Research Article

Study of Simulation Platform for BDS/INS/CNS Deep Integration Navigation

Zhaoyang Zuo, Bo Yang, Chunguo Yue, and Dongrong Meng

1School of Mechanical Engineering, Xijing University, Xi'an, Shaanxi 710123, China
2Xi'an Research Institute of High Technology, Xi'an, Shaanxi 710025, China

Correspondence should be addressed to Zhaoyang Zuo; zuozhaoyang2002@163.com and Bo Yang; yangbo8093@sina.com

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In this paper, INS/CNS (CINS) is integrated into a module, and then CINS and BDS are further combined to form a deep integrated BDS/INS/CNS navigation system, which can significantly improve the navigation, positioning, and attitude measurement accuracy under high dynamic and strong interference conditions. It has broad application prospects for specific users such as high-altitude long-endurance Unmanned Aerial Vehicle (UAV) and high-maneuvering glider. In order to verify and analyze the algorithm and performance of the deep integrated navigation system, the design and implementation of BDS/INS/CNS deep integrated navigation simulation platform are presented and the overall architecture, information flow, and the composition of each subsystem of the simulation platform are introduced. The simulation results show that, under high dynamic conditions, the position accuracy of the BDS/INS/CNS deep integrated navigation system is better than 1 m, the speed accuracy is better than 0.1 m/s, and the overall performance is better than the BDS/INS deep integrated navigation system. It also verifies the availability of the simulation platform, which has guiding significance for the next design of BDS/INS/CNS deep integrated navigation prototype.

1. Introduction

Global Navigation Satellite System (GNSS) and Inertial Navigation System (INS) have good complementary advantages. Therefore, GNSS/INS integrated navigation is called “golden combination” [1–5]. According to different observation information, it can be divided into three combination modes: loose combination, tight combination, and deep combination [1, 6, 7]. GNSS/INS deep combination is a deep and hardware-based combination method, which can realize the fusion of I/Q signals output by GNSS receiver correlators and INS navigation parameters and has excellent navigation performance in high dynamic, strong interference, weak signal, and occlusion environment [2, 8], which is the main development direction of GNSS/INS integrated navigation in the future. The algorithm research in this area has also been widely concerned [5, 9–11]. The Celestial Navigation System (CNS) can determine the attitude of the aircraft through real-time sensitive star map, stellar extraction, star map recognition and tracking, attitude calculation, and other operations, with an accuracy of angular second [12]. INS/CNS integrated navigation can meet the need of long-endurance and autonomous navigation [13]. Now, China’s BeiDou Navigation Satellite System (BDS) has launched 41 BeiDou satellites, which can provide services along the “belt and road” by the end of 2018 and achieve global services around 2020. At present, INS and CNS have been widely installed on some high-altitude aircraft. The research on GNSS/INS/CNS combination at home and abroad mainly focuses on the federal filter fusion processing and the improvement of related algorithms [14–17]. Loose combination is still the main mode, and the combination information has not been fully utilized. The BDS/INS/CNS deep integrated navigation is to combine INS/CNS into a mode (CINS). The deep combination of CINS and BDS can improve the accuracy of navigation and
positioning and can be applied in the fields of unmanned reconnaissance aircraft and high-mobility gliding aircraft in the air. It has broad application prospect.

The deep combination of BDS/INS/CNS is the fusion of INS information and CNS information with the tracking level of the BDS receiver. It involves the internal programming of the BDS receiver. It is difficult to carry out physical or semiphysical simulation test in the application environment of high dynamic and strong interference, and many factors are taken into account [18, 19]. The BDS/INS/CNS deep integrated navigation simulation platform can establish and provide close to the real physical model and working parameters and provide the basis for the engineering demonstration and engineering design, with strong economy and adaptability. Referring to the GSNRx-utTM design idea developed by the PLAN research team, this paper constructs the BDS/INS/CNS deep integrated navigation simulation platform and gives the simulation platform architecture, information flow, and the composition of each subsystem. The simulation platform can output BDS intermediate frequency data, INS observation data, and observation data of CNS synchronously. The functions of baseband signal processing, INS navigation calculation, and CNS navigation solution are realized. It can be used to simulate and analyze the navigation performance of the BDS/INS/CNS deep combined navigation system in high dynamic and long-period navigation environment. The simulation results show that the overall performance of the BDS/INS/CNS deep integrated navigation system is better than that of the BDS/INS deep integrated navigation system under high dynamic conditions, which verifies the effectiveness of the simulation platform. The reserved interface of the platform can be extended to other GNSS/INS/CNS deep integrated navigation systems.

2. Deep Integrated Navigation System

The concepts of GNSS/INS deep combination is derived from the “vector tracking” proposed by Spilker [8]. Its main idea is to generate new navigation parameters by using the residual error of correlator and to predict the BDS signal tracking loop parameters by using updated navigation parameters [20]. At present, there are generally two design systems [1, 2, 21, 22]. One is the cascade deep combined navigation system. The measurement value of integrated navigation filter is the baseband I/Q information processed by the baseband signal preprocessing filter. The other is the centralized deep integrated navigation system. The measured value of the integrated navigation filter is the difference between the baseband I/Q information and the inertial navigation estimation I/Q information. From the perspective of information fusion optimal criteria, the centralized deep integrated navigation system is the best in improving navigation performance. Here, a centralized deep integrated navigation system is taken as an example for simulation analysis. In order to make full use of the CNS information on the aircraft, the deep composite module is extended to the BDS/INS/CNS deep combination mode, and the INS/CNS combined module (CINS) is further combined with BDS. The CINS architecture is shown in Figure 1.

The BDS/INS/CNS deep integration architecture is shown in Figure 2.

As can be seen from the structure diagram, the combined model integrates CINS navigation parameter estimation and BDS signal tracking and can simultaneously track and process all visible BeiDou satellite signals. The integrated navigation system can make full use of the high precision of pose measurement and navigation of CINS, provide accurate dynamic information, enhance the adaptability of BDS receiver to dynamic stress, and reduce the bandwidth of BDS signal tracking loop. At the same time, CINS is corrected by using the output information of navigation filter so that the tracking loop of the BDS receiver can only track the Doppler frequency shift error caused by the CINS calculation error, crystal vibration of BDS receiver, and external noise, which effectively improves the tracking accuracy of BDS signal. When the BDS signal is disturbed or blocked, the CINS measurement value can meet the requirements of seamless navigation. Meanwhile, the integrated navigation system can predict the aircraft’s dynamic information, continuously predict the Doppler and phase shift information of the BDS signal, and significantly reduce the recapture time of the BDS receiver.

3. The Simulation Platform of BDS/INS/CNS Deep-Integrated Navigation

The BDS/INS/CNS deep integrated navigation simulation platform is mainly composed of the following parts: trajectory generator, IF Signal simulator of BDS, BDS receiver baseband signal processing, IMU signal generator, star sensor simulator, INS mechanical arrangement, and integrated navigation filter. UKF filtering algorithm is adopted. The overall structure of the platform is shown in Figure 3.

3.1. Trajectory Generator. Trajectory generator is the basis for the deeply BDS/INS/CNS integrated navigation simulation platform [1], which can simulate the aircraft’s various kinds of sports, such as constant speed, acceleration, turn, and dive. First of all, it is used to input information, including the position, velocity, and acceleration, and simulate IMU output, star sensor output, BDS satellite navigation message, pseudo-orange and the ionosphere, and troposphere delay correction information. Secondly, as the reference value and evaluation criteria, the simulation results are analyzed to verify the correctness and superiority of the BDS/INS/CNS deep combined navigation theoretical model and algorithm. The commonly used method in trajectory simulation is the fourth-order Runge–Kutta method to solve a set of trajectory differential equations, and the specific simulation process is shown in [13].

3.2. IMU Signal Generator. Based on the error model of INS components, the gyroscope and accelerometer simulators are built to simulate the angular and linear acceleration information output. In order to simplify the analysis, it is
assumed that the inertial alignment has been completed and the installation error is effectively compensated.

3.2.1. Gyro Simulator. Given the error information of the gyroscope, its output is

\[ \omega^b_{ib} = \omega^b_{ib} + \epsilon^b_g, \]

where \( \epsilon^b_g \) represents the error of gyro component and \( \omega^b_{ib} \) indicates the angular rate of \( b \)-frame from \( i \)-frame in the \( b \)-frame and represents...
\[ \omega_{lb} = R_{lb}^c(\omega_{a}^c + \omega_{e}^c) + \omega_{lb}, \]  
where

\[ \omega_{lb} = \begin{bmatrix} \cos r & 0 & \cos p \sin r \\ 0 & 1 & \sin p \\ \sin r & 0 & \cos p \cos r \end{bmatrix} \left[ \begin{array}{c} \hat{r} \\ \hat{\tau} \\ \hat{y} \end{array} \right]. \]  

3.2.2. Accelerometer Simulator. The output of accelerometer is

\[ \mathbf{f}^b = \mathbf{f}^b + \mathbf{v}^b, \]

where \( \mathbf{v}^b \) represents the error of accelerometer and \( \mathbf{f}^b \) represents the acceleration of the carrier relative to the inertial coordinate system and is expressed as follows:

\[ \mathbf{f}^b = R_{lb}^c \left[ \mathbf{v}^l + (2\Omega_{lc}^c + \Omega_{cl}^c) \times \mathbf{v}^l - g^l \right], \]

where the relevant parameters are referenced in literature [1, 19, 21].

3.3. BDS Intermediate Frequency Signal Simulator. BDS intermediate frequency signal simulator can simulate the intermediate frequency signal of BDS satellite received based on the simulated aircraft’s motion track, combined with BDS satellite ephemeris and integrated multiple error factors.

3.3.1. Digital Model of Intermediate Frequency Signal. The signal of B1 is composed of the “range-finding code + navigation message” orthogonal modulation of the two branches of I and Q on the carrier wave [19, 23]. Here, the B11 signal is taken as an example for analysis. When the B11 signal transmitted by the \( j \) visible BDS satellite passes through the space environment, its analytical expression is

\[ R_{B11} = \sqrt{2}PD_j(t - T_p - \delta t_{\text{iono}} - \delta t_{\text{tropo}} + \delta t_{\text{SV}}) \cdot C_j(t - T_p - \delta t_{\text{iono}} - \delta t_{\text{tropo}} + \delta t_{\text{SV}}) \cdot \cos\left[ \omega_{B11}(t - T_p + \delta t_{\text{iono}} - \delta t_{\text{tropo}} + \delta t_{\text{SV}}) + \phi_0 \right] + n(t), \]

where \( P \) represents the power of the \( j \) visible satellite signal received by the receiver, \( T_p \) represents the transmission delay from the satellite to the receiver, \( \delta t_{\text{iono}} \) represents ionospheric delay, \( \delta t_{\text{tropo}} \) represents tropospheric delay, \( \delta t_{\text{SV}} \) represents satellite clock, \( \phi_0 \) represents initial phase, and \( n(t) \) represents received noise. In order to facilitate the subsequent baseband signal processing, the received BDS signal need to be mixed frequency processing, the signal down conversion to intermediate frequency, and then sampling processing. Let the local signal be

\[ \text{LO} = 2 \cos(\omega_{\text{LO}}(t + \delta t_r)). \]

After BDS signal is mixed with frequency, the low-pass filter is expressed as follows:

\[ S_{\text{IF}j} = \sqrt{2}PD_j(t - T_d - \delta t_{\text{iono}})C_j(t - T_d - \delta t_{\text{iono}}) \cdot \cos\left[ \omega_{B11}(t - T_d + \delta t_{\text{iono}}) - \omega_{\text{LO}}(t + \delta t_r) + \phi \right] + n_j(t), \]

where \( \delta t_r \) represents the clock error of the receiver. Let

\[ \omega_{\text{IF}} = \omega_{B11} - \omega_{\text{LO}}, \]

\[ t_s = T_d + \delta t_{\text{iono}}, \]

\[ \varphi = \phi_0 - \omega_{B11}(T_d - \delta t_{\text{iono}}) - \omega_{\text{LO}}\delta t_r. \]

Equation (8) is further simplified as follows:

\[ S_{\text{IF}j} = \sqrt{2}PD_j(t - t_s)C_j(t - t_s)\cos[\omega_{\text{IF}}t + \varphi] + n_j(t), \]

where \( \omega_{\text{IF}} \) represents the desired angular frequency of intermediate frequency signal. When the aircraft is moving at high speed, the change of carrier phase IF caused by Doppler frequency shift should be considered. Therefore, the intermediate frequency signal including all visible satellites can be expressed as follows:

\[ S_{\text{IF}} = \sum_{j=1}^{N} \left\{ \sqrt{2}PD_j(t - t_s)C_j((1 + \eta)(t - t_s))\cos[(\omega_{\text{IF}} - \omega_d)t + \varphi] + n_j(t) \right\}. \]
the number of visible satellites in the simulation period. The IF signal simulator is reserved for GPS and Galileo constellation, and the navigation message can be generated according to the corresponding ICD file. Combined with the carrier frequency of different constellations, it can be extended to the IF signal under the corresponding constellation.

Transmission time calculation, various error simulation, signal sampling, and quantitative reference [23]. Different from the GPS signal C/A code, the B1I signal distance code (CB1I) code speed is 2.046 Mcps, and the code length is 2046. CB1I codes are generated by two linear sequences, \( G_1 \) and \( G_2 \) mode 2, and the truncated 1 code fragment that generates the balanced Gold code. \( G_1 \) and \( G_2 \) sequences are generated by two II-level linear shift registers, and their generating polynomials are

\[
G_1(X) = 1 + X + X^7 + X^8 + X^9 + X^{10} + X^{11},
\]

\[
G_2(X) = 1 + X + X^2 + X^3 + X^4 + X^5 + X^6 + X^9 + X^{11}.
\]

(12) An adaptive step size calculation method is adopted to precisely control the Doppler signal. The criteria are

\[
\begin{align*}
V & \leq 100 \text{ (m/s)}, & t_{\text{step}} &= 1\text{ms}, \\
100 \text{ (m/s)} < V & \leq 1000 \text{ (m/s)}, & t_{\text{step}} &= 100\text{μs}, \\
1000 \text{ (m/s)} < V & \leq 10000 \text{ (m/s)}, & t_{\text{step}} &= 10\text{μs}. 
\end{align*}
\]

The baseband signal processing algorithm of the BDS receiver refers to the design idea of the GNSS software receiver to realize the acquisition, tracking, demodulation, and loop estimation of the BDS signal direct input navigation filter for subsequent combination calculation, which is not detailed here.

3.4. Star Sensor Simulator. At present, the main equipment of astronomical observations for the aircraft is the star sensor. Therefore, the CNS data simulation is to simulate the altitude angle and azimuth angle output by the star sensor in the carrier system near the latitude and longitude of the aircraft. With the optimal estimation method, the estimation
of the platform error angle is realized, which simulates the 
star sensor to achieve “star light, error out” [12,13], and the 
effect of the data using the new FK5 star catalog is dated. The 
measurement accuracy of the star sensor has reached an-
gular second level (1σ), and the error will not accumulate 
with time. Therefore, the measurement error of the star 
sensor can be considered as a white noise process with the 
zero mean value. The star sensor simulation process is shown in 
Figure 5.

3.5. INS Mechanical Arrangement. INS mechanical ar-
angement is to select an appropriate mathematical model 
according to the observation information of INS to calculate 
the navigation positioning parameters such as the speed, 
position, and attitude information of the carrier. Specifically, 
the rotation angular velocity of the vector relative to the 
inertial coordinate system measured by the gyroroscope is used 
to calculate the transformation matrix of the vector coordi-
inate system to the navigation coordinate system. The 
transfer matrix is used to transfer the acceleration measured 
by the accelerometer from the inertial space to the naviga-
tion coordinates, compensate for gravity and Coriolis 
acceleration, and obtain navigation and positioning infor-
mation through integration [1]. The corresponding data flow 
is shown in Figure 6.

The mechanical arrangement equation in the local 
horizontal coordinate system can be expressed as follows:

\[
\begin{align*}
\hat{X}_L &= [\hat{V}_L, \hat{\Omega}_L] = \\
&= \begin{bmatrix}
D^{-1} V_L^- \\
R_y b - \left(\Omega_{ib}^L + \Omega_{cl}^L\right) V_L + g_L^- \\
\end{bmatrix},
\end{align*}
\]

(14)

where \( \Omega \) is the antisymmetric matrix of the angular velocity 
vector \( \omega \), \( \Omega_{ib}^L = [\omega_i^L \times] \), \( \Omega_{cl}^L = [\omega_c^L \times] \), and \( \Omega_{cl}^L = [\omega_c^L \times] \). 

\( \hat{F}_b = \begin{bmatrix} f_b^x & f_b^y & f_b^z \end{bmatrix}^T \) is acceleration measurement information, 
\( \omega_{ib}^b = \begin{bmatrix} \omega_{ix} & \omega_{iy} & \omega_{iz} \end{bmatrix} \) is gyroscope measurement information, 
\( \mathbf{r} = [\varphi \lambda h]^T \) is position vector information, 
\( \mathbf{V} = \begin{bmatrix} V_E & V_N & V_T \end{bmatrix}^T \) is velocity vector information, 
\( \mathbf{g}_L = \begin{bmatrix} 0 & 0 & -g \end{bmatrix} \) is the attitude transition matrix, and

\[ D^{-1} = \begin{bmatrix}
1/((N + h) \cos \varphi) & 0 & 0 \\
0 & (1/M + h) & 0 \\
0 & 0 & 1
\end{bmatrix} \]
is transition matrix. For more detailed parameter information, see ref-
ence [1, 24, 25].

3.6. Filtering Algorithm. Among these nonlinear filtering 
methods, the UKF is widely used due to its elimination of the cumbersome derivation and low-computational complexity 
[2, 8, 19].

(1) Initialization:

(2) Calculating the sigma points:

\[
\begin{align*}
\chi_{k-1} &= \tilde{X}_{k-1} + \sqrt{(m+\lambda)}P_{k-1} \tilde{X}_{k-1} - \sqrt{(m+\lambda)}P_{k-1}.
\end{align*}
\]

(16)

(3) Timing-updating:

\[
\begin{align*}
\chi_{k,i} &= f(\chi_{k-1,i}), \\
\tilde{X}_k^- &= \sum_{i=0}^{2m} W_{m}^{i} \chi_{k,i}, \\
P_{x,k}^- &= \sum_{i=0}^{2m} W_{m}^{i} (\chi_{k,i} - \tilde{X}_k^-)(\chi_{k,i} - \tilde{X}_k^-)^T + P_k^+.
\end{align*}
\]

(17)

(4) Measurement-updating:

\[
\begin{align*}
y_{k,i} &= g(\chi_{k,i}), \\
\tilde{y}_k &= \sum_{i=0}^{2m} W_{m}^{i} y_{k,i}, \\
P_{y,k}^- &= \sum_{i=0}^{2m} W_{m}^{i} (y_{k,i} - \tilde{y}_k)(y_{k,i} - \tilde{y}_k)^T, \\
P_{x,y,k}^- &= \sum_{i=0}^{2m} W_{m}^{i} (\chi_{k,i} - \tilde{X}_k^-)(y_{k,i} - \tilde{y}_k)^T.
\end{align*}
\]

(18)

(5) Filter-updating:

\[
\begin{align*}
K_k^- &= P_{x,y,k}^- (P_{y,k}^-)^{-1}, \\
\tilde{X}_k^+ &= \tilde{X}_k^- + K_k^- (y_k - \tilde{y}_k), \\
P_k^+ &= P_k^- - K_k^- P_{y,k}^- (K_k^-)^T.
\end{align*}
\]

(19)

4. Performance Simulation Analysis

In order to verify the performance of the BDS/INS/CNS 
deep combined navigation simulation platform, the
reference moment was selected at 0:0:0 second on September 9, 2018, the satellite altitude cutoff angle was set at 15 degrees, the sampling frequency of the BDS signal was 30 MHz, the IF was 7 MHz, and the predetection integral was 1 ms. And the combined cycle was 1 s. The device characteristic parameters of simulated tactical INS is shown in Table 1, and the update frequency is 100 Hz. Aircraft speed is 1000 m/s, accelerating to 100 m/s², and the attitude angle is 0°. For the inertial position information of longitude 108°, latitude 39°, and altitude of 200 m, the initial position error is 1 m, the velocity error is 0.1 m/s, and the alignment attitude angle error is 0.1°. The simulation time was 120 s, and three experiments were designed. Taking the nominal motion trajectory of simulation as the truth value, the simulation results are compared with the nominal trajectory.

Scheme 1: INS/CNS combined performance analysis.
Scheme 2: BDS/INS deep-combined performance analysis.

| Components   | Parameters          | Value  | Unit      |
|--------------|---------------------|--------|-----------|
| Gyroscope    | Bias instability    | 1      | (deg/h)   |
|              | Random walk         | 0.01   | (deg/√h) |
| Accelerometer| Bias instability    | 0.01   | (mg)      |
|              | Random walk         | 0.001  | (mg/√Hz) |

![Figure 6: Data flow arrangement of mechanics in the local horizontal coordinate system.](image)

![Figure 7: East position error.](image)
Figure 8: North position error.

Figure 9: Up position error.

Figure 10: East velocity error.
Scheme 3: BDS/INS/CNS deep-combined performance analysis.

The position and velocity error are, respectively, shown in Figures 7–12, and the error comparison under the three schemes is shown in Table 2.

From the above simulation results, it can be seen that

(1) Under high dynamic condition, the error information of INS can be corrected by using the observation information of CNS in the combined mode of INS/CNS. The position error is stable in the range of 3 m, the Up position error RMS is 1.4986, the velocity error is stable in the range of 0.2 m/s, and the Up velocity error RMS is 0.0786.

(2) The position and velocity error of BDS/INS deep integrated navigation system rapidly converges and stabilizes in small error range. The position error is stable within 1 m, the Up position error RMS is 0.7446, the velocity error is stable within 0.1 m/s, and the Up velocity error RMS is 0.0582.

Table 2: Error comparison of three schemes.

|       | Position (m) |       | Velocity (m/s) |
|-------|--------------|-------|----------------|
|       | RMS          | East  | North          | Up  | Ve  | Vn  | Vu  |
| INS/CNS| 0.3546       | 0.9884| 1.4986         | 0.0227| 0.0483| 0.0786 |
| BDS/INS| 0.1846       | 0.5251| 0.7446         | 0.0149| 0.0367| 0.0582 |
| BDS/INS/CNS| 0.1258 | 0.3919| 0.4161         | 0.014 | 0.0335| 0.05  |
The position accuracy of the BDS/INS/CNS deep combined navigation system is better than 1 m, the Up position error RMS is 0.4161, the velocity accuracy is better 0.1 m/s, and the Up velocity error RMS is 0.05. The accuracy of position and velocity is better than that of the BDS/INS deep integrated navigation system.

(4) The accuracy of the position and velocity in the East is better than that in the north, which is caused by the poor observability of the carrier northward during simulation.

5. Conclusions

BDS/INS/CNS deep combined navigation has broad application prospect and is the focus of current research. Physical and semiphysical simulation experiments are expensive and difficult to be carried out, while the construction of full digital simulation platform can establish and provide physical models and working parameters close to the actual situation. Therefore, it provides the basis for the project demonstration and engineering design with strong economy and adaptability. This paper presents the design and implementation method of BDS/INS/CNS deep integrated navigation simulation platform and introduces the architecture and information flow of the simulation platform in detail. The simulation analysis based on this platform shows that, under the background of high dynamic application, the position accuracy of the BDS/INS/CNS deep combined navigation system is better than 1 m, and the velocity accuracy is better than 0.1 m/s, which verifies the correctness and effectiveness of the BDS/INS/CNS deep combined navigation platform constructed in this paper. The research on BDS/INS/CNS deep combined navigation accuracy under interference will be carried out in the future. With the further development of artificial intelligence and neural network theory, the centralized deep combination fault detection algorithm will be further studied. This research content has guiding significance for the next step of the design of BDS/INS/CNS deep combined navigation prototype. The related achievements of the subject can be widely used in the precision guidance weapons of various services and arms and have broad application prospect in the civil field (civil unmanned aerial vehicle navigation, control, etc.). Some algorithm models designed in this paper still need to be further verified by actual measurement data.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] P. Chen, Research on Theories and Methods of Deeply Coupled GNSS/INS Integrated Navigation, PLA Information Engineering University, Zhengzhou, China, 2013.
[2] T. S. Zhang, Research on the Tracking Technology of GNSS/INS Deep Integration Based on Hardware Prototype, Wuhan University, Wuhan, Hubei, China, 2013.
[3] K. H. Tang and M. P. Wu, "Design of MEMS IMU aided high-performance GPS receiver," Acta Geodaetica et Cartographica Sinica, vol. 37, no. 1, pp. 128–134, 2008.
[4] P. Gao and L. E. Yan, System Design of an Ultra-tight MIMU/Software Receiver Integration, Tsinghua Tongfang Knowledge Network Technology, Beijing, China, 2010.
[5] G. Hu, W. Wang, Y. Zhong, B. Gao, and C. Gu, "A new direct filtering approach to INS/GNSS integration," Aerospace Science and Technology, vol. 77, pp. 755–764, 2018.
[6] R. Babu and J. Wang, "Analysis of INS derived doppler effects on carrier tracking loop," Journal of Navigation, vol. 58, no. 3, pp. 493–507, 2005.
[7] G. Hu, S. Gao, and Y. Zhong, "A derivative UKF for tightly coupled INS/GPS integrated navigation," ISA Transactions, vol. 56, pp. 135–144, 2015.
[8] R. Babu and J. Wang, "ultra-tight integration of pseudolites with INS," in Proceedings of IEEE/ION Plans April 2006San Diego, CA, USA, 2006.
[9] G. Hu, S. Gao, Y. Zhong, B. Gao, and A. Subic, "Modified strong tracking unscented kalman filter for nonlinear state estimation with process model uncertainty," International Journal of Adaptive Control and Signal Processing, vol. 29, no. 12, pp. 1561–1577, 2015.
[10] G. Hu, B. Gao, Y. Zhong, and C. Gu, "Unscented kalman filter with process noise covariance estimation for vehicular ins/gps integration system," Information Fusion, vol. 64, pp. 194–204, 2020.
[11] B. Cui, X. Chen, X. Yu, H. Huang, and X. Liu, "Performance analysis of improved iterated curvature kalman filter and its application to GNSS/INS," ISA Transactions, vol. 66, pp. 460–468, Jan. 2017.
[12] D. W. Wang, Technology Research on Physical Simulation of Celestial Navigation, PLA Information Engineering University, Zhengzhou, China, 2017.
[13] P. Chen, Research and Simulation on INS/CNS Integrated Navigation System[D], PLA Information Engineering University, Zhengzhou, China, 2009.
[14] H. Z. Wang, Research on Key Technology of Unmanned Aerial Vehicle All Source Navigation Based on Multi-Source Information Fusion, Nanjing University of Aeronautics and Astronautics, Nanjing, China, 2017.
[15] J. L. Pan, Z. Xiong, and L. N. Wang, "A simplified UKF algorithm for SINS/GPS/CNS integrated navigation system in launch inertial coordinate system," Acta Armamentarii, vol. 36, no. 3, pp. 484–491, 2015.
[16] B. D. Zhou, Research on Integrated Navigation, National University of Defense Technology, Changsha, China, 2010.
[17] J. L. Pan, Z. Xiong, and H. Zhao, "SINS/GPS/CNS multi-integrated navigation system algorithm in launch inertial coordinate system and realization," Chinese Space Science and Technology, vol. 35, no. 2, pp. 9–16, 2015.
[18] W. William and N. Joseph, "A software defined real-time ultra-tightly coupled gnss-.ins architecture," in Proceedings of ION GNSS 19th International Technical Meeting of the Satellite Division, pp. 2695–2703, Fort Worth, TX, USA, September 2006.
[19] L. Wen and R. Li, *Multi-Constellation GNSS/INS Deep Integration Algorithm with Application to Compass System*, Beijing, China, 2010.

[20] G. Hu, L. Ni, B. Gao et al., ”Model predictive based unscented kalman filter for hypersonic vehicle navigation with INS/GNSS integration,” *IEEE Access*, vol. 8, pp. 4814–4823, 2020.

[21] D. Zhu, *Ultra-Tight GPS/Reduced IMU for Land Vehicle Navigation*, University of Calgary, Calgary, Canada, 2010.

[22] K. Tang, ”Simplified ultra-tightly coupled BDS/INS integrated navigation system,” *Science China*, vol. 59, no. 3, pp. 1–16, 2016.

[23] C. Jia and H. Xiao, ”Test and analysis of BeiDou receive based on the satellite signal simulator,” *Journal of Navigation and Positioning*, vol. 1, no. 4, pp. 14–17, 2013.

[24] A. Jovancevic, A. Brown, S. Ganguly et al., ”Ultra tight coupling implementation using real time software receiver,” in *Proceedings of ION GNSS 2004*, pp. 1575–1586, Long Beach, CA, USA, September 2004.

[25] X. He, *Algorithms for BD/MIMU Integrated Navigation Systems*, National University of Defense Technology, Changsha, China, 2009.