Research Article

Performance Analysis and Architectures for a MEMS-SINS/GPS Ultratight Integration System

Jianxin Ren,1 Junlin Zi,2 Hao Yang,1 and Jin Li3

1School of Automation, Northwestern Polytechnical University, Xi’an 710129, China
2The 10th Research Institute of China Electronic Technology Corporation, Chengdu 610036, China
3Science and Technology on Electronic Information Control Laboratory, Chengdu 610036, China

Correspondence should be addressed to Junlin Zi; 1595569745@qq.com

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In order to analyze the performance of strapdown inertial navigation system/global position system (SINS/GPS) ultratight integration system with low-precision microelectromechanical system (MEMS) under challenging environments, a new MEMS-SINS/GPS ultratight integration scheme is designed. The time-space difference carrier phase velocity (TSDCP-v) is used to assist the carrier tracking loop, the measurement model including nonlinear term is established, and the corresponding filtering algorithm is designed. A simulation and verification platform is established to analyze and verify the performance of the MEMS-SINS/GPS ultratight integration system designed in this paper. Compared with the SINS/GPS tight integration navigation system, the MEMS-SINS/GPS ultratight integration system has higher dynamic performance, anti-interference capability, and navigation performance. At the same time, the MEMS-SINS/GPS ultratight integration system improves the carrier tracking performance of SINS-assisted GPS ultratight integration system when using low-precision MEMS and in high dynamics, strong interference environments.

1. Introduction

The strapdown inertial navigation system/global position system (SINS/GPS) ultratight integration system assists the tracking loop to increase the equivalent bandwidth of the loop and enhance the system’s dynamic performance and anti-interference ability, so that the system’s accuracy and reliability can be improved [1]. It is gradually becoming the main research direction of SINS/GPS coupled system. The SINS/GPS ultratight integration system can be divided mainly into the vector-tracking based SINS/GPS ultratight coupled mode and the SINS-assisted GPS ultratight coupled mode. Microelectromechanical system (MEMS) has the advantages of cheap price, small volume, low energy consumption, and light weight [2]. Currently, the accuracy and reliability of MEMS inertial sensors have been rapidly improved. It is very meaningful to study a high-performance MEMS-SINS/GPS ultratight integration system.

In vector-tracking based SINS/GPS ultratight coupled mode, the In-phase/Quadrature (I/Q) signals are processed by prefilters. The prefilters estimate loop tracking error to assist carrier loop. The integration navigation filter uses the estimation of prefilters to correct the SINS errors [3, 4]. In addition to using I/Q signals as measurement information, some researchers used quaternion errors as state variables to build nonlinear quaternion errors model [5, 6]. Due to the strong nonlinearity of the models above, the nonlinear filtering algorithms were used, including extended Kalman filter (EKF), unscented particle filter (UPF), and unscented Kalman filter (UKF) [7–9], to avoid large numbers of nonlinear errors and degrades system’s performance caused by highly dynamic, strong interference, and low-precision MEMS. Although this ultratight integration mode has stronger signal tracking and navigating ability, it is criticized for high complexity of the model, heavy computation load, residual time error, and low realizability [10, 11]. To address these problems, in [12], a linear measurement equation was
obtained by time-space difference of I/Q angular rate and phase information that reduced the model error and complexity.

Based on the tightly coupled SINS/GPS, the SINS-assisted GPS ultratight integration mode uses modified SINS parameters to calculate carrier Doppler frequency, assisting GPS carrier tracking loop. This ultratight integration mode has relatively simple model and higher realizability [6, 13]. However, in this mode, Doppler assist error increases rapidly in low-precision MEMS and highly dynamic and strong interference environments. When the Doppler assist error is large and the tracking loop does not have enough bandwidth to track it, the GPS measurement error would be related to the SINS velocity error. It would decrease the integrated Kalman filter (IKF) estimation accuracy, cause the carrier loop lose lock, and even cause the system to diverge [14]. In [15], the carrier-tracking errors were expanded as the IKF state variables, thus making the pseudorange-rate (PR-rate) error decorrelation. In [14], a new tracking-error estimator was designed, and it can remove the pseudorange (PR) and PR-rate error correlation. At the same time, this model of SINS/GPS ultratight integration introduces strong nonlinearity into the measurement equation of IKF when using the raw GPS PR and PR-rate measurements. Although EKF is a nonlinear filtering algorithm, it can result in a large modeling error and a divergent solution [16, 17] retaining the high-order nonlinear terms of pseudorange measurement by expanding pseudorange measurement second-order Taylor series, and the UKF was used to process it.

Compared with PR measurement, the carrier phase measurement has higher accuracy and smaller error [18, 19]. In [20], the GPS receiver velocity was estimated by time-difference carrier phase (TDCP) measurement. In [21], the TDCP was applied to the SINS/GPS tightly integrated system. In [22], the TDCP velocity was used in the SINS/GPS ultratight integrated system to assist the GPS carrier tracking loop.

In this paper, a new structure for the MEMS-SINS/GPS ultratight integration system based on the SINS-assisted GPS ultratight integration system is designed. The time-space difference carrier phase velocity (TSDCP-v) is used to assist the carrier loop, reducing Doppler-assisted error caused by low-precision MEMS and avoiding GPS measurement errors related to MEME-SINS velocity errors. The TSDCP-v and PR are used as the measurements of the IKF, and the second-order nonlinear term in the PR measurement is retained. The corresponding filtering algorithm is designed to improve the accuracy of IKF estimation. The simulation and verification platform is established to analyze and verify the performance of the MEMS-SINS/GPS ultratight integration system designed in this paper. Compared with the SINS/GPS tight integration navigation system, the MEMS-SINS/GPS ultratight integration system has higher dynamic performance, anti-interference capability, and navigation performance. At the same time, the MEMS-SINS/GPS ultratight integration system improves the carrier tracking performance of SINS-assisted GPS ultratight integration system when using low-precision MEMS and in high dynamics, strong interference environments.

2. The Architectures of MEMS-SINS/GPS
Ultratight Integration System

The architecture of MEMS-SINS/GPS ultratight integration system designed in this paper is shown in Figure 1. The IKF measurements included the GPS PR $\rho_s$ minus the PR $\rho_1$ calculated by SINS and the TSDCP-v $V_{sd}$ minus the SINS velocity $V_s$. The SINS error is estimated by IKF and used to correct the SINS solution result. The TSDCP-v is used to calculate Doppler aiding frequency $f_{\text{aid}}$. By aiding the Doppler aiding frequency $f_{\text{aid}}$ and the carrier loop filter output $f_{\text{PLL}}$ to generate the driving signal $f_{\text{PLL}}$ for carrier NCO, the carrier NCO is controlled by $f_{\text{PLL}}$ to adjust the carrier frequency and carrier phase of the local signal, leaving only the Doppler aiding error to be tracked by the carrier tracking loop. The carrier loop equivalent bandwidth is increased, and the system’s dynamic and anti-interference ability is enhanced. The frequency $f_{\text{PLL}}$ is converted to code frequency to assist the code tracking loop. In the IKF measurements, the second-order nonlinear term in the PR $\rho_1$ measurement is retained. In addition, the nonlinear PR measurement is processed by UKF, which overcomes the nonlinear error introduced by the linearized PR measurement.

In the conventional SINS-assisted GPS ultratight integration system shown in Figure 2, the IKF measurements included linearized PR and PR-rate and the Doppler aiding frequency $f_{\text{aid}}$ calculated by the corrected SINS velocity. In the SINS-assisted GPS ultratight integration system, various measurement errors of GPS and SINS are coupled deeply. When using low-precision MEMS and in high dynamics, strong interference environments, the Doppler aiding frequency error $\delta f_{\text{aid}}$ can increase rapidly. If the tracking loop does not have enough bandwidth to track it, relatively large correlated components in tracking errors ($\delta \phi_s$ and $\delta \rho_s$) can be induced. Consequently, the GPS measurement errors ($\delta \rho_s$ and $\delta \rho_1$) increased. The GPS measurement errors can be correlated with the SINS velocity error, reduce the estimation accuracy of the IKF, and then further increase Doppler aiding frequency error; they can even result in losing lock of the tracking loop. In addition, for the linear IKF, when using linearized PR and PR-rate measurements, it can result in large nonlinearity error and a divergent solution. In this paper, high-precision TSDCP-v is used to calculate Doppler aiding frequency, reducing the Doppler-assisted error and avoiding the GPS measurement errors related to the MEMS-SINS velocity errors. Adopting TSDCP-v and nonlinear PR as the measurements of the IKF could improve the estimation accuracy of the filter and then improve the integration navigation accuracy.

3. The Time-Space Difference Carrier
Phase Velocity

The measurement models of PR and carrier phase at time $k$ are as follows:
\[ \rho_k = r_k + c(\delta t_{u,k} - \delta t_{k}) + I_k + T_k + O_k + M_{\rho,k} + \varepsilon_{\rho,k}, \]

\[ \phi_k = \lambda^{-1}\left[r_k + c(\delta t_{u,k} - \delta t_{k}) - I_k + T_k + O_k + M_{\phi,k}\right] + N + \varepsilon_{\phi,k}, \]

where \( \rho_k \) and \( \phi_k \) are the pseudorange measurement and the carrier phase measurement, respectively; \( r_k \) is the geometric distance from the receiver to the satellite; \( \delta t_{k} \) and \( \delta t_{u,k} \) are the satellite clock error and the receiver clock error, respectively; \( \lambda \) is the L1 carrier wavelength; \( I_k \) and \( T_k \) are the ionosphere error and the troposphere error, respectively; \( O_k \) is the satellite orbit error; \( M_{\rho,k} \) and \( M_{\phi,k} \) are the multipath errors; \( N \) is the integer ambiguity; \( \varepsilon \) is the white noise; and \( c \) is the light velocity.

By subtracting the carrier phase measurement \( \phi_k \) from two consecutive moments in the case of continuous carrier tracking, the integer ambiguity can be eliminated. The error
of satellite clock, satellite orbit, the troposphere, and ionosphere delay can also be eliminated. When the GPS receiver receives signals from different satellite at the same moment, the GPS receiver clock error is the same; and it can be removed by space difference. A high precision velocity measurement can be obtained by time-space difference carrier phase (TSDCP).

According to [22], the result of TDCP is as follows:

$$\lambda \cdot \Delta \phi_k^{(s)} = -\delta r_{M,k} \cdot e_k^{(s)} + c \cdot \delta t_{M,k} + \Delta \xi,$$  \hspace{1cm} (3)

where $\delta r_{M,k}$ is the position change of receiver in the time interval from $k - 1$.

When the receiver receives the satellite signals numbered $m$ and $n$, the GPS receiver clock error can be wiped out by space difference.

$$\lambda \cdot \Delta \phi_k^{(s,m)} = \lambda \cdot \Delta \phi_k^{(s)} - \lambda \cdot \Delta \phi_k^{(m)}$$

$$= -\delta r_{M,k} \cdot (e_k^{(m)} - e_k^{(s)}) + (\Delta \xi^{(n)} - \Delta \xi^{(m)})$$

$$= -\delta r_{M,k} \cdot (e_k^{(m)} - e_k^{(s)}) + \eta^{(s,m)},$$

where $\lambda \cdot \Delta \phi_k^{(s,m)}$ is the result of time-space difference carrier phase, $\lambda \cdot \Delta \phi_k^{(s)}$ is the result of TDCP of satellite $s$, and $e_k^{(s)}$ is the line-of-sight unit vector from the GPS receiver to the satellite $s$.

When the number of satellites observed by the receiver is more than two, it is necessary to perform TSDCP on the measurements from two different satellites, and the TSDCP measurement equation is

$$Z = H \cdot \delta r_{M,k} + \eta_{\phi},$$  \hspace{1cm} (5)

where the matrices $H$ and $Z$ are

$$H = \begin{bmatrix} - (e_k^{(m)} - e_k^{(s)})^T \\ - (e_k^{(n)} - e_k^{(s)})^T \\ \vdots \\ - (e_k^{(p)} - e_k^{(s)})^T \\ \lambda \cdot (\Delta \phi_k^{(s,m)} - \Delta \phi_k^{(m)}) \\ \vdots \\ \lambda \cdot (\Delta \phi_k^{(s,o)} - \Delta \phi_k^{(o)}) \\ \vdots \\ \lambda \cdot (\Delta \phi_k^{(s,p)} - \Delta \phi_k^{(p)}) \end{bmatrix},$$

$$Z = \begin{bmatrix} \lambda \cdot (\Delta \phi_k^{(s,m)} - \Delta \phi_k^{(m)}) \\ \vdots \\ \lambda \cdot (\Delta \phi_k^{(s,o)} - \Delta \phi_k^{(o)}) \\ \vdots \\ \lambda \cdot (\Delta \phi_k^{(s,p)} - \Delta \phi_k^{(p)}) \end{bmatrix}.$$

The TSDCP-v of the receiver can be calculated by

$$\delta r_{M,k} = (H^T H)^{-1} H^T Z,$$  \hspace{1cm} (7)

$$V_{cp} = \frac{\delta r_{M,k}}{\Delta t},$$

where $V_{cp}$ is the time-space difference carrier phase velocity TSDCP-v; $\Delta t$ is the time interval from $k - 1$ to $k$.

Using $V_{cp}$ as the velocity estimation of the GPS receiver in ECEF, $X'_i$ is satellite’s position, $V'_i$ is satellite’s velocity, and $X'_i$ is receiver’s position. The Doppler assist frequency $f_{aid}$ can be calculated by

$$f_{aid} = \frac{f_{LL}}{c} \cdot V_{aid} = \frac{f_{LL}}{c} \cdot (V'_i - V_{cp}) \cdot \frac{(X'_i - X'_j)}{\|X'_i - X'_j\|}$$

$$= \frac{f_{LL}}{c} \cdot (V'_i - V_{cp}) \cdot \overline{L}_i,$$  \hspace{1cm} (8)

4. The Model of the MEMS-SINS/GPS Ultratight Integration System

4.1. State Equations.

From [23, 24], the state equation of the system is expressed as

$$\dot{X} = FX + GW,$$

$$X = [\phi^n \delta \nu^n \delta \mathbf{p}^n \mathbf{e}_b \mathbf{v}_b \mathbf{b}_{clk} \mathbf{d}_{clk}]^T,$$  \hspace{1cm} (9)

where $\phi^n = [\phi_E \phi_N \phi_U]$ is the error angle, $\delta \nu^n = [\delta \nu_E \delta \nu_N \delta \nu_U]$ is the velocity error, and $\delta \mathbf{p}^n = [\delta L \delta \lambda \delta h]$ is the position error. The constant bias of gyroscope is $e_i = [e_{bx} e_{by} e_{bz}]$, and the constant bias of accelerometer $\mathbf{v}_b = [v_{bx} v_{by} v_{bz}]$ is the accelerometer constant bias. $b_{clk}$ and $d_{clk}$ are the clock error and the clock frequency error of receiver, respectively.

4.2. Measurement Equations. The measurement equations of MEMS-SINS/GPS ultratight integration system are composed of TSDCP-v and PR. In order to avoid the nonlinear error due to the linearization of PR measurement in high dynamics and strong interference environments, a new PR measurement equation that retains the second-order nonlinear term is constructed. The measurement model of PR at time $k$ shown in (1) can be rewritten as

$$p^j_i = R^i + b_{clk} + v^i,$$  \hspace{1cm} (10)

where $R^i = \|r_i - r_i^0\|$, $r$ is the actual position of receiver, $r_i^0$ is the satellite position, and $v^i$ is the measurement error modeled as white noise.

Assuming that $r_i$ is the receiver position vector estimated by MEMS-SINS, the pseudorange estimate $p^j_i$ is as follows:

$$p^j_i = ||r_i - r_i^j||.$$  \hspace{1cm} (11)

Denote the MEMS-SINS position error in ECEF by $\delta r$, $\delta r = r_i - r$, and expend equation (11) by a Taylor series about $r$ to the second-order term; the pseudorange estimated by MEMS-SINS is as follows:

$$p^j_i = R^i + \text{Jacobi}^j (r) \cdot \delta r + \frac{1}{2} \delta r^T \cdot \text{Hess}^j (r) \cdot \delta r,$$  \hspace{1cm} (12)

where $\text{Jacobi}^j (r) = (\partial p^j_i / \partial r_i)|_{r=r}$ is the Jacobian matrix and $\text{Hess}^j (r) = (\partial^2 p^j_i / \partial r_i \partial r_j)|_{r=r}$ is Hessian matrix.

According to equations (10) and (12), the pseudorange measurement of satellite $j$ is as follows:
\[ \delta p^i = \rho_1^i - \rho_2^i = \text{Jacobi}^{(i)}(r) \cdot \delta r \]
\[ + \frac{1}{2} \delta r^T \cdot \text{Hess}^{(i)}(r) \cdot \delta r - b_{clk} + \nu^i. \quad (13) \]

The pseudorange measurement equation of MEMS-SINS/GPS ultratight integration system is as follows:

\[
Z_p = \delta \rho = H_p X + \frac{1}{2} \left[ \begin{array}{c} X^T(D_p^T C_p^T \text{Hess}^{(1)} C_p D_p X) \\
X^T(D_p^T C_p^T \text{Hess}^{(2)} C_p D_p X) \\
\vdots \\
X^T(D_p^T C_p^T \text{Hess}^{(n)} C_p D_p X) \end{array} \right] + V_p
\]

\[ = H_p(X) + V_p, \quad (14) \]

where
\[ \delta \rho = \rho_1 - \rho_2 = [\delta \rho^1, \delta \rho^2, \ldots, \delta \rho^n]^T, \]
\[ H_p = [0_{m \times 6}, D_u, 0_{m \times 6}, -e 0_{m \times 6}]. \]
\[ D_u = [\text{Jacobi}^{(1)}(r) \ \text{Jacobi}^{(2)}(r) \ \ldots \ \text{Jacobi}^{(m)}(r)]^T, \]
\[ D_v = [0_{j \times 6} I_{j \times j} 0_{j \times 6}], \]
\[ e = [1 \ 1 \ \ldots \ 1]_{1 \times m}, \]
\[ V_p = [\nu^1 \ \nu^2 \ \ldots \ \nu^n]^T. \]

(15)

\[ C_p^T \] is the transition matrix from geographic coordinates to ECEF coordinates:

\[
C_p^T = \begin{bmatrix}
-(R_N + h)\sin L \cos \lambda & -(R_N + h)\cos L \cos \lambda & -(R_N + h)\sin L \\
-(R_N + h)\sin L \sin \lambda & (R_N + h)\cos L \cos \lambda & (R_N + h)\cos L \\
-R_N(1 - e^2) + h & 0 & \sin L
\end{bmatrix}. \quad (16)
\]

The velocity measurement can be obtained by the difference between TSDCP velocity \( V_{cp} \) and MEMS-SINS velocity \( V_I \):

\[ Z_v = V_I - V_{cp} = H_v X + V_v, \]

\[ H_v = [0_{m \times 6} I_{m \times m} 0_{m \times 9} 0_{m \times 1}]. \quad (17) \]

Equations (14) and (17) are the measurement equations of the MINS/GPS ultratight integrated system.

4.3. Integrated Kalman Filter. Because the velocity measurement is linear, the pseudorange measurement is nonlinear, and there are different noise characteristics between the measurements; the IKF uses a sequential filtering configuration. In the process of IKF update, \( \hat{X}_0 \) and \( \hat{P}_0 \) are the initial state estimates. The state equations processed by the conventional Kalman filter (KF) are

\[
\hat{X}_{k|k-1} = \Phi_k X_{k-1} + Q_{k-1}, \quad (18)
\]

As the pseudorange measurement is nonlinear, it is processed by UKF. The UT transformation of pseudorange measurement prediction is as follows:

\[ X_{k|k-1} = \begin{bmatrix} \hat{X}_k(0) \\ \hat{X}_k(1) \\ \hat{X}_k(2) \end{bmatrix}, \quad (19) \]

The state estimate by UKF is

\[
K_k = P_{yk}(k) K_{yk}(k), \quad (20)
\]

\[ \hat{X}_k(k) = \hat{X}_k(0) + K_k(1)(Z_k(k) - \hat{X}_k(k-1)), \]

\[ P_k(k) = P_k(0) - K_k(1) P_{yk}(k-1)(K_k(1))^T, \quad (21) \]

where \( Z_k(k) \) and \( R_k(k) \) are the velocity measurement and the measurement noise variance matrix at epoch \( k \), respectively.

As the velocity measurement is linear, it is processed by the KF as follows:

\[ K_k = P_k(1) H_k T (H_k P_k(1) H_k T + R_k(2))^{-1}, \]

\[ \hat{X}_k(k) = \hat{X}_k(1) + K_k(2) \left( Z_k(2) - H_k \hat{X}_k(2) \right), \]

\[ P_k(k) = (I - K_k(2) H_k) P_k(1), \]

where \( Z_k(2) \) and \( R_k(2) \) are the velocity measurement and the measurement noise variance matrix at \( k \). \( \hat{X}_k \) and \( P_k \) are the IKF outputs at epoch, respectively.

5. Simulation and Analysis

To analyze the anti-jamming capability, dynamic performance, and navigation performance of MEMS-SINS/GPS ultratight integration system under challenging environments, the simulation experiments are designed, and the simulation platform is shown in Figure 3. The trajectory generator generates the ideal trajectory of the carrier. The ideal trajectory is used to simulate the IF signal and the IMU
outputs. The IF signal and the IMU outputs are used in the SINS/GPS tight integration system, the SINS-assisted GPS ultratight integration system, and the MEMS-SINS/GPS ultratight integration system to verify system performance. The carrier ideal trajectory is shown in Figure 4. The system uses low-precision MEMS, the gyro constant bias is $3'/h$, the random noise is $0.3'/\sqrt{h}$, the acceleration constant bias is $1000\mu g$, and its random noise is $100\mu g/\sqrt{Hz}$. In MEMS-SINS, the initial attitude error is $[0.2, 0.2, 0.2]'$, the initial velocity error is $[0.05, 0.05, 0.05] m/s$, and the initial position error is $[10,10,15] m$. The GPS IF signal frequency is $2 MHz$; narrowband noise interference and broadband noise interference with SNR $= -27 dB$ are modulated on the IF signal. In the GPS software receiver module, the sampling frequency is $10MHz$, the noise bandwidth is adjustable, and the damping factor is $0.7$. The integrated system navigation output cycle is $10 ms$.

5.1. Result and Analysis of TSDCP Velocity. The high-precision TSDCP velocity is calculated by time-space difference carrier phase measurement. The carrier phase measurement is output by carrier tracking loop, and the carrier phase measurement and the carrier phase measurement error are shown in Figure 5.

The TSDCP velocity error is shown in Figure 6.

As shown in Figure 6, the accuracy of TSDCP velocity can reach the centimeter, and the TSDCP velocity error is less than $0.04 m/s$. Therefore, using TSDCP velocity to calculate the Doppler frequency to aid the GPS carrier tracking loop, the proposed MEMS-SINS/GPS ultratight integration system reduces the Doppler aiding error introduced by low-precision MEMS and avoids GPS measurement error related to MEMS-SINS velocity error.

5.2. The Dynamic Performance Analysis of MEMS-SINS/GPS Ultratight Integration System. In the MEMS-SINS/GPS ultratight integration system, TSDCP-v is used to calculate the Doppler aiding frequency to aid the GPS carrier tracking loop. Figure 7 shows the Doppler aiding frequency of carrier tracking loop corresponding to PRN8 and the carrier tracking frequency error output by carrier loop filter in the MEMS-SINS/GPS ultratight integration system.

In the SINS/GPS tight integration system, the GPS carrier tracking loop is not assisted by the aid information, and the carrier NCO is modulated by the output of carrier loop filter. The carrier tracking frequency error output by carrier loop filter in the SINS/GPS tight integration system is shown in Figure 8.

The Doppler aiding frequency and the carrier tracking frequency error of MEMS-SINS/GPS ultratight integration system in Figure 7 are compared with the carrier tracking frequency error of SINS/GPS tight integration system in Figure 8. The Doppler aiding frequency in MEMS-SINS/GPS ultratight integration system can accurately estimate the carrier frequency variation of the carrier loop filter output, so that the carrier tracking loop only needs to track the remaining small aid frequency error.

In the MEMS-SINS/GPS ultratight integration system, the carrier tracking loop is assisted by Doppler aiding frequency. On the one hand, the influence of carrier dynamic on tracking loop is eliminated, the dynamic tracking ability of the tracking loop is enhanced, and the probability of losing lock of carrier tracking loop is reduced. On the other hand, equivalent bandwidth of tracking loop is increased, so as to reduce the dynamic stress error. Therefore, compared with the SINS/GPS tight integration system, the MEMS-SINS/GPS ultratight integration system has higher dynamic performance.

5.3. The Antijamming Capability Analysis of MEMS-SINS/GPS Ultratight Integration System. The GPS carrier tracking loop measurement error is one of the factors influencing the carrier tracking performance of PLL. The measurement errors and tracking thresholds are closely related because the carrier tracking loop loses lock when the measurement errors exceed a certain tracking threshold.

Considering the thermal noise and dynamic stress error, the conservative rule-of-thumb tracking threshold for PLL is described as

$$
\delta_{PLL} = \delta_{PLL} + \frac{\theta}{3} \leq 15'.
$$

The 1-sigma thermal noise and dynamic stress error can be described as

$$
\delta_{PLL} = \frac{360}{2\pi} \sqrt{B_n \frac{C/N_0}{1 + \frac{1}{2T(C/N_0)}}} (\circ),
$$

$$
\theta_c = \frac{d^nR/dt^n}{u_0},
$$

where $B_n$ denotes the noise bandwidth of PLL, $C/N_0$ represents the carrier-to-noise ratio, $T$ is the predetection integration time, $d^nR/dt^n$ is the maximum of the LOS acceleration between the receiver and the satellite, and $n$ and $u_0$ denote the order and the natural frequency of PLL, respectively. The relationship between $u_0$ and the noise bandwidth $B_n$ is $B_n = 0.25u_0$ for a first-order PLL, $B_n = 0.53u_0$ for a second-order PLL, and $B_n = 0.7845u_0$ for a third-order PLL.

For a second-order PLL, suppose that the predetection integration time is $1 ms$, and the maximum of the LOS acceleration between the receiver and the satellite is $10g$. Considering the thermal noise and dynamic stress error, the relationship between SINS/GPS tight integration carrier tracking loop measurement error, noise bandwidth, and carrier-to-noise ratio is shown in Figure 9.

It can be seen from Figure 9 that the SINS/GPS tight integration system has a contradiction between restraining the thermal noise and dynamic stress error. Decreasing the bandwidth would reduce the thermal noise but would result in large dynamic stress error simultaneously.

In the MEMS-SINS/GPS ultratight integration system, the carrier tracking loop is assisted by the TSDCP velocity, and the dynamic stress error is compensated. The GPS
carrier tracking loop measurement error is mainly related to thermal noise. The relationship between PLL measurement error, noise bandwidth, and carrier-to-noise ratio in ultratight integration system is shown in Figure 10. It can be seen from Figure 10 that, in the MEMS-SINS/GPS ultratight integration, the contradiction between the dynamic performance and antinoise capability can be solved. On one hand, the equivalent bandwidth increased, thereby reducing the dynamic stress error. On the other hand, it restrains the thermal noise. With the noise bandwidth decreasing, the PLL measurement error decreases, and the carrier-to-noise ratio threshold of the carrier loop becomes lower. The PLL can track under lower signal-to-noise ratio conditions, and the antijamming capability is improved.

Analyze the antijamming capability of the system by calculating the ratio of interference to signal power (J/S). Table 1 shows the antijamming performance comparison of SINS/GPS tight integration system and MEMS-SINS/GPS ultratight integration system. It can be seen from Table 1 that, compared to the tight integration system, the antijamming ability of the MEMS-SINS/GPS ultratight integration system is improved by about 5 dB.

The carrier-to-noise ratio of satellite signals in SINS/GPS tight integration system and ultratight integration system are shown in Figure 11. In SINS/GPS tight integration system, when the noise bandwidth is 14 Hz, in addition to the PRN17, the carrier-to-noise ratios of other satellite signals are lower than 20 dBBH, and the corresponding tracking channel is lose lock. The C/N estimation of SINS/GPS tight
integration system is shown in Figure 11(a). In MEMS-SINS/GPS ultratight integration system, when the noise bandwidth is 5 Hz, the signal carrier-to-noise ratio is higher than 30dBHz, the corresponding tracking channel can work normally, and the C/N estimation is shown in Figure 11(b). Compared with SINS/GPS tight integration system, the
ultratight integration system has higher anti-interference ability.

5.4. The Performance Analysis of Carrier Tracking Loop Compared with SINS-Assisted GPS Ultratight Integration System. The carrier tracking loop performances of SINS-assisted GPS ultratight integration system and the MEMS-SINS/GPS ultratight integration system can be compared by the outputs of PLL lock detectors. The outputs of PLL lock detectors can be calculated by the carrier tracking phase error output by the carrier phase discriminator in carrier tracking loop. The closer the output value of PLL lock detectors is to 1, the better the signal tracking performance of carrier tracking loop is. The PLL lock detector outputs of SINS-assisted GPS ultratight integration system and the MEMS-SINS/GPS ultratight integration navigation system are shown in Figure 12.

The RMS of the PLL detector outputs of SINS-assisted GPS ultratight integration system and the MEMS-SINS/GPS ultratight integration system are shown in Table 2.

From Figure 12 and Table 2, when using low-precision MEMS and in high dynamics and strong interference environment, the MEMS-SINS/GPS ultratight integration navigation system can avoid the correlation between GPS measurement error and SINS velocity error by introducing TSDCP-v to assist the carrier tracking loop, which can keep the signals tracked stably. Compared with SINS-assisted GPS ultratight integration system, the MEMS-SINS/GPS ultratight integration navigation system has higher signal tracking ability.
5.5. The Navigation Performance Analysis of MEMS-SINS Ultratight Integration System. Figures 13–15 show the navigation errors of the SINS/GPS tight integration system, the SINS-assisted GPS ultratight integration system, and the MEMS-SINS/GPS ultratight integration system. At the same time, the navigation accuracy comparison of the three integration navigation systems above is shown in Table 3. In high dynamics and strong interference environment, the SINS/GPS tight integration system carrier tracking loop is easy to lose lock. As a result, the satellite signal tracked by
the tracking loop becomes less, or even the satellite signal cannot be tracked, as shown in Figure 11(a). The navigation accuracy of SINS/GPS tight integration system decreases or even diverges. In the SINS/GPS ultratight integration system, the carrier tracking loop is assisted by assist information, improving the system’s dynamic performance and anti-jamming ability. Then, the navigation performance is also improved.

Comparing the navigation errors of the SINS-assisted GPS ultratight integration system and the MEMS-SINS/GPS ultratight integration system, the navigation solution error of the MEMS-SINS/GPS ultratight integration system is smaller, and the IFK is more stable. On the one hand, the carrier tracking performance of the MEMS-SINS/GPS ultratight integration system is higher than the SINS-assisted GPS ultratight integration system when using low-precision

|                  | PRN1   | PRN17  | PRN7   | PRN11  | PRN8   | PRN18  |
|------------------|--------|--------|--------|--------|--------|--------|
| SINS-assisted GPS ultratight integration | 0.9285 | 0.9548 | 0.9155 | 0.9252 | 0.9206 | 0.9132 |
| MEMS-SINS/GPS ultratight integration     | 0.9465 | 0.9546 | 0.9353 | 0.9422 | 0.9206 | 0.9222 |

Figure 12: (a) The PLL detector outputs of SINS-assisted GPS ultratight integration. (b) The PLL detector outputs of MEMS-SINS/GPS ultratight integration.

Figure 13: SINS/GPS tight integration system navigation errors. (a) Position error. (b) Velocity errors.
MEMS and in high dynamics and strong interference environments. It makes the observation accuracy of the tracking loop output used for the combined filter become higher. On the other hand, in the MEMS-SINS/GPS ultratight integration system, the second-order nonlinear term in the PR measurement is retained, and the nonlinear PR measurement is processed by UKF, which overcomes the nonlinear error introduced by the linearized PR measurement.

6. Conclusions

In the MEMS-SINS/GPS ultratight integration system, the TSDCP velocity assists the carrier tracking loop and improves the dynamic performance of the system. By reducing the noise bandwidth of the loop filter, on the one hand, the anti-interference tolerance of GPS is improved, and the carrier-to-noise ratio threshold of the tracking loop is reduced; on the other hand, noise interference can be
suppressed by reducing the noise bandwidth and the carrier-to-noise ratio can be improved. By constructing the PR measurement that retains the second-order nonlinear term and designing the corresponding filtering algorithm, the accuracy of IF estimation is improved. Compared with the SINS/GPS tight integration navigation system, the MEMS-SINS/GPS ultratight integration system has higher dynamic performance, anti-interference capability, and navigation performance. At the same time, the MEMS-SINS/GPS ultratight integration system improves the carrier tracking performance of SINS-assisted GPS ultratight integration system when using low-precision MEMS and in high dynamics, strong interference environments.

**Data Availability**

The data and software used to support the findings of this study are included within the supplementary information file.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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**References**

[1] Y. H. Kou and H. Zhang, “Sample-wise aiding in GPS/INS ultra-tight integration for high-dynamic, high-precision tracking,” Sensors, vol. 16, no. 4, p. 519, 2016.

[2] 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.

[3] M. Y. Wu, J. C. Ding, and L. Zhao, “An adaptive deep-coupled GNSS/INS navigation system with hybrid pre-filter processing,” Measurement Science Technology, 2018.

[4] P. D. Groves, Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems, Artech House Publisher, Boston, MA, USA, 2013.

[5] L. Di, “System design and performance analysis of extended kalman filter-based ultra-tight GPS/INS integration,” in Proceedings of the 2006 IEEE/ION Position, Location, And Navigation Symposium, pp. 291–299, Coronado, CA, USA, April 2006.

[6] K.-W. Chiang, T. Duong, and J.-K. Liao, “The performance analysis of a real-time integrated ins/gps vehicle navigation system with abnormal gps measurement elimination,” Sensors, vol. 13, no. 8, pp. 10599–10622, 2013.

[7] L. H. Ma, Z. B. Fang, and B. H. Ying, “Application of fixed matrix square root UKF in the ultra-tightly coupled integrated GPS/SINS navigation system,” ICIC Express Letters, 2015.

[8] X. Zhao, J. Li, and S. Ji, “Robust adaptive cubature kalman filter and its application to ultra-tightly coupled SINS/GPS navigation system,” Sensors, vol. 18, no. 7, pp. 2352–2370, 2018.

[9] G. Yan, 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.

[10] R. Babu and J. Wang, “Ultra-tight GPS/INS/PL integration: a system concept and performance analysis,” GPS Solutions, vol. 13, no. 1, pp. 75–82, 2009.

[11] R. Babu, Ultra-tight Integration of GPS/Pseudolites/INS: System Design and Performance Analysis, University of New South Wales, Sydney, Australia, 2006.

[12] W. D. Zhou, J. N. Cai, L. Sun et al., “Time-space difference based GPS/SINS ultra-tight integrated navigation method,” Measurement, pp. 87–92, 2014.

[13] D.-J. Jwo, C.-F. Yang, C.-H. Chuang, and K.-C. Lin, “A novel design for the ultra-tightly coupled gps/ins navigation system,” Journal of Navigation, vol. 65, no. 4, pp. 717–747, 2012.

[14] X.-l. Wang and Y.-f. Li, “An innovative scheme for SINS/GPS ultra-tight integration system with low-grade IMU,” Aerospace Science and Technology, vol. 23, no. 1, pp. 452–460, 2012.

[15] J. Yu and X.L. Wang, “Design and analysis for an innovative scheme of SINS/GPS ultra-tight integration,” Aircraft Engineering and Aerospace Technology: An International Journal, vol. 82, pp. 4–14, 2010.

[16] W. Wang, Z.-y. Liu, and R.-r. Xie, “Quadratic extended Kalman filter approach for GPS/INS integration,” Aerospace Science and Technology, vol. 10, no. 8, pp. 709–713, 2006.

[17] 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.

[18] K. Ben, H. Soon, and S. Scheding, “An approach to aid INS using time-differenced GPS carrier phase (TDCP) measurement,” GPS Solut, vol. 12, pp. 261–271, 2018.

[19] D. Gebre, J. D. Powell, and P. Enge, “Design and performance analysis of a low-cost aided dead reckoning navigation system,” Gyroscopy Naving, vol. 4, pp. 83–92, 2001.

[20] W. Ding and J. Wang, “Precise velocity estimation with a stand-alone GPS receiver,” Journal of Navigation, vol. 64, no. 2, pp. 311–325, 2011.

[21] J. Wendel and G. F. Trommer, “Tightly coupled GPS/INS integration for missile applications,” Aerospace Science and Technology, vol. 8, no. 7, pp. 627–634, 2004.

[22] Q. Li and Y. Zhao, “An innovative high-precision scheme for a GPS/MEMS-SINS ultra-tight integrated system,” Sensors, vol. 19, no. 10, pp. 2291–2309, 2019.

[23] X. L. Wang, Y. F. Li, and X. C. Ji, SINS/GPS Integrated Navigation Technology, pp. 126–129, " Beihang university press, Beijing, 2014.

[24] G. Hu, L. Ni, B. Gao, X. Zhu, W. Wang, and Y. Zhong, “Model predictive based unscented kalman filter for hypersonic vehicle navigation with INS/GNSS integration,” IEEE Access, vol. 8, pp. 4814–4823, 2020.