An Indoor Navigation Solution for Visually Impaired People

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Abstract. *This article describes the development of a mobile application designed to assist the navigation of visually impaired individuals in indoor environments. The application interacts with Bluetooth devices called beacons, which help identify the trajectory. The beacons' arrangement and the environment's computational modeling were carried out using techniques such as trapezoidal decomposition and graph representation. The application uses threads to identify the shortest paths between source and destination beacons. It also provides audio instructions about the locations the user must pass through to reach the destination, correcting routes if the user is heading in the wrong direction or location. We validated the solution in a real-world environment and proved capable of successfully guiding the user within the studied environment.*

1. Introduction

The evolution of mobile and embedded devices enables the development of applications capable of using context information to provide new services, such as navigation. Navigation consists of guiding the movement of an individual or object from the point of origin to a destination and can occur in an outdoor or indoor environments. Outdoor navigation occurs in open environments (e.g., streets, highways, parks, campus) and is used in traffic monitoring and delivery control applications. Outdoor solutions commonly adopt the Global Positioning System (GPS), which uses satellites to obtain location information decoded by GPS receivers. Indoor navigation, on the other hand, is characterized by movement in indoor environments, generally limited by coverage (e.g., ceilings, roofs, walls, halls) and other types of obstacles (e.g., furniture). Although GPS is a reference technology in outdoor location systems, its use in indoor environments is not suitable due to the attenuation of satellite signals and consequent loss of accuracy [Li et al. 2016]. Due to this, it is necessary to use alternative communication and positioning technologies in indoor environments that are less subject to interference and loss of signal quality due to obstacles.

Several applications use navigation data primarily, such as delivery services, transportation, and route planning, or secondary, such as social networks and online games [Huang et al. 2018]. However, a field not explored in the literature concerns indoor navigation for people with visual impairments. According to the National Health Survey conducted in 2019 by the Brazilian Institute of Geography and Statistics (IBGE) in partnership with the Ministry of Health, approximately 6.9 million Brazilians have advanced or total vision loss [IBGE 2019]. This number reinforces the need and viability of indoor navigation solutions to provide greater autonomy to this group regarding their orientation in buildings.

With this problem as the primary motivation, this article presents the development of a navigation solution in indoor environments for people with visual impairments. The issues of developing and evaluating a software prototype for mobile devices (e.g., smartphones, tablets) that use Bluetooth Low Energy (BLE) devices, called beacons, as a location reference for subsequent navigation are addressed. The solution has the premise of not requiring additional hardware from the user other than their mobile device. The navigation mechanism is modeled on graph theory, which allows the use of shortest-path algorithms between the user's point of origin and the desired destination in the building. Each beacon acts as a checkpoint in the user's navigation, enabling handling cases in which a route deviation has occurred. The solution design uses data structures instead of more complex localization strategies, such as trilateration, aiming to reduce the processing load and energy consumption. The solution was evaluated in the real environment of a public university building.

The organization of this paper is as follows: Section 2 presents the technologies used, such as BLE and beacon, in addition to literature studies that addressed indoor navigation. Section 3 describes the modeling of the solution and the architecture of the Mobile Navigation App. Section 4 presents the experiments performed with a visually impaired user, in addition to the analysis of the collected navigation results. Finally, Section 5 presents the conclusions of the study developed, as well as suggestions for future work.

2. Background

Navigation in indoor environments is quite challenging, since indoor areas contain various obstacles whose location can be easily changed. Indoor navigation systems are commonly used to guide users in bus stations, museums, libraries, among other environments. Navigation systems typically consist of three main modules [Kunhoth et al. 2020]. The Positioning System Module indoor is responsible for estimating the user's position in the environment. Since GPS is not an option, this module adopts other technologies such as computer vision, radio-frequency signals and reduced calculation techniques (deduced reckoning). In the latter, the user's position is estimated by comparing data provided by device sensors (e.g. accelerometer) and pre-existing data related to the environment indoor. The Navigation Module uses the location data measured by the positioning system, evaluates possible paths and defines a route between the user and their destination. Graph modeling is one of the most commonly used methods for defining routes, enabling algorithms such as Dijkstra and Bellman-Ford [Alqahtani et al. 2018] to obtain the shortest path between vertices, or graph colouring algorithms [Afshar et al. 2022]. The Human-Machine Interaction Module enables interaction between the user and the navigation system. Through this module, the user defines their destination and receives instructions regarding the route defined from their origin. This guidance can be returned to the user through voice messages, notifications, animations, and vibrations.

2.1. Navigation Technologies

Regarding communication with devices for navigation purposes, some applicable technologies are Wireless Fidelity (Wi-Fi), Radio-Frequency Identification (RFID), Ultra-Wideband (UWB), ZigBee and Bluetooth Low Energy (BLE) [Kárník and Streit 2016, Al-Ammar et al. 2014, Zare et al. 2023].

In particular, BLE technology is an evolution of the Bluetooth IEEE 802.15 standard, designed for wirelessly exchanging data between two devices without the need for intermediate equipment (infrastructure). BLE adopts the single-hop protocol, in which data is transmitted directly from a source node to a destination node in a Point-to-Point (P2P) communication, which helps reduce energy consumption, delay, and packet loss [Pešović et al. 2010]. In addition, it allows communication between devices within a radius of up to 200 meters. These characteristics have made BLE a commonly adopted technology in smart environments and ubiquitous computing projects.

BLE is present in several devices, from wireless mouses to context-based or location-based services [Shi and Gong 2024]. Its fourth version allows transfer via broadcast [Bluetooth 2010], a crucial feature for using beacons and other Internet of Things (IoT) devices, as it allows mesh topology and simultaneous transmission to several users. The BLE protocol stack consists of two main parts: the controller and the host. The controller is implemented as a System on Chip (SOC) with an integrated radio comprising the Physical and Link layers. The host runs in an application on a BLE system and manages the functionalities of higher layers of the protocol. The Host Controller Interface enables communication between the host and the controller.

Beacon is an embedded device designed by Apple [Newman 2014], which uses BLE to transmit its identifier to portable electronic devices within its range. A beacon emits radio signals to send data frames that can be captured by BLE-compatible receiving devices (e.g., smartphones) for location purposes and other applications. Depending on the model, they can be powered by a battery or connected to the electrical grid. Since they are only transmitters, once the connection is established, the application on a receiver can store the received data and perform some action [Kontact 2022].

2.2. Related Work

The first system for indoor localization was the RADAR [Bahl and Padmanabhan 2000] created by Microsoft and uses Wi-Fi network and reception maps Received Signal Strength Indicator (*RSSI*). The user's device measures the Access Points (AP) signal strength in range and obtains the coordinates of a Cartesian plane corresponding to the environment. The user's probable position is determined by querying the database containing information from the *RSSI* map.

PERCEPT [Ganz et al. 2012] uses RFID tags, a smartphone with Android operating system and a scanner attached to a glove. Each RFID tag contains navigation information for specific locations, which is also written in Braille, allowing the user to decide on the destination, read the tag via scanner, and have the navigation information passed on to their smartphone. The Digital Sign System (DDS) from [Legge et al. 2013] works similarly to PERCEPT but uses bar codes from a 2D matrix. A scanner reads the location data, which transmits it to the smartphone via Bluetooth.

[Rosiak et al. 2024] evaluated the accuracy of UWB beacons comparing it to LiDAR and identifying strengths and limitations of each. It shows the benefits of sensor fusion and AI integration to enhance localization. [Amutha and Nanmaran 2014] uses ZigBee in a portable device attached to a belt worn by the user, with guidance functions, voice commands, and a database to determine route information. In indoor environments, the location is restricted to the user's device and three ZigBees that exchange *RSSI* values.

BlindNavi [Chen et al. 2015] is an application prototype that seeks to provide outdoor navigation information through the exchange of data between the user's smartphone and beacons positioned in strategic locations. The desired destination can be searched via voice command in the application itself. StaNavi [Kim et al. 2016] uses BLE to provide navigation information, current location, and points of interest at Tokyo Station. Its architecture is based on beacons, a smartphone, and a server. An application uses data from the beacons and queries infrastructure information on the server to determine the client's location. The user can interact with the application through gestural input and Text-to-Speech output with audio and haptic feedback. [Nagarajan et al. 2020]'s solution uses beacons, each with two identifiers, one for the infrastructure and the other for the device. The smartphone determines the user's location based on the signal strength emitted by multiple beacons and infrastructure data. The application retrieves the destination via text and provides audio navigation.

3. Development

The research carried out in this work is of an applied nature, with a qualitative approach and exploratory objective, which seeks a solution to the navigation problem of people with visual impairment in indoor environments. The focus environment of the study is the building of one of the institutes of a public university.

3.1. Solution Modeling

We model the environment with graph theory, in which the vertices represent physical spaces (e.g., rooms, bathrooms, corridors), and edges represent the connections between them. The resulting graph illustrates the network of connections, indicating the spaces reachable from one another. With shortest path algorithms, it is possible to identify the vertices and the order in which they should be visited to reach the destination vertex. Identifying the user's location makes it possible to instruct them on the next vertex that should be visited. Unlike navigation models based on triangulation and trilateration, which obtain the location from coordinates, the adopted strategy is based on the adjacencies of the vertices, which act as checkpoints.

To estimate the user's location, the navigation App installed on the mobile device receives frames of data from the beacons within its range. It identifies the closest beacon, using measurements such as *RSSI* and *Accuracy*. In the checkpoints approach, after receiving the data and measuring the user's current position, the application returns the instructions that the user must follow to reach the next vertex of the path.

Figure 1 illustrates the operation of the navigation solution. In Step 1, the user searches for the destination location. The App continuously receives data frames from the beacons in its range, containing values of *TX power* (*TXp*), *RSSI*, *Accuracy* (*Acc*), and MAC address of the beacon. A data structure called *General Frames List* (GFL) of size n stores the frames. When a GFL is complete, in Step 2, a specific queue for each beacon of size q stores their respective frames. Newer frames replace old ones using the First In, First Out (FIFO) strategy. In Step 3, the App calculates each queue's average Accuracy ($\overline{Acc}$) value, returning the lowest average and the corresponding beacon's MAC. Accuracy estimates the distance between the mobile device and the beacon. In Step 4, the algorithm verifies whether the most minor $\overline{Acc}$ is less than 3 meters. This range is defined as the trigger for sending instructions to the user. If the user is in the correct location, the App sends instructions to the next beacon on the path (e.g., go to G). Otherwise, the user will receive instructions on correcting the route (e.g., return to C). Steps 2 and 3 are executed in a cycle, which ends only when the destination beacon is reached.

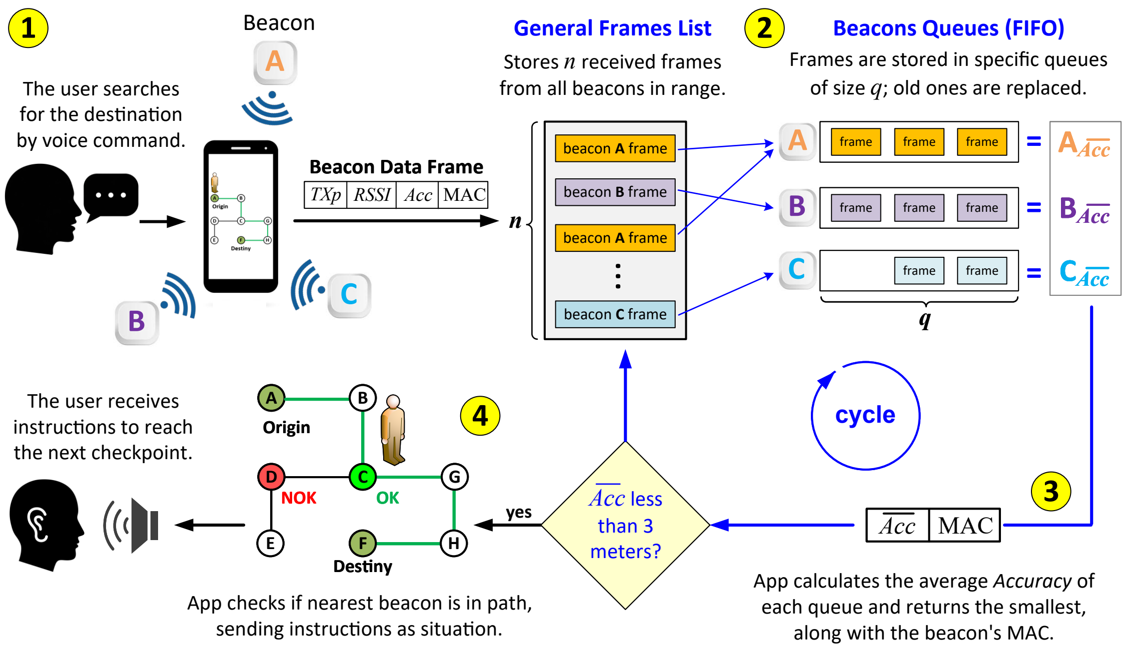

Figure 1. Details of the indoor navigation solution functioning.

The arrangement of the beacons was defined based on the trapezoidal decomposition [Barraquand and Latombe 1991]. This method divides a region into trapezoids or rectangles of smaller areas through vertical lines drawn at each obstacle. Figure 2 shows the result of the trapezoidal decomposition in the studied environment, with the regions in different colors and unique numbers, in addition to the installation location of the beacons, represented by letters inside circles.

A unique beacon could sometimes represent multiple areas (e.g., beacon B, regions 1 and 2). Only the regions constituting the two paths defined for the solution tests are highlighted for simplicity. Both paths originate at beacon A, located on the 1^{st} Floor of the building's side entrance. The first path leads to the bathrooms on the 2^{nd} Floor and consists of beacons of *id* A, B, C, K, L, and M. The second path leads to the institute's secretariat, also located on the 2^{nd} Floor and consists of beacons of *id* A, B, C, D, E, F, G, H, I, and J. The beacons were fixed to the ceiling.

The edge weights of the graph resulting from the trapezoidal decomposition correspond to the distances in meters between the beacons considering the corridors. The beacons were installed in corners, corridors, confluence points, and rooms. Priority was given to installing them in corners, as these are places where a visually impaired person typically has more difficulty due to the wall in front of them on the path. There are also beacons positioned in longer corridors to ensure signal coverage and that the user does not offer extended periods without instructions.

Figure 2. Trapezoidal Decomposition of the test environment and beacons positioning on the evaluated paths.

3.2. Indoor Navigation App Architecture

The deployment diagram in Figure 3(a) presents an overview of the mobile application architecture, including the hardware, software, and communication components. The Navigation App was developed for the Android operating system in the Dart v2.17.6 language and Flutter v3.0.5 framework. A cloud file server stores the APK file for installing the app. The idea is to fix a QRCode at the entrances of buildings, with an explanatory text in Braille and a link to download it via HTTP. All application processing is performed on the user's device without a server.

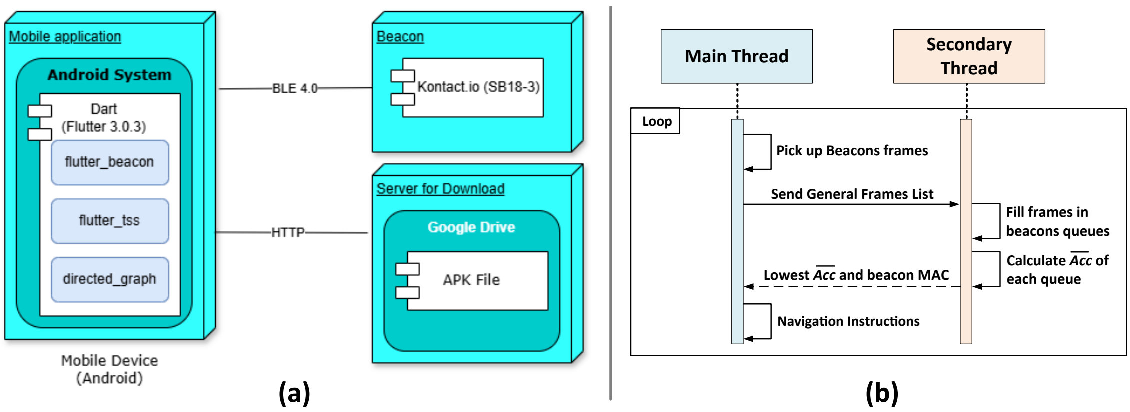

Figure 3. In (a) Architecture of the Indoor Navigation Mobile App (b) Operation of the Mobile App's Threads.

The Mobile App interacts directly with the beacons via BLE 4.0 through the flutter_beacon v0.5.1 plugin. The directed graph v0.3.7 package was used to model and manipulate the graph. The flutter_tts v3.5.0 plugin converts navigation directions from text to speech. The Mobile App was developed and tested on an Infinix Zero 5G smartphone, Android 11.0, 8GB of RAM, 128GB of internal storage, and Bluetooth 4.0. The development environment was Ubuntu 20.04.5. The codes are available at the link `https://github.com/joaovitorgit/App-Indoor-Navigation`.

As illustrated in Figure 3(b), the Navigation App is multi-threaded. The function of the *Main Thread* is to receive the data frames emitted by the beacons, store them as records in the GFL, and send them to the *Secondary Thread*. The latter then evaluates the received frames and organizes them into individual queues for each beacon. When filling each queue, the *Secondary Thread* calculates the average of the Accuracy of the stored frames, returning the lowest average of all queues, along with the MAC of the beacon associated with it.

Beacons from the manufacturer Kontakt.io, model SB18-3, were used. They are battery-powered and have a maximum range of 50 meters. They are stationary and can be fixed to walls, ceilings, or objects. Each frame contains the following data: (*i*) *TX power*, configured in the beacon and defines the transmission power; (*ii*) *RSSI*, indicates the signal strength received by the mobile device; (*iii*) *Accuracy*, is an estimate of the distance between the emitting device (e.g., beacon) and the receiver (e.g., smartphone); and (*iv*) MAC address, uniquely identifies each beacon. The App obtains timestamp data upon receipt of data frames.

4. Experiments and Results

The experiments aim to evaluate the developed solution for navigation for visually impaired people in indoor environments. For this purpose, we perform two sets of tests: (*i*) Calibration Tests and (*ii*) Functional Tests. The value considered for the size of the *General Frames List* is $n = 20$, and that of each *Beacon Queue* is $q = 5$. The Calibration Test aims to obtain data to support the operation settings of the beacons. Since the environment influences the behavior of the beacons, measuring the accuracy of the distance between it and the mobile device is necessary. The *TX power* is a parameter that influences the distance calculation. Therefore, tests were performed in the test environment with different values to verify the most appropriate one. The tests consisted of installing the beacon at a fixed point and the mobile device at a distance of 1, 3, and 5 meters, measured with a tape for data collection. The average of the constant distances in the frames is then compared with the real distances.

Table 1 contains the average distance in meters, obtained from readings with *TX power* values equal to 4, 5, 6, and 7. The difference between the estimated distance and the real one is more significant at lower *TX power* values. Low precision can negatively impact correct user instruction. For example, if the user is 6 meters away from a checkpoint but the data indicates that he is less than 3 meters away, the navigation instructions would be triggered early, which could confuse and cause him to deviate from the route. Even if the definition of the parameter value is well-founded, the distance values returned by beacon may vary depending on the environment. The *TX power* level influences battery life and signal range. We decided to parameterize *TX power* equal to 7 since the correct calculation of the distance is crucial to the success of this solution. Other parameters were maintained according to the manufacturer's standard.

Table 1. Averages of estimated distances with different values of *TX power*.

Real Distance (meters)	TX 4	TX 5	TX 6	TX 7
5	1.79	1.89	2.27	4.08
3	1.03	1.52	1.95	2.16
1	0.84	0.84	0.90	0.93

In the Functional Test, the objective is to verify the App's functioning. A user with congenital total visual impairment who was skilled with a guide cane performed the test. The user is familiar with technologies and is a student in the institution's Information Systems course. We also tested with a user with normal vision for reference purposes. Both were accompanied during the tests but did not receive any assistance; they only received the instructions provided by the App. Figure 2 (Subsection 3.1) shows the details of the two paths defined to validate the proposed solution. Path 1 is the shortest, originating at the side entrance of the 1^{st} Floor of the building (beacon A) and ending at the bathrooms on the 2^{nd} Floor (beacon M). Path 2 is the longer, originating at beacon A and ending at the institute's secretariat (beacon J). Whether the user with a disability reached the destinations correctly is considered a success factor of the solution. To this end, in addition to the on-site observations, the data collected during the route were analyzed. Before the test, the visually impaired user stated that he only knew Path 1 but still did not feel safe moving around alone due to the large size and divisions of the building. She said she did not know Path 2 to the secretariat. The user with normal vision did not know either paths.

Figure 4 illustrates the checkpoint times of users when reaching each of the beacons on Path 1. Both users reached their destination without deviations from the route. The disabled user reached the destination in 2m22s, while the other user reached the destination in 1m27s. The disabled user was more hesitant between beacons K, L, and M due to the corners and the shorter corridor. The time difference is slight and justifiable since the disabled user does not have visual location information, which helps to reduce travel time. In certain moments, it was necessary to provide more detailed information about the environment, for example, between beacons A and B, where the instruction could warn that there is a ramp to access the 2^{nd} Floor, or even at beacon J, which has a staircase nearby.

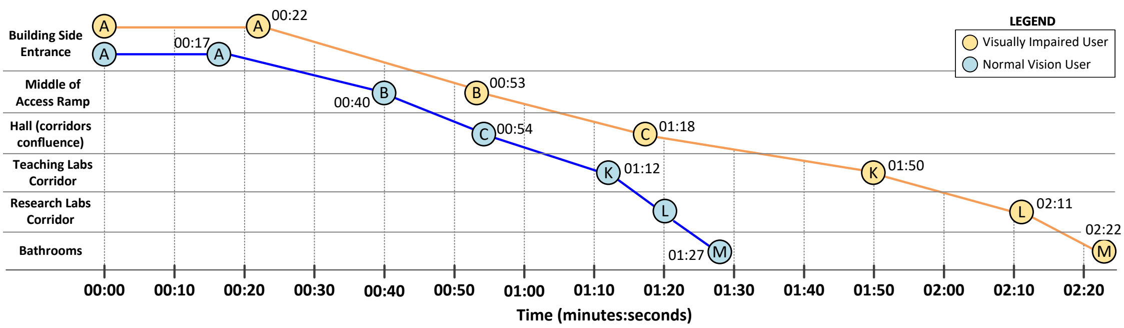

Figure 4. Checkpoint times of users when reaching each beacon on Path 1.

Regarding Path 2, both users reached their destination successfully, with the disabled user doing so in 4m16s. The graph in Figure 5 illustrates the displacement of the disabled user, in which the abscissa axis describes the arrival time at the beacon in minutes:seconds format and the ordinate axis describes the distance of the mobile device about the beacon. Each line corresponds to a beacon, and only records with an average distance of less than 5 meters are considered for better interpretation. The parabolas show a standard behavior in the displacement, in which the estimated distance between the user and a beacon starts high (between 4.5 and 5 meters) and decreases until the user arrives at the beacon checkpoint (vertex of the parabola), and increases as the user moves away. The section involving beacons A, B, and C behaves differently, which is justified by the architecture of the place. Beacon A is located on the 1^{st} Floor, while beacon C is just above it on the 2^{nd} Floor. In this arrangement, beacons A and C are closer to each other than they are to beacon B located on the ramp between them. Therefore, as the user moves away from beacon A, the same occurs with beacon C. The user is equidistant from the points where the lines of two beacons intersect.

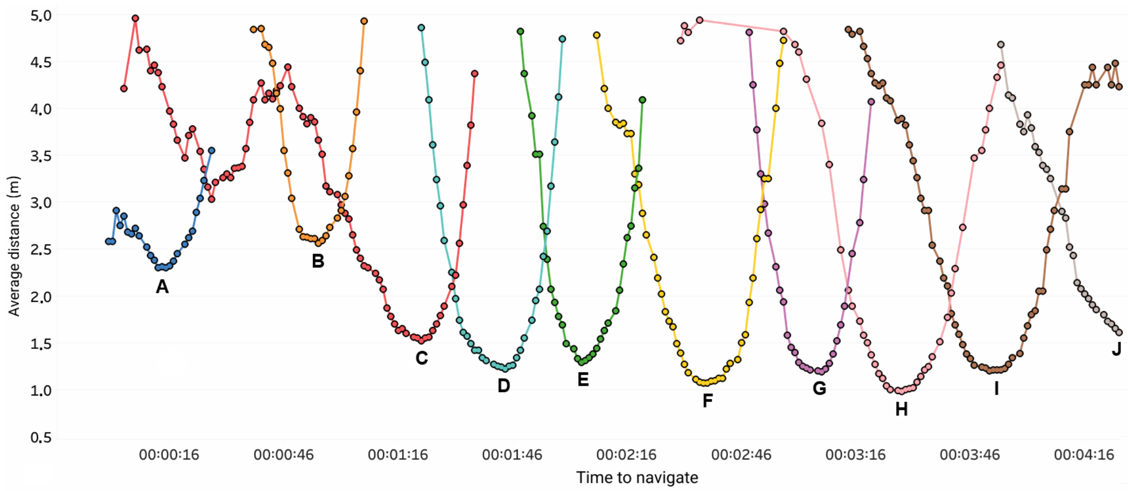

Figure 5. Navigation graph of the visually impaired user in the Path 2 with destiny to the secretariat room.

Figure 5 shows that the user always had signal coverage throughout her journey, reducing the risk of getting lost in the environment due to a lack of instructions. This behavior shows that the number of devices required for full coverage of the environment can be optimized, considering that a single beacon can represent more than one region that Trapezoidal Decomposition identified.

As a general result, the Indoor Navigation App can correctly guide users to their destinations. There were no failures or location errors, and the instructions provided were sufficient for both users to reach the next checkpoint. Finally, questions were asked to the visually impaired user to obtain their feedback, the answers to which are listed below:

- **Q1. What did you think of the voice guidance? Did it work properly? Did the app provide clear instructions that were easy to understand?** *"I was impressed with the voice guidance. It worked efficiently, providing clear and easy-to-understand directions."*

- **Q2. What features were good, and which ones did you miss?** *"One useful feature was the app's ability to alert you to corridors to ignore, as I wouldn't have noticed this on my own. However, I did miss the option to repeat instructions, as this would have been useful in noisy environments like busy places where it can be easy to miss a necessary instruction."*
- **Q3. Would it be possible to reach the destination using the application exclusively? Consider the options: 1. I Strongly Disagree; 2. I Disagree; 3. I Neither Agree nor Disagree; 4. I Agree; 5. I Strongly Agree.** "*4. I Agree*".
- **Q4. Would you use this prototype for guidance in other indoor environments with inefficient GPS? Consider the following options: 1. Never would; 2. Not very likely; 3. Unable to say; 4. Very likely; 5. Definitely would.** "*5. Definitely would.*".
- **Q5. How satisfied are you with the prototype? Consider the following options: 1. Very Dissatisfied; 2. Dissatisfied; 3. Neither Satisfied nor Dissatisfied; 4. Satisfied; 5. Very Satisfied.** "*5. Very Satisfied.*"

The user's opinion was positive, and the suggestions helped improve the solution. In question Q3, the user justified his answer by stating that the instructions sent for moving around sections A–B–C that involve a ramp might not be sufficient for someone unfamiliar with the environment. Improvements in navigation could be obtained from more detailed instructions for this user profile.

The study's weakness is related to the small sample size, which is justified by the specificity of the target audience, which is people with some visual impairment. However, the tests were carried out with a participant in an extreme situation of disability since he has total congenital blindness. Because of this, we believe that the developed solution can also serve people with partial visual impairment.

5. Conclusions

This paper addresses the problem of indoor navigation for visually impaired people and presents the development of a mobile app capable of assisting people with this disability. We model the solution using graph theory, which proved to be coherent in representing the problem and enabling the use of shortest-path algorithms for efficient navigation. Beacon technology was adopted to locate the user, and trapezoidal decomposition supports the most suitable locations for its installation.

The developed solution was tested in a real environment by a user with congenital total visual impairment. The results of the tests with the App demonstrated its correct functioning, which was able to locate the user in the environment and guide them from a starting point to a destination of interest. The use of multithreads was crucial for the processing of the frame queues. It made it possible to correct synchronization problems in sending the instruction at the correct time to the user. The results prove that the checkpoints approach is an efficient alternative to trilateration and triangulation location methods for indoor navigation. An evolution of the solution would be its integration with outdoor navigation, in which the use of BLE and GPS technologies would alternate according to the user's context, being util to interbuilding navigation.

One of the main drawbacks of the solution is the cost of beacons, which tends to decrease with the technology popularization but is still expensive compared to more popular approaches (e.g., Wi-Fi). In this sense, studies that evaluate the feasibility of developing lower-cost beacons using microcontrollers or prototyping platforms are valid as alternate commercial solutions.

Finally, the presented solution did not consider using other sensors typically available in smartphones, such as accelerometers and gyroscopes. These sensors can increase navigation efficiency by enabling route deviation alerts to be sent before the user approaches the next beacon, in this case, the wrong one, so that he can receive corrective instructions.

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