Infrastructurless Indoor Positioning System for First Responders

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ABSTRACT

To overview the site of operation in case of an emergency is crucial for effective emergency management. This is a difficult task, in particular within large buildings or underground structures. Information about the whereabouts of the staff is a key element of effective disaster management. This paper presents an indoor positioning system which is able to track and locate people within buildings independent of any infrastructure (global navigation satellite system, WLAN installations, etc.). The system is based on inertial measurement units computing the track of its wearer and a component verifying this position estimates using floor plans of the building. This novel approach allows robust tracking and locating of action forces within buildings and underground structures.

Keywords

Indoor positioning, Disaster Management, Inertial Navigation

INTRODUCTION

Managing emergency situations is a difficult task. The complexity of this task grows with the size and the loss of the bird's eye view of the scene. If emergencies take place in large buildings or underground structures the first responders are quite immediately out of sight of the commanding personnel. Even for different teams inside the building it is not possible to be aware of other team's actions if they do not take place in the same room.

The key to efficient onsite emergency management is keeping track of available resources and their current location. In outdoor scenarios the first responders can be tracked by any global navigation satellite system (GNSS) device. In indoor scenarios, in the absence of GNSS signals this is mostly done by the first responders describing its current location using radio communication and a pinboard in the command center with marks indicating the position of the emergency teams. This procedure inherently contains a trade-off between accuracy of the position known at the command center and the distraction of a team member from its primary work by updating the team's position.

The system presented in this paper allows real time position information at the command center and zero distraction of emergency staff. It is based on inertial measurement sensors which results in complete autonomy of infrastructure such as WLAN which must be installed and gauged preliminarily. Using the floor plans of the building the system can further enhance the position accuracy by several map matching mechanisms. Once the position is determined by the devices worn by the staff it is transmitted to any other device whose wearer could be interested in its position, especially the command center.

The computer aided disaster management system (CADMS) is composed of the following components: Indoor positioning system, user interface, and communication facilities. An overview of the system is given in [1]. This paper focuses on the indoor positioning system and its performance.

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INDOOR POSITIONING SYSTEM ARCHITECTURE OVERVIEW

The indoor positioning system (IPS) is composed of two components. The first processes the raw data from the inertial measurement unit (IMU) which ends up in relative position coordinates which are passed to the second component. The second component transforms the relative coordinates into global ones and brings them into the context of the building. Having a simple building information model at hand the positions are verified and corrected if necessary using map matching techniques.

Sensor Data Processing

A low-cost MEMS-based IMU generally consists of a three-axis accelerometer, a three-axis gyroscope, a three-axis magnetometer, a temperature sensor, an A/D converter and a microcontroller or alternatively a digital signal processor [2]. Furthermore measurement errors are either deterministic or stochastic in nature. Time-dependent deterministic measurement errors produced by an IMU are typically minimized using the measured temperature. Time-independent measurement errors (e.g. scale factor and bias errors) are minimized by the manufacturer of the IMU during the initial calibration process. Thus, the remaining measurement errors are the sum of the residual deterministic errors and the stochastic errors or noise, respectively.

Our system uses the classical double integration of the acceleration signals (aXG, aYG, aZG) over time to calculate the distances (dXIMU, dYIMU, dZIMU). Furthermore all three Euler-angles (roll, pitch, yaw) are calculated by integration of the angular rate over time. Unfortunately, small measurement errors could induce large errors of position without any additional sensors and methods. Therefore an extended Kalman filter (EKF) [3] stabilizes the measurement of the IMU's orientation. In this context the earth's magnetic and gravitational field are measured and utilized. The orientation can be expressed by a quaternion (q0, q1, q2, q3), the Euler-angles (roll, pitch, yaw) or the matrix for transformation of coordinates. In (1) the transformation of the acceleration signals from the local to the global reference frame is shown.

$$\begin{bmatrix} a_{XG} \\ a_{YG} \\ a_{ZG} \end{bmatrix} = \begin{bmatrix} 1-2(q_2^2+q_3^2) & 2(q_1q_2-q_0q_3) & 2(q_1q_3+q_0q_2) \\ 2(q_1q_2+q_0q_3) & 1-2(q_3^2+q_1^2) & 2(q_2q_3-q_0q_1) \\ 2(q_1q_3-q_0q_2) & 2(q_2q_3+q_0q_1) & 1-2(q_1^2+q_2^2) \end{bmatrix} \begin{bmatrix} a_{XL} \\ a_{YL} \\ a_{ZL} \end{bmatrix}$$

The distances (dXIMU, dYIMU, dZIMU) parallel to the three axes (x, y, z) are calculated using the shortest feasible period of time which is one footstep. Zero velocity updates (ZUPT) [4] and drift compensation are also carried out. Hence, the acceleration signal parallel to the z-axis in the global reference frame (aZG) triggers the movement recognition and the IMU is mounted on the user's foot. This method minimizes the errors of the distances to an acceptable range. Inside of a building with heavy disturbances of the earth's magnetic field the integration of additional building information is essential to compensate the remaining error of the heading.

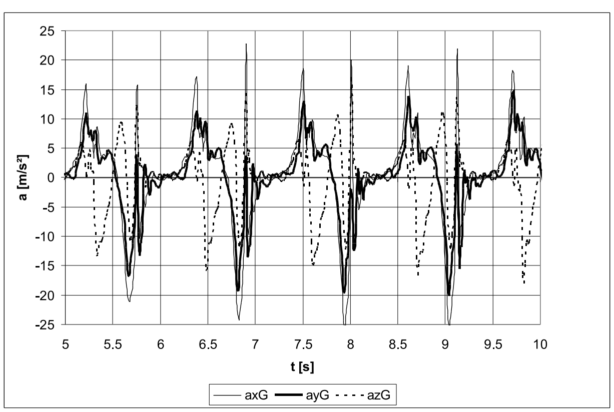


Figure 1. Three acceleration signals (axG, ayG, azG) in the global reference frame measured with an IMU mounted on the user's foot.

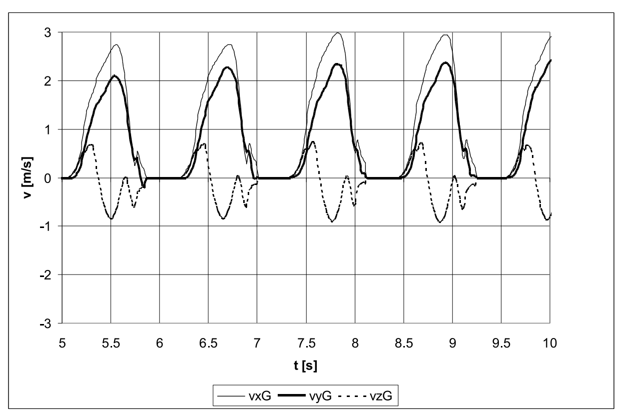


Figure 2. Three velocity signals (vxG, vyG, vzG) in the global reference frame measured with an IMU mounted on the user's foot.

Experimental Results of the Sensor Data Processing

Figure 3, 4, 5, 6, and 7 show the performance of our inertial subsystem in a trial inside of a tunnel and a trial on the expanse of ruins with heavy disturbances of the earth's magnetic field. These trials have taken place on a military training area (Figure 8 and 9). The ruins consist of ferro-concrete with a high amount of steel. Therefore the error of the heading and subsequently the error of position are unsatisfying. The test subject walked along the smaller rectangle. The lager hatched rectangle marks the boundary of the expanse of ruins. Also the trial inside of a tunnel produces errors of the heading and subsequently errors of position. However, these errors are relatively small and could be easily compensated by the integration of building information.

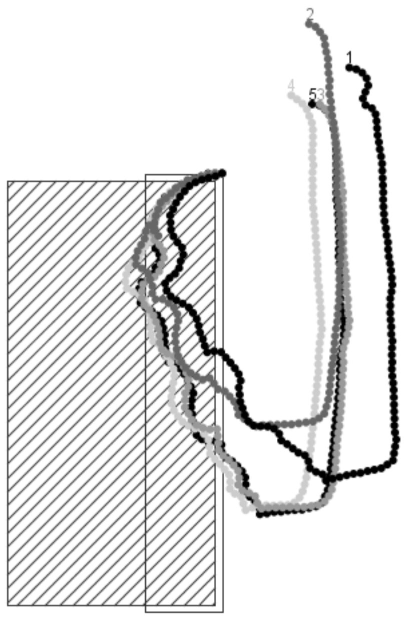


Figure 3. Five trials on the expanse of ruins with heavy disturbances of the earth's magnetic field.

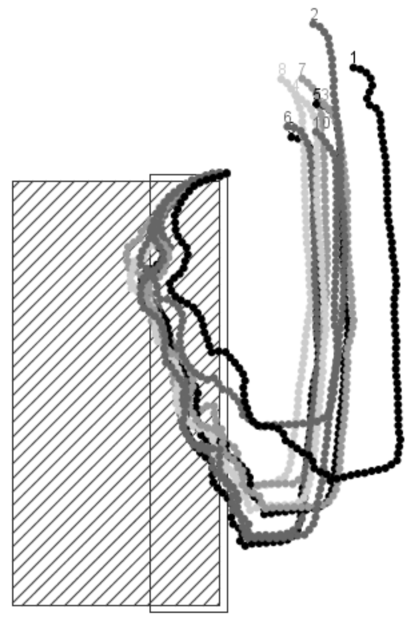


Figure 4. Ten trials on the expanse of ruins with heavy disturbances of the earth's magnetic field.

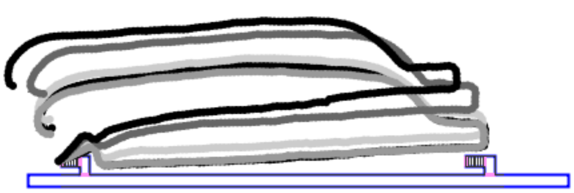


Figure 5. Five trials inside of a tunnel with small disturbances of the earth's magnetic field.

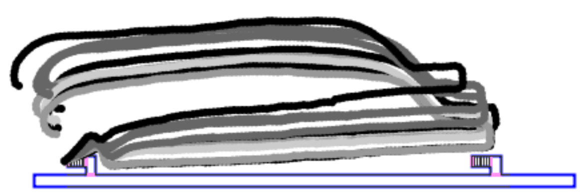


Figure 6. Ten trials inside of a tunnel with small disturbances of the earth's magnetic field.

Figure 7. Two trials inside of a tunnel with small disturbances of the earth's magnetic field. The pedestrian passed the track in both directions.

Figure 8. The military training area with ruins of ferro-concrete. The man in front wears the prototype of the system: IMU and a ultra mobile PC used to process the data.

Figure 9. Entrance of the tunnel on the military training area.

BUILDING INFORMATION MODEL BASED MAP MATCHING

The following sections first show how the presented approach is related to existing position verification and correction techniques. Once the rationale is given the utilized data structures used are depicted and the developed algorithms are explained. This chapter finally concludes with a performance evaluation of the system.

Existing Map Matching Approaches - Rationale for a New Approach

Map matching in general is not a new field of research. The area of GNSS based navigation and associated map matching has now been a very active field of research for the last decade (e.g. [5], [6]). These map matching algorithms use geometrical graphs called navigation networks as input. Navigation networks are a very appropriate abstraction of traffic routes.

Unfortunately, there is a big difference between cars driving on traffic routes and persons walking inside buildings. While the traffic routes cover only a very small percentage of the whole area, the situation in a building is the complete opposite. The accessible area within a building constitutes the biggest part of the gross area.

If the system was built to track persons following exclusively predefined routes such as visitors in a museum it could be feasible to use the well known map matching algorithms and model the permitted tracks as navigation network. But the system is built to be used by emergency staff in large buildings which walk on unpredictable routes.

A New Approach for Indoor Map Matching

The new approach presented in the following sections works on a simple building information model. Based on this information various heuristics form the basis to verify and correct position coordinates if necessary.

The Building Information Model

The used building information model is mostly comprised of the building's geometry with some semantic extensions:

- Polygons describing the outline of the accessible areas of a room.
- Transition objects describing doors and other facilities to walk from one area to another, including areas on different floors.

The biggest part of information needed can easily be extracted from computer aided design (CAD) floor plans of the building or computer aided facility management (CAFM) databases. IFC [7] models could also be used as source of the needed building information. Depending on the quality of the available data the conversion into the building information model's structure works completely automatically.

The polygons and transition objects are assembled to an attributed graph. The areas objects represent the vertices and the transition objects constitute the edges. The geometric properties of the area or transition objects are saved as vertex and edge attributes, respectively. Connecting them together is straight forward.

In the following sections the border lines an area polygon has in common with transition objects are labeled as *door* and the others as *wall*.

The Map Matching Heuristics

The map matching heuristics are based on the properties of paths walked by humans as well as on the properties of the positioning errors that may occur using the IMU.

The walls of an area constitute the natural boundary for walked paths. Therefore consecutive positions forming a path intersecting a wall must be corrected. Figure 10a shows this first correction mechanism on a sample path. The circles depict the path measured by the sensor. Starting at the left the positions could be verified by the model and used unmodified by the system. The path between the 6th and 7th position crosses the wall resulting in the correction mechanism to come into effect and correcting the position to be on the correct side of the wall, depicted by a blue cross. As a new position is always relative to the previous one this correction affects the following two positions as well (blue crosses for corrected/verified positions, empty red circles for uncorrected IMU data). The

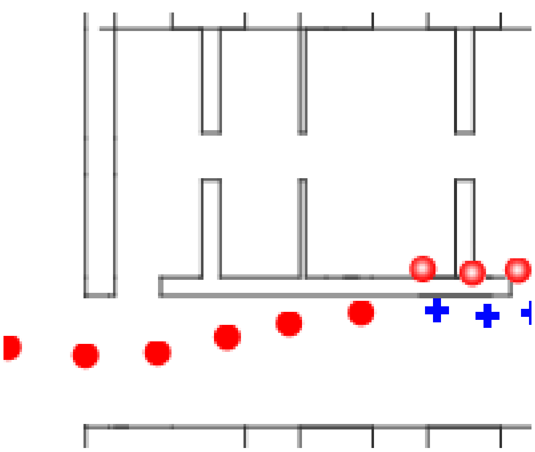


Figure 10a. Position correction at area boundaries.

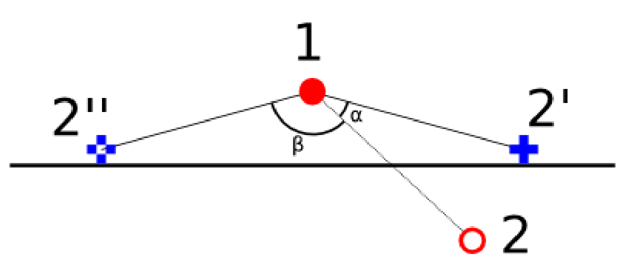


Figure 10b. Schematic explanation of the position correction at area boundaries: Last correct position (1), incorrect position provided by sensor subsystem (2), and the two correction candidates (2', 2'') of the map matching which favors 2' as α is smaller than β.

The red circles mark positions as measured by the IMU. While the filled ones are verified by the map matching and used unmodified, the empty ones are corrected by the algorithm to the positions marked by the blue crosses.

correction is performed as schematically depicted in Figure 10b: The correction algorithm tries to maintain the walked distance by only rotating the relative position vector from the last known correct position (position 1) to the incorrect one (position 2). The correct position is the center of the rotation. The idea is to rotate until the resulting position is on the correct side of the area boundary (wall). As the rotation can be performed in two directions two corrected position candidates are generated (2' and 2''). The one with the smaller absolute angle (2') is then taken as corrected and verified position.

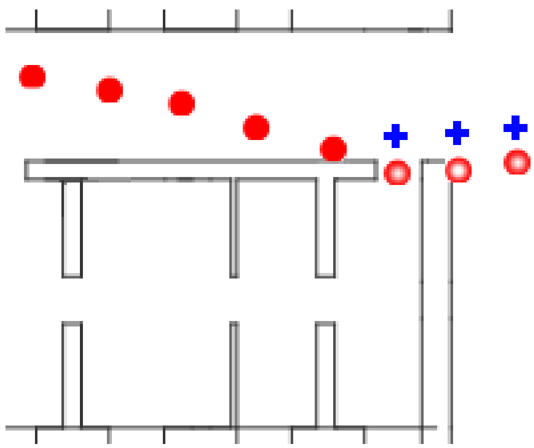


Figure 11a. Position correction using wrong path-to-door angle.

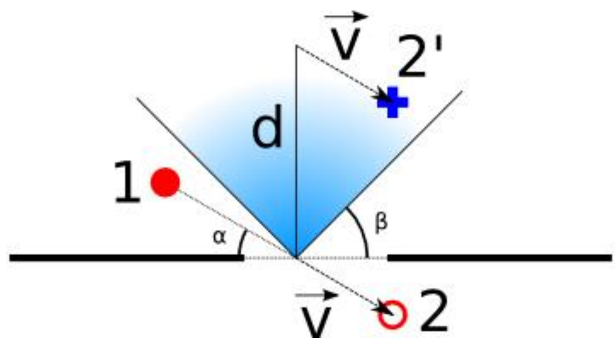


Figure 11b. Schematic explanation of the wrong path-to-door angle correction: Last correct position (1), incorrect position provided by sensor subsystem (2), and the corrected position (2').

The red circles mark positions as measured by the IMU. While the filled ones are verified by the map matching and used unmodified, the empty ones are corrected by the algorithm to the positions marked by the blue crosses.

While changing the area through walls instead of doors is quite an obvious indication the measurements are not accurate, changing the area through a door may indicate inaccuracy as well. Based on the observation that persons do not walk through (narrow) doors under an acute angle, such path properties can be used to correct the position as well. Figure 11a shows such a situation. Figure 11b shows the detailed analysis performed by the system: If a door is crossed the angle α of the line between the last verified position (position 1) and the position provided by the sensor subsystem (position 2) through the line describing the door is measured. If it is smaller than a given threshold β it is considered to be too acute and the position has to be corrected. The correction is performed by splitting the relative position vector where it crosses the line describing the door and moving the part on the other side of the door into the current room as depicted in figure 11b.

It is quite obvious that the doors are crucial elements when it comes to walking from one area to another. In some cases crossing a wall is an indication that the previously measured path is too long or too short. If the crossing takes place close to a door and other path properties (such as angle under which the path crosses the wall) would match with a nearby door to be crossed, the position can be corrected accordingly (Figure 12a). Figure 12b depicts the details: If the line between the last verified position (position 1) and the position provided by the sensor subsystem (position 2) crosses a wall the distance (d) of this intersection to the closest door is computed. In case d is smaller than a given threshold and the intersection angle α (as depicted in figure 11b) is bigger than the threshold β it is assumed that the user left the room using the nearby door. Again the traveled distance is maintained by the correction as the vector is split at the intersection point and the part being inside the other room is moved to start at the center of the traversed door.

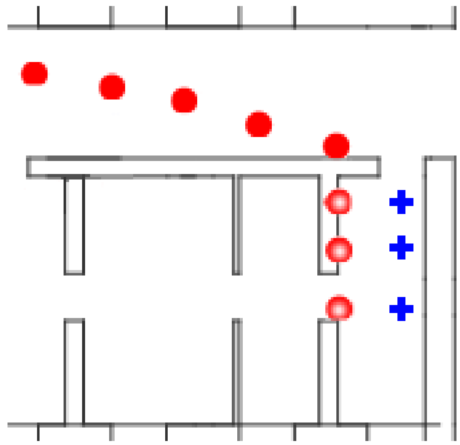


Figure 12a. Position correction replacing crossing wall by nearby door traversal.

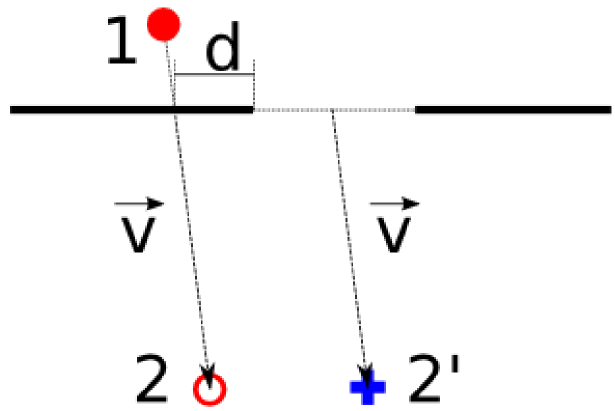


Figure 12b. Schematic explanation of correction in case where crossing a wall is replaced by traversal of a nearby door: Last correct position (1), incorrect position provided by sensor subsystem (2), and the corrected position (2').

The red circles mark positions as measured by the IMU. While the filled ones are verified by the map matching and used unmodified, the empty ones are corrected by the algorithm to the positions marked by the blue crosses.

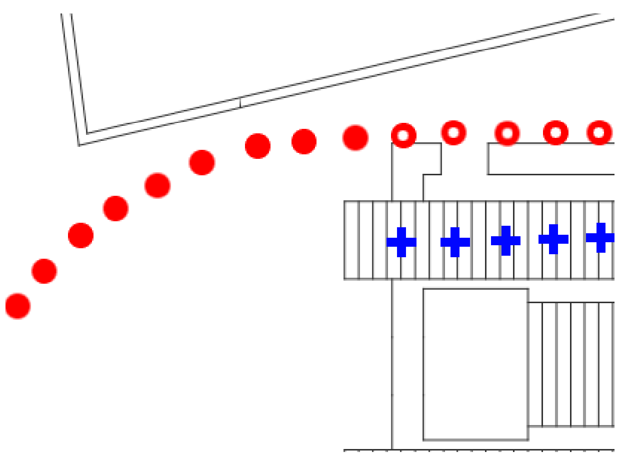


Figure 13a. Position correction using altitude information and nearby stairs.

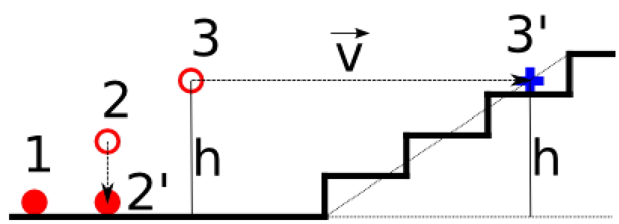


Figure 13b. Schematic explanation of correction using altitude information and nearby stairs: Last verified/correct positions (1, 2'), incorrect positions provided by sensor subsystem (2, 3), and position corrected according to its altitude (3').

The red circles mark positions as measured by the IMU. While the filled ones are verified by the map matching and used unmodified, the empty ones are corrected by the algorithm to the positions marked by the blue crosses.

But not only the 2D geometry of the building can be used. Stairs and ramps lead to characteristic changes of the z-coordinate of the positions. This leads to another heuristics to correct positions: If characteristic changes of the z-coordinate take place but the track is not on a stair or ramp but one is located close-by the position can be corrected according to its z-coordinate. Figure 13a shows an example of this kind of position correction. Figure 13b depicts the details of this correction: It is triggered if two consecutive positions (2, 3) determined by the sensor subsystem show significant change of the z-coordinate in the same direction (up or down). The first position with significant z-coordinate inconsistency with the building model is corrected by just correcting its z-coordinate (2'). But the second position showing the same z-coordinate characteristics (3) triggers the correction. The system searches for nearby stairs in the building model. The position is then moved to the center of the stair element whose height corresponds with the z-coordinate (3').

This set of heuristics is then combined to a map matching algorithm which allows correcting the positioning errors that occur when an IMU tracks the path of a walking person. The heuristics are combined as shown in figure 14.

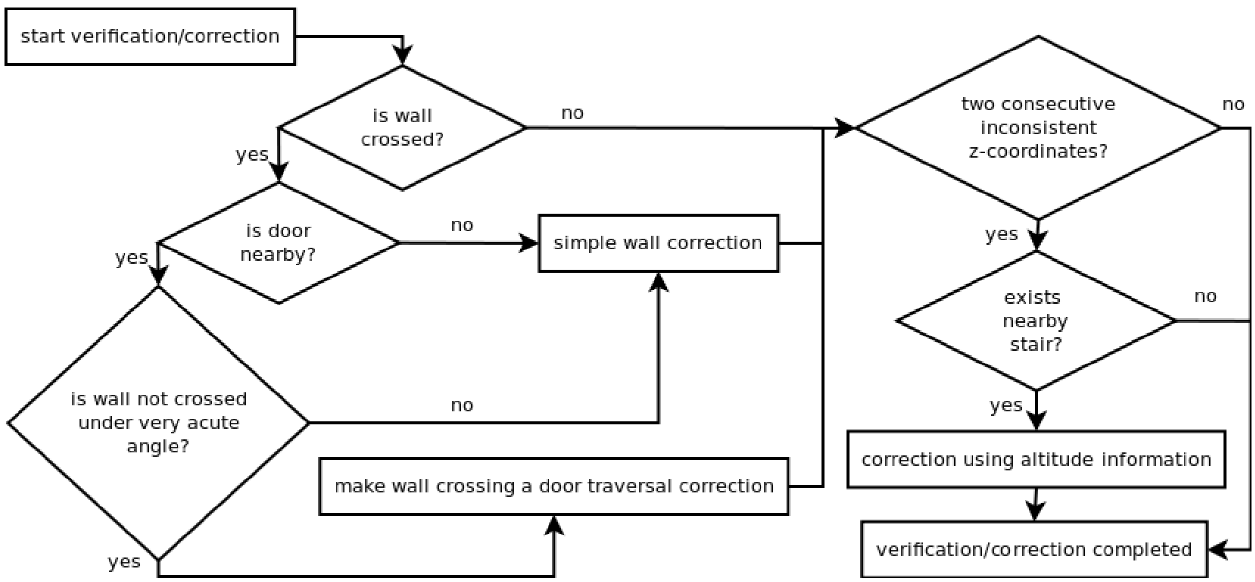


Figure 14. Combination of the heuristics to the map matching algorithm.

Performance Evaluation of the Map Matching Algorithm

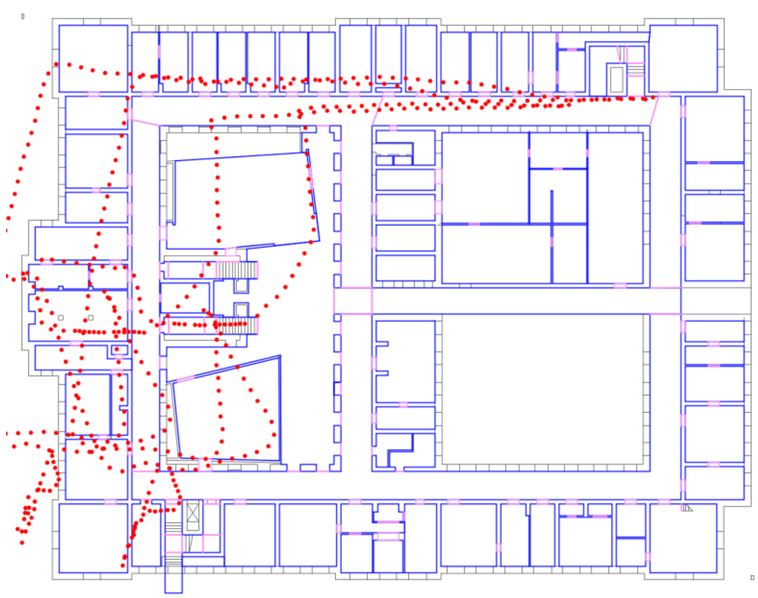
The presented algorithms have been evaluated for different tracks in various buildings. To show the effectiveness of the map matching two examples are presented which show above average IMU positioning errors. Generally the IMU data is more accurate than the presented data.

Both presented tracks (figure 15 and figure 16) cover two floors to show the algorithm working well for tracks including vertical changes such as stairs. In both cases the involved floors have very similar layout therefore path has not been split in two pictures but uses the dominantly used floor as background.

Figure 15 shows the raw sensor data and the corrected path of a 235m track. The path covers two floors and the improvement of applying the described map matching is quite obvious.

Generally the positioning error of the uncorrected IMU data increases over time. Therefore the improvement achieved by correcting the erroneous positioning data increases over time which is generally related to longer tracks. Figure 16 shows the path of a 640m track. The obvious improvement can be quantified: Over the 640m the error of the uncorrected positioning data increases up to 25.7m. The error of the corrected positions stays below 3.5m and most of the time (95%) even below 1.7m.

Figure 15. Uncorrected and corrected path of a person walking 235m inside a building covering two floors.



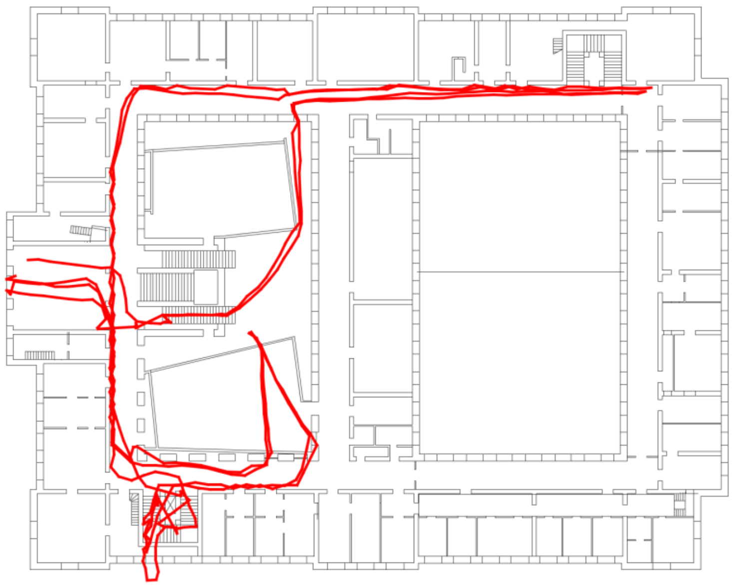


Figure 16. Uncorrected and corrected path of a person walking 640m inside a building covering two floors.

CONCLUSION

The presented system combines off-the-shelf hardware with new algorithms. Using IMU data as basis for positioning results in a system being independent of any preinstalled infrastructure such as WLAN or RFID tags. Not using GNSS signals allows the system to remain functional in tall buildings and even underground structures. Good and robust indoor positioning performance is achieved by combining inertial measurement sensor data with a new map matching algorithm. Extensive tests in various buildings have shown that the new approach to map matching is able to correct even considerable positioning errors.

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