Study on Moving Base Alignment of INS/CNS Integrated Navigation System

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Abstract: Aiming at INS/CNS moving base alignment problem, this paper designs a moving base alignment method based on comprehensive calibration mode of INS error. Based on attitude and position measurement information of INS/CNS, this paper deduces linear status equation of INS/CNS, and meanwhile analyzes and establishes measurement equation for the alignment equation. It designs a moving base alignment solution based on the information integration method with Kalman filtering technology, and verifies the effectiveness of alignment with the method under moving base conditions through simulation analysis. The simulation results show the method may reach heading precision superior to 15” within 60min under dynamic navigation of ships.

1. Introduction

The navigation system is a key part for modern military weapon, and its precision and reliability decide smooth completion of navigation tasks, and speed and quality of task fulfillment. In order to improve performance of navigation system, meet demands of ships for long-time and far-distance navigation, and reduce dependence on satellite navigation, each country introduces CNS and INS and integrates to the passive integrated navigation system. In the past 40 years, CNS technology has been developed rapidly. In terms of application fields, from marine sextant, underwater periscope to on-board and on-satellite aster tracker for aerospace, CNS keeps improving its performance as well. It is developed from small field aster tracker with servo to large field, high dynamic, high-precision, full automation, all-weather small and global day and night strap-down CNS [1,2]. Therefore, the integrated navigation system comprising INS and CNS is featured in high precision, high reliability, independence and concealing, and could greatly improve the survivability of ships.
2. Moving base alignment of the integrated system

When the ship berths, the INS/CNS uses the known dock position information to help CNS acquire high-precision carrier attitude. At that time, the carrier attitude acquired by CNS is only related to its precision and the dock’s position precision regardless of INS horizon attitude as horizon information so as to avoid INS horizon attitude error.

After acquiring CNS high-precision attitude information, it could directly assign rough attitude value to INS, and INS is unnecessary to analyze course alignment in solidification inertial system. Although the INS course alignment time may be saved, CNS attitude information assignment has delay error, and INS could further measure and compensate element error with fine alignment.

During offshore alignment, since ships are navigating on the sea, and the carrier position is changing in the real time. In order to finish alignment, it is usually necessary to refer to satellite navigation information. However, the alignment time is long by purely relying on satellite navigation information and it is difficult to guarantee the precision. For offshore moving alignment of CNS/INS, this paper proposes CNS/INS alignment study under comprehensive error calibration mode based on INS error.

3. Measurement information conversion under moving base

The offshore alignment method of INS/CNS refers to the design mode in document [3], and meanwhile considers CNS’s better and more accurately realizing INS and carrier coordinate system conversion and solution with assistance of satellite navigation precision position information.

The on-board CNS positioning and orientation needs SINS to provide horizon benchmark information, which may introduce horizon attitude error of SINS inevitably. If position information is provided externally, such information shall be used to directly convert information outputted by CNS to attitude information in geological coordinate system. The precision of the attitude information is mainly affected by position information precision provided. When satellite navigation provides position information, the position information it outputted could not only match position with INS but also assist CNS for information transformation [3]. With the assistance of position information provided by the satellite navigation, the information of CNS inertial coordinate system will be transformed to geological coordinate system, i.e.,

\[ C_b^n = C_e^n C_i^e C_s^i C_b \]  

(1)

In the formula, matrix \( C_i^e \) and \( C_e^n \) are respectively the relationship between inertial coordinate system and earth-based coordinate system, and between the earth-based coordinate system and navigation coordinate system. The transformation principle can be as seen in Fig. 1 below:

Fig. 1CNS information transformation based on GPS assistance
During offshore alignment, the ships shall move ahead straightly at an even speed. The satellite navigation provides necessary initial position information when initially aligning CNS/INS, and meanwhile INS finishes rough alignment with the assistance of satellite navigation. During fine alignment, the satellite position information is introduced as observed quantity, and the high-precision star sensor attitude information with assistance of satellite navigation is used as the observed quantity to speed up convergence toward azimuth and improve system attitude error (particularly heading error) so as to rapidly and accurately finish fine alignment of the integrated system.

4. Filter model design of the integrated system

The satellite navigation/CNS/INS integrated system adopts the combination mode of attitude + position. The basic principle is: to combine parameters outputted by extension system, and use Kalman filter technology with error equation of INS as status equation of the integrated system, use output parameter error of INS/CNS as system measurement according to the carrier navigation information acquired by CNS, and estimate and compensate INS error through filtering.

The combination mode of attitude + position adds position combination based on attitude combination, and could effectively compensate navigation error accumulation caused by gyro drift in INS so as to realize the purpose of inertial device drift compensation from multiple aspects. On the other hand, it could directly correct navigation output parameters of INS so as to improve precision of INS.

Main process of the attitude + position combination can be summarized as follows: With error equation of INS as the status equation of the integrated system, navigation information solved by INS and heading and position information provided by celestial position finder are used to establish corresponding measurement equation; the optimal filtering method is used to estimate and compensate error of inertial devices in the real time. Star sensor data output frequency is lower than the updating frequency of INS data. Therefore, after several INS solution cycles, the INS solution results and star sensor data will be integrated to correct the INS.

1) Establish INS status equation

When navigating, the ships shall move at even speed straightly. The Kalman filter method is adopted to establish the fine alignment model of SINS/GPS/CNS integrated system.

The variable of the system status is:

\[ X_{13\times1} = [\phi_x, \phi_y, \phi_z, \delta v_x, \delta v_y, \delta v_z, \delta \lambda, \varepsilon_x, \varepsilon_y, \varepsilon_z, \nabla_x, \nabla_y, \nabla_z]^T \]

The system status equation still adopts SINS error equation, and system status variables can be seen in Document [4].

2) Establish measurement equation for CNS/INS integrated system

When integrating the two systems, suppose that the installation error of CNS has been compensated. Since the celestial information observed by CNS is under the carrier system, and attitude information outputted is the attitude of carrier system relative to INS. It is unable to correct directly with the navigation information of INS in local geological coordinate system. The system status of CNS/INS integrated system is the error angle of mathematical platform. Thus, it is necessary to convert the attitude error angle to mathematical platform error angle before it could be used as the
observed quantity of the Kalman filter\textsuperscript{[5,6]}. The mathematical platform error angle acquired through
transformation of attitude error angle:

\[
\begin{align*}
\delta \gamma &= -\frac{1}{\cos \theta} \left( \phi_x \sin \psi + \phi_y \cos \psi \right) \\
\delta \theta &= -\phi_x \cos \psi + \phi_y \sin \psi \\
\delta \psi &= -\frac{1}{\cos \theta} \left( \phi_x \sin \psi \sin \theta + \phi_y \cos \psi \sin \theta - \phi_z \cos \theta \right)
\end{align*}
\]

In matrix form:

\[
\begin{bmatrix}
\delta \gamma \\
\delta \theta \\
\delta \psi
\end{bmatrix} = \begin{bmatrix}
\phi_x \\
\phi_y \\
\phi_z
\end{bmatrix} = H_\phi \begin{bmatrix}
\phi_x \\
\phi_y \\
\phi_z
\end{bmatrix}
\]

For transformation from mathematical platform error angle to attitude error angle, the
transformation coefficient matrix $M_\phi$ shall be:

\[
H_\phi = -\frac{1}{\cos \theta} \begin{bmatrix}
\sin \psi & \cos \psi & 0 \\
\cos \psi \cos \theta & -\sin \psi \cos \theta & 0 \\
\sin \psi \sin \theta & \cos \psi \sin \theta & -\cos \theta
\end{bmatrix}
\]

\[
Z_1(t) = \begin{bmatrix}
\phi_{E,INS} - \phi_{E,CNS} \\
\phi_{N,INS} - \phi_{N,CNS} \\
\phi_{U,INS} - \phi_{U,CNS}
\end{bmatrix} = H_1(t) X(t) + V(t)
\]

The strap-down INS in CNS/INS integrated system could output attitude (roll angle $\gamma_I$, pitch
angle $\theta_I$, heading angle $\psi_I$), position (longitude $\lambda_I$, latitude $\phi_I$, height $h_I$) information; the celestial
position finder could output attitude heading angle $\psi$ and position (longitude $\lambda$, latitude $\phi$ )
information. Since the latter could not output height information, the height information $h$ of height
measurement carrier is introduced as supplementation.

3) Establish GPS/INS measurement

The balance between GPS and INS position information is used as measurement information of
the Kalman filter:

\[
Z_2(t) = \begin{bmatrix}
\varphi_{INS} - \varphi_{GNS} \\
\lambda_{2,INS} - \lambda_{2,GNS}
\end{bmatrix} = H_2(t) X(t) + V(t)
\]

Therefore, the measurement information of CNS/INS/GPS shall be:
\[
Z(t) =\begin{bmatrix}
\alpha \\
\beta \\
\gamma \\
\delta \phi \\
\delta \lambda
\end{bmatrix} = H(t)X(t) + V(t)
\] (7)

In the formula, \(\alpha, \beta, \gamma\) is respectively the horizon attitude and heading error, and \(\delta \phi, \delta \lambda\) is respectively the longitude and latitude error.

5. Simulation comparison

The simulation conditions are compared in status of mooring and navigating, and the results are respectively shown in Fig. 6 and Fig. 7.

Mooring status: The GPS position is more accurate than 5m and output frequency is 1Hz; the celestial attitude measurement precision is 5'', output frequency is 1Hz and measurement noise is 3''; gyro stability is 0.02°/h, accelerometer bias is \(1 \times 10^{-5}g\), latitude initial value is 39.183°, longitude initial value is 117.142°, horizontal rolling period is 20s with amplitude of 20', and heading swing cycle is 25s with amplitude of 10'.

Navigating status: When assumptions of inertial elements, GPS, star sensor and position remain unchanged the carrier heads to 14min at the same latitude at even speed, and turns 180° with quickly at 8°/s and then keeps even speed. The horizontal rolling period is 20s with amplitude of 3°, and heading swing cycle is 30s with amplitude of 0.5°.
6. Conclusion

This paper analyzed moving alignment characteristics of CNS/INS integrated system. It designed integrated system moving base alignment technology based on Kalman filter, acquired attitude information and INS integrated solution through transformation of CNS with assistance of GPS information. With attitude information as the measurement information of the integrated system, it could guarantee filter convergence of the integrated for quick move of ships. Simulation analysis shows the moving base alignment and heading alignment is more accurate than 15″.

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References

[1] LONG Rui, QIN Yongyuan, XIA Jiahe. A new and Effective A algorithm of Attitude Matching for INS/Star Sensor Integrated Navigation System[J]. Journal of North western Polytechnical University.2011,29(3): 476-479.

[2] Bona B E, Smay R J. Optimum reset of ship's inertial navigation system[J]. IEEE Transactions on Aerospace and Electronic Systems, 1966, Aes-2(4): 409-414.

[3] ZHOU Ling-feng , ZHAO Xiao-ming, etc. Initial alignment of CNS/INS integrated navigation system based on recursive least square method[J].Journal of Chinese Inertial Technology, 2015 , 23(3): 357-363.

[4] ZHOU Ling-feng , ZHAO Xiao-ming, etc.CNS/SINS integrated calibration technique based on damping [J]. Journal of Chinese Inertial Technology, 2017,25(5):561-565.

[5] GaoWei, Ben Yueyang, Zhang Xin, Li Qian, Yu Fei. Rapid fine strapdown INS alignment method under marine mooring condition[C]. IEEE Transactions on Aerospace and Electronic Systems, 2011, 47(4): 2887-2896.

[6] Sun Feng, Xia Jianzhong, LanHaiyu, Liu Xintao. Research on integrated alignment of rotary strapdown inertial navigation system[C].Proceedings of 2012 IEEE International Conference on Mechatronics and Automation. Chengdu, China: 725-730.