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A calibration method for misalignment angle of vehicle-mounted IMU

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Abstract

In order to get accurate navigation data via Strapdown Inertial Navigation System (SINS), calibration of misalignment angle between Inertial Measurement Unit (IMU) and vehicle is necessary. The misalignment angle model is simplified, assuming that vehicle travels on a horizontal plane. Due to the velocity of vehicle is small, equation of specific force is simplified. And then equation of misalignment angle is deduced on condition that vehicle travels on a horizontal plane, making straight motion ideally. Angular rate is used to discriminate that vehicle making straight motion. Steps for calibrate misalignment angle are established. In calibration experiment, data are collected and misalignment angle of vehicle-mounted IMU is calibrated using simple techniques of data processing. Analysis shows that, compensation of misalignment angle helps improving the accuracy of SINS. Position error of SINS solution is decreased and the acceleration of vehicle is more accurate.

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Keywords: vehicle-mounted SINS, misalignment angle, navigation

1. Introduction

SINS is widely used to get navigation data. IMU, as a crucial part, should be installed on the centroid of vehicle. The 3 axes of IMU should be aligned with the 3 axes of vehicle. The existing of the misalignment angle always leads bad influence on the navigation accuracy of SINS. It is difficult to install IMU in vehicle without misalignment angle. It is necessary to find a way to calibrate misalignment angle for improving the accuracy of SINS.

Cheng et al. (2004) proposes an extended filter and velocity and attitude matching method to estimate IMU misalignment. Xu et al. (2008) presents a new filter and the improved BP neural network approach to estimate IMU misalignment. These methods are complex, the validness of which is just testified by simulation results.

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Yan et al. (2009) uses theodolite goniometer to calibrate the misalignment angle between IMU and gun barrel. Xu et al. (2010) calibrates the misaligned error of IMU and rotation axis using IMU rotating technology. Other precise instruments are used in these two studies.

This paper introduces a way to calibrate misalignment angle of vehicle-mounted IMU, using simple data processing method without other equipment. The result shows that the compensation of misalignment angle helps improving the accuracy of SINS. Acceleration error is decreased and position of SINS is more accurate.

The remainder of this paper is organized as follows. Section 2 presents the calibration method. The misalignment model is simplified assuming that vehicle travels on a horizontal plane. Equation of specific force is simplified to deduce the equation of misalignment angle. The data processing method and calibration steps are proposed. Section 3 presents calibration experiments to get misalignment angle using proposed method. Section 4 presents the analysis of influence of error compensation on vehicle navigation. Section 5 provides conclusion and recommendations for future work.

2. Calibration method

2.1. Principle of Calibration

Ideally, assuming that vehicle travels on a horizontal plane, roll and pitch angle of vehicle platform is 0 and yaw angle is Ψ_0. The vehicle coordinate system is t. The origin of t is at the center of gravity of the vehicle, and x_t-axis, y_t-axis, and z_t-axis are aligned with the sideway (to the right), forward, and up directions associated with the vehicle. The geographic coordinate system is n, the origin of which is at centroid of the vehicle. The vehicle coordinate system t is transformed from the geographic coordinate system n by rotating Ψ_0. The transformation matrix from n to t is as follows:

$$\boldsymbol{C}_n^t = \begin{bmatrix} \cos\Psi_0 & \sin\Psi_0 & 0 \\ -\sin\Psi_0 & \cos\Psi_0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where Ψ_0 represents the yaw angle of vehicle. Ψ_0 is measured in coordinate n. The transformation matrix from t to n is as follows:

$$\boldsymbol{C}_t^n = \begin{bmatrix} \cos\Psi_0 & -\sin\Psi_0 & 0 \\ \sin\Psi_0 & \cos\Psi_0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Misalignment of IMU consists of misalignment position and misalignment angle. Unlike aircraft, vehicle has no rapid angular motion, when traveling on the road. Because of that, misalignment position can be ignored (Wang et al., 2007). The IMU coordinate system is b, which is right handed. Assuming that the IMU is installed at the centroid of the vehicle, the origin of b is located at the origin of t. The misalignment angle is Δx, Δy,and Δz, when vehicle travelling on road. The misalignment angle is illustrated in Fig. 1.

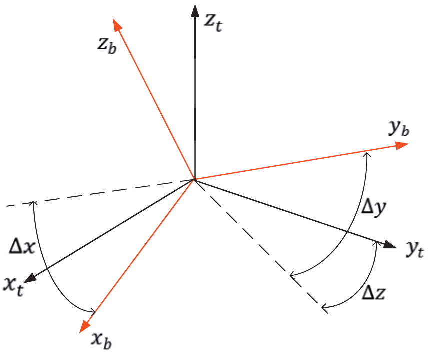


Fig. 1. misalignment angle

Just like strapdown attitude matrix, the transformation matrix from t to b is as follows:

$$\boldsymbol{C}_t^b = \begin{bmatrix} \cos\Delta x\cos\Delta z - \sin\Delta x\sin\Delta y\sin\Delta z & \cos\Delta x\sin\Delta z + \sin\Delta x\sin\Delta y\cos\Delta z & -\sin\Delta x\cos\Delta y \\ -\cos\Delta y\sin\Delta z & \cos\Delta y\cos\Delta z & \sin\Delta y \\ \sin\Delta x\cos\Delta z + \cos\Delta x\sin\Delta y\sin\Delta z & \sin\Delta x\sin\Delta z - \cos\Delta x\sin\Delta y\cos\Delta z & \cos\Delta x\cos\Delta y \end{bmatrix} \tag{3}$$

where Δx, Δy,and Δz are the misalignment angle. As Δx, Δy,and Δz are small angles, Eq. (3) can be simplified as follows:

$$\boldsymbol{C}_t^b = \begin{bmatrix} 1 & \Delta z & -\Delta x \\ -\Delta z & 1 & \Delta y \\ \Delta x & -\Delta y & 1 \end{bmatrix} \tag{4}$$

Δx, Δy,and Δz are measured in coordinate t.The transformation matrix from b to t is as follows:

$$\boldsymbol{C}_b^t = \begin{bmatrix} 1 & -\Delta z & \Delta x \\ \Delta z & 1 & -\Delta y \\ -\Delta x & \Delta y & 1 \end{bmatrix} \tag{5}$$

Setting the coordinate n as navigation coordinate, strapdown attitude matrix is $\boldsymbol{C}_b^n$ (Wu, 2009). And $\boldsymbol{C}_b^n$ can be written as the product of $\boldsymbol{C}_t^n$ and $\boldsymbol{C}_b^t$. That is,

$$\boldsymbol{C}_b^n = \boldsymbol{C}_t^n \boldsymbol{C}_b^t \tag{6}$$

Spreading Eq. (6), parts of the matrix elements are as follows:

$$T_{12} = -\Delta z\cos\Psi_0 - \sin\Psi_0 = -\sin(\Psi_0 + \Delta z) \tag{7.1}$$

$$T_{22} = -\Delta z\sin\Psi_0 + \cos\Psi_0 = \cos(\Psi_0 + \Delta z) \tag{7.2}$$

$$T_{31} = -\Delta x \tag{7.3}$$

$$T_{32} = \Delta y \tag{7.4}$$

$$T_{33} = 1 \tag{7.5}$$

where T_{ij} represents the element in $\boldsymbol{C}_b^n$'s the ith row and the jth column. Then the roll angle γ, the pitch angle θ, and the yaw angle Ψ from SINS can be calculated as:

$$\gamma = \arctan\left(-\frac{T_{31}}{T_{33}}\right) = \Delta x \tag{8.1}$$

$$\theta = \arcsin T_{32} = \Delta y \tag{8.2}$$

$$\Psi = \arctan\left(-\frac{T_{12}}{T_{22}}\right) = \Psi_0 + \Delta z \tag{8.3}$$

Thus it can be seen that, misalignment angle Δx and Δy are the roll angle γ and the pitch angle θ from SINS solution respectively. Only Δz has influence on the calculation of vehicle motion data. It is Δz that the only misalignment angle which is needed to calibrate.

The projection of specific force onto coordinate t is as follows:

$$\dot{\boldsymbol{v}}_t = \boldsymbol{f}_t - (2\boldsymbol{\omega}_{ie} + \boldsymbol{\omega}_e) \times \boldsymbol{v}_t + \boldsymbol{g} \tag{9}$$

where $\dot{\boldsymbol{v}}_t$ is the acceleration vector of vehicle, and $\boldsymbol{f}_t$ is the specific force on vehicle, and $\boldsymbol{\omega}_{ie}$ is the earth's angular speed of rotation, and $\boldsymbol{\omega}_e$ is the centripetal acceleration from the motion of vehicle travelling on the earth (circular motion around the earth), and $\boldsymbol{v}_t$ is the velocity vector of vehicle, and $\boldsymbol{g}$ is acceleration of gravity.

Since that the velocity of vehicle travelling on road is very small compared with aircraft, the item $(2\boldsymbol{\omega}_{ie} + \boldsymbol{\omega}_e) \times \boldsymbol{v}_t$ in Eq. (9) is approximately equal to $\boldsymbol{0}$. Eq. (9) can be simplified as follows:

$$\dot{\boldsymbol{v}}_t = \boldsymbol{f}_t + \boldsymbol{g} \tag{10}$$

Eq. (10) can be written in components as follows:

$$\begin{bmatrix} \dot{v}_{tx} \\ \dot{v}_{ty} \\ \dot{v}_{tz} \end{bmatrix} = \begin{bmatrix} f_{tx} \\ f_{ty} \\ f_{tz} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} \tag{11}$$

where f_{tx}, f_{ty}, and f_{tz} are the projection of $\boldsymbol{f}_t$ onto coordinate t's 3 axes respectively.

The specific force on IMU is $\boldsymbol{f}_b$, and then $\boldsymbol{f}_t = \boldsymbol{C}_b^t \boldsymbol{f}_b$. That is,

$$\begin{bmatrix} f_{tx} \\ f_{ty} \\ f_{tz} \end{bmatrix} = \begin{bmatrix} 1 & -\Delta z & \Delta x \\ \Delta z & 1 & -\Delta y \\ -\Delta x & \Delta y & 1 \end{bmatrix} \begin{bmatrix} f_{bx} \\ f_{by} \\ f_{bz} \end{bmatrix} \tag{12}$$

where f_{bx}, f_{by}, and f_{bz} are the projection of $\boldsymbol{f}_b$ onto coordinate b's 3 axes respectively.

Assuming that vehicle travels on a horizontal plane, making straight motion, ignoring all errors, it is got that $\dot{v}_{tx} = 0$, and $\dot{v}_{tz} = 0$. That is,

$$f_{tx} = f_{bx} - \Delta z f_{by} + \Delta x f_{bz} = 0 \tag{13}$$

Then Δz can be calculated as follows:

$$\Delta z = \frac{f_{bx} + \Delta x f_{bz}}{f_{by}} \tag{14}$$

According to Eqs. (8.1), (12) and (14), only if the specific force on IMU $\boldsymbol{f_b}$ and roll angle γ have been measured when vehicle making straight motion, misalignment angle Δz will be calculated approximately.

Ideally, when vehicle making straight motion or parked on horizontal plane, it can be assumed that $\omega_{tz} = 0$, where ω_{tz} is the projection of $\boldsymbol{\omega}_t$, the angle rate of vehicle, onto z_t-axis. In practice, when vehicle moving on the road, because of bumps, gyro error and so on, ω_{tz} cannot be identically equal to zero. However, ω_{tz} should be in a range when vehicle travelling on a horizontal straight road. Range of ω_{tz0} is set as Ω, when vehicle is parked on horizontal plane. If $\omega_{tz} \in \Omega$ when vehicle travelling on a horizontal straight road, it can be assumed that vehicle makes straight motion on horizontal plane. $\boldsymbol{\omega}_t$ can be calculated as follows:

$$\boldsymbol{\omega}_t = \boldsymbol{C}_b^t \boldsymbol{\omega}_b \tag{15}$$

where $\boldsymbol{\omega}_b$ is the angular rate of IMU relative to coordinate n. So,

$$\omega_{tz} = -\Delta x \omega_{bx} + \Delta y \omega_{by} + \omega_{bz} \tag{16}$$

where ω_{bx}, ω_{by}, and ω_{bz} are the projection of $\boldsymbol{\omega}_b$ onto coordinate b's 3 axes respectively.

2.2. Steps for Calibration

(1) Vehicle is parked on proximate horizontal plane, which can be seen as vehicle under stationary state. Get roll angle γ_0, pitch angle θ_0, and angle rate ω_{b0} from SINS solution after self-alignment. Get ω_{tz0} via Eq. (16) and determine its value range Ω.

(2) Vehicle travels on horizontal road. We try to keep the vehicle making straight motion, and accelerate or make brake frequently. Get specific force f_b, roll angle γ, pitch angle θ, and angle rate ω_b from SINS solution.

(3) Calculate ω_{tz} via Eq. (16), where $\Delta x = \gamma$ and $\Delta y = \theta$.

(4) In order to eliminate the error, choose the data groups in which the absolute value of f_{by} is bigger. Set the value range of f_{by} as F.

(5) Choose the data groups in which $f_{by} \in F$ and $\omega_{tz} \in \Omega$. Calculate Δz via Eq. (14). Then calculate the mean value of Δz as the estimate of Δz.

3. Calibration Experiments

3.1. Data Collection

In experiments, the IMU is a MEMSIC™ VG440. Data are recorded using ADVANTECH™ IPC wtih operating system of Windows 7. And the vehicle is a CHANG'AN™ Yuexiang.

Experiments for gathering static vehicle data is carried out in campus of Beihang University. The vehicle is located on horizontal ground under parking state. Data are gathered after SINS's self-alignment. Data collection is carried out three times, getting 2930 groups of data.

Experiment for gathering moving vehicle data is carried out at Changping District, Beijing. Data is gathered after SINS's self-alignment. In the experiment, the vehicle is driven on a horizontal straight road, and accelerated or taken brake frequently. 5607 groups of data are collected.

3.2. Data Processing

(1) Data when vehicle is parking

Statistics of roll angle γ and pitch angle θ is illustrated in Tab. 1 when vehicle is parking. Mean value of γ is 0.0105(rad) and θ, 0.0044 (rad). So γ and θ can both be assumed as small angles.

Table 1. Statistics of γ and θ when vehicle is parking.

	N	Mean	Max	Min
γ	2930	0.0105	0.0117	0.0093
θ	2930	0.0044	0.0055	0.0035

The value of ω_{tz0} is calculated via Eq. (16). The histogram of ω_{tz0} is illustrated in Fig. 2. The percentile of ω_{tz0} is illustrated in Tab. 2.

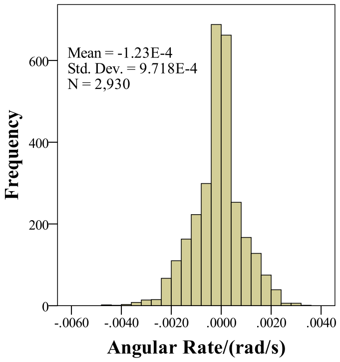


Fig. 2. histogram of ω_{tz0}

Tab 2 Percentile of ω_{tz0}.

Percentile						
5th	10th	25th	50th	75th	90th	95th
-0.0017	-0.00134	-0.0007	-0.0000	0.0003	0.0010	0.0014

The value range of ω_{tz} is chosen from 5th percentile to 95th percentile, that is

$$\Omega = [-0.0017, 0.0014] \tag{17}$$

(2) Data when vehicle moving

Statistics of roll angle γ and pitch angle θ is illustrated in Tab. 3 when vehicle moving. Mean value of γ is 0.0276(rad) and θ, 0.00158(rad). So γ and θ can both be assumed as small angles.

Table 3. Statistics of γ and θ when vehicle moving.

	N	Mean	Max	Min
γ	5607	0.0276	0.0523	-0.0059
θ	5607	0.0158	0.0564	-0.0174

In order to eliminate the error, value of f_{by} should be bigger. So F is set as follows:

$$F = (-\infty, -1] \cup [1, +\infty] \tag{18}$$

The value of ω_{tz} is calculated via Eq. (16). Groups of data are chosen, in which $f_{by} \in F$ and $\omega_{tz} \in \Omega$, to calculate the value of Δz. 384 groups of data are chosen. And Δz is calculated via Eq. (14), the mean value is -1.4066 (in degree). So $\Delta z = -1.4066°$. The histogram of Δz is illustrated in Fig. 3. The distribution of Δz is similar to normal distribution.

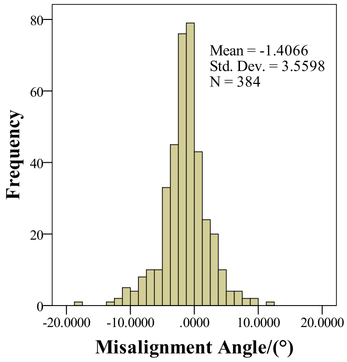


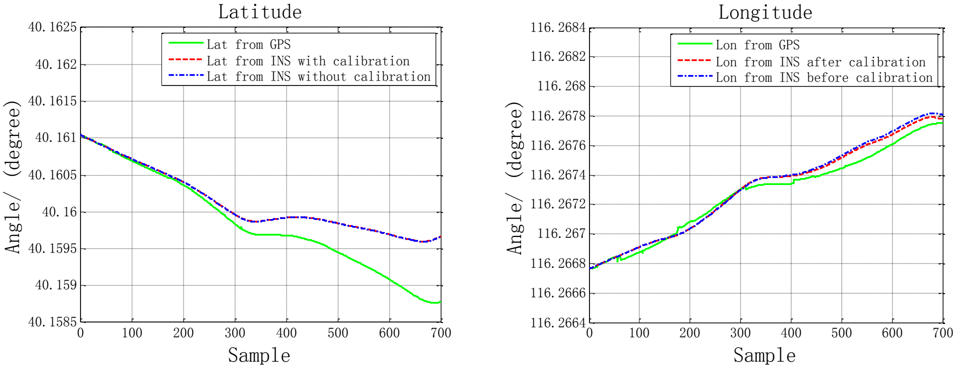
Fig. 3. histogram of Δz

4. Results and analysis

According to Eq. (8.3) the real yaw angle Ψ of SINS is calculated as follows:

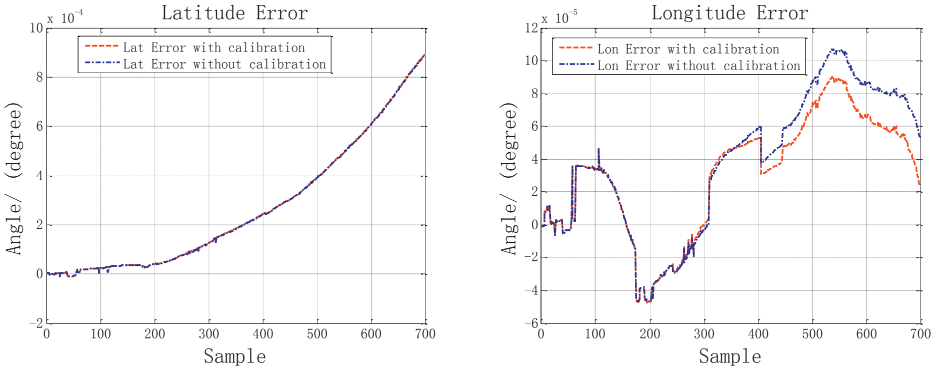
$$\Psi = \Psi_0 - \Delta z \tag{19}$$

SINS solution is carried out using a piece of data when vehicle moving. The initial yaw angle of vehicle is provided by high-accuracy GPS. SINS solution is carried out using Ψ_0 and Ψ as the yaw angle of SINS to get latitude and longitude respectively (illustrated in Fig. 4).



(a) (b)

Fig. 4. (a) latitude; (b) longitude



(a) (b)

Fig. 5 (a) latitude error; (b) longitude error

In Fig. 4 the green curve represents latitude and longitude measured by high-accuracy GPS, and the red curve represents latitude and longitude calculating using Ψ as the yaw angle of SINS, and the blue one, Ψ_0. Latitude and longitude measured by GPS can be used as reference of position. Latitude error and longitude error are illustrated in Fig. 5. The red curve represents the position error between position measured by GPS and position calculated from SINS without calibration, and the blue one with calibration. It can be seen that, after calibration, the accuracy of position from SINS solution is certainly improved. But due to the inaccuracy of the IMU, position calculated has rapidly divergent.

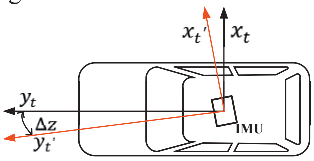


Fig. 6. misalignment angle Δz

As illustrated in Fig. 6, since Δz is a small angle, acceleration of vehicle can be calculated as follows:

$$a_x^t = a_x^b \cos\Delta z - a_y^b \sin\Delta z \approx a_x^b + a_y^b \Delta z \tag{20.1}$$

$$a_y^t = a_y^b \cos\Delta z + a_x^b \sin\Delta z \approx a_y^b + a_x^b \Delta z \tag{20.2}$$

where a_x^t and a_y^t are acceleration in directions of x_t-axis and y_t-axis respectively, and a_x^b and a_y^b are acceleration in directions of x_b-axis and y_b-axis respectively.

Due to that vehicle makes straight motion on horizontal plane approximately, and has obvious accelerating and braking, generally value of a_y^t is bigger than a_x^t statistically. As a result, the calibration has influence on decreasing the error of acceleration in x_t-axis direction (as illustrated in Fig. 7). In the experiment above, the yaw angle of vehicle is about 160° . That is, vehicle travels from nearly north to south. The error of acceleration in east direction from SINS solution decreases, the error of longitude decreasing finally.

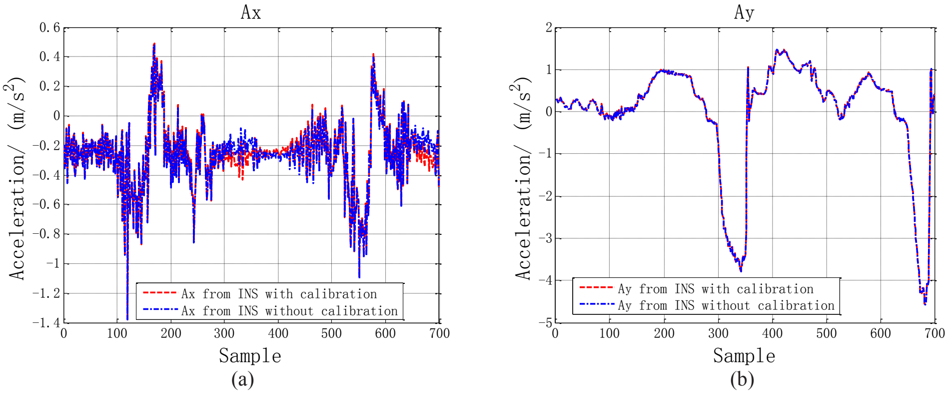


Fig. 7. (a) lateral acceleration a_x^t ; (b) longitudinal acceleration a_y^t

5. Conclusion

This paper introduces a calibration method for misalignment angle of vehicle-mounted IMU. Model of misalignment angle is simplified according to actual motion of vehicle. Calibration steps are established. In experiments, misalignment angle is calibrated. The result of misalignment angle is satisfied. Results and analysis show that compensation of misalignment angle helps improving the position accuracy of SINS and decreased acceleration error. The study of this paper provides basis for simple calibration on misalignment angle of vehicle-mounted IMU.

In this paper gyro and accelerometer drifts is ignored, which has some influence on SINS solution. Gyro and accelerometer drifts can be estimated using data filtering. And in order to increase the accuracy of navigation, integrated navigation system can be put into use. Future research work is needed to address these issues.

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