The Research of PNS Based on Micro Inertial Sensors

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Abstract: In order to reduce the dependence of pedestrian navigation on satellite navigation system and wireless communication, a new method is proposed to construct pedestrian navigation system (PNS) based on micro inertial technology. In this paper, the distributed system structure is arranged on human feet and trunk, and the key technologies, namely the system initial alignment, the error correction, the precise gait-phase detection, the effect and the inhibition of environmental magnetic field, have been studied. Besides, theories and applications of the key technologies are also discussed, and the performance of the PNS has been analyzed in the environment of electromagnetic interference. Experimental results show that the positioning error of the route with electromagnetic interference accounts for 2% of the travel distance. The key technologies proposed in the study can effectively improve the positioning accuracy of PNS, and independently achieve longer time personal navigation in the attenuate or even invalid global navigation satellite system (GNSS) and wireless communication signal environment.

Keywords: PNS; micro inertial technology; gait-phase detection; zero velocity update; fault detection

0. Introduction

As an emerging branch of navigation technology, pedestrian navigation has attracted intensive research in recent years. The pedestrian navigation system (PNS) is able to effectively determine individual user's location. Due to its light weight, small volume, affordable price, and portability, PNS has shown a broad prospect in both military and civilian applications[1]. At present, the PNS based on global navigation satellite system (GNSS) and wireless communication technology has been able to demonstrated satisfying performance. However, accurate personal positioning in the presence of electromagnetic interference, for instance, when the GNSS and the wireless communication are interfered, still remains an open issue in the development of pedestrian navigation technologies.

Recently, many research institutions and scholars have carried out the research of pedestrian navigation based on MEMS inertial technology to deal with the situation when GNSS becomes unreliable or completely unavailable. Draper laboratory [1-3] first proposed to install MEMS inertial measurement unit (IMU) on the feet of a soldier, and it focused on the calibration of the MEMS sensor's drift error when the foot is motionless. X. Yun et.al [13] changed the way of the installation of the MEMS IMU by fixing it on the dorsum of the foot, and use the zero velocity update method at the time of foot-landing to identify the dynamic phase model of human walking. That method corrects the way of the position error accumulation from over time to over distance and hence prevents the accumulation of positioning error. The Swedish defense research institute [9] has studied the indoor personal navigation method based on the foot-fixed MEMS IMU. Their result shows that the random errors of the inertial sensors could significantly affect the effectiveness of the zero velocity updating and the compensation accuracy. Also, the real-time zero velocity updating could be affected by the accuracy of the gait phase detection, and this could have direct impact on the navigation performance of the PNS. Northwestern Polytechnic University [12] designed a PNS based on the MIMU fixed on the foot. Its gait phase detection method is realized by combining the mode and the sliding variance of the specific force. The zero velocity updating is implemented

during the foot-landing, and the improved Kalman filter is adopted to correct the velocity errors of the INS to restrain the divergence of position error. Beihang University [14] designed a system based on micro-inertial/geomagnetic measurement unit, which is mounted on the waist of the body. For the identification of the gait phase, the parameters of the amplitude and phase of the gait are estimated through FIR digital filtering. This method can realize the dead reckoning to help to maintain the positioning performance when the GPS becomes unavailable in a short period of time.

The above studies indicate that pedestrian navigation in the absence of GNSS has attracted much attention. The core idea is based on the zero velocity updating or dead reckoning. However, the current studies focus on human's smooth walking, and the method for pedestrian navigation during complicated motions should be further studied.

The recent literature shows that the micro inertial navigation systems (MINS) based on the micro (MEMS) inertial sensors can be mounted to an individual's feet to serve as an effective complement to the GNSS. Nevertheless, due to the low accuracy of the MEMS sensors, the positioning function of the MINS could be considerably affected by the system's initial alignment error and the real-time error of the sensors. Furthermore, electromagnetic interference generally exists in a wireless communication environment. As a result, with the PNS going through the engineering process, how to deal with the environmental magnetic field that can adversely affect the system's azimuth accuracy has become an urgent issue for the scholars and researchers [1-3].

This paper presents a research on the key techniques for personal navigation system (PNS), including system initial alignment, phase identification of human gait, correction of inertial sensor error, and suppression of the effect of environmental magnetic field. Also, it conducts extensive test and analysis with respect to the performance of a prototype PNS in both indoor and outdoor environments. This research aims to design personal navigation system in complex environments.

1. The structural design and working principle of PNS

A distributed system structure has been adopted in the micro inertial technology based PNS. Thanks to the small size and light weight, the micro inertial measurement unit (MIMU) and micro-miniature magnetic sensors can be mounted to an individual's feet, with micro-miniature power module attached if necessary. The micro navigation computer and its power supply could also be mounted to the human trunk. To maintain structural integrity of the device, the interfaces for the GNSS module, the GPRS and the GSM wireless communication modules are reserved for future functional extension. The distributed structure of a PNS is shown in Figure 1. As illustrated, the data between the MEMS inertial/magnetic field measurement unit and the micro navigation computer could be transmitted via electronic cables or wireless communication modules such as Bluetooth, Zigbee, WIFI or UWB (ultra wide band) module.

Fig.1 The structure of a PNS

In accordance with the characteristics of human foot movements, gait phase detection is carried out to realize zero velocity update (ZUPT), whereby the navigation system errors and part of the drift errors of gyroscopes and

accelerometers can be estimated in real time [4]. Besides, through gait phase detection, the kinestate of human feet can be identified, and this allows the error characteristics of the micro inertial system to be analyzed. As a result, the weighted optimization of the two groups of navigation system data can be realized. Magnetic heading of the PNS can be determined through the real-time information supplied by the magnetic sensors and the modification of declination. The working principle of the system is illustrated in Figure 2.

Fig.2 The working principle of a PNS

2. Initial alignment

The initial alignment of a PNS includes two aspects, namely, a) the error calibration and compensation of the magnetic sensors; b) the horizontal attitude alignment of the MINS.

2.1 Calibration and error compensation of magnetic sensors

Reluctive transducer is commonly used in the micro-miniature magnetic sensor. It involves various errors such as the installation error, the zero error and the scale factor error, and error calibration ought to be conducted. In a laboratory environment, the aforesaid errors could be calibrated and corrected through mathematical modeling and parameter identification [5]. In addition to that, the reductive transducer may have to function in an environment exposed to the hard/soft material magnetic field and the random errors. As reported in the literature, the carrier's magnetic fields in most applications are induced by hard magnetic and soft magnetic. As for the random magnetic field, its interference can be well weakened or even completely avoided through a proper selection of installation positions. The measured values of the geomagnetic field vector in the coordinate system of the carrier can be expressed as follows [5][6]:

$$\mathbf{H}_m^b = (\mathbf{I} + \mathbf{A}_{soft})\mathbf{H}_e^b + \mathbf{H}_{hard}^b + \mathbf{H}_w^b \quad (1)$$

In equation (1), $\mathbf{H}_m^b$ stands for the measured value by the tri-axial magnetic sensors, $\mathbf{H}_e^b$ stands for the theoretical value of the geomagnetic field, $\mathbf{A}_{soft}$ stands for the magnetic field of soft magnetic materials, $\mathbf{H}_{hard}^b$ stands for the magnetic field of hard magnetic materials, and $\mathbf{H}_w^b$ stands for the measurement noise (whose

minimal influence can be neglected). The vector of geomagnetic field can then be written as follows:

$$\mathbf{H}_e^b = \mathbf{M}\mathbf{H}_m^b - \mathbf{H}_{hard}^b, \quad \mathbf{M} = (\mathbf{I}_{3 \times 3} + \mathbf{A}_{soft})^{-1} \quad (2)$$

When the carrier moves within a region where the geomagnetic field only slightly varies, the modulus value of the geomagnetic field vector can be regarded as a constant, and the coefficients of the surface equation hereof can be derived from the quadric surface equations of each carrier's magnetic parameters, which are described as follows:

$$(\mathbf{H}_m^b)^T \mathbf{M}^T \mathbf{M} \mathbf{H}_m^b - 2(\mathbf{H}_{hard}^b)^T \mathbf{M} \mathbf{H}_m^b + (\mathbf{H}_{hard}^b)^T \mathbf{H}_{hard}^b = \|\mathbf{H}_e^b\|^2 \quad (3)$$

In order to conduct the curved surface fitting of the geomagnetic field, the error calibration as well as the compensation of the hard/soft material magnetic error, the quadric surface can be projected into three planes, X-Y, Y-Z and X-Z, respectively. In this way, the measured tracks of the magnetic field after projection could be approximately regarded as elliptical orbits offset from the origin. Therefore, the calibration of the carriers' magnetic fields could be achieved by the following steps: firstly, obtain the measured data from the tri-axial magnetic sensors; secondly, fit the three elliptical equations with the least-square fitting based on elliptical constraints; thirdly, calibrate the magnetic field error of hard and soft magnetic materials according to the fitting parameters; lastly, compensate the errors of the tri-axial magnetic sensors [5][6].

2.2 The horizontal attitude alignment method

When the PNS starts up, the initial alignment is essential. It consists of two steps, namely, the coarse alignment and the horizontal attitude alignment on a moving base. In the coarse alignment process, the horizontal attitude angle of the carrier is first calculated by the tri-axial accelerometers; after that, the magnetic heading is provided by the tri-axial magnetic sensors after error compensation; finally, the geographical heading is obtained through the modification of magnetic variation in accordance with geographical information.

In the horizontal attitude alignment on a moving base, the optimal estimation and compensation are adopted to complete the process. Provided that the micro inertial sensors have undergone a high-precision calibration, the horizontal attitude error of the inertial system would generally be reduced to degree-level after the coarse alignment. Meanwhile, in view of the capability of the PNS navigation computer, the linear error model of the classical strap-down inertial navigation system has been built to perform the Kalman filter to finally complete the alignment process [7].

The error model of the inertial system is comprised of the platform error angle model, the velocity error model, the position error model, and the inertial sensor error model. The equation of the platform error angle model is described as follows [15]:

$$\dot{\boldsymbol{\varphi}} = \delta \boldsymbol{\omega}_{in}^n + \boldsymbol{\varphi} \times \boldsymbol{\omega}_{in}^n + \boldsymbol{\varepsilon}^n \quad (4)$$

The equation of the velocity error model is described as follows [15]:

$$\delta \dot{\mathbf{V}} = \dot{\mathbf{V}}^c - \dot{\mathbf{V}}^n = \mathbf{f}^n \times \boldsymbol{\varphi} + \nabla^n - (2\delta \boldsymbol{\omega}_{ie}^n + \delta \boldsymbol{\omega}_{en}^n) \times \mathbf{V}^n - (2\boldsymbol{\omega}_{ie}^n + \boldsymbol{\omega}_{en}^n) \times \delta \mathbf{V} + \delta \mathbf{g} \quad (5)$$

The superscript/subscript i denotes the inertial coordinate system, e denotes the earth coordinate system, n denotes the navigation coordinate system, c denotes the computation coordinate system. $\boldsymbol{\varphi}$ is the attitude error, $\boldsymbol{\omega}$ is the angular rate, δ symbolizes the error. $\boldsymbol{\varepsilon}$ is the gyro's drift, ∇ is the accelerometer's bias. $\mathbf{V}$ is the velocity, $\mathbf{f}$ is the output of the accelerometer.

The equation set of the position error model is described as follows [15]:

$$\left. \begin{aligned} \delta \dot{L} &= \frac{\delta v_N}{R_M + h} \\ \delta \dot{\lambda} &= \frac{\delta v_E}{R_N + h} \sec L + \frac{v_E}{R_N + h} \sec L \tan L \delta L \\ \delta \dot{h} &= \delta v_U \end{aligned} \right\} \quad (6)$$

L, λ, h represent the latitude, longitude and altitude respectively.

The errors of the MEMS inertial sensors after the coarse alignment can be approximated to the combination of random constants and white noise. Although the errors of the inertial components during the high-precision alignment and navigation process are time-varying, basically they could fit the following models of random constants:

$$\dot{\varepsilon} = 0 \quad (7)$$

$$\dot{\nabla} = 0 \quad (8)$$

The physical quantities indicated in equations (4) to (8), as well as the state equations and observed equations of the linear Kalman filter, have been elaborated in the fundamental literature of the inertial navigation.

During the initial alignment, the “position+velocity” matching mode is used in the observation equation while the geographical location is known. During the zero velocity updating, the position information cannot be obtained by the external observation system. As a result, the “velocity” matching mode is used instead in the observation equation. The parameters in equations (4) to (8) and the establishment of the linear Kalman filter can be found in reference [12].

Since the eastward and northward platform error angles of the inertial system bear sound observability under both static and dynamic conditions [7], the high-precision alignment could be conducted during the pedestrian proceeding. After the covariance convergence of the errors of the systems is achieved, the inertial system enters the navigation mode. And zero velocity updates of the system errors are performed with the assistance of the gait phase identification. The system error model adopted by the zero velocity update is the same as the one in the initial alignment, as is presented in equations (4) to (8).

3. Gait phase detection and discipline for weighted optimization

Gait phase detection serves as the grounds for the PNS to apply zero velocity updates, and the kinetic characteristics of human gaits play a similar role in the weighted optimization of the navigation data of left foot/right foot micro-inertial systems. In this sense, the accuracy of gait phase detection has great impact on the properties of the PNS.

According to the kinesiology, the gait cycle of human walking can be generally divided into several separate movements, including stand-still, heel-lifting, leg-swinging, heel-landing, etc., which normally occur in a chronicle sequence and are therefore termed “basic gait phases of human walking”. Other complex foot movements generally include the aforementioned basic gait phases [1][2].

With regard to the PNS, the gait phase detection is conducted in order to precisely identify whether the foot is in the stance phase to further apply the zero velocity updates at a proper time. Various methods of gait phase detection have been proposed in the literature [1-3][8], by which reasonably good detection results could possibly be obtained. Nevertheless, in the case of more complex foot movements such as side-stepping, sliding-stepping, leg-lifting, foot-turning and so on, false or missed detections are prone to occurring. In addition, the missing ratio would remain at a relatively high level, when the inertial sensors suffer from low precision and only a single detection method is adopted.

In reference [12], the modulus and the variance of the specific force are established according to the outputs of the tri-axial accelerometer in a fixed-length frame window. The motion state of the body can be detected by

comparing accelerometer output with the gravity vector. Based on this detection method, this paper proposed a new method for gait phase detection. In this method, the vector, scalar and the cross coupling value of the outputs of the tri-axial accelerometers are established. According to the values and the outputs of the tri-axial gyroscopes, the motion state of the body can be determined. The proposed method not only takes the ratio of the specific force mode to the gravity mode into consideration, but also utilizes the cross coupling value to determine the time for foot-landing. Thus, the detection accuracy of the gait phase detection during the complex foot movements can be improved.

3.1 Gait phase detection based on MEMS accelerometers

Firstly, the outputs of the three perpendicular axes accelerometers are denoted by f_x, f_y, f_z , respectively. Based on them, the following variables can be defined.

$$\begin{cases} E_f = \sqrt{f_x^2 + f_y^2 + f_z^2} \\ P_{fij} = f_i f_j \quad i, j = x, y, z \text{ \& } i \neq j \\ S_f = f_x + f_y + f_z \end{cases} \quad (9)$$

In equation (9), E_f stands for the amplitude of the tri-axial accelerometer outputs. Through calculating the deviation between E_f of the present sampling instant and the local gravitational acceleration amplitude $|g|$, as well as the sliding variance of E_f in a number of neighboring sampling periods (set according to the length of the sampling period), it can be determined whether IMU is in the resting state [12]. The sliding variance of E_f is represented as follows [3]:

$$Std_{E_f} = std(E_{fN-m}, \dots, E_{fN-1}, E_{fN}, E_{fN+1}, \dots, E_{fN+n}) \quad (10)$$

In equation (10), Std_{E_f} stands for the standard deviation of the E_f sequence, m and n stand for the numbers of the samples before and after the sampling instant in the sample sequence.

Because the product of the acceleration components can be expanded as a quadratic function of the acceleration variations, as is shown in equation (11), P_{fij} stands for the pairwise product ($P_{fij} = P_{fji}$) of the components of the outputs produced by the accelerometers in the three axes.

$$P_{fij} = f_i f_j = (g_i + \Delta a_i)(g_j + \Delta a_j) = g_i g_j + (\Delta a_i g_j + \Delta a_j g_i + \Delta a_i \Delta a_j) \quad i, j = x, y, z \text{ \& } i \neq j \quad (11)$$

In equation (11), g_i and g_j stand for the components of the gravity vector sensed by the accelerometers in the three axes. When the attitude of the carrier changes due to angular movements, g_i and g_j would change accordingly. Meanwhile, Δa_i and Δa_j stand for the acceleration variations caused by the motion of the carrier, which would increase over time when the linear overload of the carrier occurs. The linear movements of the carrier could be effectively observed through $(\Delta a_i g_j + \Delta a_j g_i + \Delta a_i \Delta a_j)$. Thus, a comprehensive observation of the linear and angular movements of IMU can be obtained through a calculation of the value P_{fij} and its sliding variance. In addition, the local extremes of P_{fij} can also be used to determine the moments when a foot touches or leaves the ground.

S_f is the scalar sum of tri-axial accelerometer output components. The sliding variance of S_f could also be utilized to identify the kinetic characteristics of foot movements, which could be regarded as an assistive method of gait phase detection [1].

In gait phase detection, the periods that meet all the static conditions of E_f , P_f and S_f are regarded as the stance phases of foot motion, during which the zero-velocity upgrades are performed. Compared with singular detecting criterion, the detection method based on E_f , P_f and S_f can effectively improve the accuracy of gait phase detection in complex foot movements.

In practical applications, the threshold used to detect the deviation between E_f and $|g|$, as well as the

threshold used to detect the sliding variance of E_f , P_f and S_f , should be set according to the zero position offset and the noise characteristics of the MEMS accelerometers. And the data length of the sliding variance of E_f , P_f and S_f should be adjusted with respect to the sampling frequency of the accelerometers [3].

3.2 Gait phase detection based on MEMS gyroscopes

The gait-phase could be detected through calculating the sum of the angular rate vectors, that is, judging whether the vector sum of the angular rate in equation (12) exceeds a certain threshold value Ω_{th} , it is used to predicate whether the foot is in the motional phase. The threshold Ω_{th} is set based on the zero drift and the noise characteristics of the gyroscopes.

$$\omega_i = \sqrt{\omega_{xi}^2 + \omega_{yi}^2 + \omega_{zi}^2} \quad (12)$$

An experiment has been carried out to verify the proposed gait phase detection method, with the adoption of MTi-10 measurement unit developed by Xsens Technologies. The essential performance parameters of the inertial sensors in MTi-10 unit are presented in Table 1:

Tab.1 Essential performance parameters				
Zero bias stability		X axis	Y axis	Z axis
MTi-10	gyroscope/ °/h	38.5542	35.6812	45.5568
	accelerometer/ mg	0.8311	0.7812	0.7880

According to the measurements of the inertial sensors, the value of the point that would result in obvious error is set as the threshold. The threshold for accelerometer is $9.7 < E_f < 10.3$, and the threshold for gyroscope is $\omega_i < 1.18$.

According to the accelerometer error, the threshold of P_{fij} is $0 < P_{fij} < 49$, the sliding variance threshold is 0.06, the length of the sliding window is 10.

Set S_f to S_{f0} when the individual stays still, if the output of the any accelerometer changes, the S_f changes, which means that the individual is in motion. That is to say, we can choose appropriate thresholds based on the sensor data to determine the individual's motion status. The threshold for S_f is $(S_{f0}-2.2) < S_f < (S_{f0}+1.8)$.

The detection experiment is conducted under multiple basic foot movements. They are the pitching movements, the reciprocating rectilinear movements, the azimuth rotating movements, and the compound movements comprised of the first three types. In the three groups of experiments, the testing time is fixed as 300s, and the number of the times of the sensors' movements is fixed as 200 for all the four movement types. The angular rate of the pitching movements and azimuth rotating movements is about 30°/s, and the sampling frequency is 100Hz. The traveled distance of the reciprocating rectilinear movements is about 0.5m. In the gait phase detection, the amplitude and the threshold of the sliding variance are set in accordance with the performance parameters of the MEMS inertial sensors. The results of the gait phase detection experiments are presented in Table 2:

Tab.2 The experiment result of gait-phase detection				
Movement type	pitching	Reciprocating rectilinear movement	Azimuth rotating	compound movement
Movement times	200	200	200	200
Detected times	200	200	200	198

As shown in Table 2, the gait phase detection method proposed in this paper enjoys high precision in detecting the typical foot movements. In the case of compound movements, a missing ratio around 1% is expected.

In real human movements, compound movements hardly occur. A missing detection will only result in a minor loss of time for zero-velocity upgrades, rather than mistaken updates in the moving state. Therefore, this experiment demonstrates the efficacy of the proposed gait phase detection method.

3.3 Grounds for the weighted optimization of the navigational information

When the PNS works, the motion state of the foot can be accurately estimated by the gait phase detection method described in section 3.1 and 3.2, and then the time for the zero velocity updating can be determined. If the gait phase detection shows that the foot is in motion phase, then the MIMU on the foot would work on the strap-down inertial navigation mode, and the location error would increase with the time in a second- or higher order relationship [9]; otherwise, if the gait phase detection shows that the foot is in the stance phase, then the MIMU on the foot would work on the zero velocity updating mode. In this case, the velocity matching Kalman filter will be used to estimate the sensor error so as to restrain the navigation error accumulation and prevent the divergence of the positioning error. Thus, the gait phase detection can be used to detect the motion state of the foot, and the weighting coefficients of the INS can be further optimized [10]. The optimization method is described as follows:

1) When one foot is in stance phase, the navigation information obtained by the PNS on one foot will be used to correct the position information of PNS on the other foot.

2) When both feet are in motion, the ratio of the sensors bias between the two sets of INS, which are estimated during the zero velocity updating modes, would be used as the weighting coefficient for the navigation.

4. Assistive technologies of magnetic heading

Electro-magnetic interference generally exists in the environment where a PNS is deployed. The environmental magnetic field can have a considerable impact on the azimuth accuracy of the navigation system, and severe electromagnetic interference could even cause a temporary failure to the navigation system. In this paper, a magnetic sensor fault detection and system reconfiguration method is discussed. It is based on measurement residual χ^2 test and is used to realize discontinuous magnetic assistance to the PNS.

The azimuth calculation of the strap-down inertial navigation algorithm is retained while the PNS is in operation. During the zero velocity updates, the heading information calculated by the magnetic sensors is treated as an observed quantity for zero velocity updates. The state equation and observation equation of the system error are adopted to define the following measurement residual vectors [11]:

$$r_{k+1} = Z_{k+1} - \hat{Z}_{k+1/k} = Z_{k+1} - H_k \hat{X}_{k/k-1} \quad (13)$$

As it is indicated in equation (13), r_{k+1} error $\delta\gamma$ caused by the electro-magnetic interference in the motion environments can have a negative impact on the filtering through the measurement residual vectors, or in a more severe sense, it could result in filter divergence, which is regarded as a fault in this paper.

When the carrier is in an environment free of magnetic interference (i.e. without fault), r_{k+1} is a zero-mean Gaussian noise with the variance described in equation (14).

$$A_{k+1} = H_{k+1} P_{k+1/k} H_{k+1}^T \quad (14)$$

When the carrier is in an environment with magnetic interference (i.e. with fault), r_{k+1} is no longer zero-mean noise. Therefore, it is feasible to tell whether the carrier is exposed to magnetic interference by checking r_{k+1} , and the availability of the heading information calculated by the magnetic sensors could thereby be judged.

A dualism hypothesis concerning r_{k+1} is put forward as follows:

H0, faultless condition (with non-interference):

$$E\{r_{k+1}\} = 0, E\{r_{k+1} r_{k+1}^T\} = A_{k+1} \quad (15)$$

H1, faulty condition (with interference):

$$E\{r_{k+1}\} = \mu, E\{(r_{k+1} - \mu)(r_{k+1} - \mu)^T\} = A_{k+1} \quad (16)$$

Thus, the fault detection function $\lambda_{k+1} = r_{k+1}^T A_{k+1}^{-1} r_{k+1}$ follows the χ^2 distribution with 2 degrees of freedom.

Rules of fault detection are presented as follows:

1) If $\lambda_{k+1} > T_D$, it can be declared that the carrier is exposed to magnetic interference, and the data of the magnetic sensors become invalid. In this case, the magnetic sensors will be shielded and system reconfiguration is carried out.

2) If $\lambda_{k+1} \leq T_D$, it can be declared that the carrier is in an environment free of magnetic interference, and the data of the magnetic sensors are reliable. In this case, the original system structure is maintained.

In the fault detection procedure, the threshold of the fault, T_D , is determined by specific error characteristics of the magnetic sensors as well as the false alarm rate limits.

5. Experiments on performance evaluation of the PNS

To verify the pedestrian navigation scheme proposed in section 1, we carried out the following experiment. During the experiment, the MIMU fixed on the feet communicated with micro-computer by the Bluetooth module type HC-05. An individual walked along one building twice to test the system in different environment. The walking distance and the time were about 300m and 600s. And the person went back to the starting point at the end. In the first test, the electromagnetic interference objects in the environment were removed. In the second test, the electromagnetic interference objects were placed back in the environment. In both tests, the GPS was used to acquire the real-time position information and retained as the ground truth to evaluate the positioning performance of the PNS. The experimental result is illustrated in Figure 3.:

Fig.3 Positioning result in an experiment using a rectangle route

Figure 3 shows that: ① If there is no significant electromagnetic interference, the performance of the PNS has been greatly improved with the INS errors corrected by the gait phase detection, the navigation optimal weighting and so on. Taking the geographical location as the reference, the positioning error of the PNS is within 4.3m. The similar experimental in reference [8] was lack of an alternate assistant of single-foot-fixed INS, and therefore the period of the zero velocity updating was long and the positioning error was larger. ② If there is significant electromagnetic interference, the magnetic heading error caused by the measurement errors of the magnetic sensors cannot be effectively restrained by the zero velocity updating only. In this case, the heading error could be beyond 27.7° , and the positioning error would be more than 11.6m. ③ With the magnetic sensor error detection based on the χ^2 test, the system is reconstructed. The average shielded time of the magnetic heading for the PNS is about 20s, and the magnetic heading can be assisted for every 20s. If the assisted time is 3s, the heading error for the PNS is within 3.4° , while the location error is within 8.5m. The experimental result has sufficiently demonstrated the efficacy of the proposed method in this paper.

6. Summary

In this paper, a new personal navigation and positioning scheme through foot-mounted micro inertial/geomagnetism measurement units is presented to resolve the issue of GNSS failure in the presence of electromagnetic interference. Theoretical analysis and experimental study are conducted with respect to the structure of the PNS, the error calibration and compensation of the magnetic sensors, the initial alignment of the navigation system, and the process of gait phase identification and zero velocity update. As indicated by the experimental results, the positioning properties of the navigation system can be effectively improved with the proposed navigation approach, and accurate personal navigation could be achieved in a relatively longer period time without the help of GNSS. Thus, the significance of the PNS under attenuated or even failed GNSS and wireless communication is clearly demonstrated.

7. Acknowledgment

This work is supported by the National Science Foundation for Young Scholars of China (Grant No. 61301021).

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