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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, which are accumulated in the integration process. The paper describes the determination of a pedestrian trajectory using 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 floormap, what allows the verification of the pedestrian position and detects the collision of the trajectory with the floormap. The proposed algorithm significantly increases the accuracy of the resulting trajectory. Another extension of the proposed algorithm is the implementation of the barometer measurements for determination of the height differences. This fact allows change the floor in a multi-storey buildings. The experimental measurement was realized with a smartphone Samsung Galaxy S4.

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

1. Introduction

Today navigation used in a mobile phone or tablet has become a normal part of our life. For a man there is nothing exceptional when it gets into the unknown territory. Each of us was in an unknown environment where it was necessary to find some target. This problem is nowadays easily solvable by smart phones. In open space we can use global navigation satellite systems (GNSS) but the problem occurs in situations when the user is located in indoor areas where the used device has no connection to the satellites. This fact motivates the developer to search

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for suitable alternatives to overcome this barrier in navigation. Navigation in indoor space finds its utilization in various shopping centres, underground car parks, hospitals, school buildings and other various structures. To find an optimal design of navigation system for indoor environment, it is necessary to examine various options on this way (Jain et al. 2013).

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

The paper deals with determination of a pedestrian trajectory using 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 adaptive step detection method with map matching algorithm. The first method represents the utilization of adaptive step length estimation as it is known that the length of a pedestrian step is changing according to the type of 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 and Park 2011). The second method uses information from maps and is often referred to as "map matching" (Lan and Shih 2014). The aim of this method is the utilization of a map not only for visualization of the user's location. Information from maps allows the verification of a pedestrian position; resp. detects a collision of a trajectory with maps. On a base of the building 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. Related Work

There is an evident huge increase in activities aimed at automated processes and services in recent years. Their integral part is a creation of an "intelligent environment" in which vehicles, machines and people are navigated. Nowadays there are lots of suggested projects of navigation systems for indoor navigation, mainly due to the increasing interest in these technologies. Among others, for example, inertial measurement systems (Lukiankto and Sternberg 2011) which provide information about the orientation and position in 3D space via sensors (accelerometers and gyroscopes). Another possibility is a system based on WLAN network (Puertolas-Montañez et al. 2013, Stook and Verbree 2012, Panyov et al. 2014) whose great advantage is especially the flexibility and the high coverage. Operating system based on Bluetooth (Puertolas-Montañez et al. 2013, Hallberg et al. 2003, Bekkelien 2012) was originally designed for the short-range connection for personal devices but its utilization can be applied also in the methods of indoor navigation based on the triangulation method using received signal strength. Another solution is to use UWB (Ultra Wide Band) (Puertolas-Montañez et al. 2013, Renaudin et al. 2007, Feldmann et al. 2003) when the radio signals penetrate into buildings also through a very full environment. However, its disadvantage is very short range. Often used method is also positioning by ultrasound, RFID (radio frequency identification) (Puertolas-Montañez et al. 2013, Lin et al. 2011, Nakamori et al. 2012), and also the system based on scanning barcodes. Simple characteristics and advantages and disadvantages of many of these systems are described in Puertolas-Montañez et al. (2013).

In Chang and Wang (2007), Serra et al. (2010), Woodmann (2007), Marotto et al. (2013) is described an Indoor Navigation System (INS) based on the capabilities of a typical modern smart-phone equipped with accelerometers, compass, camera and internet connectivity. The user initially takes a photo of a geo-referenced 2D-bar code in order to acquire the map of the building and the initial position.

Foot-mounted INS which uses combined method of calculation used by ZUPT (zero-velocity-update) is described in Colomar (2012). ZUPT method is also used in Li et al. (2012b).

In Atzori et al. (2012) there is used the smart phone's video camera to identify known and geo-referenced key points in the building map.

In Attia et al. (2013) there is developed a map aided navigation solution. This research develops an aiding system that uses geospatial data to assist the navigation solution by providing virtual boundaries for navigation trajectories and limits its possibilities only when it is logical to locate the user on a map. The algorithm develops a Pedestrian Dead Reckoning (PDR) based on smart-phone accelerometer and magnetometer sensors to provide the navigation solution.

Our experiments were focused on the utilization of the step detection method, adaptive step length estimation and map matching algorithms. Previous step detection algorithms based on accelerometers and gyroscopes in cooperation with Kalman filter were presented in Garcia (2011), Opiela (2013) and Tran et al. (2012). In Shin et al. (2012) there is developed the indoor navigation system based on PDR (Pedestrian Dead Reckoning) using various sensors in smart phone with help of the Artificial Neuron Network to recognize the walking status such as stop, walking and running and to estimate the step length.

An adaptive step length estimation using optimal parameters is also used in previous work (Shin and Park 2011) and (Wang et al. 2013) where the movement status awareness was used. In Ryu et al. (2013) there is calculated the variable amplitude threshold for current position of the user.

A map matching algorithm is a method for mapping the estimated position from the navigation system to digital map data. The general purpose of MM algorithms is to identify the correct road segment on which the pedestrian or vehicles are travelling and to determine the position on that segment. Some map matching algorithms are described in White et al. (2000) and this paper considers map matching algorithms that can be used to reconcile inaccurate locatable data with an inaccurate map.

In Shin et al. (2010) there is presented a map-matching (MM) algorithm which combines an estimated position with digital road data. The presented algorithm using a virtual track is appropriate for a MEMS-based pedestrian dead reckoning (PDR) system which can be used in mobile devices. In Lan and Shih (2014) there was exploited the geometric similarity between the user trajectory and the floor map, map matching algorithm includes three different filters to calibrate the direction errors from the gyro using building floor plans.

3. Processing of the Measurement

This presented paper deals with determination of the trajectory of pedestrian movement based on inertial sensors placed in smart phone (acceleration sensors, gyroscopes and magnetometers) where the suppression of the systematic errors of measurement plays an important role in order to improve the accuracy in determination of the pedestrian position. Calculation of the pedestrian position can be divided into two basic steps – distance calculation and calculation of the pedestrian orientation.

In order to suppress the systematic component of accelerometers, the step detection method in combination with the method of adaptive step length estimation were used in the calculation of the travelled distance. This step of the processing is described in detail in Section 3.1.

During the calculation of the pedestrian orientation the gyro bias is parameterised at the beginning of the measurement and later updated during measurement. During the elimination of systematic components there were also used magnetometer measurements and main directions of the building. Calculation of the orientation is described in Section 3.2.

To increase the long-term accuracy in the determination of the pedestrian position the Map Matching method was implemented into the calculation process. This method uses information from maps for verification and correction of the determination of pedestrian position. The process of the map utilization is described in Section 3.3. Scheme of the whole process can be seen in the flowchart (Fig. 1) – Calculation of

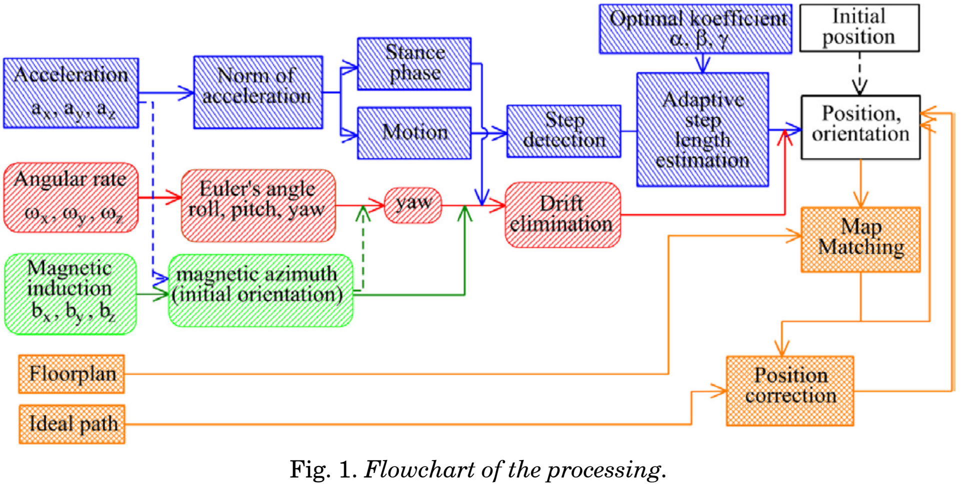

Fig. 1. *Flowchart of the processing.*

the travelled distance – blue; calculation of the pedestrian orientation – red and green; the utilization of the Map Matching method – orange).

3.1. 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 of 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 and Park (2011), Wang et al. (2013), Ryu et al. (2013), Attia et al. (2013), Ilkovičová et al. (2015).

Often used method is a step detection based on the *detection of the peaks* in the measured acceleration. To eliminate false detected step, it is necessary to define the threshold above which the searched maximum as well as the minimum time interval between peaks should be detected. This method of step detection was also used in our previous experiment (Ilkovičová et al. 2015). The disadvantage of this method is the fact that with the changing movement speed the value of the maximum threshold is changing as well.

Step detection based on the *flat zone detection* is less used method. This method identifies the beginning of the step as a flat zone in the time series of measured acceleration (at the moment when the foot rests on the ground). By this method the sensor has to be placed directly on the leg of a pedestrian (Cho et al. 2003).

In the presented article there is used the step detection method based on the *zero-crossing* of the acceleration standard. These zero-crossings are later used in the method of adaptive step length estimation. Acceleration norm (1) represents the resultant vector of the sensor acceleration. By defining of thresholds for the acceleration norm (2) there are identified areas of movement where the step detection can be used. 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 (Fig. 2, Fig. 3). This fact is taken into an account by estimating the adaptive step length:

$$\bar{a} = \sqrt{a_x^2 + a_y^2 + a_z^2}\ , \tag{1}$$

$$\bar{a} < th\_a\ , \tag{2}$$

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 a zero-crossing is resistant to changes in the speed of a pedestrian which becomes evident in changes in local maxima 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 l can be expressed

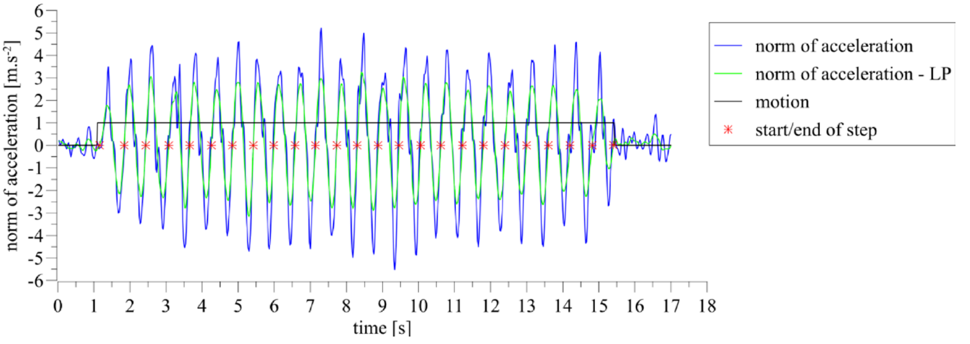

Fig. 2. *Step detection method – zero cross in a norm of acceleration.*

as a linear combination of the step frequency f, average amplitude of the acceleration norm v and optimal parameters α, β, γ (Shin and Park 2011).

The optimal parameters express dependence of the step length on the walking frequency and average amplitude of the acceleration norm (Fig. 4).

$$l = \alpha \cdot f + \beta \cdot v + \gamma \tag{3}$$

where

α, β, γ – parameters of an adaptive step length estimation (individual for each user)
f – walking frequency
v – average amplitude of an acceleration norm

$$f = \frac{1}{t_k - t_{k-1}} \tag{4}$$

$$v = \frac{1}{n-1} \sum_{k=1}^{n} \left(a_k - \bar{a} \right)^2 \tag{5}$$

t_k, t_{k-1} – time of detected steps
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 et al. 2012a). The values of these coefficients are estimated from calibration measurements. A pedestrian walked a straight trajectory of known length during calibration. Optimal coefficients are estimated by regression analysis from known travelled distance and measured accelerations:

- α (defined by a slope of a linear regression function k_f which defines correlation between step length and walking frequency):

$$l = k_f \cdot f + q_f, \qquad \alpha_{opt} = \frac{1}{2} k_f, \tag{6}$$

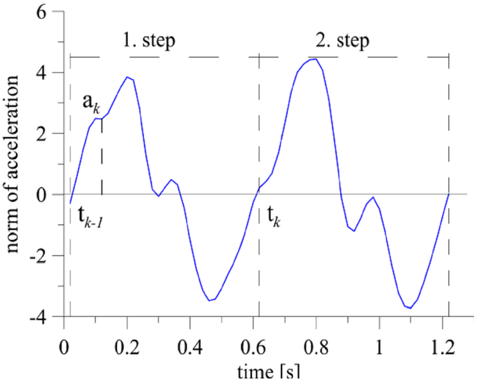

Fig. 3. *Each step defined by step frequency and average variation of an acceleration norm.*

- β (defined by a slope of a linear regression function k_v which defines correlation between step length and amplitude of an acceleration norms):

$$l = k_v \cdot f + q_v\,, \qquad \beta_{opt} = \frac{1}{2} k_v\,, \tag{7}$$

- γ (defined by a sum of the offset from both regression functions):

$$\gamma_{\mathrm{opt}} = q_f + q_v\,. \tag{8}$$

Step length varies during the walk according to the environment (stairs, obstacles, doors, surface of 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 an amplitude of norm of accelerations (Fig. 4). These variables are directly used in formula for the calculation of a step length (formula 3), ensuring an adaptive estimate of a step length.

3.2. Calculation of the Pedestrian Orientation

The pedestrian orientation is described with help of Euler angles which 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):

$$\varphi = \int_{t_n+1}^{t_n} \omega_x(t)dt\,, \qquad \theta = \int_{t_n+1}^{t_n} \omega_y(t)dt\,, \qquad \psi = \int_{t_n+1}^{t_n} \omega_x(t)dt\,, \tag{9}$$

where

φ, θ, ψ – Euler angles roll, pitch a yaw
ω_x, ω_y, ω_z – angular velocity in direction of X, Y, Z.

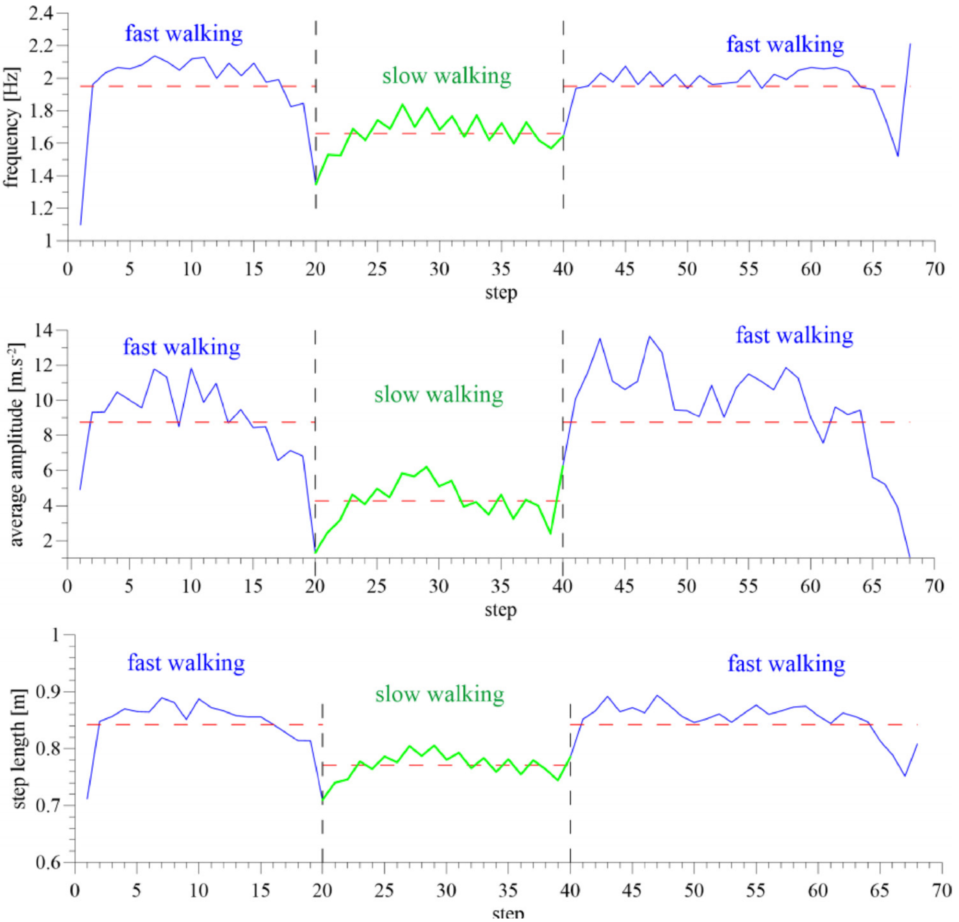

Fig. 4. *Change of walking frequency and change of average amplitude of acceleration for different types of walk.*

The integration of the angular velocity signal cumulates errors whose influence could be described by linear regression model. The initial determination of the model parameters could be determined when the smart phone is stable, staying in the same position without any rotation. These are calculated during the measurement from the signal when the smart phone is moved approximately with constant azimuth – relative long parts of the trajectory (lines) of min. 6 sec duration.

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

$$A_{mag} = \arctan\left(\frac{by}{bx}\right), \tag{10}$$

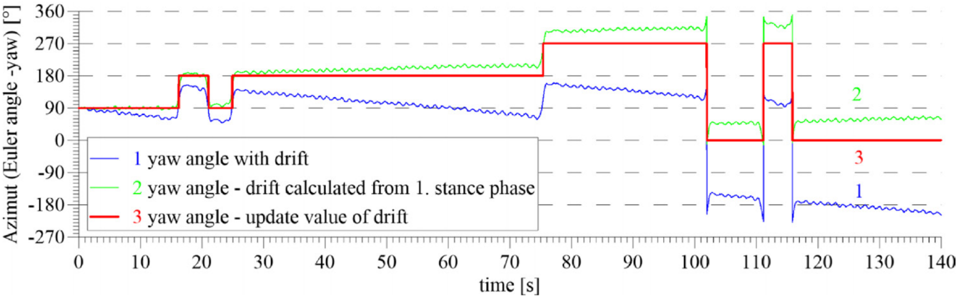

Fig. 5. *Smartphone orientation using drift calculated in the first step (green line) and their correction using long lines with constant orientation of sensors (red line).*

where

bx, by – magnetic induction measured in X,Y direction of the smart phone frame.

The magnetometer must be in a horizontal position. If it is not possible, the measured values will be transformed into the local horizon using inclination angles φ, θ:

$$\begin{bmatrix} b_x^{\ h} \\ b_y^{\ h} \end{bmatrix} = \begin{bmatrix} b_x^{\ m} \cdot \cos(\varphi) + b_y^{\ m} \cdot \sin(\theta) \cdot \sin(\varphi) - b_z^{\ m} \cdot \cos(\theta) \cdot \sin(\varphi) \\ b_y^{\ m} \cdot \cos(\theta) + b_z^{\ m} \cdot \sin(\theta) \end{bmatrix}, \tag{11}$$

where

$b_x^{\ m}, b_y^{\ m}, b_z^{\ m}$ – measured magnetic induction in direction of *X*, *Y*, *Z*

$b_x^{\ h}, b_y^{\ h}$ – magnetic induction transformed into the local horizon (Moafipoor et al. 2007).

The acceleration at the beginning of the measurement was used for determination of the orientation (resp. inclination) of the *X* and *Y* axis of accelerometer when the smart phone is in a stance phase. The accelerometer in a horizontal position and stance phase is influenced by zero acceleration of *X* and *Y* axis and gravitational acceleration in *Z* axis. In the case of non-horizontal position of accelerometer, the gravitational acceleration influences all axis of it. In this situation acceleration of individual axis is depended on a smart phone inclination. The initial inclination of smart phone is calculated by formula 12, 13 (Groves 2008):

$$\varphi_0 = \arctan\left(\frac{-a_y}{a_z}\right) \tag{12}$$

$$\theta_0 = ar\,\mathrm{ctg}\left(\frac{-a_x}{\sqrt{a_y^{\ 2} + a_z^{\ 2}}}\right) \tag{13}$$

where

φ_0 – the initial inclination of the accelerometer (smart phone) in *X* axis
θ_0 – the initial inclination of the accelerometer (smart phone) in *Y* axis
a_x, a_y, a_z – measured acceleration in direction of *X*, *Y*, *Z*.

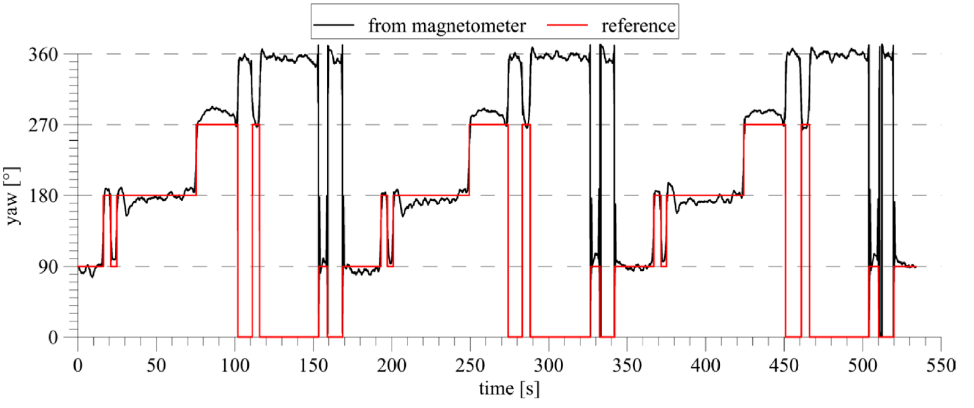

Fig. 6. *Magnetic azimuth calculated from magnetic induction.*

Using magnetometers could be determined the absolute orientation of the pedestrian during the whole measurement (Fig. 6) (Tian et al. 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 a sensor neighbourhood. Because of this fact the magnetometers will be used only for approximate correction of the absolute orientation of a pedestrian.

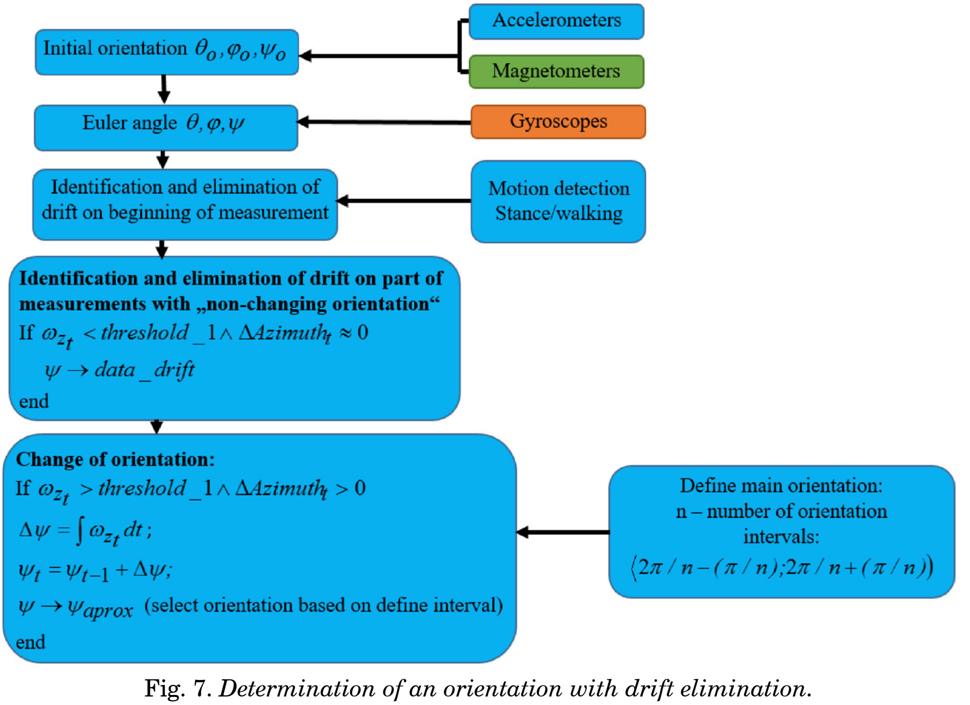

Fig. 7. *Determination of an orientation with drift elimination.*

3.3. Verification and Correction of Pedestrian Position Based on the Floor Map

Trajectory of pedestrian is calculated with using of the recursive algorithm which is well known as a pedestrian dead reckoning algorithm. The current location of a pedestrian is calculated from previous known location, travelled distance and orientation of a movement in an actual time epoch:

$$\begin{aligned} X_t &= X_{t-1} + step_t \cdot \cos(azimuth_t) \\ Y_t &= Y_{t-1} - step_t \cdot \sin(azimuth_t) \end{aligned} \tag{14}$$

where

X, Y – position
step – step length
azimuth – azimuth of the steps.

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

After calculation of the current position of 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 (Fig. 8, Fig. 9).

There are many map matching algorithms, which have different approach to use the map information. Most of the applications used the map matching algorithm as a search problem, where find nearest point of the ideal path to the position calculated by IMS (White et al. 2000). In our work is map matching algorithm used only for the situation, where is the trajectory in the collision with floor map. There are used three conditions for finding correct position (current orientation of pedestrian, range of stationing of the corrected position and minimum length of the offset), which limited set of probably solution to one (see below).

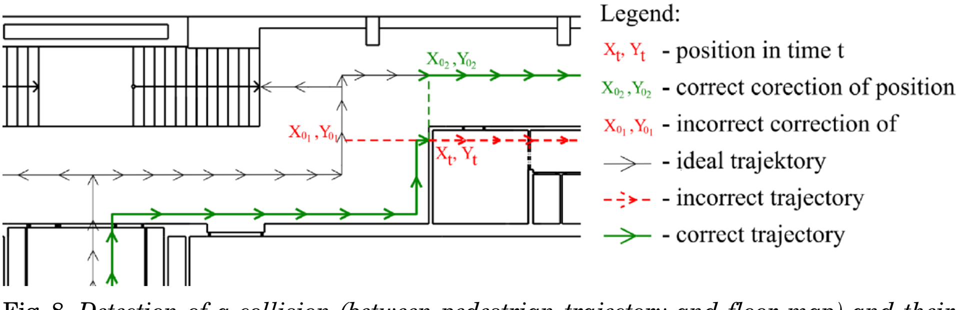

Fig. 8. *Detection of a collision (between pedestrian trajectory and floor map) and their correction.*

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 position X_t, Y_t of pedestrian is corrected, the direction of pedestrian movement has to be taken into the account. It is used for a selection of the ideal part of a path. This condition prevents an incorrect adjustment of a point. It could happen in the case when the adjustment process would be limited only to searching of the nearest point (Fig. 9).

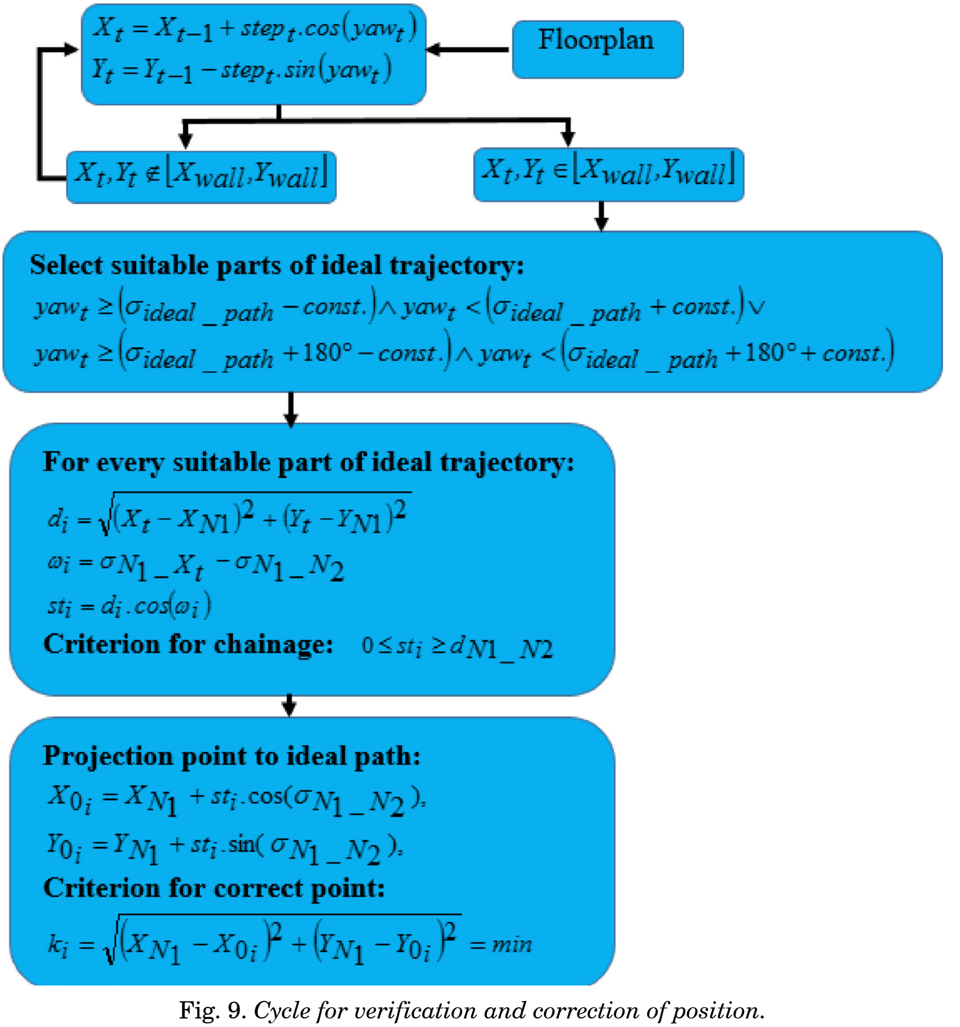

Fig. 9. *Cycle for verification and correction of position.*

Note: The value of a constant depends on the geometry of the building. When it is about the simple building with four main directions, the value of a constant is 45°. When it is about atypical buildings, the value of a constant depends on the number of selected main directions of building.

Corrected position of a pedestrian has to satisfy the following conditions (Fig. 10):

- The current orientation of pedestrian belongs to a range defined by selected part of an ideal path,
- The stationing of the corrected position belongs to a range of $\langle 0, d_{Ni\_Ni+1} \rangle$
- The minimum length of the offset k_i .

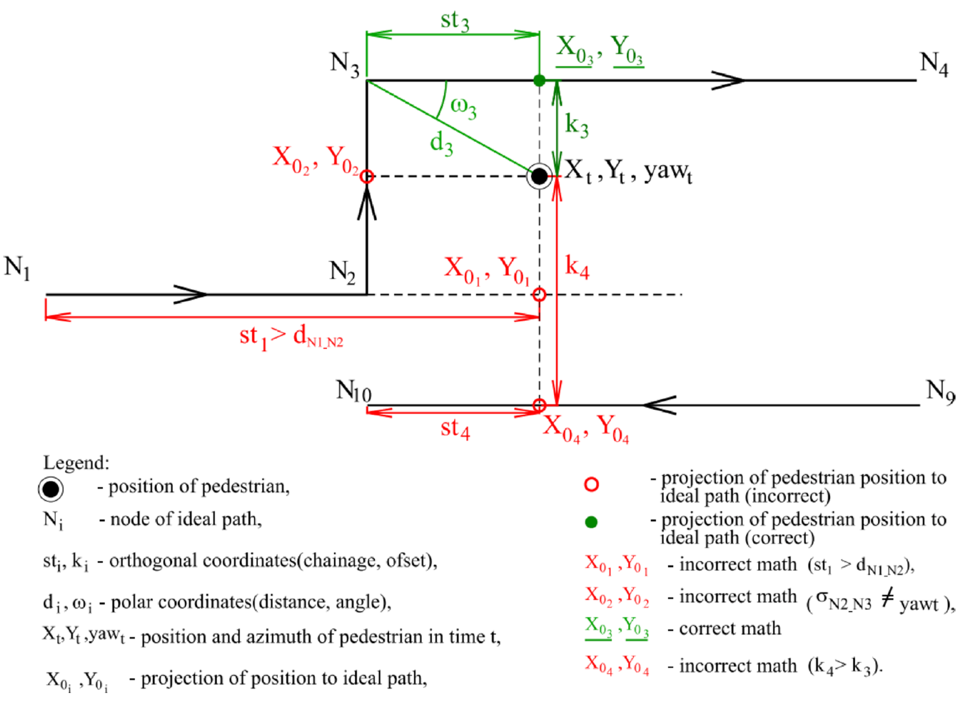

Fig. 10. *Map matching algorithm using floor map and ideal path.*

4. Analyses of Results

The experimental measurement was realized to test the proposed model of the processing. For this experiment Samsung Galaxy S4 smart phone was used. This type of smart phone has 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 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 of pedestrian was defined by 11 traverse points whose position is signalized by the labels stuck on the floor. Traverse points were used for the analysis and verification of results.

Table 1. *Used sensors in experiment from Samsung Galaxy S4.*

Sensor	Type	Range	Accuracy
Accelerometers	K330 (STMicroelectronics)	±2, ±4, ±8, ±16 g	220 μg/$\sqrt{Hz}$ *
Gyroscopes		±250, ±500, ±2000 °/s	0.03 °/s/$\sqrt{Hz}$ *
Magnetometers	YAS532 (YAMAHA)	±1200 μT	0.15 μT (*X*, *Y*), 0.25 μT (*X*, *Y*)
Pressure sensor	Sensortec BMP 180 (BOSH)	300–1100 hPa	950–1050 hPa / ±0.12 hPa / 25 °C / ±1.0 m 700–900 hPa / ±0.12 hPa / 25–40 °C / ±1.0 m

*Note: * accuracy defined by random walk*

The trajectory of the pedestrian 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.

The coordinates of measured points as the result from each method were used for comparison of these methods. The Table 1 shows the coordinate differences between the reference positions of the measured points defined at the beginning of the measurement and position calculated by method 1–3.

Fig. 11 shows a trajectory of a pedestrian calculated with the first method where the constant step length was used. It is possible to see that the worst results were achieved in the short parts of a trajectory (2–3, 3–4, 6–7, 7–8, 9–10, and 10–11) where the orientation of a pedestrian has been changed very often. The reason for decreasing accuracy of a pedestrian position and bad repeatability of a trajectory

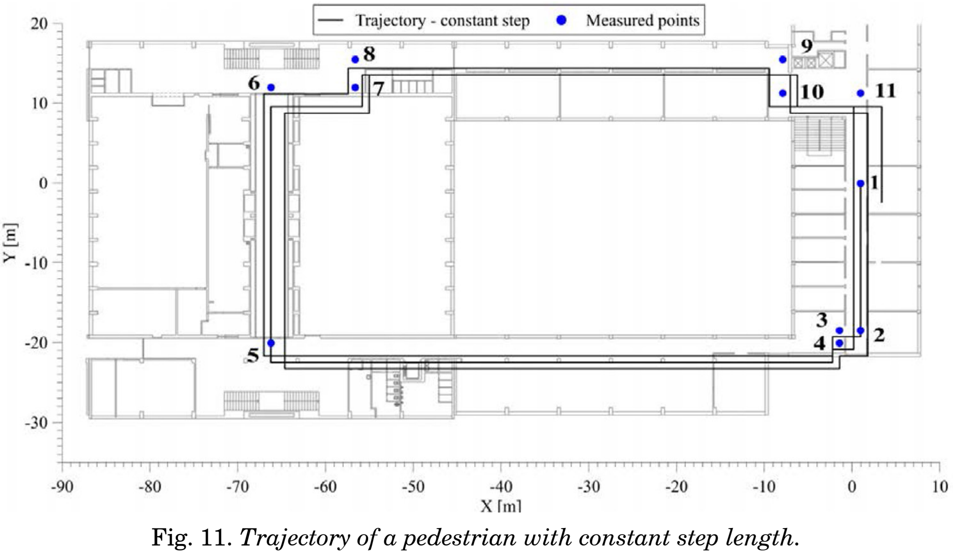

Fig. 11. *Trajectory of a pedestrian with constant step length.*

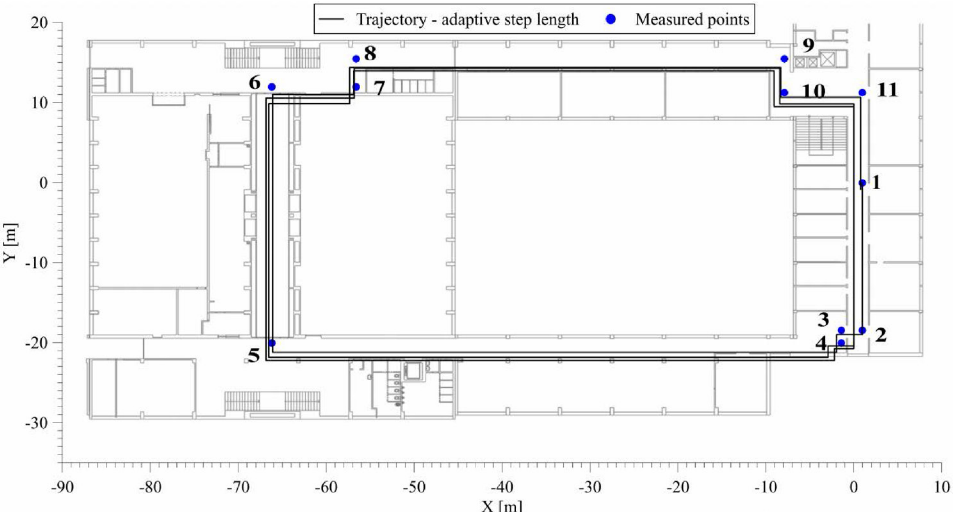

Fig. 12. *Trajectory of a pedestrian with an adaptive step length.*

is a significant change of a step length (caused by a change of a pedestrian velocity) which is approximated by a constant step length.

In the second method of processing (Fig. 12) an adaptive step length estimation algorithm was used which improves the accuracy of a pedestrian position at the problematic parts of the trajectory (2–3, 3–4, 6–7, 7–8, 9–10, and 10–11). Improved results can be seen in the repeatability of the trajectory (a pedestrian walked through the predefined trajectory three times).

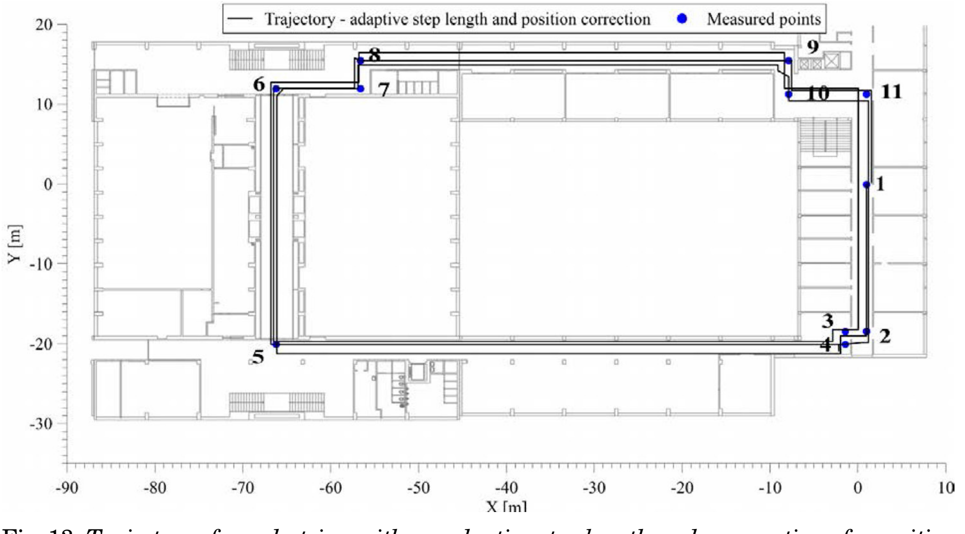

Fig. 13. *Trajectory of a pedestrian with an adaptive step length and a correction of a position.*

The third method of processing (Fig. 13) combined an adaptive step length estimation algorithm with Map Matching algorithm. Using the Map Matching algorithm the incorrect positions of a pedestrian were corrected to an ideal path which increases the accuracy of a position.

The differences between used methods of processing are shown in each details of the trajectory (Fig. 14). The detail shows a part of the trajectory which consists from a short section with the different orientation. In this situation a step length was significantly changed. In this part of the trajectory is a high probability of the wrong selection of a part of an ideal path as well. For this reason, a condition for finding of the nearest point from an ideal path was designed (Fig. 10).

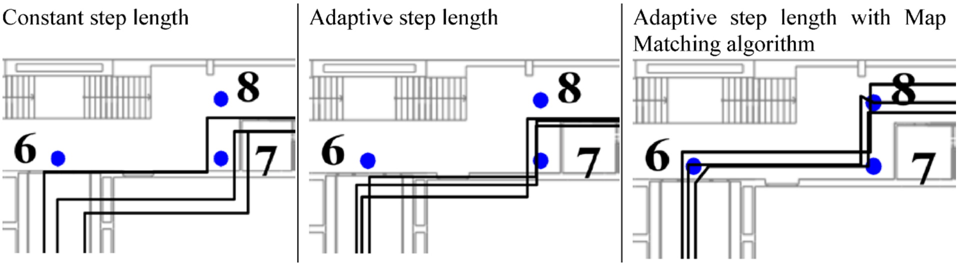

Fig. 14. *Detail of a part of the trajectory with high probability of the wrong selection of a part of an ideal path processed with three proposed methods.*

The results of the experiment (Table 2) 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 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 calculated position was 2.5 m (maximum of the whole experiment). Position errors are probably caused by an error in the orientation of a pedestrian (due to the approximation of an 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 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 the worse results.

Table 2. *Comparison of the coordinate difference on measured points (during the last repetition trajectory).*

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

Adaptive step length estimation improved the accuracy of travelled distance. This fact is possible to see in the results in the Table 3. 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 environment (entering the room, avoiding the obstacles). Calculations with help of Map Matching are not a part of the comparison (Table 3) because it does not influence the accuracy of travelled distance. The position of a pedestrian is directly corrected.

Table 3. *Comparison of travelled distance between a constant step length and an adaptive step length.*

Part of predefined trajectory	**Travelled distance**				
	Reference [m]	**Constant step length [m]**	**Difference [m]**	**Adaptive step length [m]**	**Difference [m]**
1st travelled trajectory	205.3	208.0	–2.7	204.1	1.2
2nd travelled trajectory	205.3	208.0	–2.7	207.3	–2.0
3rd travelled trajectory	205.3	208.0	–2.7	205.9	–0.6
Total	615.9	624.0	–8.1	617.3	–1.4

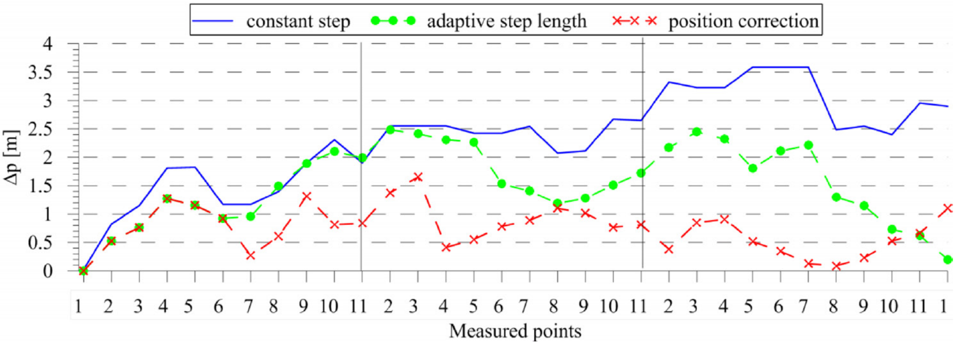

Fig. 15. *Comparison of the position error on measured points during experimental measurement.*

5. Other Possibilities of Using the Floor Map

In the above mentioned calculation process 2D pedestrian positioning was designed. But the utilization of this algorithm is limited only for single storey buildings. The process used for verification of a pedestrian positioning which is based on the Map Matching algorithm can also be used for detection of such places where the floor can be changed (e.g. elevators, stairs). These places are defined by a traverse in the floor plan.

In such situation when the algorithm detects the position of a pedestrian in a given traverse (which represents the stairs or an elevator) measurements from atmospheric pressure sensors are used in formula for calculation of an actual height of a pedestrian (Gadeke et al. 2012):

$$h_t = h_0 + \frac{R \cdot T_0 \cdot \ln\left(\frac{P_t}{P_0}\right)}{-g \cdot M}, \tag{15}$$

where

h_0 – initial height (for the first time when algorithm detects the position of a pedestrian on stairs) [m]
T_0 – temperature [K]
P_0 – initial atmospheric pressure (for the first time when algorithm detects the position of a pedestrian on stairs) [Pa]
P_t – atmospheric pressure in time t [Pa]
g – gravitational acceleration constant (9.80665 m/s^2)
M – molar air mass (0.0289644 kg/mol)
R – universal gas constant (8.31432 Nm/molK).

The short experiment was realized with a purpose to establish the accuracy of height calculated from the atmospheric pressure. A pedestrian walked from the ground floor to the fifth floor and back during this experiment. An atmospheric pressure sensor of Samsung Galaxy S4 smart phone was tested in the experiment. The results of the experiment are in Table 4 where it is possible to see that the maximum difference between the reference height of a pedestrian and the height calculated from atmospheric pressure is 0.6 m. These results confirm the possibility of using the suggested solution (Fig. 16) for detection of a change of the height (detection of a change of the floor).

Table 4. *Comparison of the measured height (calculated from a change of pressure) and the reference height.*

Floor	**Reference height [m]**	**from the ground floor to the 5th floor**		**from the 5th floor to the ground floor**		**Difference [m]**
		Measured height [m]	**Error in height [m]**	**Measured height [m]**	**Error in height [m]**	
ground floor	100.0	100.0	0.0	100.3	0.3	–0.3
mezzanine	101.9	101.7	0.2	102.2	0.3	–0.4
1	103.8	103.7	0.1	104.2	0.4	–0.5
mezzanine	105.7	105.7	0.0	106.3	0.6	–0.6
2	107.5	107.7	–0.2	108.2	0.6	–0.5
mezzanine	109.4	109.6	–0.2	109.8	0.4	–0.2
3	111.3	111.4	–0.1	111.5	0.1	0.0
mezzanine	113.2	113.1	0.1	113.5	0.3	–0.5
4	115.1	115.2	–0.1	115.4	0.3	–0.2
mezzanine	117.0	117.2	–0.2	117.1	0.1	0.1
5	118.9	119.2	–0.3	119.2	0.3	0.0

The accuracy of height calculated from the change of atmospheric pressure is significantly affected by thermal noise and quantization noise which is generated due to the low resolution of the pressure sensor. That is why the process of actualization of the height of a pedestrian will be realized only in such situations when the pedestrian will be located on stairs (or on another place where the height is changed) (Tanigawa et al. 2008). The floor map will be updated according to the actual height of a pedestrian (Fig. 16).

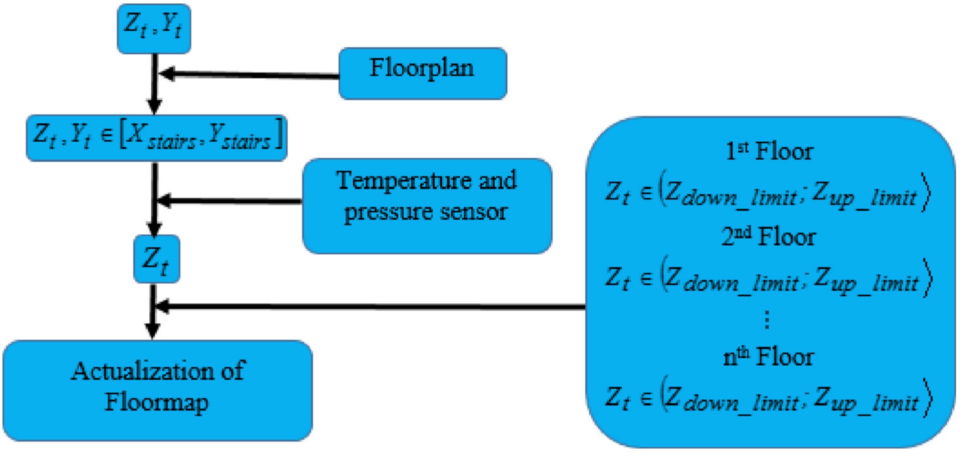

Fig. 16. *Cycle for the height change detection and actualization of floor map.*

6. Conclusion

From the origin point of view errors in determination of a pedestrian position could be divided into two basic components – errors in determination of a trajectory length and errors in orientation of a pedestrian movement. The chapter 1.1 deals with the first component of errors. In indoor environment the pedestrian step length is often influenced by entering the doors, direction changes, etc. 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 3 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 3.2 presents the possible elimination of errors in the pedestrian orientation. The procedure for azimuth calculation includes a drift elimination part which corrects the pedestrian azimuth according to the building geometry. This is based on limitations of the pedestrian trajectory which are strictly given by the building geometry – doors, corridors, stairs, etc. The inspection of pedestrian orientation was realized on a 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.).

The next application of "Map Matching" is its utilization in combination with barometric determination of heights to determine height information of the pedestrian trajectory. It was possible to achieve the accuracy of 0.6 m. This value is acceptable for the exact determination of the actual floor (level) of the pedestrian trajectory.

According to the results it can be assured 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 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 combination of the adaptive step length algorithm with "Map Matching" where the average deviation in position was 0.7 m and the maximal deviation was 1.7 m.

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Pozicioniranje i praćenje pješaka u zatvorenom prostoru koristeći senzore pametnih telefona, otkrivanje koraka i algoritam za geokodiranje

SAŽETAK. Rad se bavi navigacijom u zatvorenom prostoru koristeći inercijalne senzore (akcelerometre, žiroskope, itd.) ugrađene u pametne telefone. Najveći nedostatak korištenja inercijalnih senzora je netočnost koja se ubrzano povećava produljenjem vremena mjerenja. Razlog smanjenja točnosti je prisutnost pogrešaka inercijalnih mjerenja koje se akumuliraju kroz proces integracije. Rad opisuje određivanje putanje pješaka koristeći metodu praćenja koraka koja je poboljšana korištenjem algoritma za procjenu prilagodljive duljine koraka. Ovaj algoritam odražava promjene u duljini koraka s različitim vrstama kretanja. Prijedlog obrade podataka koristi informacije iz tlocrta katova što omogućava potvrdu položaja pješaka i otkriva koliziju putanje s tlocrtom. Predloženi algoritam znatno povećava točnost dobivene putanje. Drugi dodatak predloženog algoritma se odnosi na upotrebu barometarskih mjerenja pri određivanju visinskih razlika. Ova činjenica omogućava promjenu kata u višekatnoj zgradi. Eksperimentalno mjerenje je izvršeno uz pomoć pametnog telefona Samsung Galaxy S4.

Ključne riječi: pametni telefon, inercijalni senzor, sustavna pogreška, praćenje koraka, procjena prilagodljive duljine koraka, geokodiranje.

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