Chapter 14
Sensor Placement Modes for Smartphone Based Pedestrian Dead Reckoning

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Abstract These days, most of the smartphones come with integrated MEMS (Microelectromechanicalsystems) sensors like accelerometer, magnetometer, gyros etc. It has opened the ways to use them for location based applications. The big advantage of these sensor based navigation system is that they are environment independent in contrast to other existing positioning technologies. A lot of work is already done on fixed position sensor based systems where sensors are either attached to foot or belt. This work is focussed on developing a smartphone based pedestrian dead reckoning (PDR) system. The big issue with smartphone's sensor based PDR system is that the position of mobile is not deterministic in contrast to fixed position inertial measuring unit. In this work, three different modes of smartphone placement (Idle, Handheld and Listening) are investigated and accelerometer and magnetic sensors are used for step detection and heading determination respectively. Various step detection and stride length estimation methods are implemented and a comparison is given at the end.

Keywords Dead reckoning · Accelerometer · Heading · Step detection · Stride length

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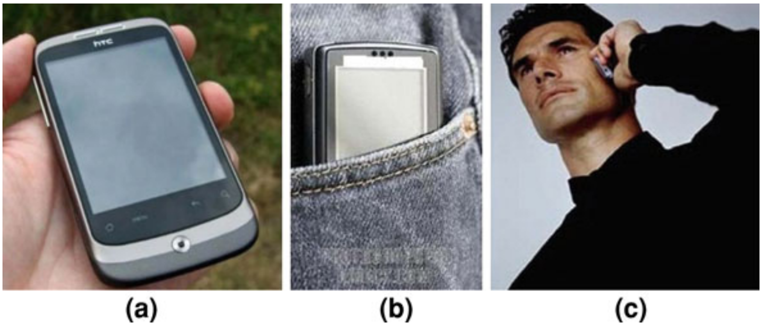

Fig. 14.1 Smartphone placement modes (**a**) handheld mode (**b**) idle mode (**c**) listening mode

14.1 Introduction

Positioning and navigation systems have gained a great success in location based services (LBS), such as personnel security, tracking of assets and people, intelligent guidance, location aware multimedia services etc. In recent years, due to rapid growth in MEMS sensors technology, such as low cost magnetic, barometer, accelerometer, gyros sensors, has opened the ways to use them for various location based services. Since inertial sensors can only provide relative information, so, the integration of inertial sensor based navigation with other positioning technologies is gaining importance to enhance the overall accuracy of the system. This paper presents an aided dead reckoning navigation system for mobile devices.

Dead Reckoning [1] is an estimation of the current position by using a predetermined start point and then updating the position estimate through knowledge of the acceleration or speed over time and the direction that the person is facing using inertial sensors. Dead Reckoning System based on fixed IMU (Inertial Measuring Unit) [2–4] have been in existence for several years. In fixed position IMU based PDR, sensor block is either attached to shoe [2] or fitted around the belt [4], while in smartphone based systems the position of sensors is not deterministic. So, one has to be careful about the position of sensors as signal pattern may change in different modes. In this work three most common smartphone placement scenarios are discussed under various PDR algorithms as shown in Fig. 14.1. The main idea of PDR mechanization is to use accelerometer signals to detect steps, estimate step length and propagate position using a measured heading. Heading can be computed using gyroscopes or a digital compass.

The structure of this paper is as follows. Section (14.2) describes the fundamentals of Pedestrian Dead Reckoning using smartphones. In Sect. (14.2.1) modes selection is discussed. After that the Signal processing to detect the footsteps and a comparison of three stride length estimation approaches is given in Sects. (14.2.2 and 14.2.3), in Sect. (14.2.4) heading determination is discussed. In Sect. (14.3) Experimental results are shown. Finally, conclusion and future work is discussed in Sect. (14.4).

14.2 Smartphone Based PDR System

These days, most of the smartphones come with integrated sensors like accelerometer, magnetometer and gyros etc. These sensors provide useful information by monitoring the human walking behaviour. The acquired information is used by the Dead Reckoning algorithms to accurately compute the position. In general, there are two methods used to find the displacement by using accelerometer sensor signal, (1) Integration Method and (2) Signal Processing Method. A lot of earlier research is based on finding the displacement by double integration of the signal from the accelerometer [2, 3]. The problem with the integration method is that the error is accumulated in each step and any drift in acceleration results in worse calculation after a few steps. The one way to reduce this drift is the zero velocity updating (ZUPT) at each stance event. ZUPT algorithm performs zero velocity updates every time a step is detected. At foot stance, the velocity is known to be zero, so it is needed to correct the linear velocities obtained after integrating the accelerometer values. In this way, any drift in one step is not propagated further. The best scenario to use the ZUPT algorithm with high precision is when sensor unit is attached to foot to detect the stance event.

Another way to find the linear displacement is the foot step detection method [2] followed by stride length calculation. In this method, accelerometer signal is analysed for footstep detection. A specific pattern is repeated at each foot step. A linear displacement is calculated during each step by using stride length estimation methods. As in case of mobile phone the big issue is that placement of phone is not deterministic and can be varied with time in contrast to foot mounted IMU. So, integration method is not suitable for smartphone based PDR systems. In this work the most common scenarios of mobile placements are discussed. This work is aimed to determine the direction and distance travelled by a person in indoor environment for different smartphone placement modes. The process flow of PDR algorithm can be summarized as, at first basic filtering of accelerometer signal is done then mobile placement mode is selected and after that foot step detection is done. The stride length in each footstep is estimated and finally heading is determined. Figure 14.2 shows the block diagram of the algorithm flow of smartphone based PDR system, the following subsections describe the each block of the flow chart in detail.

14.2.1 Mode Filtering

In this work, the following mobile phone placement modes are investigated.

(1) Idle Mode (Placed in trouser pocket)
(2) Handheld Mode (Placed in hand)
(3) Call listening mode (Placed near to ear)

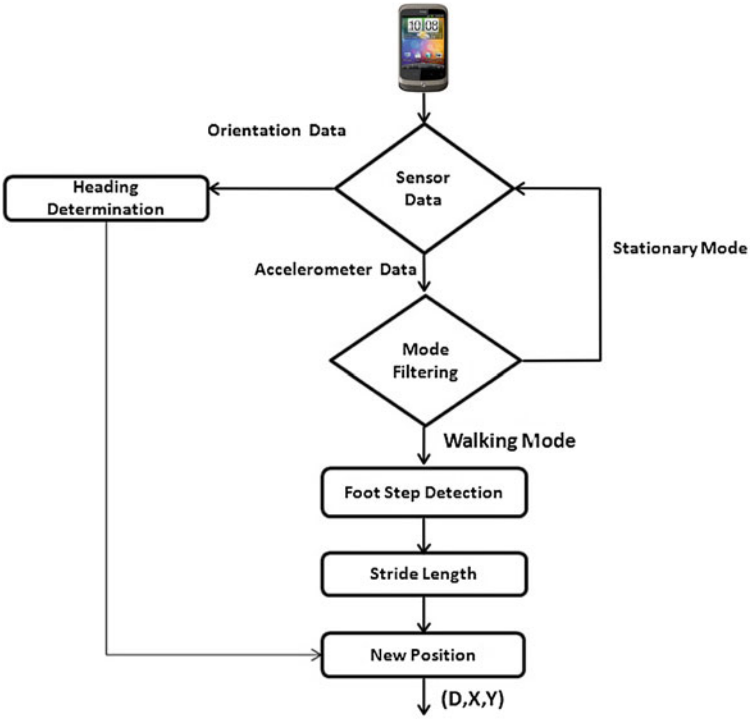

Fig. 14.2 PDR algorithm for smart phones

At first filtering is done to differentiate between the walking and non-walking modes of the mobile. One approach to differentiate between the two is to calculate the difference between the two consecutive windows of acceleration samples, if it is greater than some threshold level then samples are selected for foot step detection process.

$$T < \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2} \tag{14.1}$$

Modes are selected by observing the average of acceleration along each axis. In idle mode, the average value along x and z axis is near to zero and along y axis it is near to g. In handheld mode, the average values of x and y axis are near to zero and z axis is near to g as shown in Fig. 14.3. In call listening mode, the average value along z axis is zero and along x axis it is near to 0.7 g and along y axis near to 0.7 g. So, by careful observation of accelerometer data, we can differentiate between one of these modes and any other mobile movement. If the observations follow the trend of any of the above three walking modes the data is selected for further processing to calculate the new position, otherwise discarded. The next step is to perform the footstep detection according to the specific mode. Once the data is selected for

Fig. 14.3 Smart phone's sensors

specific mode the signal processing of the acceleration data is performed to make it suitable for footstep detection process. The signal obtained from the accelerometer sensors is first passed through the low pass filter to remove the fluctuations from the data and to make it smooth. The frequency of the data signal obtained from the sensor is 25 Hz. Interpolation is done to increase the rate of samples. After interpolation, resampling process is performed at 50 Hz. The resultant magnitude of acceleration is used further for step detection. By selecting the resultant value for foot step detection one can resolve the problem of tilting the mobile while walking, as resultant will remain same whether the mobile is tilted or not.

14.2.2 Footstep Detection

A zero crossing detector is implemented in this work. It has been observed from experiments that acceleration variance and peak-to-peak difference of acceleration have a trend to increase with walking frequency. Based on these observations, moving variance method is also implemented for comparison.

Zero Crossing Detector During walking mode a specific pattern of acceleration is repeated in each step. It has been observed by looking at this pattern that the signal crosses the zero level twice in each step as shown in Fig. 14.4a. So, one way to calculate the number of steps is to count the zero crossings and dividing it by two to calculate the number of footsteps. One condition that needs to be fulfilled is that the number of samples between two crossings should be within certain thresholds. If they are greater than maximum threshold or less than minimum

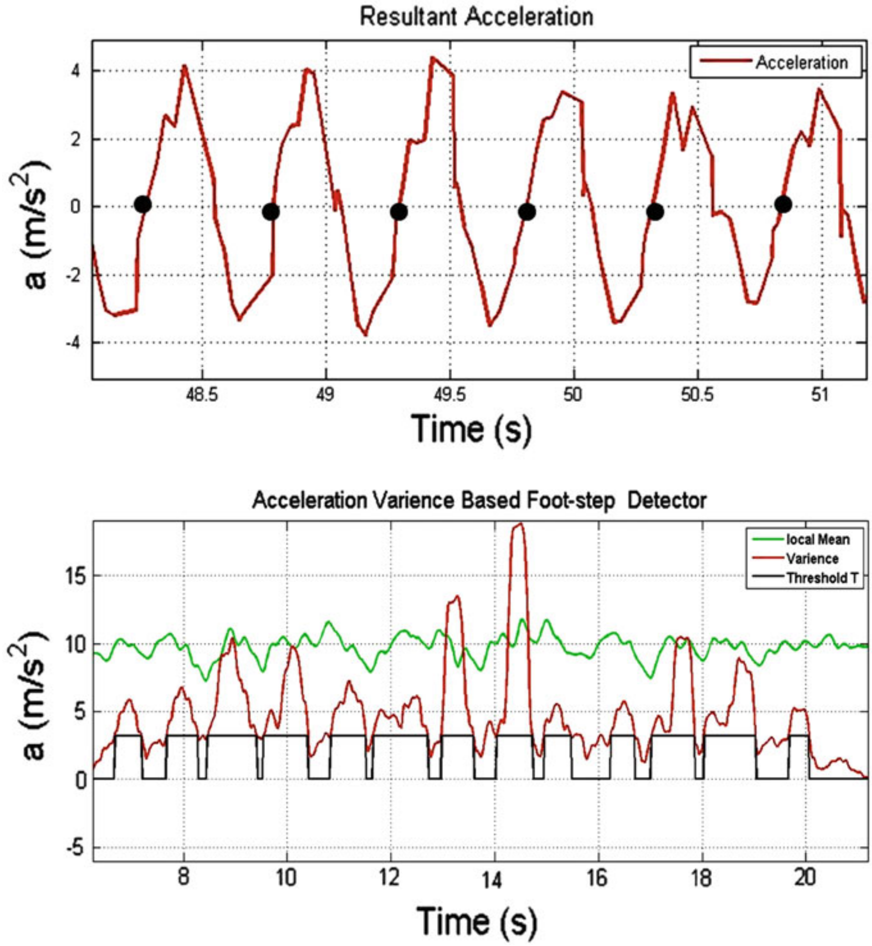

Fig. 14.4 Foot step detectors (**a**) zero crossing method (**b**) acceleration variance method

threshold, step is not counted. It has been observed from foot step detection process that number of steps have a trend to decrease with increasing walking frequency for a fixed distance.

Moving Variance Detector It has been also observed form experiments that acceleration variance has a trend to increase w.r.t the stride length, while keeping in view this thing the Moving Variance Filter [3] is implemented. At first the magnitude of every sample is calculated using x, y, z components of acceleration. By selecting the resultant magnitude of acceleration for processing, the problem of tilt can be solved because the pattern of resultant value will be same whether the mobile is tilted or not. Then local mean acceleration $\bar{a}_n$ is calculated for each sample n of resultant acceleration, after that a moving variance filter is applied to make the foot activity more prominent.

$$\sigma_n^2 = \frac{1}{2 * w + 1} \sum_{j=n-w}^{n+w} (a_n - \overline{a}_n)^2$$

where w is the window around a sample n, $\sigma 2$ is the moving variance. The last step is to apply a variance threshold to detect a step. A step is detected in sample n when acceleration variance is above a certain threshold level. Figure 14.4b shows the results after applying variance filter and number of footsteps detected. The modes can also be differentiated from each other also by observing the acceleration signal. As in case of idle mode, the position of the phone is assumed to be in the pocket of trousers, only the accelerations of one leg are recorded. In this case, the number of steps taken is multiplied by two in contrast to handheld mode; the same is applied to listening mode.

14.2.3 Stride Length Measurement

After step detection, the stride length is determined to estimate the actual distance travelled. The one way to find [1] the step size is to keep the distance travelled during each step constant according to height and sex of the person. The static step size [1] can be calculated using $Stepsize = height * k$, where k is different for different sex. It is only a rough approximation, because the step size is not a constant value but related to walking speed and acceleration magnitude. It has been observed that as step frequency increases the number of steps decreases and peak acceleration difference increases. In human walking behaviour, a period becomes shorter, a stride becomes larger and vertical impact becomes bigger as the walking speed increases. To increase the accuracy, the step size should be determined continuously while the steps are taken. There are different methods for stride length calculation, but in most of them the accelerometer was attached to foot, which results in inaccurate step size than when it is put somewhere else. The following stride length calculation approaches are compared in this paper to get the better estimate of stride length.

1st Approach This approach is based on Weinberg algorithm [2] which states that the vertical bounce in an individual's step is directly correlated to that person's stride length. This bounce is calculated in the form the difference of the peaks at each step. Stride length is calculated using this filtered signal by using the following equation.

$$SL = k * \sqrt[4]{a_{\max} - a_{\min}}$$

Peak values are calculated in a window of size w around the sample corresponding to the step detection. k is constant and is determined experimentally or through calibration. Calculating the distance using only the peak values gives widely varying results when walking at different paces or different persons walk.

2nd Approach In [5], a simple solution for step size is determined. There is correlation between the maximum and minimum values, average of acceleration and Step length.

$$SL = k * \frac{1}{N}\sum_{i=1}^{N} a_i - a_{\min}/a_{\max} - a_{\min}$$

where N is the number of samples, $a_{\max}$ and $a_{\min}$are the maximum and minimum acceleration in a specific window for step detection.

3rd Approach In [4] a relationship is proposed between mean of acceleration and stride length during a step.

$$SL = 0.98 * \sqrt[3]{\sum_{i=1}^{N} a_i/N}$$

14.2.4 Heading Determination

A navigation co-ordinate frame is the locally levelled geographic frame with its x-axis pointing east, y-axis pointing north and z-axis pointing up as shown in Fig. 14.3. Smartphones also provides an orientation vector that is used to detect the orientation of the phone in space. The orientation is given through three angles yaw, pitch and roll. When the axes of mobile phone are aligned with geographic frame, then all the three angles should be zero. In the case where the mobile is in idle or handheld mode, Azimuth value can be used to get the direction of movement. In listening mode, the direction can be determined approximately by shifting the azimuth value by 90°.

14.3 Experimental Results

In this work, three mobile placement modes are investigated for pedestrian navigation and a comparison of foot step detection and stride length estimation algorithms is presented. The tests were conducted by walking along an L shape corridor in a building recording the acceleration and orientation with the smartphone in each of the three modes. Figure 14.5 shows the actual path and trajectory estimated from experiment along with floor plan of the building where measurements took place, the red star is the start point, which is already known, blue star is the end point, and total length is 25 m. For each of three modes several recordings were taken and it has been observed that results of smartphone based PDR system are acceptable, though they are not as accurate as fixed position based systems.

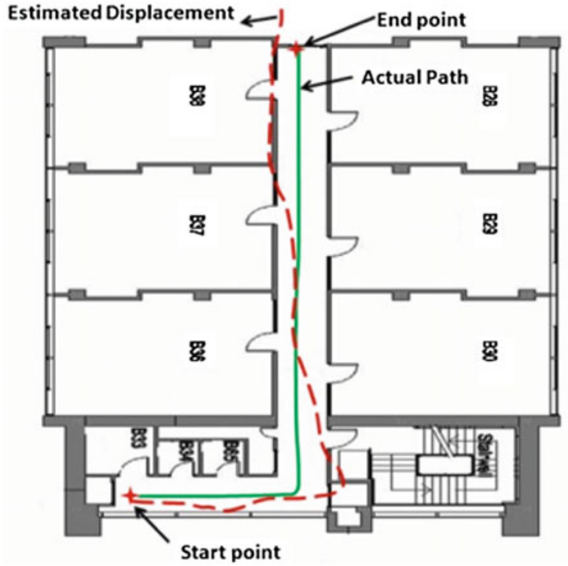

Fig. 14.5 A trajectory estimated from experiment along with floor plan of the building where measurements took place, the *red star* is the start point, *blue star* is the end point and total length is 25 m

Table 14.1 Comparison of step detection and stride length estimation methods

	Methods	Idle mode (%)	Handheld mode (%)	Call listening mode (%)
Stride length estimator	1st approach	5.24	6.54	14.54
	2nd approach	3.55	5.77	9.5
	3rd approach	6.82	7.6	15.3
Step detectors	Zero crossing	1.6	1.5	2.4
	Variance detector	3.5	4	5

Table (1) shows the percentage error between the actual distance and distance estimated using Stride length approaches for each mode Table 14.1. It has been observed that approach (2) for stride length calculation provides more accurate estimation than other approaches. Moreover it is observed from the results that zero crossing detector is more robust than moving variance step detection method. The results of step detection process show the percentage error between the actual number of steps and steps calculated using each detector.

14.4 Conclusion and Future Work

In this work three different mobile placement scenarios are discussed to make it ensure that smartphones can be used well for pedestrian dead reckoning systems. While knowing an initial point, an estimated path is measured which is almost close to actual trajectory. In addition a comparison of step detection and stride length determination methods is performed to get better estimate. There are further tasks that can be extended to this work to make smartphone based PDR system more reliable. It has been observed that heading is affected by magnetic interference in indoor environments, in future a combination of gyros and magnetic sensors can be used for an accurate heading. Further this system can be made more robust by finding more reliable method of differentiating between different modes. In this work, a simple scenario of L shaped path is tested on a leveled surface; it can be extended to other scenarios like up and down stairs and running etc. Step detection method can also be made more precise by eliminating unnecessary components from acceleration signal.

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