Pedestrian Navigation Method based on PDR/INS KF fusion and Height Update for Three-Dimensional Positioning

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Abstract. Inertial navigation system (INS) and pedestrian dead reckoning (PDR) that use wearable MEMS inertial measurement units (IMUs) can track the location of a pedestrian on two-dimensional (2D) plane. This paper proposes a pedestrian navigation method based on INS/PDR Kalman filter (KF) fusion to calculate the trajectory of a pedestrian in indoor corridors, which can effectively suppress the heading drift. Besides, the height update algorithm is introduced based on the pressure output of a barometer to constrain the height divergence for three-dimensional (3D) positioning. The results of motion experiment show that the navigation accuracy of INS/PDR Kalman filter fusion method is significantly increased compared with the INS. The proposed height update algorithm have better correction effect on the problem of height divergence compared with ZUPT-aided inertial navigation algorithm.

1. Introduction
Indoor pedestrian navigation becomes an indispensable research field with the increasing number of complex buildings, and its services are widely used in public safety. Global Navigation Satellite System (GNSS) provides location information outdoors but it is inapplicable to the indoor positioning [1]. Many indoor navigation methods are based on radio systems, such as visual Wi-Fi [2], Radio Frequency Identification (RFID) [3], Ultra Wideband (UWB) [4]. In addition to wireless radio-based methods, PDR and INS based on inertial sensors provide alternative methods for indoor navigation. As an inertial sensor-based positioning method, PDR has the advantages of compact size, low cost and high autonomy. INS is able to achieve autonomous navigation without additional infrastructure assistance. Nevertheless, the existing positioning methods are still facing the issues of accumulated errors due to the drift errors. Therefore, reducing the cumulative errors of PDR and INS becomes more urgent because of the need for precise navigation information.

1.1 PDR-Based Pedestrian Position Estimation
In the PDR system, the IMU can be fixed on leg, foot, waist or other positions of the body. In general, the foot reflects the most movement information and thus the IMU is often fixed on the surface of the shoe. PDR-based methods are advantageous, as they obtain the current position by adding the estimated displacement and heading angle to the previous position, independent of the additional infrastructure. Therefore, the positioning accuracy of PDR is determined by step detection [5], step length estimation [6] and heading estimation [7].
1.2 INS-Based Pedestrian Position Estimation
The INS-based method obtains the position, speed and attitude of a pedestrian by direct integration of the strap-down inertial navigation equation. The main error of this method is heading drift caused by the integral error of acceleration. Based on this, the zero velocity update (ZUPT) algorithm [8-9] is widely used for the foot-installed inertial navigation system. In a normal gait cycle, the foot contacts the ground for a short time. Aiming at position divergence caused by heading drift, Lu et al. proposed an INS/PDR hybrid navigation method based on motion recognition [10]. Jimenez et al. proposed that ZARU, HDR and Compass were used in ZUPT-INS/EKF framework to reduce the drift error [11].

Height divergence is a major problem in 3D positioning based on ZUPT-aided inertial navigation algorithm. Many scholars utilized a barometer to measure atmospheric pressure to calculate altitude. Kim et al. used a barometer to estimate height location of pedestrians and designed a KF to minimize the height error [12]. Abdulrahim et al. proposed a height limitation method based on height change of adjacent steps to correct the height error [13]. This paper proposes a new height update algorithm based on a barometer to suppress the height divergence when pedestrians walking on the stairs.

The main contents of this paper are as follows: The second part explains the process of ZUPT-aided Kalman filter. The third part introduces three modules of PDR: step detection, step length estimation and heading estimation. In the fourth part, INS/PDR KF fusion algorithm on two-dimensional plane and height update algorithm for three-dimensional positioning are proposed. The fifth part presents the consequences of the experiment to verify the effectiveness of the proposed method. Finally, the sixth part summarizes the work of this paper and puts forward some suggestions for future research.

2. ZUPT-aided inertial navigation algorithm
The inertial navigation system uses IMU to measure acceleration and angular rate in body frame and obtains velocity and attitude in navigation frame by integral operation. Since low cost inertial sensor has large drift error, a Kalman filter is adopted to compensate cumulative error terms of INS. Firstly, the stationary phase of a pedestrian in a gait cycle should be detected. Then, the ZUPT method is used to update state estimation during the stationary phase, and the velocity measurement is selected as observation. We express the navigation frame as east-north-up and the body frame as forward-left-up.

(1) The 9-element state vector is:
$$ x = \left( \delta P^n, \delta V^n, \delta \varphi^n \right)^T $$
(1)

Where $\delta P^n$, $\delta V^n$ and $\delta \varphi^n$ are position, velocity and attitude error in navigation frame respectively.

(2) The error model of INS is:
$$ \delta \dot{P}^n = \dot{\delta V}^n $$
$$ \dot{\delta V}^n = \left( C_b^a f^b \right) \times \delta \varphi^n + C_b^n \dot{\varphi}^b $$
$$ \delta \dot{\varphi}^n = -C_b^n \varepsilon^b $$
(2)

Where $\varphi^b$ and $\varepsilon^b$ are bias errors of the accelerometer and gyro respectively, $f^a$ is specific force in body frame, the matrix $C_b^n$ represents the direction cosine matrix from body to navigation frame.

(3) The discrete-time state equation is:
$$ x_k = F_{k,k-1} x_{k-1} + G_{k-1} w_{k-1} $$
(3)

Where $F_{k,k-1}$ is the state transition matrix, $G_{k-1}$ is control matrix, and $w_{k-1}$ is process white noise.

(4) The observation equation is:
$$ z_k = H_k x_k + v_k $$
(4)

Where $H_k$ is the measurement matrix, $z_k$ is observation, and $v_k$ is measurement white noise.

When the stationary phase of pedestrians is detected, the velocity should be zero in theory. ZUPT
method takes the deviation between zero and velocity output, namely $\delta V^{*T}$ as observation:

$$ z_k = \delta V^{*T} = V^{*T} - (0 \ 0) $$

Then the corresponding measurement matrix is:

$$ H_k = (0_{3 \times 3}, I_{3 \times 3}, 0_{3 \times 3}) $$

3. Dead reckoning algorithm

3.1. Step detection

Firstly, the peak and valley outputs of the accelerometer and gyro are analyzed to find the optimal step detection scheme. It can be found that inertial data with different axes reflect different peak features. For normal walking, the y-axis angular rate works well to partition single step and the detection results are shown in figure 1. The peaks and valleys are marked by red and green dots respectively.

3.2. Step length estimation

In this paper, a new step length model is proposed by combining the Weinberg step length model with the linear step length model, as shown below:

$$ L = \alpha \sqrt{a_{\text{max},i} - a_{\text{min},i}} + \beta f_i + \lambda v_i $$

Where $\alpha, \beta, \lambda$ are step parameters, $a_{\text{max},i}, a_{\text{min},i}$ are the maximum and minimum of the acceleration respectively at step $i$, $f_i$ is step frequency at step $i$, $v_i$ is acceleration variance at step $i$.

3.3. Heading calculation

Heading is calculated by the magnetometer. The heading can be calculated by the following equation:

$$ \psi = \arctan \left( \frac{-h_z \cos \gamma + h_y \sin \gamma}{h_z \cos \theta + h_y \sin \theta \sin \gamma + h_x \sin \theta \cos \gamma} \right) + D $$

Where $\left(h_x, h_y, h_z\right)$ represents the magnetic field intensity in body frame, $\gamma, \theta$ are roll angle and pitch angle respectively, $D$ is the magnetic declination.

4. Correction

4.1. Kalman filter fusion of PDR and INS

When pedestrians walk along the corridor in a straight line, the trajectory can be obtained according to PDR and INS respectively. The improved direction estimation method by Kalman filter can effectively
restrain the heading drift and make the navigation results better than INS. The observation equation and measurement matrix are:

\[
\begin{align*}
    z_k &= y_{PDR}^n - y_{INS}^n = H_k x_k + v_k \\
    H_k &= \begin{bmatrix} 0 & 1 & 0 & 0_{3x3} & 0_{3x3} \end{bmatrix}
\end{align*}
\] (9)

Where \( y_{PDR}^n \) is the northern position calculated by PDR in navigation frame, \( y_{INS}^n \) is the northern position calculated by INS in navigation frame.

### 4.2. Height update algorithm (HUPT)

Firstly the mean filtering is applied to smooth the measured pressure \( P_i \) by the barometer. Then the formula for calculating height from the pressure is as follows:

\[
h_i = \frac{44330 \times \left(1 - \frac{P_i}{101.325}ight)^{0.190}}{1} \]

(11)

The height difference obtained by the barometer and INS is:

\[
\delta h(i) = h_i - h_{INS}(i)
\]

(12)

The observation equation and corresponding measurement matrix are:

\[
\begin{align*}
    z_k &= \begin{bmatrix} 0 & 0 & \delta h(i) \end{bmatrix}^T = H_k x_k + v_k \\
    H_k &= \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} 0_{3x3} 0_{3x3}
\end{align*}
\] (13)

### 5. Experimental evaluation

#### 5.1. Experimental apparatus

In order to verify the effectiveness of the method proposed in this paper, we chose the MTi-G-710 IMU module. In each experiment, the IMU was fixed on the shoe surface. At the beginning of data collection, it is necessary to keep the foot stationary for a period of time to achieve the initial alignment of the IMU, and then conduct the dynamic foot walking experiment.

#### 5.2. Experimental process

The experiment is divided into two parts. The first part verifies the accuracy of PDR, INS and INS/PDR Kalman filter fusion method respectively when pedestrians walk in a straight line. The second part verifies the validity of proposed height update algorithm based on the ZUPT-aided inertial navigation algorithm when pedestrians walk on the stairs. The proposed method only relies on the inertial measurement unit (IMU), and the effectiveness is verified by indoor experiment.

Experiment 1: The pedestrian walked normally in a straight line from west to east along the indoor corridor for 58.96 m, a total of 48 steps, each step is about 1.2 m long.

Experiment 2: The pedestrian walked along the corridor in a straight line from the west landing of the first floor to the east landing. Then she went from the first floor to the second floor and continued along the corridor to the west landing. Finally she went down to the first floor. It is roughly measured that the stair height is about 0.15 m and a total of 27 steps. Thus the altitude variation is about 4.05 m.

#### 5.3. Results and conclusions

##### 5.3.1. Experiment on 2D Plane

The data obtained from experiment 1 were used for navigation calculation of PDR, INS and INS/PDR Kalman filter fusion method respectively. The navigation results of PDR algorithm are shown in figure 2. The estimated trajectory is close to a straight line on
the horizontal plane, with a travel distance of 58.86 m, and a north-direction error of 0.19 m and an east-direction error of 0.1 m compared with the real trajectory. The navigation results of INS algorithm and INS/PDR Kalman filter fusion method are compared as shown in figure 3. When INS algorithm is used for navigation calculation, the error will accumulate with time and the heading drift will occur due to the inconsistency of walking speed or walking mode. The north-direction error is 2.13 m, accounting for 3.61% of travel distance. Compared with the INS algorithm, the INS/PDR Kalman filter method can effectively suppress the error accumulation in north direction due to the heading drift and the north-direction error is only 0.21 m, accounting for 0.36% of travel distance.

5.3.2. Experiment in 3D Space. The navigation results of ZUPT-aided inertial navigation algorithm and proposed height update algorithm are compared as shown in figure 4. The terminal height error of the former algorithm is 0.28 m. The positioning errors of 2D and 3D are 1.28 m and 1.30 m respectively. The terminal height error of proposed height update algorithm is only 0.033 m, while the 2D and 3D positioning errors are basically unchanged at 1.22 m. Figure 5 shows the height variations of two methods. It can be seen from the figure that the proposed height update algorithm effectively constrains the height divergence when pedestrians walk on the stairs.
6. Conclusion
In this paper, a two-dimensional pedestrian navigation method and a height update algorithm for three-dimensional positioning are proposed. A pedestrian navigation method based on INS/PDR KF fusion is proposed to calculate the trajectory of a pedestrian in indoor corridors in this paper, which can effectively suppress the heading drift. In addition, the height update algorithm is introduced based on the pressure output of a barometer to constrain the height divergence for three-dimensional positioning. Since human gait and behavior are complex and changeable, and walking paths will be complicated, the focus of future work will be to consider more ways of walking paths. At the same time, to provide more services, the IMU will be fixed on different parts of human body and the corresponding positioning accuracy will be discussed.

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