A Study on High Precision MEMS-IMU/GPS/Magnetometer/Barometer Integrated Navigation System

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Abstract. Considering the urgent need of low cost, high performance and high precision navigation system, a MEMS-IMU / GPS / magnetometer / barometer integrated navigation system based on DSP is designed. Using the output of MEMS-IMU, we can obtain the carrier's attitude, velocity and position with SINS algorithm. We use a barometer to dampen the inertial altitude path. Then combined with the information of GPS and magnetometer, an integrated navigation algorithm based on Kalman filter is designed, We conduct static and dynamic experiments on the integrated navigation system and the results show that the system can achieve high navigation accuracy.

1. INTRODUCTION

With the rapid development of micro-electric-mechanical systems technology, the accuracy of inertial sensors based on MEMS technology continues to increase. There are many outstanding advantages in MEMS inertial sensors, such as small size, low cost, low power consumption and high reliability. So they has been widely used in the field of navigation [1]. When using the MEMS-IMU alone for navigation, the navigation errors will build up over time. At the same time, the errors of GPS system does not accumulate over time. References [2-6] have studied MEMS-IMU and low-cost GPS integrated navigation system. In [7-8], researchers use a barometric altimeter to assist the calculation of the inertial altitude path. In [9], researchers design a small-scale UAV integrated navigation system, which consists of a tri-axis gyroscope, a tri-axis accelerometer, a tri-axis magnetometer, a GPS receiver and a differential pressure transducer. In order to improve the accuracy of the navigation system, we use Kalman filter to combine the output of MEMS-IMU with the information of GPS, and introduce a magnetometer to enhance the observability of the heading angle. To get a better height we apply a barometer to dampen the inertial altitude path. In this paper, we will introduce the hardware of the integrated navigation system, integrated navigation algorithm and experiment results.

2. INTEGRATED NAVIGATION SYSTEM DESIGN

The hardware structure of the integrated navigation system is shown in Fig. 1. It consists of a secondary power module, an ADIS16488 inertial sensor, a GPS receiver, a navigation computer and a data transmission module. The secondary power module supplies power to all devices in the system. The ADIS16488 includes a tri-axis gyroscope, a tri-axis accelerometer, a tri-axis magnetometer, and a pressure sensor. It communicates with the navigation computer via the SPI interface. Its operating voltage is 3.3 volts and maximum working current is 254 milliampere. And its size is 47*44*14(mm) and weight is only 58 grams. We choose the OEM628 GPS receiver developed by Novatel. The receiver has small size, low power consumption and high precision. It can output data stream of GPGGA and GPRMC format. And its size is 60*100*9(mm) and weight is only 37 grams. The maximum power of the receiver is 13 watts. Its horizontal positioning accuracy is 1.2m (rms) and velocity accuracy is 0.03m/s. We select TMS320C6747 digital signal processing

produced by TI company as the navigation computer, which collects the data of ADIS16488 via SPI interface, and gathers GPS data via UART interface. Using the data to carry on the integrated navigation algorithm, we can get the carrier's attitude, velocity and position. At last we send all the results to the laptop to display and store via the data transmission module.
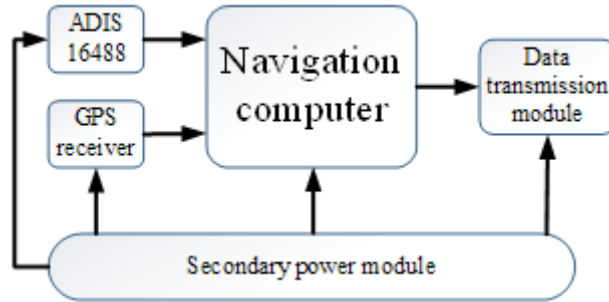

Figure 1.   The hardware structure of the Integrated navigation system

3. INTEGRATED NAVIGATION ALGORITHM

In this system, the navigation coordinate is the "east-north-up" geographic coordinate, and the carrier coordinate is "right-front-up". Firstly, the output of the MEMS-IMU is used to calculate the attitude, velocity and position of the carrier by the SINS algorithm. After that we use the navigation parameters to integrate with the velocity and position provided by GPS, and the heading angle provided by the magnetometer. We adopt Kalman filter to design the integrated navigation algorithm. Next we will introduce the system state equation describing the dynamic characteristics of the integrated navigation system and the measurement equation reflecting the relationship between the measured states and the states [11].

A. System state equation

The navigation system we design adopts a 13-dimensional Kalman filter, whose system state variables can be written as:

$$X = \begin{bmatrix} \varphi_E & \varphi_N & \varphi_U & \delta V_E & \delta V_N & \delta L & \delta \lambda \\ \varepsilon_x & \varepsilon_y & \varepsilon_z & \nabla_x & \nabla_y & \delta \psi_{mg} \end{bmatrix}^T_{13\times1} \quad (1)$$

Where φ_E, φ_N and φ_U are the error angles of the platform; δV_E and δV_N are velocity errors; δL and $\delta \lambda$ are position errors; ε_x, ε_y and ε_z are the gyro drifts; ∇_x and ∇_y are accelerometer zero bias; $\delta \psi_{mg}$ is the magnetic heading angle error.

The state equation of the integrated navigation system can be described as:

$$\dot{X}(t) = F(t) \cdot X(t) + G(t) \cdot W(t) \quad (2)$$

Where F is system state transition matrix; W is system noise matrix. The specific expression of F is as follows:

$$F = \begin{bmatrix} F_{N(7\times7)} & F_{S(7\times5)} & 0_{7\times1} \\ 0_{6\times7} & 0_{6\times5} & F_{M(6\times1)} \end{bmatrix} \quad (3)$$

Where F_N is a system dynamic matrix about 7 errors (east / north / up platform deflection angle; east / north speed error; longitude / latitude error) of the inertial navigation system. The non-zero items of F_N are defined as follows:

$$F_N(1,2) = \omega_{ie} \sin L + V_E \tan L/R_{xt}$$
$$F_N(1,3) = -\omega_{ie} \cos L - V_E/R_{xt}, F_N(1,5) = -1/R_{yt} \ F_N(2,1) = -\omega_{ie} \sin L - V_E \tan L/R_{xt}$$
$$F_N(2,3) = -V_N/R_{yt}, F_N(2,4) = 1/R_{xt}$$
$$F_N(2,6) = -\omega_{ie} \sin L, F_N(3,1) = \omega_{ie} \cos L + V_E/R_{xt} \ F_N(3,2) = V_N/R_{yt}, \ F_N(3,4) = \tan L/R_{xt}$$

$$F_N(3,6) = \omega_{ie} \cos L + V_E \sec^2 L/R_{xt}, \ F_N(4,2) = -f_U$$

$$F_N(4,3) = f_N, \quad F_N(4,4) = V_N \tan L/R_{yt}$$

$$F_N(4,5) = 2\omega_{ie} \sin L + V_E \tan L/R_{xt}$$

$$F_N(4,6) = (2\omega_{ie} \cos L + V_E \sec^2 L/R_{xt})V_N$$

$$F_N(5,1) = f_U, F_N(5,3) = -f_E$$

$$F_N(5,4) = -2(\omega_{ie} \sin L + V_E \tan L/R_{xt})$$

$$F_N(5,6) = -2(\omega_{ie} \cos L + V_E \sec^2 L/R_{xt})V_E$$

$$F_N(6,5) = 1/R_{yt}, \quad F_N(7,4) = \sec L/R_{xt}$$

$$F_N(7,6) = V_E \sec L \tan L/R_{xt}$$

The F_S and F_M in (3) can be written as follows:

$$F_S = \begin{bmatrix} C_b^n & 0_{3\times2} \\ 0_{2\times3} & C_{b(2\times2)}^n \\ 0_{2\times3} & 0_{2\times2} \end{bmatrix}_{7\times5}, F_M = \begin{bmatrix} 0_{5\times1} \\ -1/\tau_{MG} \end{bmatrix}_{6\times1} \quad (4)$$

B. Measurement equation

The measurements of the navigation system are 5 dimensions, including the east / north speed error, the east / north position error and the heading error. The calculation of the measurement vector is expressed as:

$$Z_k = \begin{bmatrix} V_{E\_INS} - V_{E\_GPS} \\ V_{N\_INS} - V_{N\_GPS} \\ L_{INS} - L_{GPS} \\ \lambda_{INS} - \lambda_{GPS} \\ \psi_{INS} - \psi_{GPS} \end{bmatrix} \quad (5)$$

The measurement equation can be described as:

$$Z_k = H_k \cdot X + V \quad (6)$$

The non-zero items of H_k are defined as follows:

$$H_k(1,4) = 1, H_k(2,5) = 1$$

$$H_k(3,6) = 1, H_k(4,7) = 1$$

$$H_k(5,3) = 1, H_k(5,13) = -1$$

After estimating the system state with Kalman filter, we carry on the closed-loop correction. Then the filter is reset accordingly. The correction method is that we use the position and velocity of inertial navigation to subtract the errors estimated directly. And the attitude matrix is corrected by the skew symmetry matrix and then the quaternion of attitude will be updated.

4. NAVIGATION EXPERIMENTS AND ANALYSIS

C. Static navigation experiment

Static experiment can reflect the most basic performance of a navigation system and must be conducted before in-vehicle experiment. The system is left to rest. After initial alignment, we do a static navigation experiment for 1 hour. The test results of attitude, velocity and position are shown in the following figures.
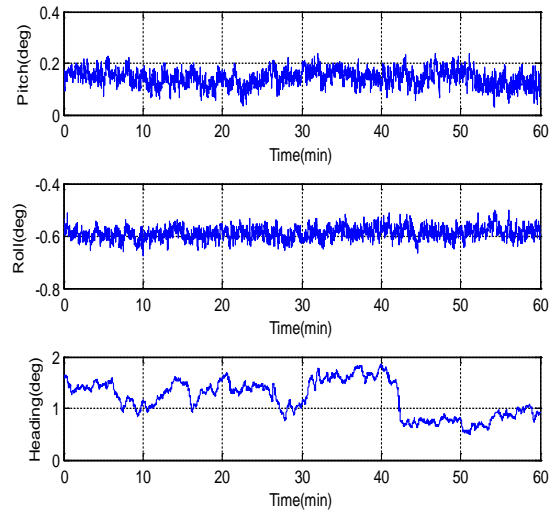
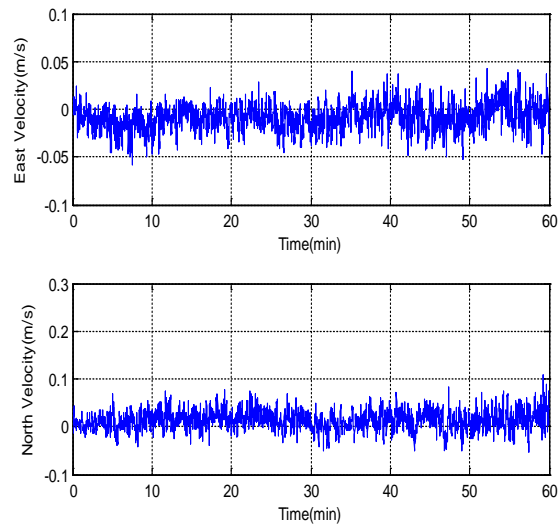Figure 2. The attitude curve

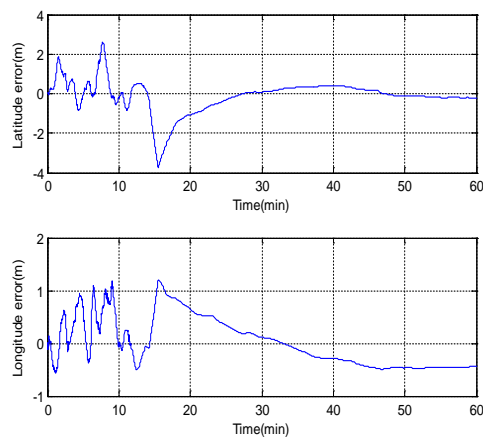Figure 3. The velocity curve
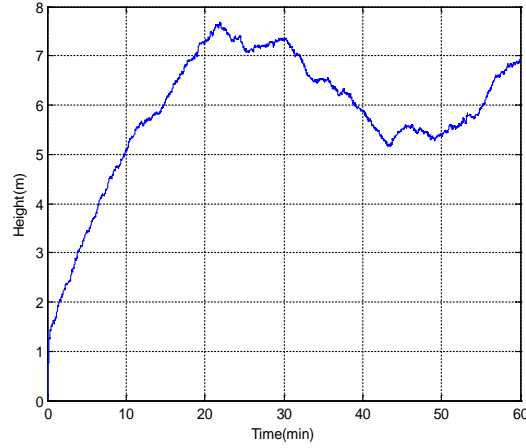

Figure 4. The position error curve

Figure 5.   The height curve

The figures above illustrate that all the outputs of the system converge and the system meets the need of long-time navigation.

After calculation, the standard deviations of the pitch angle, roll angle and heading angle error are respectively 0.0301°, 0.0225°, 0.3423°; The standard deviations of the east and north velocity are 0.0124m/s and 0.0184m/s respectively; The standard deviations of latitude and longitude error are respectively 0.4707m and 0.8529m; The standard deviation of height error is 1.4063m.

D. In-vehicle experiment

In-vehicle navigation experiment can fully test the impact of various error factors on the navigation accuracy. The experiment car carried the system and proceeded from Jimen Bridge to Yansha Bridge on the third ring road in Beijing. The test time is about 1300 seconds. First we average the output of the system by one second, and then use the new data to minus the output of GPS respectively as the error of the system. The test results are as follows:
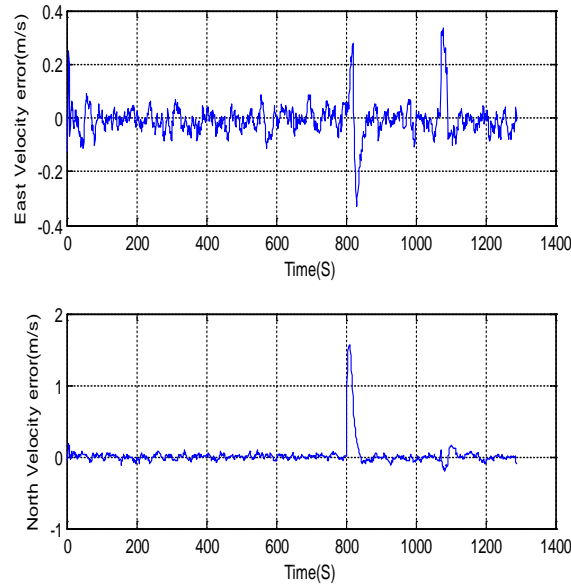

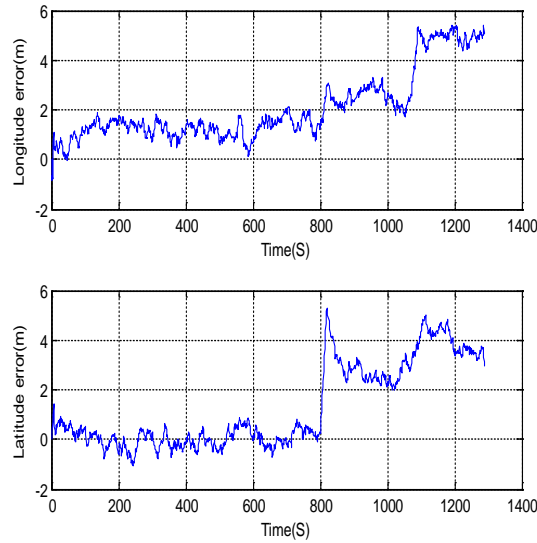Figure 6.   The velocity error curve

Figure 7.   The positon error curve

   As can be seen from the figures above, the velocity and position of the navigation system can maintain good convergence.

   After calculation, the standard deviations of the east and northward velocity errors are 0.156m/s and 0.167m/s respectively, and the standard deviations of longitude and latitude errors are 1.4148m and 1.7054m respectively.

5. CONCLUSION

   In this paper, we propose a MEMS-IMU/GPS/ magnetometer/barometer integrated navigation system based on DSP, and design an integrated navigation algorithm based on Kalman filter. Finally we complete some experiments with the system we design. The results show that the system is of high precision. The integrated navigation system has certain practical value with the advantages of small size, low power consumption and high precision, which can be applied to UAVs, airships and so on.

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