Indoor-outdoor navigation without beacons: Compensating smartphone AR positioning errors with 3D pedestrian network

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ABSTRACT

Despite the extensive use of positioning and navigation in outdoor space, indoor positioning and navigation systems, essential for intelligent building and smart city services, are unsatisfactory in either performance or price, sometimes in both. This paper analyzes and compares the performances and prices of existing indoor positioning technologies that are categorized into a few classes according to their spatial sensing and referencing methods. Based on the previous work in walkability, this paper proposes a novel Walkability network-based Augmented Reality (WaNAR) method using smartphones with AR positioning function for positioning and navigation. In WaNAR, drifting of the AR positioning signals are corrected continuously by the ground-truth 3D indoor/outdoor walkability network (e.g., nobody is supposed to walk through a wall) in a 3D model. The error at the vertical axis of the walking direction is corrected continuously and that of the walking direction is compensated at every turn. WaNAR can be used in both indoor and outdoor navigation, its performance and price are proved to be largely improved compared to existing technologies. The only investment for a typical building is a 3D drawing of indoor walkable space in a few staff-hours. WaNAR has broad application prospects at various positioning and navigation scenarios.

Keywords

Augmented reality positioning, pedestrian network, error compensation, indoor navigation, indoor-outdoor integration

INTRODUCTION

Location is becoming a prerequisite for various smart applications, be they navigation or weather reporting services. Therefore, the sensing of locations has attracted vast interests from both researchers and practitioners. Actually, the contactless location-sensing technologies have developed rapidly within recent years. GPS (Global Positioning System) is the most widely used technology in positioning and navigation. However, it is suffering from its weakness in indoor positioning (Xu et al., 2019). To overcome such limitations, radio signal based technologies including RFID, Ultra-wideband (UWB), Bluetooth, and WiFi are meanwhile explored to be used for positioning, mainly at indoor environments. Relying on specific radio devices and a remote server makes such approaches expensive and not hard to use and therefore hinders their widespread use. With the emerging of AR (augmented reality), a new AR-based positioning solution was proposed. AR, as a real-time interactive user interface technology that augments the user's real environment with computer generated virtual entities in 3D (Xue et al., 2018), is widely embedded in smartphones. AR applications can thus benefit from smartphone sensors, e.g., accelerometers and magnetometers, to facilitate positioning. Most AR positioning solutions use object detection and recognition techniques and consequently require reference databases of 3D virtual objects or images, which is time-consuming and not accurate (Paucher & Turk, 2010).

3D walkable network is the 3D network of walkable roads, streets, tunnels, footbridges, stairs, elevators, lifts, etc (Sun et al., 2019). It contains the connectivity, Euclidean and geometric relationship between pedestrian path segments (e.g., sidewalk, crosswalk, and footpath), as well as other path characteristics such as, for example, path width. It is believed to have the potential in a variety of applications such as pedestrian navigation systems/services, urban planning and urban design. However, 2D map services usually fail to provide accurate and interactive 3D walkable network for pedestrians. 3D maps also suffer from the lack of mature integrated indoor-outdoor navigation technology. Pedestrians have to explore by themselves or ask for other pedestrians in a complex and 3D high density city. A visible and interactive 3D walkable network is in desperate demand.

This paper aims to develop an accurate and novel Walkability network-based Augmented Reality (WaNAR) positioning method using calibration of *ad hoc* 3D pedestrian network for seamless indoor-outdoor positioning and navigation at a very low cost. In WaNAR, drifting of the AR positioning signals is corrected continuously (every 5 seconds) by the ground-truth 3D indoor/outdoor walkability network (e.g., nobody is supposed to walk through a wall). The calibration eliminates the vertical distance of the pedestrian *ad hoc* location and his/her nearest walkable line and directly adjust his/her location to the nearest walkable line. By doing so, two hidden assumptions are made: pedestrians always walk along with the walkability network, and the deviation of AR positioning along a walkable line is within 5%. WaNAR is very accurate, easy to implement, and inexpensive, where the only investment for a typical building is a 3D drawing of walkable indoor space in a few staff-hours. In contrast, the popular radio frequency (RF) beacon-based methods such as Bluetooth Low-Energy (BLE) and UWB are expensive, heavy in carbon footprint, and hard to manage. It can be used for seamless indoor-outdoor navigation, facility management, and intelligent business.

The rest of the paper is organized as follows. Followed by the Introduction, related works on AR positioning methods, indoor positioning and indoor-outdoor integration methods, and 3D model-based error calibration methods are reviewed. Afterward, the algorithm of compensating smartphone AR positioning errors with 3D pedestrian networks are introduced. A method is then presented thoroughly based on AR smartphone hardware and software architecture, with a pilot study carried out at a university campus. Finally, a conclusion and future work are drawn.

RELATED WORK

AR Positioning Methods

AR, augmenting the user's real environment with computer-generated 3D virtual entities, is often jointly used with location sensors for mobile applications, especially for facility maintenance (Koch et al., 2014) and emergency management (Bellini et al., 2014). Those mobile applications are mainly designed for smartphones, which are ubiquitously embedded with various advanced sensors and technologies. The ever-enhancing hardware and computing capacities make smartphones perfect platforms for high-tech applications. Therefore, mobile AR applications can take advantage of smartphone sensors such as gyroscopes, digital compasses, accelerometers, and magnetometers to improve its performance and facilitate user tracking (Paucher & Turk, 2010).

In AR community, there are several methods used to do positioning, including marking, pose estimation, and SLAM (simultaneous localization and mapping). The most used one is marking the objects in the environment with a unified code. This method is robust and requires low computing capacity, but meanwhile requires additional marking works and thus leads to the increase of investment and difficulties of promotion (Paucher & Turk, 2010). The pose estimation method is also very commonly used with the pervasive adoption of 6 DoFs (degree of freedoms) position sensor and the increasing computing capacity of smartphones. It also requires an image database of the environment and thus is constrained in large and unknown environments. The SLAM method tracks the user's location by constructing a map on-the-fly using several different sensors, mainly optical sensors such as 2D camera or 3D laser scanner. It is widely used in unknown environments for robots, UAV (unmanned aerial vehicles), and self-driving cars, etc. Since the sensing and processing of the mapping and positioning data require powerful computers, such an approach is now more available for small scenarios. To conclude, most current AR-based positioning and navigation methods rely on either high-quality tracking of a small, constrained environment with given tracking devices or low accuracy outdoors environment only with GPS that delivers positional information worldwide.

Indoor Positioning and Indoor-outdoor Integration Methods

Despite the extensive use of positioning and navigation in outdoor space, indoor positioning and navigation systems, vital for 3D cities, are unsatisfactory in either performance or price, sometimes in both. Existing indoor positioning technologies can be categorized into a few classes according to their spatial sensing and referencing methods, see Table 1. We compared the performance (accuracy and easiness to use) and price (from the user side) of different techniques. Sonic signals can be divided into audible sound and ultrasound, though they are cheap in use but can only reach a decimeter level accuracy. Magnetic signals are accessible for users with smartphone magnetometers but easy to be affected by magnetic field anomalies (Li et al., 2012). Vision analysis can also be used for indoor positioning, but its performance is questionable, and the initial investments on cameras can be quite high (Kawaji et al., 2010). There are lots of radio frequency based indoor positioning and navigation, such as Infrared, light, GSM, WiFi, BLE, RFID, and UWB (Deng et al., 2019). These techniques are capable of reaching centimeter accuracy, but initial investments on RF devices, system development and maintenance can be high (Xu et al., 2019). Pedestrian Dead Reckoning (PDR) is also applied in smartphones and smartwatches; however, it suffers from very low-performance accuracy (Kang & Han, 2014). Current AR methods, as discussed above, also suffer from low performance problems and requires high initial investments of databases and high-profile AR smartphones. The WaNAR we proposed can function very accurately and easily with any low-profile AR smartphones.

Table 1. Comparison between different indoor positioning techniques

Technique classes	Performance	Price	Examples
Sonic	★★★	★	
Magnetic	★★★	★★	
Vision	★★	★★★★★	Marker, floor pattern, image-to-location reasoning
Radio Frequency (RF)	★★★★	★★★	Infrared, light, WiFi, BLE, GSM, UWB, etc.
Pedestrian Dead Reckoning (PDR)	★	★★★★★	Step counter + motion sensors
Augmented reality (AR)	★★	★★★★★	iPhone 11, Google Tango / Pixel, Huawei Mate 30P
Our WaNAR	★★★★★	★★★★	Ditto.

Apart from indoor positioning, another heated research topic is the integration of indoor and outdoor positioning information and systems. With people moving seamlessly between buildings and surrounding areas, positioning and navigation tools should support seamlessly integrated indoor-outdoor scenarios instead of merely outdoor or indoor guidance (Vanclooster et al., 2016). A plethora of research works on the integration of GPS, the preferred outdoor positioning and navigation technology, and other indoor positioning technologies. For example, Cheng et al. (2014) proposed a seamless outdoor/indoor pedestrian navigation system where GPS serves for stable and continuous outdoor navigation and WiFi as a reliable and stable indoor navigation technique. Other emerging technologies such as BIM (building information modeling), stereo-vision are also applied for indoor-outdoor integrated positioning. Stereo-vision based navigation system for unknown indoor and outdoor environments was designed and introduced for both flying robots and pedestrians. Again, these solutions are dependent on specific equipment and constrained by initial investment and precision problems.

Related 3D Model-based Error Calibration Methods

The 3D model-based error calibration method used in this paper is not a newly-created one. Eisert (2002) used synthesis analysis to calibrate extrinsic and intrinsic camera parameters based on a 3D computer graphics model. Sochor et al. (2017) calibrated traffic surveillance camera by 3D model bounding box alignment for accurate vehicle speed measurement. The model-based error calibration method is also widely applied in robot calibration, in which it can be divided into four parts, i.e., robot kinematic definition, robot position measurement, robot kinematic model identification, and compensation of position errors (Bai, 2007). When adopted in other scenarios, the steps are more or less the same. The compensation is based on the deviation between the real-time value and the model. If it is assured that the kinematic features are based on the predefined model, then the deviation can be eliminated within a preset tolerance scope.

THE PROPOSED METHOD

The research methods of this study is shown in Figure 1. There are two inputs prior to the study. One is literature review which helps conclude and compare different error compensation methods and AR positioning methods. The other input is a 3D walkability network. Under the ground-truth assumption that people only walk along horizontal lines such as roads, paths, corridors and slopes including stairs of qualified walking conditions and go through doors that can be opened, the 3D walkability network can be drawn based on surveying. Based on the methods reviewed and the linear features in the walkability network, a WaNAR error compensation algorithm is designed for consistent mitigation of drifting errors in AR positioning. Accordingly, coding work builds the prototype application in an Android APP. After debugging and testing, the APP is ready for pilot studies. By gathering and revising with the validation data and feedbacks from pilot studies, the WaNAR application can be upgraded and deployed.

The WaNAR error compensation algorithm, as shown as pseudo codes in Figure 2, is the core part of the propose method. It receives two inputs at any time: one is the translations on *x, y, z* axes ($translation_{\mathrm{AR}}$), and the other is a set of 3D lines of the walkability network ($network_{\mathrm{3D}}$). There is a drifting vector *drifting_vec* recording the accumulated errors from comparing the AR motions to the walkability network. Before the compensation, the vector of drifting error is assumed as zero. First, the nearest line of walkable way is selected and the perpendicular foot from the AR-sensed translation to the line is computed. The distance from the foot to the AR-sensed translations is the estimated drifting error. However, if the translation is too close to the end of the line (i.e., within the constant value of *TURNING_BUFFER*) or too far away from the nearest line (i.e., meeting the constant value of *OFF_TRACK*), the compensation will be dropped due to arrival at a possible turning point or unfollowing the guided pedestrian network.

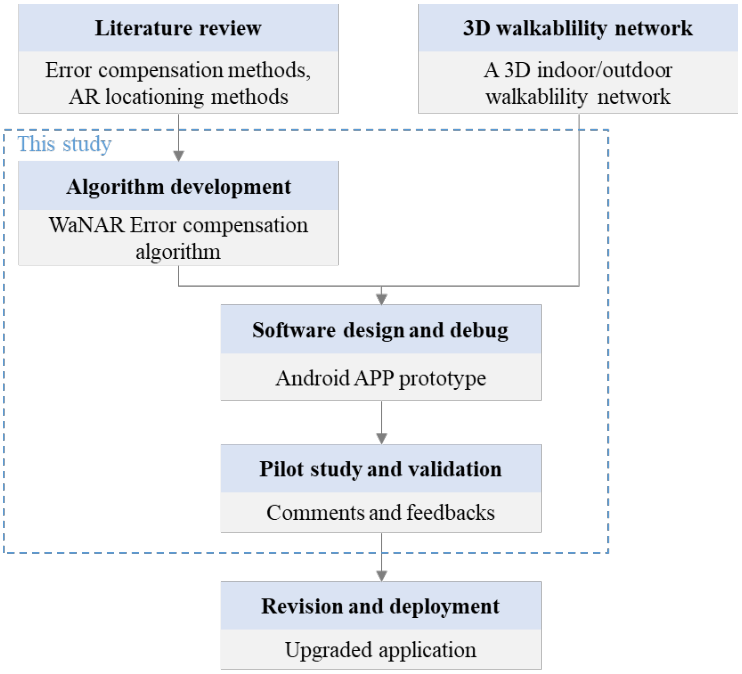


Figure 1. Research methods of this study

For realizing the WaNAR algorithm in a beacon-free AR positioning method and demonstrating the replicability, we used a Google Tango (model: Lenovo PB2-690Y) smartphone with Android 4.4. In the prototype Android APP, the 3D translation (positions on *x, y, z* axes) and the rotation (on *x, y, z* axes) of the AR phone pose are consistently read from the Tango API *TangoSupport.getPoseAtTime()*. The vector of translation is an input to the WaNAR algorithm ($translation_{AR}$ in Figure 2) subjecting to correction, while the rotation of camera pose is used for the graphic display of the APP via *updateRenderCameraPose()* to synchronize the AR experience. It should be noted that although Google Tango phone is very powerful in "area learning" through infrared distance sensor, the "area learning" options are disabled to simulate a low-end AR phone. That is, only the position and rotation vectors data collected and integrated from inertial motion sensors (including the accelerator and gyroscope) are used in the realization of the method.

```
procedure WaNAR_error_compensation:
    input $translation_{AR}$, $network_{3D}$, $drifting\_vec$
    $way$ := nearest_path ($network_{3D}$, $translation_{AR}$)
    if distance ($translation_{AR}$, tails_of ($way$)) > $TURNING\_BUFFER$ then
        $foot$ := perpendicular_foot ($translation_{AR}$, $way$)
        $drifting\_vec$ := $drifting\_vec$ + ($translation_{AR} - foot$)
        if $\| drifting\_vec \| \leq OFF\_TRACK$ then
```

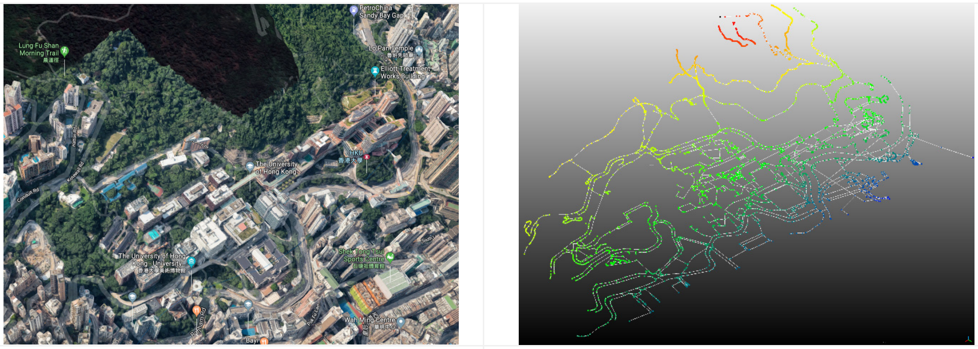
```
            $translation_{AR} := translation_{AR} - drifting\_vec$
        end if
    end if
    return $translation_{AR}$
end procedure
```

Figure 2. Pseudo codes of the WaNAR error compensation algorithm

BEACON-FREE AR POSITIONING WITH A PILOT STUDY

Experimental Setup

A pilot study, as shown in Figure 3, was conducted at an area around the Main Campus, the University of Hong Kong (HKU). The study area is a hilly area with compact campus buildings and complex vertical and horizontal connections between the buildings. Therefore, a 3D walkability network for guidance and navigation is much desired. We employed a 3D walkability network developed in Sun et al. (2019). The network covers the whole outdoor pedestrian paths and some indoor areas.



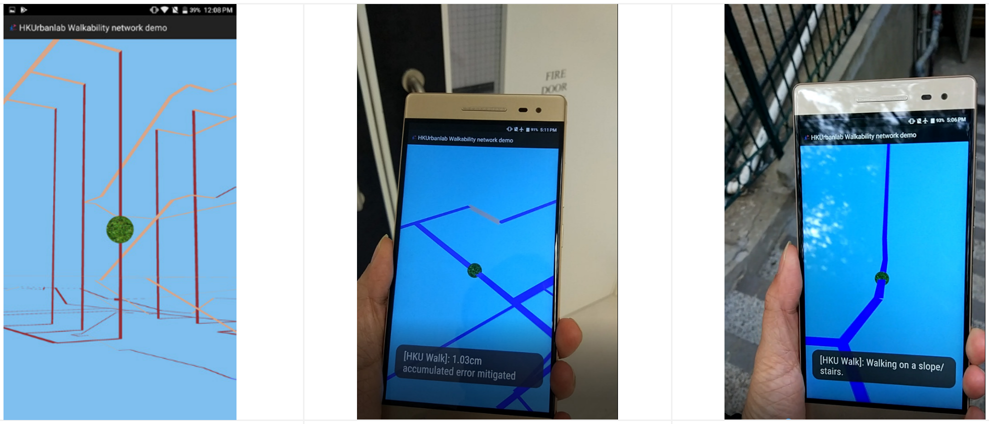
(a) The study area around HKU Main Campus

(b) The 3D walkability network, warmer color indicates higher altitude

Figure 3. 3D walkability network in the study area

Android APP Demonstration

Figure 4 shows the user interface of the prototype APP which was called "HKU Walk." The development environment was Android Studio (version 3.1). The 3D walkability network-based error calibration is made to compensate for the error of AR positioning. The results of error compensation were showed regularly as messages, as shown in Figure 4.b. And the APP can sense slopes and stairs ($0.05 \leq \Delta z / ||\Delta location|| \leq 0.7$) and elevators ($\Delta z / ||\Delta location|| > 0.7$), as shown in Figure 4.c. After some trials and errors, the two constant values were also set for a fluent navigation experience, where *TURNING_BUFFER* = 0.5m and *OFF_TRACK* = 0.5m. By using such passive methods, no RF beacon signals are required.



[HKU Walk]: 1.03cm accumulated error mitigated

[HKU Walk]: Walking on a slope/ stairs.

(a) Android APP (b) Error compensation (c) On slopes

Figure 4. HKU Walk demonstration snapshots

User can rotate and pan the screen to attach the green ball, which represents one's location, to the 3D walkability network as the start location; so it is the same with the re-position on demand. The accumulated vector *drifting_vec* will be reset to [0, 0, 0] at the mean time. After starting from a specific point, the APP can guide the navigation by keep compensating the error.

Results and validation

We conducted an indoor-outdoor walking test for about 10 minutes. A video about the test results was recorded during the test, of which the full version is available at: https://www.youtube.com/watch?v=jFy_MFYSgBY. In the test, the user walked from the Knowles Building, G/F to the entrance of Chong Yuet Ming Cultural Centre, back to Knowles Building, G/F, then walking upstairs to 1/F and 2/F. The "Flight mode" was on through the test, so the conventional radiofrequency signals including GSM, WiFi, Bluetooth, GPS, and RFID, were disabled.

The results showed that the indoor/outdoor positioning by AR and WaNAR was accurate all through the test path in the 10-minute period. With the error compensation algorithm, the proposed WaNAR method can mitigate the sensor drifting and maintain AR sensing accuracy at a subcentimeter level, which is much better than most of the other positioning techniques. Therefore, the pilot study validated the technological feasibility of the WaNAR method. The application can even notice pedestrians the slopes and stairs and elevators.

We also had a few findings regarding the implementation. Firstly, during the test, users are asked to walk along the center line of the roads which will lead to smaller error. Secondly, the better the drifting error is compensated, the more precise the APP works. Thirdly, most walkable roads indoor is not very wide. Therefore, the 0.5 meter is an acceptable value for the parameter *OFF_TRACK* in the pilot case.

Limitations and Discussion

For the scalability, any phone with simple motion sensors and basic AR function can run and utilize the application very well even under the flight mode. And the error compensation requires no external beacon signals, which means the WaNAR solution has no on-cost in maintenance. The only prerequisite is a 3D indoor-outdoor map which can be released by the building's owner and promoted to users via WiFi access points or so.

However, due to the linear 3D pedestrian network, the WaNAR method performs the best in linear indoor-outdoor spaces, and cannot well cover large open areas such as a podium. Another drawback is the presented method may lead to a small error if the user is not walking on the center line. In addition, the functionality of the demonstration APP requires user's manual re-positioning.

There are future development directions to resolve the above problems. First, the linear 3D pedestrian network can be extended with areas. Secondly, the infrared depth sensor can offer the depth image (as 3D point cloud) of the path, which can be processed automatically for the symmetry, center line, and iconic 3D objects (Xue et al., 2019a; 2019b) for additional error compensations, e.g., perpendicular to the guide walkability line and iconic environment object-based re-positioning. Thirdly, for automatic repositioning and the new comers who is not acquainted with the environment, we expect to integrate passive beacons, such as QR code or near-field communication (NFC) tags, for the start point and re-positioning in complex indoor-outdoor navigation.

CONCLUSION AND FUTURE WORK

This paper developed a straightforward, beacon-free error compensation method for precise smartphone AR positioning based on previous works of AR positioning, indoor positioning, indoor-outdoor positioning integration, and 3D model-based error calibration. It was proven to be more effective, accurate, and cheaper than other positioning methods in the pilot study in both indoor and outdoor positioning as long as the 3D walkability network covers. Different from other AR positioning methods which require high-profile AR phones with more sensors and big databases to store the images or models of the environment, our method just needs low-end AR phones with basic motion sensors and several manual hours to draw a 3D walkability network for a building.

However, it also has some obvious limitations. First of all, it may not work in small and complex environments such as an equipment room because walkability network in such an environment is hard to draw. Besides, for very wide roads and areas, several parallel lines should be drawn to ensure diversity of route choice.

Even though, it has great potential in areas including seamless indoor-outdoor navigation, facility management, and any other location-based services. When integrating with map services, it can contribute to the precise and seamless indoor-outdoor integration for positioning and navigation. It enables facility managers to provide better indoor navigation services for users which will furtherly enhance the convenience for users and efficiency of businesses. It also has excellent potential in location-based services such as shop searching in shopping malls, UAV navigation in unmanned warehouses, and office navigation in hospitals.

Future research directions include walkability areas in 3D map, infrared depth sensor and on-the-fly 3D path recognition, and integration of inexpensive beacons like NFC tags. Further development work includes rich navigation functions, map services integration, and automated walkability network generation.

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