INDOOR POSITIONING AND NAVIGATION FOR PEDESTRIAN GUIDANCE IN PUBLIC TRANSPORT FACILITIES

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ABSTRACT

We propose a system for indoor navigation in public transport transfer buildings that is an element of a dynamic seamless mobility planning and travel guidance application for public transportation networks of metropolitan areas.

The components of the smartphone based system include sensor fusion from camera, WiFi, GPS, Bluetooth and pressure sensor as well as inertial measurement units for *Pedestrian Dead Reckoning* and 2.5D navigation in arbitrary building structures. Maps of multi-level buildings are collected from escape/rescue floor maps and *OpenStreetMap* data to be displayed on the mobile device. Navigational aids collected from sensors provide en-route orientation. The indoor route over multiple levels, elevators, stairs and escalators is calculated by a combination of route search and grid based pathfinder algorithm. Changes of floor levels are detected by relative barometric pressure measurements.

Keywords: Transport Telematics, Public Transportation, Indoor Positioning, Indoor Navigation

1. INTRODUCTION AND PROBLEM STATEMENT

Indoor navigation is a key element of multi-modal door to door journeys especially during transfer events between public transport vehicles at complex station buildings. Indoor positioning and navigation services are realized by various components of an *Android* smartphone application to build up a dynamic seamless mobility planning and travel guidance system for large public transportation networks of metropolitan areas. See Figure 1 for typical use case.

The objective is to accomplish a multi-modal door-to-door journey planner and navigation application using real time data for seamless mobility. Thereby, the indoor navigation provides important information on location of the user during transfer from public transport route segment to his next public transport (mass transit) opportunity.

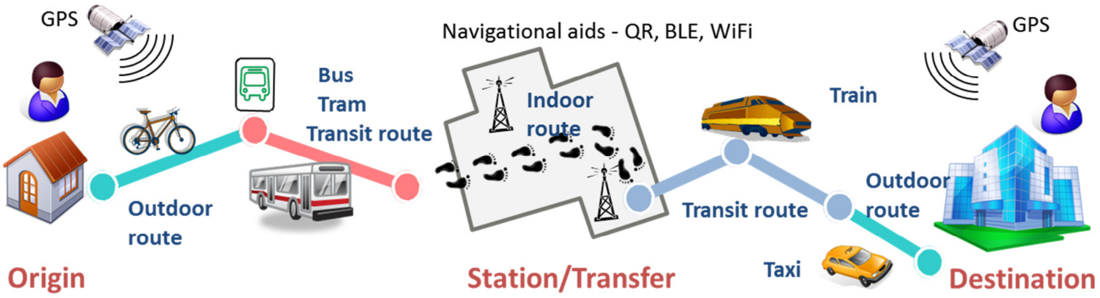


Figure 1 Indoor navigation is a key element of public transport of the multi-modal door to door journey especially during transfer of trains at complex station buildings.

The purpose is to provide orientation guidance to passengers unfamiliar with localities during transfer between public transport services. Further it is intended to help commuter trip planning and to improve reckoning of transfer times. Public transit transfer facilities are multiple level building structures including pathways, floors and platforms connected by stairways, escalators and elevators. Therefore, indoor routing includes grid based navigation on floors of each individual level as well as network graph based navigation between all reachable levels and floors of the transfer facility.

2. APPROACH

As a central component of the indoor navigation system (see Figure 2) *Pedestrian dead reckoning (PDR)* is implemented using smartphone sensors accelerometer, gyroscope and magnetometer for step and heading detection. Navigational aids include GPS, WiFi, Bluetooth and camera and feed the location (LOC) component. Building layout data and floor maps are collected from *OpenStreetMap* [11] and are projected to conformal Web Mercator coordinate system (EPSG:3857) [14] to compose the line layer.

For any given building, a topological 2.5D floor network is constructed. The nodes of this network represent contiguous areas of a building level, denoted as a floor. The edges of this network represent floor transfer opportunities such as elevators, escalators and stairs. The term 2.5D refers to the fact that for positioning in the x-y plane a continuous value domain is used, whereas for the z-axis only discrete values, i.e. integer level numbers are allowed. The component denoted as pathfinder conducts a *Breadth-first* path search between origin and destination coordinates to analyze reachability and to obtain a list of transfer points between levels of the building. A method to test if a position found is located indoor or outdoor is implemented based on map information to provide information on potential deviations of the user from calculated path’s.

Given the transfer points within the building, for each floor on which a pedestrian can move, a grid based network is generated. The preferred shape of the grid element is a hexagon. This hexagon grid is similar to those as used in models for *Simultaneous Localisation and*

Mapping (SLAM), see Robertson (2003). It is temporarily constructed to observe inner and outer walls, obstacles and other constraints for each floor level between transfer points. For navigation on the floors an A* algorithm is applied with modified Manhattan distance heuristic that takes the hexagonal grid as input. En-route directions are passed to the user by dynamic display updates of position and path to destination as well as by voice guidance.

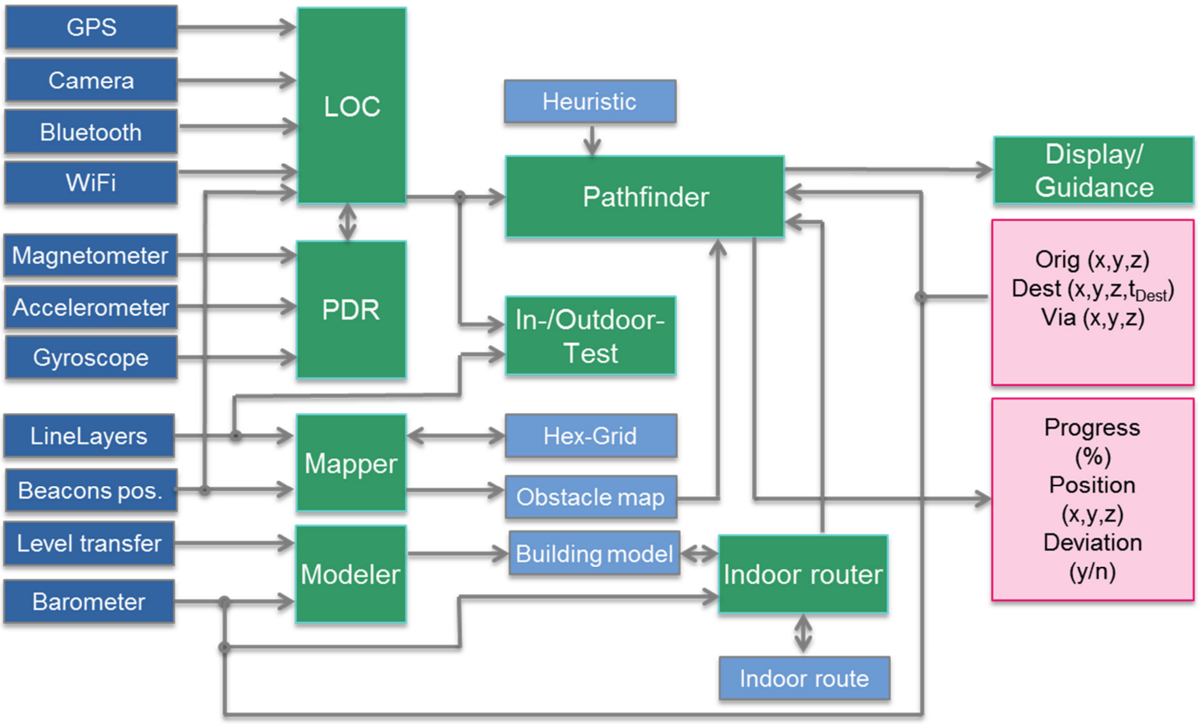


Figure 2 Sensors and functional components of the indoor navigation system.

As an interface to other services it is defined to exchange messages with content on starting position, target position and en-route way points (via) in three dimensional coordinates as input parameters for the indoor navigation system. During active navigation messages are passed to calling services providing information on position in x,y,z coordinates, progress of entire route throughout the building, and possible deviations from the route.

In the following sections the components introduced above are discussed in further detail.

3. INDOOR NAVIGATIONAL AIDS

3.1 Bluetooth Cell Positioning

The concept of *Bluetooth Low Energy* (BLE) cell positioning involves distributed beacons placed at indoor positions of main pedestrian route choice locations. BLE beacons such as shown in Figure 3 are used as navigational aids to support the pedestrian dead reckoning algorithm processed on the mobile phone. Installation positions of BLE beacons are planned according to geometric conditions of the building. Recommendations for beacon placement include locations at entry doors as well as stairs, escalators, elevators, and additional orientation points within larger pedestrian walkable areas where main pedestrian flows cross each other. All attributes of distributed beacons are made available to the indoor navigation system prior to its usage. With an interval of one second, BLE beacons send periodical broadcast signals that are uniquely identified by their network (MAC) address.

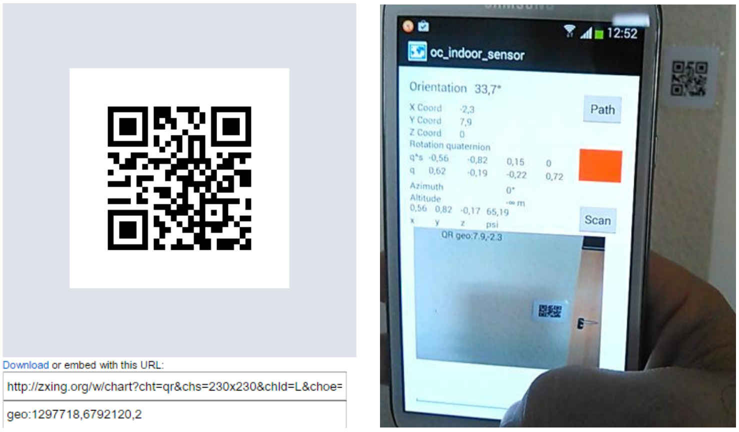
On the receiver side the received signal strength, RSSI is evaluated. RSSI values of greater than -65 dBm indicate a beacon-receiver distance of less than 1 m which is assessed as sufficient accuracy to adopt the beacon location as a position fix. The total set of installed indoor beacon parameters are registered at initial state and, by this way. made available to cell positioning algorithm as navigational aids for positioning updates. Parameters of the beacon are its position in 2.5D coordinates, whereas x- and y-coordinates represent its location in EPSG:3857 (Web Mercator Projection) and z-coordinate denotes the building floor level in discrete values.

Figure 3 Bluetooth low energy beacon deployed for indoor cell positioning mounted in a rigid case of 6 cm x 4 cm x 2 cm.

In order to save battery energy, the time regime of BLE scans is organized as follows. For an interval of 10s a BLE device scan is carried out to detect any existing and known device in the vicinity of the mobile unit. If a BLE beacon is detected, the scan interval is reduced to 1s until the RSSI value reaches the defined maximum value of -65 dBm or passes a maximum peak. After recognition of the beacon it is omitted from further detection for a defined time interval of 20s to enable scan and detection of other beacons with a higher priority. Acoustical feedback is given to the user by a sequence of generated tones to indicate the received signal strength for each detection and acknowledgement of position fix.

3.2 QR-Codes

The widespread use and prevalence of QR-codes for quick response and coding of machine readable data and their transfer into mobile units suggest their application for the provision of additional navigational aids in an appropriate way. A formatted QR-Code is specified including a free text starting with the keyword “geo:, followed by comma separated x-,y-, and z-coordinates, as shown in Figure 4.



Download or embed with this URL:

http://zxing.org/w/chart?cht=qr&chs=230x230&chld=L&choe=

geo:1297718,6792120,2

```
Orientation  33,7°
X Coord    -2,3
Y Coord    7,9
Z Coord    0
Rotation quaternion
q*s  -0,56   -0,82   0,15    0
q     0,62   -0,19   -0,22   0,72
Azimuth              0°
Altitude             -∞ m
0,56  0,82  -0,17  65,19
x     y     z      psi
QR geo:7.9,-2.3
```

Figure 4 QR-Code generation and usage for 2.5D coded coordinates of code locations as supplementary navigational aids

The camera sensor of the smart mobile phone is used for semi-automatic acquisition and decoding of tag locations. The process of QR-code scan designed to be handled by the user requires a minimum of interaction.

3.3 WiFi cell positioning

The method for cell positioning using known locations of WiFi access points was implemented in a similar way like it was realized for Bluetooth cell positioning. Prior to usage any location coordinate of WiFi access points must be identified, collected, and made available to the indoor navigation system through an interface of comma separated text file. This method does not require the prior collection of WiFi fingerprint data, which is widely used in numerous indoor navigation methods, referenced exemplarily in [5]-[10]. The present method uses only known geographic positions of access points if received signal strength of broadcast messages have RSSI value greater than -50 dB which is equivalent of a distance of approximately 1-3 m. Under these conditions it is noted that WiFi cell positioning in the context of the described system is employed mainly as a supplementary navigational aid.

3.4 Global Positioning System

The GPS is used as a supplementary navigational aid in phases of transition from outdoor areas to indoor areas. It may also be used whenever GPS signals are receivable and the user is located in an outdoor area of a transfer building, e.g. at ground level platforms of public transport stations situated in the open air. Received latitude and longitude coordinates of the WGS84 system (EPSG:4326) are continuously transformed into Web Mercator projected coordinates (EPSG:3857) similarly used in web mapping application such as *Open Street Map* [11] or *Google Maps* [12] or *Microsoft Bing* [13]. Web Mercator is the mapping of ellipsoidal latitude and longitude coordinates onto a plane using spherical Mercator equations.

The necessity to use a projected coordinate system for the mapping of indoor areas is substantiated by the requirement of a conformal mapping of its objects such as buildings, platforms, and floors etc.

Conformal mapping is defined by the property that every small feature of the map is depicted correctly, i.e. the projection preserves shape and angle. An important property of conformal Web Mercator projection is the local scale in every direction around one point is constant. That characteristic is crucial for pedestrian navigation in relatively small objects.

Because transformation and retransformation of coordinates between both coordinate systems is performed continuously during run time of the indoor navigation system the user's current position is provided instantly in WGS84 as well as in Web Mercator coordinates to other service components regardless if the users position is indoor or outdoor. The equations for transformation from geographic coordinates into Easting E and Northing N of Web Mercator are given as follows:

$$E = a(\lambda - \lambda_0) \tag{1}$$

$$N = a \ln \left[\tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \left(\frac{1 - e \sin\phi}{1 + e \sin\phi}\right)^{\frac{e}{2}} \right] \tag{2}$$

$$h = k = \frac{\sqrt{1 - e^2 \sin\phi}}{\cos\phi} \tag{3}$$

with a = 6378137 m as semi-major ellipsoidal axis, and e = 0.081819191 as eccentricity, λ as geographic longitude and ϕ as geographic latitude.

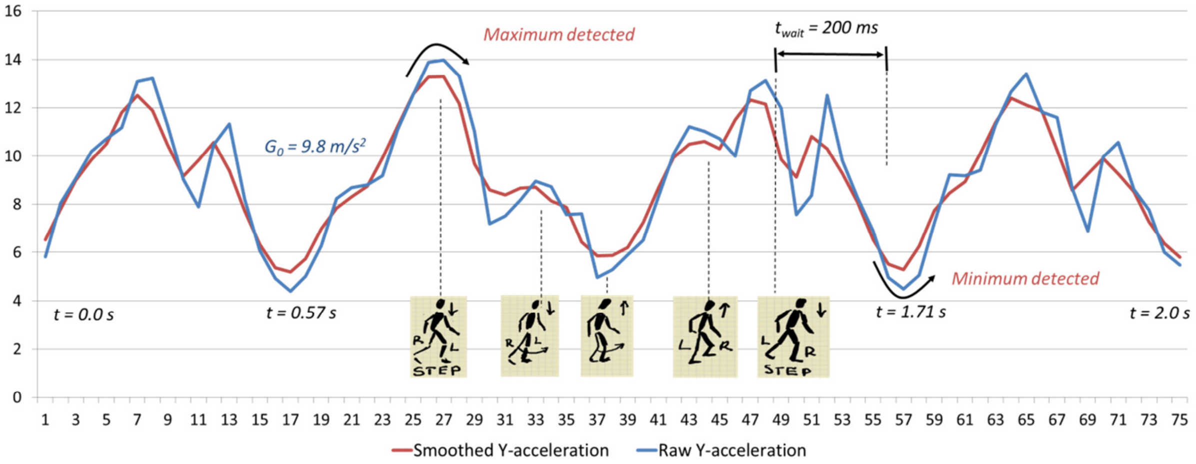
The scale factors 'h' for North-South direction, and 'k' for East-West direction are equal because the scale factor at a point is the same in all direction on the ellipsoidal Mercator projection.

4. PEDESTRIAN DEAD RECKONING

4.1 Walking cycle detection

The vertical acceleration component is the primary inertial sensor signal of smart mobile unit to be observed and evaluated for walking cycle and step detection. The accelerometer signal is acquired with a sampling rate of 25 ms. The accelerometer's vertical component is assumed to be collinear with the y-axis of the mobile units body frame if the phone is carried in upright position. The signal is subtracted by gravity (9.81m/s^2), filtered through a first order low pass filter and differentiated to detect minima and maxima of the signals time progress.

A state machine of two discrete states represents the gait cycle: (a) right leg in front, left leg behind and (b) left leg in front, right leg behind. Transitions between these two states are controlled by interpretation of derivation of y-axis acceleration, shown in Figure 5.



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Algorithm 1: Gait detection dual-state machine
    input  : $m_Y$ - Smoothed time discrete acceleration signal
    output: Gait cycle control → (a) right leg in front, left leg behind
              (b) left leg in front, right leg behind
    Ensure the unit to be stowed → wait for 3000 ms;
    // maximum of downward force - gravity → step detected
    (1) if minimum $m_Y$ detected and $m_Y$ is negative and state == 1
    then
        set state = 0;
        Calculate new x and new y position using PDR algorithm
    (2) if maximum $m_Y$ detected and $m_Y$ is positive and state == 0
    then
        set state = 1;
    (3) update heading estimation
```

Figure 5 Walking cycle detection algorithm from smoothed Y-acceleration signal using two states of gait postures for left and right leg swing. A waiting time of 200 ms after maximum detection is inserted to prevent signal gutter effects.

4.2 Heading estimation

For heading estimation the virtual rotation sensor provided by *Android* operating system is utilized. The rotation sensor signal is computed internally by means of a Kalman filter that performs the fusion of gyroscope, accelerometer and magnetometer sensors which are integrated into hardware as micro electro mechanical system units (MEMS). Thereby the rotation sensor signal is represented in a quaternion form:

$$q = [q_1\ q_2\ q_3\ q_4] = \left[i \sin\left(\frac{\varphi}{2}\right)\ j \sin\left(\frac{\varphi}{2}\right) k \sin\left(\frac{\varphi}{2}\right)\ \cos\left(\frac{\varphi}{2}\right)\right]^T \tag{4}$$

with φ as rotation angle about the complex unit vector $[i\ j\ k]$ which represents the axes in x-y-z-directions. The values of the quaternion $[q_1\ q_2\ q_3\ q_4]$ represent the rotation from world reference frame defined as y-axis along earth rotation axis, x-axis points towards east and z axis points towards zenith to sensor body frame coordinate system defined as y-axis along the long screen axis of the smartphone, x-axis along the short screen axis of the smartphone and z-axis pointing perpendicular out of the screen surface, in general towards the user.

The problem to determine the heading of the pedestrian holding the smartphone is solved like calculating the vector of projection of the smartphones z-axis onto the earth surface. This approach is useful to avoid the common Gimbal lock problem [4] to occur with Euler angles (roll, pitch, yaw) when they in a range close to 90 degrees as it is in the given case. See Figure 6 for geometric coherence of Earth's surface and user orientation by smartphones screen axis.

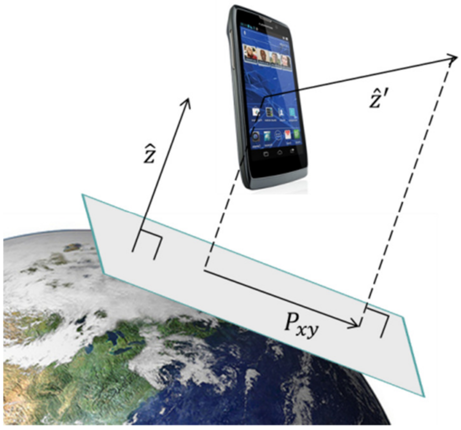


Figure 6 Projection of smartphones z-axis onto earth's surface plane. $\hat{\mathbf{z}}'$ is the plane normal vector of smartphone's screen, $\hat{\mathbf{z}}$ is the plane normal vector of earth's surface

The z-axis of the mobile phone is expressed by the following quaternion product (operator *)

$$\hat{z}' = q * \hat{z} * q^{-1} \tag{5}$$

with q from equation (5) as the measurement provided by rotation sensor signal and the quaternion vector for z-axis

$$\hat{z} = [0\ 0\ 1\ 0] \tag{6}$$

The projection of the vector $\hat{z}'$ onto the earth surface plane is

$$P_{xy} = \hat{z}' - (\hat{z}' \cdot \hat{z}) * \hat{z} \tag{7}$$

with regard to different operations of dot product (operator ·) and quaternion product (operator *) as well as the requirement of normalization of any quaternion value prior to processing. We use the opposing vector $-P_{xy}$ to obtain the estimate of the direction of walking by further trigonometric calculus. In result the heading orientation is determined as azimuth degrees from magnetic north in clockwise direction. Magnetic declination in central Europe is approximately ±3 degrees (East/West) and therefore can be neglected for the intended purpose of short range pedestrian navigation.

5. INDOOR ROUTING AND NAVIGATION

5.1 The building/facility model

The model of buildings for public transport facilities such as transfer stations etc. entails all indoor areas that are publicly reachable by transport users. These users are considered in the context of this paper as pedestrians only.

A building is described as a collection of geometric areas enclosed by polygons situated at discrete floor levels that are connected by stairs, escalators or elevators, denoted as level connectors. Each distinct platform constitutes one node, whereas each level connector represents an edge of the virtual graph describing the entire building. A real example of a building model is shown in Figure 7.

Figure 7 Geo-referenced model of a railway and subway station with corresponding topological 2.5D graph of floors (nodes) and floor transfer connectors (edges).

Selected attributes of the graph edges are for example number of floor levels to be connected with, height difference and geographical coordinates of bottom and top points of the stair for instance. The nodes bear attributes such as unique identification codes, the discrete floor number, and the current barometric pressure used for floor level detection. The directed building graph is constructed once during initialization of the application when the first position fix has been acquired and three dimensional destination coordinates have been received. The process of navigation includes continuous parallel processing of system components such as route search within the directed building graph, grid based navigation upon enclosed floor levels and floor level detection by barometric pressure evaluation. Each of these system components are described in the following.

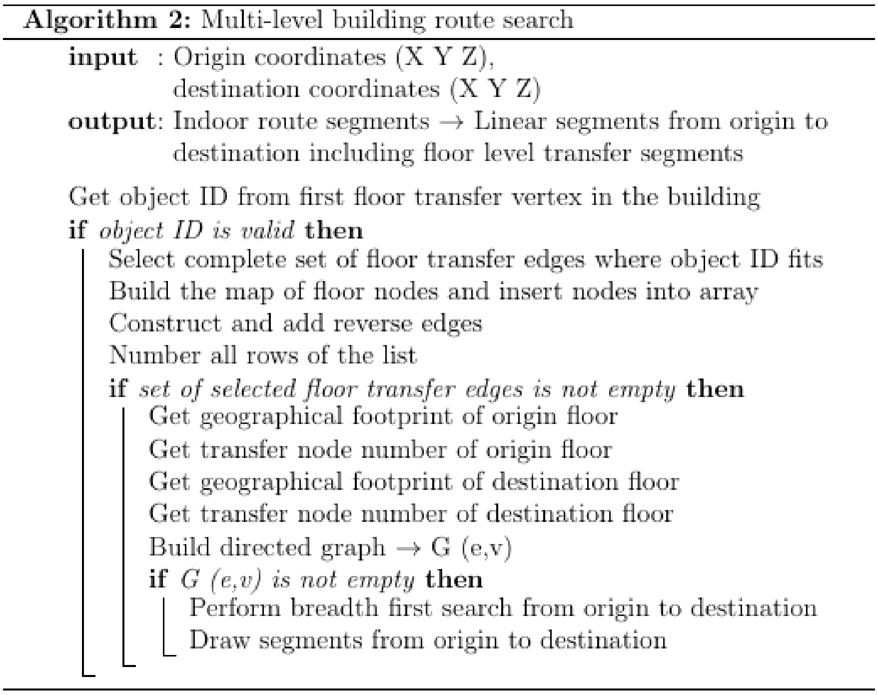
5.2 Route search within building model

The general use case for indoor navigation involves an initial indoor positioning of the public transport user by means of navigational aids such as Bluetooth, WiFi or QR-Codes whenever the indoor area of the referring building is entered, whether through an entry door or by alighting a public transport vehicle.

At the same time, the destination coordinate within the same building or facility must be obtained from a superior service component that maintains the entire multi-modal route of the respective traffic user.

Given the origin and destination coordinates, the indoor part of the multi-modal route is found through a route search using the building model in shape of the directed building graph in combination with a grid based building navigation at each enclosed floor level.

Provided the directed building graph has been constructed successfully during initialization of the indoor navigation service component, the route through the multi-level building is determined by the algorithm, shown in Figure 8.



```
Algorithm 2: Multi-level building route search
input  : Origin coordinates (X Y Z),
         destination coordinates (X Y Z)
output: Indoor route segments → Linear segments from origin to
         destination including floor level transfer segments

Get object ID from first floor transfer vertex in the building
if object ID is valid then
    Select complete set of floor transfer edges where object ID fits
    Build the map of floor nodes and insert nodes into array
    Construct and add reverse edges
    Number all rows of the list
    if set of selected floor transfer edges is not empty then
        Get geographical footprint of origin floor
        Get transfer node number of origin floor
        Get geographical footprint of destination floor
        Get transfer node number of destination floor
        Build directed graph → G (e,v)
        if G (e,v) is not empty then
            Perform breadth first search from origin to destination
            Draw segments from origin to destination
```

Figure 8 Algorithm of route search through a multi-level building

A *Breadth-first* search delivers a node list of intermediate nodes, respectively platforms of the building. For each edge connecting consecutive nodes of the node list, the nearest floor transfer facility (stair, elevator or escalator) is searched. Between actual positions of the user on each level and the known end points of the floor transfer facilities a hexagonal grid is created, taking into account walls, curvatures of the floor and obstacles. Given the hexagonal map an A* search algorithm using a modified Manhattan heuristic is applied to find the path on each floor until destination is reached, which is further described in the following section.

5.3 Grid based building navigation

The motivation to apply hexagonal grids for navigation and guidance of pedestrians within indoor areas of multi-level buildings is manifold. Initially, a grid of geometric objects can be automatically and temporarily generated to be overlaid to geometric and geographically referenced objects of the building levels. Further, a predefined path oriented network for pedestrian traffic in buildings is a priori not available. A grid based approach appears to be more suitable to model the free directional flow of pedestrian users within indoor areas rather than a topological node/link network where motions are allowed only over predefined pathways. Finally the hexagon grid was preferred because of its geometric property, that distances between any neighboring hexagons are equal which facilitates calculation of cost functions.

As described before, the grid based navigation is applied for each segment found by prior *Breadth first* route search. Therefore, a hexagonal grid is generated between coordinates of start and end point of the respective segment. During generation of the hexagonal grid it is overlaid on top of existing building geometries. For each hexagon to be created it is tested if an intersection with a building geometry, such as a line or polygon, exist. If the intersection exists, the hexagon will not be created, and its position is mapped as an obstacle. Thus, walls and other indoor installations come out as constraints in the hexagonal grid map used by the path finding algorithm within the hexagonal grid.

The A* algorithm, presented in Hart et al. (1968) [2] was employed for navigation in the floor grid map as the preferred pathfinding algorithm. The A* algorithm calculates the shortest path between source and target node of the map. It takes advantage of a heuristic function to search in a target-oriented manner for the path and therefore reduces its run time.

For the present case it was applied a *Manhattan heuristic* modified for the specialized requirements of the hexagonal grid. This heuristics accounts for diagonal steps to incur same costs of one unit as horizontal and vertical steps within the hexagonal grid as required.

In Figure 9 the route segments representing multiple levels of an indoor route inside a subway interchange station in Frankfurt (Main) are displayed from left to right. The route starts at ground level and leads over emphasized -1 level (left screen) to -2 level (middle left screen) to -3 level (middle right) to departure platform at -3 level. Green hexagons are magnified (right screen) denote the found path of A* algorithm within hexagonal grid including obstacle map.

During navigation the PDR algorithm updates position estimates of the user and triggers the recalculation of the path at the current level.

En-route directions are passed to the user by dynamic screen updates of position and path to destination and by voice guidance. Announcements such as “turn left”, “turn right”, “make a u-turn”, “destination reached” are played out according to specified angle differences between vectors of users heading and his course along updated path.

```
STATE
X   963070.0
Y   6434343.5
Z   0.0
LON 08.651405°
LAT 49.931050°
HDG 267.1°
IND true
```

```
STATE
X   963070.0
Y   6434343.5
Z   0.0
LON 08.651405°
LAT 49.931050°
HDG 273.3°
IND true
```

```
STATE
X   963070.0
Y   6434343.5
Z   0.0
LON 08.651405°
LAT 49.931050°
HDG 281.3°
IND true
```

```
STATE
X   963066.3
Y   6434342.8
Z   0.0
LON 08.651372°
LAT 49.931046°
HDG 256.1°
IND false
```

Figure 9 Indoor route segments as result of A* pathfinding in hexagonal grids on multiple floors of a subway interchange station.

5.4 Floor level detection

The detection of floor levels takes place during the entire process of indoor positioning and navigation. The continuous measurement of barometric pressure is used to observe both the floor level during grid based navigation and during transfer to a different level using stairs, elevators or escalators.

At the time of detection of the first beacon within the building the current barometric pressure for the respective level is measured. Since floor height differences of the building are known from definitions of floor transfer connectors, temporary mean pressure values can be assumed to remain valid for time interval of approximately 1 hour. Therefore instantly, for each of the remaining floor levels the current barometric pressure values are computed and attributed to each node of the building model, representing a unique floor level.

During the stay and navigation of the public transport user throughout the multi-level building complex his vertical position can be determined by observation and evaluation of the barometric pressure sensor signal. A floor level transfer event from level *-1F* to level *0F* is detected by a decrease of barometric pressure of approximately $\Delta p_h = 0.5\ mBar$, as shown in Figure 10.

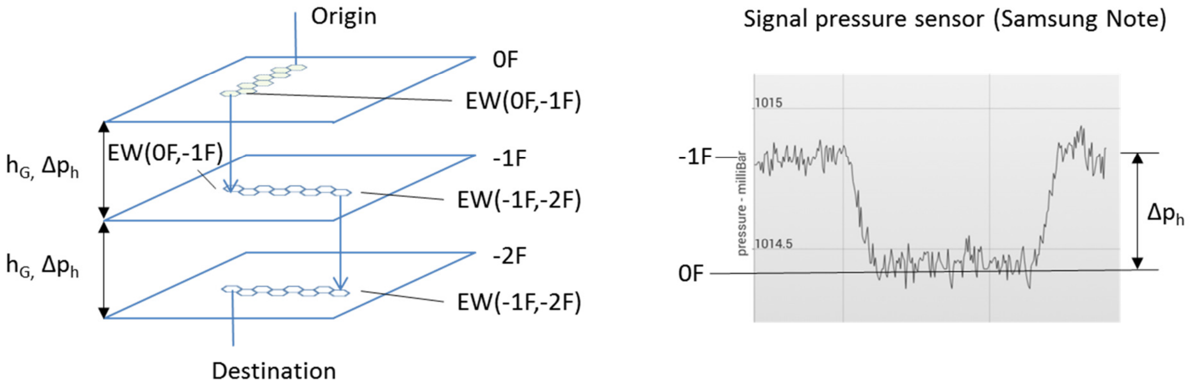


Figure 10 Barometric pressure detection of floor level transfer event for indoor navigation throughout a multi-level building complex.

During the time frame of the indoor navigation the general atmospheric pressure is considered to remain constant and will therefore not interfere with floor level detection algorithm.
Navigation guidance is supported by vocal direction announcements driven by observations of pedestrian's headings and their difference between path's course. Directions are similar to those of existing pedestrian navigation applications used to facilitate indoor motion of the passenger throughout the building.

6. CONCLUSIONS

By the described indoor navigation system it has been proved by field trial experiments that the proposed solution is suitable for employment in large scale public transport networks during the projects runtime in Frankfurt (Main) area.
It has been shown that positioning accuracy depends on inherent drift of heading and step detection and adds up with increasing distance from a beacon. The deviation is likely to be expected in a range of up to 5 m from ground truth path in a distance of approximately 50 m from last cell positioning fix.
Therefore it is appropriate to distribute beacon positions within a building in a grid from 50 m to 100m distance. Further, building related restrictions such as walls and floor layout can also be used to correct drift related deviations from ground truth path. Despite of inherent limitations, the indoor positioning and navigation application is suitable for pedestrian guidance in public transportation facilities in order to provide orientation and directions to travelers unfamiliar with localities.

7. ACKNOWLEDGMENT

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