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Pocket Mattering: Indoor Pedestrian Tracking with Commercial Smartphone

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***Abstract*—Heading estimation is a major problem for indoor PDR systems. For PDR systems based on smart phones in pockets, one new factor deteriorates heading estimation accuracy that mobile phones will swing during movement. Converting gyroscope readings into the world coordinate system will not help, for unreliable readings of magnetometers must be included. Concentrating on trousers' front pockets where mobile phones are usually carried, an interesting observation is found that swing of mobile phones will cause readings of gyroscopes lower than real angular velocity of person movement during turning or moving on curved paths, which is called Turn Insufficient Effect and proved with geometric analysis. Motivated by this observation, this paper presents an indoor Pedestrian tracking system based on one Smart phone residing in trousers' front Pocket (PSP), exploiting only built-in accelerometers and gyroscopes. PSP extends the feedback control system of HDE (Heuristic Drift Elimination), compensating not only for drift bias of gyroscopes but also for Turn Insufficient Effect. A prototype of PSP is deployed on an Android based smart phone and evaluated with five participants under two indoor trajectories. The experimental results show that the average returning position error of PSP is 1.33% and 81% lower than HDE approach on the trajectory with repeated circles.**

Keywords-dead reckoning; pedestrian tracking; smartphone; gyroscope; heading

I. INTRODUCTION

The proliferation of Inertial Measurement Unit (IMU) has fostered the demand for Pedestrian Dead Reckoning (PDR) applications in GPS denied environments [1]. The major problem of PDR system is the accumulation of heading errors when only using IMUs. Magnetometers cannot provide precise heading estimation in indoor environments where the earth magnetic field may be superimposed by other magnetic fields or distorted by nearby ferrous materials. Recently, more and more smart phones are integrated with low cost IMUs. The performances of these o the shelf sensors are, however, far less accurate than non-commercial IMUs, further decreasing the precision of heading estimation.

In order to bound heading errors, J. Borenstein et al. [2] proposed Heuristic Drift Elimination (HDE) to calibrate gyro readings of the foot-mounted IMUs, exploiting an interesting feature that corridors and walls are straight and either parallel or orthogonal to each other in man-made buildings. When a walker turns or moves on curved paths, HDE simply suspends calibrating actions [3]. During that time, gyro drifts accumulate through integration.

For PDR systems based on smart phones, the sources of heading estimation error are not only drifts of low cost IMUs, but also swing of the phones during human movement. Because mobile phones are usually carried in pockets, not as fix-mounted as dedicated IMUs are. Concentrating on trousers' front pockets where mobile phones are usually carried, an interesting observation is found that swing of mobile phones will cause readings of gyroscopes lower than real angular velocity of person movement during turning or moving on curved paths. We call this fact Turn Insufficient Effect (TIE). So we improve the feedback control system of HDE, compensating not only for drift bias of gyroscopes but also for TIE.

This paper presents a Pedestrian tracking system based on one Smartphone residing in trouser' front Pocket (PSP), exploiting built-in accelerometers for stride detection and stride length estimation, and gyroscopes for heading estimation. A prototype of PSP is deployed on an Android based SAMSUNG smart phone, whose price is only about 360$. PSP is evaluated by five participants under two trajectories in indoor environments. The experimental results show that the average returning position error of PSP is 1.33% and 81% lower than HDE approach on the trajectory with repeated circles.

II. THE INDOOR TRACKING SYSTEM

We illustrate TIE and present PSP system in this section. PSP system is decomposed into the stride detection and length estimation part and the heading estimation part. For the first part, we implemented the stride detection algorithm with a little modification to [4] to adapt to the low cost accelerometers of smart phones, and utilized an experimental equation proposed in [5] to calculate the stride length. The following contents will emphasize on the illustration of TIE and present a detailed implementation of the heading estimation part of PSP.

A. Turn Insufficient Effect

Heading estimation is especially difficult for PDR systems based on smart phones, because the mobile phone is often not fix-mounted on human body, but casually carried in user's pockets. Swing of mobile phone in pockets is unpredictable as

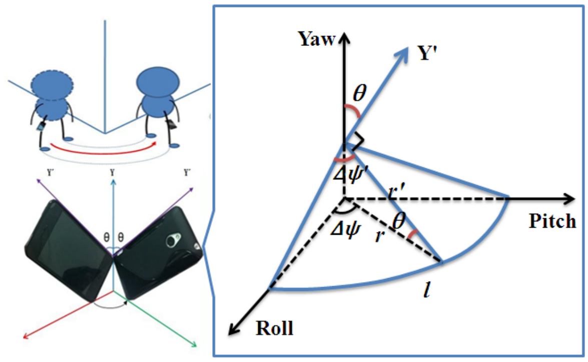


Figure 1. Illustration of Turn Insufficient Effect

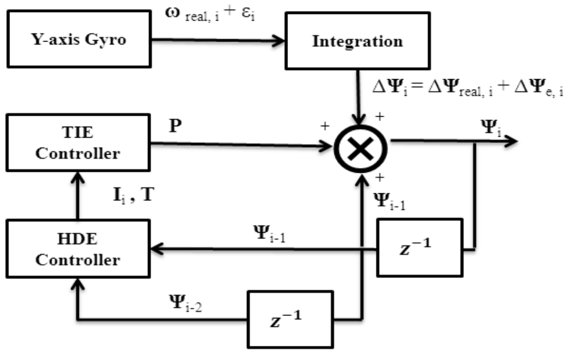


Figure 2. Block Diagram of PSP

the walk behavior is different from one step to another and from one person to another. So the gyroscope readings cannot be directly applied for heading estimation, which is evaluated with our experiments in next section.

A possible method to compensate for swing of the phone is to convert the gyroscope readings into the world coordinate systems, where Yaw readings will indicate the heading direction. The conversion process needs the input of magnetometers which are error prone in indoor environments. When the phone is put nearly straight in the front pocket, one interesting observation is discovered in our experiments, that swing will cause the Y-axis readings of gyroscope lower than the real angular velocity of person movement during turning, which is called as TIE.

A typical TIE example is demonstrated in Fig. 1. When a walker turns around a corner, his steering angle will be 90° around the physical axis of Yaw. And the phone is nearly straight in his pocket, whose gyroscope will record a steering angle around Y' axis of the phone coordinate system. It is observed that the steering angle recorded by gyroscope is always lower than the real steering angle when turning or walking on a curved path.

In order to analyze this observation, we use following notations as shown in Fig.1: θ, the angle between axis Yaw and Y'; $\Delta\Psi$, the steering angle in the world coordinate system for a short time period of Δt; r, the turning radius in the world coordinate system; l, arc length of the corresponding steering angle $\Delta\Psi$. And the angular velocity about the Yaw axis in world coordinate system is indicated as ω. $\Delta\Psi'$, r' and ω' are the corresponding notations in the phone coordinate system.

Theorem: $\omega' \leq \omega$, when travelling the arc of length l *for* Δt period.

Proof: According to geometry analysis,

$$\begin{gathered} l = r * \Delta\psi = r' * \Delta\psi',\ r = r' * \cos\theta. \\ so,\ \Delta\psi' = \Delta\psi * \cos\theta. \\ When\ \Delta t \to 0, \lim_{\Delta t \to 0} \frac{\Delta\psi'}{\Delta t} = \lim_{\Delta t \to 0} \frac{\Delta\psi}{\Delta t}\cos\theta. \\ so,\ \omega' = \omega * \cos\theta. \\ Finally,\ \omega' \leq \omega. \end{gathered} \tag{1}$$

Therefore, Y' readings will be lower than the real angular velocity. And the steering angle $\Delta\Psi'$ integrated from Y' readings will be lower than $\Delta\Psi$ according to (1), which is observed in our experiment shown in next section. TIE indicates that Y' values of gyroscope on smart phones should be compensated during turning process.

This motivates us to construct our heading estimation algorithm. As the angle θ is caused by swing and not predictable, it is still an important challenge on how to compensate TIE, which will be answered in next subsections.

B. Heading Estimation

Upon detection of a stride, it is necessary to estimate the heading of this stride in order to calculate the next displacement of a person. Gyroscopes are useful for heading estimation, for they are much less noisy than accelerometers or magnetometers, and relatively immune to environmental disturbances. However, gyroscopes measure angular velocity, which must be numerically integrated to produce heading information, so heading errors will accumulate over time without bound. In addition, TIE will add new heading errors. HDE only deal with drift, so we make some enhancement to the feedback control system of HDE, compensating not only for drift bias of gyroscopes but also for TIE. Fig. 2 shows the diagram of PSP algorithm.

The detailed implementation of PSP is as following:

Initially, the user's heading is set to be his current walking direction. During the walking process, Y readings of gyroscope between the starting and ending time of a detected stride i are integrated to get the increment angle $\Delta\psi_i$. Then the estimated heading ψ_i at stride i will be the summation of $\Delta\psi_i$, ψ_{i-1} and the compensation signal P.

Signal P is calculated by HDE controller and TIE controller. HDE controller is used to compensate heading errors when the user is walking on straight paths. So it is needed to determine whether the user is walking straight or turning. Turning detection is calculated through (2).

$$T = \begin{Bmatrix} 0, if\ |\psi_{i-1} - \psi_{i-2}| < Th \\ 1, if\ |\psi_{i-1} - \psi_{i-2}|\ > Th \text{ and } \psi_{i-1} > \psi_{i-2} \\ -1, if\ |\psi_{i-1} - \psi_{i-2}|\ > Th \text{ and } \psi_{i-1} < \psi_{i-2} \end{Bmatrix} \tag{2}$$

Th is a constant threshold and we choose *Th* = 10°, ψ_{i-1} and ψ_{i-2} are the prior two estimated headings of current stride *i*. *T* = 0 means that the user is walking on a straight path and no turning happens. *T* = 1 means that the user is turning left. If the user is turning right, *T* = -1.

HDE compensation process in [2] is shown in (3), where I_i stands for the compensation value of HDE on stride *i*, c is a small constant increment that compensate for heading errors for every sample point, and *n* is the sample number in a detected stride.

$$I_i = \begin{Bmatrix} I_{i-1} - n * c, \psi_{i-1} > 45^\circ \\ I_{i-1}, \qquad \psi_{i-1} = 45^\circ \\ I_{i-1} + n * c, \psi_{i-1} < 45^\circ \end{Bmatrix} \qquad (3)$$

However, HDE compensation in (3) is an oscillating process that the estimated heading varies around a dominant direction. For example, the estimated heading ψ_{i-2} is to the right of the dominant direction at the detected stride *i-2*, and ψ_{i-1} is to the left of the dominant direction, I_i should be 0 directly in order to attenuate oscillating of compensation value. So we add (4) to limit oscillating.

$$I_i = 0, if\, (\psi_{i-1} - 45) * (\psi_{i-2} - 45) \le 0. \qquad (4)$$

Signal *T* and I_i are passed from HDE controller to TIE controller. TIE controller first records the value of I_i and pass the I_i out if *T* = 0, indicating that it does not work on the straight path. If *T* ≠ 0, TIE controller should work to compensate the heading error caused by swing of the phone during turning.

As swing is somehow a random behavior even during one stride, it is hard to quantify. And swing of the phone happens not only during the walking process of turning but also on a straight line. This gives us a clue that HDE controller's feedback value I_i is not only caused by drifts of the gyroscope, but also by swing of the phone. So the average of all I_i values contains the elements of swing of the phone when walking on the straight line, which can be used for compensation of TIE. The result is verified through experiments in next section.

Therefore, the output signal of TIE controller is shown as (5), where $\bar{I}$ is the average of all compensation values derived from HDE on a straight path and recorded by TIE controller.

$$P = \begin{Bmatrix} I_i, if \;\; T = 0 \\ T * \bar{I}, if \;\; T \neq 0 \end{Bmatrix} \qquad (5)$$

Finally, the user's heading ψ can be calibrated as follows:

$$\psi_i = \Delta\psi_i + \psi_{i-1} + P.$$

III. EXPERIMENTS AND RESULTS

The performance of an implemented prototype of PSP has been evaluated, comparing to HDE, Gyro and Magnetometer readings directly used approaches.

TABLE I. AVERAGE RETURN POSITION ERRORS (m)

Trajectory	PSP	HDE	Gyro	Magnetometer
I	1.967	2.134	20.547	19.410
II	3.868	19.922	22.112	25.796

A. Experimental Setup

We have deployed a PSP prototype on a commercial Android based smartphone, Samsung Galaxy R [6], whose price is only about 360$. This model of smart phone can simultaneously log accelerometer, gyroscope and magnetometer signals with a frequency of nearly 100Hz. During our experiments, the smart phone was placed nearly straight in trousers' front pockets. Five users walked on two trajectories: Trajectory I only composed of straight paths and Trajectory II included a long circular path which is repeated for 5 times, as shown in Fig. 3(a) and 3(b). Both trajectories are closed, whose total length are 204.0m and 290.0m respectively.

B. Results

After analyzing 50 tests with five participants on both trajectories, the average returning position errors are compared in Table I. The results confirmed that PSP performs better than other approaches, especially when circular paths are included.

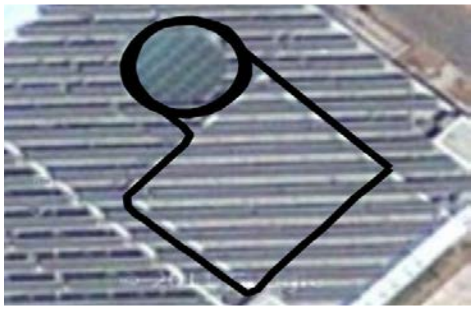
Some samples of tracking results concerning one male user are shown in Fig. 3. Fig. 3(c) and 3(d) demonstrate that at each corner, the steering angle estimated from Gyro is less than the real steering angle, indicating that Gyro suffers from TIE. And gyro drift also accumulates during the integration process. The two factors lead to a large returning position error comparing HDE to PSP. Meanwhile, the heading results estimated directly from magnetometer are also unreliable as shown in Fig. 3.

Both PSP and HDE methods perform quite well in eliminating the drift of heading by taking the advantage of the dominant directions on trajectory I, as shown in Fig. 3(c) and 3(d). But Fig. 3(e) and 3(f) show that PSP is more precise than HDE on Trajectory II. The reason is that when the user walks on a circular path, HDE simply suspends its correction action, but errors due to TIE adds up, leading to large heading errors after a long curved path. PSP exploits signal *P* to compensate heading errors effectively. The average returning position error of PSP is 1.33% and 81% lower than HDE approach on Trajectory II, confirming compensation improvement of TIE.

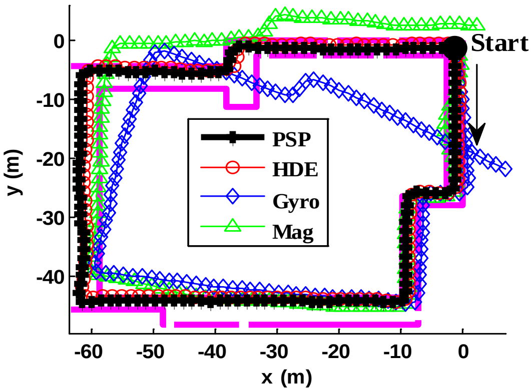
IV. CONCLUSIONS

This paper presented PSP, an indoor Pedestrian tracking system using one Smartphone residing in trousers' front Pocket. The key point is the observation that swing of mobile phones in trousers' pockets will cause readings of gyroscopes lower than real angular velocity of person movement during turning or moving on curved paths. PSP improves the feedback control system of HDE, reducing errors due to gyro drift and Turn Insufficient Effect. Experimental results have shown that PSP achieved a low level of returning position error, and outperformed HDE.

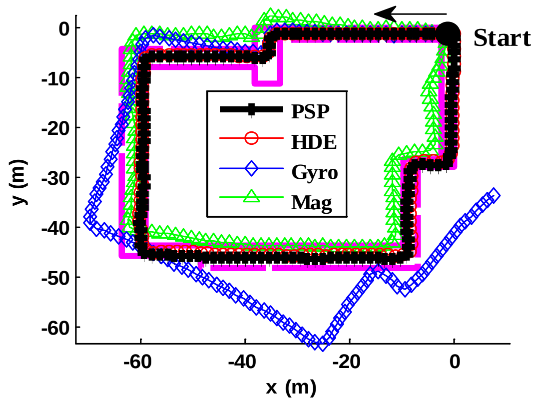
(a) Trajectory I



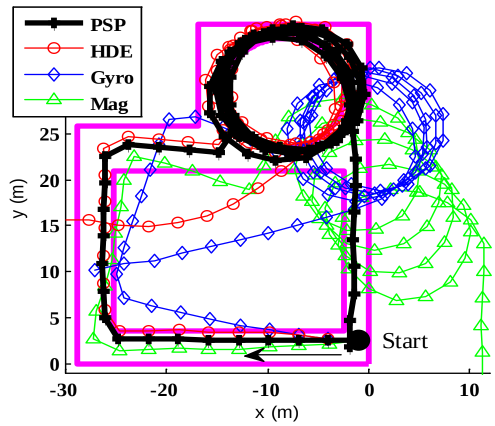
(b) Trajectory II



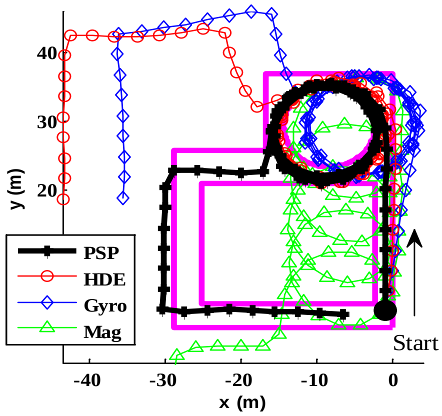
(c) Trajectory I: Left Pocket Clockwise



(d) Trajectory I: Left Pocket Counter Clockwise



(e) Trajectory II: Left Pocket Clockwise



(f) Trajectory II: Left Pocket Counter Clockwise

Figure 3. Results Comparison on Trajectory I and Trajactory II for PSP, HDE, Gyro, and Mag. Trajectory I is 204.0 m and trajectory II is 290.0 m

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