Carrier-phase Differential GPS/INS Integrated Navigation System

Lu Zhang, Gongliu Yang
School of Instrumentation Science and Opto-electronics Engineering
Beihang University
Beijing, China
e-mail: lu_leehom@163.com, bhu17-yang@139.com

***Abstract*—According to high accuracy demand in the measurement field, this paper designs a high precision inertial measurement system by using DSP and ARM processor to realize carrier-phase differential GPS/INS integrated navigation. This paper chooses Kalman filter to estimate the systematic error, uses closed loop method to correct, and carries out carrier-phase differential GPS/INS data fusion. Through manipulating actual measurement data, the integrated navigation results indicate that position accuracy reaches cm level; velocity accuracy reaches cm/s level and attitude achieves high precision. The experiment proves the feasibility and effectiveness of carrier-phase differential GPS/INS integrated navigation system.**

Keywords-Kalman filter, carrier-phase differential GPS, GPS/INS integrated navigation, high precision

I. INTRODUCTION

Carrier-phase differential GPS is a precise positioning system which is commonly used in geodetic engineering [1]. However, there are some shortcomings: data frequency is lower; the reliable baseline range is limited; signal will be jammed and bring the cycle slip. INS (Inertial Navigation System) has strong autonomy and can provide overall parameters, but its error will accumulate over time [3].

Consequently, this paper designs a high precision inertial measurement system by using ARM and DSP to realize carrier-phase differential GPS/INS integrated navigation. This system is able to fulfill the advantages of carrier-phase differential GPS and INS, overcome their disadvantages, improve the accuracy and performance [5]. This paper discusses the systematic state model and observation model deeply, uses Kalman filter to estimate systematic error, chooses closed loop method to correct, and carries out carrier-phase differential GPS/INS data fusion. By manipulating actual measurement, integrated navigation result indicates that the position error is cm level; velocity error is cm/s level; and attitude achieves high precision, so it proves the feasibility and effectiveness of the system.

II. DESIGN OF CARRIER-PHASE DIFFERENTIAL GPS/INS INTEGRATED NAVIGATION SYSTEM HARDWARE

A. System Structure

The system structure is shown as “Fig.1”.The system consists of high-precision IMU (Inertial Measurement Unit) which include three-axis laser gyroscopes and three-axis accelerometers, navigation solver circuit board (board 1) and data acquisition storage circuit board (board 2). Board 2 has a Novatel L1/L2 GPS OEMV-1DF which is used as GPS User Station. When working with GPS Reference Station and transceiver, it can accomplish carrier-phase differential positioning.

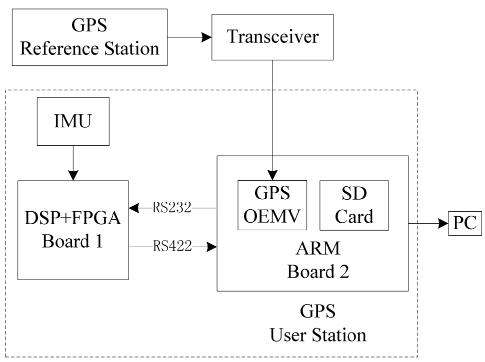

Figure 1. Integrate System Hardware Structure

B. System Workflow

The FPGA on board 1 acquires the signals of IMU’s three-axis laser gyroscopes and three-axis accelerometers signal. After A/D transforming it will get angular rates and accelerations. And then the DSP on board 1 use the angular rates data to calculate the attitude, and utilize the accelerations data to calculate velocity and position.

The board 2 acquired carrier-phase differential GPS position and velocity results and sends them through RS-232 with the 1PPS seconds pulse signal to board 1. Board 1 using the 1PPS solve the problem of clock synchronization and then sends the IMU original data, INS calculation result and integrated navigation result to Board 2 through RS-422, at last save to SD card. Through the USB or LAN port on board 2, user can read the data saved on SD card to PC.

III. DESIGN OF CARRIER-PHASE DIFFERENTIAL GPS/INS INTEGRATED NAVIGATION SYSTEM ALGORITHM

This paper selects Kalman filter to do the carrier-phase differential GPS/INS integrated navigation data fusion, the specific implementation process as follows. Firstly, determine the system state equation, observation equation and the noise variance matrices. Secondly, discretize the state and observation model, and then determine the filtering method. Thirdly, program Kalman filter, and calculate the results.

A. System State Equation

The system state equation of carrier-phase differential GPS/INS integrated navigation is:

$$\dot{X}(t) = F(t)X(t) + G(t)W(t). \qquad (1)$$

Where: $X(t) \in R^{17}$ is 17 dimensions error state vector, $F(t) \in R^{17\times17}$ is system error matrix, $W(t) \in R^{7}$ is the system noise vector, and $G(t) \in R^{17\times7}$ is system noise matrix.

$$X(t) = [\phi_E, \phi_N, \phi_U, \delta V_E, \delta V_E, \delta V_U, \delta L, \delta\lambda, \delta h, \varepsilon_x, \varepsilon_y, \varepsilon_z, \nabla_x, \nabla_y, \nabla_z, \delta_t, \delta_f]^T \qquad (2)$$

Where: E, N stand for east axis, north axis, and U is vertical axis that is perpendicular with E, N ; ϕ_E, ϕ_N, ϕ_U are attitude errors; $\delta V_E, \delta V_N, \delta V_U$ are velocity errors; $\delta L, \delta\lambda, \delta h$ are position errors; $\varepsilon_x, \varepsilon_y, \varepsilon_z$ are gyroscope random drifts; $\nabla_x, \nabla_y, \nabla_z$ are accelerometer biases; δ_t is GPS equivalent distance error caused by clock error; and δ_f is GPS equivalent distance error caused by clock frequency error.

$F(t)$ can be determined by the INS error models [2] and GPS error models.

$$W(t) = \left[\omega_{\varepsilon x}, \omega_{\varepsilon y}, \omega_{\varepsilon z}, \omega_{\nabla x}, \omega_{\nabla y}, \omega_{\nabla z}, \omega_f\right]^T \qquad (3)$$

Where: $\omega_{\varepsilon x}, \omega_{\varepsilon y}, \omega_{\varepsilon z}$ are gyroscope white noises; $\omega_{\nabla x}, \omega_{\nabla y}, \omega_{\nabla z}$ are accelerometer white noises; ω_f is equivalent clock frequency error white noise [6].

$$G(t) = \begin{pmatrix} C_b^n & 0_{3\times3} & 0_{3\times1} \\ 0_{3\times3} & C_b^n & 0_{3\times1} \\ 0_{3\times3} & 0_{3\times3} & 0_{3\times1} \\ 0_{3\times3} & 0_{3\times3} & 0_{3\times1} \\ 0_{3\times3} & I_{3\times3} & 0_{3\times1} \\ 0_{1\times3} & 0_{1\times3} & 1 \end{pmatrix} \qquad (4)$$

Where: C_b^n is attitude transfer matrix.

B. System Observation Equation

The system observation equation of carrier-phase differential GPS/INS integrated navigation is:

$$Z(t) = H(t)X(t) + \upsilon(t). \qquad (5)$$

Where: $Z(t) \in R^6$ is 6 dimensions system observation vector, $H(t) \in R^{6\times17}$ is the observation matrix, and $\upsilon(t) \in R^6$ is the observation noise vector.

$$Z(t) = \left[\delta V_E, \delta V_U, \delta L, \delta\lambda, \delta h\right]^T \qquad (6)$$

Where: $\delta V_E, \delta V_U, \delta L, \delta\lambda, \delta h$ are the residual errors of INS and carrier-phase differential GPS, $\delta V_E = V_{EINS} - V_{EGPS}$, $\delta V_N = V_{NINS} - V_{NGPS}$, $\delta V_U = V_{UINS} - V_{UGPS}$, $\delta L = L_{INS} - L_{GPS}$, $\delta\lambda = \lambda_{INS} - \lambda_{GPS}$, and $\delta h = h_{INS} - h_{GPS}$.

$$H(t) = [0_{6\times3} \quad I_{6\times6} \quad 0_{6\times8}] \qquad (7)$$

$$\upsilon(t) = [\upsilon_{\delta VE}, \upsilon_{\delta VN}, \upsilon_{\delta VU}, \upsilon_{\delta L}, \upsilon_{\delta\lambda}, \upsilon_{\delta h}]^T \qquad (8)$$

Where: $\upsilon_{\delta VE}, \upsilon_{\delta VN}, \upsilon_{\delta VU}$ are velocity observation noises, and $\upsilon_{\delta L}, \upsilon_{\delta\lambda}, \upsilon_{\delta h}$ are position observation noises.

C. Kalman filter equation

Discretize system state equation (1) and observation equation (5), we can get discretized system equation:

$$X_k = \Phi_{k,k-1}X_{k-1} + \Gamma_{k-1}W_{k-1} \qquad (9)$$

$$Z_k = H_k X_k + V_k \qquad (10)$$

The discretized Kalman filter equations are:

$$\hat{X}_{k/k-1} = \Phi_{k,k-1}\hat{X}_{k-1} \qquad (11)$$

$$P_{k/k-1} = \Phi_{k,k-1}P_{k-1}\Phi_{k,k-1}^T + \Gamma_{k-1}Q_{k-1}\Gamma_{k-1}^T \qquad (12)$$

$$\hat{X}_k = \hat{X}_{k/k-1} + K_k(Z_k - H_k\hat{X}_{k/k-1}) \qquad (13)$$

$$P_k = P_{k/k-1} - P_{k/k-1}H_k^T(H_kP_{k/k-1}H_k^T + R_k)^{-1}H_kP_{k/k-1} = (I - K_kH_k)P_{k/k-1} \qquad (14)$$

$$K_k = P_{k/k-1}H_k^T(H_kP_{k/k-1}H_k^T + R_k)^{-1} \qquad (15)$$

The one step transition matrix of system state and the system noise matrix can be gotten form the equations as follows:

$$\Phi_{k,k-1} = \sum_{n=0}^{\infty}\left[\boldsymbol{F}(t_h)T\right]^n / n! \qquad (16)$$

$$\Gamma_{k-1} = \left\{\sum_{n=1}^{\infty}\frac{1}{n!}\left[\boldsymbol{F}(t_k)T\right]^{n-1}\right\}\boldsymbol{G}(t_k)T \qquad (17)$$

T is the iteration cycle. In actual calculation, according to the required accuracy the equation (16) and (17) are limited.

IV. EXPRIMENT RESULTS AND ANALYSIS

In order to verify the availability of the algorithm in this paper, static experiment has been done. The experimental data come from the carrier-phase differential GPS/INS integrated navigation system which is mentioned in part II. The GPS and INS technical indexes are: carrier-phase differential GPS position accuracy is 1cm (RMS), velocity accuracy is 0.03m/s (RMS) and sampling frequency is 20Hz. Gyroscopes accuracy is $0.008°/h$, accelerometers accuracy is 10 μg, and sampling frequency is 200Hz [4].The experiment acquires data for 30 minutes. During the experiment, GPS tracks satellites in a good condition.

The velocity errors, position errors and attitude errors calculated by INS are shown on the left side of Fig.2, Fig.3, and Fig.4. While the velocity errors, position errors and attitude errors calculated by carrier-phase differential GPS/INS integrated navigation system are shown on the right side of Fig.2, Fig.3, and Fig.4.

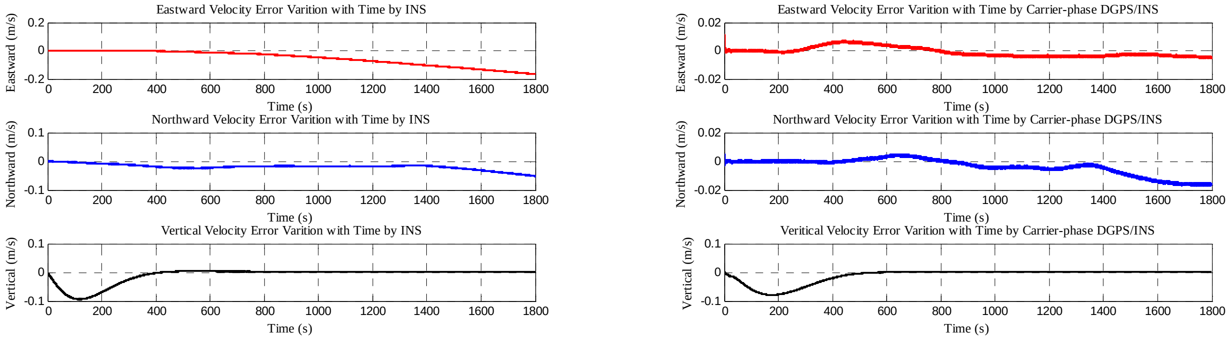

Figure 2. Velocity errors by INS and by carrier-phase differential GPS/INS

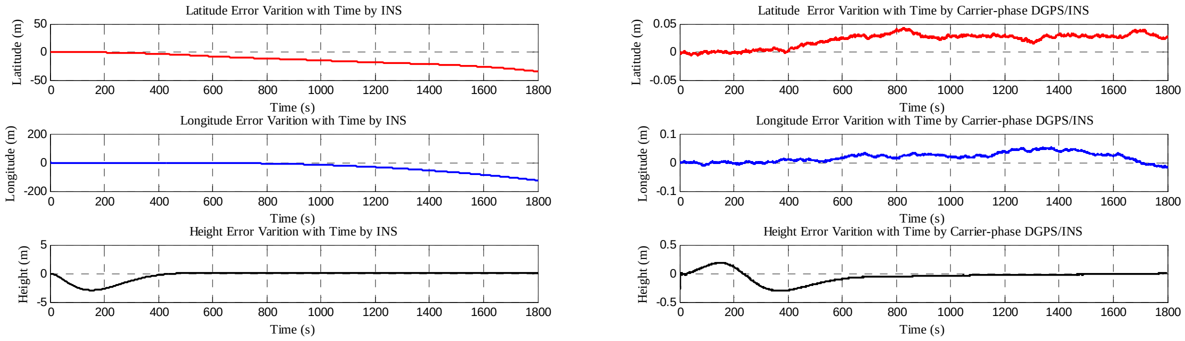

Figure 3. Position errors by INS and by carrier-phase differential GPS/INS

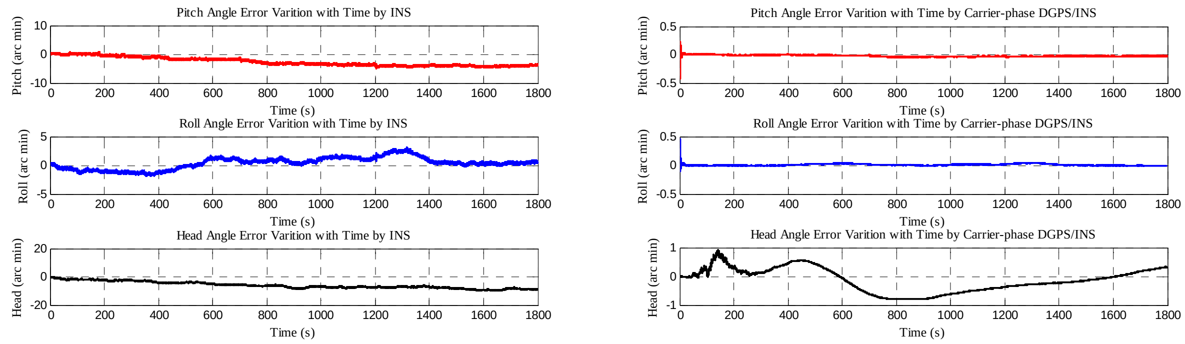

Figure 4. Position errors by INS and by carrier-phase differential GPS/INS

The left figures in Fig.2, Fig.3, and Fig.4 bring out the velocity, position, attitude errors which are calculated by INS accumulate over time. The reason why the vertical velocity error and height error are not divergence is that the system adopts the three-step damp method. Although the gyroscopes and accelerometers are high precision, they can't ensure accuracy in long endurance. However, the right figures in Fig.2, Fig.3, and Fig.4 show that the carrier-phase differential GPS/INS integrated navigation system restrains the errors divergence and gets a high precision result by using Kalman filter to estimate systematic error, closed loop method to correct. From Fig.2, we can know by using carrier-phase differential GPS/INS data fusion the velocity errors reduce one order of magnitude and reach cm/s level. From Fig.3, we can find out position accuracy reach cm level after integrated navigation. From Fig.4, we can be aware of attitude errors also decrease one or two orders of magnitude.

In order to contrast more visually, the errors statistics results including the expectation and variance of velocity, position and attitude are listed in Table I.

TABLE I. THE ERRORS STATISTICS RESULTS

	INS		Carrier-phase DGPS/INS	
	Expectation	***Variance***	***Expectation***	***Variance***
Eastward Velocity	-0.05303	0.05172	-0.0008657	0.003262
Northward Velocity	-0.01907	0.009895	-0.003467	0.005626
Vertical Velocity	-0.009489	0.02626	-0.01117	0.02366
Latitude	-13.36	9.584	0.02103	0.01243
Longitude	-28.67	35.23	0.01829	0.01645
Height	-0.317	0.8379	-0.04865	0.09925
Pitch Angle	-2.63	1.478	-0.02166	0.01515
Roll Angle	0.3827	1.014	0.009042	0.01513
Head Angle	-5.926	2.395	-0.1318	0.01513

Table I shows 9 items errors statistic results of Carrier-phase Differential GPS/INS integrated navigation system are better than INS, and the expectations show that the integrated navigation system accuracy is far higher than the INS. This experiment indicates the feasibility and effectiveness of the system.

V. CONCLUSION

This paper designs a high precision inertial measurement system to realize carrier-phase differential GPS/INS integrated navigation which can fulfill the high precision demand in the measurement field. The carrier-phase differential GPS eliminates the most common error through differential treatment can output higher precision velocity and position information. Fully utilizing the high precision velocity and position observation of carrier-phase differential GPS can significantly improve the positioning accuracy of the integrated navigation system. This paper discusses the Kalman filter arithmetic deeply which is used to carrier-phase differential GPS/INS data fusion. The static experiment shows the integrated navigation arithmetic restrains the errors divergence of INS and gets high precision results that are velocity accuracy reach cm/s level, position accuracy reach cm level and attitude accuracy is also a high level. As a result, the carrier-phase differential GPS/INS integrated navigation system has a very good application prospect in high precision navigation and measurement field.

ACKNOWLEDGMENT

It is a project supported by Science and Technology on Inertial State Key Laboratory and Fundamental Science on Novel Inertial Instrument & Navigation System Technology Laboratory. The authors wish to thank their funding and support for us, without which the work would not have been possible.

REFERENCES

[1] G. Xie, "Principles of GPS and receive design," Beijing: Publishing House of Electronic Industry, 2011, pp. 156-165 and pp.192-207.

[2] Y.Y. Qin, "Inertial navigation," Beijing: Science Press, 2006, pp. 287-360.

[3] J.J. Luo, W.H. Ma, J.P. Yuan, "Integrated navigation principle and application," Xian: Northwestern Polytechnical University Press, 2012, pp.146-190.

[4] NovAtel inc.,"OEMV Family Installation and Operation User Manual," Revision 7, Canada Cagarly: NovAtel inc., 2007.

[5] Y.Z. Wen, J. Wu, "Carrier phase GPS/SINS integrated navigation for spacecraft on high earth orbit," Journal of Beijing University of Aeronautics and Astronautics, vol. 38, Jun. 2012, pp.726-730.

[6] B.J. Yue, Y.Q. Tang, Y.J. Zhang, "Application of integrated navigation technology in inertial pipeline surveying system," Journal of Chinese Inertial Technology, vol. 16, Dec. 2008, pp.712-716.