Design of an MEMS-IMU/GNSS integrated navigation algorithm

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Abstract. In order to simplify the MEMS-IMU/GNSS integrated navigation system model, improve the navigation accuracy of the carrier under the motion condition of large Angle or frequent steering turning, two navigation modes are adopted. When GNSS signals are available, horizontal velocity and height error are used to construct three-dimensional measurement equations for partial integrated navigation. When GNSS signals are unavailable, kinematic constraint equations are introduced to assist MEMS-IMU for auxiliary navigation. Considering the problem that MEMS gyroscope zero is too large and compass effect is difficult to be reflected, a partial attitude feedback strategy is adopted for the feedback correction. The experimental results show that when GNSS signals are available, compared with the six-dimensional integrated algorithm of speed and position, the partial integrated algorithm simplifies the system model, reduces the dimension of the system, and reduces the amount of calculation, it also has better accuracy. When GNSS signals are unavailable, kinematics constraints auxiliary navigation can effectively restrain position offset, reduce navigation errors and improve navigation accuracy.

1. Introduction

Inertial navigation system(INS) is an autonomous navigation system with good concealment, strong anti-interference and high short-time accuracy. It can provide navigation information such as speed, position and attitude with high bandwidth in all-weather and all-region real-time[1], but its navigation errors will accumulate over time. Global Navigation Satellite System(GNSS) can provide global users with all-weather and full-time continuous high-precision speed, position and time information, but its signal is vulnerable to occlusion and interference, and its dynamic performance is poor. Therefore, combined inertial/satellite navigation can realize complementary advantages, and improve the accuracy and reliability of navigation system.

In recent years, with the rapid development of MEMS technology, MEMS-IMU/GNSS integrated navigation algorithm has been widely developed and applied. The current research mainly focuses on the coupled method, filtering algorithm and the introduction of auxiliary constraints. In the coupled method, although the tightly coupled navigation and the deep coupled navigation have obtained the gratifying development, owing to the realization aspect superiority of the loosely coupled navigation in the engineering, the present coupled method mainly uses loosely coupled navigation. In the loosely coupled navigation, the Kalman filter based on the complete velocity and position can suppress the velocity and position error well, but the restraining effect of the azimuth attitude error is not ideal. In order to solve this problem, some scholars introduced the azimuth attitude error[2] into the measurement equation, and combined speed and position when the carrier moves in a straight line or...
approximately linear motion, and adopted speed and position combination[3] in turning. However, when the carrier has a large Angle or multiple turns, the course error increases, and even the travel direction velocity error of the carrier increases significantly[4]. Literature[5] introduces the course and altitude information into the compact combination system, and improves the system performance through an improved filtering method. Literature[6] improves the observability of the system by introducing the attitude Angle into the observed quantity and by using the autoregressive neural network data fusion. However, the introduction of attitude information measured by GNSS into the measurement equation tends to reduce attitude accuracy due to GNSS signal interference[7]. Since the filtering algorithm uses the observed quantity to estimate the minimum variance of the state quantity, the error of the observed information is directly related to the filtering accuracy of the system[8].

Aiming at the above problems, in order to simplify the system model and improve the navigation accuracy of the carrier under the complex motion conditions of large Angle steering or multiple steering, the paper adopts the horizontal velocity and height position error to construct the kalman loosely coupled filter for integrated navigation, At the same time, GNSS star loss and signal interference were considered. When GNSS signals are lost, kinematic constraint equations are introduced to assist MEMS-IMU for auxiliary navigation. Considering the problem that MEMS gyroscope zero is too large and compass effect is difficult to be reflected, a partial attitude feedback strategy is adopted for feedback correction. Finally, the algorithm is verified by experiments.

2. Algorithm overall structure

The overall structure of the algorithm is shown in Figure 1. When GNSS signals are normal, the navigation system works at GNSS/SINS integrated navigation based on Kalman filter, and the navigation results are corrected in real time by partial feedback correction. When GNSS signals are abnormal, the navigation system works at kinematic constraint auxiliary navigation based on Kalman filter, and the navigation results are corrected in real time feedback correction.

![Figure 1. Overall structure of the algorithm.](image)

2.1. System error model

According to the mathematic model of SINS, the system error model is shown as below[9-10].

The differential equation of velocity error is:

\[
\delta \dot{v}^n = f^\times \times \phi^n - (2\omega_m^n + \omega_m^c) \times \delta v^c + v^n \times (2\delta \omega_m^n + \delta \omega_m^c) + C_p\delta v^b
\]  

(1)

The differential equation of attitude error is:

\[
\dot{\phi}^n = -\omega_m^c \times \phi^n + \delta \omega_m^c - C_p\varepsilon^b
\]  

(2)

The differential equation of position error is:
where \( n \) denotes navigation frame (North-Upward-East local-level frame), \( b \) denotes body frame, \( i \) denotes earth-centered inertial frame, \( e \) denotes earth-centered earth-fixed frame.

2.2. Kinematic constraint model
Since the installation error Angle of the inertial navigation is a small Angle after installation and compensation, after initial alignment, the moving coordinate frame of the carrier and the body frame can be regarded as coincident[11], so the rod arm and installation error of MEMS-IMU can be ignored:

\[
\mathbf{v}^b = C_n^b \mathbf{v}^n.
\]

The differential of the velocity is:

\[
\delta \mathbf{v}^b = C_n^b \delta \mathbf{v}^n + \delta C_n^b \mathbf{v}^n + \left[ \mathbf{v} \times \delta C_n^b \right] \mathbf{v}^n = C_n^b \delta \mathbf{v}^n - \left[ C_n^b \mathbf{v}^n \times J^b \right].
\]

Take the velocity components in the north and upward directions as the velocity constraints. When the carrier is turning, the instantaneous motion can be regarded as the circular motion with a point on the carrier as the center of the circle, while the linear motion can be regarded as the circular motion with the center of the circle on the Y-axis and an infinite radius[12]. Therefore, from the circular motion theory, it can be concluded that the centripetal acceleration generated by the turning of the carrier is:

\[
\mathbf{a}_c = f_x^b + (C_n^b g,)_x (C_n^b V^n)_x, \quad \mathbf{a}_c = \omega_{by} (C_n^b (\omega_n^b + \omega_n^e)),.
\]

During the turn, \( \omega_n^e \) and \( \omega_n^m \) is small, it can be ignored, then:

\[
\mathbf{a}_c = \omega_{by} (C_n^b \delta V^n)_x.
\]

The error of centripetal acceleration is:

\[
\delta \mathbf{a} = f_x^b + (C_n^b g,)_x (C_n^b V^n)_x - \omega_{by} (C_n^b \delta V^n)_x - \omega_{by} (C_n^b \delta V^n)_x - \omega_{by} (C_n^b \delta V^n)_x + \nabla \mathbf{a}_c - (C_n^b \delta V^n)_x, \quad \nabla \mathbf{a}_c = \delta L = \frac{1}{R_N + h} \delta V_N - \frac{V_N}{(R_N + h)^2} \delta h
\]

\[
\delta L = \frac{1}{(R_N + h) \cos L} \delta V_L + \frac{V_L \sin L}{(R_N + h) \cos^2 L} \delta h = \frac{V_L}{(R_N + h)^2 \cos L} \delta h
\]

\[
\frac{\delta h}{\delta h} = \frac{\delta V_U}{\delta h}.
\]

\[
\delta \mathbf{a} = f_x^b + (C_n^b g,)_x (C_n^b V^n)_x - \omega_{by} (C_n^b \delta V^n)_x - \omega_{by} (C_n^b \delta V^n)_x - \omega_{by} (C_n^b \delta V^n)_x + \nabla \mathbf{a}_c - (C_n^b \delta V^n)_x, \quad \nabla \mathbf{a}_c = \delta L = \frac{1}{R_N + h} \delta V_N - \frac{V_N}{(R_N + h)^2} \delta h
\]

\[
\delta L = \frac{1}{(R_N + h) \cos L} \delta V_L + \frac{V_L \sin L}{(R_N + h) \cos^2 L} \delta h = \frac{V_L}{(R_N + h)^2 \cos L} \delta h
\]

\[
\frac{\delta h}{\delta h} = \frac{\delta V_U}{\delta h}.
\]

2.3. Partial feedback correction
The partial feedback correction strategy is to provide feedback correction for position, horizontal velocity and horizontal attitude Angle, but not correct azimuth error in attitude Angle. Assuming that at any time \( k \), the state of the Kalman filter is estimated as:

\[
\hat{X}_k = \left[ \delta \mathbf{V} \quad \phi_e \quad \theta \quad \delta \mathbf{P} \quad \mathbf{e} \quad \mathbf{V} \right]^T
\]

After Kalman filter, the velocity, position and horizontal attitude Angle of the inertial navigation system are corrected by feedback. After correction, the state of the filter is:

\[
\hat{X}_k = \left[ 0_{3 \times 3} \quad 0 \quad 0 \quad 0 \quad 0_{3 \times 3} \quad \mathbf{e} \quad \mathbf{V} \right]^T.
\]

3. Navigation filter design
3.1. Partial integrated navigation Equations of state and measurement equation
Select speed, attitude, position error, gyro drift and accelerometer zero deviation as system state variables, then:

\[
\dot{X} = FX + GW
\]

\[
X = \left[ \delta \mathbf{V} \quad \phi \quad \delta \mathbf{P} \quad \mathbf{e} \quad \mathbf{V} \right]^T, W = \left[ w_{xg} \quad w_{yg} \quad w_{zg} \quad w_{x} \quad w_{y} \quad w_{z} \right]^T.
\]
When GNSS signal is abnormal, choose the east and upward direct ions kinematic constrained velocity error and Centripetal acceleration error to construct the observation equation:

\[
\begin{align*}
\delta \mathbf{x} & = \mathbf{F} \delta \mathbf{x} + \mathbf{v} \\
\mathbf{z} & = \mathbf{H} \mathbf{x} + \mathbf{v}
\end{align*}
\]

Where:

\[
\mathbf{F} = \begin{bmatrix} F_{11} & F_{12} & F_{13} & 0_{3 \times 3} & C_p^e \\ F_{21} & F_{22} & F_{23} & -C_s^e & 0_{3 \times 3} \\ F_{31} & F_{32} & F_{33} & 0_{3 \times 3} & 0_{3 \times 3} \\ 0_{3 \times 3} & 0_{3 \times 3} & 0_{3 \times 3} & 0_{3 \times 3} & 0_{3 \times 3} \end{bmatrix}, \quad \mathbf{G} = \begin{bmatrix} 0_{3 \times 3} & C_s^p \\ C_s^p & 0_{3 \times 3} \end{bmatrix}, \quad \mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & 0_{5 \times 3} & 0 & 0_{5 \times 6} \\ 0 & 1 & 0_{5 \times 5} & 0 & 0_{5 \times 6} \\ 0 & 0 & 1 & 0_{5 \times 5} & 1 & 0_{5 \times 6} \end{bmatrix}
\]

When GNSS signals are available, the velocity difference between north and east, and height differences of inertial navigation system and satellite navigation system are selected as the system observation values, and the observation equation is as follows:

\[
\mathbf{z} = \mathbf{H} \mathbf{x} + \mathbf{v} = \begin{bmatrix} \mathbf{H}_{xe} & \mathbf{H}_{e} \\ \mathbf{H}_{xe} & \mathbf{H}_{e} \end{bmatrix} \mathbf{x} + \begin{bmatrix} v_{xe} \\ v_{re} \end{bmatrix}
\]

\[
(7)
\]

3.2. Kinematic constraints auxiliary navigation measurement equation

When GNSS signal is abnormal, choose the east and upward directions kinematic constrained velocity error and Centripetal acceleration error to construct the observation equation:
Where, ( ), represents the ith row of the matrix.

4. Experimental results and analysis
The algorithm is verified by vehicle-mounted experimental data. Before the test, two sets of GNSS system and two sets of inertial navigation system were installed on the test vehicle. One of the GNSS systems serves as a reference benchmark for speed and position, and its position accuracy is better than 0.2m (RMS). The other serves as an experimental system, and its position accuracy is better than 1.8m (RMS). One of the inertial navigation systems is the laser gyro inertial navigation system with high precision as the attitude reference system, whose horizontal attitude accuracy is better than 0.05 degrees, and course accuracy is better than 0.15 degrees. The other is the low-precision MEMS-IMU, whose gyro-zero-deviation stability is 18deg/h, and the accelerometer zero-deviation stability is 0.04mg.

Through the figure 2, figure 4 to figure 6, table 1 to table 6 contrast analysis shows that when the carrier under the motion condition of large Angle or frequent steering turning, the experimental results of the algorithm in this paper are still in good agreement with the reference values. The accuracy of the partial integrated navigation algorithm is better than the six-dimensional integrated algorithm of speed and position. The dynamic speed accuracy of the algorithm is better than 0.2m/s, the horizontal position accuracy is better than 2m, and the horizontal attitude is better than 0.3 degrees, and the azimuth attitude accuracy is better than 1.8 degrees.

Figure 3 shows the trajectory of kinematic constraints auxiliary navigation with GNSS signal loss in the navigation process. It can be seen from the figure 3 that at the GNSS signal loss point (about 210 seconds), the navigation mode is switched to the kinematic constraint auxiliary navigation, when the carrier is moving in a straight line or approximate straight line, the kinematic assisted navigation results have a good coincidence effect with the reference value. When the carrier is turning, the error increases but does not diverge. After the turning, the kinematic constraint assistance navigation can quickly correct the error. The kinematic constraints auxiliary navigation can effectively restrain position deviation, the maximum deviation of carrier position reaches 15.7 meters.
Figure 2. The trajectory of integrated navigation.

Figure 3. The trajectory of kinematic constraint auxiliary navigation.

Figure 4. The velocity and velocity error.

Table 1. Speed accuracy of complete integrated and partial integrated navigation.

|                | Northward (m/s) | Upward (m/s) | Eastward (m/s) |
|----------------|-----------------|--------------|----------------|
| Fully integrated navigation | 0.2685          | 0.3481       | 0.1994         |
| Partial integrated navigation | 0.1943          | 0.1909       | 0.1276         |

Table 2. Speed accuracy.

|                   | Experiment 1     | Experiment 2   | Experiment 3   | Mean    |
|-------------------|------------------|----------------|----------------|---------|
| Northward Velocity (m/s) | 0.0369           | 0.1085         | 0.4403         | 0.1943  |
| Upward Velocity (m/s)   | 0.1122           | 0.2951         | 0.1655         | 0.1909  |
| Eastward Velocity (m/s) | 0.0384           | 0.1401         | 0.2044         | 0.1276  |

Table 3. Position accuracy of complete integrated and partial integrated navigation.

|                  | Northward (m)    | Upward (m)    | Eastward (m)   |
|------------------|------------------|---------------|----------------|
| Fully integrated navigation | 0.8881           | 0.9969        | 2.0680         |
| Partial integrated navigation | 0.7730           | 1.4292        | 2.0447         |
Figure 5. The position and position error.

Table 4. Position accuracy.

|                  | Experiment 1 | Experiment 2 | Experiment 3 | Mean  |
|------------------|--------------|--------------|--------------|-------|
| Northward Position (m) | 0.0300       | 1.9067       | 0.3823       | 0.7730|
| Eastward Position (m)  | 0.6285       | 2.0046       | 3.501        | 2.0447|
| Upward Position (m)   | 1.2537       | 2.8757       | 0.1581       | 1.4292|

Figure 6. The attitude and attitude error.

Table 5. Attitude accuracy of complete integrated and partial integrated navigation.

|                  | Roll (degree) | Yaw (degree) | Pitch (degree) |
|------------------|---------------|--------------|----------------|
| Fully integrated navigation | 0.1760        | 1.8681       | 0.2272         |
| Partial integrated navigation | 0.1840       | 1.7387       | 0.2264         |

Table 6. Attitude accuracy.

|                  | Experiment 1 | Experiment 2 | Experiment 3 | Mean  |
|------------------|--------------|--------------|--------------|-------|
| Roll Angle (degree) | 0.1209       | 0.2096       | 0.2215       | 0.1840|
| Yaw Angle (degree)  | 1.7825       | 1.6633       | 1.7702       | 1.7387|
| Pitch Angle (degree) | 0.1418       | 0.2035       | 0.3340       | 0.2264|
5. Conclusion
This paper constructs two navigation modes for MEMS-IMU/GNSS integrated navigation algorithm. When GNSS signals are available, the paper uses horizontal speed and height position error to build three-dimensional measurement equations for the partial integrated navigation, and uses the partial attitude feedback strategy to feedback correction in real time. When GNSS signals are unavailable, the kinematic constraint equations are introduced to assist MEMS-IMU for auxiliary navigation. Experiments show that the partial integrated navigation algorithm simplified the algorithm model, reduced the amount of calculation, the precision is better than six-dimensional integrated navigation algorithm of speed and position, and when the GNSS signal are unavailable, kinematics constraints auxiliary navigation can effectively restrain position deviation, reduce navigation errors, improve the navigation accuracy, simplify the filtering model. It lays a foundation for improving the filter model of the system in the next step.

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