{b_0}}^{i_{n_0}}$ is a constant matrix. Once the initial attitude matrix $\boldsymbol{C}_{i_{b_0}}^{n_0}$ can be estimated, the attitude matrix can be obtained by Eq. (1).

2.2. Velocity computation

In the i_{b_0}-frame, there exits

$$\dot{\boldsymbol{v}}_i^{i_{b_0}} = \boldsymbol{C}_b^{i_{b_0}} \boldsymbol{f}^{\,b} + \boldsymbol{C}_{i_{n_0}}^{i_{b_0}} \boldsymbol{C}_{n_0}^{i_{n_0}} \boldsymbol{C}_n^{n_0} \boldsymbol{g}_m \tag{9}$$