Reduction of Heading Error Using Dual Foot-mounted IMU

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Abstract. In this paper, we propose a mitigating heading error using dual foot-mounted IMU in pedestrian dead reckoning (PDR) system. The heading error, which is one of the causes of position error, is an unobservable state in the standard PDR system. The previous studies reduce the heading error with the assumption that the movement direction of the pedestrian is parallel to the corridor direction of the building. Those are effective methods, but they are limited in that it requires the prior information on the building direction. The proposed method estimates the pedestrian position based only on IMUs using heading error characteristics of both shoes without building information. The heading error of both shoes shows a symmetrical tendency in a straight-line trajectory. As this time, the average heading of each shoe is regarded as a reliable walking direction, like a dominant direction. An extended Kalman filter using this measurement value was designed and the heading error of each shoe was reduced by IMU only. The experimental results show that the heading error reduced with the proposed method.

Keywords: Pedestrian dead reckoning, dual foot-mounted IMU, heading error

1 Introduction

As the interest of the indoor location service has increased, studies have been carried out to apply the pedestrian dead reckoning (PDR) system to an actual situation. Unlike infra-based pedestrian navigation systems, which require preliminary data collection, the PDR system can estimate the position using IMU. This system is categorized into two types. One of the systems is a parametric approach, which estimates the position by accumulating the step length and direction of movement. This method is mainly used when the sensor is attached to the waist or held by hand like a smartphone. The other is the integration approach, which is based on the inertial navigation system (INS) with extended Kalman filter (EKF) and zero-velocity update (ZUPT). In the integration approach, ZUPT is used to correct the INS error by gyro and acceleration [1-3]. Unfortunately, the heading error is an unobservable state in the standard PDR system.

In order to reduce the heading error, various studies have been carried out, such as heuristic drift reduction (HDR) and heuristic drift elimination (HDE) [4-6]. These methods involve the assumption that pedestrian usually walks in a direction parallel to the corridor in the building. When a pedestrian walking meets the assumption, the estimated heading is compensated toward the corridor direction to reduce the error. However, in order to apply these methods, they are limited in that it requires to know the corridor direction information in advance.

The proposed method is a PDR system using only two IMUs with the characteristic that the heading error of both shoes is symmetrical. It is known as a PDR system using dual foot-mounted inertial sensors to compensate for position error due to symmetrical errors using sensors attached to both shoes [7-9]. The proposed method focuses on correcting the heading error in a straight walking situation. The average of each shoe heading is assumed to be a reliable and accurate walking direction since the symmetric errors cancel each other out. The heading error can be compensated toward walking direction in the straight walking situation. To verify the proposed algorithm, several experiments were conducted. The pedestrian repeatedly walked a trajectory including a straight line. The results of the experiment show that the performance is improved by the proposed algorithm.

2 PDR system using single foot-mounted IMU

The integration approach estimates the pedestrian position based on INS. The INS calculates the attitude, velocity, and position of the shoe while integrating the angular rate and acceleration measured by the IMU. However, since the INS error gradually diverges, it is combined with EKF and ZUPT to correct the error [1,3].

In the standard PDR system, the error state variable is 15 or 9-order. The 15-order state variable includes position ($\delta\mathbf{p}$), velocity ($\delta\mathbf{v}$), attitude ($\delta\boldsymbol{\varphi}$), gyro bias and acceleration bias ($\nabla^{\mathbf{b}}$). In this paper, we constructed 11 state variables except for unobservable yaw ($\delta\psi$) and gyro bias estimated from initial alignment. The error states are expressed as follows:

$$\delta\mathbf{x} = \left[\delta p_N \; \delta p_E \; \delta p_D \quad \delta v_N \; \delta v_E \; \delta v_D \quad \delta\phi \, \delta\theta \quad \delta\nabla_X \, \delta\nabla_Y \, \delta\nabla_Z\right]^T . \tag{1}$$

The state transition matrix is

$$\mathbf{\Phi} = \begin{bmatrix} \mathbf{I}_{3\times3} & \mathbf{I}_{3\times3}\cdot dt & 0_{3\times2} & 0_{3\times3} \\ 0_{3\times3} & \mathbf{I}_{3\times3} & \mathbf{S}_{3\times2}\cdot dt & \mathbf{C}_b^n \\ 0_{2\times3} & 0_{2\times3} & I_{2\times2} & 0_{2\times3} \\ 0_{3\times3} & 0_{3\times3} & 0_{3\times3} & I_{3\times3} \end{bmatrix}, \tag{2}$$

where $\mathbf{C}_b^n$ is the rotation matrix that transforms values from the body (b) to the navigation (n) frame, dt is the sampling time, and $\mathbf{S}_{3\times2}$ is the first- and second-column

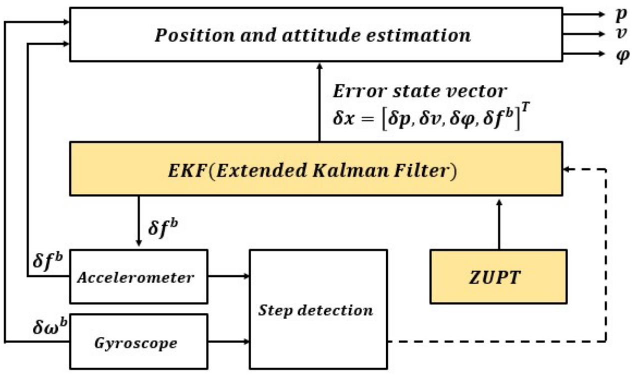

Fig. 1. The PDR system diagram

vector of $\mathbf{S}$, which is the skew-symmetric matrix for accelerations in the navigation frame.

There is a zero velocity moment in the stance phase when the shoe touches the ground, and the error is corrected through ZUPT at that moment. The velocity error is used for the error measurement update in EKF. The error measurement is $\hat{\mathbf{v}} - \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}$, $\hat{v}$ is the estimated velocity and $\begin{bmatrix} 0 & 0 & 0 \end{bmatrix}$ is the zero velocity because the velocity of the foot is nearly zero during the stance phase. The measurement matrix is given as:

$$\mathbf{H} = \begin{bmatrix} 0_{3\times3} & \mathbf{I}_{3\times3} & 0_{3\times2} & 0_{3\times3} \end{bmatrix}. \tag{3}$$

The block diagram of the integration approach is shown in Fig. 1. Stance phase detection is required in order to use ZUPT. The stance phase is the moment when the bottom of the shoe is attached to the ground in step motion. We have modified the stance phase detection method using the magnitude and variation of acceleration and angular rate [10].

3 Heading error reduction

3.1 Symmetrical heading error

Previous studies show that the estimated positions of each shoe drift symmetrically in the PDR system [7]. Since the heading error is one of the factors causing the position error, we considered the tendency of the heading error for the symmetrical position.

The heading error can be assumed to be a linear model considering the error that increases with time due to the gyro bias or periodic gait motion, and the constant error such as alignment. The heading error by the assumption is expressed as follows for the k-th step.

$$\Delta\psi_k^i = \Delta\psi_{drift} + \Delta\psi_{bias} \qquad where\ \Delta\psi_{drift} = \alpha^i \cdot k\ , \tag{4}$$

where $i \in \{left(L),\ right(R)\}$ and α^i is drift rate, which is a similar magnitude but the opposite sign for each shoe.

The walking trajectory is a straight line, but the direction of the shoe is not parallel to the trajectory, and there is slight fluctuation. It is assumed that the stride direction obtained through the position difference between two steps is heading. The average of the stride headings of each shoe is defined as the walking direction. Since the errors varying with time are canceled each other and the constant error is smaller than the largest of both heading errors, it can be assumed that the walking direction is relatively accurate. It can be assumed that the error caused by the bias is small because the gyro bias is estimated through on-time status before the start of the walk.

$$\psi^i = \tan^{-1}\left(\frac{p^i_{E,k} - p^i_{E,k-1}}{p^i_{N,k} - p^i_{N,k-1}}\right), \tag{5}$$

$$\Delta\psi_{WD} = \frac{1}{2}(\psi^L + \Delta\psi^L + \psi^R + \Delta\psi^R) = \psi + \frac{1}{2}(\Delta\psi^L_{bias} + \Delta\psi^R_{bias})\ . \tag{6}$$

3.2 PDR system using dual foot-mounted IMU

In this section, we propose a method to correct heading error using dual foot-mounted IMU. The previous researches proposed a method to correct the position difference of both shoes to within a certain boundary [8,9]. However, the error can not be reduced less than the position boundary, and the boundary will not be constant for various gait motion. First, we need to detect a straight walk that can identify symmetric heading errors. Then, the heading error is reduced through a filter that uses the walking direction as a measurement value when walking on a straight line.

Straight Trajectory Detection. In order to use the heading error characteristic, it is required to determine whether the pedestrian is walking on a straight line. We determine this situation using heading up to five steps before the current step. The variance for the five-step heading and the difference between the current heading and average of the previous headings are the criteria for judging.

$$\mathrm{var}(\psi_{k:k-5} < \theta_{th}\ \ and\ \ (\psi_k - mean(\psi_{k-1:k-5})) < \theta_{th2}\ , \tag{7}$$

where θ_{th} and θ_{th2} denote thresholds, and ψ_k is stride direction at k-step.

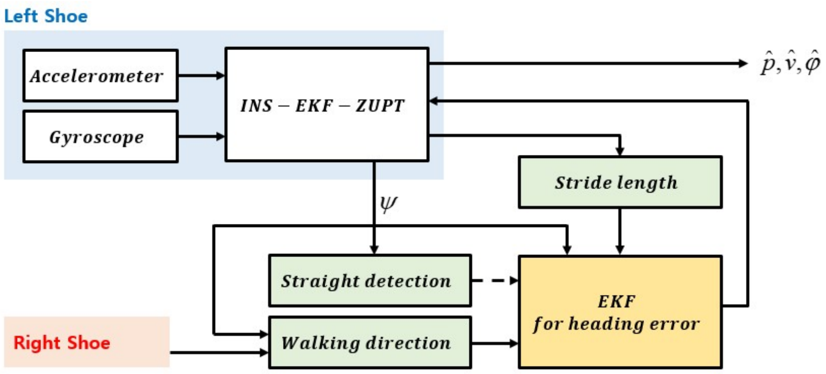

Fig. 2. The PDR system using dual foot-mounted IMU

Estimating Heading Error. We considered the walking direction as a similar concept to the dominant direction and designed the filter to use it as the measurement value. The position of each step including the heading error is as follows

$$\begin{aligned} p_{X,k} &= p_{X,k-1} + SL \cdot \cos(\psi + \Delta\psi) \\ p_{Y,k} &= p_{Y,k-1} + SL \cdot \sin(\psi + \Delta\psi) \end{aligned}, \tag{8}$$

where SL is stride length. To estimate the heading error, the error-state of EKF consist of four-element, which is expressed as follows:

$$\delta\mathbf{x} = \begin{bmatrix} \delta p_N & \delta p_E & \delta\Delta\psi_{bias} & \delta\Delta\psi_{drift} \end{bmatrix}^T. \tag{9}$$

The δp_N and δp_E are position errors, $\delta\Delta\psi_{bias}$ and $\delta\Delta\psi_{drift}$ are heading error elements.
The state transition matrix is

$$\mathbf{\Phi} = \begin{bmatrix} 1 & 0 & SL \cdot (-\cos\psi \sin\Delta\psi - \sin\psi \cos\Delta\psi) & 0 \\ 0 & 1 & SL \cdot (\cos\psi \cos\Delta\psi - \sin\psi \sin\Delta\psi) & 0 \\ 0 & 0 & 1 & t_{step} \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{10}$$

The process error covariance for time propagation is designed as follows:

$$\mathbf{Q} = diag\begin{bmatrix} 0 & 0 & (\sigma_{\Delta\psi_{bias}})^2 & 0 \end{bmatrix}. \tag{11}$$

Here $\sigma_{\Delta\psi_{bias}}$ denotes the variance of process noise and design the appropriate value.

When straight-line detection is detected from straight detection, the filter performs the measurement update. Fig. 2 shows the heading correction diagram for the proposed algorithm. The blue (red) box of Left (right) shoe means the PDR system of Fig. 1, and Fig. 2 shows the focus of the left shoe. It has the same structure for the right shoe.

4 Experimental Results

To verify the performance of the proposed algorithm, we used the Xsens mtw sensor. The pedestrian moved 76 m along the straight path and experimented 20 times. Fig. 3

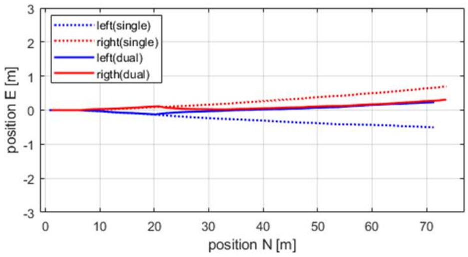

Fig. 3. The trajectory comparison of single IMU and proposed method

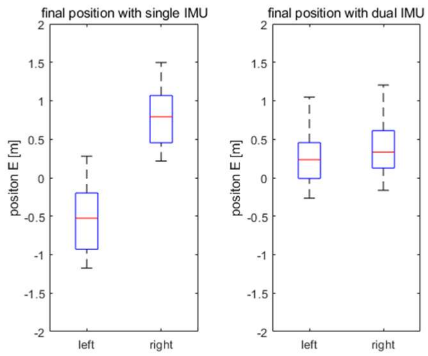

Fig. 4. The position error at the last step (E-axis)

is the mean of estimated trajectory to apply the algorithm. It can be found that the position error is reduced when the proposed algorithm is used. Fig. 4 indicates the estimated position of the last step. Position E has an error due to the heading error. When the proposed algorithm is applied, it can be seen that the error distribution is close to zero. This means that the proposed algorithm reduces the heading error.

5 Conclusion

In this paper, we proposed a method to correct the heading error of the PDR system using dual foot-mounted IMU. The proposed method uses the walking direction based on the heading error characteristics of both shoes as a measurement value. We set the correction interval as a straight line walking condition that can observe the symmetrical error and corrected the heading instead of the position. Even if there is no prior information such as building direction, the effect of reducing heading error can be obtained only by two IMUs. Experimental results show that the proposed algorithm improves the estimation performance.

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