CityGuide: A Seamless Indoor-Outdoor Wayfinding System for People With Vision Impairments

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***Abstract*—GPS accuracy is poor in indoor environments and around buildings. Thus, reading and following signs still remains the most common mechanism for providing and receiving wayfinding information in such spaces. This puts individuals who are blind or visually impaired (BVI) at a great disadvantage, and thus, 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 work designs, implements, and evaluates 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 recently developed indoor wayfinding solutions in conjunction with GPS 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 navigating between an indoor starting point to an outdoor destination within an unfamiliar university campus scenario showed it to be effective in reducing end-to-end navigation times and distances of almost all participants.**

***Index Terms*—Navigation and wayfinding, accessibility, vision impairments**

I. Introduction

Wayfinding remains a challenge for people with disabilities in our communities. 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 remains the most common mechanism for providing and receiving wayfinding information. This puts individuals who are blind or visually impaired (BVI) at a great disadvantage. Thus, there still 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. 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 general population in unfamiliar, disorienting spaces.

There has been some 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 using computer vision [2], [7]. 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 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 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 towards the eventual destination. Upon exiting an indoor environment, it seamlessly switches to utilize GPS signals towards 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.

Evaluations of CityGuide were conducted with six BVI human subjects in an unfamiliar indoor and outdoor university campus scenario. 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. Transitions from an indoor to an outdoor environments were seamless to participants and provided for a stress-free and efficient experience. More importantly, the evaluations allowed a better understanding of minor limitations of the initial prototype and what need to be done to improve future versions.

II. 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]–[4], [4], [5], [10].

While different technologies have been used for indoor wayfinding, outdoor wayfinding systems usually have relied on 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 then make personal route choices to head towards the desired destination. Unlike Soundscape, BlindSquare provides the distance and direction to a destination without using 3D audio cues.

CityGuide combines many of the features of the above mentioned indoor and outdoor wayfinding systems/apps but adds the 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 towards 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 involves 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.

III. The CityGuide System

A. 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 are described next along with the solutions implemented to meet some of the challenges outlined in the previous section.

B. 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 not impossible within a building. To solve this problem, it is required to assign a geographic coordinate to each beacon. These coordinates need to be the same (center of a building) for beacons which are not assigned as the building's exit and as close as possible to the building's exit if they are assigned to them. It is also important to distinguish the exits (elevators, stairs, etc.) at each floor from the exit points of the building. The app guides a user from a 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.

Although placing and utilizing beacons in outdoor environments 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 1d 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 (if they have a mobility impairment as opposed to a visual impairments, for example).

C. Navigation Module

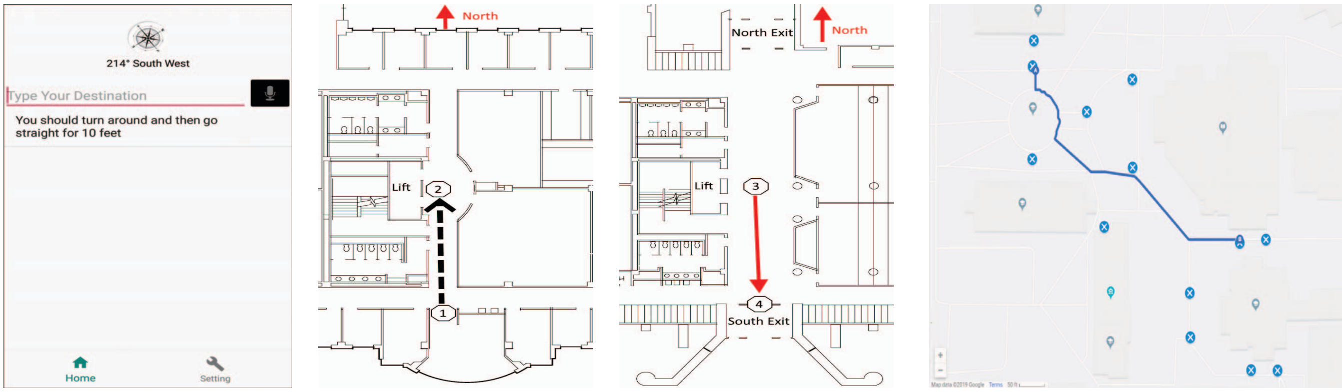
The navigation module is responsible for generating guidance instructions to help users find their path from a source to a destination. It has the following sub-parts:

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 route (similar to the destination chosen for this study), 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 has a ramp. 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 entrance with ramp if it is searched by any user with a mobility impairment. Having this 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 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 current version of 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.

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 either exit door if the destination is outside the building or another location within the building if 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



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

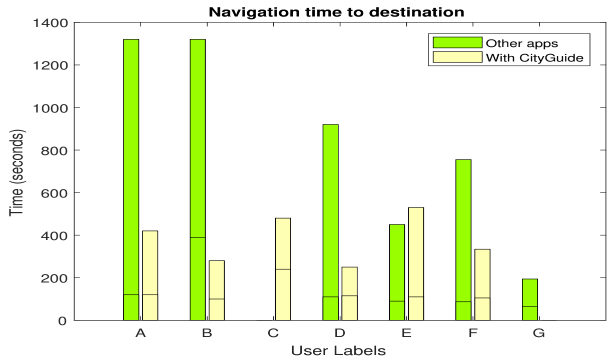
outdoor wayfinding instructions even though the user is within a building. The other factor which plays a substantial role in choosing between GPS and beacon is the nature of destination that is assigned by the user. If the first detected beacon belongs to the indoor beacons and the destination is outside, as long as the designated edge beacon is not found, the system does not use the GPS information.

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 for a given user. When the map of the indoor space is downloaded in the form of a graph representation with user's current location as the source s, weights on edges (paths) provided to the modified Dijkstra's shortest path algorithm incorporates a user's characteristics and preferences so that a shortest path that is computed factors in details specific to each user. Proximity of 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. Having the information related to 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.

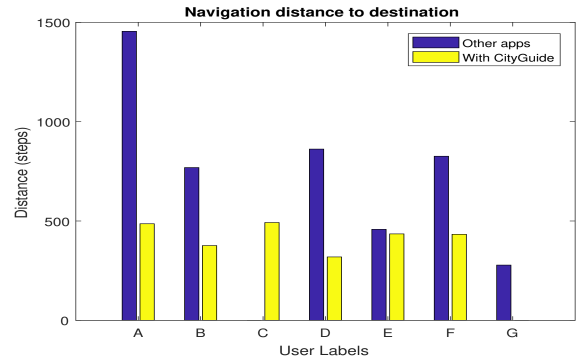
4) Outdoor Routing: In order to generate turn by turn instructions to help users in outdoor environment, a user's current location as well as the destination are sent to the Google API to acquire the Google Maps polyline. Polylines in Google Maps consist of a collection of latitude/longitude (lat/lng) 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 move 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 [14]. 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 [14]–[16]. 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) are 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 is updated.

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.

6) User Interface: The user interface of the app is equipped with 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 1a illustrates the user interface used in the app for BVI users.



(a) Navigation time.



(b) Navigation distance.

Fig. 2: Results comparing the use of other apps for indoor-outdoor wayfinding to CityGuide for navigation time and distance. The horizontal line in the middle of each result bar in (a) indicates the time to exit the building.

IV. System Evaluation

To test CityGuide we used 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 minute walk using the shortest path. The representation in Figure 1b and 1c were 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 on Figure 1d. The indoor space was chosen to make it 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 be in the correct direction towards the destination. Six human subjects, either Blind or only light perception (LP) were recruited for the study after obtaining appropriate Institutional Review Board (IRB) approvals. 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 paid \$50 for the study that lasted 60-75 minutes. Varying test patterns were used to isolate impacts of familiarity gained by navigating the path a first time. Participant 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.

A. Metrics

Effectiveness of the CityGuide system was judged based on *two metrics*: navigation time and navigation distance.

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. An observer noted the difference in time between navigation start time and end time to measure this metric.

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 our 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 why a user may have taken a certain amount of time.

B. System Configuration

The underlying BLE beacon system, configured similarly to the work in [5], used with CityGuide is based on Gimbal [17] Series 10 and Series 21 beacons. All beacons were used with default paramters set. Since the main objective of this research was the seamless indoor-outdoor navigation experience, the indoor environment only used 5 beacons on the path from the starting location to the exit location. 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. 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.

C. Results

1) Navigation Time: Figure 2a 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 towards 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 user completed the end-to-end route in less than 9 minutes 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.

2) Navigation Distance: Figure 2b gives another perspective of the comparison of effectivness 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 varied a lot, 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.

V. Conclusion

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. Evaluations of CityGuide with BVI subjects 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 much shorter than those taken when the app was not used.

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