Initial Alignment for SINS based on Low-cost IMU

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***Abstract*—The initial alignment is vital to the strapdown inertial navigation system (SINS). In this work, an efficient initial alignment method for SINS based on a six-degree of freedom inertial measurements unit (IMU) is proposed. The three dimensional linear accelerations and angular rates are acquired from a data acquisition board which contains a low-cost IMU. Preprocess the gyro data and modeling the SINS error model for initial alignment. Analysis the observability of this SINS error model and then simplify the model based on the observability. A kalman filter is conducted to estimate the misalignment angle. The results show that the initial alignment method proposed in this paper is advisable for a SINS based on low-cost IMU on a stationary base.**

***Index Terms*—SINS; Initial Alignment; Kalman Filter; Obervability; Data Acquisition**

I. INTRODUCTION

Since the 1950s, the strap-down inertial navigation system (SINS) has been widely used in many fields such as positioning and navigation of ships, aeroplanes, vehicles, and missiles etc. The initial misalignment is one of the major error sources of SINS. Considering the initial alignment errors will affect the system error in the position, velocity and attitude (PVA), the SINS must be preferable aligned before positioning and navigation.

The aim of initial alignment of SINS is to get a coordinate transformation matrix from body frame to navigation frame and conduct the misalignment angles to zero or as small as possible. In a broad sense, initial alignment of SINS can be divided into two categories i.e. stationary based and moving based alignment. SINSs are entirely self-contained, by using the measurements of the local gravity and Earth rate [1]. Theoretically, an analytic self-alignment method for strapdown inertial navigation system is functionally equal to the physical gyrocompassing in gimbaled systems. The error characteristics of both systems seem to be identical at steady state in a stationary base [1]. Generally, alignment of SINS can be divide into two phases i.e. the coarse and the fine alignment. The purpose of coarse alignment is to estimate the orientation of the instrumental axis relative to navigation frame. The purpose of fine alignment is to compute the small misalignment angles between reference frame and the body frame accurately through processing the information of various sensors data [2].

The requirements of initial alignment of SINS are high accuracy and short time. There are many complications that make alignment both time consuming and complex. Accurate alignment is crucial, however, this is based on alignment over long periods of time. A compromise of accuracy and time consumption of initial alignment should be made.

This paper proposes initial alignment for SINS based on low-cost IMU on a stationary base. First, acquire linear accelerations and angular rates from IMU, then denoise the gyro data. Next, modeling the initial alignment model and analysis the observability of alignment, simplify the alignment model based on the observability. Subsequently, a kalman filter was conducted to estimate the misalignment angle. Finally, the test results are presented to show performance of the proposed initial alignment for SINS based on low-cost IMU on a stationary base.

II. SINS ARCHITECTURE

Generally, a strapdown system is a major hardware simplification of the navigation system. The accelerometers and gyros are mounted in body coordinates and are not mechanically moved. Instead, a software solution is used to keep track of the orientation of the IMU and rotate the measurements from the body frame to the navigational frame. This method overcomes the problems encountered with the navigation system, and most importantly reduces the size, cost, power consumption, and complexity of the system. This section will give a brief overview of the SINS architecture, which is shown in Fig. 1.

It consists of a data acquisition unit (DAU) and a navigation process unit (NPU). The DAU is composed of a FPGA and a MEMES-based IMU which contain a temperature sensor, a triple axis gyroscope and a triple axis accelerometer. A personal computer (PC) serves as the NPU. The gyroscope and accelerometer of IMU can provide angular rates and linear accelerations for the SINS respectively. The GPS receiver and barometer

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shown in the architecture is for the GPS/SINS/BARO integrated navigation system [3]. Besides, the compass and magnetometer interfaces are reserved for future developments. The data of GPS, barometer, and IMU are sent to FPGA, then packed and acquired by PC via USB controller. The data are processed in PC.

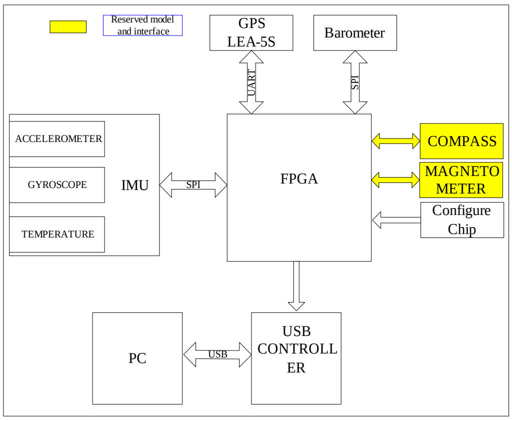

Figure 1. Architecture of SINS.

III. ALGORITHM OF INITIAL ALIGNMENT

In this article the initial alignment have three stages, that is, the data preprocess, the coarse and fine alignment. In the data preprocess stage, the null bias of gyro is stripped almost and the random walk of gyro is minimized. In the coarse alignment stage, a fairly good initial condition for the fine alignment is provided and it can made the total alignment time shorter. In the fine alignment stage, the small misalignment angles between references frame and the body frame are computed accurately.

A. Data Preprocess

The error model of gyro can be depicted as:

$$\varepsilon = \varepsilon_b + \varepsilon_g \tag{1}$$

Where, ε_b is null bias, ε_g is the random walk which regarded as white noise. Null bias of gyro is a slowly changing signal, it can be regarded as a constant on every start. We can strip it from the outputs of gyro in mean filter. After the null bias is stripped, minimize the random walk of gyro effectively is very important to improve the accuracy of the output of gyroscope. Considering the random walk of gyro is weakly nonlinear, unsmooth and effected by the uncertain factors easily, the wavelet threshold filter is very effective to denoise the random walk. In this work, we choose the 5 scales db4 wavelet to improve the gyro's data.

B. Coarse Alignment

The purpose of coarse alignment is to provide a fairly good initial condition for the fine alignment. This can made the total alignment time shorter. Generally, the coarse alignment method can be divided into analytic coarse alignment and optical alignment. Here, the analytic coarse alignment method is adopted. The accelerometers and gyros measure the gravity vector and Earth rate vector related to body frame, respectively. These two vectors are known constant in navigation frame, assume that the navigation axes are aligned with the local-level north, east, and down. Then the gravity and Earth rate vectors can be expressed as:

$$g^n = [0 \quad 0 \quad -g]^T \tag{2}$$

$$\omega_{ie}^n = [\omega_{ie}\cos L \quad 0 \quad -\omega_{ie}\sin L] \tag{3}$$

The transformation of gravity vector and Earth rate vector from body frame to navigation frame are respectively depicted below:

$$g^n = C_b^n g^b \tag{4}$$

$$\omega_{ie}^n = C_b^n \omega_{ie}^b \tag{5}$$

Where, C_b^n is the transformation matrix. Define $v = g \times \omega_{ie}$, the transformation matrix can be depicted as:

$$C_b^n = \begin{bmatrix} (g^n)^T \\ (v^n)^T \\ (v^n \times g^n)^T \end{bmatrix}^{-1} \begin{bmatrix} (g^b)^T \\ (v^b)^T \\ (v^b \times g^b)^T \end{bmatrix} \tag{6}$$

The relationship between strapdown navigation frame and real reference frame can be depicted in three misalignment angles ϕ_N , ϕ_E and ϕ_D . Analysis the error of the coarse alignment, the misalignment angles can be derived [4]:

$$\begin{cases} \phi_N = \delta f_{\mathrm{E}} / g \\ \phi_E = (-\delta f_{\mathrm{N}} + tgL\delta f_{\mathrm{D}}) / 2g - \delta\omega_{\mathrm{D}} \sec L / 2\omega_{ie} \\ \phi_D = -\delta f_{\mathrm{E}} tgL / g + \delta\omega_{\mathrm{E}} \sec L / \omega_{ie} \end{cases} \tag{7}$$

It is observed from above formulation that not only the north specific force but also the vertical force and azimuth gyro uncertainties will induce the east level error. This situation is quite different from that occurred in a gimbaled system [1].

C. Fine Alignment

Fine alignment is a precise alignment stage in which the small misalignment angles between references frame and the body frame are computed accurately through processing the information of various sensors. In this section, a model for initial alignment is depicted and the kalman filter for fast alignment is presented.

a. Model of Initial Alignment

Considering the situation where it is required to align a SINS to the local geographic coordinate frame defined by North-East-Down (NED) frame. For the purpose of this analysis, it is assumed that the navigation system is stationary with respect to the Earth. In this situation, the accelerometers measure three orthogonal components of the specific force needed to overcome gravity whilst the gyroscopes measure the components of the Earth's turn rate in the same directions [2]. In order to look into the behavior of an inertial navigator, a proper error model should be derived. It is well known that the description of the SINS error propagation using a linearized error model is quite a good approximation. The characteristics of SINS can be derived from the linear error model. The SINS error model plays an important role in implementing a Kalman filter for alignment. The model of SINS initial alignment is formed in the NED geographic frame, which is denoted n. The computational navigation frame is denoted n'. The carrier body frame is denoted b, and its three axes parallel the three axes of carrier, the positive direction is Forward- Right-Down.

The state equation of initial alignment is:

$$\dot{X} = FX + GW \tag{8}$$

Where X , F , G, W serve as system states, transfer matrix, noise matrix and system noise vector of the system, respectively. Therein, G is a 8×8 unit matrix. Ignoring the position and velocity errors, the state of initial alignment can be written:

$$X = \begin{bmatrix} \phi_N & \phi_E & \phi_D & \varepsilon_N & \varepsilon_E & \varepsilon_D & \nabla_N & \nabla_E \end{bmatrix}^T \tag{9}$$

Where the subscripts N, E and D denote the north, east and down of geographical frame. ϕ_N , ϕ_E , ϕ_D are the attitude errors; ε_N , ε_E , ε_D and ∇_N , ∇_E are the constant error of gyros and accelerometers, respectively. The derivatives of them are zero. So, the state transportation matrix and system noise vector can be depicted as:

$$F = \left[\begin{array}{cccccc|c} 0 & -\omega_{ie}\sin L & 0 & -1 & 0 & 0 & \\ \omega_{ie}\sin L & 0 & \omega_{ie}\cos L & 0 & -1 & 0 & 0_{3\times 2} \\ 0 & -\omega_{ie}\cos L & 0 & 0 & 0 & -1 & \\ \hline & & & 0_{5\times 8} & & & \end{array}\right] \tag{10}$$

$$W = [\omega_{gn} \quad \omega_{ge} \quad \omega_{gd} \quad 0_{1\times 5}]^T \tag{11}$$

Considering the coupling of vertical specific force and level misalignment angle is very weak, the measurement of vertical specific force can be ignored, so we can take the level specific force as measurement signal. The measurement equation of initial alignment is:

$$Z = HX + V \tag{12}$$

$$Z = [\, f_N \quad f_E \,]^T \tag{13}$$

V is the measurement noise, it can be depicted as:

$$V = \begin{bmatrix} v_{aN} & v_{aE} \end{bmatrix}^T \tag{14}$$

H is the measurement matrix, it can be depicted as:

$$H = \begin{bmatrix} 0 & g & \\ & & 0_{2\times 6} \\ -g & 0 & \end{bmatrix} \tag{15}$$

b. Observability analysis

The estimation result of the system state is a good performance index for the degree of observability of the states of the initial alignment. If the estimation of a state by Kalman filter is convergent, the state will be observable. If the estimation of a state is not convergent, the state will be unobservable. The faster the convergent rate is, the higher the degree of observability of the state is [5].

Consider a linear time-invariant system. If the rank of the observability test matrix is equal to the order of the system, then the system is completely observable. On the contrary, if the system is not completely observable, the number of unobservable states is the difference between the order of the system and the rank of the observability test matrix [4].

For the reason that some states can not be estimated have effects on estimating the azimuth misalignment, the azimuth misalignment can not be estimated as well as the leveling misalignment. A rank test of observability matrix can determine whether the system is completely observable or not. The observability matrix can be written as:

$$O = [F \quad FH \quad FH^2 \quad \ldots \quad FH^7]^T \tag{16}$$

$rank(O) = 5$, the number of unobservable states is the difference between the order of system and the rand of the observability matrix. So, the system is not completely observable, there are only 5 observable states and left 3 unobservable states. It is necessary that the misalignment angles be all observable. The combination of three unobservable states could be $\nabla_N, \nabla_E, \varepsilon_E$ or $\nabla_E, \varepsilon_E, \varepsilon_D$. The faster the convergence rate is, the higher the degree of observability of the state is. According to the analysis, the most reasonable choice of the three unobservable states are $\nabla_N, \nabla_E, \varepsilon_E$ for the initial alignment process [6].

Once the unobservable states have been selected, the improved estimation algorithm for computing the estimates of misalignment angles should be designed. The fast convergence of ϕ_D requires higher degree of observability of ϕ_D , but the degree of observability of it can't be increased because of the limitation of ε_E . The characteristic of SINS determines that ε_E is unobservable as analyzed above. The estimate of the ϕ_D can be depicted as:

$$\hat{\phi}_D = (\hat{\dot{\phi}}_E - \omega_{ie} \sin L \hat{\phi}_N) / (\omega_{ie} \cos L) \tag{17}$$

Equation 17 shows that the azimuth error can be computed directly from the estimates of the leveling error about the north axis and the leveling error rate about the east axis. Therefore, the convergence rate of $\hat{\phi}_D$ can be greatly increased. This azimuth error estimation method is identical to that often shown in the delf-alignment schemes. It should be pointed out that the measured signals should be first converted to the input of the digital low-pass filter [7] [8] [9]. From the above equation we know that when the system is located at the Earth pole, the azimuth error become unobservable. Considering this system won't used at Earth pole, we can neglect this effect.

D. Kalman filter for fast alignment

According to the analytic result of observability, the constant null drift of accelerometers and constant drift of east gyro can be ignored. In terms of the error model and the observation of SINS, the discrete Kalman Filtering equations are formulated as follows:

$$\begin{cases} \hat{X}_k^- = F_k \hat{X}_{k-1} + Gu_{k-1} \\ P_k^- = F_k P_{k-1} F_k^T + Q_k \\ K_k = P_k^- H_k^T (H_k P_k^- H_k^T + R_k)^{-1} \\ \hat{X}_k = \hat{X}_k^- + K_k (z_k - H_k \hat{X}_k^-) \\ P_k = (I - K_k H_k) P_k^- \end{cases} \tag{18}$$

The simplified system state vector of initial alignment is depicted below.

$$X = [\phi_N \quad \phi_E \quad \phi_D \quad \varepsilon_N \quad \varepsilon_D]^T \tag{19}$$

$$F = \begin{bmatrix} 0 & -\omega_{ie}\sin L & 0 & -1 & 0 \\ \omega_{ie}\sin L & 0 & \omega_{ie}\cos L & 0 & 0 \\ 0 & -\omega_{ie}\cos L & 0 & 0 & 0 \\ & & 0_{1\times 5} & & \end{bmatrix} \tag{20}$$

The process of kalman filter is depicted in Fig. 2. F_k is the discrete system state transformation matrix. H_k is the discrete measurement matrix.

Assumption that the initial misalignment angels of north, east and down are about 5°, 5° and 50°, respectively. The constant drifts and angular random walk of each gyro are $0.015^\circ/s$ and $4.2^\circ/\sqrt{h}$, respectively. The constant drifts and velocity random walk of each accelerometer are $700\mu g$ and $300\mu g$, the latitude is about 31.28°.

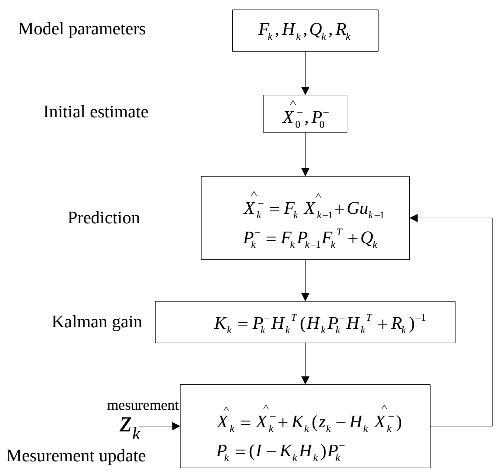

Figure 2. The Structure of Discrete Kalman Filter

IV. APPLICATION TEST AND ALIGNMENT RESULT

The data acquisition board which is shown in Fig.3 is applied to a GPS/SINS/BARO integrated system [3]. The GPS applied to this system is a GPS module Ublox LEA-5S, this module provides excellent performance and flexibility at an economical price. A 32-channel acquisition engine with over 1 million effective correlators is capable of massive parallel searches. This enables a Time To First Fix (TTFF) less than 1 second. The barometer is VTI's SCP1000-D01 pressure sensor, it detects the smallest barometric pressure changes, enabling easy local altitude measurements. It communicates over standard SPI interface and the resolution is 2 Pa. The altitude measurement based on pressure is a relative measurement it compares pressures at different places. The altitude H as a function of pressure P is obtained from (21) below.

$$H_{BARO} = 44.33km * [1 - (P/101325Pa)^{0.19}] \tag{21}$$

IMU give angular rates and linear accelerations for the inertial navigation. The SINS can utilize either and off-the-shelf ring laser gyroscope (RLG) IMU or MEMS IMU. Considering the performance-price ratio, a low cost MEMS based tri-axis inertial sensor is applied. This IMU is a complete triple axis gyroscope and triple axis accelerometer inertial sensing system which is precision-aligned across axes, and is calibrated for offset and sensitivity. The data of GPS, BAROMETER, and IMU are sent to FPGA and packed in it. Then send the packages to PC via a USB microcontroller. The specification of the IMU is presented in table 1.

Figure 3. Data Acquisition Board

The noise of gyro is shown in Fig.4. The results of the data preprocess is shown in Fig. 5 and Fig.6. Fig.5 is the noise of gyro after mean filter, Fig.6 is the noise of gyro after 5 scales db4 wavelet denoise. The alignment result is given in Fig. 7, in which the misalignment angle errors are result using the method proposed in this paper. It is obviously observed that the convergence speed of the two leveling misalignment angle ϕ_E and ϕ_N are very quick, they are about 40s, respectively. The optimal time of

TABLE I.
SPECIFICATION OF IMU

Parameter			Conditions	Value	Unit
Gyro	*sensitivity*		25°,±300°/s	.07326	°/s/LSB
			25°,±150°/s	.03663	°/s/LSB
			25°,±75°/s	.01832	°/s/LSB
	Bias	*In Run*	25°,1σ	.015	°/s
		Radom walk	25°	4.2	°/rthr
	Noise		25°,±300°/s, 2-tap filter	0.60	°/s rms
			25°,±150°/s, 8-tap filter	0.35	°/s rms
			25°,±75°/s, 32-tap filter	0.17	°/s rms
Accel	*sensitivity*		25°	2.522	mg/LSB
	Bias	*In Run*	25°,1σ	0.7	mg
		Radom walk	25°	2	°/rthr
	Noise		25°, no filtering	35	mg rms

azimuth misalignment angle ϕ_D is about 100s. This initial alignment method for SINS that is proposed here can reduce the time of initial alignment greatly, it is verified to be quite effective.

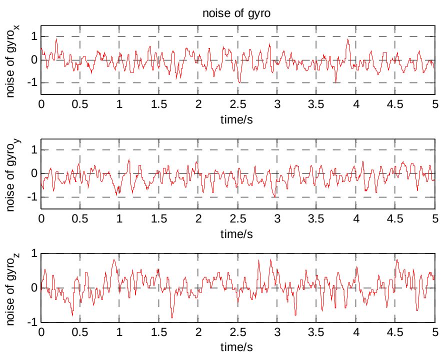

Figure 4. Noise of gyro

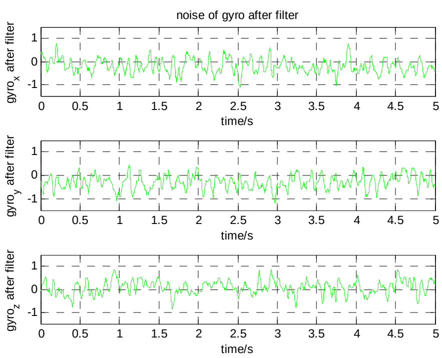

Figure 5. Noise of gyro after filter

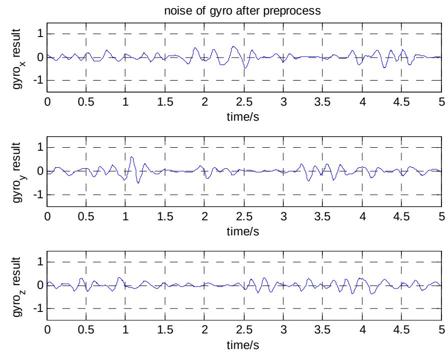

Figure 6. Noise of gyro after wavelet denoise

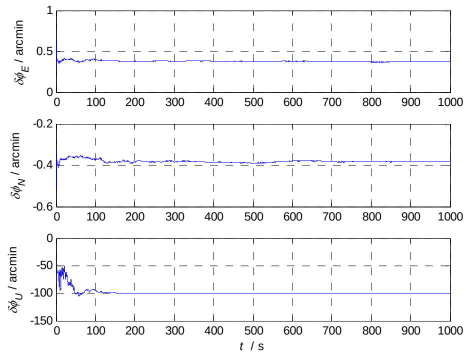

Figure 7. Error estimation of misalignment angle.

V. CONCLUSION

In this paper, initial alignment for SINS based on low-cost IMU on a stationary base is proposed. The hardware is designed to acquire the outputs of gyros and accelerometers, meantime, the GPS data is also acquired. The acquired gyro data are preprocessed to denoise the null bias and random walk. The simplified system states are obtained based on the analysis of the obervability of system states. To shorten the convergent time, the simplified kalman filter for initial alignment is adopted. The test result show that the initial alignment method proposed in this paper is superior to the traditional method and it is advisable for a SINS based on low-cost IMU on a stationary base.

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