Pedestrian Indoor Positioning and Tracking using Smartphone Sensors, Step Detection and Map Matching Algorithm

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Abstract. The paper deals with indoor navigation using inertial sensors (accelerometers, gyroscopes, etc.) built in a smartphone. The main disadvantage of the use of inertial sensors is the accuracy, which rapidly decreases with the increasing time of the measurement. The reason of the deteriorating accuracy is the presence of errors in inertial measurements that are accumulated in the integration process. The paper describes the determination of a pedestrian trajectory using a step detection method which is improved with utilization of the adaptive step length estimation algorithm. This algorithm reflects the change of the step length with different types of movement. The proposal of the data processing uses information from floor map, which allows the verification of the pedestrian position and detects the collision of the trajectory with the floor map. The proposed algorithm significantly increases the accuracy of the resulting trajectory. The experimental measurement was realized with a smartphone Samsung Galaxy S4.

Keywords: adaptive step length estimation, inertial sensor, map matching, smartphone, step detection, systematic error.

1. Introduction

Today, navigation used in a mobile phone or in a tablet has become a normal part of our life. For man there is nothing unusual when it comes to the unknown territory. Each of us has at least once been in an unknown environment where it was necessary to find a certain destination. This problem is nowadays easily solvable by smart phones. Outdoors, in the open space we can use global navigation satellite systems, (GNSS) but the problem occurs in situations when the user is located in the indoor areas where the used device has no connection to the satellites. This fact motivates the developers to search for suitable alternatives to overcome this barrier. Navigation in indoor space finds its utilization in shopping centres, underground car parks, hospitals, school buildings and other structures with the access to satellite connection. To find an optimal design for
the indoor navigation system, it is necessary to examine various options [Jain 2013].

The development of the MEMS technology allows the production of easy, energy-efficient and affordable inertial measurement systems (IMS) that have become a part of modern smart phones. This has brought the possibility of the IMS utilization for the navigation of pedestrians. IMS allows using the inertial sensors (gyroscopes and acceleration sensors) for monitoring the spatial position without depending on external information. Their disadvantage is the accuracy that rapidly decreases with the increasing time of measurement. The reason of the deteriorating accuracy is the presence of errors in inertial measurements that are accumulated in the integration process with the increasing time of measurement. The accentuation of this effect occurs particularly by double integration of the measured acceleration [Ryu 2013]. In order to suppress the influence of systematic errors in determination of the trajectory of the pedestrian movement, a stepwise method is often used. This method uses the fact that the pedestrian movement consists of the steps that can be detected by measuring the acceleration (or from other inertial measurements – an angular velocity).

The paper deals with the determination of the pedestrian trajectory using the step detection method which is not limited by the sensor position on the object as it is in the case of smart phones (in pedestrian hands). To increase the accuracy of the determination of position, this suggested project combines the adaptive step detection method with a map matching algorithm. The first method represents the utilization of the adaptive step length estimation, as it is known that the length of a pedestrian step is changing according to the type of the environment (stairs, passage of the door and the obstacle). This fact reflects the adaptive estimation of steps where the step length is functionally depended on the frequency of steps and the average acceleration amplitude at a given step [Shin 2011]. The second method uses information from the maps and is often referred to as "map matching" [Lan 2014]. The aim of this method is the utilization of a map not only for the visualization of the user's location, but the information obtained from the map allows the verification of a pedestrian position; resp. detects a collision of a trajectory with the map. On a basis of the building of geometrical shape obtained from maps, it is possible to design the ideal route of pedestrians which is used in algorithm for the correction of the position.

2. Step Detection and Adaptive Step Length Estimation

The movement of a person is a specific type of a periodic mechanical movement which can be divided into individual steps. The step detection is most often realized by measuring the acceleration. There are several methods for the detection of the steps: detection of the peaks, zero-crossings and flat zone detection, as described in [Shin 2011], [Wang 2013], [Ryu 2013], [Attia 2013], [Kopáčik 2015].

In the paper presented, the step detection method based on the zero-crossing of the acceleration standard is used. These zero-crossings are later used in the
method of adaptive step length estimation. The acceleration norm (1) represents the resultant vector of the sensor acceleration. By defining the thresholds for the acceleration norm, (2) areas of movement where the step detection can be used, are identified. The low-pass filter (moving average) is applied on the acceleration norm to suppress the noise and reduce the probability of the detection of false steps. Each step has three zero-crossings [Figure 2.1], [Figure 2.2]. This fact is taken into account by estimating the adaptive step length:

$$\bar{a} = \sqrt{a_x^2 + a_y^2 + a_z^2},$$  \hspace{1cm} (1)

$$\bar{a} < th_a,$$ \hspace{1cm} (2)

where

- $\bar{a}$ – acceleration norm,
- $a_x, a_y, a_z$ – acceleration in axis $X, Y, Z$,
- $th_a$ – threshold for the acceleration norm.

Step detection method based on the zero-crossing is resistant to changes in the speed of a pedestrian which becomes evident in changes in local maxima in the acceleration norm.

**Figure 2.1** Step detection method – zero cross in the acceleration norm

The result of the step detection method is the division of time series of measurements into individual steps. Each current step with the length can be expressed as a linear combination of the step frequency, average amplitude of the acceleration norm $v$ and optimal parameters $\alpha, \beta, \gamma$ [Shin 2011]:

$$l = \alpha.f + \beta.v + \gamma.$$ \hspace{1cm} (3)

The optimal parameters express dependence of the step length on the walking frequency and average amplitude of the acceleration norm [Figure 2.2]:

- walking frequency:
  $$f = \frac{1}{t_k-t_{k-1}},$$ \hspace{1cm} (4)

- average amplitude of an acceleration norm:
  $$v = \frac{1}{n}\sum_{k=1}^{n}(\bar{a}_k - \bar{a})^2$$ \hspace{1cm} (5)

$t_k, t_{k-1}$ – time of detected steps,

$\bar{a}_k$ – norm of an acceleration in $k$ time,

$\bar{a}$ – average of an acceleration norm in a step.
The step length depends on a pedestrian profile (weight, height, age, sex, style of walk) and therefore optimal coefficients have to be defined for each user separately [Li 2012]. The values of these coefficients are estimated from the calibration measurements. The pedestrian walked along a straight trajectory of a known length during calibration. Optimal coefficients are estimated by regression analysis from a known travelled distance and measured accelerations.

Step length varies during the walk according to the environment (stairs, obstacles, doors, surface of the floor). The change of the step length will be reflected in the measured acceleration as the change of the walking frequency (speed of movement) and changes in the amplitude of the norm of accelerations. These variables are directly used in the formula for the calculation of a step length (formula 3), ensuring its adaptive estimate.

2.1. Calculation of the Pedestrian Orientation (Heading)

The pedestrian orientation is described with help of Euler angles that define the relative orientation of the smart phone own coordinate system to the reference frame used for determination of the pedestrian position in space. The Euler angles could be calculated from the angle velocity measured by gyros mounted in the smart phone [Groves 2008]:

\[ \varphi = \int_{t_{n+1}}^{t_n} \omega_x(t)\,dt, \quad \theta = \int_{t_{n+1}}^{t_n} \omega_y(t)\,dt, \quad \Psi = \int_{t_{n+1}}^{t_n} \omega_z(t)\,dt, \]

where:
\[ \varphi, \theta, \Psi \] – Euler angles roll, pitch, yaw,
\[ \omega_x, \omega_y, \omega_z \] – angular velocity in direction of X, Y, Z.

The gyroscopes are not able to determine the absolute orientation in space, thus the absolute initial orientation of the smart phone is needed. This problem is possible to solve with the help of magnetometers which generate the azimuth value calculated from magnetic induction and measured in direction of X, Y.

\[ A_{mag} = \arctg \left( \frac{b_y}{b_x} \right), \]

where:
\[ b_x, b_y \] – magnetic induction measured in X, Y direction of the smart phone frame.

The absolute orientation of the pedestrian during the whole measurement could be determined by using magnetometers [Figure 2.3] [Tian 2014]. The disadvantage of these sensors is the high sensitivity to the magnetic field variations due to the steel structures and electrical equipment situated in the sensors neighbourhood. Therefore, the magnetometers will be used only for approximate correction of the absolute orientation of a pedestrian.
2.2. Verification and Correction of Pedestrian Position Based on the Floor Map

The pedestrian trajectory is calculated by using the recursive algorithm that is well known as a pedestrian dead reckoning algorithm. The current location of the pedestrian is calculated from a previously known location, travelled distance and the orientation of a movement in the actual time epoch:

\[
X_t = X_{t-1} + \text{step}_t \cdot \cos(\text{azimuth}_t) \\
Y_t = Y_{t-1} + \text{step}_t \cdot \sin(\text{azimuth}_t)
\]

where:

- $X, Y$ – position,
- $\text{step}$ – step length,
- $\text{azimuth}$ – azimuth of the steps.

First the initial position of pedestrian $X_0, Y_0$ is defined, which is because of the relative determination of the position with inertial sensors. The initial position is defined by using other navigation methods (QR code, RFID, UWB, computer vision) that enable to determine the absolute position of the user [Karimi 2015].

After calculation of the current position of a pedestrian, the algorithm finds a collision trajectory with the floor map (e.g. a passage of the user through the wall). If the algorithm evaluates the position as an incorrect position then it finds another most suitable point to the ideal path [Figure 2.4], [Figure 2.5].

There are many map matching algorithms that have different approach to use the map information. Most of the applications use the map matching algorithm as a search problem, meaning where to find the nearest point of the ideal path to the position calculated by IMS [White 2000]. In our work the map matching algorithm is used only for the situation, where the trajectory is in collision with the floor map. Three conditions are used to find the correct position (current orientation of pedestrian, range of stationing of the corrected position and minimum length of the offset), which limited the set of probable solutions to only one (see below).
The ideal path is defined by the longitudinal axes of the corridors, and its traverse points are represented by the intersection of corridor axes and stairway axes.

When the position $X_t, Y_t$ of a pedestrian is corrected, the direction of pedestrian movement has to be taken into account. It is used for a selection of the ideal part of the path. This condition prevents an incorrect adjustment of the point. It could happen in the case when the adjustment process is limited only to searching of the nearest point [Figure 2.4].

Corrected position of a pedestrian has to satisfy the following conditions [Figure 2.5]:

- projection of pedestrian position to ideal path (incorrect)
- projection of pedestrian position to ideal path (correct)
- incorrect math ($s_t > d_{N1,N2}$)
- incorrect math ($c_{N2,N3} \neq \text{yaw}_t$)
- correct math
- incorrect math ($k_4 > k_3$)
• The current orientation of pedestrian belongs to a range defined by selected part of an ideal path,
• The stationing of the corrected position $s_{t_i}$ belongs to a range of $\langle 0, d_{N_{i,N_{i+1}}} \rangle$,
• The minimum length of the offset $k_i$.

3. Analyses of Results

The experimental measurement was realized to test the proposed model of the processing. For the purpose of this experiment Samsung Galaxy S4 smart phone was used. It is a type of a smart phone with built-in inertial sensors (three-axial acceleration sensor, three-axial gyroscope), three-axial magnetometer, and atmospheric pressure sensor. The smart phone was held in a horizontal position by a pedestrian, so Z-axis of coordinate system of the smart phone represented the direction of gravity (this condition was important for the correct interpretation of a pedestrian orientation).

A pedestrian walked along a predefined trajectory three times during the experiment. The trajectory was defined by 11 traverse points whose position was signalized by the labels stuck on the floor. The traverse points were used for the analysis and verification of results.

The pedestrian trajectory was calculated by 3 methods:
1. using a constant step length,
2. using an adaptive step length,
3. using an adaptive step length and the map matching algorithm.

Figure 3.1 Trajectory of a pedestrian with an adaptive step length and a correction of a position
The coordinates of measured points as the result from each method were used for comparison of these methods. The table [Table 3.1] shows the coordinate differences between the reference positions of the measured points defined at the beginning of the measurement and the position calculated by method 1 - 3.

**Table 3.1** Comparison of the coordinate difference on measured points (during the last repetition trajectory)

<table>
<thead>
<tr>
<th>Point number</th>
<th>Constant step</th>
<th>Adaptive step length</th>
<th>Adaptive step length and position correction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Δp [m]</td>
<td>Δp [m]</td>
<td>Δp [m]</td>
</tr>
<tr>
<td>1</td>
<td>2.9</td>
<td>0.2</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>3.3</td>
<td>2.2</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>3.2</td>
<td>2.4</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>3.2</td>
<td>2.3</td>
<td>0.9</td>
</tr>
<tr>
<td>5</td>
<td>3.6</td>
<td>1.8</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>3.6</td>
<td>2.1</td>
<td>0.3</td>
</tr>
<tr>
<td>7</td>
<td>3.6</td>
<td>2.2</td>
<td>0.1</td>
</tr>
<tr>
<td>8</td>
<td>2.5</td>
<td>1.3</td>
<td>0.1</td>
</tr>
<tr>
<td>9</td>
<td>2.5</td>
<td>1.1</td>
<td>0.2</td>
</tr>
<tr>
<td>10</td>
<td>2.4</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>11</td>
<td>3.0</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Average (1st travelled trajectory)</td>
<td>1.4</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Average (2nd travelled trajectory)</td>
<td>2.5</td>
<td>1.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Average (3rd travelled trajectory)</td>
<td>3.1</td>
<td>1.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Total average</td>
<td>2.3</td>
<td>1.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>

The results of the experiment [Table 3.1] show that the largest coordinate differences were achieved in the first method of processing where the constant step length was used. The maximum position difference between the reference position of a measured point and calculated position was 3.6 m (maximum of the whole experiment). Position errors resulting from the constant length step are transmitted through the whole calculating process and cause their accumulation because of the increasing time of measurement.

The coordinate differences between the reference position of measured points and the position of measured points calculated by the second method (using an adaptive step length estimation algorithm) are smaller than in the first method (using a constant length step). The maximum position differences between the reference position of a measured point and the calculated position was 2.5 m (maximum of the whole experiment). Position errors are probably caused by an error in the orientation of the pedestrian (due to the approximation of the orientation to the main direction) and by an incorrect step detection (unidentified or incorrect identified step).
The best results (the lowest coordinate differences of measured points) were achieved with the third method of calculation (using an adaptive step length estimation algorithm and Map Matching). The maximum position difference of the measured point was 1.6 m (from the whole experiment). The increased accuracy based on the information from the floor map is closely related to the geometry of the building (orientation and width of corridors). In the case of narrow corridors, the motion of a pedestrian is significantly limited that directly affects the effectiveness of corrections. On the other hand, the wide corridors with an atypical geometry can cause worse results.

Adaptive step length estimation improved the accuracy of travelled distance. This fact is possible to see in the results in the table [Table 3.2]. The error of total travelled distance calculated with a constant step length was 2.7 m (1.3% of total travelled distance) but with an adaptive step length estimation error decreased to 1.2 m (0.2% of total travelled distance). This difference in the accuracy of the individual methods is influenced by the variation of a step length which depends on the speed of pedestrians and it is also influenced by the environment (entering the room, avoiding the obstacles). Calculations with the help of Map Matching are not a part of the comparison [Table 3.2] because this does not influence the accuracy of travelled distance. The position of a pedestrian is directly corrected.

<table>
<thead>
<tr>
<th>Part of predefined trajectory</th>
<th>Reference [m]</th>
<th>Constant step length [m]</th>
<th>Difference [m]</th>
<th>Adaptive step length [m]</th>
<th>Difference [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; travelled trajectory</td>
<td>205.3</td>
<td>208.0</td>
<td>-2.7</td>
<td>204.1</td>
<td>1.2</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; travelled trajectory</td>
<td>205.3</td>
<td>208.0</td>
<td>-2.7</td>
<td>207.3</td>
<td>-2.0</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; travelled trajectory</td>
<td>205.3</td>
<td>208.0</td>
<td>-2.7</td>
<td>205.9</td>
<td>-0.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>615.9</strong></td>
<td><strong>624.0</strong></td>
<td><strong>-8.1</strong></td>
<td><strong>617.3</strong></td>
<td><strong>-1.4</strong></td>
</tr>
</tbody>
</table>

**Table 3.2** Comparison of travelled distance between a constant step length and an adaptive step length

![Figure 3.2](image.png)

**Figure 3.2** Comparison of the position error on measured points during experimental measurement
4. Conclusion

From the origin point of view errors in the determination of a pedestrian position could be divided into two basic components – errors in the determination of a trajectory length and errors in the orientation of a pedestrian movement. The chapter 1.1 deals with the first component of errors. In the indoor environment the pedestrian step length is often influenced by entering the doors, direction changes, and the like. To minimize these influences, the adaptive step detection was used. This method defines the step length according to the frequency and the average amplitude of the acceleration norm of a pedestrian movement. The importance of the utilization of adaptive step detection underlines the results in Table [Table 3.1] where the difference in the length between the given and measured trajectory is 1.3% in the case of constant step detection and 0.2% in the case of an adaptive step detection method.

Chapter 1.2 presents the possible elimination of errors in the pedestrian orientation. The procedure for azimuth calculation includes a drift elimination part that corrects the pedestrian azimuth according to the building geometry. This is based on limitations of the pedestrian trajectory that are strictly given by the building geometry – doors, corridors, stairs, etc. The inspection of the pedestrian orientation was realized on the base of a magnetic azimuth from measurements with magnetometers which express the absolute pedestrian orientation.

“Map Matching” method was included to increase the accuracy of determination of position (trajectory). The calculated pedestrian position is verified with the actual map (drawing, 3D model) and corrected to the nearest point of the ideal trajectory in the case of collision. The effectiveness of the “Map Matching” application is limited by the building geometry. Better results could be achieved in the building with a regular geometry in comparison to the building of an irregular shape (historical buildings, underground spaces, caves, etc.) or pedestrian navigation in large halls (galleries, sport halls, etc.).

According to the results it can be confirmed that by using a constant step length algorithm the average deviation in position was 2.3 m (maximal deviation in single position was 3.6 m). Using the adaptive step length algorithm, the average deviation in position was 1.5 m (maximal deviation was 2.5 m). The best result was achieved with the combination of the adaptive step length algorithm and “Map Matching” where the average deviation in position was 0.7 m and the maximal deviation was 1.7 m.

References


Institute of Navigation and CIGTF 22nd Guidance Test Symposium, pp. 122-127.


Pozicioniranje i praćenje pješaka u zatvorenim prostorima pomoću senzora pametnih telefona, detekcije koraka i map matching algoritma

Sažetak. Rad se bavi s navigacijom u zatvorenim prostorima pomoću inercijalnih senzora (akcelerometra, žiroskopa, itd.) ugrađenih u pametni telefon. Osnovni nedostatak inercijalnih senzora je njihova točnost, koja se naglo smanjuje s vremenom mjerenja. Razlog smanjenja točnosti je prisustvo pogrešaka koje se akumuliraju u procesu integracije. U radu je opisano određivanje putanje pješaka pomoću metode detekcije koraka koja je poboljšana primjenom algoritma prilagodljive procjene duljine koraka. Ovaj algoritam uzima u obzir promjenu duljine koraka pri različitim načinima kretanja pješaka. Prilikom obrade podataka koristi se plan zgrade koji omogućuje provjeru pozicije pješaka i detektira neslaganje kretanja pješaka s planom zgrade. Predloženi algoritam značajno povećava točnost određene putanje pješaka. Testna mjerenja provedena su pomoću pametnog telefona Samsung Galaxy S4.

Ključne riječi: detekcija koraka, inercijalni senzori, map matching, pametni telefon, prilagodljiva procjena duljine koraka, sustavne pogreške.