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LONG PAPER

CityGuide: a seamless indoor–outdoor wayfinding system for people with vision impairments

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Abstract
The accuracy of satellite-based positioning systems is poor in indoor environments and around built environments. Reading and following visual cues still remain the most common mechanism for providing and receiving wayfinding information in such spaces. This reliance on visual function for wayfinding puts individuals who are blind or visually impaired (BVI) at a great disadvantage, and there remains a great need to provide a low-cost, easy-to-use, and reliable wayfinding system within indoor and outdoor spaces that complements existing satellite-based systems. This paper presents the design, implementation, and evaluation of an initial prototype wayfinding system and smartphone application called CityGuide that can be used by BVI individuals to navigate their surroundings beyond what is possible with just a GPS-based system. CityGuide enables an individual to query and get turn-by-turn shortest route directions from an indoor location to an outdoor location. CityGuide leverages recently developed Bluetooth Low Energy (BLE) indoor wayfinding solutions in conjunction with satellite signals to provide a seamless indoor–outdoor navigation and wayfinding system that guides a BVI individual to their desired destination through the shortest route. Evaluations of CityGuide with BVI human subjects within an unfamiliar university campus scenario demonstrated its potential to be effective compared to other popularly used apps.

Keywords Wayfinding · Blind or Low Vision · Assistive Technologies · Accessibility · Beacons · Build Environments

1 Introduction

Wayfinding has become easier for the general population compared to the last decade, but there are still challenges. For outdoor environments, recent advances in satellite-based systems and mapping technologies along with the pervasiveness of smartphones provide an accurate and simple to use means for wayfinding. However, there remain many outdoor areas such as sidewalks, within and around office buildings, public recreational areas, and university campuses, where the effectiveness of satellite-based systems such as global positioning systems (GPS) is limited. Furthermore, wayfinding remains a challenge in many indoor environments, especially those that are geographically large, such as grocery stores, airports, sports stadiums, office buildings, and hotels. Reading and following visual signs still remain the most common mechanism for providing and receiving wayfinding information. Thus, the challenges for individuals who are blind or visually impaired (BVI) are far greater, and there is still a great need to provide a low-cost, easy-to-use, and reliable wayfinding system within indoor and outdoor spaces that complements existing satellite-based systems. A solution to this "auxiliary" wayfinding problem for BVI individuals in our communities also has broad applications for people with other disabilities and the rest of the population in unfamiliar, disorienting spaces.

There has been recent work in developing systems for indoor wayfinding using either low-cost, stamp-size BLE "beacon" devices embedded in the environment that interact wirelessly with smartphones carried by users [1–6], or

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using computer vision [2, 7]. Satellite-based navigation applications from Google, Apple, Bing, etc. are just not accurate and refined enough to be useful for BVI individuals in all outdoor pedestrian navigation scenarios and are limited by GPS capabilities both indoors and in many outdoor areas. Other approaches used outdoors [8, 9] lack the capability to utilize sidewalk information and route around obstacle landmarks or buildings. These current efforts are also typically bifurcated as either indoor or outdoor wayfinding approaches and do not seamlessly allow a BVI individual to move from an indoor to an outdoor environment without having to switch apps; the handoff or handover between technologies/solutions adds an extra layer of challenge on top of the already challenging individual scenarios of wayfinding in indoor and outdoor environments. This scenario also takes on additional importance given that crisis or emergency settings often require autonomous movement from indoor spaces to designated outdoor spaces.

This paper proposes a wayfinding system and smartphone application called CityGuide that can be used by BVI individuals to navigate their surroundings beyond what is possible with just a GPS-based system. CityGuide enables an individual to query and get turn-by-turn shortest route directions from an indoor location to an outdoor location. When navigation starts within an indoor environment leading to or through any outdoor location, CityGuide leverages any BLE beacons in the indoor environments to guide the user to the best exit of the building that lies on the shortest path toward the eventual destination. Upon exiting an indoor environment, it seamlessly switches to utilize GPS signals toward the desired destination on the shortest route. CityGuide additionally implements mechanisms to make outdoor wayfinding more fine grained and accurate to improve the navigation performance and experience of end-users. The same principles presented in this work (but not explicitly studied in this work) can be used to navigate in the reverse direction as well: starting from any outdoor location, a user could specify an indoor location and be guided toward that destination.

Evaluations of CityGuide were conducted with six BVI human subjects in an unfamiliar indoor and outdoor university campus scenario. Quantitative results showed that CityGuide was effective in reducing end-to-end navigation times of almost all participants in addition to guiding them on paths that were often much shorter than those taken when the app was not used. Qualitative evaluation results showed that transitions from an indoor to an outdoor environments were seamless to participants and provided for a stress-free and efficient experience. Overall, the evaluations allowed a better understanding of limitations of the initial prototype and what needs to be done to improve future versions toward more independent wayfinding tools for persons with disabilities.

The CityGuide prototype presented in this work is just scratching the surface toward a truly seamless (all locations indoors or outdoors) and scalable wayfinding system by considering a limited deployment of one indoor space from which a person seeks to navigate to an outdoor space in a campus environment. However, even the small scale deployment makes some important contributions on this long journey and highlights important limitations to consider for future work. The novel contributions for this paper can be summarized as the following: (i) a system and an app called CityGuide for navigation and wayfinding by BVI individuals that provides precise and timely turn-by-turn instruction delivery in indoor and outdoor environments utilizing dead reckoning and an intelligent combination of BLE beacons and GPS signals as appropriate, (ii) the design and implementation of seamless and timely handover mechanisms between indoor BLE-equipped environments and outdoor GPS-covered environments, and (iii) human subject evaluations of an indoor to outdoor wayfinding/navigation scenario with comparisons to commodity outdoor wayfinding/navigation systems.

The rest of this paper is organized as follows. Section 2 presents related work in the area of wayfinding for persons with disabilities, with a particular emphasis on technology-based solutions. Sections 3 and 4 discuss the challenges in designing a seamless indoor–outdoor wayfinding system and the foundations upon which a system can be implemented. Section 5 presents the technical details of the CityGuide indoor–outdoor wayfinding/navigation system including the handover mechanism implementation. Section 6 presents the objectives of our human subject evaluation, methods, and results. Finally, in Sect. 7, concluding remarks and future work are presented.

2 Related work

In spite of progress on GPS-based outdoor wayfinding, wayfinding in areas without accurate GPS coverage remains a big challenge. There have been many recent efforts in indoor wayfinding utilizing wireless devices, such as radio-frequency identification or Bluetooth Low Energy (BLE), or computer vision to provide location information and context within such spaces [2–5, 10]. These efforts either utilize tag-based approaches to acquire external signals or rely on detecting familiar markers or patterns for localization in conjunction with an indoor representation or map. These are limited to indoor environments and do not consider extending the navigation scope to outdoor environments due to the much larger geographical scope and limitations that are introduced.

While different technologies have been used for indoor wayfinding, outdoor wayfinding systems usually have relied on satellite-based GPS technology for some or all their data gathering. GPS-based navigation apps such as Google Maps, Apple Maps, BlindSquare [9], GetThere [11], and Microsoft Soundscape [8] provide routes in unfamiliar urban environments using different approaches. For example, while Google Maps, Apple Maps, and GetThere use turn by turn navigation to guide users in outdoor places, Soundscape replaces step-by-step navigation instructions with 3D audio cues, enabling BVI users to build a mental map and subsequently make personal route choices to head toward the desired destination. Unlike Soundscape, BlindSquare provides the distance and direction to a destination without using 3D audio cues. These apps are exclusively designed for outdoor environments and do not consider the indoor navigation challenge for the most part except some rare scenarios where some limited indoor maps have been downloaded and annotated (for example, in the case of Google Maps) for indoor wayfinding; even in those limited scenarios, indoor positioning in these apps relies on techniques such as Wi-Fi fingerprinting, which have not proved reliably accurate due to the need for a high density of access points.

CityGuide combines many of the features of the above-mentioned indoor and outdoor wayfinding systems/apps while adding an extra layer required to combine them and create a seamless indoor–outdoor navigation experience. It uses BLE beacons in the surrounding infrastructure to localize within indoor environments, utilizing pre-constructed maps from floor plans. This enables navigating indoor spaces effortlessly. In outdoor environments, it utilizes GPS signals and pedestrian walking maps to provide turn-by-turn directions, combining information from any BLE beacons it encounters along the way (for example, at entrances of other buildings along the way) and utilizing algorithms like dead reckoning to improve accuracy. Routing with knowledge of walking paths allows users to avoid being stuck at dead-ends (as can happen with SoundScape or BlindSquare) without knowledge of what paths to take. Similar to BlindSquare, CityGuide provides the distance a user needs to walk on a path before the next direction is given allowing BVI individuals to be more confident navigators. The seamless integration between indoor and outdoor navigation enables a user to set the destination within the comfort of an indoor space. Subsequently, they can move toward their destination (receiving turn-by-turn directions) whether it is within the same building or outdoors without having to switch apps along the way. Alternative approaches to solve wayfinding challenges involve the use of using someone else's assistance through a smartphone's camera over a video call. Consumer applications such as Skype and FaceTime are not easy to use in providing directional information without adequate integration with real-time location updates. Other dedicated BVI-specific applications such as Aira and BeMyEyes [12, 13] allow seeking assistance over video calls from a remote helper; such approaches, in addition to possibly being expensive or not as effective within indoor spaces (due to lack of indoor localization integration), are in conflict with the preference for independent living.

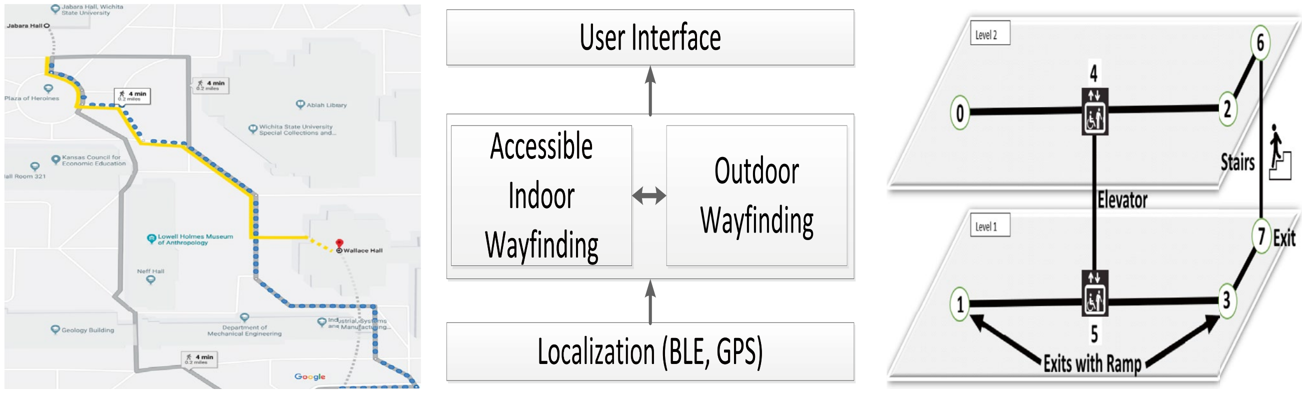
Prior work by the authors in [14] studied a smartphone application for emergency evacuation from indoor environments. That work did not consider how users could be guided from an indoor space to a designated spot in an outdoor space due to lack of integration between indoor localization technology and GPS outdoors. Many emergencies such as earthquakes and fire alarms require users to evacuate and gather in designated spots outside; such scenarios can easily be handled by the CityGuide application presented in this paper.

A preliminary version of this work appeared at [15] where only quantitative results from the human subject experiments were presented with limited details and analysis. This full version of the paper presents both quantitative and qualitative results and adds many details about foundational challenges, system implementation, experiment methodology, metrics, and potential limitations and opportunities in this direction of research. This work is part of the dissertation work of the first author which can be found at [16].

3 Challenges in designing seamless indoor–outdoor wayfinding systems

While the promise of just running a shortest path algorithm to route from one point to another in indoor spaces and using available GPS data for outdoor environment sounds simple, several modifications are needed to equip any accessible indoor wayfinding system with a seamless handoff to other forms of localization and wayfinding (such as GPS) outdoors. This section describes some important challenges that need to be addressed to enable seamless handoff between various localization and wayfinding technologies when navigating from a point indoors to a point outdoors.

Challenge 1: Handoff Harnessing GPS data, applications such as Google Maps can provide step-by-step instruction for navigation and wayfinding purposes. Since



(a) Inaccuracies with Google Maps walking routes. The route from Jabara Hall to Wallace Hall leads instead to the closest parking lot near Wallace Hall. The actual shortest path is shown in yellow.

(b) CityGuide shown as a layered system.

(c) Floorplan from Figure 2b and 2c modeled as a graph showing vertices and edges.

Fig. 1 Inaccuracy with existing outdoor mapping applications, CityGuide layers, and modeling indoor spaces through a graph representation

GPS and associated advances for outdoor environments do not apply to indoor spaces, it is important to utilize other technologies to provide location information and context within indoor spaces. However, switching between an app for indoor spaces and an app for the outdoor environment is not a very usable solution. To solve this problem, a capable indoor–outdoor wayfinding system should be intelligent enough to not only recognize where the user is but also when to switch between technologies to provide the best wayfinding experience. For example, switching to utilizing GPS while a user is inside a building can mislead a user to an incorrect location (assuming GPS signals can even be received) or constantly searching for BLE beacons when a user is away from BLE equipped buildings can affect the user's experience. Additionally, in areas where both BLE beacons and GPS signals are simultaneously strong (such as at the entrance/exit of a building), the app should recognize direction of motion in making transitions and avoid switching back and forth.

Challenge 2: GPS Coverage There remain many outdoor areas such as sidewalks, around office buildings, public recreational areas, and university campuses, where the effectiveness of satellite-based systems such as GPS is limited. Among these, locations around buildings play a crucial role in terms of providing a seamless handover from indoor spaces to outdoor environments. Lack of accurate GPS data around buildings can continue to pose issues for BVI users and make them unsure and uneasy about the next step they need to take even after they exit a building.

Challenge 3: Mapping Inaccuracies Representing an indoor space in the form of a graph data structure in order to find the shortest route from a starting point to a destination point can be easily done either by using tools such as the ones part of NavCog [2] or manually. However, the process for outdoor spaces has additional challenges. Using a maps API to find a point of interest (POI) in outdoor spaces and then generating the shortest path to that point is common. However, the lack of information about the entrance point of buildings, or the existence of ramps or stairs can be an issue in terms of generating the best route for a user who wants to walk into a building. Figure 1a shows the route that Google Maps generates if a user searches for a building from its starting point to a destination location. As it can be seen in this figure, the lack of information about the correct entrance of the building prevents Google Maps from generating the correct shortest path to the entrance of the building. Additionally, when a user intends to go to an outdoor location from an indoor location, there is no single integrated map that combines indoor and outdoor information that can lead to computation of the entire end-to-end shortest walking path. Thus, a user typically has to first exit a building somewhere and then start utilizing outdoor map information from that point even if it may not be on the shortest path from the original indoor location.

4 Foundations of CityGuide

The goal of any accessible indoor–outdoor wayfinding system is to route users from one point within a building to another point in an indoor or outdoor environment, preferably with turn-by-turn instructions. For BVI individuals, such a system should be easy to interact with and receive instructions.

An indoor–outdoor wayfinding system usually comprises of three layers (as shown in Fig. 1b): localization layer, wayfinding layer, and an instruction delivery layer. The localization layer is responsible for locating the user and tends to be a very important component in any navigation application. Once a user's current location is known (used as the source point s), an accessible wayfinding layer's objective is to find the best end-to-end path from a source s to a destination d. The top most layer is the user interface which provides navigational instructions for the user to traverse along the route.

For the wayfinding layer to find the best path from a source s to a destination d, all potential paths between these points should be known. Given that it is very challenging to know all potential paths from any indoor/outdoor location to any other indoor/outdoor location, we limit this work to a sub-problem with the objective of finding a path from an indoor location to some outdoor location. This outdoor location could be the entrance point of another building.

This objective of routing from an indoor to an outdoor location is achieved by splitting this problem into two parts. Initially, the shortest path from the indoor source location s's building to the outdoor destination d_o is found using Google Maps from each potential exit s_o^i of the building, where $i = 1 \cdots n$ with n legal exits from the building. The exit, say with index k, found to lead to the shortest path to d_o is stored as the indoor exit point $d_i = s_o^k$. Subsequently, an indoor route is found from the current location of the user s to the exit point d_i. This gives us an end-to-end path from s to d_o as (i) a path from s to d_i using BLE beacons, and (ii) from d_i to d_o using GPS.

With existing mapping solutions such as Google Maps used for outdoor routing, there is only a need for indoor routing capabilities. This is achieved by creating topological representations of the indoor facility as a connected graph data structure (say $G(V, E)$) upon which shortest-path algorithms are executed. Points of Interest (POIs) within the space typically represent the set of vertices V while paths between these POIs represent the set of edges E. Weights on the edges are typically distances between each pair of endpoints, but can incorporate other metrics such as congestion on a path, features or characteristics of the path, etc. Figure 1c shows an example graph representation of one indoor space with BLE beacon deployments.

5 The CityGuide system

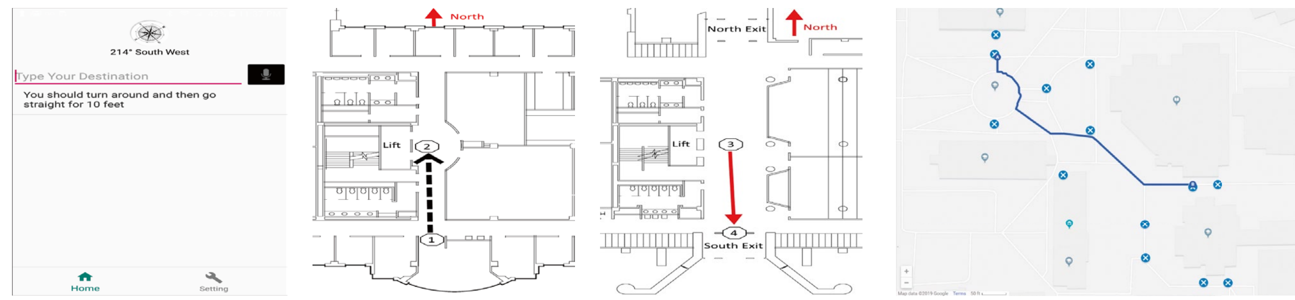
This section describes the CityGuide system's technical details starting with an overview of how it operates followed by details of the navigation module (including the handover algorithm) and the user interface (UI).

5.1 Overview

Upon activation, the CityGuide app on a smartphone detects the user's current location and waits for the user to provide the desired destination. The phrase from the user is then looked up in a database of points of interest (POIs) in the indoor space as well as sent as a query to the Google Places API for outdoor locations. If matches are found, they are listed out to the user one by one until the user confirms one of them. Upon confirmation that there is a match for the desired destination, CityGuide calculates the best available route from the user's location to one of the building's exit points (assuming the user is within a building and searches for a location outside the building) and subsequently to the destination in outdoor environments. The calculated end-to-end route is then used within the navigation module of the system that is responsible for turn-by-turn instructions to advance the users till the destination. Each of the main modules/components of CityGuide is described next along with the solutions implemented to meet some of the challenges outlined in the previous section.

5.2 Beacon placement & setup

The current implementation of CityGuide utilizes methods previously developed in a BLE beacon-based indoor wayfinding system called GuideBeacon in [5]. Based upon that system's guidelines, beacons are affixed near each POI, and as users come in proximity of a beacon, a unique identifier is received from the beacon at the smartphone. This identifier is then translated to relevant context and location information with the assistance of a beacon manager/server. The floor plan of the indoor space of interest is paired with the connected graph data structure to enable navigating the space. In order to prepare for finding and placing a request for outdoor places, the app requires access to a user's starting location in the form of Latitude and Longitude (Lat/Lng pair). Having access to this information, CityGuide is able to query for any place information based on geographic locations. However, acquiring accurate satellite coordinates requires users to have a direct line of sight to satellites which is difficult if



(a) User interface for BVI users. (b) Shortest route from the starting point to the elevator in the second floor of the Jabara Hall. (c) Shortest route from the elevator in the first floor to the south exit of the Jabara hall. (d) Shortest route from Jabara Hall to the Wallace Hall as well as beacon placement outside at the buildings entrances.

Fig. 2 User Interface and the shortest calculated route from the study room in the 2nd floor of Jabara Hall to the closest Wallace Hall entrance

not impossible within a building. To solve this problem, a geographic coordinate is assigned to each beacon. These coordinates can be chosen as the center of the indoor space for beacons that are not designated as entry/exit beacons; for entry/exit beacons, we choose coordinates as close as possible to the building's exit using known outdoor coordinates. It is also important to distinguish the ingress/egress points (elevators, stairs, etc.) of each floor from the entry/exit points of the building. When a user specifies an outdoor destination, the CityGuide app guides the user from the starting point on any floor to the first floor (also called as ground floor in some countries) and then to the building's exit door from where GPS signals can be used toward the final destination. Figure 1c shows a graph representation of two floors of a building with multiple potential exit locations.

Although placing and utilizing beacons in outdoor environments (in addition to using GPS signals) would increase the accuracy of outdoor navigation due to GPS inaccuracies, this is cost-prohibitive and thus largely infeasible. However, there are some locations where beacons can be assumed to be present such as the entry/exit points of buildings, bus stops, and any major landmarks. Figure 2d shows the assignment of 12 beacons in an outdoor environment. CityGuide currently utilizes such beacons it can find outdoors in addition to GPS to improve accuracy, even though they are not required. This approach also helps the app to provide extra information about the existence of stairs or ramps outside a building and enables the accurate guidance of a user to the entrance appropriate to them (for example, if they have a mobility impairment as opposed to a visual impairments).

5.3 Navigation module

The navigation module is responsible for generating guidance instructions to help users find their path from a source to a destination. It has the following sub-parts:

5.3.1 Database of locations

After determining a user's location and getting a desired destination through either a voice command or from the keyboard, a look-up for the destination is done in three different databases: (i) a database of indoor beacons installed in the building where the user is, (ii) a database of any outdoor beacons near the vicinity of current indoor location, (iii) the Google Maps database. If a user searches for a destination while outside, only the outdoor beacon database and Google Maps database would be searched. This is because if a building has a separate accessible pathway (for example, one with a ramp), the system can find the beacon assigned to it and navigate the user accordingly. Since the Google Maps API does not have the necessary information about the accessibility of building entrances, beacons assigned to entrances are marked with an additional property if it is accessibility friendly. This feature enables the app to modify the destination point based on user needs. For example, GPS coordinates received from Google API for the destination building used in this research study would be replaced with an alternate entrance with a ramp if the user is known to be someone with a mobility impairment (Fig. 1a). Such a mechanism also helps the system to continuously update a building entrance based on GPS data. For instance, if a BVI user misses an entrance to the destination building due to lack of GPS data or by not detecting a beacon, the system can update the path and provide the next closest entrance. Virtual beacon placement is another attribute that is added to the system. This concept helps the system to reduce the cost of beacon placement and maintenance while improving a user's wayfinding experience in outdoor places. For example, assigning a virtual beacon to a bus stop can help the system to provide information about the surrounding environment such as if there is any bus stop cube or bench close to the bus stop. However, unlike BLE beacons, virtual beacons must only be used under open-sky environments where the GPS positioning accuracy is not degraded due to buildings, bridges, trees, etc.

Algorithm 1 Handoff Algorithm

```
Store received advertisement j from beacon i with RSSI value r_ij
if we have received n samples from beacon i in the last 2n*BI seconds OR GPS_(Lat,Lng) gets updated then
  Compute the WMA for i over last n samples
  if WMA ≥ PRX_THR1 then
    Use Beacons data and discard GPS information.
    Count number of values k from set {r_ij, r_i(j-1), ···, r_i(j-n+1)} that are ≥ PRX_THR2
    if k ≥ K then
      if i ∈ Indoor_Beacons then
        Use the beacon for indoor wayfinding.
      else if i ∈ Edge_Beacons then
        Indoor-outdoor transition or vice versa
      else if i ∈ Outdoor_Beacons then
        Use the beacon for outdoor wayfinding.
      end if
    end if
  else if GPS_ACCURACY < GPS_THR1 then
    User could be outside or inside a building.
    if r_ij ∈ Indoor_Beacons received within the last 5 seconds then
      User is inside the building (close to windows or in a balcony). Discard received GPS signal.
    else
      Use the GPS data for outdoor wayfinding.
    end if
  else
    if Edge_Beacons is visited or the first GPS_ACCURACY > GPS_THR1 was received then
      if GPS_THR1 < GPS_ACCURACY < GPS_THR2 then
        User is outside the building. Use Kalman Filter.
      end if
    end if
  end if
end if
```

5.3.2 Handoff

The current implementation of CityGuide relies on using BLE beacon proximity detection indoors, and both GPS positioning and BLE beacon proximity detection for outdoor wayfinding. The biggest challenge in designing an accessible indoor–outdoor wayfinding system is to determine when to switch from one localization technology (GPS) to another (beacons) and vice versa, given that both signals may be received in some areas. To describe the handoff process, we divide beacons into the following three categories:(i) indoor beacons: this refers to beacons that are placed for indoor wayfinding only. They are represented in the form of a weighted connected graph data structure and can be used for navigation. (ii) outdoor beacons: beacons that are only used to provide extra information about outdoor locations such as if there is a stair close to the entrance of a building or if the entrance is blocked due to construction, etc. These beacons contain latitude and longitude pairs as well as extra information about their location. (iii) edge beacons: beacons that are located strategically to act as a transition between indoor and outdoor spaces and vice versa. Edge beacons have access to the graph representation of a building as well as the closest GPS coordinates to the entrances of that building. Proximity to beacons from the user are divided into three categories or zones: proximity zone, active zone, and passive zone. In order to differentiate between these zones, a weighted moving average (WMA) over a window size of last n RSSI values received from each beacon is calculated as in [5].

If the resulting WMA value is below a threshold PRX_THR1, then that beacon is considered a "candidate" for proximity zone. If the resulting WMA value is below a threshold PRX_THR2 but above PRX_THR1, the beacon is considered to be within the active zone. Every other beacon which does not belong to the previous two groups is classified as being in the passive zone.

When a user is in an outdoor environment and not in the beacon proximity zone, it must wait until the app gets GPS updates with high accuracy (better than GPS_THR1). If a user is inside a building and within the beacon proximity zone, then the app can find the shortest path from a user's location to any of the exit doors if the destination is outside the building, or another location within the building if the destination is inside. In case a user is within a indoor beacons' active zone and if a GPS update with high enough accuracy is received, the app tries to find the closest beacon and check if it is an edge beacon or an indoor beacon (in case a user is close to windows or in an open space). In case the located beacon is an edge beacon and a GPS update with high enough accuracy is received, the app assumes the user is standing outside a building. In case the received signal strength indicator (RSSI) received by the user's smartphone comes from beacons assigned for outdoor places, the app gets the beacons Lat/Lng pairs and assumes the user is in an outdoor environment; hence, it is very important to place indoor and outdoor beacons so as to minimize this interference; otherwise, it is possible that the app provides outdoor wayfinding instructions even though the user is within a building. The other factor which plays a substantial role in choosing between GPS and beacon is the nature of destination that is assigned by the user. If the first detected beacon belongs to the indoor beacons and the destination is outside, as long as the designated edge beacon is not found, the system does not use the GPS information.

5.3.3 Indoor routing

The routing feature of CityGuide has the objective of combining user characteristics/needs with those of the indoor space to find the best end-to-end route between any two points. The map of the indoor space is downloaded in the form of a graph representation with user's current location as the source s and the shortest path computed to the desired destination. The weights on edges (paths) incorporate a user's characteristics and preferences so that a shortest path that is computed (using Dijkstra's shortest path algorithm) factors in details specific to each user. Proximity of the user to POIs is assessed continuously (utilizing a beacon proximity detection algorithm similar to that used in [5]) throughout the route to confirm if a user is moving through the points on the computed route, triggering a re-routing mechanism if they stray off path. Having information about the accessibility of exits enables the app to choose the best edge beacon with respect to each user's need. For example, a building exit door for a BVI user may not be appropriate for a wheelchair user if it does not have a ramp outside the building.

5.3.4 Outdoor routing

In order to generate turn by turn instructions to help users in an outdoor environment, a user's current location as well as the destination is sent to the Google API to acquire the Google Maps polyline. Polylines in Google Maps consist of a collection of latitude/longitude (lat/lng) pairs, including details about the path from source to destination. The app splits the lat/lng pairs and chooses the first one from the list as the temporary destination. Progressing through each temporary destination, the system moves to the next one until the final destination coordinate. In order to prevent the app from changing its lat/lng pairs list frequently, the app requests to update the Google Maps polyline only if it detects an outdoor beacon or receives GPS information with high accuracy (accuracy better than GPS_THR1). Reaching a temporary destination depends on generated coordinates from the "Dead Reckoning" module. Dead reckoning is the process to estimate next location based on previous location [17]. Since GPS does not provide accurate information (better than GPS_THR1) about a user's location consistently, an accurate estimation of a user's location is created using a combination of IMU, GPS, and Kalman filter [17–19]. Harnessing the compass and step counter on the smartphone, the app can estimate the next Lat/Lng pair. This estimated value as well as GPS information (as long as it is better than GPS_THR2) is given to the Kalman filter to find the next location. The distance between estimated location and the next Lat/Lng pairs from the polyline is measured, and if negligible, then the Lat/Lng pairs are updated.

5.3.5 Re-routing

This subroutine is called when it is confirmed that a user has strayed off the computed path provided by the system. The re-routing is triggered by the system when it is expecting to reach the proximity of a beacon b_u or an expected Lat/Lng pair $(Lat, Lng)_x$ within the polyline, but instead arrives in proximity of a beacon b_v or within a meter radius of $(Lat, Lng)_y$. Re-routing then uses the current location estimate and the destination as end points in computing a new route and guides the user according to this new route.

5.3.6 User interface

The user interface of the app utilizes built-in accessibility tools of smartphones. For the Android OS, TalkBack provides a text-to-speech functionality that allows BVI users to utilize traditional text-based GUIs. Turn-by-turn directions are displayed as a list on the screen in addition to audio narration, which enables users to hear current and upcoming instructions. Audio and haptic feedback is provided to every user through vibrations, audio beep, and text-to-speech to ensure they are oriented in the right direction for the next path to be taken. Figure 2a illustrates the user interface used in the app for BVI users.

6 System evaluation

The main objective of the CityGuide's evaluation was to measure its effectiveness in assisting BVI individuals to seamlessly navigate in unfamiliar indoor and outdoor environments. This section presents details about the methods employed to evaluate its effectiveness followed by extensive quantitative and qualitative results.

6.1 Methods

To test CityGuide, we recruited human subjects to navigate from the second floor of a building within a university campus to the closest entrance of another building which is a 3-4 min walk using the shortest path. The representation in Fig. 2b and c was actually of this indoor space with users having to go from a study room (2nd floor) to the south building exit and then to the destination point as illustrated in Fig. 2d. The indoor space was chosen such that it was not very difficult to find the elevator to go down to level 1, but there were multiple directions one could possibly head to exit the building in different directions. It was not easy for the users to know what exit will lead to the shortest path for the destination. Six human subjects, either blind or with only light perception (LP), were recruited for the study after obtaining appropriate Institutional Review Board (IRB) approvals. We believe this number of human subjects was sufficient to gather effectiveness data on this initial prototype given that the indoor wayfinding capabilities of CityGuide have been extensively tested before in [5, 14]. These participants were either cane users or dog users, and were mostly unfamiliar with the campus. One subject (E) was familiar with the campus, but not the specific buildings and paths chosen for the test. Participants were recruited through an open call that specified the objectives of the study and what to expect. All participants were unfamiliar with the evaluation site where they were asked to navigate, but were smartphone users on a day-to-day basis. Participants were compensated for the study that lasted 60-75 min. Counter balancing test patterns were used to isolate impacts of familiarity gained by navigating the path a first time. Participants A, B, D, and F tested with the pattern without CityGuide, then with CityGuide. Participant C tested only with CityGuide, while participant E tested with CityGuide first and then without. An additional sighted user G, very familiar with the campus and paths, was added as a control/reference. BVI participants, and in general anyone unfamiliar with the route, are expected to need more time to complete the route than the control and this helps establish a baseline.

6.2 Metrics

Effectiveness of the CityGuide system was judged based on *three metrics*, two quantitative (navigation time, navigation distance), and one qualitative (user opinion).

6.2.1 Navigation time

This metric measures the effectiveness in terms of time in navigating to a desired destination in unfamiliar spaces. If a BVI user can navigate to the destination within a reasonable amount of additional time as compared to a sighted user who is not only familiar with the indoor space but can also easily find the route in outdoor environment using outdoor navigation tools such as Google Maps, then the system could be termed effective. Similarly, when a user utilizing CityGuide can navigate to destinations much faster than other users (who can use any indoor/outdoor wayfinding tools except CityGuide) with similar visual impairments, the system can be considered effective.

6.2.2 Navigation distance

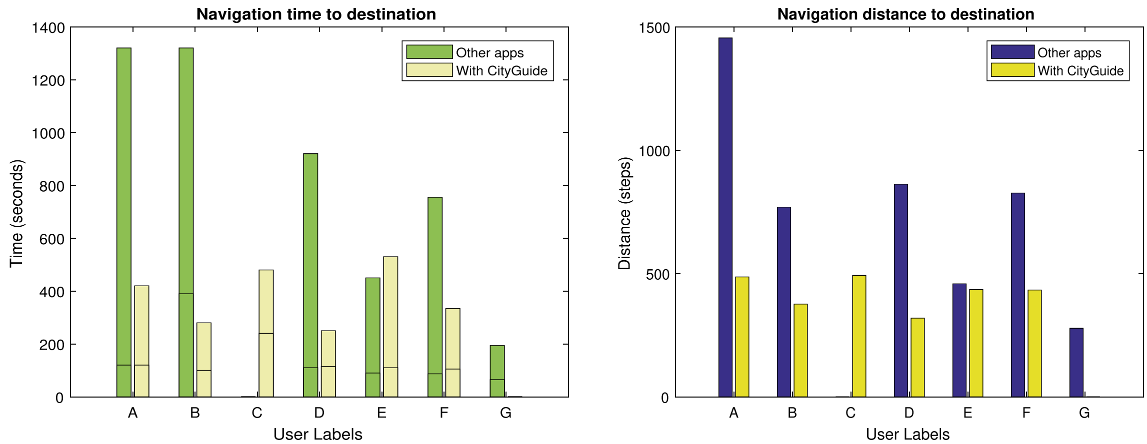
This metric measures the effectiveness in terms of distance (in terms of steps) walked before navigating to a desired destination in unfamiliar environments. This metric removes the impact of walking speed on results and allows a better understanding of how many false paths were taken in navigating to a destination. If a user does not stray off the navigation path much, it can again be considered as a sign that interaction with the system is easy and the navigational instructions are easy to follow and useful. This metric was measured through the use of step counters on participant phones; even though step counters are known to be not 100% accurate, we believe that these provide good enough estimates to interpret the navigation time data and can provide additional insight into navigation time of a user.

6.2.3 User opinion

This metric aims to capture the qualitative aspect of interacting and utilizing the CityGuide system. Through a questionnaire, participants were asked to rate (on a scale from 1 to 10, 10 being the best) the user experience in terms of clarity and timeliness of instructions, challenges when not using CityGuide, benefits of using CityGuide, and possible improvements that could be made. A separate usability study of the app was not done in the context of this work because study participants were mostly iOS users while the current app is built upon Android. We believe that usability is important and necessary, but can wait until the effectiveness of the underlying system is thoroughly tested, refined and proven to work toward providing accessible indoor and outdoor wayfinding, which are the objectives of this paper.

6.3 System configuration

The underlying BLE beacon system, configured similarly to prior work in [5], used with CityGuide is based on Gimbal [20] Series 10 and Series 21 beacons. All beacons were used with default parameters set. Since the main objective of this paper was to report on the seamless indoor–outdoor navigation experience, the indoor environment only used 5 beacons



(a) Navigation time. (b) Navigation distance.

Fig. 3 Results comparing the use of other apps for indoor–outdoor wayfinding to CityGuide for the quantitative metrics of navigation time and distance. The horizontal line in the middle of each result bar in **a** indicates the time to exit the building

on the path from the starting location to the exit location.[1] CityGuide was written as an app for the Android OS and can work using its native TalkBack accessibility tool. For all our evaluation tests, user directions were given as left, right, straight ahead, or turn around to keep the instructions simple and voice-based interaction capability was enabled in the UI to enter destinations at the beginning. All GPS and proximity thresholds used in the handoff algorithm presented earlier were discovered and set by experimentation within the environment before evaluations. GPS_THR1 was set as 6 m and GPS_THR2 was set as 20 m, with proximity threshold values used as in [5]. All tests were conducted on a Samsung Galaxy S7 phone that used a Wi-Fi connection to communicate to Google API to get outdoor routes as well as private servers. The campus environment had good Wi-Fi coverage in most of the test area, but there were a few areas with gaps depending on paths taken.

6.4 Results

The quantitative results are presented first, followed by corresponding user behavior data and system limitations leading to those quantitative results, and then the qualitative results.

6.5 Quantitative results

These results fall into the measurement of the two metrics of navigation time and distance.

6.5.1 Navigation time

Figure 3a shows the navigation time required by each user tested with and some without the use of CityGuide. In terms of the indoor part of the experiment without CityGuide (and with no others indoor wayfinding tools available), participants took varying amounts of time to exit the building, and (except user D) did not come out through the optimal exit toward the destination. With CityGuide, they took similar times to come out, but all participants exited through the optimal exit which benefits the total time to navigate. All BVI subjects took more time to complete the outdoor navigation part (and the entire start to destination exercise) except user E. User B did not complete the task at all and the experiment was aborted after pre-determined cutoff time, while user A needed numerous assists to have a chance at going in the right direction. All users completed the end-to-end route in less than 9 min with CityGuide. The average navigation time benefit by using CityGuide (compared to other apps that users may be currently using) was 52% with a standard deviation of 40%. The benefits may be greater if an incomplete task was not truncated.

6.5.2 Navigation distance

Figure 3b gives another perspective of the comparison of effectiveness with and without CityGuide in terms of navigation distance measured as steps walked for each user tested with and without the use of CityGuide. The average navigation distance benefit by using CityGuide (compared to other apps that users may be currently using) was 47% with a standard deviation of 25%. It can be observed that for all users that used CityGuide, the steps taken are consistent (within a narrow range of about 100 steps) and less; on the other hand, the steps taken by users not using CityGuide

[1] Readers interested primarily in indoor navigation can refer to papers such as [2, 5].

varied significantly, with some users not able to reach the destination. This indicates that those using CityGuide had a deterministic path to the destination, with some variability only due to personal walking styles and how they followed the instructions provided. Even user E, who reached the destination faster without CityGuide, took more steps to get to the destination, highlighting that CityGuide keeps users on shortest paths and barring issues of network connectivity, has a good chance of being the best option. This result, that CityGuide leads users through the shortest deterministic paths, also shows the utility of CityGuide for those with mobility or cognitive impairments in reducing their wayfinding effort and stress.

6.6 Additional testing details

Additional details on user behavior, interventions, and limitations provide insights on the reasons for the quantitative results presented before.

6.6.1 User behavior

Within the indoor environment, Participants A and B did not find the shortest path down through the elevators, but instead took a longer route down through stairs. Users D and F found the elevator, which was the straight path from the start point, and this helped their indoor navigation times. User E had become familiar with the indoor path due to the use of CityGuide first, so did well on time. Only user D found the optimal exit (in the right direction to destination) out of the building; all the other participants (except user E who learnt the path in prior trial) exited the building from various other exits, some of which were in the opposite direction of the optimal exit. Because most of the participants who tested without CityGuide first took sub-optimal exits (and hence sub-optimal paths), we believe that the subsequent navigation time they achieve with CityGuide was not influenced heavily by their prior navigation experience. When all users used CityGuide within the indoor environment, they came out through the optimal exit. They had to listen to navigation instructions along the way which adds a few seconds to their navigation time. User C had some trouble with the compass accuracy (possibly due to need for recalibration) indoors and needed extra time to exit the building.

For the outdoor part of the evaluations, user A took a long time to get to the destination and required assistance multiple times when they got stuck at dead ends. This participant tried Google Maps, iOS Maps, and BlindSquare, with only the latter helping him somewhat. With BlindSquare, going around obstacles buildings was a challenge with no path-specific information given. User B went completely in the wrong direction using Google Maps; this was after receiving help to get started in finding the destination location (Wallace Hall). iOS Maps could not find the destination in a campus environment while Google Maps does. This participant's study was aborted after a pre-determined maximum time (of 20 min) and marked as an unsuccessful attempt. User F used Google Maps to find the destination without getting help. The only user who could find the destination faster than CityGuide was user E. As a regular Soundscape user, she was used to finding things in campus environments with it and knew this campus to some extent (but not the building or the route). There was one instance where the Wi-Fi network became suddenly spotty while en route (with user E) and a temporary hotspot had to be used to continue navigation with CityGuide.

6.6.2 Interventions and limitations

There were a total of three occasions (twice for user C and once for user F) across the six subjects where minor directional assistance was given when using CityGuide; these scenarios were identified as due to a loss of compass calibration or spotty Wi-Fi in some outdoor areas. A simple compass re-calibration technique of making a figure 8 can be adopted before navigation to avoid such issues. Spotty Wi-Fi will likely not be an issue when used on a smartphone with both Wi-Fi and cellular data capabilities.

Without CityGuide, a total of seven assists were given (three to user A, three to user B, and two to D), mostly to help route around perceived dead-ends (building obstacles), or a completely incorrect direction beyond a few attempts to come back to the correct route. Without these interventions, the results without CityGuide will look far worse.

6.7 Qualitative results

The user opinion results from the study are presented in Table 1. Users have generally expressed a sense of satisfaction with CityGuide and its ability to seamlessly allow indoor and outdoor wayfinding and navigation. In terms of positives, the major takeaways were the ability of CityGuide to takes users from an indoor environment all the way through an outdoor environment to a destination, seamlessly. Users generally liked the clarity and timing of instructions and found the application very effective with an average score of 8.25 out of 10. Some users liked the ability of the app to re-route if an incorrect turn is taken, while others liked clear instructions on how many feet to walk before the next action. Indoor wayfinding was definitely a plus in leading the user out of the building through a legal exit; without the indoor wayfinding ability, a BVI individual may sometimes end up taking a prohibited emergency exit. Not having to switch apps after coming out a building definitely improved overall experience. The major

Table 1 User information and subjective scores (1–10, 10 being best) and feedback. LP is an abbreviation for light perception

User label	Vision category	Effectiveness score	Strengths & possible improvements
A	Blind, Cane user	8	Strengths: Clarity and timeliness of instructions were great, except in some outdoor areas. Especially useful indoors to get to the right exit that leads to the destination, avoiding fire exits. Gave a specific route all the way to outdoor destination, and I did not even notice it switching to using GPS outdoors. Will be useful in both familiar and unfamiliar environments, confirming any new routes I may take. Like how the app always gives me turn instructions such as left, right, straight as opposed to north, east, west, south. Possible Improvements: Adding more beacons outdoors may help accuracy even more given GPS issues in a campus environment. Will help to crowdsource problem areas on campus from other users and add beacons at those locations.
B	Only LP, Cane user	8	Strengths: Clarity of instructions was great; timeliness not as much. Without the app, unfamiliar locations are really challenging, both indoors and outdoors. Even though app is not perfect, I always felt like I was making progress to the destination unlike the other apps I tried. Will be useful in both familiar and unfamiliar environments. Possible Improvements: Timeliness of instructions and be improve; ability to repeat last instruction a plus in case I miss it.
C	Only LP, Cane user	7.5	Strengths: Instruction clarity was good; timeliness about right. Without app, was difficult to know how many more feet to walk in a certain direction and perhaps will not find what I am looking for in an unfamiliar setting. App can also be useful in familiar areas where walking paths are not a grid or parallel lines, such as on a university campus.
D	Blind, Guide Dog user	9	Strengths: Clarity and timing was good. I had used BlindSquare for navigation first and it was irritating due to a continuous countdown and lack of helping me avoid obstacle buildings on the way, may have been more challenging for a cane user. Got concise instructions from the app and always made sure I am using legal exits/paths. Will be useful in both unfamiliar and familiar settings; curvy sidewalks can always be challenge even if familiar. Campus environments are always challenging and this app does as best as I have seen any app do and it is great to know I am making progress all the time. Possible Improvements: A clock notation of providing directions is preferable in areas like a campus where paths can be at acute angles.
E	Blind, Cane user	9	Strengths: Instructions were clear and timely, more human like. Without this app, complex indoor environments can be challenging. Even outdoors, this app helps you avoid obstacles in the first place unlike Soundscape which only tries to move you in the right direction without helping you find the right obstacle-avoiding paths in the first place. Possible Improvements: Degrees or clock notation for instructions may be easier than left, right, etc. SoundScape user-interface was simpler to follow, perhaps because I am used to it. App could be useful even in large hospitals.
F	Only LP, Cane user	8	Strengths: Clarity and timeliness were very good. Google Maps never re-routed me when I made the wrong turns outdoors while this app does so immediately. The instructions were precise and guided me in the right path (and exit) from my starting location indoors. Will be useful in unfamiliar environments, and also in familiar environments if no one else is around and paths do not have grid patterns. This app got me to my destination in exactly the time Google Maps said it would take me on a pedestrian route, in spite of being blind. Possible Improvements: Network connectivity was poor in some areas where the app became silent for a few seconds before it became active again.

improvement suggestions revolved around using clock or degree notation for directions, given that campus sidewalks tend to not always be at right angles or parallel to each other.

7 Conclusions and future work

This paper proposed a wayfinding system and smartphone application called CityGuide that can be used by BVI individuals to navigate their surroundings beyond what is possible with just a GPS-based system. CityGuide enables an individual to query and get turn-by-turn shortest route directions from an indoor location to an outdoor location. CityGuide leverages wayfinding technologies such as BLE beacons in indoor environments and some limited outdoor areas, and combines this with GPS signals to seamlessly guide the users. Evaluations of CityGuide with BVI subjects showed that CityGuide was reasonably effective (within the scope of the limited testing scenario) in reducing end-to-end navigation times of almost all participants in addition to guiding them on paths that were much shorter than those taken when the app was not used.

Future work with CityGuide includes making the necessary improvements suggested by subjects who tested the app, testing it in additional environments (beyond a campus-like environment), even though a campus environment may be one of the most challenging for outdoor wayfinding. Usability testing of the app including the development of an iOS version will be part of next steps. With some modifications, CityGuide can leverage additional approaches in the future to localize in indoor or outdoor locations such as computer vision [7, 10, 21] or other wireless technologies such as ultra-wide band (UWB) and Wi-Fi. Additionally, modifications primarily to the user-interface of CityGuide and its POI database can allow indoor to indoor wayfinding through an outdoor environment and also enable routing to an indoor environment from an outdoor location.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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