Universal Access in the Information Society
https://doi.org/10.1007/s10209-021-00843-x

REVIEW PAPER

Accessible wayfinding and navigation: a systematic mapping study

Catia Prandi[1] · Barbara Rita Barricelli[2] · Silvia Mirri[1] · Daniela Fogli[2]

Accepted: 31 August 2021

Abstract

Urban environments, university campuses, and public and private buildings often present architectural barriers that prevent people with disabilities and special needs to move freely and independently. This paper presents a systematic mapping study of the scientific literature proposing devices, and software applications aimed at fostering accessible wayfinding and navigation in indoor and outdoor environments. We selected 111 out of 806 papers published in the period 2009–2020, and we analyzed them according to different dimensions: at first, we surveyed which solutions have been proposed to address the considered problem; then, we analyzed the selected papers according to five dimensions: context of use, target users, hardware/software technologies, type of data sources, and user role in system design and evaluation. Our findings highlight trends and gaps related to these dimensions. The paper finally presents a reflection on challenges and open issues that must be taken into consideration for the design of future accessible places and of related technologies and applications aimed at facilitating wayfinding and navigation.

Keywords Architectural barrier · Indoor navigation · Outdoor navigation · Universal design · Urban accessibility · Wayfinding system

1 Introduction

Wayfinding and navigation technologies are strategic in improving the quality of life of people. A variety of devices and software applications are daily used by several persons to detect their position and provide them with useful information while moving across the urban environment and within buildings [106]. These technologies are becoming increasingly important for people with special needs, such as visually or mobility impaired users, to support them in obstacle avoidance and coping with architectural barriers. However, the same devices and software applications can represent a different form of barrier: if their user interface is not accessible or not suitable for assistive technologies, they fail in reaching the goal of providing persons with disabilities with a tool that could actually enforce their independent living [117]. Thus, current research on wayfinding and navigation technologies should consider both types of accessibility requirements: accessibility of the urban environments and buildings [51] and accessibility of the applications that provide information about it (e-accessibility) [102].

A wealth of research has been conducted, along the last decade, to study and design software and devices devoted to improve the quality of life of users with disability while moving across the urban environment, with the aim of shifting the smart mobility paradigm into a smart and accessible mobility [5, 118]. Scholars provided variegate approaches to accessible wayfinding and navigation, focused on different aspects, ranging from specific citizens' needs (i.e., blind users, wheelchair users [3, 16]), to different contexts of use (i.e., indoor or outdoor [20, 27]), to specific technologies (for instance to identify user's position [28]), to different data sources exploited (such as open data provided by municipalities or crowdsourced and crowdsensed data [31, 48]). In

✉ Silvia Mirri
silvia.mirri@unibo.it

Catia Prandi
catia.prandi2@unibo.it

Barbara Rita Barricelli
barbara.barricelli@unibs.it

Daniela Fogli
daniela.fogli@unibs.it

1 Department of Computer Science and Engineering, University of Bologna, Mura Anteo Zamboni, 7, 40124 Bologna, Italy

2 Department of Information Engineering, University of Brescia, Via Branze, 38, 25123 Brescia, Italy

Published online: 08 September 2021

spite of that, the presented approaches do not seem mature enough to be deployed in large-scale scenarios and in a pervasive fashion.

Among the several studies conducted on this field, only very few are devoted to survey research papers (for instance [34] and [140]) aimed at describing different approaches to support persons with different kinds of disabilities through systems for accessible wayfinding and navigation, to be used in different contexts and exploiting different kinds of technological solutions. While some investigations have been conducted with the aim of reviewing proposed technologies (such as those presented in [93] and in [111]), the users' points of view in terms of accessibility and usability are generally left out by those surveys. Hence, a systematic mapping study, analyzing and classifying the research works conducted on different dimensions characterizing this topic (including also the target users' needs and the roles played by the users in the design and evaluation phases of the proposed solutions), could bring a wider and more complete comprehension of the current state of the art.

In this paper, we present a systematic mapping study that aims at investigating the different proposed solutions in literature and identify the challenges that still need to be solved. To do so, the study aims at answering this Research Question (RQ): *Which devices and software applications for accessible wayfinding and navigation have been proposed in scientific literature?*

The final goal is to categorize and summarize the knowledge currently available in the literature about this topic, in order to identify gaps in current research for suggesting areas of investigation and for providing indications to novice research practitioners in this field. The adopted methodology is inspired to the work reported in [23, 89], and [54].

The rest of the paper is organized as follows. Section 2 presents related work, focusing on studies that illustrate similar literature analyses. Section 3 describes the methodology that has driven our study. Section 4 presents the results of the analysis of the selected papers. A discussion about the conducted analysis is presented in Sect. 5. Finally, Sect. 6 concludes the paper.

2 Related work

Considering city accessibility, with a focus on sidewalks and points of interest (restaurants, parking lots, etc.), Comai et al. [34] present a literature review and an analysis of the app market. They underline that literature work includes a variety of users' surveys and studies mostly targeted at users with mobility impairments; in addition, the apps available on the market usually focus on the accessibility of points of interest (POIs). The work of Comai et al. [34], however, examines a limited amount of literature and does not deepen the details of the proposals; in addition it can be considered too dated now.

Indoor navigation for blind and visually impaired people is considered by Wise et al. [140] who propose a set of criteria for evaluating navigation devices. Three applications are analyzed and compared taking the previously defined criteria into account. The work is very preliminary: it proposes an initial basis for further exploration into indoor navigation systems for blind and visually impaired users. More recently, Silva and Wimalaratne [127] have presented a survey of indoor navigation and positioning aids for the same target users. They present an interesting taxonomy of assistive technologies for traveling and compare the different sensor technologies adopted for positioning and navigation, with a specific focus on indoor positioning and sensor fusion.

Obstacle avoidance in indoor and outdoor navigation is considered in [38], where 22 portable and wearable solutions for blind and visually impaired people are surveyed, by underlining their advantages and disadvantages, with a specific focus on the feedback provided to the user (e.g., audio, tactile). In the paper, electronic devices are classified as electronic travel aids (ETAs), electronic orientation aids (EOAs), and position location devices (PLDs). This classification is adopted in a more recent and extended survey [50]; here, further dimensions (e.g., coverage, time, range) are used for an in-depth analysis of several electronic devices for visually-impaired people. The paper [80] classifies walking assistants for visually-impaired people in sensor-based walking assistants, computer vision-based walking assistants, and smartphone-based walking assistants. These are described and evaluated in the paper, on the basis of performance features concerning capturing device, feedback, coverage area, weight, and cost. A systematic review of outdoor pedestrian navigation systems for visually impaired people reported in literature from 2015 to 2020 is presented in [49]; even though the system analysis is very accurate leading to an interesting hierarchical taxonomy, the scope of this review is limited to one type of users moving in urban environments only. A systematic review of solutions for blind and visually-impaired people is presented in [87]: 191 most relevant articles published between 2011 and 2020 have been selected from different digital libraries and analyzed according to different dimensions, such as approaches and technologies proposed for navigation, hardware components used for obstacle avoidance, and adopted performance metrics. This is the most recent and extended review available in literature, but it pays attention only to visual disabilities.

Camenar et al. [25] have analyzed papers discussing urban mobility issues faced by people with physical disabilities in cities of developing countries. They considered different characteristics to compare the applications proposed in six papers, such as the availability of code, the use of open data, the type of device needed to run the application, how the collection of accessibility information took place, the involvement of the population in the application development and advertising, the quality of the problem verification, and the methods employed for route calculation. We have taken these characteristics into account in the definition of our analysis dimensions.

An analysis of the works dealing with indoor and outdoor navigation for wheelchair users, published in the literature over a period of eighteen years, is reported in [41]. This work presents a tabular mapping of the systems described in the retrieved papers with respect to a set of features (e.g., outdoor navigation, indoor navigation, information visualization, etc.) and adopted technologies (such as, GPS, beacons, fiducial markers). It demonstrates the scarcity of research that addresses the problem of supporting wheelchair users to navigate in complex indoor environments through mobile augmented reality; given this result, the authors of [41] propose their architecture and mobile application filling the identified research gap. Even though the proposed mapping is interesting, the analysis focuses only on wheelchair users. The review presented in [111] also focuses on solutions aimed at supporting people with mobility impairments; this paper compares the technological components employed in different system architectures based on crowdsensing and crowdsourcing and proposes a novel architecture to overcome the main limitations of the analyzed solutions. The review selected only six systems for the comparison, and therefore does not provide an extended overview of all existing solutions in the literature.

A more in-depth work is presented in [93]; the authors carried out a systematic literature review on digital libraries with the search string "accessible maps". Paper search found more than 500 papers, which were then filtered down to arrive at a set of 43 papers to be analyzed. The analysis mainly focused on the activities reported in the papers for the creation of accessible maps, such as crowdsourcing, open data, tagging, and automatic capturing of data; indeed, the authors explicitly declared that they were interested in the use of collective intelligence to improve the quality and quantity of data necessary for the creation of accessible maps. The work in [139] surveyed approaches for localization and navigation in indoor environments based on sensors embedded in users' smartphones; these approaches allow designing infrastructure-independent solutions, which may guarantee universal availability and avoid outage and disruption problems. However, this paper does not consider the accessibility aspect in its analysis. Even though these two last surveys (i.e., [93] and [139]) have been very well conducted and provide interesting results, both of them have a narrow scope, by considering only some specific aspects of the proposed solutions. We considered the data source dimension in our study, as well as the different types of technologies employed in indoor and outdoor contexts, but we also adopted further analysis dimensions.

The literature review described in [70] selected and analyzed 15 papers that present state-of-the-art solutions for wayfinding in emergency situations based on mobile applications and sensors embedded in the smartphone or in the environment; both actual disabilities and situational disabilities (e.g., impaired vision from smoke or impaired hearing from alarms) are considered in these papers, and thus, universal design is taken as a framework to examine the various solutions. Unfortunately, none of the analyzed papers takes a universal design perspective. In our work, we deepen this aspect to understand if this is an actual limitation of the approaches proposed in the scientific literature.

As it emerged from the above discussion, very few studies aimed at surveying research papers that describe approaches to support people with different types of impairments through systems for accessible wayfinding and navigation, to be used in different contexts and employing different types of technologies. In addition, these surveys are focused on the proposed technological solutions, while the perspective of end users in terms of e-accessibility is often neglected. Therefore, there is space for a systematic mapping study that presents a different analysis and classification of the research carried out so far in the field, by identifying the main strengths and weaknesses of the proposed solutions.

3 Methodology

This study has been carried out following the guidelines for systematic mapping studies proposed in [23] and [89]. A systematic mapping study provides an objective procedure for identifying and classifying the papers published in a given research field. Therefore, after defining the research question of the study and the search process, exclusion criteria are defined for data selection. Selected papers are then analyzed to answer the research question.

The goal of this paper is to describe the characteristics and evolution of systems for accessible wayfinding and navigation that have been proposed in literature, in order to underline their most interesting features and weaknesses to be considered in future development of similar systems.

3.1 Research question

The general RQ for this study, introduced in Sect. 1, is: *Which devices and software applications for accessible wayfinding and navigation have been proposed in scientific literature?*

We defined five dimensions to deeply investigate the proposed devices and software applications:

- **(D1)** *Context of use*: this dimension refers to the context of use of the proposed solutions, considering indoor, outdoor, and indoor/outdoor contexts;
- **(D2)** *Target users*: this dimension takes into account the different users' characteristics and related needs, also in terms of information support required for wayfinding and navigation;
- **(D3)** *Technologies*: this dimension analyses the hardware and software technologies adopted to implement the proposed solutions;
- **(D4)** *Data sources*: this dimension reports about the exploited datasets, i.e., open data, official data, data provided by users through crowdsourcing mechanisms, and data gathered by sensors (crowdsensing);
- **(D5)** *User role*: this dimension considers the role end users have played in the design and evaluation of the proposed solutions.

3.2 Paper search process

The process of paper search has been carried out on March 9, 2021, with an automatic search in the Scopus citation database[1] using a search string applied to title, abstract and keywords of the publications. To compose the search string, we selected the main dimensions we would like to investigate: indeed, we were searching for papers that presented *applications* about *accessible wayfinding* and/or *navigation* in a given *place* (e.g., city or indoor). Therefore, we identified the following main and related concepts:

- main concepts: *accessible; city, indoor; wayfinding, navigation; application;*
- related concepts: *accessibility; urban, campus, university; mobility; system, map.*

Consequently, the following search string was defined:

(accessible OR accessibility) AND (city OR indoor OR urban OR campus OR university) AND (wayfinding OR navigation OR mobility) AND (application OR system OR map)

In addition, to narrow the search scope, we limited the query to the Scopus subject areas "Computer Science" and "Engineering". Finally, we set the publication time range between years 2009 and 2020.

At the end, the automatic search provided 806 results. Then, as described in Sect. 3.3, we selected a subset of those papers (111) by applying two sets of exclusion criteria. We then analyzed in detail the selected papers, according to our RQ and the five dimensions.

3.3 Paper selection

All of the 806 papers have been considered to decide which to include in the study and which were to be excluded. Paper selection consisted of two stages. In the first stage, we applied a set of exclusion criteria by analyzing the title, abstract, and type of each paper. We excluded the papers that met at least one of the following criteria:

- Off-topic papers;
- Duplicates;
- Introductory papers to conference and workshop proceedings;
- Papers not written in English.

At the end of this first stage, we excluded 609 papers; thus, 197 papers out of 806 were still under consideration. In the second stage, we examined the remaining 197 papers and we applied a second set of exclusion criteria:

- Papers presenting a preliminary work or an extended abstract;
- Papers presenting only a requirements analysis and not a working system;
- Papers presenting systems for data collection and storage, rather than for wayfinding and navigation;
- Papers presenting a conceptual model (e.g., an accessibility ontology), a user study, or a list of guidelines;
- Papers presenting a survey, a review or a comparative study (these papers have, however, been taken into consideration in the Related Work section).

After the second stage, 111 out of 197 papers were selected.

Figure 1 shows the distribution of the 111 selected papers according to the publication year.

We also analyzed the selected papers' keywords (out of the 111 papers, 97 have keywords). The average number of keywords per paper is 4.53 (standard deviation 2.34, median 5). The most frequent keywords are *Visual impaired people* (25 occurrences), *Navigation* (20 occurrences), *Indoor navigation* (14 occurrences), *Mobile application* (12 occurrences), *Assistive technology* (11 occurrences), *Impaired people* (9 occurrences), *Blind people* (9 occurrences), *Crowdsourcing* (8 occurrences), *Beacons* (7 occurrences), and *Wayfinding*, *GIS*, and *Wheelchair* (6 occurrences).

Table 1 reports the references of the selected papers classified according to their publication year and venue - journal publication, book chapter, or conference proceedings.

Figure 2 summarizes the search strategy and the selection carried out at the different stages of evaluation.

All papers included in the study have been downloaded from the respective digital libraries and uploaded on a Mendeley private group. The papers have been assigned to two

[1] https://www.scopus.com/

Fig. 1 The 111 selected papers grouped by publication year

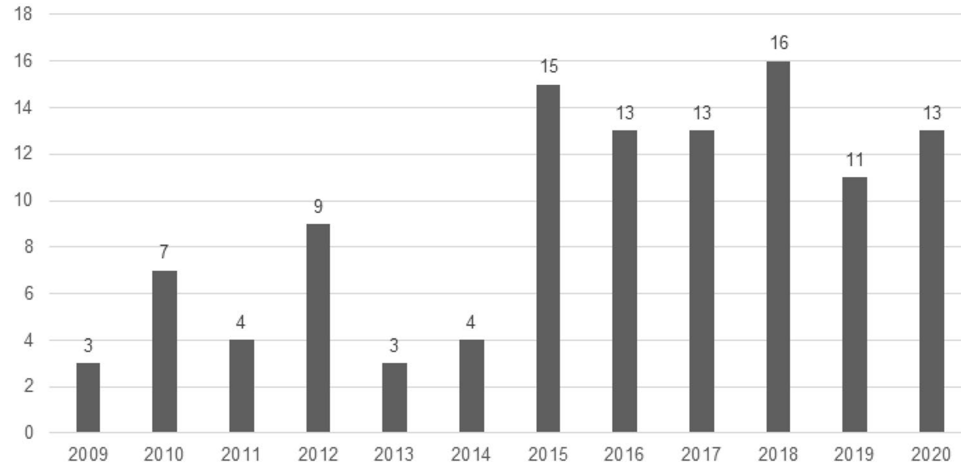
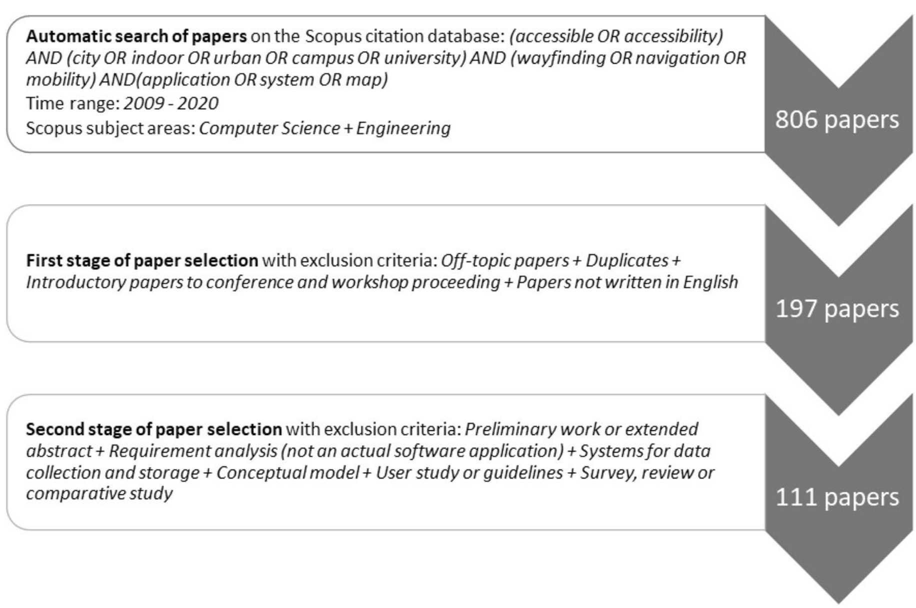


Table 1 Papers included in the study

Year	Journal	Book chapter	Conference
2009	–	–	[8, 11, 40]
2010	[1, 22, 28]	–	[52, 63, 99, 104]
2011	–	–	[66, 85, 138, 141]
2012	[53, 67]	–	[4, 64, 77, 96, 124, 130, 133]
2013	–	–	[5, 95, 123]
2014	[84]	–	[65, 102, 105]
2015	[20, 68, 125]	–	[10, 17, 24, 55, 61, 78, 79, 82, 83, 92, 108, 114]
2016	[7, 41, 76, 103]	[19]	[6, 32, 73, 97, 100, 101, 110, 122]
2017	[119, 121, 143]	[90, 126]	[9, 33, 72, 74, 88, 115, 116, 129]
2018	[15, 16, 58, 98]	–	[3, 12, 14, 31, 42, 44, 57, 71, 81, 128, 134, 142]
2019	[107]	–	[2, 13, 21, 29, 30, 36, 37, 47, 48, 137]
2020	[59, 75]	–	[27, 43, 46, 62, 69, 86, 91, 109, 112, 120, 135]

Fig. 2 The flow of search and selection of papers to be included in the study



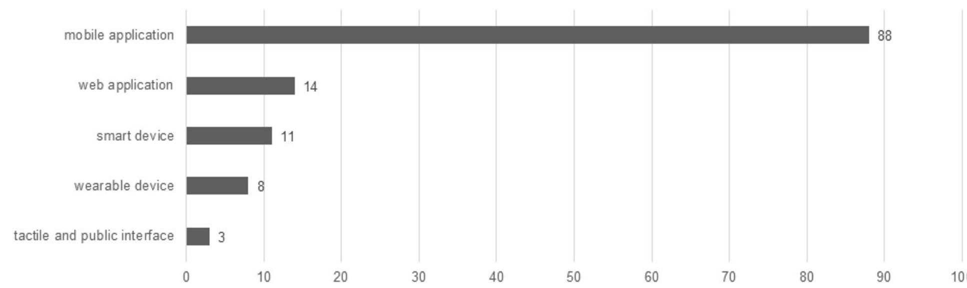


Fig. 3 Distribution of the analyzed papers according to the type of application/device

of the authors (half each), who first read and then classified them using a shared spreadsheet. The other two authors cross-checked the classification of the papers. All doubts and disagreements have been discussed by at least two authors.

4 Results

This section aims at answering our main RQ: *Which devices and software applications for accessible wayfinding and navigation have been proposed in scientific literature?* Section 4.1 classifies and summarizes the different solutions proposed in the selected papers.

Then, to deepen the characteristics and use of the above solutions, we analyzed them by considering the dimensions presented in Sect. 3.1: D1) Context of use, D2) Target users, D3) Technologies, D4) Data sources, and D5) User role. Paper analysis according to these five dimensions is presented in Sects. 4.2–4.6.

Finally, in Sect. 4.7, the most interesting mapping results are reported, in order to analyze how the selected applications and their dimensions are related one another.

4.1 Devices and software applications for accessible wayfinding and navigation

This section provides the answers to our main RQ by illustrating the solutions proposed in the literature to support users in accessible wayfinding and navigation. We classified the analyzed devices and software applications as follows:

- *mobile applications*: these include native applications for smartphones, personal digital assistants (PDAs), and special tablets;
- *web applications*: these applications are mainly oriented to support wayfinding and identify accessibility information of places and roads;
- *wearable devices*: these devices include smart glasses, smart watches and other smart objects that the user may wear to obtain real-time information about the environment and instructions for moving inside it;
- *smart devices*: these are physical objects used by people with disabilities, such as white canes and wheelchairs, which are endowed with sensors, actuators, and communication features to detect obstacles and find the most suitable routes within an environment;
- *tactile and public interfaces*: this category includes solutions that provide citizens with accessibility information in public spaces.

Figure 3 shows the distribution of papers by considering the above mentioned classification. The total number of proposed solutions is 124 (more than the number of selected papers, that is 111), since some papers propose more than one application: for instance, in [76] the authors propose a smart white cane coupled with a mobile application, or in [59] the authors provide end users with a mobile application and experts with a web application to set up the system and populate the database. As expected, the majority of papers propose a mobile application, usually for only one platform, Android or iOS, rarely for both. There are then a limited number of papers that propose a web application, to be used on different types of devices, but with fewer functionalities than native mobile applications. Finally, an interesting number of papers (22 out of 111) experimented advanced solutions for wearable devices, smart devices, and tactile and public systems.

Figure 4 provides an overview of the selected papers classified according the type of device/application they propose. The adopted diagram allows to also obtain an account of papers describing more than one solution component.

4.1.1 Mobile applications

Most of the proposed mobile applications described in the surveyed papers are smartphone-oriented (85); 3 works (developed a few years ago) present mobile applications for PDAs or special tablets [1, 28, 123].

Considering the smartphone operating system, in the majority of the cases, the applications are developed to run on Android, taking advantages of the high diffusion and the affordability of Android devices (e.g., [16, 29, 88, 119]). The Apple iOS architecture seems the best choice for applications focused on blind and visually impaired users, thanks to the advanced built-in accessibility features provided by Apple devices (e.g., [6, 13, 57, 71, 75]). To solve the issues

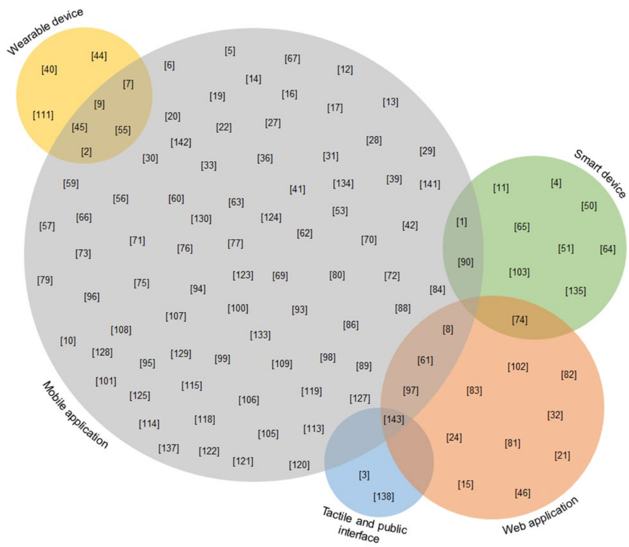


Fig. 4 Overview of paper distribution among the identified application/device categories (for the sake of readability, the size of the sets is not proportional to their numerosity)

about architecture compatibility, a few studies illustrate applications for both the operating systems, exploiting also hybrid solutions (e.g., [12, 44, 100]).

When the mobile application is targeted to blind and visually impaired people, different strategies are proposed to guarantee e-accessibility, including speech recognition (speech-to-text) (e.g., [88]), synthesis (text-to-speech) (i.e., [133]), verbal cues and simplified touch interfaces (e.g., [5]). Gintner et al. describe a conversational UI within a mobile application, which provides the user with the instructions about the localization process using VoiceOver [71], the built-in text-to-speech engine of Apple iOS. VoiceOver is also adopted in the applications described in [13, 69, 73]. In the Android platform, Google's speech recognition and speech synthesis application programming interfaces have been utilized in [90]. Android TalkBack is exploited in the most recent solutions, such as SafeExit4All [30], which supports visually impaired people (as well as the general population) to independently find a safe exit in case of emergency.

To enhance indoor navigation for wheelchair users, de Oliveira et al. [41] presented an Android application that exploits Augmented Reality (AR): the app is capable to find the best route for wheelchair indoor navigation (taking stairs and other obstacles into account), allowing the visualization of virtual directional arrows in the smartphone display. Moreover, this solution also incorporates touch and voice commands to interact with the application [41]. AR has been also investigated in a recent study that presents an app built on ARKit (Apple's augmented reality platform). This app provides turn-by-turn assistance for indoor navigation using real-time localization obtained by exploiting 2D video frames captured by the device camera, and following the movement of detected visual feature points, estimating their position in the 3D space.

4.1.2 Web applications

The web applications presented in [92, 99, 143] are conceived as additional tools, with respect to mobile applications, to obtain information about accessible wayfinding and navigation. The works in [8, 16, 53], instead, present original web-based solutions that deal with GIS (Geographical Information System) data and applications.

A social network where users can share information about the level of accessibility has been proposed in [63]. A similar approach is described in [85], where a web application allows users to report information about the accessibility of city facilities (such as restaurants). In [32], the authors present a web application, designed following a mobile-first approach, so as to be compatible with both Android and iOS devices, as well as with desktop environments.

An interactive web mapping service, called PAM (Personalized Accessible MAP) and presenting the map of the accessible sidewalk network of the University of Pittsburgh's main campus, has been introduced in [83, 84]. Through its visualization component it is able to communicate the accessibility of travelling environments to people with disabilities, urban planners, and software developers.

AccessMap [21] is able to provide information about route accessibility according to the user's profile and it is widely used in several towns in the US. It is not properly a navigator, but a website that highlights routes with different colors on the basis of their accessibility.

In the research reported in [76], the authors provide a web interface to visualize the collected tracking information, while the actual device used in mobility is a smart cane.

4.1.3 Wearable devices

In [7], the use of Google Glass, coupled with QR codes mapping information about POIs, has been investigated to assist visually impaired users. Smart glasses are also exploited in [2]: this paper proposes the ARSAWP (Augmented Reality System for the Assistance of Wheelchair People) system, which allows wheelchair users wearing smart glasses to select a destination, obtain information about its accessibility, receive indications to reach the desired destination, and be notified of obstacles detected during navigation that may lead to redirection on an emergency route.

An application for smart watches has been implemented in [57]. The idea is that a blind person can use an iPhone app, controllable through an Apple Watch, to record a path as a sequence of turns and step counts between turns. If the user wants to backtrack the same path, the system can provide assistance by tracking the user's location in the recorded path, and producing directional information in speech form about the next turns and step counts to follow [57].

A wearable visual aid able to accept speech commands by visually impaired people and provide them with audio instructions to reach a required object is described in [42]. This solution exploits a Raspberry PI with a universal headphone jack for audio output, a USB port through which a microphone can be connected to enable speech input, and a camera module to take videos and images of the surrounding, thus allowing object detection and signboard recognition.

The wearable device proposed in [46] integrates different devices and sensors, including a camera to capture the images of the surrounding environment, an ultrasonic sensor to provide information about the detected obstacles, and a heart rate sensor to determine if a message must be sent to the user's caregiver along her/his location. The device is able to perform live tracking of visually impaired people and provide them with assistance to move anywhere.

Bluetooth headsets enriched with a commercial voice assistant (Amazon Alexa) have been experimented in [47]. This solution is specifically designed for museum exploration: natural language interaction is implemented to obtain indoor navigation information, as well as descriptions about objects and gallery spaces encountered during museum exploration.

4.1.4 Smart devices

Different types of smart devices, able to exchange information with the deployed infrastructure, have been proposed in the surveyed papers. They include smart wheelchairs [1, 66, 105, 135], smart canes enhanced with RFID (Radio-frequency identification) readers [52], and haptic sensors to detect obstacles above the waistline [67, 112].

Mancini et al. investigated the usage of a modular sensor box that exploits the benefits of ROS (Robot Operating System) in integrating the different sensors installed according to the selected operational scenario, i.e., able to detect and analyze obstacles in real-time when the impaired user is following the planned path. This sensor box can be embedded in a white cane or in a wheelchair [92], and provide information to a smartphone application that performs route planning.

In [4, 53], the authors designed ad-hoc devices able to provide text-to-speech, a 4-button command-pad, and vibratory output.

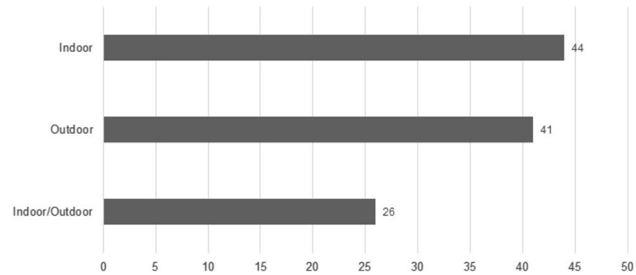


Fig. 5 Distribution of the analyzed papers along the context dimensions: Indoor, Outdoor, and both

4.1.5 Tactile and public interfaces

In [3], tactile elements in the bus stop, as well as a braille guide, are employed to provide information about the public transportation system. In the system described in [143], the users are able to acquire accessibility information about POIs while interacting with tactile street maps on pin-matrix displays.

A touch screen public display (i.e., a kiosk) has been experimented by Wen et al. to allow users to download the mobile application and the maps of the area through Bluetooth or USB connection [138]. To make the kiosk accessible to blind users, NVDA, an open-source screen reader for Windows, is adopted, and alternative texts for images are used.

4.2 Context of use

All selected papers were then analyzed by considering dimension D1, the context of use of the solutions they propose. We identified the following contexts:

- *Indoor*: this category includes papers proposing solutions to be used inside buildings, such as houses, hospitals, and malls. These papers address problems related to user localization, to generate paths inside buildings that may avoid stairs, and/or to provide paths to points of interests, like toilets, meeting rooms, and exits;
- *Outdoor*: papers proposing solutions for this context of use mainly consider path findings and navigation inside cities or university campuses. Different kinds of paths and information are identified, beyond pedestrian ones, such as bus routes, private car routes, or inter-modal transportation;
- *Indoor and outdoor*: finally, there are papers addressing the more complex problem of supporting both indoor and outdoor navigation, by integrating different localization technologies, types of maps, and path finding algorithms.

Figure 5 shows the distribution of papers along the three context types. As one may notice, out of 111 papers, 44 (39.6%) consider the indoor context of use, 41 (36.9%) the outdoor context, and only 26 (23.4%) address the problem of both indoor and outdoor accessible wayfinding and navigation.

4.2.1 Indoor

Indoor wayfinding and navigation should be facilitated for wheelchair users, blind people, or simply those who are new in an environment (like a big hospital, an airport, or a train station). The work in [104] describes one of the first projects aiming at creating a mobile application for indoor wayfinding, which helps people easily reach specific locations within a hospital by taking into account accessibility needs of different people; in this way, a wheelchair user might be directed on a route that include elevators or ramps rather than stairs, while blind users might be directed via audio instructions.

A critical problem in indoor navigation is the accuracy of *user localization*, which cannot exploit the GPS technology available in most of mobile devices, but must rely on other technologies that are usually tuned and tested specifically for a project. The article by Chang and Wang [28] presents an approach to localization based on wireless sensor networks with Bluetooth Low Energy (BLE) beacons placed at decision points (doorways, corners, room interiors, intersections of hallways) and proposes an ambient intelligence system to provide context-specific navigation assistance. Even though the system exploits mobile technologies provided at that time (a PDA with limitations in the graphical interface and interaction possibilities), it represents one of the first attempts addressing indoor navigation problems of users with different disabilities. Almost ten years later, the work by Murata et al. [107] experimented the use of beacons and smartphone-based localization to help blind people navigate in complex indoor environments, such as shopping malls.

As explained in [1][125], indoor navigation can be classified as *local navigation* or *global navigation*: the former indicates moving around in a space to identify walking paths and avoid obstacles, as in the case of blind people using a white cane to explore the surrounding environment; the latter stands for navigation in large buildings to reach specific locations. Different kinds of technologies are proposed to address these two types of navigation. As to local navigation, in WizMap [73] the user may take a photo of the environment with her/his smartphone and obtain information about nearby POIs. Computer Vision is exploited also in the wearable visual aid described in [42], which allows visually impaired users to detect objects and sign boards around them. PERCEPT-II is instead a system supporting global navigation in complex buildings (e.g., university buildings); it exploits Near Field Communication (NFC) tags for landmark identification and generation of navigation instructions [65]. Global navigation is also implemented in [114] and [79]: both works use QR codes to localize the user and generate paths to desired destinations.

Further approaches to user localization and navigation in indoor environments are discussed in Sect. 4.4.

4.2.2 Outdoor

Surveyed papers addressing outdoor accessibility have different scopes that span from just knowing the level of accessibility of an urban place, to obtaining information about specific places (e.g., parking lots for disabled people), until supporting user navigation in open spaces.

In 2010, Galan-Marti et al. [63] developed a social network, called Vadeo, to help users share information about the physical barriers and POIs in their neighborhood; a mobile application was then able to identify the user location through the GPS and show it along with the nearby obstacles. Detecting obstacles in outdoor environments is an important problem for blind people who desire to move autonomously; to cope with it, in [67] a smart white cane is proposed, which provides the user with haptic feedback. SIMON, the mobile application proposed in [55], helps users find parking solutions.

Most of the surveyed papers considering outdoor accessibility are focused on solutions and algorithms for generating accessible paths. For instance, the MEP (Maps for Easy Paths) project [17][19][33] exploits, for path generation, the traces collected by the smartphones of different users (with different disabilities) and integrated through the MEP fusion engine. The work by Balata et al. [15] aimed at generating landmark-enhanced itineraries, that is, itineraries including information about sidewalks, railings, crossings, etc., to improve safety and efficiency.

Another aspect that allows characterizing papers focused on outdoor accessibility is the area they considered: we may distinguish between works addressing city accessibility, papers that propose solutions to make a university campus accessible, and papers specifically oriented to the public bus network. The whole city is taken into consideration in [98], where a platform based on microservices and open data for the development of scalable and multi-modal mobility services is presented. Karimi et al. [84] present a wayfinding service that supports trip planning by university students with and without disabilities; it has been applied and experimented in the University of Pittsburgh's main campus, and provides both pedestrian paths and information about nearest shuttle stops. As to public transportation, [24] presents an approach to supporting wheelchair users to use public buses in the city of Madrid.

4.2.3 Indoor and outdoor

Dealing with both indoor and outdoor accessibility means implementing different techniques for localization and navigation, as well as managing different types of maps and data. System architectures for addressing the various issues characterizing indoor and outdoor localization/navigation thus become more complex, such as that of the e-Adept project [40] in the city of Stockholm. In e-Adept architecture, the functionalities are implemented on the server, interact with external services (e.g., public transport, taxi service), and apply various algorithms for localization and navigation (depending on the context); in addition, since indoor- and outdoor-related data are stored in different databases, they must be properly integrated and used.

Indoor–outdoor intermodal navigation is considered in [15]; in this case, the problem is providing navigation instructions that guide the user in the transitions between indoor and outdoor environments and in the usage of public transportation. Similarly, CityGuide [29] is a system specifically designed to cope with indoor–outdoor intermodal navigation problems; it leverages indoor wayfinding solutions in conjunction with GPS signals, in order to provide users with turn-by-turn shortest route directions from an indoor location to an outdoor location.

Most of the surveyed papers that present approaches to supporting indoor–outdoor navigation experimented their solution in university campuses. The paper [53] presents SmartVision, a system that allows blind users to navigate in the University of Trás-os-Montes and Alto Douro campus in Portugal, by providing information about obstacles and POIs like zebra-crossings, building entrances, etc. AlmaWhere [44] combines navigation support for disabled people with information about cultural heritage encountered in ancient buildings belonging to the University of Bologna, Italy, thus creating an accessible tourist guide. Almawhere is based on beacons, which are regarded as a flexible means to provide a rich and invisible context-aware digital signage that can be used in different situations and buildings. Similarly, Yang et al. [141] propose TP3, a mobile location-aware system targeted at visually impaired people to visit unfamiliar environments and gain spatial awareness thanks to enhanced environment legibility, surrounding environment exploration, and serendipitous discovery. Particularly, this work addresses the problem of fostering spatial awareness in different types of buildings: to this aim, TP3 is not conceived as a turn-by-turn direction system but as a mixture of navigation modes corresponding to different modules: (1) Automatic Notification, to obtain automatic notifications of POIs; (2) Nearby Locations, to receive indications about distance from target locations; and (3) Directional Finder, which offers directional finding features.

4.3 Target users

A further analysis we performed on the selected papers aims at investigating dimension D2: the different target users' characteristics and related information support required for wayfinding and navigation. Most of the papers included in the study propose solutions to help people with a specific kind of disability. There are, however, also papers that address the problem according to a Universal Design (UD) approach [132], thus proposing solutions that can be customized to different user profiles and that we regard as solutions for all users. Therefore, we classified the papers according to the following users' characteristics:

- *Visually impaired*: this category includes both blind and low-vision people;
- *Mobility impaired*: this category refers to people with physical disabilities, including wheelchair users;
- *Other kinds of impairments*: in this category we collect those few papers addressing people's cognitive problems, such as dementia or autism, one considering people with hearing impairments, and papers that address the needs of users with different disabilities, that is, visual or cognitive impairments, and visual or mobility impairments;
- *All users*: the papers in this category aim at designing solutions for all users, including non-disabled people, elderly people, and people with the disabilities mentioned above.

Figure 6 shows the distribution of papers according to this classification. As one may notice, out of 111 paper, 65 (58.6%) propose solutions for visually impaired people; among them, there are 53 papers where visual impairment is the only characteristic taken into consideration, 10 papers that consider both visually and mobility impaired users, and 2 papers addressing the problems of visually and cognitive impaired people. Then, there are 35 papers out of 111 (31.5%) proposing solutions for mobility impaired people, including 25 focused on mobility impaired users only, and 10 that consider both blind and mobility impaired users. There is 1 paper focused on cognitive impairments only, and 1 on hearing impairments. Finally, among the 111 papers included in the study, 19 (17.1%) propose solutions for different user profiles, both with or without impairments.

4.3.1 Users with visual impairments

Visually impaired people can be supported by novel technologies in indoor and outdoor pedestrian paths, with speech information that describe them the routes, the obstacles, and the points of interest. iCampus [22] is one of the first projects aimed at creating an ambient intelligence environment able to improve the mobility of blind and low-vision

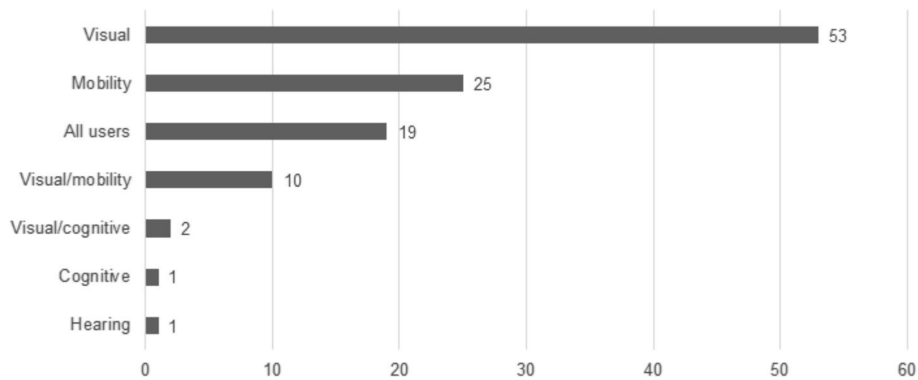


Fig. 6 Surveyed papers grouped by addressed kind of disability

students within a university campus. A student may download a guide, which is a software agent for mobile phones able to help proactively the student find places, events, and friends within the campus; the screen reader reads to her/him the information visualized on the screen; the user may also ask the system to guide her/him to a specific destination along a pedestrian path. NavCog [6] has similar goals, but provides a more up-to-date solution based on smartphone technology, BLE beacons, artificial intelligence algorithms, and a simplified touch interface. NavCog also encompasses an authoring tool to prepare the maps used in the system.

Public transportation poses further hurdles to low-vision and blind people: identifying and recognizing the correct bus line and bus stop are fundamental for independent mobility in a city, as well as for obtaining information about bus location and route. Article [58] presents a system that helps blind people know which bus line to take, when its departure is, and where to board it; while inside a bus, passengers may receive information about the progress of the bus along the foreseen route. Similarly, paper [3] addresses the accessibility of public transportation for visual impaired people; however, it does not require users to hold a smartphone, but proposes two devices: the former must be anchored to a bus stop, to provide audiovisual information about bus routes; the latter, on board the bus, to provide information about bus location on its route.

Visually impaired and blind older adults are considered in [126]; this work proposes an assistive system aimed at supporting navigation and personalized services within residential facilities. The system comprises a cloud-based repository and web-based services to allow facility staff members to carry out appropriate data management, a smartphone client for older adults providing a multi-modal interface, and localization hardware constituted of beacon devices.

Service personalization is the standpoint taken by recent papers that propose solutions to enrich the experience of blind people visiting museums [13, 47]: they provide not only turn-by-turn navigation instructions inside the museum, but also a novel type of interaction with its exhibitions, by means of continuous user tracking and audio content provided in front of each artwork.

4.3.2 Users with mobility impairments

Most of the surveyed papers that focused on mobility impaired people propose solutions for wheelchair users. Among them, [11] presents an ambient assisted route planner for intelligent wheelchairs. The work by Montella et al. [105] describes the Smart Wheelchair System, which is able to autonomously navigate in outdoor environments thanks to 3D perception sensors for detecting ground planes, obstacles, and landmarks. Recently, a similar approach has been investigated in [135], where an intelligent wheelchair, endowed with a variety of sensors and motion controllers for path planning and object grabbing, is presented.

Other papers paying attention to wheelchair users propose software applications for visualizing paths that are suitable to wheelchairs. In [16], a sidewalk-based model is specified to satisfy the requirements of a wheelchair route planning service; characteristics of sidewalks are very important for wheelchair users because they may present different accessibility conditions (e.g., inclinations, curb ramps, path width). A prototype of an Android mobile application is then proposed, which calculates wheelchair routes and displays them according to their accessibility characteristics; it also allows citizens to report accessibility issues to the department of urban planning.

Among the selected papers, solutions aimed at supporting people with reduced mobility (including elderly people) in using public transportation or following multimodal paths are proposed. The paper by Melis et al. [97] presents a microservice-based platform that allows orchestrating smart mobility applications; one of them helps users find multimodal paths tailored to their characteristics and preferences about street lights, crossing facilities, stairs, etc. The SIMON project [55] focuses on public transportation and private car usage by people with reduced mobility, including the need of information about parking areas and restricted traffic areas.

4.3.3 Other types of impairments

The authors of [92] consider people with visual and/or physical disabilities who move in an urban scenario. They underline the lack of integration between the information about obstacles coming from sensors and the tools that support navigation. Therefore, they propose a framework integrating an ad-hoc route planner running on a smartphone with a sensor box embedded in a white cane or a wheelchair, which is able to identify possible threats to navigation.

As to cognitive impairments, [61] presents a study on how to adapt an existing cloud-based application for people with mild dementia. The system aims to provide users with help when they are outdoor, including suggestions to find the way back home, to keep track of their movements, and to get in touch with their caregivers. Gong et al. [74], instead, consider people with special needs, including visually impaired people, people with Autism Spectrum Disorder (ASD), or simply those with navigation challenges. Visual and cognitive disabilities are also addressed in [28].

Finally, the focus of [100] is on accessible tourism for deaf people: the authors propose two mobile apps to visit indoor and outdoor archaeological sites, respectively. These apps are designed to visualize interesting locations on the site map and obtain related information in the form of videos for hearing impaired people.

4.3.4 All users

Papers that adopt a UD approach propose applications that could be used by any kind of user, regardless of her/his disability or temporary impairment condition, through a proper setting of user profile in the application. UniBS4All [12, 59] pursues this goal for outdoor wayfinding and navigation, by providing route generation for private cars and public transportation, beyond accessible pedestrian paths; users that do not declare any type of disability can use the application as well, finding the same features of well-known commercial map navigators. A similar approach is adopted in [10], where the goal is making a university campus accessible to all students and visitors. All kinds of users are considered in [108], with a focus on public transportation, while only pedestrian paths in indoor and outdoor environments are taken into account in the GAWA project [121], which adopts UD and multi-modal interaction customized to users' characteristics.

4.4 Technologies

This section aims at analyzing the papers according to dimension D3, by presenting the hardware and software technologies adopted to implement the proposed solutions. Therefore, we analyzed the selecting papers and classified these technologies as follows:

- *Technologies for environment representation and modeling*: this category includes all those hardware and software technologies that allow obtaining information about the environment where the users should move, and properly modeling it for accessible wayfinding and navigation; this is a crucial issue in the indoor context, while, in the outdoor context, standard solutions are usually adopted;
- *Technologies for localization*: this category includes hardware and software technologies for user or POI localization; this is again a challenge in indoor environments and thus different approaches are proposed; in the outdoor context, data from GPS are accurate enough to solve this problem;
- *Technologies for wayfinding and navigation*: this category includes technologies for searching accessible paths towards desired destinations (global navigation) or for obtaining real-time guidance to explore the nearby environment (local navigation).

4.4.1 Technologies for environment representation and modeling

In the indoor context, the challenge of creating a 2D/3D modeling of the environment is investigated. Wireless devices, Internet of things (IoT)-enabled equipment, and smartphone sensors (such as accelerometers and gyroscopes) are used by the AccessBIM model to generate an indoor map in real-time [81]. Smartphone built-in sensors have been used for environment representation in [7], where the building map is created by tracking movements of sighted people through accelerometer and compass.

To address the same issue, the smartphone camera is often exploited. VizMap uses videos taken by on-site sighted volunteers to create a 3D spatial model [73]. These video frames are semantically labeled by remote crowd workers with key visual information and embedded into the reconstructed 3D model, forming a query-able spatial representation of the environment. Real-time video feeds from surveillance cameras are also used by Gong at al. [74]. These data are combined with additional software and hardware techniques, like visual analytics, facility semantic models, BLE beacons, and terrestrial laser scanner, in order to create a high-fidelity 3D model of the facility [74].

When similar automatic approaches are not feasible or would require to address challenging issues, scholars rely on web applications where expert users or administrators could manually insert the needed information about the environment. In the system described in [11], floor maps, accessibility information, available routes and calibration landmarks are coded in XML description files, which are created, located and maintained in a server application specifically dedicated to this purpose. Similarly, Delnevo et al.

take advantage of a web application to allow experts to configure the system providing information about the indoor environment layout and POIs [44].

In the outdoor context, a feasible solution to present map-based information and routes is leaning on Google Maps web services (e.g., [4, 16, 31, 82, 85]). Alternatively, OpenStreetMap is an open-source web mapping service that is often adopted by developers for the same purposes (e.g., [22, 92, 97, 99, 114, 121, 122]). Finally, in [8, 124, 125], information is retrieved from a GIS that can feed the system with spatial or geographic data about the urban environment.

4.4.2 Technologies for localization

In the indoor context, the most frequent technologies adopted for user localization are BLE beacons (e.g., [6, 44, 74, 88, 107, 128]).

The authors of [52] use RFID transponders to provide contextualized geographical information to blind users exploring the environment with a smart cane. RFID technology is also investigated in [90, 95].

An interesting approach, targeted to visually impaired people, exploits wireless optical communications; in particular, an indoor localization system is implemented using LED lamps as beacons: the LED lights and smartphone cameras are employed as a receiver, and headsets as a transceiver for translating information into voice [116].

QR codes are also used in indoor localization scenarios. In [79], the authors present an Android application for assisting blind users in navigating on pre-defined paths: when a QR code is scanned, it provides the user with the information of the current location and asks the user to select the destination.

In [1], a mix of sensors and communication strategies are exploited to create an intelligent environment, including ultrasound beacons, sonar, radio-frequency, and a Zigbee sensor network. A similar approach, but including also a wheelchair controller, is investigated by Garcia et al. [66].

The WiFi infrastructure can be used to increase the localization accuracy of the smartphone (e.g., [4, 58]) or as localization strategy exploiting passive tracking and WiFi triangulation (e.g., [10, 130]). This technique has the advantage to avoid the deployment of additional infrastructures, benefiting from existing WiFi network infrastructures.

Several software strategies are proposed to calculate the user's position once the communication technologies have been defined. For example, knowing the last known user position (thanks to beacons, RFID, WiFi, etc.), and the person's speed and direction (using accelerometers and gyroscopes), the dead reckoning method can be used to estimate the current position (e.g., [5, 11]). Another well-known method that scholars are using is K-Nearest Neighbor (K-NN) algorithm, which is able to estimate the position of the device by comparing the current RSSI (Received Signal Strength Indicator) readings with previously gathered RSSI fingerprints [6]. A similar approach is described in [137].

In the outdoor context, GPS is the obvious solution, both to locate the users and to report, using the GPS coordinates, urban accessibility barriers, POIs and facilities (e.g., [102, 119]).

The authors of [52, 53] investigated the use of computer vision, together with GPS and RFID tags, to improve the accuracy of the user's localization in both indoor and outdoor environments. A Light Detection and Ranging (LIDAR) sensor has been used to quantitatively validate the reliability of the proposed method and collect ground truth localization data both in indoor [107] and outdoor [105] contexts. Computer vision is also employed in [62] to estimate the user's location in an indoor environment by combining informational sign recognition (e.g., exit signs detection), 2D maps annotated with a variety of information (including walls and barriers), and dead reckoning. In [27], an approach based on ARWorldMap and ARKit is proposed: the local area map stored in the ARWorldMap can be retrieved and used for determining the user's local position using ARkit, which detects the visual feature points and estimates their position in 3D space.

4.4.3 Technologies for wayfinding and navigation

Different solutions for wayfinding and navigation are based on the use of the smartphone camera. The paper [133] presents an indoor guidance system, where the captured pictures of the user's surroundings are transmitted to the server. The server processes the images and matches them to a database of stored images of the building (along with their stored feature points); after matching, the location and orientation of the user are estimated; finally, the direction information is transmitted back to the smartphone and communicated to the user via text-to-speech. A recent work exploits smartphone camera and machine learning (Convolutional Neural Network) for object detection; the distance to the objects is then calculated to guide the users in the right directions and warn them about obstacles [86].

Beyond the camera, other smartphone built-in sensors are exploited for navigation. In [17], the authors propose a system able to record raw data coming from the GPS receiver, accelerometer, magnetometer, gyroscope, and barometer and to employ the back camera to take several pictures at a fixed frequency. These data allow reconstructing the path followed by the user through a multi-sensor fusion algorithm, called ROAMFREE [17, 33]. To fuse the data gathered by all the sensors available on the phone (WiFi chipset, accelerometers, and magnetic field sensor), a Kalman filter is instead applied in [64].

The approach presented in [142] takes advantage of the information coming from preregistered AR markers, which identify specific accessible facilities (e.g., hallways, restrooms, staircases, and offices). An RGB-D sensor (a sensor that provides color and depth information of every pixel) captures the scene that includes the AR markers; such a scene-based information is then processed by a neural network to recognize and localize obstacles and accessible facilities, thus allowing visually impaired users to explore the nearby, avoid obstacles and find desired destination.

Another technology supporting local navigation is represented by NFC tags. The authors of [65] developed an Android application to read NFC tags on existing signage at specific landmarks in the environment (i.e., next to the Braille signs). In this way, users can obtain aural navigation instructions when they "touch" the NFC tags using their smartphones.

The installation and maintenance of the infrastructure is a critical aspect of all projects addressing accessible indoor navigation. Gong et al. [74] studied the navigation problem in large transportation hubs; they proposed a cyber-physical system to transform a transportation hub into a smart facility able to provide location-aware services. The authors proposed the retrofitting of existing facilities to make them smarter by using Internet of Things, Big Data analytics, and affective computing; the idea is implementing minimum infrastructure changes but leveraging existing cyber infrastructures such as mobile phones, surveillance cameras, facility semantic models, and integrating a minimum number of beacons for localization. Alternatively, the exploitation of crowdsourcing is proposed in [72, 73] as a way to associate semantics to visual POIs. The idea is that on-site volunteers take videos of the environment to create a 3D model and then remote crowdworkers assign labels to key visual information; in this way, the system described in [73] becomes able to localize a user through the photos taken with a smartphone, without the need of installing any kind of sensors and of maintaining a physical infrastructure; however, the preliminary version of this solution resulted to be quite ineffective, due to the difficulties encountered by blind users to take good photos. Crowdsourcing is proposed in [72] for the installation and maintenance of a beacon-based infrastructure, by defining simple tasks that can be completed by volunteers with little to no training. The core idea is using a chatbot to coordinate the overall deployment/maintenance of the infrastructure by assigning volunteers in beacon placement, data collection, or quality assurance tasks. The final goal is to deploy and maintain a beacon infrastructure to benefit visually impaired users.

As to outdoor wayfinding and navigation, the main challenge is generating accessible pedestrian paths for visually impaired people and wheelchair routes for mobility impaired people. To this purpose, existing web mapping services are often exploited in the selected papers. In [59], wayfinding is achieved by exploiting Google Maps APIs: accessible paths, suitable to the users' characteristics and preferences, are obtained by repeatedly calling the Google Maps Directions service passing as parameters the alternative points associated with the architectural barriers identified in the path returned by the same service; the procedure ends when a path avoiding all architectural barriers is generated. The OpenStreetMap web mapping service is instead used in [98]; in this case, the OpenTripPlanner routing engine has been customized, in order to generate paths that keep into account the user's needs and preferences about accessible POIs. Balata et al. [15] describe a system based on a specifically modified GIS and a variation of the Dijkstra's algorithm, which is able to automatically generate human-like landmark-enhanced itineraries for navigation of visually impaired users. A GIS is used also in [16]: it stores data about a graph model, composed of sidewalks and pedestrian crossings, and its edge costs, such as distances, path inclination, maintenance conditions, etc.; a geo-spatial library for shortest path routing is then exploited for wheelchair route planning.

4.5 Data sources

A critical issue to deal with when designing and developing wayfinding systems able to address specific needs and preferences is the definition of the dataset to use, which should be up-to-date, trustworthy and dense enough to allow to compute accurate paths. For this reason, we considered the data sources used in the selected literature as one of the key characteristics to investigate (dimension D4).

In particular, we grouped the different datasets on the basis of the approach adopted for data collection:

- *Crowdsourcing*: in this case, data are collected by volunteers/end users while interacting with a system;
- *Crowdsensing and pervasive sensing*: the approach adopted in this case for data collection is based on sensors;
- *Official and expert data*: in this case, data are collected by experts and/or provided by official sources (e.g., municipality open data);
- *Multi-source data*: this category refers to solutions encompassing the combination of different data sources.

Figure 7 shows the distribution of papers along the above categories. In this case, we could classify only 96 papers out of 111, since the remaining papers do not clarify how the dataset is created. A comparable number of papers use crowdsensing and pervasive sensing or official and expert data (36 and 28, respectively), thus highlighting that very different research directions are adopted in the selected

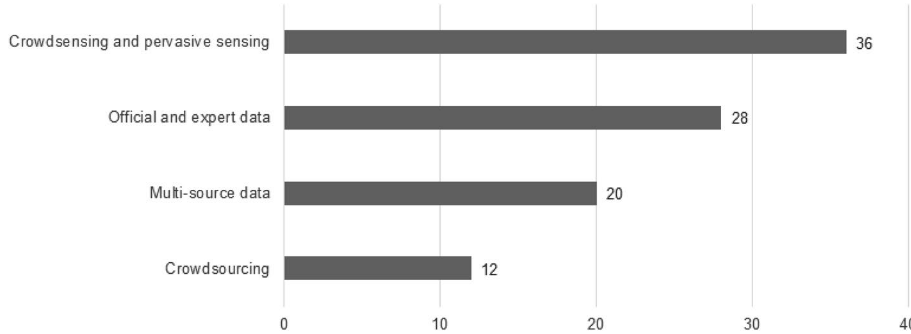


Fig. 7 Distribution of the analyzed papers according to the data source dimension

papers. There are also 20 out of 96 papers that adopt solutions using different types of data sources; these ones contribute to obtain more reliable and trustful systems, but require much more effort and investment. The adoption of crowdsourcing is chosen in 12 papers out of 96.

4.5.1 Crowdsourcing

The HandYwiN [31] project exploits crowdsourcing to collect data about the accessibility of public and private spaces for people in wheelchairs. To collect such data, an Android application has been developed and the level of accessibility can be estimated by answering some predefined questions. Moreover, pictures can be uploaded, together with their GPS location. A similar approach is employed in MAPAAL [92], a system based on crowdsourcing to report data about urban accessibility, such as sidewalks (e.g., slope, roughness, and width), crosswalks (length, type) and acoustic signals. These data, and the related metadata, are then used to compute accessible paths both for wheelchair and visually impaired users. EasyWheel focuses on the need of wheelchair users to know accessibility information about the POIs of an urban environment [99]: it is a mobile social navigation system where users are engaged through reputation and reward strategies. In [37] da Silva et al. propose a solution where crowdsourcing is used to directly mark accessibility issues on a digital map. Users can take photos of city places that may represent barriers for people with reduced mobility and properly rate them. These data are then presented to the end users with a heatmap visualization. A different approach has been investigated in Vadeo [63], a social network developed to let users share information about the level of accessibility of their neighborhood. The authors of [143] describe a system that allows sighted volunteers and visually impaired people to collaboratively annotate geographic features with accessibility information. The possibility to engage users in contributing to the dataset is also described in [85], where people can register and upload categorized information about the services offered in the metropolitan areas. In [129], data collected by citizens are combined with comments and pictures through fuzzy logic. Ruta et al. [122] make use of the crowdsourcing information about indoor/outdoor accessibility of POIs, not only to provide mobility impaired users with personalized paths, but also to visualize such information by means of AR.

4.5.2 Crowdsensing and pervasive sensing

Pervasive technologies and ubiquitous infrastructures are increasing the possibility to exploit sensors to collect data.

In [1], the authors propose a context-aware intelligent environment to support people with or without disabilities, which exploits a network of sensors and intelligent wheelchairs. A different approach [27] takes advantage of Wi-Fi/cellular data connectivity, beacon signal strength and 3D spatial models, to create hybrid models of the interiors.

In [7], the indoor map is created by tracking the movements of sighted people with the smartphone accelerometer and compass. Similarly, inertial sensors in the iPhone have been used to backtrack a route taken in a building, recording the sequence of turns and of step counts between turns [58].

Sensors, and in particular sensors commonly available on a smartphone, are often used to collect data and provide wayfinding services in the outdoor context. The most common ones are the GPS, for locating the user, and the accelerometer and gyroscope for computing the direction (e.g., [17]). GPS traces can also be used to identify urban pedestrian pathways, by tracking people with mobility impairments and sharing collected paths with the community [19]. Moreover, cameras can be exploited to collect data and train a machine learning algorithm to recognize objects and/or signs in the environment [5, 62, 86].

Machine learning is used in the WheelShare system [48] to classify the surfaces encountered in the built environment into accessible and inaccessible surfaces, depending on the vibration data coming from a wheelchair that moves through them. To this end, the wheelchair is endowed with sensors (geo-tagged accelerometer and gyroscope) and readings are used in the training phase of the classification algorithm. In the live phase, surface classification reliability is improved by crowdsensed surface information provided by contributors (volunteering wheelchair users). Route requesters may then use a web-based routing application to retrieve a path to their destination: an accessibility level is overlaid on the retrieved routes thanks to the previous surface classification.

4.5.3 Official and expert data

Open data or data created by expert users are exploited in approaches that rely on official data sources. In [3], the authors present a bus stop assistant to provide audiovisual information about the bus routes, gathered from the official website of the municipality of Tunja. Open data about transportation and real-time General Transit Feed Specification (GTFS) feed are used in [88]. The authors of [20] use open data from the municipality, which include information about the urban environment, such as a path that is blocked by work in progress, or a sidewalk that is unusable due to poor conditions.

When open data are not available, experts manually create the needed data. Following this approach, in [11], the authors designed an Ambient Assisted Route Planner, which uses XML files, created by the building administrators, to describe the floor characteristics. Similarly, though in the outdoor context, barriers and alternative points are mapped and uploaded by experts in the UniBS4All system through an easy-to-use web application designed for this purpose [59].

GIS datasets are exploited to address different problems: reproducing an urban environment for testing purpose [4], creating the indoor map (exploiting CAD software) [8], or saving information about landmarks and POIs [124, 125]. Scalable Vector Graphics (SVG) is finally adopted to represent floor plans, along with information about rooms, walls or doors, with the advantage of keeping the correct map scale, which allows mapping graphical items to real world conditions [130]. Additional information about areas and POIs, as well as the connectivity of rooms and buildings, must be added by manual annotation.

In [41], the authors propose an architecture that supports indoor navigation by means of a system capable to configure CAD drawings of the building and record the position of fiducial markers, POIs and obstacles to be avoided by wheelchair users.

4.5.4 Multi-source data

Often, one single type of data input is not enough to provide accurate solutions. As an example, the authors of [16] use input data coming from three main sources: city sensing (referring to the possibility of collecting data from general sensors, mobile phones, social media), wheelchair users' and other citizens' feedback, and urban planning authority's feedback. mPASS [103, 119] exploits heterogeneous data, including municipality and public transportation open data, OpenStreetMap data, crowdsourcing from citizens, and crowdsensing from wheelchair users. The e-Adept system [40] integrates data about the pedestrian network with local data and accurate real-time position data, to provide high precision navigation for a visually challenged pedestrian in the urban environment. In [121], different mechanisms are used: automatic data retrieval of information about POIs from web pages (Wikipedia, DBpedia, etc.), an online management service that allows users to integrate and update information about accessibility issues, the Google maps database for outdoor locations, and a GIS database for indoor environments.

With reference to the indoor modelling, a recent study discusses the possibility to exploit Building Information Modeling (BIM) and OpenStreetMap data [120].

4.6 User role

We finally analyzed the surveyed papers on the basis of dimension D5, that is, the role that end users have played in the development of the proposed solutions. In particular, we classified the papers as follows:

- *No user involved*: this category includes all those papers focused on system architectures, technologies, and algorithms that address specific problems, such as service orchestration or data integration, which do not necessarily require user involvement for their design and development;
- *Users involved at design time*: papers that present solutions designed with the participation of end users by means of different research methods; these papers usually arrive at presenting prototypes that have not yet been tested with users;
- *Users involved in system evaluation*: this category includes papers that describe novel solutions for accessible wayfinding and navigation and present their evaluation with users;
- *Users involved in both design and evaluation*: these papers describe the user-centered approach adopted for designing the proposed solution and the evaluation carried out with users.

Figure 8 shows the distribution of papers in this classification. As one may notice, 36 papers out of 111 (32.4%) do not involve users neither in design nor in the evaluation of the proposed solution, 16 papers (14.4%) discuss how they involved users for designing the proposed system, 25 papers (22.5%) present system evaluation with users, and 34 (30.6%) discuss how users have been involved both in design and evaluation.

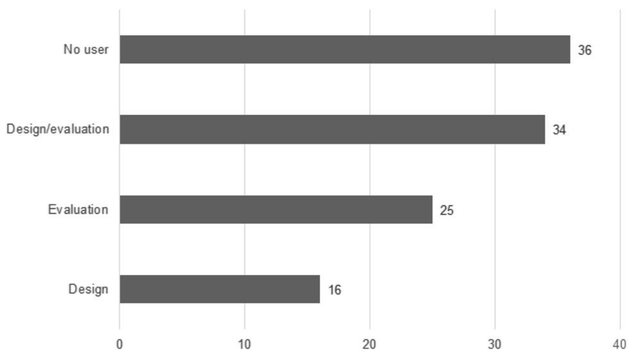


Fig. 8 Distribution of the analyzed papers along the user role dimensions: no user, design, evaluation, and design/evaluation

4.6.1 No user involved

A high number of papers do not mention the role that users played in the design and evaluation of the proposed system.

Abascal et al. [1] present an ambient intelligence middleware to support the development of different types of applications tailored to the different users' needs; the paper focuses on technology for precise localization in indoor environments and on how to foster the development of context-aware services. The work in [20] addresses outdoor navigation by focusing on data processing and integration aimed to generate a graph of paths to enable accessible routing. A processing algorithm for image and depth profiling aimed at supporting obstacle avoidance inside buildings for visually impaired people is presented in [142]. Faria et al. [52] present the design and development of a novel electronic white cane for blind people, while Deepthi et al. [42] propose a wearable visual aid based on image processing to help blind people reach recognized objects.

4.6.2 User role in design

Most of the works that involved users in system design mention user-centered design (UCD) as their preferred research methodology. For instance, the authors of the MEP project [33] explicitly declare that a UCD approach has been adopted, as well as the authors of the project BlueEyes [128], which aims at supporting the orientation and navigation of blind people moving in a city. The latter is carried out and supported by three Beacon's Living Labs constituted by three Portuguese towns; at the time of the paper publication, the project was under development, thus the system had not been evaluated yet.

Specific UCD techniques are mentioned also in other surveyed papers: personas and scenarios related to the most significant use cases are considered in [97] [98] [44]; focus groups and paper prototyping have been adopted in [99] to design EasyWheel; the work [134] derives a conceptual model on the basis of a survey with 85 potential users (either with disabilities or not); interviews with 17 participants with visual impairments are mentioned in [3].

4.6.3 User role in system evaluation

Twenty-five papers selected for this study do not explicitly mention the design approach adopted in the reported project, therefore the role played by users in the design phase is not apparent. However, they describe evaluation activities carried out with users. Usually, these evaluations involve a good number of representative users, even considering that recruiting people with disabilities to carry out user tests is often a difficult task. Around 5-6 blind people are normally involved in the evaluation of tools targeted at this type of users: [4] mentions a pilot study in an outdoor environment with 5 users; Flores and Manduchi [57] have carried out a test with 6 blind people (5 using a white cane, 1 with the help of a dog) in a controlled indoor environment; 6 visually impaired people participated in the study described in [68]; user tests and interviews with 4 blind people have been conducted in [58]; three applications have been experimented in [123] with 5, 6, and 6 blind people, respectively.

A few studies involve a greater number of users: 9 visually impaired users participated in the study within a shopping center described in [115]; 11 users (8 blind people and 3 low-vision people) participated in the usability evaluation of the system presented in [112]; 12 participants have been involved in the evaluation of the system presented in [78]; 24 participants (15 sight people and 9 blind people) participated in the evaluation of Ebsar [7].

4.6.4 Users in system design and evaluation

A good percentage of works have involved representative users both during design and evaluation. Biagi et al. [19] report that they adopted focus groups, personas, scenarios, wireframes, and mock-ups for application design and then describe the tests of mock-ups carried out with 2 users, the former on electric wheelchair and the latter on manual wheelchair. UCD has been followed by Spindler et al. [130], who present an evaluation consisting of a Wizard-of-Oz experiment with one blind expert and a pilot study with 6 blind users. The article [121] declares to adopt a UD approach and presents the results of an evaluation with 20 participants, divided in 4 groups associated to different disabilities, contexts, and types of smartphone. During requirements analysis of the GeoCoach project [143], an international survey has been conducted with the participation of 64 blind subjects and 33 people with low vision; after system implementation, two user studies (with 5 visual impaired participants and 10 participants, respectively) have been carried out. In the design of the Ways4All system [95], a target

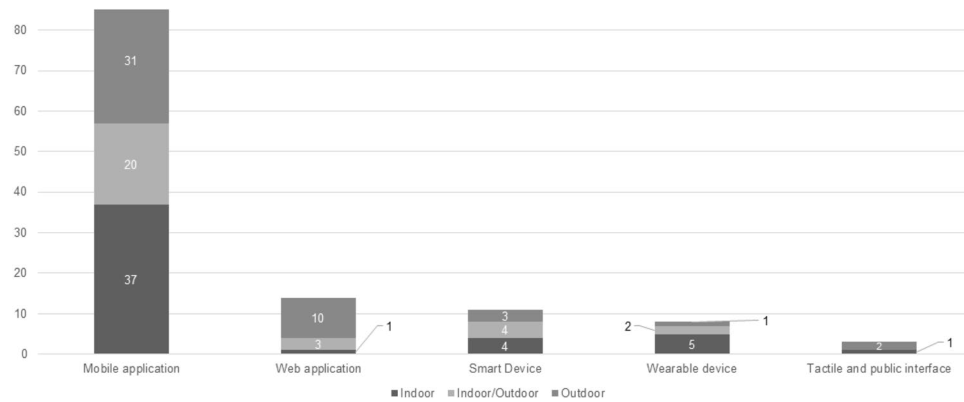


Fig. 9 Mapping application types to contexts of use

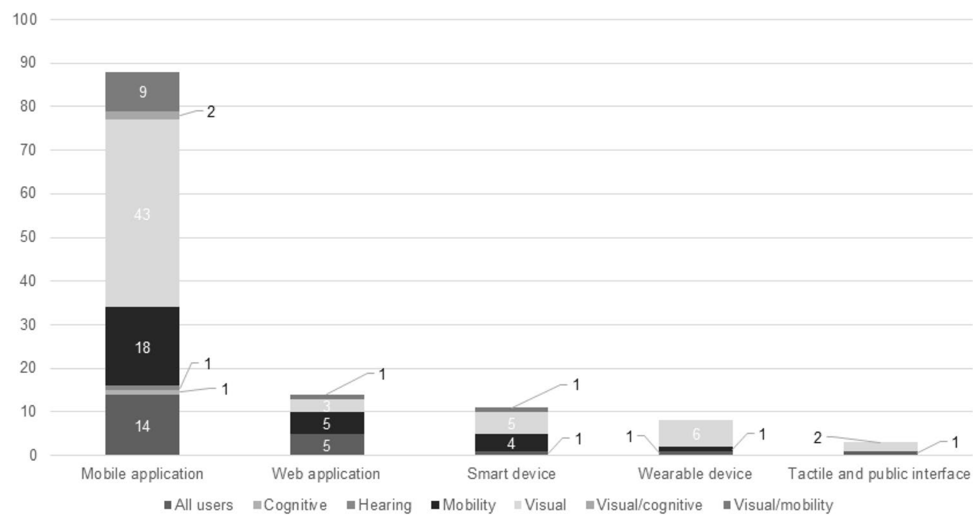


Fig. 10 Mapping application types to target users

group of people has been involved repeatedly from an early stage of development; the system has been evaluated in a field test with 16 participants, by adopting a thinking aloud technique. UD and participatory design has been adopted in [59], which reports on an iterative design approach involving various stakeholders and the system evaluation with 20 participants. In [13], a survey with 19 participants allowed to specify the system requirements, while 9 blind participants have been involved in the user study conducted in a real museum.

Only two papers [31, 100] describe long-lasting iterative design and evaluation activities. Another important gap is the lack of evaluation with different types of target users.

4.7 Mapping results

We combined the results obtained by analyzing the papers included in the study to provide some additional insights about the characteristics of solutions for accessible wayfinding and navigation proposed in the scientific literature. In what follows, we discuss the most interesting mapping results emerged from this additional analysis.

Figure 9 shows how the different types of applications map to the type of context. One can observe that mobile applications and smart devices have been almost equally experimented in indoor, outdoor, and indoor/outdoor contexts. Web applications have been proposed primarily for outdoor contexts, while the use of wearable devices have been mainly considered for indoor environments.

Figure 10 shows the mapping of applications to users' disabilities. Most of the mobile applications (54 out of 88) have been designed to support visually impaired people or people also affected by visual impairments, thus highlight that operating systems of mobile devices are ready to offer robust APIs for accessible interaction with such devices. Mobile applications can be easily developed according to a UD approach (note that there are 14 papers that provide mobile solutions for all users), thus promoting social inclusion: indeed, these applications could be better accepted by users than ad-hoc solutions like smart white canes, smart glasses or other wearable devices.

As expected, Fig. 11 shows that crowdsensing and pervasive sensing is proportionally more used in mobile applications than in other solutions, since they exploit the variety

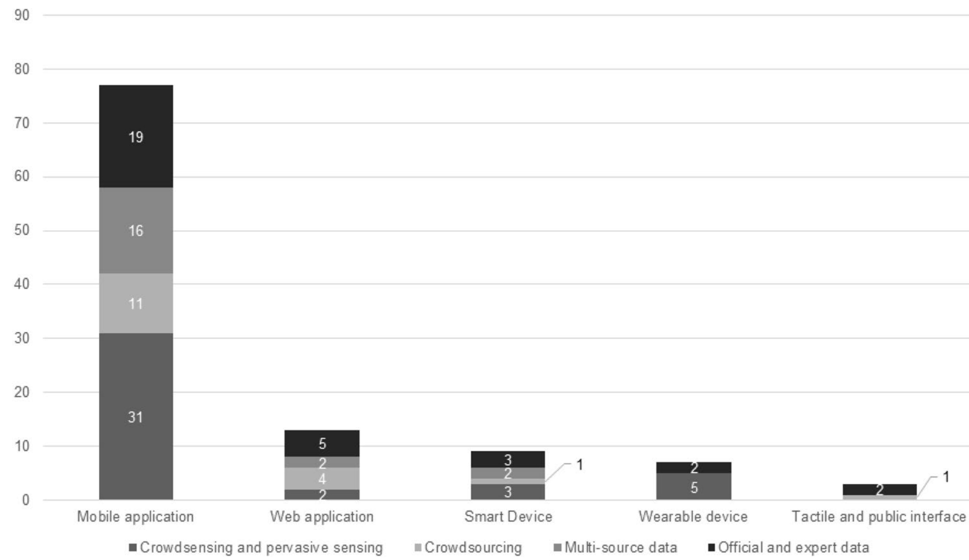


Fig. 11 Mapping application types to data sources

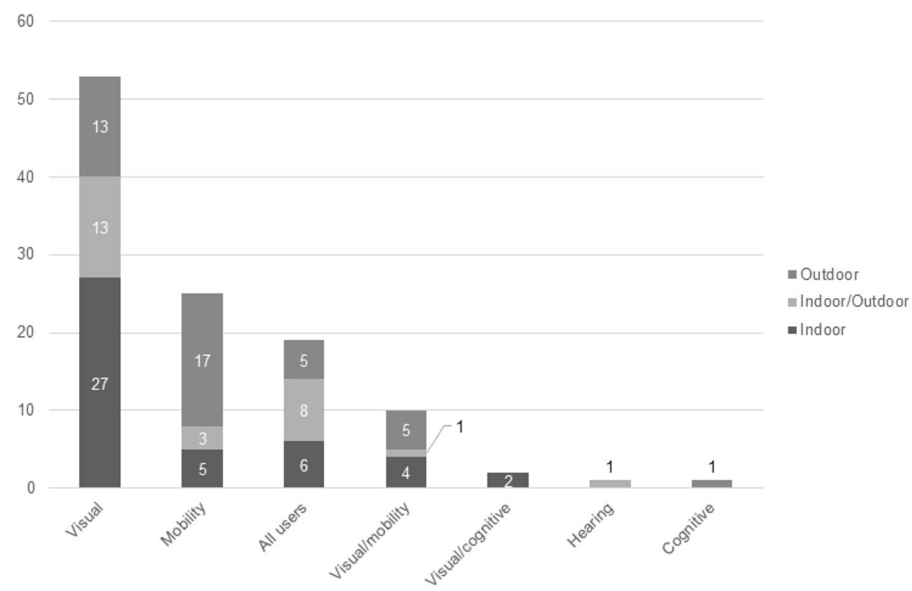


Fig. 12 Mapping target users to contexts of use

of sensors currently embedded in smartphones. However, there is still a quite high number of papers (19 out of 88) proposing mobile applications that rely on data coming from experts or official databases; this is the same type of data source exploited in the majority of web applications. Multi-source data, which represent the most promising solution, are less adopted, in proportion, than other methods in all types of applications.

Another interesting mapping is related to the dimensions that investigate target users and contexts of use. Figure 12 shows the mapping between these two: as one may observe, visually impaired people have been more considered in solutions for indoor contexts, while mobility impaired (mainly wheelchair users) are more supported in outdoor contexts. The solutions targeted at all users are more equally distributed among indoor, outdoor, and indoor/outdoor contexts, although these solutions can be found in a limited number of papers.

Finally, Fig. 13 shows how the data source and context dimensions are related to one another in the selected papers. Crowdsensing and pervasive sensing result to be more used in indoor environments than in other contexts; this seems an obvious result, even though it is not so obvious that the same type of data source is used in 18 papers out of 36, which also consider the problem of outdoor navigation; this requires general solutions for user tracking and localization to be applied in different kinds of environment. As expected, official and expert data, multi-source data, and crowdsourcing

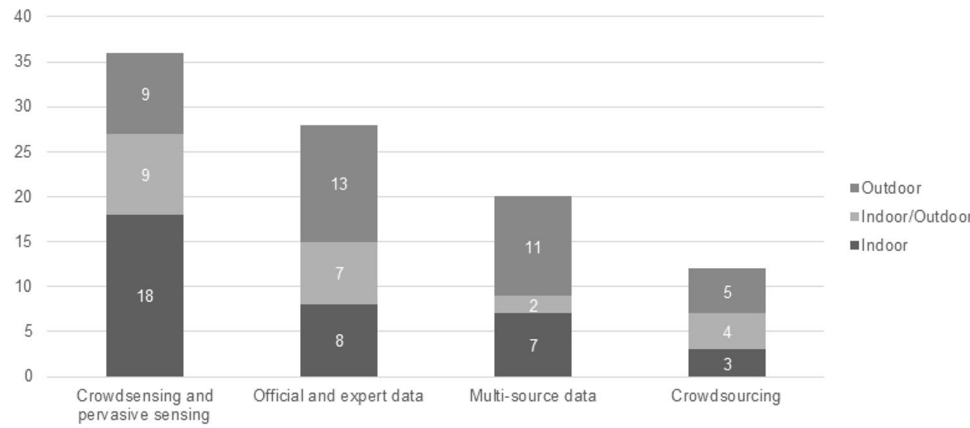


Fig. 13 Mapping data sources to contexts of use

are more used in outdoor than in indoor and indoor/outdoor contexts. However, multi-source data often mean that official open data are combined with data coming from crowdsensing and pervasive sensing, thus highlighting once again that general solutions for indoor and outdoor navigation should rely on different types of data.

5 Discussion

This section highlights the main challenges and open issues that emerged from our literature analysis. Limitations of the study are also reported at the end of the section.

5.1 Challenges and open issues

As a general consideration, we observe that the actual deployment of a complete system for accessible wayfinding and navigation working both in indoor and outdoor environments seems far from reality. This is due to several methodological and technological issues.

5.1.1 Methodological issues

Unfamiliar spaces may become more familiar whenever someone or something helps people orient themselves and guides them toward desired places. The solutions proposed in the majority of papers included in this study address the needs of specific groups of users; however, they do not consider that the general goal should be improving the quality of life and independent mobility of all users, regardless their permanent or temporary impairments, if any. Therefore, not only *inclusiveness* but also *universal design* [132], to the greatest extent possible, should guide the development of future solutions, without the need for adaptation or specialized design [131].

Another methodological issue is concerned with *user participation* in system design and evaluation. Our analysis highlights that one third of selected papers did not talk about user involvement, neither in design nor in evaluation. Recruiting representatives of different disability groups can be a hurdle that designers and developers have to overcome. On the one hand, user-centered and participatory design approaches allow adopting a user perspective and better understanding system requirements. On the other hand, extended evaluation with users is important to discover usability problems and e-accessibility issues: for instance, speech-only instructions revealed to become annoying and irritating for visually impaired users and imposed higher cognitive load [78]; however, non-speech audio cues are inadequate in complex situations. A combination of speech and non-speech audio resulted to be a successful solution in this case. Combining more than one interaction method to satisfy different requirements is usually a good solution, but it requires to carry out tests on the field to demonstrate its validity [44].

Besides the evaluation of usability and accessibility, it is relevant to measure the *user acceptability* of tools and technologies [39]. Knowing the extent to which users may accept the presence of a new technology in their life, may help in understanding the issues that need to be addressed before technology deployment and distribution. Among the papers analyzed in this study, nine directly refer to user acceptability, user acceptability evaluation, and acceptance of technology and applications (e.g., [7, 71, 143]) as hints of the potential success of the technology and tools they present.

It is fundamental to involve the users not only in evaluation, but also in deployment and evolution of systems for indoor and outdoor navigation. Providing non-expert users with mechanisms for tailoring and customization of applications in a real context might contribute to guarantee the long-lasting *sustainability* of complex projects. For instance, caregivers may personalize the application of the older adults they are assisting [60] or facility staff members may collaborate to (1) enrich the environment with sensors used by the system for correct navigation [72], (2) carry out data management [126], or (3) prepare maps with suitable authoring tools [6]. In summary, techniques for end-user development [18] [113] might support maintenance and evolution of both the infrastructure and the software application over time.

Finally, it could be interesting to conceive more general systems, namely systems that go beyond accessible indoor/outdoor navigation but that can provide further services, such as tourist information [44][100] emergency management [45][69] or assistance for independent living [26]. This requires addressing the problem from a wider perspective and promote *system openness and evolution* [56].

5.1.2 Technological issues

Creating and maintaining the *infrastructure* that supports the correct operation of a system for wayfinding and navigation is one of the main technological challenges. In the indoor case, there is the need of retrofitting existing facilities with proper sensors, or to design and construct new ones by adopting the most suitable instrumentation for intensive data collection [137]. However, technology is rapidly evolving and a solution developed today might become obsolete in just a few years. The outdoor case is even more complex since the deployed infrastructure and used technologies must be contextualized in the wider themes of smart cities and smart mobility [31]. As underlined in [92], smart accessible cities need a proper infrastructure that requires a long-term planning of investments, so as new systems (e.g., a new smart public transportation) could be integrated in the smart city, and technology evolution could be accommodated over time.

Aspects related to *efficiency*, *availability* and *reliability* of the technology may influence long-term adoption of systems for wayfinding and navigation. For instance, some solutions propose route computation on server side, but this may have negative effects on the efficiency of route navigation service and on real-time availability of information [40]; turn-by-turn instructions are seen as fragile in outdoor environments due to their high dynamicity [141]; the use of crowdsourcing for outdoor accessible navigation poses questions about data reliability [119]; the need of accurate user localization in indoor context presents several challenges in the design of navigation systems, considering in particular blind users who need accurate turn-by-turn instructions [107].

The *accessibility* of the device used by impaired people plays a fundamental role in the exploitation of a smart environment or a smart city. For instance, solutions that require blind persons to take photos of POIs or that ask wheelchair users to reach a QR code are doomed to fail in real situations. Developing different methods to carry out the same actions by different users and providing multi-modal sensory feedback (such as text, vibration and voice) might represent a successful approach to achieve universal design.

The quality of *data sources* is a further technological issue. Several approaches have been proposed in the outdoor case collecting information about accessibility barriers and facilities: information could be included in official reports supplied by experts, they may be provided by citizens through crowdsourcing, or they may be collected by mobile sensors through crowdsensing. However, these different sources of data must not only be properly integrated and constantly updated, but their trustworthiness must be evaluated through adequate models [119]. As mentioned, in indoor navigation it is necessary to install and maintain over time the instrumentation for intensive data collection [137]. Moreover, after the installation, digital maps representing the indoor environment have to be kept updated and data samples must be collected to construct a signal model of the environment to be navigated [72]. Finally, in indoor/outdoor navigation there may be data coming from different sources, which are referred to the same place (e.g., a building entrance); in this case, data must be properly integrated and kept aligned over time.

5.2 Limitations of the study

Some limitations affect our systematic mapping study. First of all, we limited our paper search to the period January 2009–December 2020. Regarding the starting period, only three papers selected for our analysis were published in 2009, and they were very preliminary with respect to up-to-date proposals due to the rapid evolution of the technology for localization and geo-mapping; therefore, we may assume that the study covers an adequate period of time. At the date of submission, there are probably other papers published in 2020 and early months of 2021 that might have been indexed in Scopus and could have been included in our survey.

Moreover, our paper search was performed on the Scopus citation database, rather than searching papers in several digital libraries. This choice allowed us to include all indexed articles appeared in venues of different publishers; we assume that most significant works have been published in international conferences and journals indexed in Scopus.

Finally, in choosing the concepts for our search string, we tried to be as inclusive as possible, but it was also important to obtain a manageable number of papers to be scrutinized. For this reason, there can be more papers that cannot be found through our search string, since they do not report our keywords in their metadata. In particular, the concepts *accessible* and *accessibility*, which we considered fundamental for our study, are not always included in papers proposing obstacle avoidance systems (e.g., [35][94][136]); however, removing these concepts from our search string leads to obtain a list of more than 23,000 papers instead of

806. Systematic reviews focused on navigation systems for blind and low-vision people (e.g. [49][87]) better address topics like obstacle avoidance, crosswalk navigation, and walkable area detection.

6 Conclusion

Scientific literature in different research fields includes several works dealing with the problem of supporting disabled people and persons with special needs to move freely and independently in urban environments and complex buildings. Most of these works address specific issues, by taking a given perspective and proposing a novel solution to a portion of the whole problem. No in-depth survey exists, which considers the variety of dimensions that are involved in the design and deployment of systems for accessible wayfinding and navigation.

The aim of our systematic mapping study was to identify the nature and extent of the available research and properly classifying it, in order to derive indications for future development of such systems. The selected 111 papers out of 806 retrieved through an automatic search have been read and analyzed, to answer our research question. We firstly classified the solutions proposed in the analyzed papers into five categories (mobile applications, web applications, wearable devices, smart devices, and tactile and public interfaces) and discuss frequencies and trends, by finally describing several examples of the solutions proposed in each category. We further defined five dimensions (context of use, target users, adopted technologies, data sources, and user role) to deeply analyze the characteristics and usage of the proposed solutions. As to the context of use, our findings reveal that the proposed solutions focus on indoor or outdoor contexts and in a few cases on both contexts at the same time. When analyzing the different target users' characteristics, it emerged that only visual impaired people or mobility impaired people are usually considered, while rarely other kinds of impairment are taken into account. However, recent papers are proposing solutions for all users (including the elderly and people without disabilities, beyond visually and mobility impaired users); these papers underline the importance of adopting UCD and UD approaches. We then reported the technologies adopted for solution implementation, by classifying them into: technologies for environment representation and modeling, technologies for localization, and technologies for wayfinding and navigation. Considering the data sources, it emerged that crowdsensing and pervasive sensing is the preferred solution for data collection, but that the combination of different data sources is a promising alternative able to cope with sensor limitations. Finally, this study considered the role of users in the selected works, offering a further classification that discriminates in no user involvement, user involvement at design time, users enrolled for system evaluation, and users involved both at design and evaluation time. The findings highlight that, in a high percentage of works, users have not been involved neither in design nor in evaluation, and thus their validity in real contexts cannot be demonstrated.

In light of the results of this study, and considering our expertise and research interests in the field of human–computer Interaction, we would like to promote the adoption of user-centered and universal design approaches. We consider these approaches as promising not only when designing solutions for people with disabilities, but also when the goal is facilitating people who access a place for the first time or are prevented from moving freely (e.g., they carry a suitcase or a stroller). Furthermore, we believe that it would be desirable to aim for long-term investments not only in physical infrastructures for facilitating accessible wayfinding and navigation, but also in socio-technical environments that support the management of these infrastructures over time and in an easy manner.

Acknowledgements The authors would like to thank prof. Paola Salomoni for her precious suggestions and for having inspired this work. They are also grateful to the anonymous reviewers who provided stimulating comments and suggestions for improving the paper.

Authors' contributions All the authors contributed equally to this manuscript.

Funding Open access funding provided by Alma Mater Studiorum - Università di Bologna within the CRUI-CARE Agreement. Not applicable.

Availability of data and materials The dataset of the papers analyzed for this manuscript is available from the corresponding author on request.

Declarations

Conflict of interest Not applicable: none of the authors have neither any conflict of interest nor any competing interest.

References

1. Abascal, J., Lafuente, A., Marco, A., Falco, J., Casas, R., Sevillano, J., Cascado, D., Lujan, C.: An architecture for assisted navigation in intelligent environments. Int. J. Commun. Netw. Distrib. Syst. **4**(1), 49 (2010). https://doi.org/10.1504/ijcnds.2010.029737
2. Abdallah, S., Ajmi, F., Othman, S.B., Vermandel, S., Hammadi, S.: Augmented reality for real-time navigation assistance to wheelchair users with obstacles' management. In: Computational Science—ICCS 2019, pp. 528–534. Springer, Cham (2019)
3. Abril, C.R.V., Najar, A.C., Martinez-Tejada, L.A., Alvarez, C.P.A.: Public transport access system for people with visual disability, case of study: Tunja, Colombia. In: 2017 Congreso Internacional de Innovacion y Tendencias en Ingenieria, CONIITI 2017—Conference Proceedings, vol. 2018-Janua, pp. 1–6. IEEE (2018). https://doi.org/10.1109/CONIITI.2017.8273350
4. Adao, T., Magalhães, L., Fernandes, H., Paredes, H., Barroso, J.: Navigation module of blavigator prototype. World Autom. Congr. **2012**, 1–6 (2012)
5. Ahmetovic, D.: Smartphone-assisted mobility in urban environments for visually impaired users through computer vision and sensor fusion. In: Proceedings of IEEE International Conference on Mobile Data Management, vol. 2, pp. 15–18 (2013). https://doi.org/10.1109/MDM.2013.58
6. Ahmetovic, D., Gleason, C., Ruan, C., Kitani, K., Takagi, H., Asakawa, C.: NavCog: A Navigational Cognitive Assistant for the Blind. In: Proceedings of the 18th International Conference on Human–Computer Interaction with Mobile Devices and Services - MobileHCI '16, pp. 90–99. ACM Press, New York, New York, USA (2016). https://doi.org/10.1145/2935334.2935361
7. Al-Khalifa, S., Al-Razgan, M.: Ebsar: Indoor guidance for the visually impaired. Comput. Electr. Eng. **54**, 26–39 (2016). https://doi.org/10.1016/j.compeleceng.2016.07.015
8. Almeida, J., Fernandes, H., Filipe, V., Barroso, J.: Web platform architecture to support the Geographic Information System of the University of Trás-os-Montes and Alto Douro Campus. In: Proceedings—2009 International Conference on New Trends in Information and Service Science, NISS 2009, pp. 1112–1117 (2009). https://doi.org/10.1109/NISS.2009.177
9. Aly, H., Youssef, M., Agrawala, A.: Towards ubiquitous accessibility digital maps for smart cities. In: Proceedings of the 25th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems, SIGSPATIAL '17, pp. 8:1–8:4. ACM, New York, NY, USA (2017). https://doi.org/10.1145/3139958.3139978
10. Amaral, M.K., Chen, P., Carter, W.S., Sanchez, J.: Access my campus. In: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 8456, pp. 238–241. Springer (2015). https://doi.org/10.1007/978-3-319-14424-5_27
11. Amaral, P.F., García, J.C.G., Bastos Filho, T.F., Mazo, M.: Ambient assisted route planner based on XML files with accessibility information. In: WISP 2009—6th IEEE International Symposium on Intelligent Signal Processing - Proceedings, pp. 147–152 (2009). https://doi.org/10.1109/WISP.2009.5286570
12. Arenghi, A., Belometti, S., Brignoli, F., Fogli, D., Gentilin, F., Plebani, N.: Unibs4all: A mobile application for accessible wayfinding and navigation in an urban university campus. In: Proceedings of the 4th EAI International Conference on Smart Objects and Technologies for Social Good, Goodtechs '18, pp. 124–129. ACM, New York, NY, USA (2018). https://doi.org/10.1145/3284869.3284900
13. Asakawa, S., Guerreiro, J.a., Sato, D., Takagi, H., Ahmetovic, D., Gonzalez, D., Kitani, K.M., Asakawa, C.: An independent and interactive museum experience for blind people. In: Proceedings of the 16th Web For All 2019 Personalization—Personalizing the Web, W4A '19, pp. 1–9. ACM, New York, NY, USA (2019). https://doi.org/10.1145/3315002.3317557
14. Balata, J., Berka, J., Mikovec, Z.: Indoor-outdoor intermodal sidewalk-based navigation instructions for pedestrians with visual impairments. In: Miesenberger, K., Kouroupetroglou, G. (eds.) Computers Helping People with Special Needs, pp. 292–301. Springer International Publishing, Cham (2018)
15. Balata, J., Mikovec, Z., Slavik, P.: Landmark-enhanced route itineraries for navigation of blind pedestrians in urban environment. Journal on Multimodal User Interfaces **12**(3), 181–198 (2018). https://doi.org/10.1007/s12193-018-0263-5
16. Barczyszyn, G.L., Camenar, L.M.D.O., Nascimento, D.D.F.D., Kozievitch, N.P., Silva, R.D.D., Almeida, L.D., Santi, J.D., Minetto, R.: A collaborative system for suitable wheelchair route planning. ACM Transactions on Accessible Computing (TACCESS) **11**(3), 1–26 (2018)
17. Bardaro, G., Vali, A., Comai, S., Matteucci, M.: Accessible urban routes reconstruction by fusing mobile sensors data. In: Proceedings of the 13th International Conference on Advances in Mobile Computing and Multimedia, MoMM 2015, pp. 84–92. ACM, New York, NY, USA (2015). https://doi.org/10.1145/2837126.2837158
18. Barricelli, B.R., Cassano, F., Fogli, D., Piccinno, A.: End-user development, end-user programming and end-user software engineering: a systematic mapping study. J. Syst. Softw. **149**, 101–137 (2019). https://doi.org/10.1016/j.jss.2018.11.041
19. Biagi, L., Comai, S., Mangiarotti, R., Matteucci, M., Negretti, M., Yavuz, S.U.: Enriching Geographic Maps with Accessible Paths Derived from Implicit Mobile Device Data Collection, chap. 5, pp. 89–113. IGI Global (2017). https://doi.org/10.4018/978-1-5225-0827-4.ch005
20. Bolten, N., Amini, A., Hao, Y., Ravichandran, V., Stephens, A., Caspi, A.: Urban sidewalks: Visualization and routing for individuals with limited mobility. In: Proceedings of the 1st International ACM SIGSPATIAL Workshop on Smart Cities and Urban Analytics, UrbanGIS'15, pp. 122–125. ACM, New York, NY, USA (2015). https://doi.org/10.1145/2835022.2835042
21. Bolten, N., Caspi, A.: Accessmap website demonstration: Individualized, accessible pedestrian trip planning at scale. In: The 21st International ACM SIGACCESS Conference on Computers and Accessibility, ASSETS '19, p. 676–678. ACM, New York, NY, USA (2019). https://doi.org/10.1145/3308561.3354598
22. Bromuri, S., Urovi, V., Stathis, K.: icampus: a connected campus in the. Int. J. Ambient Comput. Intell. **2**(1), 59–65 (2010). https://doi.org/10.4018/jaci.2010010105
23. Budgen, D., Turner, M., Brereton, P., Kitchenham, B.: Using mapping studies in software engineering. In: Proceedings of PPIG 2008, vol. 2, pp. 195–204 (2008)
24. Cáceres, P., Sierra-Alonso, A., Cuesta, C.E., Vela, B., Cavero, J.M.: Modelling and linking accessibility data in the public bus network. J. Univ. Comput. Sci. **21**(6), 777–795 (2015)
25. Camenar, L.M.d.O., do Nascimento, D.d.F., Almeida, L.D.A.: A method for analyzing mobility issues for people with physical disabilities in the context of developing countries. In: Antona, M., Stephanidis, C. (eds.) Universal Access in Human–Computer Interaction. Methods, Technologies, and Users, pp. 3–17. Springer International Publishing, Cham (2018)
26. Carmien, S.P., Fischer, G.: Design, adoption, and assessment of a socio-technical environment supporting independence for persons with cognitive disabilities. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 597–606. Association for Computing Machinery, New York, NY, USA (2008)

27. Chang, Y., Chen, J., Franklin, T., Zhang, L., Ruci, A., Tang, H., Zhu, Z.: Multimodal information integration for indoor navigation using a smartphone. In: 2020 IEEE 21st International Conference on Information Reuse and Integration for Data Science (IRI), pp. 59–66 (2020). https://doi.org/10.1109/IRI49571.2020.00017
28. Chang, Y.J., Wang, T.Y.: Indoor wayfinding based on wireless sensor networks for individuals with multiple special needs. Cybern. Syst. **41**(4), 317–333 (2010). https://doi.org/10.1080/01969721003778584
29. Cheraghi, S.A., Almadan, A., Namboodiri, V.: Cityguide: A seamless indoor-outdoor wayfinding system for people with vision impairments. In: The 21st International ACM SIGACCESS Conference on Computers and Accessibility, ASSETS '19, pp. 542–544. Association for Computing Machinery, New York, NY, USA (2019). https://doi.org/10.1145/3308561.3354621
30. Cheraghi, S.A., Sharma, A., Namboodiri, V., Arsal, G.: Safeexit4aii: An inclusive indoor emergency evacuation system for people with disabilities. In: Proceedings of the 16th Web For All 2019 Personalization - Personalizing the Web, W4A '19, pp. 1–10. Association for Computing Machinery, New York, NY, USA (2019). https://doi.org/10.1145/3315002.3317569
31. Chouikh, A.: Handywin: a crowdsourcing-mapping solution towards accessible cities. In: Proceedings of the 19th Annual International Conference on Digital Government Research: Governance in the Data Age, DG.O 2018, Delft, The Netherlands, May 30–June 01, 2018, pp. 26:1–26:6. ACM (2018)
32. Cohen, R., de Duarte, C.R.S.: Virtual accessibility guide in Brazil. In: Advances in Intelligent Systems and Computing, vol. 500, pp. 475–486. Springer (2016). https://doi.org/10.1007/978-3-319-41962-6_42
33. Comai, S., De Bernardi, E., Matteucci, M., Salice, F.: Maps for easy paths (mep): Enriching maps with accessible paths using mep traces. In: Gaggi, O., Manzoni, P., Palazzi, C., Bujari, A., Marquez-Barja, J.M. (eds.) Smart Objects and Technologies for Social Good, pp. 254–263. Springer International Publishing, Cham (2017)
34. Comai, S., Kayange, D., Mangiarotti, R., Matteucci, M., Yavuz, S.U., Valentini, F.: Mapping City Accessibility: Review and Analysis. In: Studies in Health Technology and Informatics, vol. 217, pp. 325–331. IOS Press (2015)
35. Constantinescu, A., Müller, K., Haurilet, M., Petrausch, V., Stiefelhagen, R.: Bring the environment to life: A sonification module for people with visual impairments to improve situation awareness. In: Proceedings of the 2020 International Conference on Multimodal Interaction, ICMI '20, p. 50–59. ACM, New York, NY, USA (2020). https://doi.org/10.1145/3382507.3418874
36. Constantinescu, A., Petrausch, V., Müller, K., Stiefelhagen, R.: Towards a standardized grammar for navigation systems for persons with visual impairments. In: The 21st International ACM SIGACCESS Conference on Computers and Accessibility, ASSETS '19, pp. 539–541. ACM, New York, NY, USA (2019). https://doi.org/10.1145/3308561.3354618
37. da Silva Lima, N., Leite, J.P.C., de Paiva, A.C., Maia, I.M.O., Silva, A.C., Junior, G.B., de Souza Baptista, C.: Mobile application for crowdmapping accessibility places and generation of accessible routes. In: Ahram, T.Z., Falcão, C. (eds.) Advances in Usability, User Experience and Assistive Technology, pp. 934–942. Springer International Publishing, Cham (2019)
38. Dakopoulos, D., Bourbakis, N.G.: Wearable obstacle avoidance electronic travel aids for blind: a survey. IEEE Trans. Syst. Man Cybernet. Part C (Appl. Rev.) **40**(1), 25–35 (2010). https://doi.org/10.1109/TSMCC.2009.2021255
39. Davis, F.D.: Perceived usefulness, perceived ease of use, and user acceptance of information technology. Manag. Inf. Syst. Q. **13**(3), 319–340 (1989)
40. Dawidson, E.: Pedestrian Navigation in Stockholm—How Local Data Together with Advanced Positioning Techniques can be Used for Detailed Routing. In: 16th ITS World Congress and Exhibition on Intelligent Transport Systems and Services, pp. 1–8 (2009)
41. de Oliveira, L.C., Soares, A.B., Cardoso, A., Andrade, A.d.O., Lamounier Júnior, E.A.: Mobile augmented reality enhances indoor navigation for wheelchair users. Revista Brasileira de Engenharia Biomedica **32**(2), 111–122 (2016). https://doi.org/10.1590/2446-4740.01515
42. Deepthi Jain, B., Thakur, S.M., Suresh, K.V.: Visual Assistance for Blind Using Image Processing. In: Proceedings of the 2018 IEEE International Conference on Communication and Signal Processing, ICCSP 2018, pp. 499–503. IEEE (2018). https://doi.org/10.1109/ICCSP.2018.8524251
43. Delnevo, G., Mambelli, G., Rubano, V., Prandi, C., Mirri, S.: Almawhere 2.0: a pervasive system to facilitate indoor wayfinding. In: 2020 IEEE 17th Annual Consumer Communications Networking Conference (CCNC), pp. 1–4 (2020). https://doi.org/10.1109/CCNC46108.2020.9045209
44. Delnevo, G., Monti, L., Vignola, F., Salomoni, P., Mirri, S.: AlmaWhere: A prototype of accessible indoor wayfinding and navigation system. In: CCNC 2018—2018 15th IEEE Annual Consumer Communications and Networking Conference, vol. 2018, pp. 1–6. IEEE (2018). https://doi.org/10.1109/CCNC.2018.8319242
45. Depari, A., Flammini, A., Fogli, D., Magrino, P.: Indoor localization for evacuation management in emergency scenarios. In: 2018 Workshop on Metrology for Industry 4.0 and IoT, pp. 146–150 (2018)
46. Devi, A., Therese, M.J., Ganesh, R.S.: Smart navigation guidance system for visually challenged people. In: 2020 International Conference on Smart Electronics and Communication (ICOSEC), pp. 615–619 (2020). https://doi.org/10.1109/ICOSEC49089.2020.9215289
47. Doore, S.A., Sarrazin, A., Giudice, N.A.: Natural-language scene descriptions for accessible non-visual museum exhibit exploration and engagement. In: Stock, K., Jones, C.B., Tenbrink, T. (eds.) Proceedings of the Workshop on Speaking of Location 2019: Communicating about Space co-located with 14th International Conference on Spatial Information Theory (COSIT 2019), Regensburg, Germany, September 9-13, 2019, CEUR Workshop Proceedings, vol. 2455, pp. 91–100. CEUR-WS.org (2019)
48. Edinger, J., Hofmann, A., Wachner, A., Becker, C., Raychoudhury, V., Krupitzer, C.: Wheelshare: Crowd-sensed surface classification for accessible routing. In: 2019 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops), pp. 584–589 (2019)
49. El-taher, F.E.z., Taha, A., Courtney, J., Mckeever, S.: A systematic review of urban navigation systems for visually impaired people. Sensors (2021). https://doi.org/10.3390/s21093103
50. Elmannai, W., Elleithy, K.: Sensor-based assistive devices for visually-impaired people: current status, challenges, and future directions. Sensors (2017). https://doi.org/10.3390/s17030565
51. Engel, C., Müller, K., Constantinescu, A., Loitsch, C., Petrausch, V., Weber, G., Stiefelhagen, R.: Travelling more independently: A requirements analysis for accessible journeys to unknown buildings for people with visual impairments. In: The 22nd International ACM SIGACCESS Conference on Computers and Accessibility, ASSETS '20. ACM, New York, NY, USA (2020). https://doi.org/10.1145/3373625.3417022

52. Faria, J., Lopes, S., Fernandes, H., Martins, P., Barroso, J.: Electronic white cane for blind people navigation assistance. In: 2010 World Automation Congress, pp. 1–7 (2010)
53. Fernandes, H., Conceição, N., Paredes, H., Pereira, A., Araújo, P., Barroso, J.: Providing accessibility to blind people using GIS. Univ. Access Inf. Soc. **11**(4), 399–407 (2012). https://doi.org/10.1007/s10209-011-0255-7
54. Fernandez, A., Insfran, E., Abrahão, S.: Usability evaluation methods for the web: a systematic mapping study. Inf. Softw. Technol. **53**(8), 789–817 (2011). https://doi.org/10.1016/j.infsof.2011.02.007
55. Ferreras, A., Barberà, R., Durá-Gil, J.V., Solaz, J., Muñoz, E.M., Serrano, M., Marqués, A.: SIMON: Integration of mobility and parking solutions for people with disabilities. In: Studies in Health Technology and Informatics, vol. 217, pp. 332–336. IOS Press (2015). https://doi.org/10.3233/978-1-61499-566-1-332
56. Fischer, G., Fogli, D., Piccinno, A.: Revisiting and broadening the meta-design framework for end-user development. In: New Perspectives in End-User Development, pp. 61–97. Springer, Cham (2017)
57. Flores, G., Manduchi, R.: Easy return: An app for indoor backtracking assistance. In: Conference on Human Factors in Computing Systems—Proceedings, vol. 2018, pp. 1–12 (2018). https://doi.org/10.1145/3173574.3173591
58. Flores, G.H., Manduchi, R.: A public transit assistant for blind bus passengers. IEEE Pervasive Comput. **17**(1), 49–59 (2018). https://doi.org/10.1109/MPRV.2018.011591061
59. Fogli, D., Arenghi, A., Gentilin, F.: A universal design approach to wayfinding and navigation. Multimedia Tools Appl. **79**, 33577–33601 (2020). https://doi.org/10.1007/s11042-019-08492-2
60. Fogli, D., Piccinno, A., Carmien, S., Fischer, G.: Exploring design trade-offs for achieving social inclusion in multi-tiered design problems. Behav. Inf. Technol. **39**(1), 27–46 (2020). https://doi.org/10.1080/0144929X.2019.1634153
61. Freina, L., Caponetto, I.: A mobile guardian angel supporting urban mobility for people with dementia—an errorless learning based approach. In: ICT4AgeingWell 2015—Proceedings of the 1st International Conference on Information and Communication Technologies for Ageing Well and e-Health, Lisbon, Portugal, 20–22 May, 2015, pp. 307–312 (2015). https://doi.org/10.5220/0005502503070312
62. Fusco, G., Cheraghi, S.A., Neat, L., Coughlan, J.M.: An indoor navigation app using computer vision and sign recognition. In: Miesenberger, K., Manduchi, R., Covarrubias Rodriguez, M., Peňáz, P. (eds.) Computers Helping People with Special Needs, pp. 485–494. Springer International Publishing, Cham (2020)
63. Galan-Marti, H., Navarro-Salvador, M.A., Naranjo-Martinez, J.C.: Vadeo: Social network for people with reduced mobility. In: eChallenges e-2010 Conference, pp. 1–8 (2010)
64. Gallagher, T., Wise, E., Li, B., Dempster, A.G., Rizos, C., Ramsey-Stewart, E.: Indoor positioning system based on sensor fusion for the Blind and Visually Impaired. In: 2012 International Conference on Indoor Positioning and Indoor Navigation, IPIN 2012—Conference Proceedings, pp. 1–9. IEEE (2012). https://doi.org/10.1109/IPIN.2012.6418882
65. Ganz, A., Schafer, J.M., Tao, Y., Wilson, C., Robertson, M.: PERCEPT-II: Smartphone based indoor navigation system for the blind. In: 2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC 2014, pp. 3662–3665. IEEE (2014). https://doi.org/10.1109/EMBC.2014.6944417
66. Garcia, J.C., Marron, M., Amaral, P.F., Bastos, T., Palazuelos, S., Martin, J.L., Gualda, D.: Proposal for a Building Accessibility Service (BASE). Assist. Technol. Res. Series **29**(January), 393–400 (2011). https://doi.org/10.3233/978-1-60750-814-4-393
67. Garcia Ramirez, A.R., da Silva, R.F.L., Cinelli, M.J., de Albornoz, A.D.C.: Evaluation of electronic haptic device for blind and visually impaired people: a case study. J. Med. Biol. Eng. **32**(6), 423–428 (2012). https://doi.org/10.5405/jmbe.925
68. Ge, H., Bessho, M., Koshizuka, N., Sakamura, K.: Model Design of Generating Path with Accessibility Semantics for Assisting Indoor Mobility. In: Proceedings—2015 IEEE International Conference on Data Science and Data Intensive Systems; 8th IEEE International Conference Cyber, Physical and Social Computing; 11th IEEE International Conference on Green Computing and Communications and 8th IEEE International, pp. 139–146. IEEE (2015). https://doi.org/10.1109/DSDIS.2015.55
69. Giannoumis, A.G., Gjøsæter, T., Paupini, C.: Towards an indoor navigation application for emergency evacuations and persons with visual impairments—experiences from first responders and end users. In: Murayama, Y., Velev, D., Zlateva, P. (eds.) Information Technology in Disaster Risk Reduction, pp. 159–167. Springer International Publishing, Cham (2020)
70. Giannoumis, A.G., Gjøsæter, T., Radianti, J., Paupini, C.: Universally designed beacon-assisted indoor navigation for emergency evacuations. In: Murayama, Y., Velev, D., Zlateva, P. (eds.) Information Technology in Disaster Risk Reduction, pp. 120–129. Springer International Publishing, Cham (2019)
71. Gintner, V., Balata, J., Boksansky, J., Mikovec, Z.: Improving reverse geocoding: Localization of blind pedestrians using conversational UI. In: 8th IEEE International Conference on Cognitive Infocommunications, CogInfoCom 2017—Proceedings, pp. 145–150 (2018). https://doi.org/10.1109/CogInfoCom.2017.8268232
72. Gleason, C.: Crowdsourcing the installation and maintenance of indoor navigation infrastructure. In: ASSETS 2017—Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 411–412 (2017). https://doi.org/10.1145/3132525.3134827
73. Gleason, C., Guo, A., Laput, G., Kitani, K., Bigham, J.P.: VizMap: Accessible visual information through crowdsourced map reconstruction. In: ASSETS 2016 - Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 273–274 (2016). https://doi.org/10.1145/2982142.2982200
74. Gong, J., Feeley, C., Tang, H., Olmschenk, G., Nair, V., Zhou, Z., Yu, Y., Yamamoto, K., Zhu, Z.: Building smart and accessible transportation hubs with internet of things, big data analytics, and affective computing. In: International Conference on Sustainable Infrastructure 2017: Technology—Proceedings of the International Conference on Sustainable Infrastructure 2017, pp. 126–138 (2017). https://doi.org/10.1061/9780784481219.012
75. Guerreiro, J., Sato, D., Ahmetovic, D., Ohn-Bar, E., Kitani, K.M., Asakawa, C.: Virtual navigation for blind people: transferring route knowledge to the real-world. Int. J. Hum Comput Stud. **135**, 102369 (2020). https://doi.org/10.1016/j.ijhcs.2019.102369
76. Guimares, C.S.S., Henriques, R.V.B., Pereira, C.E.: Tracking system proposal of walking sticks aiming the orientation and mobility of the visually impaired. IFAC-PapersOnLine **49**(30), 161–166 (2016). https://doi.org/10.1016/j.ifacol.2016.11.147
77. Harrington, N., Antuña, L., Coady, Y.: Able transit: A mobile application for visually impaired users to navigate public transit. In: 2012 Seventh International Conference on Broadband, Wireless Computing, Communication and Applications, pp. 402–407 (2012). https://doi.org/10.1109/BWCCA.2012.72
78. Hussain, I., Chen, L., Mirza, H.T., Chen, G., Hassan, S.U.: Right mix of speech and non-speech: hybrid auditory feedback

in mobility assistance of the visually impaired. Univ. Access Inf. Soc. **14**(4), 527–536 (2015). https://doi.org/10.1007/s10209-014-0350-7
79. Idrees, A., Iqbal, Z., Ishfaq, M.: An efficient indoor navigation technique to find optimal route for blinds using QR codes. In: Proceedings of the 2015 10th IEEE Conference on Industrial Electronics and Applications, ICIEA 2015, pp. 690–695. IEEE (2015). https://doi.org/10.1109/ICIEA.2015.7334197
80. Islam, M.M., Sheikh Sadi, M., Zamli, K.Z., Ahmed, M.M.: Developing walking assistants for visually impaired people: a review. IEEE Sens. J. **19**(8), 2814–2828 (2019). https://doi.org/10.1109/JSEN.2018.2890423
81. Jayakody, J.A., Murray, I., Hermann, J., Lokuliyana, S., Dunuwila, V.R.: Enhanced algorithmic implementation to assist real-time indoor map generation for vision impaired individuals. In: 13th International Conference on Computer Science and Education, ICCSE 2018, pp. 352–357. IEEE (2018). https://doi.org/10.1109/ICCSE.2018.8468690
82. Jimenez, L.F., Morreale, P.: Mobile assistive technology mapping and integration. In: Antona, M., Stephanidis, C. (eds.) Universal Access in Human–Computer Interaction. Access to Today's Technologies, pp. 306–317. Springer International Publishing, Cham (2015)
83. Karimi, H.A., Hashemi, M.: Accessible wayfinding testbed: infrastructure and components. In: EAI International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities (TRIDENTCOM) (2015). https://doi.org/10.4108/icst.tridentcom.2015.259709
84. Karimi, H.A., Zhang, L., Benner, J.G.: Personalized accessibility map (PAM): a novel assisted wayfinding approach for people with disabilities. Ann. GIS **20**(2), 99–108 (2014). https://doi.org/10.1080/19475683.2014.904438
85. Kawaguchi, A., Nagel, A., Chan, C., Parker, N.A.: Building a community information system for supporting disabled bus riders and local businesses. In: Filipe, J., Cordeiro, J. (eds.) Web Information Systems and Technologies, pp. 188–201. Springer, Berlin (2011)
86. Khaled, N., Mohsen, S., El-Din, K.E., Akram, S., Metawie, H., Mohamed, A.: In-door assistant mobile application using cnn and tensorflow. In: 2020 International Conference on Electrical, Communication, and Computer Engineering (ICECCE), pp. 1–6 (2020). https://doi.org/10.1109/ICECCE49384.2020.9179386
87. Khan, S., Nazir, S., Khan, H.U.: Analysis of navigation assistants for blind and visually impaired people: a systematic review. IEEE Access **9**, 26712–26734 (2021). https://doi.org/10.1109/ACCESS.2021.3052415
88. Kishore, A., Bhasin, A., Balaji, A., Vuppalapati, C., Jadav, D., Anantharaman, P., Gangras, S.: CENSE: A cognitive navigation system for people with special needs. In: Proceedings—3rd IEEE International Conference on Big Data Computing Service and Applications, BigDataService 2017, pp. 198–203. IEEE (2017). https://doi.org/10.1109/BigDataService.2017.32
89. Kitchenham, B.A., Budgen, D., Pearl Brereton, O.: Using mapping studies as the basis for further research—a participant-observer case study. Inf. Softw. Technol. **53**(6), 638–651 (2011). https://doi.org/10.1016/j.infsof.2010.12.011
90. Lim, K.L., Seng, K.P., Yeong, L.S., Ang, L.M.: RFID and dead-reckoning-based indoor navigation for visually impaired pedestrians. In: Handbook of Research on Recent Developments in Intelligent Communication Application, pp. 380–396. IGI Global (2017). https://doi.org/10.4018/978-1-5225-1785-6.ch015
91. Loitsch, C., Müller, K., Engel, C., Weber, G., Stiefelhagen, R.: Accessiblemaps: Addressing gaps in maps for people with visual and mobility impairments. In: Miesenberger, K., Manduchi, R., Covarrubias Rodriguez, M., Peňáz, P. (eds.) Computers Helping People with Special Needs, pp. 286–296. Springer International Publishing, Cham (2020)
92. Mancini, A., Frontoni, E., Zingaretti, P.: Embedded multisensor system for safe point-to-point navigation of impaired users. IEEE Trans. Intell. Transp. Syst. **16**(6), 3543–3555 (2015). https://doi.org/10.1109/TITS.2015.2489261
93. Marques, V.L., Reis Graeml, A.: Collective intelligence and accessible ways in the city collective intelligence and the mapping of accessible ways in the city: a systematic literature review. In: Americas Conference on Information Systems 2017, pp. 1–10. Association for Information Systems (2017)
94. Martinez, M., Roitberg, A., Koester, D., Stiefelhagen, R., Schauerte, B.: Using technology developed for autonomous cars to help navigate blind people. In: 2017 IEEE International Conference on Computer Vision Workshops (ICCVW), pp. 1424–1432 (2017). https://doi.org/10.1109/ICCVW.2017.169
95. Mattheiss, E., Krajnc, E.: Route descriptions in advance and turn-by-turn instructions—usability evaluation of a navigational system for visually impaired and blind people in public transport. In: Holzinger, A., Ziefle, M., Hitz, M., Debevc, M. (eds.) Human Factors in Computing and Informatics, pp. 284–295. Springer, Berlin (2013)
96. Mehigan, T.J., Pitt, I.: Harnessing wireless technologies for campus navigation by blind students and visitors. In: Miesenberger, K., Karshmer, A., Penaz, P., Zagler, W. (eds.) Computers Helping People with Special Needs, pp. 67–74. Springer, Berlin (2012)
97. Melis, A., Mirri, S., Prandi, C., Prandini, M., Salomoni, P.: A microservice-based architecture for the development of accessible, crowdsensing-based mobility platforms. In: Proceedings—2016 International Conference on Collaboration Technologies and Systems, CTS 2016, pp. 498–505. IEEE (2016). https://doi.org/10.1109/CTS.2016.91
98. Melis, A., Mirri, S., Prandi, C., Prandini, M., Salomoni, P., Callegati, F.: Integrating personalized and accessible itineraries in MaaS ecosystems through microservices. Mobile Netw. Appl. **23**(1), 167–176 (2018). https://doi.org/10.1007/s11036-017-0831-z
99. Menkens, C., Sussmann, J., Al-Ali, M., Breitsameter, E., Frtunik, J., Nendel, T., Schneiderbauer, T.: EasyWheel—A mobile social navigation and support system for wheelchair users. In: Proceedings—2011 8th International Conference on Information Technology: New Generations, ITNG 2011, pp. 859–866. IEEE (2010). https://doi.org/10.1109/ITNG.2011.149
100. Milicchio, F., Prosperi, M.: Accessible tourism for the deaf via mobile apps. In: ACM International Conference Proceeding Series, vol. 29-June-20, pp. 1–7. Association for Computing Machinery (2016). https://doi.org/10.1145/2910674.2910694
101. Mirri, S., Prandi, C., Salomoni, P.: Personalizing Pedestrian Accessible way-finding with mPASS. In: 2016 13th IEEE Annual Consumer Communications and Networking Conference, CCNC 2016, pp. 1119–1124. Institute of Electrical and Electronics Engineers Inc. (2016). https://doi.org/10.1109/CCNC.2016.7444946
102. Mirri, S., Prandi, C., Salomoni, P., Callegati, F., Campi, A.: On combining crowdsourcing, sensing and open data for an accessible smart city. In: Proceedings—2014 8th International Conference on Next Generation Mobile Applications, Services and Technologies, NGMAST 2014, pp. 294–299. IEEE (2014). https://doi.org/10.1109/NGMAST.2014.59
103. Mirri, S., Prandi, C., Salomoni, P., Callegati, F., Melis, A., Prandini, M.: A Service-Oriented Approach to Crowdsensing for Accessible Smart Mobility Scenarios. Mobile Information Systems **2016** (2016). https://doi.org/10.1155/2016/2821680
104. Montague, K.: Accessible Indoor Navigation. In: Proceeding ASSETS '10 Proceedings of the 12th international ACM

SIGACCESS conference on Computers and accessibility, p. 2. ACM (2010)
105. Montella, C., Perkins, T., Spletzer, J., Sands, M.: To the bookstore! autonomous wheelchair navigation in an urban environment. In: Yoshida, K., Tadokoro, S. (eds.) Field and Service Robotics: Results of the 8th International Conference, pp. 249–263. Springer, Berlin (2014). https://doi.org/10.1007/978-3-642-40686-7_17
106. Mora, H., Gilart-Iglesias, V., Pérez-del Hoyo, R., Andújar-Montoya, M.D.: A comprehensive system for monitoring urban accessibility in smart cities. Sensors **17**(8), 1834 (2017)
107. Murata, M., Ahmetovic, D., Sato, D., Takagi, H., Kitani, K.M., Asakawa, C.: Smartphone-based localization for blind navigation in building-scale indoor environments. Pervasive Mob. Comput. **57**, 14–32 (2019). https://doi.org/10.1016/j.pmcj.2019.04.003
108. Nicklas, J.P., Schluter, N., Winzer, P., Schnieder, L.: Accessible and inclusive mobility for all with individual travel assistance-Aim4It. In: IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC, vol. 2015, pp. 1569–1574. IEEE (2015). https://doi.org/10.1109/ITSC.2015.256
109. Oksana, L., Ihor, T., Pavlo, L.: Navigation assistive application for the visually impaired people. In: 2020 IEEE 11th International Conference on Dependable Systems, Services and Technologies (DESSERT), pp. 320–325 (2020). https://doi.org/10.1109/DESSERT50317.2020.9125013
110. Palazzi, C.E., Bujari, A.: Fostering accessible urban mobility through smart mobile applications. In: 2016 13th IEEE Annual Consumer Communications and Networking Conference, CCNC 2016, pp. 1141–1145. IEEE (2016). https://doi.org/10.1109/CCNC.2016.7444950
111. Panta, Y.R., Azam, S., Shanmugam, B., Yeo, K.C., Jonkman, M., De Boer, F., Alazab, M.: Improving accessibility for mobility impaired people in smart city using crowdsourcing. In: 2019 Cybersecurity and Cyberforensics Conference (CCC), pp. 47–55 (2019)
112. Pariti, J., Tibdewal, V., Oh, T.: Intelligent mobility cane - lessons learned from evaluation of obstacle notification system using a haptic approach. In: Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems, CHI EA '20, p. 1–8. ACM, New York, NY, USA (2020). https://doi.org/10.1145/3334480.3375217
113. Paternò, F., Santoro, C.: End-user development for personalizing applications, things, and robots. Int. J. Hum Comput Stud. **131**, 120–130 (2019). https://doi.org/10.1016/j.ijhcs.2019.06.002
114. Pereira, C., Sousa, A., Filipe, V.: Open-Source Indoor Navigation System Adapted to Users with Motor Disabilities. In: Procedia Computer Science, vol. 67, pp. 38–47. Elsevier B.V. (2015). https://doi.org/10.1016/j.procs.2015.09.247
115. Pérez, J.E., Arrue, M., Kobayashi, M., Takagi, H., Asakawa, C.: Assessment of semantic taxonomies for blind indoor navigation based on a shopping center use case. In: Proceedings of the 14th Web for All Conference, W4A 2017, pp. 1–4. ACM (2017). https://doi.org/10.1145/3058555.3058575
116. Perez-Jimenez, R., Rabadan, J., Guerra, V., Aguiar, L., Rufo, J.: Fundamentals of Indoor Vlp: Providing Autonomous Mobility for Visually Impaired People. In: 2017 International Work Conference on Bio-Inspired Intelligence: Intelligent Systems for Biodiversity Conservation, IWOBI 2017—Proceedings, pp. 1–6. IEEE (2017). https://doi.org/10.1109/IWOBI.2017.7985542
117. Prandi, C., Delnevo, G., Salomoni, P., Mirri, S.: On supporting university communities in indoor wayfinding: An inclusive design approach. Sensors **21**(9), 3134 (2021)
118. Prandi, C., Ferretti, S., Mirri, S., Salomoni, P.: Trustworthiness in crowd-sensed and sourced georeferenced data. In: 2015 IEEE International Conference on Pervasive Computing and Communication Workshops (PerCom Workshops), pp. 402–407. IEEE (2015)
119. Prandi, C., Mirri, S., Ferretti, S., Salomoni, P.: On the need of trustworthy sensing and crowdsourcing for urban accessibility in smart city. ACM Trans. Internet Technol. **18**(1), 1–21 (2017). https://doi.org/10.1145/3133327
120. Richter, J., Lorenz, J., Costantino, M., Traubinger, V., Tauchmann, N., Graichen, T., Heinkel, U.: Dynamic indoor navigation and orientation system for people with impairments. In: Proceedings of the Conference on Mensch Und Computer, MuC '20, pp. 473–477. ACM, New York, NY, USA (2020). https://doi.org/10.1145/3404983.3410000
121. Rodriguez-Sanchez, M.C., Martinez-Romo, J.: GAWA—Manager for accessibility Wayfinding apps. Int. J. Inf. Manag. **37**(6), 505–519 (2017). https://doi.org/10.1016/j.ijinfomgt.2017.05.011
122. Ruta, M., Scioscia, F., Ieva, S., Filippis, D.D., Sciascio, E.D.: Indoor/outdoor mobile navigation via knowledge-based POI discovery in augmented reality. In: Proceedings—2015 IEEE/WIC/ACM International Joint Conference on Web Intelligence and Intelligent Agent Technology, WI-IAT 2015, pp. 26–30. IEEE (2016). https://doi.org/10.1109/WI-IAT.2015.243
123. Sánchez, J., De Borba Campos, M., Espinoza, M., Merabet, L.B.: Accessibility for people who are blind in public transportation systems. In: UbiComp 2013 Adjunct—Adjunct Publication of the 2013 ACM Conference on Ubiquitous Computing, pp. 753–756 (2013). https://doi.org/10.1145/2494091.2496002
124. Serrão, M., Rodrigues, J.M., Rodrigues, J.I., Du Buf, J.M.: Indoor localization and navigation for blind persons using visual landmarks and a GIS. In: Procedia Computer Science, vol. 14, pp. 65–73. Elsevier B.V. (2012). https://doi.org/10.1016/j.procs.2012.10.008
125. Serrão, M., Shahrabadi, S., Moreno, M., José, J.T., Rodrigues, J.I., Rodrigues, J.M., du Buf, J.M.: Computer vision and GIS for the navigation of blind persons in buildings. Univ. Access Inf. Soc. **14**(1), 67–80 (2015). https://doi.org/10.1007/s10209-013-0338-8
126. Sili, M., Gira, M., Mayer, C.: Usability matters. In: Kurosu, M. (ed.) Human–Computer Interaction. User Interface Design, Development and Multimodality, pp. 384–394. Springer International Publishing, Cham (2017)
127. Silva, C.S., Wimalaratne, P.: State-of-art-in-indoor navigation and positioning of visually impaired and blind. In: 17th International Conference on Advances in ICT for Emerging Regions (ICTer)—2017, pp. 1 – 6 (2017)
128. Silva M., Gomes A., Teixeira A.R., O.J.: BLUEEYES—Easing the navigation and orientation of blind peoole. In: International Conferences Interfaces and Human Computer Interaction 2018; Game and Entertainment Technologies 2018; and Computer Graphics, Visualization, Computer Vision and Image Processing 2018, pp. 117–124. IADIS Press (2018)
129. Sinkonde, D., Mselle, L., Shidende, N., Comai, S., Matteucci, M.: Accessible urban by modeling the explicit data using fuzzy logic. In: ACM International Conference Proceeding Series, pp. 1–7. ACM (2017). https://doi.org/10.1145/3231830.3231844
130. Spindler, M., Weber, M., Prescher, D., Miao, M., Weber, G., Ioannidis, G.: Translating floor plans into directions. In: Miesenberger, K., Karshmer, A., Penaz, P., Zagler, W. (eds.) Computers Helping People with Special Needs, pp. 59–66. Springer, Berlin (2012)
131. Story, M.F.: Principles of universal design. In: Preiser, W., Ostroff, E. (eds.) Universal design handbook, chap. 4. McGraw-Hill, New York (2001)
132. Story, M.F., Mueller, J.L., Mace, R.L.: The universal design file: designing for people of all ages and abilities. School of Design, the Center for Universal Design, NC State University (1998)

133. Taylor, B., Lee, D.J., Zhang, D., Xiong, G.: Smart phone-based Indoor guidance system for the visually impaired. In: 2012 12th International Conference on Control, Automation, Robotics and Vision, ICARCV 2012, pp. 871–876 (2012). https://doi.org/10.1109/ICARCV.2012.6485272
134. Vlahovic, N., Glazar, D.: Urban accessibility application for users with mobility impairments: conceptual model based on social networking and volunteered geographic information. MIPRO **2018**, 1365–1369 (2018)
135. Wang, F., Xu, Z., Zhang, W., Wu, S., Zhang, Y., Coleman, S.: An adaptive control approach for intelligent wheelchair based on bci combining with qoo. In: 2020 International Joint Conference on Neural Networks, IJCNN 2020—Proceedings, International Joint Conference on Neural Networks (IJCNN). IEEE, United States (2020). https://doi.org/10.1109/IJCNN48605.2020.9207175
136. Wang, H.C., Katzschmann, R.K., Teng, S., Araki, B., Giarré, L., Rus, D.: Enabling independent navigation for visually impaired people through a wearable vision-based feedback system. In: 2017 IEEE International Conference on Robotics and Automation (ICRA), pp. 6533–6540 (2017). https://doi.org/10.1109/ICRA.2017.7989772
137. Watanabe, C., Minagawa, J.: Event venue navigation for visually impaired people. In: IEEE International Conference on BigData and Smart Computing (BigComp), pp. 1–6. Kyoto, Japan (2019)
138. Wen, L., Nee, C., Chun, K., Shiang-Yen, T., Idrus, R.: Application of WiFi-based indoor positioning system in handheld directory system. In: Proceedings of the WSEAS international conferences : Paris, France, April 28 - 30, 2011; European Computing Conference (ECC '11), 4th WSEAS International Conference on Finite Differences, Finite Elements, Finite Volumes, Boundary Elements (F-and-B '11), pp. 21–27. WSEAS Press (2011)
139. Winter, S., Tomko, M., Vasardani, M., Richter, K.F., Khoshelham, K., Kalantari, M.: Infrastructure-independent indoor localization and navigation. ACM Comput. Surv. (2019). https://doi.org/10.1145/3321516
140. Wise, E., Li, B., Gallagher, T., Dempster, A.G., Rizos, C., Ramsey-Stewart, E., Woo, D.: Indoor navigation for the blind and vision impaired: Where are we and where are we going? In: 2012 International Conference on Indoor Positioning and Indoor Navigation, IPIN 2012—Conference Proceedings, pp. 1 – 7 (2012). https://doi.org/10.1109/IPIN.2012.6418894
141. Yang, R., Park, S., Mishra, S.R., Hong, Z., Newsom, C., Joo, H., Hofer, E., Newman, M.W.: Supporting spatial awareness and independent wayfinding for pedestrians with visual impairments. In: The Proceedings of the 13th International ACM SIGACCESS Conference on Computers and Accessibility, ASSETS '11, pp. 27–34. ACM, New York, NY, USA (2011). https://doi.org/10.1145/2049536.2049544
142. Yu, X., Yang, G., Jones, S., Saniie, J.: Ar marker aided obstacle localization system for assisting visually impaired. In: 2018 IEEE International Conference on Electro/Information Technology (EIT), pp. 271–276 (2018)
143. Zeng, L., Weber, G.: GeoCoach: a cross-device hypermedia system to assist visually impaired people to gain environmental accessibility. Informatik-Spektrum **40**(6), 527–539 (2017). https://doi.org/10.1007/s00287-017-1071-0