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A Novel Heading Estimation Algorithm for Pedestrian Using a Smartphone Without Attitude Constraints

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***Abstract*—Pedestrian Dead Reckoning is an algorithm which uses sensors such as accelerometer, gyroscope and magnetometer to provide real-time location services. Since these sensors are integrated into smartphones, smartphone based PDR system becomes an efficient alternative of indoor positioning method. Heading estimation is a crucial part of PDR system, because step length of a pedestrian can be well modelled and a slight deviation may result in huge cumulative positioning error. Several algorithms have been proposed for heading estimation, but they need the smartphone to keep relatively stationary to the pedestrian, which is inconvenient and difficult to popularize. To remedy these disadvantages, we provide a novel method of estimating moving direction of the pedestrian using data from accelerometer. It allows different smartphone holding postures and relative motion between the pedestrian and his phone. After applying this method, it's unnecessary for pedestrian to maintain the same attitude angles of the smartphone for positioning. The experiment result shows that this method performs robust and accurate results under different smartphone holding postures. The PDR assisted with this method makes a good performance of positioning under different smartphone holding postures.**

Keywords—Heading estimation; accelerometer; pedestrian dead reckoning; smartphone.

I. INTRODUCTION

With widespread application of Global Navigation Satellite System (GNSS), Location Based Services (LBS) has been widely applied outdoors. However, GNSS signals are degraded or denied in indoor environments. Therefore, it has been one of the most important research hotspots to achieve reliable and accurate indoor navigation and positioning [1].

Increasing computational and sensing capabilities of smartphone boost emerging technologies applied in personal LBS applications [2]. Indoor positioning system based on wireless networks, such as Wi-Fi, Ultra Wideband (UWB), cellular network and Bluetooth, are growing rapidly in importance [3, 4]. However, being dependent on external hardware support restricts its further development. The crowd sensing based mobile indoor localization is enabled by sensor-rich smartphones, but there are still a lot of unsolved problems which hinder the concept of transferring into a practical system [5]. Simultaneous Localization and Mapping (SLAM) is a critical issue of autonomous vehicle navigation that has been studied over many years in both computer vision and robotics communities. Visual SLAM, which uses cameras as the sensor inputs, is favorable to be applied in platforms where the requirement of cost, energy, and weight of the system is limited [6]. But this method needs the camera open, which is inconvenient to users. Pedestrian Dead Reckoning (PDR) is an algorithm using information from sensors such as accelerometer, gyroscope and magnetometer to provide real-time positioning services [7]. Since these sensors are integrated into smartphones, using smartphone based PDR system becomes an alternative of indoor positioning methods, which can provide location with high precision and low cost [8, 9].

PDR system estimates the heading and step length from gait information of a pedestrian to calculate the current position of the pedestrian from the previous position [10]. Since PDR is a relative method, the positioning error will be accumulated over time. The heading estimation dominates the positioning accuracy because step length can be well modelled according to many research [11]. The mainstream heading estimation algorithm needs the user to hold the smartphone to keep the same heading. Some other algorithms allow existing constant offset between the heading of the user and smartphone or different fixed placement of smartphone in other words, such like being held in hand or attached on some parts of the body of the user [12]. That is, most of techniques require that the smartphone should keep relatively stationary to the pedestrian when applied these methods, which is too inconvenient to be popularized. In our daily life, we use our smartphones in different ways. For example, a smartphone may be placed in pocket or purse for female, and it would be held near ear when the user receives a

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call. In these cases, the heading of smartphone is changing rapidly and is different from heading of the pedestrian, so that most algorithms can't be applied. To remedy these disadvantages, we provide a novel method of estimating moving direction of pedestrian using data from accelerometer, which allows different smartphone holding postures and relative motion between pedestrian and the phone. After applying this method, it's unnecessary for pedestrian to maintain the same attitude angles of the smartphone for the whole process of positioning.

II. PRINCIPLES

With the development of Micro-Electromechanical Systems (MEMS) manufacturing technology, accelerometer has been integrated into smartphones to assist daily use. So we can apply accelerometer to obtain acceleration data of the user in body frame of smartphones. It's easy for us to get displacement of the user from linear accelerometer measurements with double integration algorithm [13].

However, double integration algorithm may speed up the accumulation of localization errors. In just a few seconds, the errors will reach meter level. Therefore, we don't use acceleration data to calculate the displacement of the user immediately. We obtain the speed vector from linear acceleration with integral calculation, which can reduce the computation cost and localization errors as well. Then we use the speed vector of the user to get the heading by inverse trigonometric function.

To project the acceleration data to geodetic coordinate system, we utilize Attitude and Heading Reference System (AHRS) to get the attitude of smartphone relative to the geodetic coordinate system. Then, acceleration in geodetic coordinate system will be obtained for heading estimation [7]. Figure 1 shows the flowchart of the principle of our method.

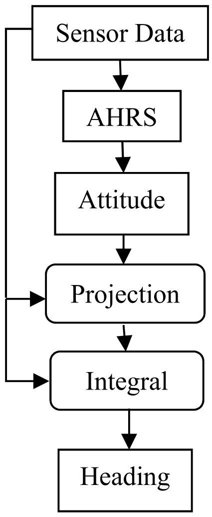

Fig.1. Flow chart of our proposed algorithm

A. Attitude and Heading Reference System

Generally, AHRS can provide at least three Euler angles including bank, elevation and azimuth, i.e. it can determine the attitude of the body relative to the geodetic coordinate system. To achieve this function, AHRS should consist of several three-axis orthogonal sensors. Magnetic, Angular Rate and Gravity (MARG) sensors is one of typical configurations. Because MARG sensors have 9 axes in sum, MARG sensors based AHRS can be also called 9 Degree Of Freedom AHRS (9DOF AHRS). Also, when just Inertial Measurement Units (IMU), i.e. 3-Axis Accelerometer and 3-Axis Gyroscope, are applied, the system can be called 6DOF AHRS. The difference is that 9DOF may be influenced by distortion of indoor electromagnetic environment, and 6DOF needs initial alignment and may cause accumulated heading error after long time running [14]. Therefore, we need to start 9DOF at the beginning for the initialization of 6DOF. Here we applied an adapted AHRS (A-AHRS) to fuse 9DOF and 6DOF according to some features of magnetic field including magnitude, horizontal and inclination components [15, 16]. Through this method, we can obtain a comparatively accurate attitude of the sensor frame relative to the earth frame.

B. Projection of Acceleration

Since we can get attitude from AHRS in form of Euler angle, then we need to build a coordinate transformation matrix to project the acceleration data into the resolving frame, that is, coordinate system consisting of coordinate axes representing motion of the object [16].

Assuming that the Euler angle representing the transformation from the coordinate system β into the coordinate system α is shown as Equation (1),

$$\Psi_{\beta\alpha} = \begin{pmatrix} \Phi_{\beta\alpha} \\ \theta_{\beta\alpha} \\ \psi_{\beta\alpha} \end{pmatrix} \tag{1}$$

we can get the coordinate transformation matrix as shown below [7].

$$C_\beta^\alpha = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\Phi_{\beta\alpha} & sin\Phi_{\beta\alpha} \\ 0 & -sin\Phi_{\beta\alpha} & cos\Phi_{\beta\alpha} \end{pmatrix} \begin{pmatrix} cos\theta_{\beta\alpha} & 0 & -sin\theta_{\beta\alpha} \\ 0 & 1 & 0 \\ sin\theta_{\beta\alpha} & 0 & cos\theta_{\beta\alpha} \end{pmatrix} \begin{pmatrix} cos\psi_{\beta\alpha} & sin\psi_{\beta\alpha} & 0 \\ -sin\psi_{\beta\alpha} & cos\psi_{\beta\alpha} & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{2}$$

Here, $\Phi_{\beta\alpha}$ represents bank angle, and $\theta_{\beta\alpha}$ is elevation angle, and $\psi_{\beta\alpha}$ is azimuth angle.

After applying this matrix to acceleration vector, the acceleration data can be projected into another frame, the earth frame in our paper [18].

C. Integral Computation of Acceleration

Experimental results show that it's impossible to get heading from projected acceleration data, because the low quality of accelerometer embedded in smartphone and interference caused by excessive movement of human body. Moreover, it's unnecessary for PDR system to estimate the heading all the time. Actually, we only need to know the heading of every step of the user so that we can calculate the current position from the previous one.

Therefore, we decide to use the result of the integral of acceleration to calculate the heading. To be more concrete, we use the integral of acceleration data during every two step. From experiment, we found that the speed obtained from the integral of acceleration from the beginning would deviate from the ground truth obviously if we had walked about ten steps along a straight line. Also, using integral of fewer steps will save more time of computation than the former.

The reason using one stride for integral instead of one step is that human will swing slightly when they walk, which means they will generate acceleration vertical to the moving direction [19, 20]. This acceleration will influence the heading estimation function. So we choose this simple way to eliminate this influence. This phenomenon and the solution will be discussed in detail in the following part.

III. METHODOLOGY

The process of this method includes four parts: collecting data of acceleration according to motions of the user from an accelerometer embedded in a smartphone, extracting acceleration information towards the direction of pedestrian using digital signal processing, projecting the acceleration information to the geodetic coordinate system, and determining the moving direction through calculating an included angle between the heading and the north direction of geodetic coordinate system. Figure 2 shows the detailed flow chart of this method.

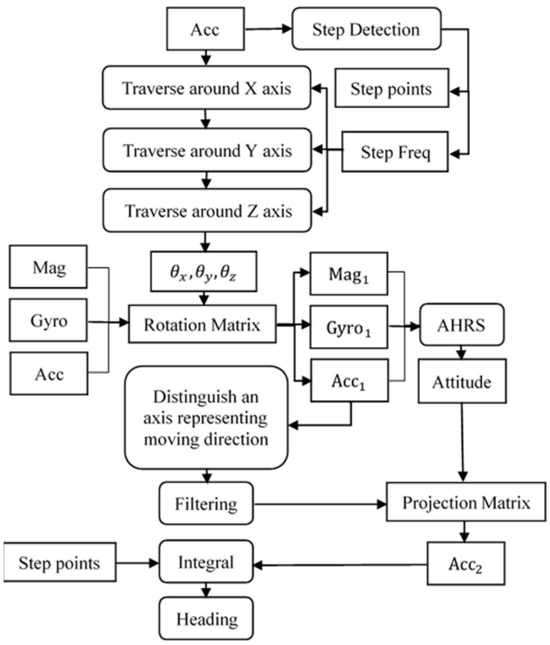

Fig.2. Flow chart of the main process of our method

In Figure 2, "Acc" means acceleration data. "Mag" means magnetic field data, and "Gyro" means data from gyroscope. The traverse around three axes of the body frame includes digital signal processing to find a rotation matrix to rotate body frame so that one of axes of smartphone coordinate system can represent the moving direction of the pedestrian, which is prepared for filtering. Therefore, different filters can be applied in three axis components of acceleration data including lowpass filter and bandpass filter. The rest parts have been introduced in the previous section.

A. Collection of Sensor Data and Step Detection

Although we only need acceleration data for heading estimation, magnetic field data and gyroscope data are also needed for AHRS to calculate attitude of the smartphone. All sensor data are collected by smartphones. Here, we apply step detection module to calculate step points for the following processing.

B. Digital Signal Processing of Acceleration Data

In this section, we will describe the processing of acceleration data in frequency domain in detail.

Figure 3 shows the waveform of raw acceleration data after FFT in frequency domain. The acceleration data were collected by smartphone held in hand like texting message, which means the Y axis of sensor frame represents the moving direction of the pedestrian, and X axis is perpendicular to the moving direction.

Figure 4 shows the acceleration data in frequency domain, which were collected by smartphone held in hand like landscape, i.e. X axis of the smartphone represents the moving direction and Y axis is perpendicular to the moving direction.

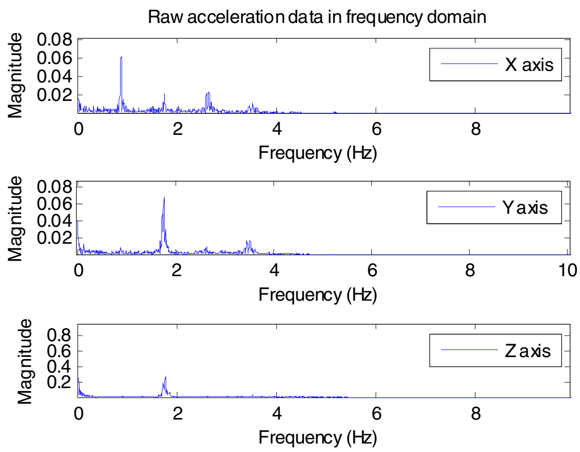

Fig.3. Raw acceleration data in frequency domain (Y axis represents moving direction)

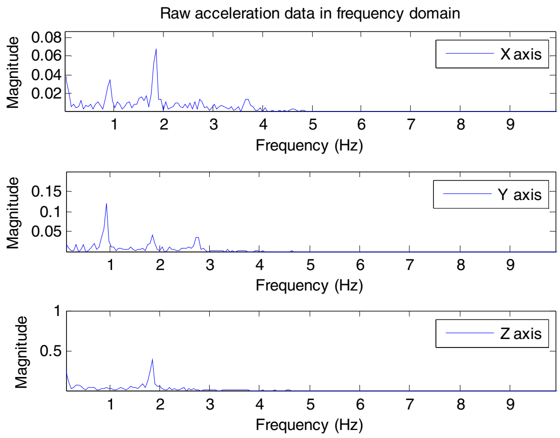

Fig.4. Raw acceleration data in frequency domain (X axis represents moving direction)

After comparing these two figures, we find that the waveform on the axis representing the moving direction has the max peak near 2 Hz, which is almost equal to the step frequency of human. And the waveform on the axis vertical to the moving direction has the max peak near 1 Hz, which is approximate to half of the step frequency of human. The swinging generated by a pedestrian walking every two steps is thought to be the main reason, according to the characteristics of human walking motion [21, 22]. This is also the reason why we use the integral of two steps for heading estimation. Moreover, the axis vertical to the ground has the max peak at the same frequency near 2 Hz, but with much higher peak value than the axis of moving direction. Therefore, we can use these characteristics to distinguish these three different axes. After experiment optimization, we use the ratio of the peak value at the step frequency and one at half step frequency to distinguish the axis of the moving direction and the axis perpendicular to the former one.

The reason why we need to distinguish these three axes is that we should apply different filters to the three axes. To filter the interference frequency components and retain valuable frequency components, a lowpass filter is applied to the axis of the moving direction with cut-off frequency slightly larger than step frequency and bandpass filters are applied to the other axes to extract components at step frequency [23]. After processed in frequency domain, the acceleration data become available for the following data processing flow.

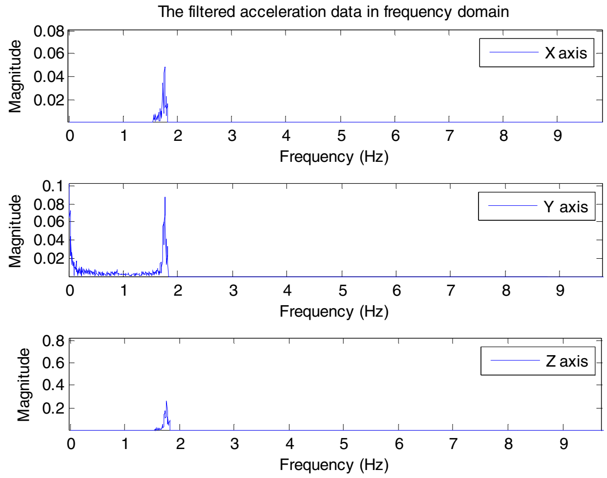

Fig.5. The filtered acceleration data in frequency domain

Figure 5 shows the acceleration data after filtering in frequency domain compared to the raw acceleration in Figure 3.

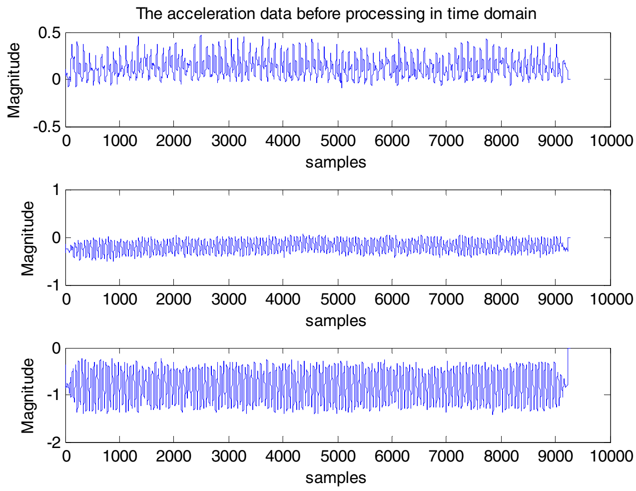

Fig.6. The acceleration data before filtering in time domain

Figure 6 and 7 show the effect of filtering. The data shown in Figure 3, 5, 6 and 7 are the same one. We can find that the data after processing have more obvious regular pattern. Although the data after filtering has been minified in magnitude, it won't influence the result of heading estimation because the ratio of integral will eliminate this effect.

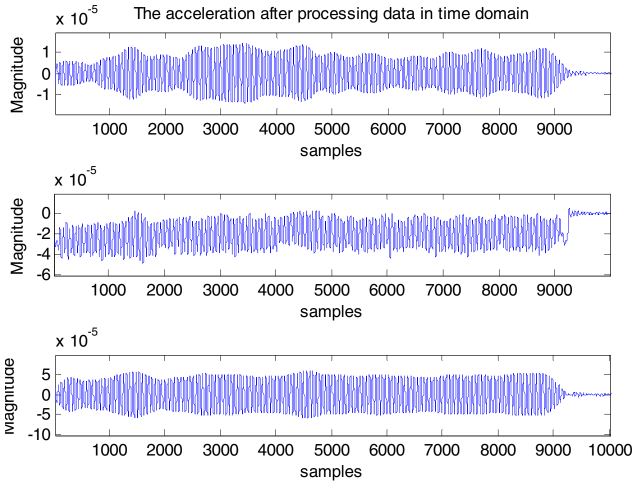

Fig.7. The acceleration data after filtering in time domain

The processing procedure mentioned above is on the basis of that one of axes of smartphone coordinates is parallel to the moving direction. To achieve positioning with more flexible ways of holding smartphone, we need to figure out one way to make one axis represents the moving direction, i.e. to find the value of $\theta_x, \theta_y, \theta_z$ in Figure 2. Therefore, we choose to make the three axes traverse the rotation of 0 to 90 degrees. But there are still some differences of processing on the traverse of different axes. The following parts are the detailed introduction of traverse which has been shown in Figure 2.

- Traverse around X axis. In every angle of traverse, we use Equation (2) to get the rotation matrix [24], and project acceleration data into another coordinate system. Then a lowpass filter is applied to eliminate the high frequency interference. Next, the acceleration data are transformed into frequency domain by FFT, and save the peak value at the mean step frequency. In the whole process of traverse, we need to find the maximum of peak value at around step frequency on the axis which has the maximum magnitude of the peak. When the maximum is found, the traverse can be stopped and angle is recorded as θ_x.

- Traverse around Y axis. We should rotate the raw acceleration data around X axis for θ_x. The other process of every angle in traverse is same as one in traverse around X axis. When the maximum is found, the traverse can be stopped and angle is recorded as θ_y.

- Traverse around Z axis. Same as traverse around Y axis, we should rotate the raw acceleration data around X, Y axes for θ_x and θ_y respectively. In every angle of traverse, the acceleration data are transformed into frequency domain by FFT, and calculate the ratio of the peak value at the mean step frequency and half mean step frequency. Then distinguish the axis of moving direction by the ratio, and save the peak value at step frequency on this axis. In the whole process of traverse, we need to find the maximum. Once the maximum is found, the traverse will be stopped and angle is recorded as θ_z.

The traverse around each axis will also influence the acceleration data on other axes. After the traverse, we get $\theta_x, \theta_y, \theta_z$ and rotate raw acceleration data by the rotation matrix generated by Equation (2) consisting of $\theta_x, \theta_y, \theta_z$. The rotated acceleration data can be available for the following filtering processing when one of smartphone axes represents the moving direction which is introduced before.

However, there are still lots of calculations in traverse. So we apply dichotomy to approximate the desired angles.

C. Projection of Acceleration Information

Use $\theta_x, \theta_y, \theta_z$ to rotate raw sensor data from accelerometer, gyroscope and magnetometer. Then the rotated sensor data are used to calculate attitude by AHRS. Next we can use the attitude to obtain the coordinate transform matrix by Equation (2). The acceleration after digital signal processing can be projected into earth frame by multiplying the coordinate transform matrix.

D. Determination of the Moving Direction

We use the step points to achieve the integral of the acceleration data during every two steps. Then we will apply arctangent to calculate an angle from the integral. The included angle is regarded as the heading of the pedestrian. So far, we have achieved heading estimation. Combined with the results of step length estimation, the position and walking trajectory of the pedestrian can be calculated.

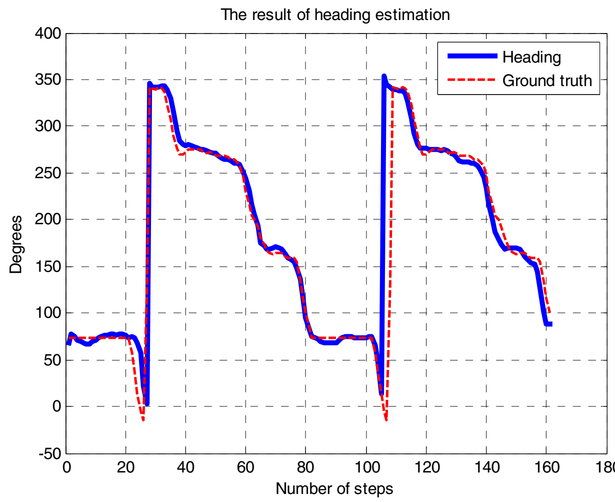

Fig.8. The result of heading estimation

Figure 8 shows the heading estimation result using data shown in Figure 7. Actually, this experiment was carried out by walking along the aisle for two circles with a smartphone in a typical office. We can see the obvious periodicity of the change of the heading in Figure 8. And in Figure 9, we can see more intuitive result of positioning.

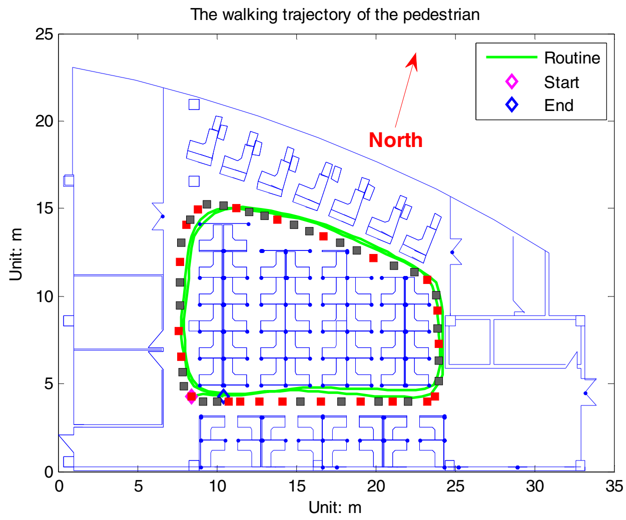

Fig.9. The walking trajectory of the pedestrian

Figure 9 shows the localization result of PDR system assisted with the proposed method. The green trajectory is the result of localization calculated by PDR system. The red and black blocks are the reference points used for evaluation of positioning.

IV. EXPERIMENTS

To verify the feasibility of this method of heading estimation, a series of experiments were carried out. The sample rate was set to 100Hz. Table I shows the information about the sensors and operating system of the smartphone utilized for testing.

TABLE I. DEVICE DESCRIPTION OF SMARTPHONES USED FOR TESTING

Devices	**Device Description**			
	Operating System	***Accelerometer***	***Gyroscope***	***Magnetometer***
Nexus 5	Android 6.0.1 (32- bit)	InvenSense MPU6515	InvenSense MPU6515	AKM AK8963

Several tests under different ways of holding smartphone are carried out including texting mode, photo mode, calling mode and pocket mode [25]. A pedestrian carried a smartphone by different modes and started to walk. After the data acquisition, we analyzed the data by our algorithm and gave the result of heading estimation and PDR positioning as well.

A. Testing by Nexus 5

1) Texting mode: In this mode, the user carried the smartphone like texting message, i.e. its Y axis representing the moving direction. As shown in Figure 8 and 9, the results of heading estimation and positioning demonstrate the basic performance of our algorithm. The 95 percentile localization error is smaller than 1 meter. The heading error analysis evaluated by root-mean-square error (RMSE) is shown in Table II. The summary of localization error under different carrying modes is shown in Table III.

2) Photo mode: In this mode, the user carried the smartphone like taking photos or recording a video, i.e. the moving direction is on the Z axis of the smartphone.

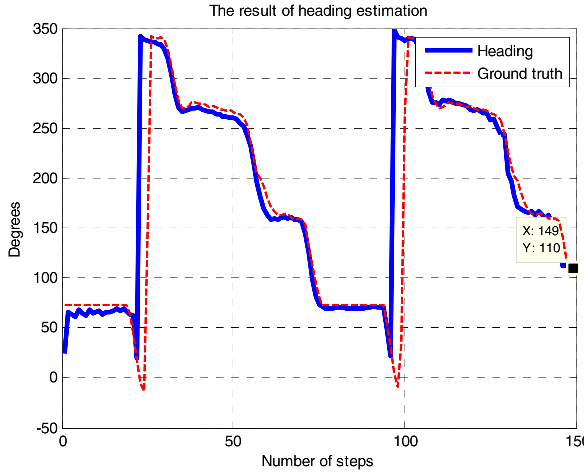

Fig.10. The result of heading estimation on photo mode

From Figure 10, we can find that the estimated heading is almost the same with the ground truth direction. The concrete heading error is shown in Table II.

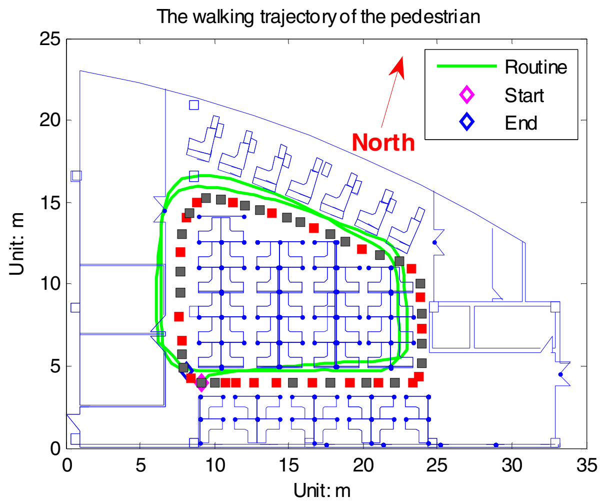

Fig.11. The walking trajectory on photo mode

Although the walking trajectory is seemed not to coincide with the ground truth, the major factor caused this problem is thought to be the error of step length estimation. From Figure 11, we see that the trajectory is parallel to the ground truth in most of the time.

3) Calling mode: In this mode, the user carried the smartphone like making or receiving a call, i.e. the smartphone is put near the ear.

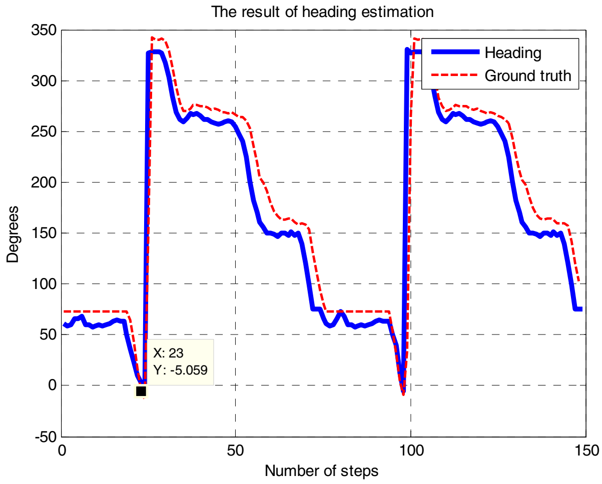

Fig.12. The result of heading estimation on calling mode

In calling mode, the result of heading estimation is not good as the result in texting mode and photo mode. The reason we guess is that the conduction of force may be different from the one in texting mode. So the characteristics of acceleration data may change to some degree.

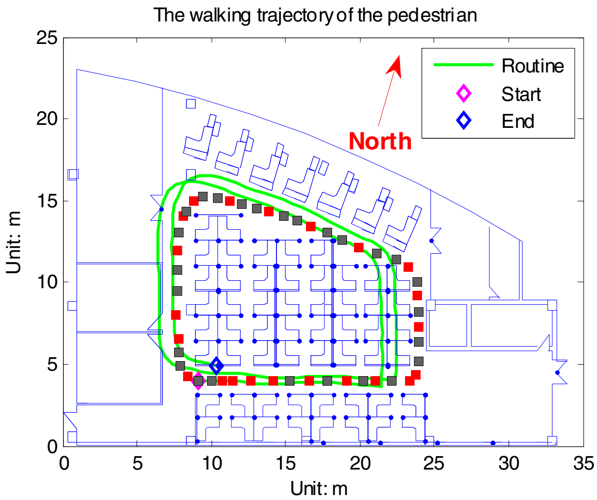

Fig.13. The walking trajectory on calling mode

In this mode, the result of localization is seemed to have the same problem as the one in photo mode. But also we can find that the trajectory is parallel to the ground truth in most of the time in Figure 12 and 13. Therefore, to evaluate the result heading estimation, we can ignore this problem.

4) Pocket mode: In this mode, the smartphone was carried in the trousers pocket of the user.

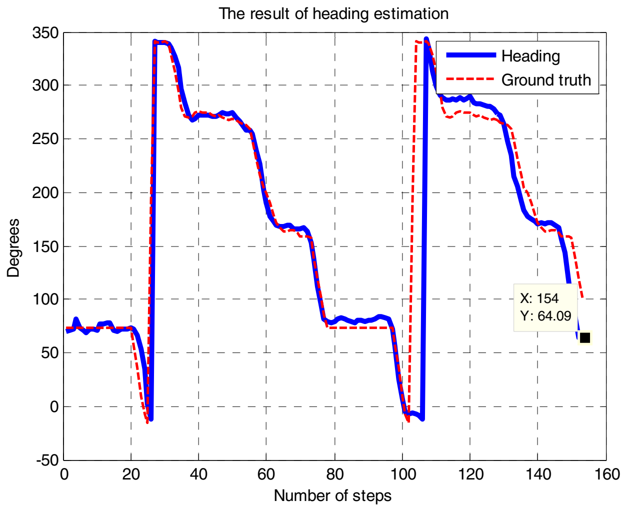

Fig.14. The result of heading estimation on pocket mode

In pocket mode, the result of heading estimation coincides with the ground truth to some degree, especially the heading of the first circle of walking trajectory. However, we can find that the heading tends to deviate from the ground truth, which influences the result of localization shown in Figure 15. We consider the main reason lies in the calculation of attitude angle, because we utilize AHRS 6DOF to calculate the attitude of the smartphone as a result that magnetometer is easily influenced by the electromagnetic field in indoor environment [26, 27]. But this treatment can cause cumulative error after a long time of running. Also, there may exist other problems leading to this phenomenon.

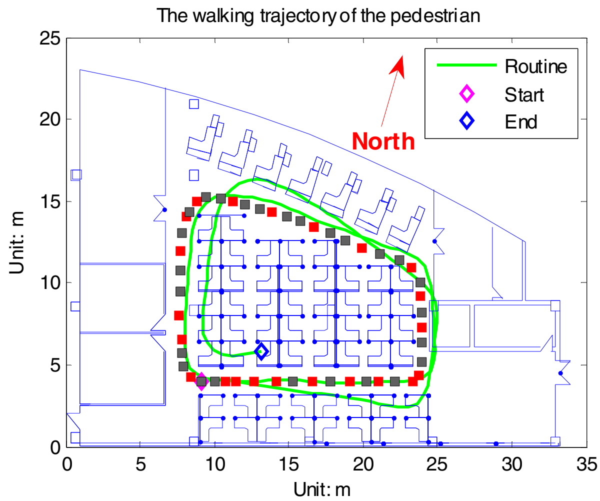

Fig.15. The walking trajectory on pocket mode

In this mode, the result of localization is seemed to be a little worse than the results in other modes, especially in the second circle of the walking trajectory. The main cause is explained before.

TABLE II. HEADING ERROR ANALYSIS OF NEXUS 5

Items	*Texting mode*	*Photo mode*	*Calling mode*	*Pocket mode*
RMSE	0.5642°	2.3182°	8.4815°	4.5248°

Table II shows the results of heading error analysis of this method in all modes using RMSE as evaluation criteria. We can find that in texting mode, this method works best, compared with ones in other modes.

TABLE III. LOCALIZATION ERROR ANALYSIS OF NEXUS 5

Items	***Texting mode***	***Photo mode***	***Calling mode***	***Pocket mode***
Mean error	0.43m	0.85m	0.70m	0.71m
95% error	0.71m	1.57m	1.60m	1.73m

Table III shows the summary of localization error analysis of this method in all modes. The factors influence localization accuracy include heading and the step length of the user. Although the heading accuracy under calling mode is worse than the one under photo mode, we can't ensure the localization error under photo mode is smaller. Also, from Fig.11, we can see that the main factor resulting in worse localization is the accumulated error of the step length, which verifies the shortcomings of PDR system. But we see that the mean positioning accuracy in all modes is smaller than 1 meter. Therefore, the PDR system assisted with this method of heading estimation make a good performance

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V. CONCLUSION

This paper proposes a novel method using acceleration information to estimate the heading of the pedestrian. The advantage of this approach is that there is no constraint on the ways of holding smartphones. Experimental results demonstrate that this method of heading estimation performs robust and accurate results under different smartphone holding postures. The PDR assisted with this method makes a good performance of positioning under different modes of smartphone holding postures.

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