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Real-time accurate odometer velocity estimation aided by accelerometers

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ABSTRACT

In strap-down gyro-compass in-motion alignment, the alignment accuracy depends not only on the quality of the gyroscopes and accelerometers, but also on the accuracy of the velocity provided by the aiding sensors such as odometers. To improve the accuracy of the in-motion alignment, real-time accurate odometer velocity estimation is required. In this paper, the effect of the noise of the odometer velocity on strap-down gyro-compass in-motion alignment accuracy is presented, based on the strap-down gyro-compass algorithm. A velocity tracking model is designed as the state model, to describe the relationship between and among the vehicle's velocity, acceleration and jerk in the vehicle frame. Based on the velocity equation applied to strap-down navigation system mechanizations, the vehicle's acceleration in the vehicle frame can be obtained from the specific forces measured by accelerometers. With the observations including the vehicle's acceleration in the vehicle frame and the vehicle's velocity in the vehicle frame obtained from the odometer using the first order difference algorithm, real-time velocity estimates are produced by a Kalman filter. The field test results show that the proposed method can successfully improve the accuracy of the odometer velocity. The comparison with the traditional method highlights the superior performance of the proposed method.

1. Introduction

Strap-down inertial navigation systems (SINS) require an initialization process that establishes the relationship between the body frame and the local geographic reference. This process, called alignment, generally requires the device to remain stationary for some period of time in order to establish this initial state. Sometimes the initialization occurs while the device is moving, and this process is called in-motion alignment [1]. In these years, Kalman filter algorithm is widely used in the in-motion alignment. However, the accuracy of Kalman filter technique depends on the accuracy of the gyroscope and accelerometer error models. With the advantages of simple algorithm, less computation and not requiring precise sensor error models, gyro-compass algorithm is gradually applied to the in-motion alignment. The first platform gyro-compass was developed by Anschutz Kaempfe who started the company Anschutz in 1905 [2]. In recent years, SINS is gradually applied to gyro-compass system, with obvious advantages of requiring less maintenance, offering wide dynamic range, less dimension and weight, starting up quickly and so on [3–6]. A typical application is that the reference inertial navigation system for artillery called SIGMA 30 developed by the SAGEM company, can achieve the azimuth alignment accuracy of 1 mil using the strap-down gyro-compass algorithm aided by an odometer [7].

In the in-motion alignment, common aids to navigation include GPS and odometers. These external sources of velocity can be used to aid in accomplishing the alignment via the gyro-compass algorithm. However, standalone GPS receivers do not work in all environments and may experience signal outages or deteriorated performance because of the multipath effects [8]. Odometer measures the distance traveled by a vehicle over a period of time and it is self-contained and hardly-disturbed. In order to be used in the gyro-compass algorithm, velocity should be transformed from the distance per unit time with high accuracy. In traditional method, the transformation is generally carried out using the first order difference algorithm. However, real-time odometer velocity is hard to be transformed at low frequency, especially when the vehicle's velocity changes rapidly. If the odometer velocity is transformed at high frequency, the noise of the velocity will be increased. To reduce the noise of the velocity, a tracking differentiator is applied to data processing for the odometer [9]. Unfortu-

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nately, it is needed to adjust the parameter called velocity factor dynamically to achieve the best trade-off between time lag and noise in tracking differentiator method.

In this current work, an improved odometer velocity estimation method aided by accelerometers is presented. The improvement availability is satisfied by using a velocity tracking mode, which is designed as the state model. The observations are the vehicle's velocity and acceleration in the vehicle frame, obtained from the odometer and accelerometer outputs, respectively. After the state model and the observation model being established, real-time accurate odometer velocity estimates can be produced by a Kalman filter formulated as a "tracking" filter.

The paper is organized as follows. In Section 2, the effect of the noise of the odometer velocity on strap-down gyro-compass in-motion alignment accuracy is presented. In Section 3, the traditional method is analyzed in detail. After that, a real-time accurate odometer velocity estimation method aided by accelerometers using the Kalman filter algorithm is proposed. In Section 4, the field test results of the improvement as well as accuracy verification are reported. In Section 5, the conclusion is discussed.

2. Effect of the noise of the odometer velocity on strap-down gyro-compass in-motion alignment accuracy

Error analysis and sensor modeling are developed in the determined coordinate frames which are orthogonal and right-handed [10]. In land applications, the inertial measurement unit (IMU) is rigidly mounted on the vehicle, and the output of inertial sensors are calibrated and compensated in the body frame directly for the solution of the navigation equation. The distance measured by the odometer is expressed in the vehicle frame. In addition, the inertial frame, the earth frame and the geographic frame have to be established for modeling and analysis. All these frames are defined in Table 1.

The principle of the strap-down gyro-compass algorithm is described as follows [11]:

Strap-down gyro-compass algorithm consists of three loops: east control loop, north control loop and azimuth control loop. Because azimuth alignment performance is a major concern in alignment technologies, we take the azimuth control loop for example for detailed analysis. The azimuth control loop can be described using the block diagram in Fig. 1. In the figure, the entity platform in platform inertial navigation system (PINS) is replaced by mathematical platform in SINS, where $\boldsymbol{\omega}_{ib}^{b}$ is the body angular rate measured by gyroscopes, and $\boldsymbol{f}^{b}$ is the specific force measured by accelerometers. $\boldsymbol{C}_{b}^{t}$ is the body attitude matrix with respect to the geographic frame. $\boldsymbol{V}_{R}^{t}=\begin{bmatrix}V_{RE}^{t} & V_{RN}^{t} & V_{RU}^{t}\end{bmatrix}^{T}$ is the reference velocity in the geographic frame obtained from the odometer output. $\boldsymbol{\omega}_{c}=[\boldsymbol{\omega}_{cE} \quad \boldsymbol{\omega}_{cN} \quad \boldsymbol{\omega}_{cU}]^{T}$ is the control angular rate to mathematical platform for east, north and upward components, respectively. $\boldsymbol{\omega}_{it}^{t}$ is the angular rate of the geographic frame with respect to the inertial frame, expressed in the geographic frame. $\boldsymbol{f}^{t}=[\boldsymbol{f}_{E}^{t} \quad \boldsymbol{f}_{N}^{t} \quad \boldsymbol{f}_{U}^{t}]^{T}$ is sensed output of accelerometers coordinated in the geographic frame for east, north and upward components, respectively.

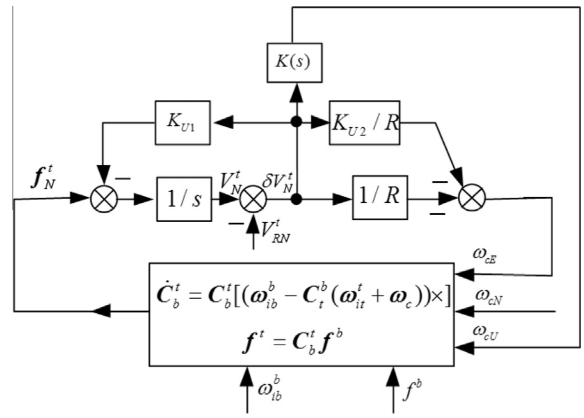

Fig. 1. Equivalent block diagram for the azimuth control loop of the strap-down gyro-compass algorithm.

In addition, the parameter $K(s)$ in Fig. 1 can be expressed as

$$K(s)=K_{U3}/((s+K_{U4})\cdot\omega_{ie}\cos L), \tag{1}$$

where K_{Uj} (j = 1,2,3,4) are the parameters of the azimuth control loop. The typical parameters are

$$K_{U1}=K_{U4}=2\sigma,\quad K_{U2}=4\sigma^{2}/\omega_{s}^{2}-1,\quad K_{U3}=4\sigma^{4}/g, \tag{2}$$

where σ, ξ and $\omega_{s}=\sqrt{g/R_{e}}$ are decaying coefficient, damping ratio and Schuler frequency, respectively.

From the figure, the east control angular rate $\boldsymbol{\omega}_{cE}$ can be written as

$$\boldsymbol{\omega}_{cE}=-(V_{N}^{t}-V_{RN}^{t})(1+K_{U2})/R, \tag{3}$$

where ground velocity in the geographic frame $\boldsymbol{V}^{t}=\begin{bmatrix}V_{E}^{t} & V_{N}^{t} & V_{U}^{t}\end{bmatrix}^{T}$ is the subscripts stand for east, north and upward velocity components, respectively. R is the radius of the earth.

From Eq. (3), we can find that the accuracy of the odometer velocity influences the accuracy of the east control angular rate. In other words, the noise of the east control angular rate is $(1+K_{U2})/R$ times the noise of the odometer velocity. Assuming the matrix $\boldsymbol{C}_{t}^{b}$ is an identity matrix, the noise of the east control angular rate is equivalent to the noise of the x-gyroscope output. To validate that the accuracy of the azimuth alignment is affected by the noise of the odometer velocity, 2 simulation tests are carried out and the description is shown in Table 2. In these tests, gyroscope bias is set as $0.01^{\circ}\,h^{-1}$ and accelerometer bias is set as 50 μg. From the azimuth alignment errors shown in Fig. 2, the lower the noise of the odometer velocity is, the higher the azimuth alignment accuracy will be. To improve the accuracy of the strap-down gyro-compass in-motion alignment, decreasing the noise of the odometer velocity is required.

Table 1
Frame definition.

Frames	Description
i frame	The inertial frame
e frame	The earth frame
b frame	The body frame
t frame	The geographic frame (East-North-Up)
m frame	The vehicle frame

Table 2
Tests description.

Test number	Test description
Test 1	Gyro-compass alignment with the standard deviation of the odometer velocity noise of 0.2 m/s
Test 2	Gyro-compass alignment with the standard deviation of the odometer velocity noise of 0.01 m/s