Research on Foot-Mounted Personal Navigation Algorithm based on MEMS Inertial Sensors

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Abstract

The navigation correction algorithm of low precision shoe personal inertial navigation system was studied. The system consists of low-precision MEMS inertial IMU unit, fixed on the shoes of the Pacers. Based on the traditional strap-down inertial navigation algorithm, a zero velocity update technique (ZUPT) is introduced. Based on the acceleration statistics of foot movement, a similarity modulus + sliding variance detection algorithm is designed to detect the walking process in the stance phase. And then through the design of improved External Kalman filter (EKF) in the quiescent period of time to filter the estimated navigation attitude, speed and location calculation error, through the feedback correction can improve the original system navigation accuracy. Finally, the validity and feasibility of the navigation correction algorithm are verified by two kinds of MEMS physical experiments, and further research directions are pointed out

Keywords

Personal Inertial Navigation, External Kalman Filter, Zero Velocity Udate Technology.

1. Introduction

Personal navigation system (PNS), also known as the pedestrian navigation system, mainly used to track and locate the real-time location of pedestrians walking, and through the wireless communication to the monitoring unit, real-time monitoring staff position changes. The PNS is fixed on the footwear of the pedestrians and forms the "navigation shoes". The applicable crowd is mainly for the soldiers, the police and the security personnel engaged in high-risk work such as fire fighting and rescue to provide a higher level of safety and security. In addition, in the underground survey, jungle adventure GPS signal is weak or missing environment, PNS can also play its own autonomous navigation function. In a variety of navigation and positioning equipment, MEMS inertial equipment with its low cost, small size, strong autonomy and good environmental adaptability to become the ideal equipment for PNS, MEMS inertial technology based on personal navigation system in foreign countries has become a major research hot. Based on this, this paper mainly studies the navigation algorithm of low precision MEMS inertial equipment for personal navigation, and verifies the validity of the algorithm.

2. PNS algorithm structure

There are two algorithms for PNS navigation based on MEMS inertial sensors: PDR (Pedestrian Dead Reckoning) algorithm and SINS algorithm. In this paper, the PDR algorithm decomposes the navigation into two parts: the azimuth calculation and the step size calculation. The two-dimensional navigation result in the horizontal plane is obtained by projecting the step size in the calculation orientation. Therefore, the algorithm can't provide the position change on the height. In contrast, SINS strap-down inertial navigation algorithm can provide complete navigation information through 6-DOF navigation solution. However, due to the low accuracy of MEMS devices, if the navigation can't be effectively corrected during the navigation, the position error will be diverged by the trend of time, loss the navigation finally. Therefore, the biggest difficulty in the SINS algorithm applied to the PNS is the design of effective correction algorithm. In this paper, SINS algorithm is used to fit the

PNS system on the shoe, and the zero update technology (ZUPT) is designed according to the movement characteristics of the foot when walking. The navigation precision is improved and the navigation precision is improved. The algorithm structure is shown in Fig.1

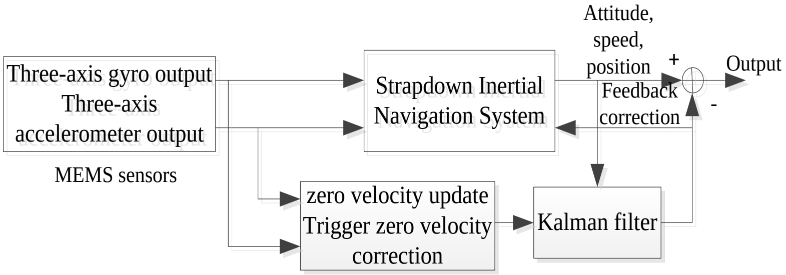

Fig.1 Navigation algorithm structure of PNS

3. MEMS inertial navigation algortihm and error analysis

The inertial solution algorithm of MEMS PNS adopts mature SINS algorithm, which consists of two parts: initial alignment and navigation solution.

The initial alignment provides initial gesture information for navigation. For MEMS inertial systems, due to the high accuracy of the gyroscope cannot be detected by the Earth's rotation angular velocity ω_{ie}, So the initial alignment cannot achieve the orientation of the alignment, it only be completed according to the output level alignment, as shown in equation (1)The estimated results $\hat{\theta}$ and $\hat{\gamma}$ of the pitch θ and the roll γ of the navigation shoe. The azimuth angle ψ needs to be given by external information, such as a magnetometer.

$$\begin{cases} f_x^b = -|g|\sin\gamma \\ f_y^b = |g|\cos\gamma\sin\theta \end{cases} \Rightarrow \begin{cases} \hat{\gamma} = \arcsin\left(-\bar{f}_x^b / |g|\right) \\ \hat{\theta} = \arcsin\left(\bar{f}_y^b / \left(|g|\cos\hat{\gamma}\right)\right) \end{cases} \quad (1)$$

Where, the superscript b represents the carrier coordinate system, x, y, z, respectively, denote the carrier of the right, front and last three directions. g represents the gravitational acceleration, f_x^b and f_y^b represent the sum output in the horizontal direction, and $\bar{f}_x^b$ and $\bar{f}_y^b$ represent the output mean over a period of time.

The above is only a coarse alignment algorithm, and the resulting $\hat{\theta}$ and $\hat{\gamma}$ also contain a large alignment error. In order to obtain more accurate alignment results, it is generally necessary to design a EKF for optimal filter estimation. As shown in Fig. 1, it can be seen that the improved EKF designed in the ZUPT algorithm also has the function of horizontally fine alignment, so that it can be achieved for a period of rest (a few seconds) as long as the above process ends Further accurate alignment of the horizontal angle.

MEMS inertial navigation using mature SINS algorithm, due to the process of walking foot angle of the larger maneuver and angular maneuvering and motor-driven coupling serious, so in order to improve the navigation accuracy, attitude update and Velocity update using two sub-sample algorithm. In addition, because the navigation range of personal navigation system is limited, the location should adopt the east-north-up navigation coordinate system (geographical coordinate system) n system, the update process as shown in equation (2), where E, N, U respectively Denote the displacement of the east, north and up directions, and the superscript T represents the transpose operation. In locations where the geographical coordinates of the navigation start position are well known, the location can also be easily converted to the traditional Earth coordinate system, expressed as longitude, latitude and altitude.

$$[E \quad N \quad U]_k^T = [E \quad N \quad U]_{k-1}^T + \left(v_{k-1}^n + v_k^n\right) \cdot T_s / 2 \quad (2)$$

The navigation error equation is the theoretical basis of the EKF model for the ZUPT algorithm. The following equation (3) gives the simplified error model of the SINS navigation algorithm.

$$\begin{cases} \dot{\varphi}^n = -\left(\left(\omega_{ie}^n + \omega_{en}^n\right)\times\right)\varphi^n - C_b^n\left(\varepsilon^b + w_g^b\right) \\ \delta\dot{v}^n = \left(\left(C_b^n f_{sf}^b \times\right)\right)\varphi - 2\left(\omega_{ie}^n + \omega_{en}^n\right)\times\delta v^n + C_b^n\left(\nabla^b + w_a^b\right) \\ \delta p\dot{o}s = \delta v^n \end{cases} \tag{3}$$

Where φ^n denotes the platform error angle, δv^n denotes the velocity error, δpos denotes the position error of the east, north and up directions; f_{sf}^b denotes the force vector, ε^b and ∇^b denotes the gyro and the additive random constant zero deviation, the derivative is 0, w_g^b and w_a^b denotes the gyro and adding the output noise, nbC denotes the gesture matrix of the strap-down inertial navigation; ω_{en}^n denotes the navigation system relative to the Earth's rotation angular velocity in the navigation system projection, because people walking speed is very low, so denotes is much smaller than ω_{ie}^n, it can be ignored in the calculation.

4. Stance phase detection algorithm

The determination of the stance phase detection is based on the measurement output from the inertial device, and the dotted line in Figure 2 shows the change in the modulus of the foot when the person is walking. It can be seen that the static modulus is stable in the vicinity of gravity, and the change of the modulus value is obvious and the change range is great. Therefore, we can see that the motion state can be detected by analyzing the modulus and variance of the ratio. The concrete method is to design a length of time window, with the time window to slide forward, the time window within the modulus and modulus variance as a static detection of the basis of judgment, referred to as the ratio of mold + Variance detection algorithm. The detection process is as follows:

①At each discrete moment of the MEMS inertia output $t_1, t_2, ..., t_N, t_{N+1}, ...$, calculate the magnitude of the magnitude of the output of the accelerometer at the current t_N .

$$|f_N| = \sqrt{f_x^2(t_N) + f_y^2(t_N) + f_z^2(t_N)} \tag{4}$$

②Calculate the two criteria: the deviation between the amplitude and the magnitude of the gravity acceleration $Bias_N$ and the sliding variance Var_N of the amplitude of the force. To avoid judging the delay, the variance Var_N is calculated as $(t_{N-M1},\quad t_{N-M2})$.

$$\begin{cases} Bias_N = \left\| f_N | - |g \right\| \\ Var_N = \text{variance}\left(|f_{N-M1}|, ..., |f_N|, ..., |f_{N+M2}|\right) \end{cases} \tag{5}$$

③According to the statistical characteristics of the accelerometer, the ratio of the threshold value $Gate_B$ and the variance judgment threshold $Gate_V$ are designed. The static detection method is: First, assume that the current t_N moment of motion state is static, that is, the default state; then compare to judge, if $Var_N \geq Gate_V$ or $Bias_N \geq Gate_B$, then determine the state of motion is motion, otherwise maintain the original hypothesis.

The choice of the judgment threshold is related to the variance characteristic of the output noise of the accelerometer, and it is necessary to analyze the added noise characteristic before the experiment. The selection of the interval length parameters $M1$ and $M2$ is mainly related to the output frequency of the IMU. The output frequency of the MEMS system used in the experiment is $200Hz$, and $M1 = M2 = 5$, $Gate_V = 0.06$ and $Gate_V = 0.06$.Figure 2, the dotted line data for static detection,

detection for the movement to determine the results set to 200, the detection is still when the judge is set to 0, the test results shown as solid line in Figure 2, It can be seen that the detection algorithm can effectively detect the quiescent time period, the algorithm is effective.

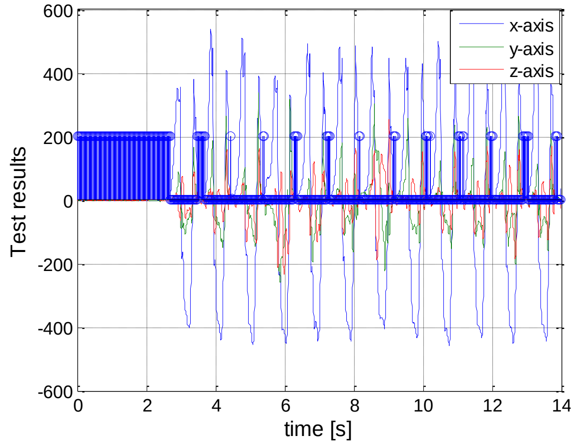

Fig.2 The result of stance phase detection

5. Zero-Velocity Update Technology

As can be seen from Fig. 1, the static detection triggers the ZUPT, and the velocity is set to zero in the time when the detection is at rest. In this paper, we use the static error to estimate more error parameters. According to the navigation error model of Eq. (3), a zero-velocity modified EKF is designed as $X=\left[\varphi^{nT} \quad \delta v^{nT} \quad \delta pos^{T} \quad \varepsilon^{bT} \quad \nabla^{bT}\right]^{T}$, The amount measurement is taken as the settlement speed error δv^{n} detected as the stationary time, that is $H_k=\left[0_{3\times3} \quad I_{3\times3} \quad 0_{3\times3} \quad 0_{3\times3} \quad 0_{3\times3}\right]$, The EJF can be expressed as:

$$\begin{cases} \dot{X}(t)=F(t)X(t)+W(t) \\ Z_k=H_kX_k \end{cases} \tag{6}$$

EKF not only to correct velocity, but also can estimate the horizontal attitude error angle to achieve horizontal attitude correction. In addition, by adding the position error δpos to the system state, it is possible to roughly estimate the accumulated position error during one-step motion based on the speed error： That is, by the ZUPT, one-step movement start time t_s speed error $\delta v^n(t_s)=0$, one-step movement end time t_e speed error for the solution of the current speed $\delta v^n(t_e)=v^n(t_e)$, The position error during motion can be approximately $\delta pos=v^n(t_e-t_s)/2$.

At this point, the design of the EKF mainly to achieve the following three functions: to correct the speed error, correct the level of attitude error, correct movement during the cumulative position error.

6. Implementation evaluation and analysis

The MEMS inertial unit used in this paper is the 3-axis inertial integrated component of the MPU6050 model developed by Analog Devices. It consists of a three-axis accelerometer and a three-axis gyroscope. Accelerometer and gyroscope of the nominal accuracy and measurement accuracy shown in Table 1, are zero partial stability as an evaluation index.

Tab.1 Sensor precision of MPU6050

Device accuracy	Stability of three - axis gyro（∘/h）	Stability of three - axis acc (mg)
Nominal accuracy	(16,16,16)	(0.70,0.70,0.70)
Accuracy of measurement	(22,20,26)	(0.62,0.57,0.67)

The validation experiment consists of two parts: a straight line walking experiment and a rectangular route walking experiment. Which direction is a straight line north, walking 32 steps, the distance is 19 m. The rectangle is a rectangle with a length of 17 m and a width of 17 m. The experimental results are shown in Fig. 3 and Fig. In order to compare the correction effect of the modified algorithm, Fig. 5 shows the un-illustrated pure inertial navigation results when the rectangular path travels.

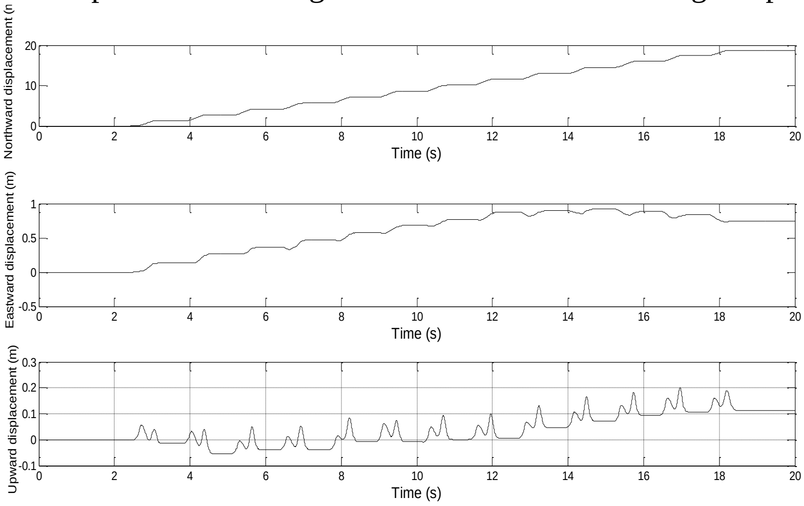

Figure.3 Navigation results of north-walking trajectory

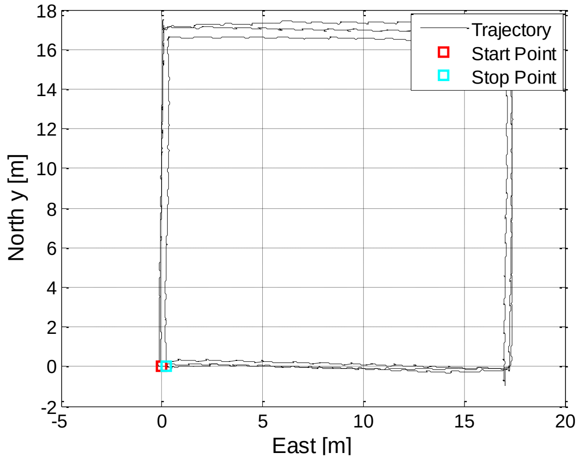

Figure.4 Navigation results of rectangle trajectory

It can be seen from Fig. 3 that the ZUPT algorithm can effectively suppress the divergence of the position error by decomposing the human motion into the superposition of the single step motion. In particular, the position of the pedestrian is no longer changed in the static time of the movement can be very clear to distinguish. As can be seen from Figure 3, the zero-speed correction algorithm by moving the human Decomposed into a single step of the movement of the superposition, can effectively inhibit the dispersion of the location error, especially in the rest time, the location of the pedestrian is basically no longer change, each step of the movement can be very clear to distinguish.

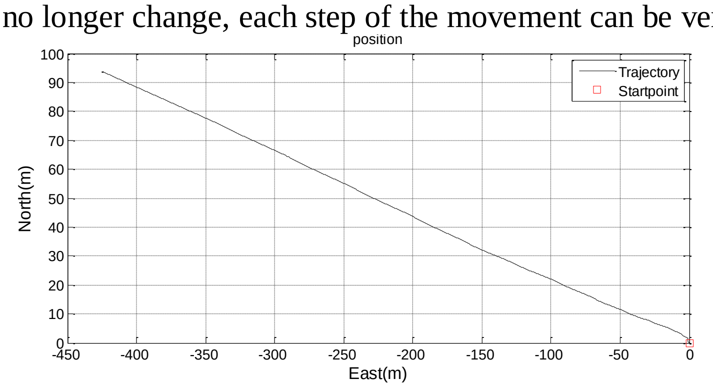

Figure.5 Navigation results of rectangle trajectory without ZUPT1

As can be seen from Fig. 5, the position error of the unrecognized inertial navigation is divergent, which is mainly due to the accumulation of horizontal attitude error and velocity error. Comparing Fig. 4 and Fig. 5, it can be concluded that the modified algorithm can make full use of the special law of human walking and can modify most of the above two kinds of errors, so as to improve the navigation accuracy of MEMS inertial system. The positioning accuracy of the two groups is within 0.9%.

7. Conclusion

Foot-mounted MEMS personal navigation system to achieve the main use of the ZUPT, the premise requires accurate static detection. In this paper, we use the motion law of foot movement to design a detection algorithm based on the ratio model. In addition, since the EKF measurement update only at rest time, this will limit the filter estimation effect, mainly reflected in the azimuth error angle can't be effectively estimated. In this way, with the extension of navigation time, the influence of azimuth error will gradually replace the device error, becoming the main error source of MEMS personal navigation system. This problem is also the difficulty of MEMS personal navigation system development. To solve this problem, it can consider combining with other sensors, such as magnetometers, image sensors, and so on.

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