Integrated Navigation System and Experiment of a Low-Cost and Low-Accuracy SINS/GPS

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Abstract  When SINS (strap-down inertial navigation system) is combined with GPS, the observability of the course angle is weak. Although the course angle error is improved to some extent through Kalman filtering, the course angle still assumes a divergent trend. This trend is aggravated further when using low-cost and low-accuracy SINS. In order to restrain this trend, a method that uses AHRS to substitute for SINS course angle information is put forward aimed at the hardware component characteristic of the low-cost and low-accuracy SINS including AHRS (attitude and heading reference system) and IMU (inertial measurement unit). Real static and dynamic experiments show that the method can restrain the divergent trend of the navigation system angle effectively, and the positioning accuracy is high.

Keywords  low-cost and low-accuracy SINS; AHRS; closed-loop Kalman filter; on-line adjustment

Introduction

The advantages and disadvantages of GPS and SINS form strong complementarity, and since the 1980s, the GPS/SINS integrated navigation system has had a broad application in planes, missiles and ships[1]. Research indicates that after the combination of SINS and GPS, indexes are all constringent such as the position and velocity error of integrated navigation systems, pitching and rolling error. Because the observability of heading angle information in an integrated system equation-of-state is weaker (coupled with the north component of the Earth’s rotation angular rate under the static state condition), after Kalman filtering correction, although the heading angle error is improved to some extent, it still assumes a divergent trend. The degree of this trend relates with the drift of the gyroscope in the direction of the azimuth axis[2].

Obviously, adopting a high accuracy SINS can maintain the high accuracy property of the integrated system’s output angle information in some time range. However, the high accuracy SINS has some limitations such as production technology and cost, thus placing restrictions on the extensive use of the GPS/SINS integrated system[3]. Therefore, there has been a shift to SINS of low-cost and low-accuracy. Deviation of the azimuth axial gyroscope of the low-cost and low-accuracy SINS is big, therefore the course angle information drifts acutely. In order to eliminate this, we put forward an integrated pattern of low-cost and low-accuracy SINS and GPS, with AHRS included in SINS and where course angle information can be adjusted online.
1 Design of integrated navigation system

In this integrated navigation system, the autonomous navigation system adopts the low-cost and low-accuracy SINS which includes AHRS and IMU; GPS is the supporting equipment of the integrated system. The integrated navigation system adopts GPS as the outer observed quantity, gets estimation of output navigation parameter error through Kalman filtering, and adopts closed-loop policy to correct the output error of the inertial navigation system. The scheme is shown in Fig.1.

![Fig.1 Scheme for the integrated navigation system](image)

An attitude and heading reference system is a system for independent course and movement, and it mainly provides the course of the carrier and the movement information⁴. For example, the system used in this paper is a certain inertial navigation system model of low cost and low accuracy whose hardware includes one set of attitude and heading system, and the course error adopts the angle of deviation and magnetic compass indication to revise itself. At the same time, it adopts a unique algorithm that estimates the conversion angle under the dynamic model from the main coordinate to the tangent coordinate system through 6-state Kalman filters of suitable gain, therefore the precision of course angle is high. In Fig.1, “Heading correction” means that the computed course of SINS is substituted by the course angle information of AHRS.

2 Establishment of integrated navigation system model

There are many error sources of low-cost SINS. In the error model, except for the gyroscope drift and the accelerometer error, the gyroscope error that is caused by the temperature and calibration factor error of the gyroscope accelerometer should be included. The error model can be written as⁴⁻⁶:

\[ \dot{X}_D = F_D X_D + G_D W_D \]  

where \( X_D = [\delta \phi \ \delta v \ \delta \gamma \ d \ b \ d_T \ k_s \ k_s]^T \), \( \delta \phi, \delta v, \delta \gamma \) are attitude error vector, speed error vector and position error vector, respectively; \( d, b \) serve as gyroscope and accelerometer error vector, respectively; \( d_T \) serves as gyroscope error that is caused by the temperature; \( k_s \) serve as the demarcation factor errors of the gyroscopes and accelerometers; \( F_D, G_D, W_D \) serve as transfer matrix, noise matrix and system noise of the system, respectively³.

In the integrated navigation system, owing to the fact that the systematic error is constantly estimated and corrected, we can adopt a simplified model for reducing operation work in the real application, not thinking over high-speed channel. In the simplified model, the random error of the gyroscopes and accelerometers is carried out from the mathematical point, the gyroscopes error is considered as the sum of colored random noise and the white noise error. Therefore, the corresponding three-dimensional gyroscopes need to be expanded for three random error states capacity, and the accelerometer error is only considered as the random white noise.

\[ \dot{X}(t)_{\text{col}} = A(t)_{\text{col}} X(t) + G(t)_{\text{col}} W(t)_{\text{col}} \]  

In Eq.(2), the state vector of the system is:

\[ X = [\phi \ \phi_a \ \phi_v \ \delta V_e \ \delta V_a \ \delta \lambda \ \epsilon_{\phi} \ \epsilon_v \ \epsilon_{\lambda} ]^T \]  

The white noise vector of the system is:

\[ W = [\omega_{\phi} \ \omega_{\phi} \ \omega_{\phi} \ \omega_{v} \ \omega_{\lambda} \ \omega_{\lambda} \ \omega_{\phi} \ \omega_{\phi} ]^T \]  

For the white-noise vector, the variance matrix \( Q(t) \) is:

\[ \text{diag} \left[ \sigma_{\phi}^2 \ \sigma_{\phi}^2 \ \sigma_{\phi}^2 \ \frac{2\sigma_{\phi}^2}{T_{\phi}} \ \frac{2\sigma_{\phi}^2}{T_{\phi}} \ \frac{2\sigma_{\phi}^2}{T_{\phi}} \ \sigma_{v}^2 \ \sigma_{a}^2 \ \sigma_{\lambda}^2 \right] \]  

Adopting the integrated model of position and speed, the observation vector is:

\[ Z(t) = \begin{bmatrix} (L_i - L_{i}) R_u \ 
(L_i - L_{i}) R_c \cos L \ 
V_{se} - V_{ge} \ 
V_{se} - V_{ge} \end{bmatrix} \]  

where:

\[ \begin{bmatrix} R \delta L + N_u \
R \cos L \delta \lambda + N_v \
\delta V_e + M_e \ 
\delta V_a + M_a \end{bmatrix} \]
The meaning of each parameter in Eqs.(2)-(6) can be referred to the Reference [1].

3 Kalman filter model of closed-loop correction

The control item $U(k-1)$ should be added to the Kalman filter in order to correct SINS, then the dynamic equation of the system is:

$$
\begin{align*}
X(k) &= \Phi(k,k-1)X(k-1) + B(k,k-1)U(k-1) + W(k-1) \\
\Gamma(k,k-1)H(k-1) \\
Z(k) &= H(k)X(k) + N(k)
\end{align*}
$$

When the quadratic performance index is considered, after derivation, it can be expressed as\cite{1}:

$$
B(k,k-1) = I
$$

At this moment, feedback control variable $U(k)$ is:

$$
U(k) = -\Phi(k+1,k)\hat{X}(k/k)
$$

In summary, under the circumstances of closed-loop completely revising and controls, the form of the Kalman filter is:

$$
\begin{align*}
\dot{X}(k/k-1) &= 0 \\
\hat{X}(k/k) &= K(k)Z(k) \\
K(k) &= P(k/k-1)H^T(k)\left[H(k)P(k/k-1)H^T(k) + \right. \\
&\left. R(k) \right]^{-1} \\
P(k/k-1) &= \Phi(k,k-1)P(k-1/k-1)\Phi^T(k,k-1) + \Gamma(k,k-1)Q(k-1)\Gamma^T(k,k-1) \\
P(k/k) &= \left[I - K(k)H(k)\right]P(k/k-1)[I - K(k)H(k)]^T + \left.K(k)R(k)K^T(k)\right]
\end{align*}
$$

4 Experiment result and conclusions

In order to verify the scheme mentioned above, one set of static experiment was carried out in a certain district, the time interval was about 1 h; one set of dynamic experiment was carried out (time interval was 3 h and 20 min) in a certain district. The precision of the gyroscope used in the experiment was $3^\circ/s$, accelerometer precision was $5 \times 10^{-3}g$, the output course angle of AHRS replaces the output course angle of SINS in real-time. The position accuracy of GPS was 20 m and speed precision was 0.5 m/s. The sampling data of the gyroscope and accelerometer was 0.01 s in the experiment, the data sample period of GPS was 5 s, the integration period was also 5 s.

The navigation parameter error curve of the static experiment result is shown in Fig.2, the standard deviation of every navigation parameter is shown in Table 1. The navigation parameter error curve of the dynamic experiment result is shown in Fig.3.

From the static and dynamic experiment curves, it can be seen that when low-cost and low-accuracy SINS is integrated with GPS, without online adjustment of AHRS, the course angle information is assumed to have a diffusing trend because of the low precision of the gyroscope. At the same time, parameters are all constrained such as the position and velocity error of the integrated navigation system, pitching and rolling attitude error.

The dynamic experiment curves (Fig.3(e)) show that the orbit of the GPS orientation coincides with the orbit of the integrated system orientation, which can be seen from Fig.3(f). Therefore, the position output of the integrated navigation system stays consistent with the position output of the GPS, and the integrated navigation system can reflect the dynamic course accurately and timely.

| Error name | Pitch (/°) | Roll (/°) | Heading with AHRS (/°) | North speed /m · s⁻¹ | East speed /m · s⁻¹ | Latitude /m | Longitude /m |
|------------|------------|-----------|-----------------------|---------------------|-------------------|-----------|-------------|
| Standard deviation | 0.41 | 0.48 | 2.1 | 0.71 | 0.64 | 12.2 | 9.7 |
Fig.2  Static experiment result

(a) Heading angle without AHRS
(b) Heading angle with AHRS
(c) Pitch and rolling angle
(d) Latitude and longitude error
(e) East and north velocity error

Fig.3  Dynamic experiment result

(a) Heading angle without AHRS
(b) Heading angle with AHRS
(c) Pitch and rolling angle
(d) East and north velocity
(e) Path contrast curve
(f) Curve of magnifying certain path

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