Marek Pilski[1]
ORCID: 0000-0003-2362-0416

Dariusz Mikułowski[2]
ORCID: 0000-0002-4567-7846

Grzegorz Terlikowski[3]
ORCID: 0000-0001-5884-3770

University of Siedlce
Faculty of Exact and Natural Sciences
Institute of Computer Science
ul. 3 Maja 54, 08-110 Siedlce, Poland

{[1]marek.pilski,[2]dariusz.mikulowski,[3]grzegorz.terlikowski}@uws.edu.pl

An indoor campus navigation system for users with disabilities

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Abstract. While supporting navigation outside buildings is currently well solved through GPS-based systems, only a few solutions support indoor navigation and user positioning in large buildings. In this paper, we propose a solution to support such navigation by creating a dedicated hierarchical map of the building and associating it with the infrastructure of Bluetooth Low Energy (BLE) transmitters installed in the building. Then a user equipped with a smartphone can easily read the signals of these transmitters and, thanks to the map, can determine their position in space. We use our method in a system that supports navigation and user safety, emphasizing users with special needs, which we are implementing on our academic campus. We describe the idea, architecture, and implementation of this system.

Keywords: Bluetooth Low Energy, navigation inside the building, users with special needs

1 Introduction

Positioning and self-navigating a user equipped with a mobile device are often used today, and we cannot imagine life without this possibility. While navigation outside buildings is currently relatively well solved through the use of GPS systems such as Google Maps [20] or Open Street Maps [17] systems, according to the knowledge of the authors, there is a lack of cheap reasonable solutions to support indoor navigation with user positioning. The only complete solution is the NavCog system [2].

One of the biggest problems in the case of indoor navigation is the correct determination of the user's position. There are solutions based on the use of stereovision cameras and image recognition [35] or measuring the distance traveled by the user [24] or using lidars [21]. An up-and-coming technology seems to be the Ultra Wideband (UWB) [3], where user Location is calculated by a mobile device using hyper-algorithms based on the angle of arrival (AOA) and time difference of arrival (TDOA) of signals arriving from radio tags installed in the building. Although UWB is already built into some mobile devices, the number of equipment supporting this technology is not too large. Nevertheless, today, the most optimal solution seems to be using beacon transmitters [34]. However, to use them, it is necessary to improve the quality of data read from them for the best user positioning.

In this paper, we propose a solution to support indoor navigation by creating a few navigation and safety system components. It consists of a unique dedicated hierarchical map of the building, which is associated with the infrastructure of Bluetooth low energy (BLE) transmitters installed in the building. In order to connect the map with the physical infrastructure, two critical elements of the system have been implemented. The first is an application on a server with a database and appropriate API that collects all the data needed for system operation. Another is a mobile application with profiles for various types of users, such as blind persons, the deaf, people in wheelchairs, or those with claustrophobia. With such a map, transmitters infrastructure, and mobile application, a user equipped with a smartphone can determine his position in space. Thanks to this, it can be freely led to any place in the building, both in an ordinary situation and when there is a threat.

The rest of the paper is organized: The following section describes existing solutions and approaches to support user navigation inside buildings. In the second section, we present the preliminary research we conducted among users regarding the need to design and implement a system that supports the navigation of users inside buildings. Next, we present the proposed method for creating a universal environment that supports user navigation. In the next one, we present the implementation of our method in the form of an application supporting the navigation of users that we implement on our campus, particularly regarding users with special needs and their safety in emergencies. The paper concludes with the possibility of using other methods to support user navigation and plans for future works.

2 Related works and solutions

The possibilities of independent movement of people with disabilities (e.g., blind or in wheelchairs) inside large buildings are a big challenge. It is crucial when a user visits the building for the first time and needs to reach a specific destination, such as a platform in an underground railway station, a check-in gate at an international airport, a walk through the list of exhibits in a museum, or a lecture hall in a large university building. The ability of people with disabilities to move independently is not only their ambition or relieving the assistants but also the goals of the United Nations announced as the Sustainable Development Goals (SDGs) [29]. DSGs, in a set of 17 interrelated goals, plan to achieve a better future for all people, including improving the lives and use of indoor services by people with visual impairments (goals: No nine and No 11). The needs of people and the development of technology favor the creation of solutions related to supporting navigation inside buildings, e.g., a specific path for a person in a wheelchair to avoid stairs or too-narrow passages.

The issue of navigating inside buildings is currently the subject of many studies, as a result of which many more or less advanced solutions have been developed. In the simplest case, they are physical items, such as metal or stone paths leading to essential places or round protrusions informing, for example, on the stairs beginning are applied. Generally, research is conducted in two main directions, supporting navigation outside buildings and supporting independent movement inside buildings. The navigation outside buildings is usually supported by systems based on GPS, including solutions designed particularly for the disabled, i.e., Blind or Visually impaired, such as Lazarillo [26], or DotWalker [6]. Lazarillo and other similar applications, in addition to the standard options, also have special functions dedicated to people who are blind, such as features of informing users with voice and vibration. The user can also set the informing level to configure which information is spoken to him during the trip. It means that on the lower informing level, he can be announced, for example, only about shops and intersections, or at a higher level, also about addresses and stops. In the case of indoor navigation, the lack of GPS signal causes problems with the proper location of the user during his travel, which makes route guidance substantially harder. Various methods are used to support indoor localization. There are systems based, for example, on acceleration sensors of mobile devices [24]. In this case, the user's location is measured by calculating the traveled distance and the direction from the established starting point. However, measurement errors accumulate due to the measurement's low accuracy and the impossibility of recognizing the user's current position in the actual place in the building. As a result, such a location is often not accurate enough. Another approach to locating the user is to use the magnetic field [12] or radio tags such as RFID [32]. In this case, the problem is that the user has to bring his device close to the magnetic label, which may be difficult for a blind or wheelchair individual. Therefore, this method will not work well in working indoor navigation systems. There are also solutions based on the use of infrared transmitters [4], laser rangefinders [10], or ultrasound [18]. These systems used infrared to position the user and detect obstacles in his path. However, currently, available smartphone models do not support these technologies. Moreover, it is necessary to construct dedicated devices, such as white laser sticks or special glasses with ultrasound transmitters. Moreover, these solutions are too expensive to distribute for broader use.

Nevertheless, the best method to precisely locate a user's mobile device seems to be using BLE transmitters [22] mainly due to their low cost and long operation time. To compute the position of the user device in the building space, methods such as multilateration [33] or fingerprint [16] can be used. The multilateration method has been used in systems such as GuideBeacon [1] or commercial NavCog [2]. In order to effectively detect obstacles in front of the user, recognize routes and guide him to his destination, it is crucial to model the space inside the building. In work [30], the author discusses the topic of indoor navigation, points to the directions of research, and compares assistive technologies for people who are blind. To improve the location accuracy and reduce the adverse effects of environmental factors, a method of fingerprint location assisted by smart phone built-in sensors is proposed in [9]. That is, to use the built-in sensors such as the accelerometer and gyroscope. Moreover, the area of Indoor Navigation indicates three basic directions of development:

– Find an object or place.
– Recognize indoor objects.
– Navigate inside buildings.

The last direction is further divided into non-radio technologies and wireless technologies. An example of a system from the first category is VizWiz, presented in [5]. This system is based on a three-step algorithm that uses the information to direct users to the appropriate facility using their phones interactively. Blind users can take and upload photos of an item and ask for help finding an item or place. The request is sent to remote workers who view the photo and answer the question. The following approach, from the recognize indoor objects category, presents a prototype system that recognizes many objects (e.g., doors, chairs, fire extinguishers, and others.) in public buildings [28]. The system focuses on aspects of navigation and recognition. It uses hardware components such as a camera and laser sensors that a blind person wears on the chest. Due to the lack of GPS signal inside buildings, this type of navigation is called Indoor Positioning Systems (IPS) [8] Furthermore,

In non-radio technologies, there are technologies based on the magnetic field of the environment, acceleration sensors and gyroscopes, barometric pressure, and intelligent lighting. Modern buildings have a unique magnetic field that interacts with steel and other materials found in structures of buildings. One of the available solutions using this local magnetic field is IndoorAtlas [25]. It is a complete software toolbox for creating building plans, collecting magnetic field maps, and an API to use data for mobile applications.

Another technique that uses sensors like the accelerometer and gyroscope is a Smart-PDR system [19]. In this solution, the sensors track the user's movement, considering body parameters, i.e., weight or height. A solution based on the barometric pressure helps record vertical movements such as walks up a flight of stairs or using escalators and elevators [23]. The smartphone or a watch barometric sensor can detect even the most minor changes in atmospheric pressure.

The last presented non-radio technology is intelligent lighting [14]. The basis of the system is the transmission of location data through special light bulbs by modulation of light, which is invisible to the human eye. However, it is readable for the hardware, e.g., a smartphone's camera.

The wireless technologies are based on Wi-Fi triangulation, signal strength, delay, and BLE beacons. Wi-Fi triangulation is one of the oldest technologies used in indoor positioning [15]. The primary reason to use a Wi-Fi signal is that there is a rich infrastructure of wireless networks in buildings, especially in shopping malls. A BLE beacon is usually a tiny device. The transmitter can send an identifier and several bytes of data, which are used to determine the device's physical location. BLE beacons are becoming increasingly common in most commercial environments. They provide a quick and cost-efficient way to create small to midsize indoor positioning deployments [27]. The paper [31] presents the results of experimental research on optimizing BLE beacon placement inside rooms to locate the user with reasonable accuracy. In the study, the optimization of the fingerprint technique was used [11]. The experiments show that the optimal location of the BLE beacons is a 7m grid. Such an arrangement of the transmitters ensures that the average location error is below 1m.

In this paper, we propose using BLE transmitters and hazard detectors, like smoke, flood, and gas sensors, together with the particular hierarchical map and routing algorithm as the basis of navigation and an emergency supporting system. Unlike the existing solutions, our system considers the needs of individuals with various disabilities and ensures their safety in an emergency.

3 Preliminary research

To verify our idea, we started with an initial survey among potential system users, taking part 27 respondents - students and employees of our university. Despite the survey being dedicated mainly to disabled people, about 37% of the respondents were non-disabled. First, we asked what kind of mobile devices they use. It turned out that 81% of them use Android devices, and the rest - iPhones. Ten respondents declared the use of a profile without amenities, while 17 would like to use profiles designed for people with disabilities. There were six visually impaired people, nine persons with hearing problems, and two using wheelchairs or having other motor disabilities in this group. According to their disability, the respondents preferred different notification methods. Visually impaired people chose to text and audio interfaces, while deaf or hard of hearing people opted for visual interfaces such as light signals or icons. A summary of answers to these questions is presented in figure 1.

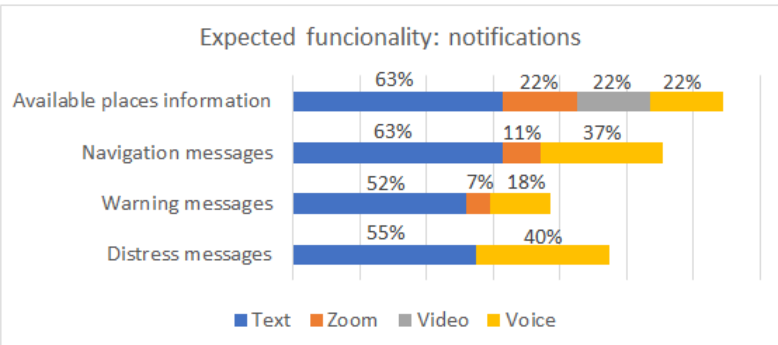

Figure 1. Expected functionality: notifications. Source: Own elaboration

Our system is designed not only to support daily navigation but also to help in an emergency. That is why we also asked respondents about such situations. Eleven respondents proposed adding voice messages to the system, guiding them to exit in a dangerous situation. A summary of answers to questions regarding emergency functionalities is presented in figure 2.

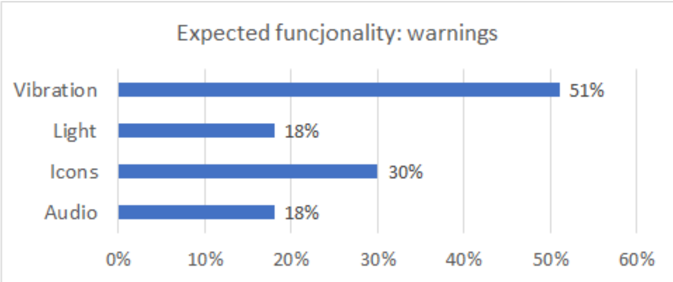

Figure 2. Expected functionality: warnings. Source: Own elaboration

We also asked the respondents about other functions they would expect in the system. A summary of answers to these questions is presented in figure 2.

Another benefit of the survey is that more than half of the respondents declared their readiness to participate in the pilot program. They will be testing the prototype versions of the system. It will allow us to test the features introduced in the system on an ongoing basis and collect user opinions.

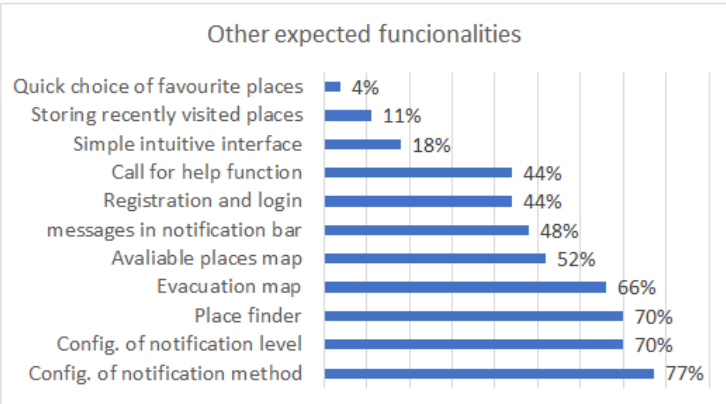

Figure 3. Other expected functionalities. Source: Own elaboration

4 A concept of navigation environment

This section discusses the crucial ideas behind our system and its implementation. We start by describing the system architecture and the building map concept.

4.1 Architecture of the Navigation and safety system

The navigation and safety system comprises three main parts: mobile application, server application with API and system administration panel, BLE transmitters, and safety sensors infrastructure. The system architecture is presented in figure 3.

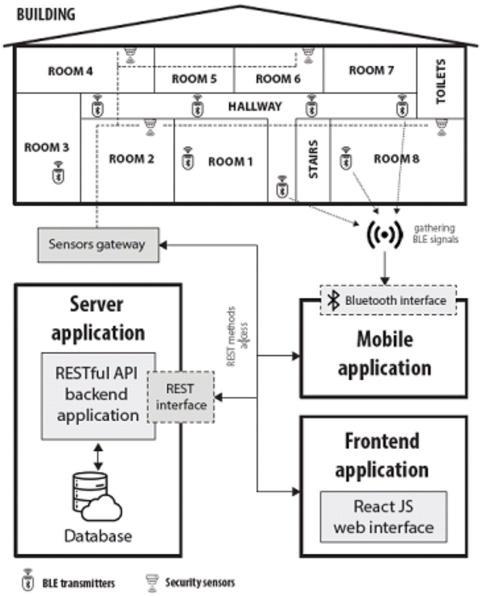

Figure 4. The navigation system architecture. Source: Own elaboration

The crucial component of the system is the server application. It provides the API consisting of services consumed by the other modules. For example, a service stores maps of a building where the system operates and the data of all installed transmitters and sensors, along with their coordinates and other necessary information. Moreover, the server provides web-based tools for the map administrator, facilitating map building. The server application is also responsible for user supervision and alarm activation in an emergency. The web application running on the server also has a part dedicated to a safety administrator. The threat detection subsystem reads data from sensors such as smoke, gas, or flood detectors and sends information about the threat to the system. Then it will automatically trigger an appropriate alarm, propagating to users' mobile applications. The safety administrator is notified of this and may take appropriate action, e.g., inform the relevant services about the need to assist the user.

The second part of the system is the BLE transmitter and sensor infrastructure. They are installed to guide users along the route and ensure their safety in the building. They are maintained by an employee who installs them physically and updates their data using a technical profile in a mobile application. Then the transmitters and sensors installed in the building are assigned to locations in the object map stored in the server application. The user's position is determined using the path loss model and multilateration method [7] or the Fingerprint method [16].

The third part of the system is a mobile application designed for the user. It runs on the user's device (smartphone) with the Android system. It allows configuring user profiles and exploring places (rooms, corridors, and stairs) available in the building. It also guides him to the destination in a joint emergency and corrects the route when lost. The mobile application has profiles according to user's preferences, i.e., profiles for able-bodied, blind, partially sighted, deaf, wheelchair, and claustrophobic user. For example, suppose the user chooses a profile intended for people who are blind. In that case, the application will inform him about the passing places and dangerous situations using vibrations and text messages that can be read via a screen reader installed on the mobile phone. Despite selecting a given profile, the user still can turn some information delivery methods on or off or choose the categories of points he wants to be informed of, e.g., lecture halls or laboratories and dangerous places, such as stairs or elevators. A separate profile with entirely different parameters is intended for a technician physically installing BLE transmitters and sensors in the building. A more detailed description of the system is provided in the following sections.

4.2 Hierarchical building map

An appropriate representation of the building is essential for properly functioning the entire system. This representation is designed as the building's hierarchical structure, modeled using several ROOM and LINK concepts. Broughly speaking, an instance of ROOM represents a cuboid fragment of space occupied by a building part, while a LINK stands for a passageway between two ROOM instances. The root branch of the hierarchical map is always a ROOM of type Building, which contains one or more ROOM instances of type Wing, and each Wing includes at least one ROOM object of type Floor. The concepts above provide a logical structure of the building and play roles of containers for "ordinary" rooms, e.g., classrooms, halls, and laboratories. They are called next ROOM and belong to some Floor object. Thus, for example, a student in a classroom is located on precisely one floor in a particular wing of the building. The ROOM objects are equipped with many attributes describing the room's dimensions, spatial position according to the global and local coordination system, and other information, like name, number, and purpose, as well as BLE beacons and security sensors in this room. Other types of objects crucial for navigation purposes are LINKs. We distinguish several links, e.g., Door, Stairs, Passage, and Elevator, which allow for computing optimal routes for users with disabilities.

5 Results

5.1 Server API implementation

We used the specification first approach to implement the server part for the proposed navigation support system to be developed optimally. We use OpenAPI [36] specification to define the standard data model and API for all system components. Then, using dedicated tools, we generate the backbone classes and interfaces for the backend (Spring and Java), the web application (TypeScript and React), and the mobile application (Java for Android). The server-side features generated from OpenApi specification include the relational database structure with Object-Relational Mapping and Neo4j graph database structures and queries. Their automatic generation is possible due to custom Mustache [13] templates and OpenApi generators. Thus, the specification-first approach allows consistency between components, despite the inevitable changes during the implementation and system evolution.

5.2 Map development and design

For the system to work correctly, the hierarchical map should be imported to be visible to other application components, i.e., the user and the fitter. This import is possible thanks to the implemented APIs described in the VI-A section. The map of the building can be imported into a system through a web interface. It is a React application coupled with some security technologies, e.g., JWT tokens. The application is available only to the personnel of the navigation system.

All other functionalities (e.g., navigation) for the end user are implemented in the mobile application described in section 5.3.

In the first step, the user defines a new building in the application to import a map. Then he can import a DXF file containing map data. The application validates the file and notices if the map is correct or not correct.

During the implementation of the system, we modeled four maps of the buildings on our university campus. Each map contains a certain number of 3DSOLID and 3DFACE objects necessary to build the structure of the building. Table 1 presents a summary of imported maps. Let us note that Each room is described by one 3DSOLID object and six 3DFACE objects

Table 1. Statistical data for loaded building maps. Source: Own elaboration

Building name	Number of ROOM types	Number of 3DSOLID objects	Number of 3DFACE objects
Faculty of Social Sciences and Humanities	159	661	3893
Faculty of Exact and Natural Sciences	195	543	3258
Institute of Computer Science	26	115	690
Main Library	70	315	1890

(because a cuboid is defined by the six faces of a 3DFACE object). In some cases, the structure of objects was more complex because of the irregular shapes of the rooms. The other space in the building was also reflected in the map, especially doors, stairs, passages, and elevators.

5.3 Mobile application development and design

The mobile application is one of the most critical parts of our system from the user's point of view. It was implemented as a Java application in the Android Studio environment. The mobile application's essential feature is guiding the user along a designated route. It also has functions for registration, logging in, managing user profiles, downloading and browsing building maps, managing favorite locations, searching for locations, and reporting the need for help. The user interface was designed in MockFlow, considering accessibility and UX recommendations [37]. The mobile application was created under the principles of universal design, which means it considers the needs of users with special needs. For this purpose, it has profiles for various types of users, such as the blind, deaf people, people in wheelchairs, or people with claustrophobia. For example, suppose the user switches to the profile of a deaf person. In that case, messages from the application about available places in the university building will be presented to him as short video sequences in sign language, see Figure 4. If, however, he selects a profile intended for people who are blind, messages will be read for him by the screen reader built into the phone.

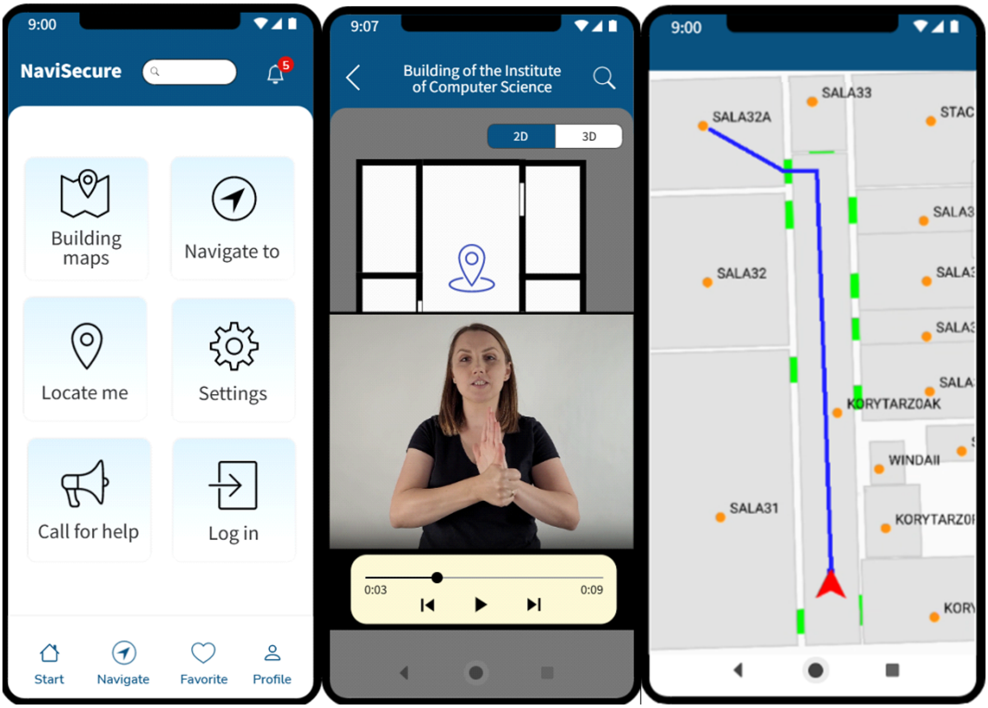

Figure 5. Mobile application: a dashboard, navigation using sign language and navigation to a selected place in the building. Source: Own elaboration

The profile that the user selects at the beginning of the application operation has an impact on two issues:

1. The way of presenting informational and warning messages to the user in an appropriate form and guiding him to the destination. Such messages may be presented as text, audio, or video sequences in sign language.
2. Determining the appropriate route, i.e., a person in a wheelchair does not use stairs, and someone with claustrophobia must avoid narrow corridors and elevators.

After launching the mobile application, the user can choose the map of the building where he wants to navigate. He can download it to his mobile device and then browse it.

As mentioned above, map objects are arranged as a hierarchical tree, with the main element being the building. Its subelements are wings, floors, and rooms. This map hierarchy allows the user to explore a floor, Wing, corridor, or room separately. He can also move to the next or previous room, regardless of its place in the hierarchy. Each map element has similar attributes, such as name, description, or resources. Rooms are at the lowest level of the hierarchy so in the room details view. The user can also mark it as a favorite. After adding a room to favorites, it becomes available on a particular list, allowing for quick route calculation to that location. A room can be removed from the favorite list. The application also has a multi-criteria search engine where users can search a specific room according to a phrase in the room description or name or the type of services provided in that room. When a person with disabilities gets lost, the system offers them two help scenarios. The first is a route calculation and navigation function, which gets a stuck user in a room. Moreover, a person with a disability can send a special assistance request to the system, including the room identifier recognized based on beacon signals. As a response, the system informs the security officer about this situation, who can help disabled users. In other exceptional situations, such as alarms caused by fire, gas leaks, or bomb threats, the system determines unique evacuation routes and explains them to everyone in the building.

6 Discussion and conclusion

In this paper, we presented a solution to solve the navigation problem of users with special needs inside buildings.

The system relays on BLE and security sensors infrastructure to safely guide users to their destination. Pathfinding the task is based on Dijkstra and A* algorithms provided by A neo4j graph database adapted to work in the context of the hierarchical map and user profile. All these features have been implemented as a navigation system consisting of a mobile application, a server part with an API, a web application, and an infrastructure of BLE transmitters and hazard sensors. Our short-term goal is to implement the system in 4 buildings of our university and perform broader tests with students and employees as users. Based on these gained experience and data, we extend and improve system features and performance. Currently, we use two methods of user positioning based on analysis of BLE signals strength and transmitted data: multilateration with a signal path loss model and fingerprint mechanism. The multilateration method can be improved by applying filters to the received data and optimizing the initial parameters of the installed transmitters.

In turn, the fingerprint mechanism can be boosted by different patterns and matching algorithms and the evolution of the place-Move grid structure in response to data collected from users moving inside the building. For example, the frequently visited places gain priority, so they are more likely to be chosen by the pathfinding algorithms. On the other hand, two closely located adjacent places with similar signal characteristics can be merged into one. This improvement could speed up the operation of routing algorithms in giant buildings with many users who, for example, could be directed to the same destination by different routes to avoid traffic jams. It would be possible because some rarely visited places would be statistically less considered, and those visited more often would have a higher priority. Such and other experiments are currently being implemented.

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