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Research on Ultra-tightly coupled Integrated Navigation Method Based on ZYNQ-7020

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***Abstract*— For conventional loosely coupled Integrated and tightly coupled Integrated, when the number of satellites is less than 4, there may be cases where positioning is impossible. Besides, market demand for miniaturization of navigation products. This paper overcomes the above shortcomings with the ultra-tightly coupled integrated method of Zynq-7020 as the platform. The paper Introduces the software scheme, the hardware scheme, the ultra-tightly coupled integrated mathematical model and filtering fusion algorithm in detail. In addition, a multi-channel SINS assisted fast frame synchronization algorithm is added to quickly recapture and track satellite signals. Finally, the feasibility and reliability of the design scheme are verified by high dynamic simulator test and vehicle test.**

***Index Terms*— Zynq-7020, Combined navigation, Super tight combination, Inertial aid.**

I. INTRODUCTION

The inertial navigation system does not rely on external information, nor radiates energy to the outside world. Its strong concealment, all-weather and all-day working characteristics make it widely used in the fields of guided weapons, aircraft, ships, rockets and missiles [1].

GNSS navigation system has a severe decline in navigation performance when signals are disturbed. Inertial navigation systems are limited by their principles, and navigation errors diverge over time. The ultra-tightly coupled integrated system of GNSS and SINS can improve the alignment accuracy of SINS and reduce the divergence of its navigation results. At the same time, SINS can assist GNSS to capture signals and track signals, improving the dynamic characteristics and anti-jamming characteristics of receivers, thus improving the accuracy and reliability of the entire integrated navigation system [2]- [4].

At present, various navigation products are developing towards miniaturization of power consumption, volume and quality. This paper uses XILINX's Zynq-7020 programmable chip. The Zynq-7020 chip can be divided into processor system part(PS) and programmable logic part(PL). the Zynq-7020 integrates dual-core ARM Cortex-A9 and FPGA programmable logic on a single chip using ARM+FPGA SOC technology. This paper abandons the traditional “FPGA+DSP” design, and the baseband digital signal processing part is designed in the form of IP core in PL. the Satellite solution, inertial navigation system solution and combined navigation filtering in PS. The use of such an architecture can greatly reduce the size and power consumption of the entire system, and the final design of the product also meets the design concept of the US micro-PNT. In this paper, the hardware architecture design and ultra-tightly coupled integrated algorithm design are introduced in detail, and the feasibility and reliability of the scheme are verified by a series of experiments.

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II. OVERALL STRUCTURE OF THE ULTRA-TIGHTLY COUPLED INTEGRATED SYSTEM

The overall scheme design of the ultra-tightly coupled integrated navigation system based on Zynq-7020 is shown in Figure 1. The overall scheme is divided into three modules. The modules are as follows:

(1) GNSS positioning navigation module: The GNSS receiver positioning navigation module acquires Doppler frequency shift information, carrier phase information, and satellite parameter information in the signal correlator, and calculates information such as pseudo-range and pseudo-range rate by analyzing the satellite ephemeris. Finally, calculating the current carrier’s location, speed and time information [5]- [6].

(2) Micro-inertial navigation module: The micro-inertial navigation module uses the gyroscope and accelerometer to measure the original angular rate and specific force information. The original data is sent to the information solving module to calculate the position, velocity, angular velocity, acceleration and attitude angle information of the carrier. Finally, the data is transmitted to the GNSS auxiliary capture tracking module, the integrated navigation module, and the host computer.

(3) Integrated navigation module: In this module, MIMU uses the satellite ephemeris information to calculate the pseudo-range and pseudo-range rate of the carrier and the pseudo-range and pseudo-range rate calculated by the GNSS positioning navigation module as the measurement information is filtered in the Kalman filter. Finally, the correction information of the carrier’s position, velocity and attitude is fed back to the system for correction, thereby outputting high-precision and high-reliability navigation information.

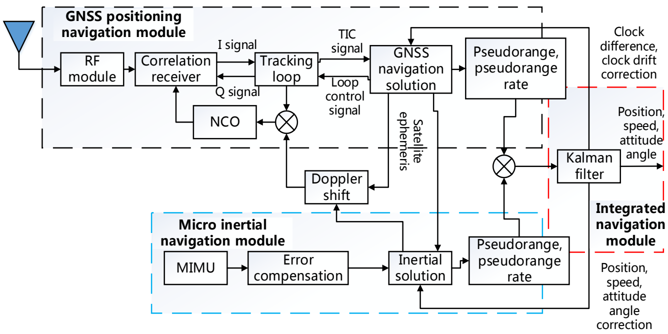

Figure 1. Overall structure of the ultra-tightly coupled integrated system

III. HARDWARE DESIGN OF ULTRA-TIGHTLY COUPLED INTEGRATED SYSTEM

The hardware structure of the ultra-tightly coupled integrated system consists of MIMU and GNSS navigation module with Zynq-7020 as the main core. The resources of each module must be fully invoked, and the configuration and communication of each module must be determined. The overall hardware structure of the system is shown in Figure 2.

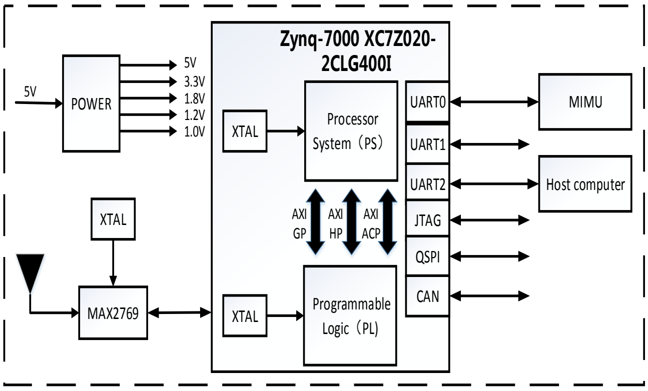

Figure 2. overall design hardware structure

(1) The power module is powered by +5V，The power supply for the PS and PL sections of ZYNQ has a power-on sequence. Therefore, by designing four DC/DC power supply chip TLV62130RGT, converting into +3.3V, +1.8V, +1.2V, +1.0V four-way power supply.

(2) Design the clock source of the PS part is 33.333MHz, the PL part of the clock source is 16.369MHz and the crystal output is connected to the FPGA's global clock (MRCC), which can be used to drive the logic circuit in FPGA.

(3) The RF module is selected by Maxim Integrated's MAX2769 chip. The PL part of the Zynq-7020 chip communicates with the MAX2769 through the SPI interface, and the MAX2769 internal registers are programmed by CS, SCLK, and SDATA pins at a certain timing. The RF front-end processing module amplifies, converts, filters, and analog-to-digital converts the current signal processed by the active antenna, and finally obtains a digital intermediate frequency signal.

(4) The PL part of Zynq-7020 provides the digital IF signal generated by the MAX2769 to the channel correlator for processing. The accumulator triggers the accumulation interrupt after latching the I and Q signals. The digital processing module of the baseband signal in PL is designed in the form of an IP core, and the multi-channel parallel processing IP core is designed to perform processing of capturing signal, tracking signal, bit synchronization, frame synchronization and navigation message.

(5) The PS part of Zynq-7020 to achieve positioning solution. The PS processor has a clock speed of 767MHz, each processor has 32KB of level 1 instructions and data cache, and 512KB of level 2 cache. The PS part and the PL part communicate via AXI-GP, AXI-HP, and AXI-ACP. The PS performs acquisition control and acquisition decision on the digital intermediate frequency signal in the PL, thereby realizing phase discrimination, filtering and GNSS positioning solution, and also processing the MIMU information received by the UART port and the overall combined filtering process.

IV. ULTRA-TIGHTLY COUPLED INTEGRATED SYSTEM SOFTWARE DESIGN

The overall software algorithm flow is: system initialization; MIMU initial alignment; GNSS receiver initialization; SINS navigation solution, sending inertial auxiliary information to the GNSS receiver; solving the position and velocity; solving the Doppler shift; Correcting the acquisition and tracking loops; solving the pseudo-range measurement error compensation of the inertial information-assisted GNSS tracking loop[7]; solving the pseudo-range and pseudo-range rate; constructing the system equation; Kalman filtering, outputting the final position and velocity. The overall software algorithm scheme is shown in Figure 3.

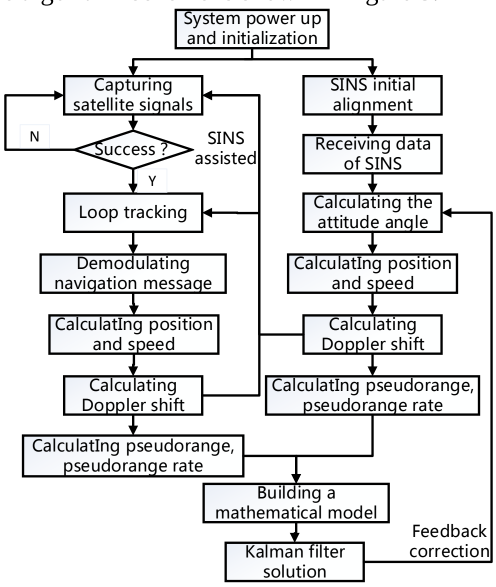

Figure 3. software algorithm flow

A. *SINS assisting the calculation of Doppler shift*

The carrier position of the SINS output is (x_u, y_u, z_u),The position of the i-th satellite is (x_s^i, y_s^i, z_s^i), The relative velocity of the computational carrier and the i-th satellite on the line-of-sight vector is:

$$v_{u\_s}^i = (\vec{v}_u - \vec{v}_s) \cdot \vec{e}_{u\_s}^i = (\vec{v}_u - \vec{v}_s) \cdot \begin{pmatrix} \dfrac{x_s^i - x_u}{r} \\ \dfrac{y_s^i - y_u}{r} \\ \dfrac{z_s^i - z_u}{r} \end{pmatrix} \tag{1}$$

Where $\vec{e}_{u\_s}^i$ is the unit direction vector of the satellite and the carrier in the line of sight direction, r is the geometric distance, $\vec{v}_u$ is the speed of the carrier, $\vec{v}_s$ is the speed of the satellite. The Doppler shift caused by the relative motion between the satellite and the carrier is:

$$f_{dopp}^i = \frac{f_{GNSS}}{c} \cdot v_{u\_s}^i = \frac{1}{\lambda} \cdot v_{u\_s}^i \tag{2}$$

f_{GNSS} is the carrier frequency of GNSS, c is the speed of light.

B. *Calculating the pseudo-range and pseudo-range rate*

The pseudo-range ρ_{Gj} calculated by satellite is :

$$\rho_{Gj} = r_j - \delta t_u - \upsilon_{\rho j} \tag{3}$$

Where δt_u is the distance error caused by the clock difference. $\upsilon_{\rho j}$ is white noise measured for pseudo-range.

The pseudo-range rate $\dot{\rho}_{Gj}$ calculated by satellite is:

$$\dot{\rho}_{Gj} = \dot{r}_j - \delta t_{ru} - \upsilon_{\dot{\rho} j} \tag{4}$$

Where δt_{ru} is the distance rate error caused by the clock drift, $\upsilon_{\dot{\rho} j}$ is white noise measured for pseudo-range rate, and $\dot{r}_j$ is the distance change rate of the carrier to the j-th satellite.

The pseudo-range ρ_{Ij} calculated by SINS is:

$$\rho_{Ij} = r_j + e_{j1}\delta x + e_{j2}\delta y + e_{j3}\delta z \tag{5}$$

The pseudo-range rate $\dot{\rho}_{Ij}$ calculated by SINS is:

$$\dot{\rho}_{Ij} = \dot{r}_j + e_{j1}\delta \dot{x} + e_{j2}\delta \dot{y} + e_{j3}\delta \dot{z} \tag{6}$$

Where δx, δy, δz, $\delta \dot{x}$, $\delta \dot{y}$, $\delta \dot{z}$ are the component of the position error and velocity error in the ECEF coordinate system on the x-axis, y-axis and z-axis.

C. Fast frame synchronization algorithm with SINS-assisted

Deriving satellite launch time by using pseudo-range calculation formula:

$$\rho = c \times (t - t^{(s)}) \tag{7}$$

Where c is the speed of light; t is the moment of reception of the signal. $t^{(s)}$ is the transmission moment of the signal :

$$t^s = TOW + (30w + b) * 0.02 + \left(c + \frac{CP}{1023} + \frac{CDP}{1023 * 2046}\right) * 0.01(s) \tag{8}$$

Where TOW is Truncate intra-week count in the previous sub-frame; w is the currently received frame navigation text; b is bit count in the current navigation text word; c is the pseudo code period received in the current bit, CP is the current code phase measurement value, CDP is the current carrier cycle count.

Since the signal transmission time is known, the bit count, word count, sub-frame count and Z count can be solved by the above formulas, finally, realizing fast frame synchronization algorithm. The entire algorithm flow is shown in Figure 4.

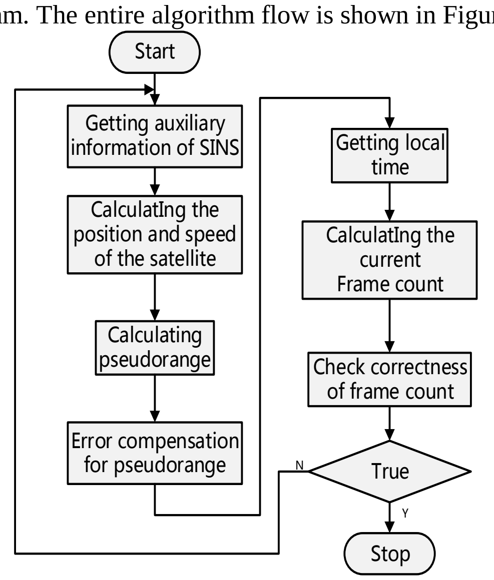

Figure 4. Fast frame synchronization algorithm flow

V. ULTRA-TIGHTLY COUPLED INTEGRATED SYSTEM EQUATION

A. State equation of the system

The equation of state for the integrated navigation system is:

$$\dot{X}(t) = F(t)X(t) + G(t)W(t) \tag{9}$$

Where $X(t)$ is the state vector, $\dot{X}(t)$ is the derivative of the state vector, $F(t)$ is the state transition matrix, $G(t)$ is the noise drive matrix, and $W(t)$ is the noise vector, as follows:

$$X = \begin{bmatrix} \phi_E, \phi_N, \phi_U, \delta V_E, \delta V_N, \delta V_U, \delta L, \delta\lambda, \delta h, \\ \varepsilon_x, \varepsilon_y, \varepsilon_z, \nabla_x, \nabla_y, \nabla_z, \delta t_u, \delta t_{ru} \end{bmatrix}^T_{17*1} \tag{10}$$

In (10), ϕ_E, ϕ_N, ϕ_U are the east, north, and sky direction angles, $\delta V_E, \delta V_N, \delta V_U$ are the carrier's east, north, and sky direction speed error, $\delta L, \delta\lambda, \delta h$ are the carrier latitude, longitude, height error, R_M is the radius of curvature of each point on the meridian circle, R_N is the radius of curvature of each point on the circle, $\varepsilon_E, \varepsilon_N, \varepsilon_U, \nabla_E, \nabla_N, \nabla_U$ are the drift of the gyro and accelerometer in the east, north, and the sky.

B. System measurement equation

The measurement equation of the integrated navigation system is:

$$Z(t) = H(t)X(t) + V(t) \tag{11}$$

Where $Z(t)$ is the measurement vector, $H(t)$ is the measurement matrix, $V(t)$ are the measurement noise. The dimension of the measurement equation and the dimension of the integrated filter vary according to the number of visible stars. If the number of visible stars is n, the dimension of Z is : 2n×1 ; the dimension of H is : 2n×17 ; the dimension of R is : 2nx2n ; the dimension of Kalman gain K is : 17x2n.

C. The pseudo-range measurement equation

$$\tilde{Z}_\rho = \tilde{H}_\rho \tilde{X} + \tilde{V}_\rho = \begin{bmatrix} 0_{n\times 6} & \tilde{H}_{\rho n1} & 0_{n\times 6} & \tilde{H}_{\rho n2} \end{bmatrix} \tilde{X} + \tilde{V}_\rho \tag{12}$$

In (12),

$$\tilde{Z}_\rho = \begin{bmatrix} \delta\rho^1 \dots & \delta\rho^n \end{bmatrix}^T_{1\times n}, \tilde{V}_\rho = \begin{bmatrix} v_\rho^1 \dots & v_\rho^n \end{bmatrix}^T_{1\times n} \tag{13}$$

$$\delta\rho_j = \rho_{Ij} - \rho_{Gj} = e_{j1}\delta x + e_{j2}\delta y + e_{j3}\delta z + \delta t_u + v_{\rho j} \tag{14}$$

$$\tilde{H}_{\rho n1} = \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \tilde{a}_{13} \\ \vdots & \vdots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \tilde{a}_{n3} \end{bmatrix}_{n\times 3}, \tilde{H}_{\rho n1} = \begin{bmatrix} 1 & 0 \\ \vdots & \vdots \\ 1 & 0 \end{bmatrix}_{n\times 2} \tag{15}$$

Where $v_\rho^1 \dots \ v_\rho^n$ is the pseudo-range measurement noise of each channel, $\tilde{a}_{ij}(i = 1\cdots n, j = 1,2,3)$ can be expanded into the following form:

$$\begin{cases} \tilde{a}_{i1} = (R_N + h)\left[-e_{i1}\sin L\cos\lambda - e_{i2}\sin L\sin\lambda\right] \\ +\left[R_N(1-f)^2 + h\right]e_{i3}\sin L \\ \tilde{a}_{i2} = (R_N + h)\left[e_{i2}\cos L\cos\lambda - e_{i1}\cos L\sin\lambda\right] \\ \tilde{a}_{i3} = e_{i1}\cos L\cos\lambda + e_{i2}\cos L\sin\lambda + e_{i3}\sin L \end{cases} \tag{16}$$

D. The pseudo-range rate measurement equation

$$\tilde{Z}_{\rho}=\tilde{H}_{\dot{\rho}}\tilde{X}+\tilde{V}_{\dot{\rho}}=\begin{bmatrix}0_{n\times3} & \tilde{H}_{\dot{\rho}n1} & 0_{n\times9} & \tilde{H}_{\dot{\rho}n2}\end{bmatrix}\tilde{X}+\tilde{V}_{\dot{\rho}} \quad (17)$$

In (17),

$$\tilde{Z}_{\dot{\rho}}=\begin{bmatrix}\delta\dot{\rho}^{1}\dots & \delta\dot{\rho}^{n}\end{bmatrix}^{T}_{1\times n},\tilde{V}_{\dot{\rho}}=\begin{bmatrix}v^{1}_{\dot{\rho}}\dots & v^{n}_{\dot{\rho}}\end{bmatrix}^{T}_{1\times n} \quad (18)$$

$$\delta\dot{\rho}_{j}=\dot{\rho}_{Ij}-\dot{\rho}_{Gj}=e_{j1}\delta\dot{x}+e_{j2}\delta\dot{y}+e_{j3}\delta\dot{z}+\delta t_{ru}+v_{\dot{\rho}j} \quad (19)$$

$$\tilde{H}_{\dot{\rho}n1}=\begin{bmatrix}\tilde{b}_{21} & \tilde{b}_{22} & \tilde{b}_{23}\\ \vdots & \vdots & \vdots\\ \tilde{b}_{n1} & \tilde{b}_{n2} & \tilde{b}_{n3}\end{bmatrix}_{n\times3},\tilde{H}_{\dot{\rho}n1}=\begin{bmatrix}0 & 1\\ \vdots & \vdots\\ 0 & 1\end{bmatrix}_{n\times2} \quad (20)$$

Where $v^{1}_{\dot{\rho}}\dots\ v^{n}_{\dot{\rho}}$ is the pseudo-range rate measurement noise of each channel, $\tilde{b}_{ij}(i=1\cdots n, j=1,2,3)$ can be expanded into the following form:

$$\begin{cases}\tilde{b}_{i1}=-e_{i1}\sin\lambda+e_{i2}\cos\lambda\\ \tilde{b}_{i2}=-e_{i1}\sin L\cos\lambda-e_{i2}\sin L\sin\lambda+e_{i3}\cos L\\ \tilde{b}_{i3}=e_{i1}\cos L\cos\lambda+e_{i2}\cos L\sin\lambda+e_{i3}\sin L\end{cases} \quad (21)$$

From the above pseudo-range, pseudo-range rate measurement equation, the measurement equation of the ultra-tightly coupled integrated navigation system can be obtained as follows:

$$\tilde{Z}=\begin{bmatrix}\tilde{Z}_{\rho}\\ \tilde{Z}_{\dot{\rho}}\end{bmatrix}=\begin{bmatrix}\tilde{H}_{\rho}\\ \tilde{H}_{\dot{\rho}}\end{bmatrix}\tilde{X}+\begin{bmatrix}\tilde{V}_{\rho}\\ \tilde{V}_{\dot{\rho}}\end{bmatrix}=\tilde{H}\tilde{X}+\tilde{V} \quad (22)$$

E. Adaptive Kalman filter

The state equation and measurement equation of the system are established, and the inertial information aided acquisition algorithm and tracking algorithm are designed. Then the state equation and the measurement equation of the system are discretized and finally filtered. The discretization equation of the system is:

$$\begin{aligned}X_{k}&=\Phi_{k,k-1}X_{k-1}+\Gamma_{k-1}W_{k-1}\\ Z_{k}&=H_{k}X_{k}+V_{k}\end{aligned} \quad (23)$$

In order to reduce the influence of process noise and measurement noise on the system and improve the adjustment ability of the system, this paper adopts innovation adaptive estimation technique [8]. The adaptive Kalman algorithm is as follows:

(1) Project the state ahead

$$\hat{X}_{k/k+1}=\Phi_{k,k-1}\hat{X}_{k-1} \quad (24)$$

(2) Project the error covariance ahead

$$P_{k/k-1}=\Phi_{k,k-1}P_{k-1}\Phi^{T}_{k,k-1}+Q_{k-1} \quad (25)$$

(3) Compute the Kalman gain

$$K_{k}=P_{k/k-1}H^{T}_{k}(H_{k}P_{k/k-1}H^{T}_{k}+R_{k})^{-1} \quad (26)$$

(4) Update estimate with measurement Z_{k}

$$\hat{X}_{k}=\hat{X}_{k/k+1}+K_{k}(Z_{k}-H_{k}\hat{X}_{k/k-1}) \quad (27)$$

(5) Update the error covariance

$$P_{k/k}=(I-K_{k}H_{k})P_{k/k-1} \quad (28)$$

Where $r_{k}=Z_{k}-H_{k}\hat{X}_{k,k\text{-}1}$ is called the measurement innovation, its covariance is $C_{rk}=H_{k}P_{k.k-1}H^{T}_{K}+R_{k}$, The optimal estimate of the sliding sample of length N of the innovation variance is $\hat{C}_{rk}=\frac{1}{N}\sum_{j=j_0}^{k}r_{j}r^{T}_{j}$ .Then getting the update equation of the process noise Q and measurement noise R .

$$\hat{R}_{k}=\hat{C}_{rk}-H_{k}P_{k,k-1}H^{T}_{k} \quad (29)$$

$$\hat{Q}_{k}=\frac{1}{N}\sum_{j=j_0}^{k}\Delta x_{j}\Delta x^{T}_{j}+P_{k}+\Phi_{k,k-1}P_{k-1}\Phi^{T}_{k,k\text{-}1} \quad (30)$$

Where $\Delta x_{k}=K_{k}r_{k}$, Combining (26) and $\hat{C}_{rk}$, the adaptive Kalman filter gain can be calculated as :

$$K^{*}_{k}=P_{k,k-1}H^{T}_{k}\left(\frac{1}{N}\sum_{j=j_0}^{k}r_{j}r^{T}_{j}\right) \quad (31)$$

After the establishment of the above system model, we have completed the design of the entire ultra-tightly coupled integrated navigation algorithm. The adaptive Kalman filter continuously adjusts Q and R to obtain different Kalman gains K to improve the filter design and reduce the actual error. The system error is optimally estimated by Adaptive Kalman filter, and then fed back to the SINS system and the GNSS receiver system for compensation.

VI. EXPERIMENTS AND RESULTS

In order to verify the performance of the ultra-tightly coupled integrated system based on Zynq-7020 platform in this paper, high dynamic simulator experiment and vehicle experiments were carried out.

We use satellite signal simulator to simulate the high-speed flight path of the carrier for high dynamic performance testing. The experimental conditions are set as follows: The flight path is set to a large circle .The orbital flight altitude is 400 km, the flight speed is about 6km/s, and the flight acceleration is about $60g/s^{2}$.

The flight trajectory is shown in Figure 5. The experimental result error is compared with the original trajectory parameters. The position error and velocity error are shown in Figure 6 and Figure 7. After calculating the root mean square error of position and velocity, we can get the position error within 5.88m(RMS) and the speed error within 0.26m/s(RMS). The experimental results show that the system designed in this paper can achieve good performance under high dynamic environment.

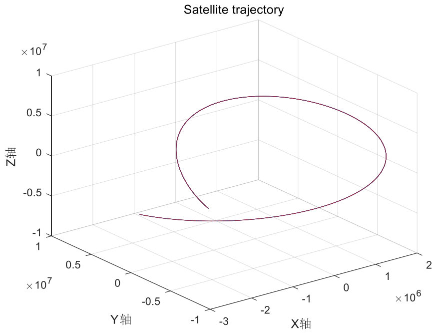

Figure 5. the flight trajectory of Carrier

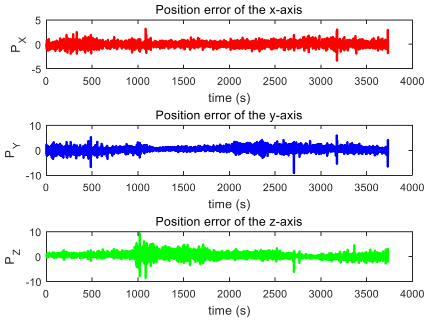

Figure 6. the position error

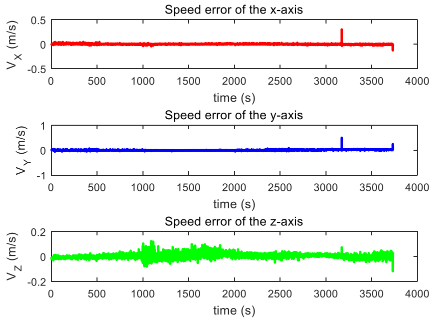

Figure 7. the speed error

The vehicle experiments were conducted in the suburbs of Nanjing. The longitude of the starting point of the vehicle experiment is 118.88692617°, the latitude is 32.01871923 °, and the height is 12.69726563m. High-precision integrated navigation system was used as a benchmark in the experiment.

Figure 8 is the vehicle experimental route. The position error and velocity error are shown in Figure 9 and Figure 10. We also calculate the root mean square error of position and velocity, we can get the position error within 6.32m(RMS) and the speed error within 0.41m/s(RMS).

Figure 8. the vehicle experimental route

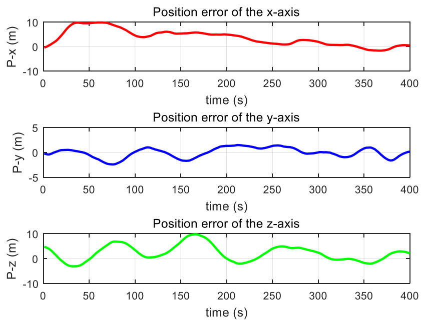

Figure 9.the position error

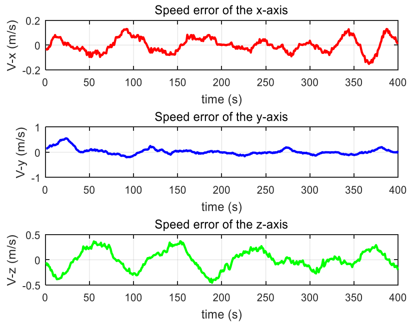

Figure 10. the speed error

VII. CONCLUSION

This paper designs an ultra-tightly coupled integrated navigation method based on Zynq-7020. The overall scheme, hardware scheme and software algorithm of the ultra-tightly coupled integrated system are introduced in detail. Besides, the system performance is verified by high dynamic simulator test and vehicle experiment. The experimental results show that the ultra-tightly coupled integrated scheme based on Zynq-7020 can meet the positioning requirements, and can provide reliable navigation services for automobiles, drones, aircrafts, etc., and has good market application value.

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