Analysis of Spatial Landmarks for Seamless Urban Navigation of Visually Impaired People

Min Wang, Aurélie Dommes, Valérie Renaudin, *Member, IEEE*, and Ni Zhu, *Member, IEEE*

***Abstract*—Navigating in urban environment is a major challenge for visually impaired people. Spatial landmarks are crucial for them to orient and navigate in their environment. In this paper, the spatial landmarks most important and commonly used by visually impaired people are identified through interviews, and geometric constraints of these landmarks are constructed to facilitate the development of map-matching algorithms. Interviews were conducted with 12 visually impaired people who had a range of visual impairments and used various mobility aids. Data were analyzed by sensory modality, occurrence of use, and number of users. 14 main landmarks for urban navigation were selected and categorized into two groups: Waypoints and Reassurance Points, depending on whether they are directly detected by touch. Geometric constraints were developed for each landmark to prepare their integration into map-matching or path-planning algorithms. The result is a comprehensive dictionary of landmarks and their geometric constraints is created, specifically tailored to help visually impaired people navigate urban environments. Our user-centric approach successfully translates the subjective navigation experiences of visually impaired people into an objective, universally accessible format. This bridges the gap between personal experiences and practical applications and paves the way for more inclusive navigation solutions for visually impaired people in urban environments.**

***Index Terms*—Pedestrian navigation, sensory modality, spatial landmarks, visually impaired people, waypoint.**

I. Introduction

According to the World Health Organization's 2020 report, there are around 2.2 billion people who have low vision at near or far distances. In at least 1 billion of these cases, the visual impairment has not yet been treated [1]. For those who suffer from visual impairment, both independence and confidence in carrying out everyday activities are affected. Some of these people use a variety of aids to navigate, such as canes, guide dogs, and technical aids. When considering the usability of navigation aids, it is important to keep in mind that their effectiveness can vary significantly among visually impaired people due to different personal preferences, varying degrees of visual impairment, and personal navigation strategies. This diversity highlights the importance of consistent and universal navigation aids. To help visually impaired people find their way and orient themselves, spatial landmarks could be of great importance and usefulness.

Spatial landmarks serve as universally recognizable reference points that can be perceived by a variety of senses, including touch, sight, and sound. Their use in navigation transcends individual preferences or the use of particular devices. However, research on which landmarks are most commonly used by visually impaired people and how these landmarks can be used for navigation, e.g., in map matching and path planning algorithms, is still very scarce. In this article, we aim to find landmarks that better match the actual needs and preferences of visually impaired people compared with the landmarks used by existing tools and APPs, and to define the geometric constraints of these landmarks from the perspective of visually impaired people. This not only deepens our understanding of the navigation strategies of visually impaired people but also provides a solid foundation for the development of advanced map-matching and wayfinding systems, thereby improving the effectiveness of navigation aid technologies.

The main contribution of this article is first to identify the landmarks used by visually impaired people and then to analyze and categorize them systematically. To do this, 12 visually impaired people were interviewed to obtain useful information about the landmarks they use when navigating three familiar places of their choice. The interviews were then transcribed and analyzed in detail to extract information useful for identifying the landmarks used by visually impaired people and the senses they use to identify them as they move around.

A second contribution is to translate the spatial landmarks into geometric constraints for future map-matching and classify them into two categories: 1) waypoints and 2) reassurance points, depending on whether they are detected directly by tactile. We identify how these landmarks can be useful for positioning by constructing geometric constraints on them, geometric constraints give the matching range and the highest probability

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the ethical standards of the institutional and national guidelines for psychology research, the French regulation for data protection (RGPD), and performed in line with the 1964 Helsinki Declaration.

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location, which can be integrated into the map-matching algorithm. Our method translates spatial landmarks into a tangible form and gives a dictionary of landmarks for visually impaired people's navigation in cities, which can integrate spatial landmarks into map-matching and path-planning algorithms in the future.

This article is an expanded version of paper [2] from the 13th International Conference on Indoor Positioning and Indoor Navigation (IPIN). The difference with IPIN is that in this article we have updated the state of the art, detailed how we identify landmarks used by visually impaired people, introduced the concept of reassurance points, and provided specific criteria for landmark selection. We give a more complete dictionary that includes applications in map-matching and path-planning algorithms. We also compared our work with new existing tools and applications that help visually impaired people to navigate.

The rest of this article is organized as follows. Section II presents the current state of the art in landmarks for visually impaired people, as well as tools and applications that use landmarks to help visually impaired people navigate. In Section III, we explore how visually impaired people interact with their environment. How we determine landmarks for visually impaired people is explained in Section IV. Section V analyzes the geometric constraints of landmarks and creates a dictionary of landmarks. Finally, Section VI concludes the article.

II. State of the Art

The state of the art includes two parts: Landmarks for visually impaired people and tools and apps that utilize landmarks to help visually impaired people navigate.

A. Landmarks for Visually Impaired People

Lynch [3] was one of the first to define a landmark as an easily identifiable object that serves as an external point of reference. Since then, research work agreed to consider a landmark to be valuable information at every step of a wayfinding and navigation task [4]. They are spontaneously used by individuals to guide their peers [5], and people who receive instructions without them deplore it [6]. A landmark is any element in the environment that is easily recognizable and used as a point of reference or as a spatial cue [3], [6], [7]. Landmarks have multiple functions. They indicate places where an action can occur, they can help to locate other landmarks that are more relevant to the task, and they can serve as confirmation during long route segments [5]. Four characteristics are generally attributed to landmarks: 1) prominence, 2) uniqueness, 3) salience, and 4) distinctiveness [8].

Caduff and Timpf [9] defined three types of saliency as follows.

1) *Perceptual saliency:* Perceptual saliency is defined as the exogenous potential of an object to grab attention. It is the most commonly accepted feature to define the attraction power of a landmark. This feature is considered to be mainly visual and can be influenced by physical attributes such as size or color for example.
2) *Cognitive saliency:* Cognitive saliency is defined as the endogenous potential of a landmark to modulate attention and relies on the observer's personal cultural, and historical experience and knowledge.
3) *Contextual saliency:* Contextual saliency is defined as depending on the task and the modalities of execution: Landmarks are generally at decision points before the road to be crossed and in the direction congruent with the next action [10], but they can differ in some very specific tasks or environments.

While visual saliency is often the main quality considered, the question arises to know how people who suffer from visual difficulties identify, use, and memorize landmarks. This question is of great interest to help them navigate in the city. Landmarks are actually rarely used in mainstream commercial systems due to the difficulty of getting updated data about them, and the ability to automatically select and integrate them in navigation devices. But a considerable number of recent works in the engineering sciences attempt to integrate landmarks into navigation assistant devices [11], by using spatial databases such as point of interest and GIS databases including road networks and cadastral maps [12], or dynamic sources such as web content, crowdsourcing data, and social networking websites [13]. These efforts are, however, focused on sighted people, and the issue could be even more delicate for visually impaired people if visual saliency is the primary quality used to recognize and use landmarks during navigation and wayfinding, and mostly if landmarks differed between sighted and visually impaired people.

Blind individuals' mental representation of space may not only include the objects categorized by sighted people, such as buildings, shops, roads, etc. but also the arrangement of things in space and time according to their functional nature, such as crosswalks, slopes indicating crosswalk entrance, or the sound of cars or traffic [14]. The detection of obstacles is of great importance, such as the perception of the ground surface, changes in texture, drop-offs, step-ups, fences, walls, and other obstacles. The perception of distal space may be perceived by observing the acoustic pattern of movements and the echo of the cane/feet on the ground and walls, allowing identifying for example open areas and roads, walls of buildings, and noisy roundabouts. Landmarks for people who are blind or visually impaired could, therefore, be as those mentioned and used by sighted individuals as familiar objects, but also sounds, odors, temperatures, and tactile clues that are easily recognizable for them, but those have discrete, permanent locations in the environment [15].

B. Navigation Aids and APPs for Visually Impaired People

There are many aids that use landmarks. The white cane is the most traditional aid for visually impaired people. It helps identify tactile landmarks such as curbs, obstacles, and surface changes. The cane for the blind is an inexpensive aid that requires training and attention from the user to recognize objects in front of them.

Microsoft Soundscape is an application designed to augment navigation capabilities for visually impaired people using 3-D audio cues [16]. Diverging from conventional turn-by-turn directives, Soundscape offers spatially contextual information, enabling users to construct a sophisticated mental representation of their environment. Soundscape relies on the GPS capabilities of the user's smartphone to obtain location information. Utilizing binaural audio techniques, Soundscape imparts a sense of directionality and spatial orientation. With stereo headphones, audio cues are perceived as originating from distinct directions corresponding to real-world landmarks, thus enhancing spatial awareness. However, relying on auditory cues for navigation might lead to distractions, as users need to pay attention to audio directions. This could potentially compromise safety, especially in busy or hazardous environments.

BlindSquare [17] is a GPS application designed specifically for the visually impaired people similar to Microsoft Soundscape but it covers both indoor and outdoor navigation. It uses GPS data and the OpenStreetMap database to provide users with accurate and reliable information about their environment, such as nearby landmarks, road intersections, and points of interest such as shops, public spaces, churches, and many others. With the help of Bluetooth Low Energy (BLE) beacons, BlindSquare provides accurate guidance information for indoor spaces. However, BLE beacons have a relatively short broadcasting range; achieving good accuracy requires numerous beacons and complex deployment. The cost of deploying in a building can be significant.

In all these applications, the landmarks used are not necessarily those that are most meaningful and useful to users, those that they perceive or even prefer. The question arises all the more for visually impaired people, who have different travel strategies and perceptions. Our innovation aims to create a more intuitive understanding of how visually impaired people interact with and perceive landmarks, and applies geometric constraints to the identification and interpretation of tactile landmarks. In this way, landmarks can be integrated into map-matching algorithms in the future.

III. Sensory Capabilities of Visually Impaired People

We had several meetings with locomotion instructors to get a good understanding of how visually impaired people get around. Locomotion instructors are professionals in the paramedical field. They help create the locomotion instructions, techniques, and strategies that enable visually impaired people to move around with ease, safely, and as independently as possible. Among other things, the instructor teaches compensatory techniques for locomotion: cane, tactile, auditory and olfactory cues, memory, step counting, etc.

For visually impaired people, orientation and navigation are complex tasks that often induce stress and fatigue. While navigating they are also affected socially and psychologically. Lack of itinerary information usually produces more difficult navigation conditions, even with a guide dog or a white cane. Moreover, the level of difficulty varies depending on environmental factors, such as the population density, the weather, architectural constraints, and the presence or absence of landmarks [18]. Visually impaired people interact with the environment through visual alternative senses: touch, hearing, smell, apparent visual contrast, and mass sense.

1) *Tactile:* For many visually impaired people, tactile perception is the most important type of spatial understanding. A city provides various tactile stimuli that help a visually impaired person move around. The most common tactile stimulation for visually impaired people is tactile paving, also called "Bandes d'Éveil de Vigilance (BEV)," which stands for the tactile paving or truncated domes embedded in public pathways to assist visually impaired pedestrians. Tactile examples also include the vibrations of a white cane as it makes contact with the sidewalk, the sensation of changing terrain texture as it rolls along the ground, or the feedback from the movement of a guide dog's harness.
2) *Audition:* Visually impaired people use their hearing to gather information about the environment and the location of obstacles. For example, many visually impaired people use a remote control to activate audible devices installed for the visually impaired: traffic lights, audible beacons, Braille (alphabet for the blind), passenger information terminals, etc. Escalators and automatic doors also produce specific sounds. The sound of a vehicle can also help identify the direction of the road, whether it is one-way or two-way.
3) *Smell:* For visually impaired people, the world unfolds not just through touch or sound but also through the myriad scents that waft through the air. Every place has a specific scent profile. For instance, the warm aroma of baked goods from a bakery, the fresh scent of greenery in a park, or the coffee in a coffee bistro. Recognizing these unique aromas allows visually impaired people to identify their location and orient themselves.
4) *Obvious visual contrast:* Visually impaired people who do not have a complete loss of vision can perceive color contrast in their view, such as black against white or yellow against blue, which can help delineate pathways, steps, entrances, or potential hazards. Many public spaces use contrasting colors to highlight stair edges or platform boundaries, aiding visually impaired people in detecting these structures. Pathways marked by strong visual contrasts, like pedestrian crossings with bold stripes, not only ensure safety but also serve as clear directional indicators. Variations in patterns, such as a change from a tiled floor to a carpeted one, can provide visual cues. These contrasting patterns can inform the individual about transitions between spaces, such as moving from a hallway into a room. High-contrast outlines, like those around signs, doors, or windows, can also guide visually impaired people.
5) *Sense of mass:* Sense of mass refers to the perceptual ability to sense the presence or absence of substantial physical objects, such as a wall or an open space between two buildings. The urban environment offers many structures that promote echo and sound reverberation, creating

acoustic fields with different characteristics [19]. Thus, depending on the spaces traveled, open or semiopen, the reverberation changes, people can feel hollows and masses, e.g., the resonance at the entrance of a building. The reverberation changes are potentially being used in locomotion by promoting echolocation.

IV. Most Used Landmarks From Visually Impaired Interviews

In this section, we extract landmarks used by visually impaired people by interviewing 12 visually impaired people to obtain useful information about the landmarks they use.

A. Interview Sequences With Visually Impaired People

To identify the landmarks, we conducted interviews with 12 visually impaired people, with the help of a French association [20]. The participants were aged between 33 and 74 years old, with a median age of 49 years old, and a standard deviation of 14.30 years. Half of the participants were females. All of the participants were living in French metropolitan cities, with a percentage of 75% in the Paris region. Four participants (two women and two men) were congenitally visually impaired (early blind) while eight of them (four women and four men) acquired visually impairment over time (late blind). According to the recommendations of the WHO Consultation on "Development of Standards for Characterization of Vision Loss and Visual Functioning" [21], five participants pertained to Category 5 of visual impairment (no light perception), two participants to Category 4 (light perception), one participant to Category 3 (blindness), and four participants to Category 2 (severe visual impairment). Three participants had a guide dog, eight of them used a white cane, one of them had both a guide dog and a white cane, and two participants did not use either. Most of the participants (11) also used technical tools like remote control, which enable visually impaired people to trigger the audible traffic lights. All participants had autonomous lives in their communities. Most of them were employed, while the three older ones were retired. Informed consent was obtained from each participant after the nature and the tasks involved in the study were described.

Interviews were conducted to obtain in-depth information about the landmarks used by visually impaired people while navigating. Participants were given the following instructions: "The aim of the interview is to explore together three common daily routes that you make on foot and alone, for about 5–10 min, such as going to the bakery or the bank. For each route, you will have to start from the point of departure, then follow the route to the point of arrival, describing all the landmarks or spatial and/or sensory cues you use to complete the route." The interviewer discussed each landmark mentioned by the participant to determine its nature (e.g., store, road infrastructure, urban furniture, remarkable place) and the sensorial modality used to identify it (vision, sound, tactile). Interviews were recorded and then transcribed to be analyzed.

The interview method provides access to mental representations of the individuals, unlike closed-answer questionnaires that require a priori definition of all possible responses. It provides access to the diversity of spatial representations memorized by different individuals. These representations contain a variety of information beyond the name of the landmark itself, such as the sensorial components associated with the landmarks (i.e., the way participants recognize the landmarks using their senses, sight, hearing touch and vestibular information, etc.), its cognitive saliency (familiarity), the order in which they are used during navigation, etc. The descriptive discourse may involve the nature and position of the landmarks which are encountered along the route as well as the instructions specifying, which actions should be executed at these critical points along the route [22]. Interviews may allow access to the internal representation of the environment to be traversed and identify those places and critical points (i.e., landmarks) where decisive actions are to be executed. All of the interviews were conducted individually thanks to a phone exchange between the interviewer and each participant. Each of the 12 visually impaired people was asked to describe three itineraries, for a total of 36 itineraries. The interview lasted about 45 min.

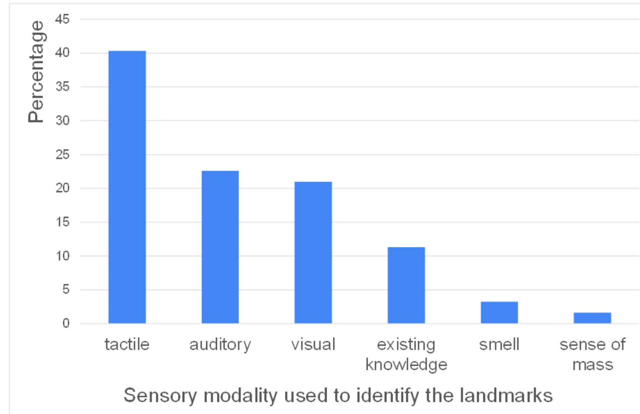


Fig. 1. Percentage of landmarks identified using a single modality recalled by the 12 interviewees.

B. Analysis of the Interviews

A total of 90 landmarks were recorded from the interviews with the visually impaired people. To analyze the sensory modality used by the interviewees to identify the landmarks in their environments while navigating, six categories were defined: tactile information, visual information, auditory information, smell, sense of mass, and existing knowledge. The category "existing knowledge" refers to the familiarity of the interviewee with a specific object or location in their memory, even though there exists no distinctive landmark that physically indicates their presence at the location.

Among the 90 landmarks recalled, 62 were described by the interviewees to be identified by a single sensory modality. Fig. 1 represents the different sensory modalities used by visually impaired people to identify landmarks when navigating in their environment. Tactile information is the most used sensory modality. Forty percent of the recalled landmarks were identified

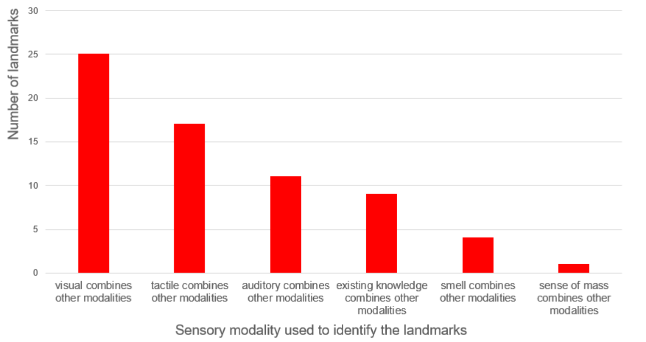


Fig. 2. Number of landmarks identified using a combination of multiple sensory modalities recalled by the 12 interviewees.

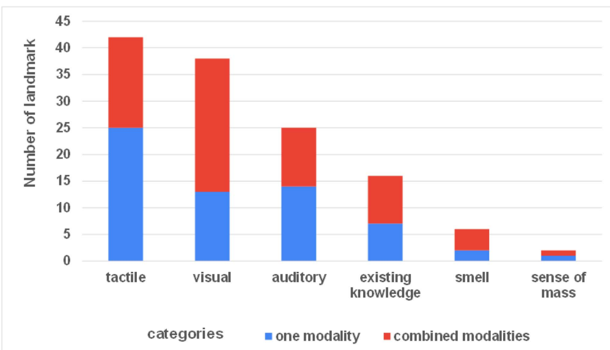


Fig. 3. Number of landmarks per modality recalled by the 12 interviewees.

using a single tactile information, which corresponds to 25 times. Auditory information (14 times) and visual information (13 times) are the other two major sensory modalities for identifying landmarks with 24% and 23%, respectively. Only a few landmarks are identified by existing knowledge, smell, and the sense of mass.

It should be noted, however, that a landmark can also be identified by the combination of several senses. A total of 28 of the landmarks fall into this group. Fig. 2 shows that for 25 landmarks, visual information supported by other modalities is used most frequently. Tactile information with the assistance of other modalities is used second most often, for 17 landmarks.

Because the combination of several modalities involves each modality individually, we completed the analysis with the sum of combined and single sensory modalities. Fig. 3 shows this sum and the proportion of landmarks related to different sensory modality categories. The global sensory modality most commonly used by visually impaired people is tactile, with 42 landmarks, which is a major difference from sighted people. Visual landmarks are the second most used, with 38 landmarks in the visual class according to our interviews.

Fig. 4 shows the various landmarks mentioned by interviewees as they recalled the 36 itineraries. We have chosen to focus on landmarks mentioned by at least four people. Of the total of 90 landmarks mentioned by participants in their itinerary recalls, 17 are used by more than four participants. In Fig. 4, these 17 landmarks are represented according to the sensory modalities used to identify them.

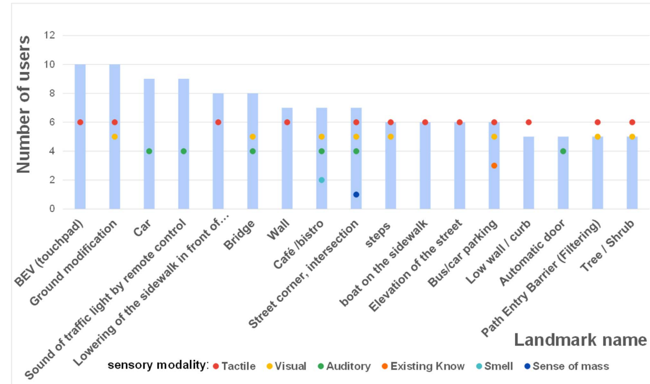


Fig. 4. Description of the landmarks recalled by more than four visually impaired participants with respect to the number of participants and the sensory modality used to identify them.

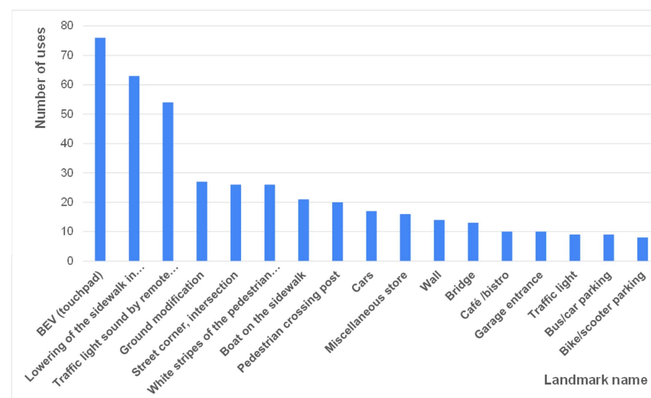


Fig. 5. Number of times per landmark is used (more than eight times).

"BEV" and "ground modification" are used by the largest number of participants. Both of these landmarks are used by ten participants. BEV is sensed by tactile recognition. "Ground modification" is sensed mainly through tactile recognition, but sometimes also visually by ground color changes. Car sounds are also used by visually impaired people to navigate in their environment (nine participants declared to use such information). "Sound of the traffic light by remote control" is moreover mentioned to be useful for them while navigating (nine users mentioned it). Finally, we can also cite "lowering the sidewalk in front of the crosswalk" which is tactile information mentioned by eight users in their interviews.

Counting the occurrence of all landmarks used in all itineraries, the 90 landmarks were used a total of 672 times in the interviews. There are 17 landmarks that were used more than eight times each. These 17 landmarks occurred a total of 393 times, which is 63% of the total occurrences. In Fig. 5, we counted the landmarks that were used more than eight times. It can be seen that the most frequently used landmark is also the BEV, 79 times. In second place, with 63 mentions, is the "lowering of the sidewalk in front of the crosswalk." And the "noise of the remote control traffic light" is used 54 times.

V. Geometric Constraints Associated With the Landmarks

In this section, we first summarize the main results of the analysis of the interviews to select available landmarks for urban navigation. We then identify how these landmarks can be useful for positioning by constructing geometric constraints on them, and classifying spatial landmarks into two categories: 1) Waypoints and 2) Reassurance Points. Finally, we compare our work with existing aids and methods that help visually impaired people navigate.

A. Selection of Landmarks for Positioning

First, we made a selection of landmarks based on the interview results. The classification of the sensory modality used by visually impaired people to identify landmarks in their environment shows that the most commonly used sensory modalities are tactile and vision. From a technical perspective, these two categories of landmark identification can be easily detected using technologies such as sensors and cameras. We discarded landmarks that occur infrequently (used less than eight times) and are adopted by only a few users (used by less than four people) to keep the landmarks as representative as possible.

Second, considering the future contribution to the map-matching algorithm, the availability of the landmarks in existing geographical information systems is essential. Therefore, we discarded landmarks such as "ground modification," for which appropriate data are barely recorded. The data we use in this study are Accessibility data [23] provided by Nantes Métropole, which is the data that provide the geographic information of landmarks necessary for accessibility for people with disabilities and takes into account the CNIG (Conseil National de l'Information Géolocalisée) standard [24] on accessibility.

Third, to be included in positioning systems, landmarks must meet three main criteria: permanent, reliable, and characteristic. These characteristics are defined by locomotion instructions.

1) *Permanent:* The selected landmark must be permanent and fixed. It cannot be a temporary sign or a moving object like a vehicle.
2) *Reliable:* Landmarks must be reliable and easy for visually impaired people to find. They must be characteristic and easily distinguished from their surroundings.
3) *Characteristic:* The landmark selected must be characteristic of the place, but does not necessarily have to be of high precision. For example, it can be a noisy area, the nature of the ground, or a succession of things on a route such as bumps.

These features are important for visually impaired people to better locate the landmarks and consequently orient themselves in their environment. Based on these characteristics, we discarded some landmarks, e.g., a "car."

Based on the above three selection criteria, we finally selected 14 landmarks for the study: BEV, crosswalk, stairs, wall, street corner, building entrance (door), bypass road, bus stop pole, remote sheltered bus stop, sheltered bus stop, mailbox, traffic light, escalator (indoor), and elevator (indoor).

B. Analysis of the Geometric Constraints of Landmarks

To determine the geometric constraints of landmarks for visually impaired people, it is first important to understand how they use these landmarks in their daily walks. To this end, we analyzed two specific walking itineraries. We selected two representative itineraries, in Nantes (France), covering the most frequently chosen landmarks. After consulting with a locomotion instructor, we obtained insights into their navigation strategies along these itineraries. We then counted the available landmarks on the itinerary and created a reference trajectory.

The first itinerary is 1 km long and contains eight different landmarks, illustrated in Fig. 6. The second itinerary is 950 m long and contains seven different landmarks, illustrated in Fig. 7.

Based on how visually impaired people use these landmarks, we created geometric constraint diagrams to represent their interactions with these landmarks as follows.

1) *BEV:* BEVs help visually impaired people identify the beginning and end points of a crosswalk or stairs. They can detect a BEV with their blind canes or by stepping on it. A standard BEV slab is 400 $\times$ 400 mm and the number of slabs used depends on the width of the path. Geometrically, the BEV is represented by a rectangle with the length and width of the BEV and a point in the center of the BEV (black rectangle in Fig. 8). In map matching, the rectangle represents the matching area and the center point is the location of the BEV with the highest probability.
2) *Crosswalk:* A crosswalk is always limited by the BEVs at both ends. To ensure safety when crossing the road, the width of the crosswalk is also specified. Therefore, it is geometrically represented by a rectangle whose sides are of the width of the crosswalk and the other two sides the width of the road. The main axis of the crosswalk can be specified by the line which connects the center points of the BEVs on both sides as shown in Fig. 8. Map-matching algorithm will match the user's position on the main axis.
3) *Stairs:* Similar to the crosswalk, the stairs are also recognized by the BEV points at both ends. So it is a line connected by two nodes of the BEV node at the top and the BEV node at the bottom of the stairs. The difference from the crosswalk is that the width of the stairs does not need to increase because people cannot walk outside the stairs. During map matching, we match the position on the line.
4) *Wall* A visually impaired person sweeps the white cane to the left and right while walking so that they can detect the obstacles in a range of about 1.2 m on their path at the ground level [25]. A wall can then be used as a landmark, whose projection is represented as a line segment at a certain distance from the building edge on the pavement. The line segment is accompanied with two nodes at the endpoints as shown in Fig. 9. During map matching, we will assume that visually impaired people walking on this line.

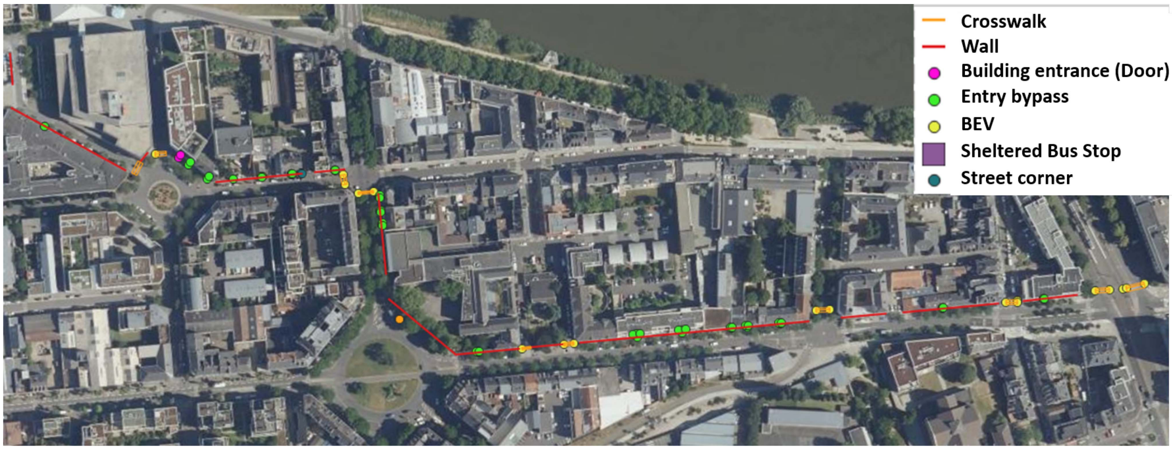


Fig. 6. Overview of schematic geometric constraints of itinerary 1.

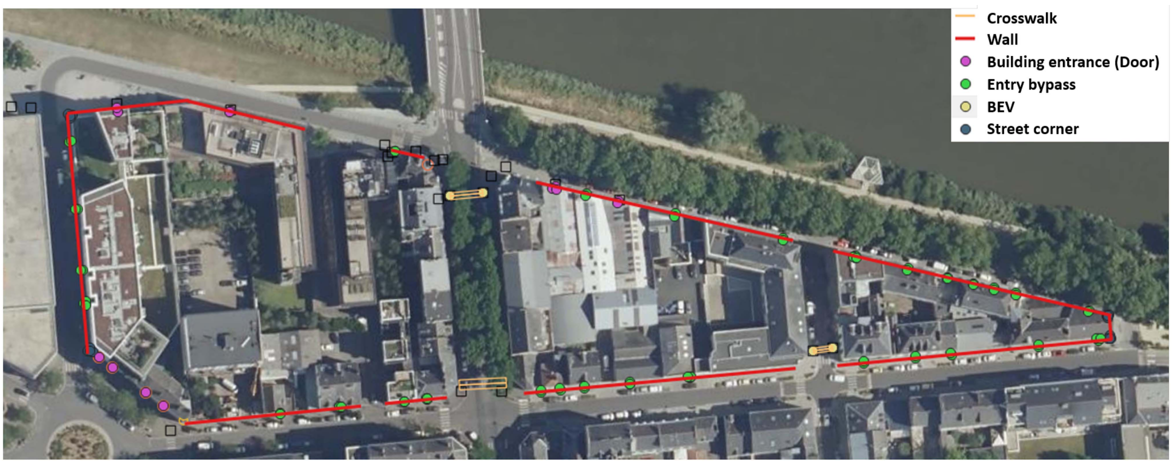


Fig. 7. Overview of schematic geometric constraints of itinerary 2.

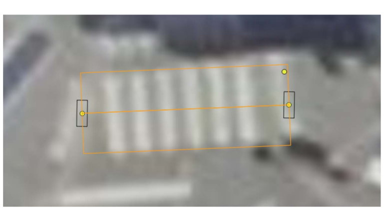


Fig. 8. Schematic geometric constraints of a crosswalk on the road.

Fig. 9. Geometric constraints schematic of wall on the road.

5) *Street corner:* Geometrically, a street corner can be represented as a point within a detection sector, with the intersection of two side walls' geometric constraints schematic serving as the sector's center and the detection range of a white cane defines the radius as shown in Fig. 10. During map matching, the position is matched to two sides of the sector, the vertex of the sector is the corner position.

6) *Building entrance (Door):* In geographical data, the entrance of a building are point object. When the trajectory passes through the door or entrance of a building, we represent the landmark geometrically as a point and a circle, where the position of the door is the center of the circle and the detection distance is the radius, and the point is the map-matching point as shown in Fig. 11.

7) *Entrance bypass:* If it is a door or a building entrance in the wall along which visually impaired people will walk, similar to the wall, it is represented geometrically as a point with a semicircle, with the projection point of the door on the wall's geometric constraints schematically as the center of the circle and the detection distance by a white cane as the radius as shown in Fig. 12.

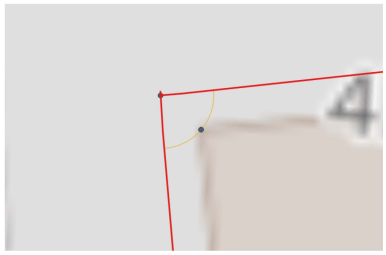


Fig. 10. Geometric constraints schematic of street corner.

Fig. 11. Schematic geometric constraints of a supermarket entrance.

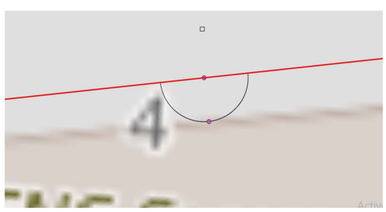


Fig. 12. Schematic geometric constraints of an entrance bypass.

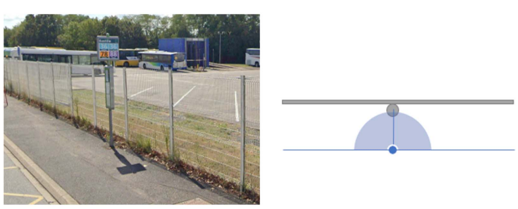


Fig. 13. Schematic geometric constraints of bus stop signs.

During map matching, the diameter of the semicircle gives the matching range, the center point gives the highest probability location of the door.

8) *Bus Stop Poles:* Due to the varying width of the sidewalks, some bus stops have shelters above while others only have bus stop signs. Those poles with bus stop signs only can be geometrically represented as a point with a semicircle as shown in Fig. 13, similar to the doors.

9) *Remote Sheltered Bus Stop:* When the sheltered bus stops are placed on the side near the driveway remote from the usual walking area of the sidewalk or along the walls, visually impaired people are prone to miss them with white canes. In this situation, they will generally need to turn around to find the bus stop when it is their target. We geometrically represent it as a polygon with the area of the bus shelter as illustrated in Fig. 14.

Fig. 14. Remote sheltered bus stop.

Fig. 15. Station with bus shelter for passing by.

During map matching, the polygon indicates the matching range, the center point is the highest probability location of the bus stop.

10) *Sheltered Bus Stop:* When a sheltered bus stop can be detected by visually impaired people passing by with a white cane, we geometrically depict it as a line segment corresponding to the length of the bus stop as shown in Fig. 15. During map matching, the interval of the line segment provides the scope of the bus stop, and the highest probability location of the bus stop is represented by the midpoint of the line segment.

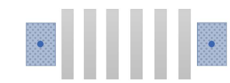
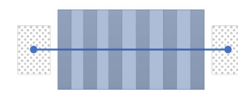
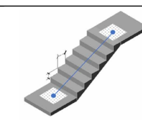
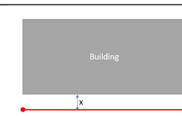
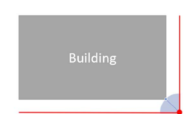
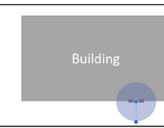
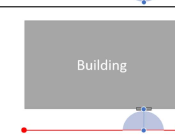
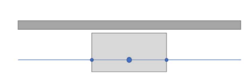
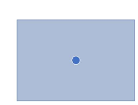
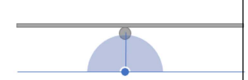
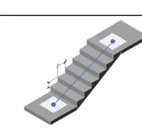
11) *Traffic lights:* Traffic lights can provide additional information for crosswalks, to let people know if they can cross, but traffic light detection does not provide specific location information. Visually impaired people use a remote control to trigger the audible traffic lights when they arrive at the crosswalk, and determine whether it is possible to cross the road through sound prompts. After analyzing the existing products in France, we obtained the detection distance is 5–20 m depending on the environment, so a traffic light can be represented as a point and a circle with the detection distance of the remote control as the radius.

12) *Mailbox:* In our study, we only consider mailboxes with bright yellow colors and large sizes on the street as landmarks; private mailboxes are not considered because they cannot be found in the map data. Visually impaired people who do not have complete loss of vision can perceive the color contrast of objects. Usually, visually impaired people identify mailboxes by the obvious visual contrast but not by tactile ones because it is difficult to distinguish from other obstacles by tactile recognition only. So, the mailbox can give information to visually impaired people, but cannot return the exact position of them by visual detection.

Based on these analyses, we divide landmarks into two categories: Waypoints and Reassurance Points.

1) Waypoints are perceptible through tactile interaction and serve as identifiable markers that help visually impaired people determine their location. Geometric constraints for waypoints indicate the appropriate area and location

TABLE I
DICTIONARY OF WAYPOINT LANDMARKS

Landmark	Features	Schematic
BEV	**Geometric Constraints**: A rectangle with the size of the BEV with a point in the center.	
	Map Matching: The rectangle sets the matching range and the center point has the highest probability.	
	Itinerary Handle: The center point.	
Crosswalk	**Geometric Constraints**: A rectangle with the size of the crosswalk, accompanied by the BEVs at each side with their centers connected through the rectangle with a segment.	
	Map Matching: Match on the segment.	
	Itinerary Handle: Center points of the BEVs.	
Stairs	**Geometric Constraints**: A line connected to the BEVs at the top and the bottom of the stairs.	
	Map Matching: Match on the line.	
	Itinerary Handle: Center points of the BEVs at both ends.	
Wall	**Geometric Constraints**: A line at a certain distance x ($x < 1.2$m) from the building edge with two endpoints and a length.	
	Map Matching: Matching on the line.	
	Itinerary Handle: The two endpoints of the line segment.	
Street corner	**Geometric Constraints**: A point on the intersection of the wall segments of the building sides with a quarter circle that touches the corner of the building.	
	Map Matching: Matching to the point.	
	Itinerary Handle: The intersection point.	
Building entrance (door)	**Geometric Constraints**: A circle with a radius as the detection distance and its center point on the door.	
	Map Matching: Match on the point.	
	Itinerary Handle: The point.	
Entrance Bypass	**Geometric Constraints**: A semicircle whose center point is the projection of the door point on the segment.	
	Map Matching: The diameter of the semicircle sets the matching range with its center being the most probable location.	
	Itinerary Handle: The center point.	
Sheltered Bus Stop	**Geometric Constraints**: A line segment corresponding to the length of the station with a point at its center.	
	Map Matching: Match on the segment with the highest probability on the center point.	
	Itinerary Handle: The center of the rectangle.	
Remote Sheltered Bus Stop	**Geometric Constraints**: A rectangle with the size of the platform and a point at its center.	
	Map Matching: Match on the segment with the highest probability on the center point.	
	Itinerary Handle: The center point.	
Bus Stop Pole	**Geometric Constraints**: A point with a semicircle touching the bus stop pole.	
	Map Matching: The semicircle sets the matching range with the center point having the maximum probability.	
	Itinerary Handle: The center point	
Escalator (indoor)	**Geometric Constraints**: A line connected to the BEVs at the top and the bottom of the escalator.	
	Map Matching: Match on the line.	
	Itinerary Handle: Center points of the BEVs at both ends.	
Elevator (indoor)	**Geometric Constraints**: A point representing the door of the elevator.	
	Map Matching: Match the point.	
	Itinerary Handle: The center point.	

with the highest probability that can be incorporated into the map-matching algorithm. The landmarks we studied include: BEV, crosswalk, stairs, wall, street corner, building entrance (door), bypass road, bus stop pole, remote sheltered bus stop, sheltered bus stop, escalator (indoor), and elevators (indoor).

2) Reassurance points, such as the traffic light and the mailbox, serve primarily to confirm to individuals that they are on the right path. They will have a different impact on our upcoming map-matching algorithms. They have the potential to play an important role in orientation applications by providing guidance information to visually impaired individuals to confirm that they are traveling their route as intended.

Based on the analysis of the two itineraries, we developed the dictionary in Table I. It summarizes the most commonly used landmarks for navigation aids targeting visually impaired people and the description of their geometric constraints as well as their schematic illustrations.

C. Discussion

We can compare our selection of landmarks with those in existing blind navigation aids. The landmarks used by Microsoft Soundscape and BlindSquare include a list of selected locations: man-made structures such as buildings, bridges, tunnels, and train stations; natural environments such as parks, rivers, and lakes; public spaces such as squares and plazas; landmarks such as restaurants, cafes, stores, museums, post offices, etc.; or streets and roads such as roads, alleys, sidewalks, crosswalks, intersections, and so on. These landmarks do not always correspond to the criteria that are of greatest importance and usefulness from the user's point of view. This issue is even more relevant for visually impaired people, as they have different travel strategies and perceptions. Our method identifies landmarks used by visually impaired people through interviews. Interviews can provide deeper insights into the real needs and preferences of visually impaired people. While these APPs focus on common landmarks such as buildings or street intersections, interviews can reveal less conventional but equally important landmarks. These can include specific sounds, tactile cues, or unique local features that are not normally marked on a map but are important to visually impaired people. Landmarks obtained through interviews are better matched to the real-world needs of visually impaired users. This holistic approach ensures that the tools and solutions developed better meet the real needs of users.

In future work, we will focus mainly on the tactile landmarks that can be detected, e.g.,, by the inertial wearable sensors data. We also define the detection range for each landmark. Our innovative method is expected to contribute to a deeper understanding of the way visually impaired people interact with and perceive landmarks by incorporating geometric constraints into the identification and interpretation of tactile landmarks. This is a crucial step toward the integration of landmarks into map-matching algorithms. We will build on previous research [26] to create a graph containing information about landmarks to represent all possible pedestrian motion. Using this graph annotated with landmark information, we will compute itineraries containing more landmarks, more suitable for visually impaired people. A particle filter for map matching based on this graph and landmark information is currently being developed.

Navigation applications rely on an accurate indoor and outdoor location system in conjunction with a digital map of the environment to function smoothly. Autonomous, accurate positioning both indoors and outdoors remains a challenge for pedestrian navigation. To mitigate accumulated positioning errors, the recognition of landmarks from different modalities is sought, as it can cope with less accurate navigation aids as long as the landmarks are roughly associated with different map pins geometrical shapes.

VI. Conclusion

In this work, we investigated the factors that influence the travel routes of visually impaired people and the characteristics of landmarks that are important to them. Using interviews with 12 visually impaired participants, we identified 90 commonly used landmarks that help them navigate. These landmarks were grouped by recognition methods, including tactile, visual, auditory, prior knowledge, smell, and sense, to illustrate the different navigation strategies used by the visually impaired. We then examined how these individuals use these landmarks to establish geometric relationships with other landmarks and divided them into two groups: 1) Waypoints and 2) Reassurance Points. Based on these studies, we created a comprehensive dictionary of landmarks and their geometric relationships to help visually impaired people navigate. Future studies will focus on using these spatial landmarks, including reassurance points, for map matching and path planning.

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