

Wayfinding and Navigation for People with Disabilities Using Social Navigation Networks

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Abstract

To achieve safe and independent mobility, people usually depend on published information, prior experience, the knowledge of others, and/or technology to navigate unfamiliar outdoor and indoor environments. Today, due to advances in various technologies, wayfinding and navigation systems and services are commonplace and are accessible on desktop, laptop, and mobile devices. However, despite their popularity and widespread use, current wayfinding and navigation solutions often fail to address the needs of people with disabilities (PWDs). We argue that these shortcomings are primarily due to the ubiquity of the compute-centric approach adopted in these systems and services, where they do not benefit from the experience-centric approach. We propose that following a hybrid approach of combining experience-centric and compute-centric methods will overcome the shortcomings of current wayfinding and navigation solutions for PWDs.

Keywords: wayfinding, navigation, social navigation networks, people with disabilities, assistive technology.

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1. Introduction

Mobility is an important human activity that often requires assistance from others who are familiar with the environment or from technologies, especially in unfamiliar environments. The advancement, uniqueness, ease of use, and affordability of various technologies have paved the way for the development of many different wayfinding and navigation approaches and tools. Today the use of technology for wayfinding and/or navigation, which are two different and related tasks, is commonplace. In this paper, we define wayfinding as searching and evaluating different route options for a given trip, and we define navigation as providing necessary instructions to guide a user along a chosen route in real time. Accordingly, wayfinding will primarily focus on route planning, while navigation will incorporate

elements of localization and tracking. In many cases, especially for PWDs, wayfinding and navigation go hand-in-hand because routes may need to be re-planned dynamically due to prevailing conditions during traversal of a pre-planned route.

Wayfinding and navigation systems for drivers made their debut in mid-1990s when GPS became fully operational. More recently, services that can assist pedestrians with wayfinding and navigation have been the focus of researchers and developers mainly due to the widespread use of smartphones. However, there are differences between wayfinding and navigation of drivers and those of pedestrians [35]. Most notable is the type of road map needed for driving versus a sidewalk map necessary for travel by foot. Equally important is the inclusion of indoor navigation and wayfinding for pedestrians in comparison to drivers. While these differences are being realized and new navigation services are becoming available on smartphones and other mobile

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devices, current services fall short of addressing the wayfinding and navigation needs and preferences of people with disabilities (PWDs). An example of this shortcoming is the lack of information regarding accessible entrances to buildings or locations of curb-cuts located at corners of intersections. In the absence of accessibility information about the environment which they are navigating, PWDs may not be able to take the routes that are suggested for the general population or may take routes that are not safe and/or comfortable.

In this paper, we focus on wayfinding and navigation solutions for PWDs. Some of the challenges for implementing services that can assist PWDs with their wayfinding and navigation needs and preferences are:

- a) developing models that can reflect the exact needs and preferences of each individual with disabilities, given the range of disability conditions and individual preferences
- b) capturing and adequately quantifying all the parameters that affect wayfinding choices and navigation preferences
- c) building accurate sidewalk network databases in a scalable and affordable manner
- d) updating sidewalk network databases with frequent changes (such as construction) in a scalable and affordable manner
- e) mapping indoor spaces in affordable and scalable ways while preserving the privacy of relevant information as needed
- f) presenting navigation information at the level of detail necessary for PWDs with different constraints and preferences

These challenges primarily affect the ubiquitous compute-centric approach adopted in most current wayfinding and navigation systems and services, where maps and algorithms are used to compute appropriate routes. Therefore, the current maps and algorithms must be enhanced in many ways to incorporate the needs and preferences of PWDs. Many of these challenges can be mitigated by adopting an experience-centric approach, where communication and collaboration among members of social navigation networks and other trusted sources form the basis of providing wayfinding assistance [32]. However, experience-centric approaches have their own limitations in dealing with erroneous data, identifying trusted sources, and obtaining and maintaining sufficient, accurate, and relevant data to cover the wayfinding and navigation needs of PWDs. In fact, experience-centric approaches are likely to be better suited for wayfinding solutions, while compute-centric approaches are often needed for successful navigation systems. However, as previously mentioned, wayfinding and navigation are both important, and solutions that integrate both wayfinding and navigation are usually more useful to both PWDs and the general population. Therefore, we propose a hybrid approach of combining experience-centric and compute-centric methods, which not only addresses the limitations of current wayfinding and navigation services in addressing the needs of PWDs, but is also likely to

enhance wayfinding and navigation solutions available to everyone.

In this paper, we next provide an overview of the current wayfinding and navigation systems and services available to PWDs in Section 2. We then explore the strengths and limitations of compute-centric and experience-centric approaches, and introduce our proposed hybrid compute-and-experience-centric approach in Section 3. In Section 4, we outline future research directions to fully realize the benefits of social networks in wayfinding and navigation solutions, and we conclude with a summary of the paper in Section 5.

2. Current Wayfinding and Navigation Systems for PWDs

A wide range of disabilities can impact the wayfinding and navigation needs and constraints of people traversing unfamiliar environments. In this section we review some examples of wayfinding and navigation systems available for PWDs. Our goal is not to provide a comprehensive review of such systems, but instead to illustrate some of the wayfinding and navigation needs for PWDs and examine some of the technology solutions available to them. We therefore focus on two major populations of PWDs: blind and visually impaired people, and wheelchair users.

2.1. Wayfinding and Navigation Technology for Blind and Visually Impaired (B/VI) People

While assistive technology for enhancing wayfinding and navigation capabilities of people who are B/VI has been a popular research topic for decades and has yielded many useful outcomes, the number of practical ubiquitous tools produced has been low due to numerous factors including the wide range of requirements among this user population. Wayfinding and navigation services for the B/VI population generally have to perform one or more of the following functions: familiarization, localization, route planning, and communicating with the user in a meaningful manner through an accessible interface.

The ability to safely and independently explore a new environment goes a long way in improving a person's quality of life. Without the use of visual information, exploring unfamiliar environments can sometimes become a hazardous task for people who are B/VI. As a result, many are reluctant to explore unfamiliar places. Therefore, familiarization with an environment is a key factor in enhancing the safety and independence of people who are B/VI during wayfinding. This familiarization usually happens with the guidance of an Orientation and Mobility (O&M) specialist, but using technologies such as tactile maps [3] or the help of sighted friends can also play a role in increasing the opportunities for independent travel for individuals who are B/VI. While it is not a

substitute to experiencing the real space with the guidance of an O&M specialist, a well-designed virtual navigation tool can allow people who are B/VI to remotely explore an unfamiliar environment and build an initial cognitive map of the space [4]. However, providing all of the needed cues in a scalable and sustainable manner through a virtual environment is not an easy task. Additionally, due to the wide range of landmarks and clues that can be used, and due to the wide range of visual impairments and preferences for different forms of guidance in the B/VI community, creating an environment that accommodates all of these constraints is a significant challenge.

A localization system assists a user to identify his/her location (and orientation in some cases) within a given environment. Various methods are used for localization both indoors and outdoors, with GPS technology dominating the outdoor localization techniques. The traditional approaches that do not employ technology are the use of a mental map built through guided exposure to the environment or through auditory instructions, and the use of tactile maps [2]. Maps can be advantageous in their flexibility of size while providing a visually impaired traveller with a comprehensive representation of an environment, catered specifically to the needs and constraints of that user. However, these maps lack the ability to dynamically provide the user with feedback during navigation, and cannot be easily customized for people with a variety of visual impairments or updated to reflect current information. Large physical maps can also be cumbersome to be carried around during navigation and hence are rarely used in a portable manner. A variety of other techniques are being explored to achieve indoor localization, some of which require alterations to the indoor environment or infrastructure that are not ubiquitous. Torres-Solis et al. [1] review a variety of such indoor localization technologies. Simultaneous localization and mapping (SLAM) is a technique used to simultaneously explore an environment, build a map, and localize a user in the map [5]. The technique of visual SLAM uses cameras to acquire data from the environment and then utilizes a combination of computer vision and odometry algorithms to map the surrounding space which enables robots to autonomously explore their environment [5]. Smartphone cameras are becoming increasingly powerful and affordable, and smartphones are simultaneously incorporating high-performance computers that have the necessary computing power to effectively use visual SLAM techniques [5]. This trend is a strong indicator that visual SLAM will be one of the main contributors to better localization systems in the near future.

In addition to localization, a wayfinding service must be capable of planning and communicating effective paths to the user. Localizing the user and planning the path to the user's desired destination go hand in hand. Once a user has been localized, the optimal path to destination can be determined and communicated to the user as accessible instructions. There is always a possibility that the user may veer from the recommended path for many

reasons, and a smart navigation aid will be capable of dynamically re-planning the path to the user's destination based on his/her new location. The directions must include landmarks that can be sensed during navigation by the user who is B/VI while remaining simple and effective. The navigation system should also take into consideration all the environmental information used by the B/VI for self-orientation. Furthermore, any change in any environment may confuse a user who is B/VI since some of the landmarks and clues used for wayfinding may have been altered or lost. Therefore, navigation systems for users who are B/VI must be able to incorporate accessible environmental landmarks and clues into their instruction sets, and notify users of relevant changes to the environment as needed.

Once an appropriate path to the destination has been planned, the wayfinding aid should translate the path into directions that a user can follow, and communicate these directions to the user in an accessible and non-intrusive manner. This translation and communication has to be customizable to the constraints and needs of the user who is B/VI. Moreover, the method of communicating these instructions to the user should not distract the user from paying attention to environmental landmarks and clues that he/she uses to navigate. In the following sections we review three categories of assistive navigation tools for B/VI users: narrated maps, smartphone solutions, and custom devices.

Technologies such as narrated maps have demonstrated great potential to encourage and assist B/VI people with navigation of unfamiliar environments. Narrative maps [6] are one approach to familiarizing B/VI people with an environment prior to physical interaction with that space. To create a narrative map, an O&M specialist would normally describe the indoor environment highlighting sensory landmarks or clues that will be useful for wayfinding. This usually includes an overall static description of the environment, followed by a dynamic description of the paths to be taken to various locations within the environment. This helps the B/VI traveller form an initial mental map of the environment based on this narrative map.

While several technologies use auditory descriptions and have attempted to automate the creation of narrative maps, no such solution is ubiquitous due to the many challenges entailed in extracting the relevant information about an environment and presenting this information in accessible form to B/VI users. "Directions" [6], a smartphone application, is one such attempt. This navigational aid allows users who are blind to use a series of prompts through an accessible touch screen interface to get directional guidance and instructions from a sighted user.

ClickAndGo Wayfinding Maps [7] eliminates the need for real-time help from a sighted user. It however requires any location (indoor or outdoor) to be manually surveyed before this service can be provided. After extensive surveying, navigation instructions are prepared and

recorded. A visually impaired person who wishes to go to an area of interest in a location can then simply enter start and destination landmarks through a portal on the website and gain access to detailed instructions which can be downloaded in text or audio format.

An example of a completely automated approach to providing narrated maps is StreetTalk GPS [8]. Users are allowed to search for a route to a destination from their current location or from a location of interest. StreetTalk then plans the route and provides turn-by-turn instructions that are announced using voice based commands and/or braille. It also provides a virtual navigation mode in which the user is allowed to explore the map or a certain route as though he/she were a pedestrian.

Trekker ([9], [10]) is another GPS-based navigation aid for the blind that provides automated speech-based detailed directional instructions that include information about cross streets and even informs the user if a street is two-way or not. Similar to StreetTalk, it also provides a virtual exploration mode which can be used either online or offline to traverse through locations of interest using the arrow keys on the keyboard. Trekker and StreetTalk are both designed for outdoor navigation.

Smartphone-based outdoor navigational aids for the blind that use GPS have been developed by several groups and are currently used by many B/VI people. BlindSquare [11] is one such application developed for iOS devices that makes use of data from FourSquare and Open Street Maps to help the user locate stores and cafes around them. Loadstone GPS, Mobile Geo and Seeing Eye GPS ([12], [13], [14]) are further examples of GPS-based systems that function as navigational aids for the visually impaired in outdoor environments.

Developing indoor navigation aids for B/VI users can be more challenging. Wang et al. [15] developed a system that uses all the sensors (gyroscope, accelerometer, etc.) in a smartphone to characterize a building by different signatures in different locations. These signatures are used as landmarks to determine the location of a device or user. Between landmarks, dead-reckoning is used and these location signatures are then used to correct the error accumulated in dead-reckoning. In this approach, problems such as electromagnetic variations in a specific part of a building (which usually affects specific sensor readings), are used as part of the signatures. A database of these signatures is required before this method can be deployed but it is not clear how often this database needs to be updated. Furthermore, because this work uses a variety of sensors on the smartphone to detect location signatures, the database may store signatures that require sensors that are not available on some smartphones.

Ravi et al. [16] use visual tags to solve the problem of indoor localization which also requires an extensive pre-deployment effort. Images are captured by the user's smartphone and periodically sent to a server. The server localizes the user by comparing these images with those already in its database. This method therefore requires extensive image collection throughout the target indoor

space along with a potentially large database which will have to be periodically updated.

Chintalapudi et al. [17] developed an approach where users move around inside a building and the phones transmit measured RSSI of WiFi signals from access points back to a server. Occasionally, there will be a GPS hit near an exit/entry or a window along with the measured RSSI. This is also sent back to the server. This information is processed by a localization algorithm running on the server to accomplish localization. However, this approach depends on occasional, and sometimes improbable, GPS hits indoors which will not work well in some locations (a basement for example).

Laoudias et al. [18] use crowdsourcing to collect WiFi RSSI data and neighborhood AP MAC addresses for indoor positioning. The participants record data by marking points on a map indicating their current location as they walk inside a building. The number of samples collected at each point on the map is pre-set by the participants before they start collecting data. The data is then added to a central database and is used in a WiFi fingerprinting algorithm to localize the user. If a large number of data points are collected, finer localization can be achieved and this approach can be used for creating or enhancing a navigational aid for the blind.

Navatar [19] is a cost-effective system designed for large-scale deployment. It attempts to provide navigational instructions to the user without augmenting a smartphone with external signal sources or other infrastructure. The system uses a virtual representation of the indoor environment that uses tactile landmarks (such as doors, walls, and hallway intersections), that the user can sense. Feedback from the user upon confirmation of landmarks in the environment is used as ground truth allowing Navatar to periodically update location data. In between landmarks, dead-reckoning (using smartphone sensors such as the accelerometer) is used to perform localization. The problem of accumulated error that comes with the use of dead-reckoning is overcome by periodic inputs from the user whenever he/she detects a landmark.

In addition to systems that use ubiquitous smartphones, several researchers have developed custom devices that B/VI users wear or carry as navigation aids. Drishti [20] is an example of a custom device that uses a wearable computer designed to be a navigation aid for B/VI people. The system is designed to be a navigational aid both indoors and outdoors. In an outdoor setting, it uses differential GPS to localize the user and provides instructions that allow the user to travel safely on sidewalks. Indoors, it uses an ultrasound positioning system which provides an accuracy of 22cm (approx. 8.6 inches). This system therefore requires additional infrastructure to be installed in indoor environments, but is able to provide localization of sufficient accuracy that it can be reliably used as a navigational aid for the blind. The system is also capable of dynamic path planning and re-planning.

PERCEPT [21], developed by a team of researchers at the University of Massachusetts, is another system that requires additional infrastructure since it employs passive RFID tags embedded in the indoor environment to provide navigation instructions to B/VI travellers. When a B/VI, equipped with a smartphone and the PERCEPT glove, enters a building, he/she scans the destination location at a kiosk. The traveller is then guided to the chosen destination with navigation instructions using landmarks. The kiosks have raised letters indicating room numbers/location labels along with their Braille equivalent. The PERCEPT glove, which has an RFID reader, Bluetooth radio, microcontroller and related circuitry, allows the user to freely use his/her hand to read signs by touch while scanning RFID tags at the same time. The user has the choice of interacting with the PERCEPT system either using buttons, the glove itself, or the phone. Navigation instructions are received by the phone over the server and relayed to the user after text-to-speech conversion.

Along the same lines as the PERCEPT glove, the Wayfinding Electronic Bracelet (WEB) [22] is a portable device that employs an ultrasonic transceiver mounted on a circular bracelet to perform object detection. The onboard processor runs a real-time system that provides the user with vibro-tactile and audio feedback about detected obstacles in the surrounding area through a motor and a buzzer, respectively.

Another example is the Digital Signage System (DSS) [23] which employs a hand-held device equipped with an infra-red emitter that the user pans until a reflection is received from one of many retro-reflective barcodes strategically placed in the indoor environment. The barcode is read by the DSS using this reflection and this information is fed to the building database (called the Building Navigator) which then returns to the user information about the content of the surroundings and routing to the destination using a synthetic voice as audio feedback.

The work by Hub et al. [24], like Dhrishti, uses a portable computer that is carried by the user. This system uses ultrasonic sensors and a stereo camera along with a 3D inclination sensor and a digital compass. The camera input is used to detect obstacles in the scene in front of the user while also getting information regarding object color, distance and size which can be used to suitably guide the B/VI user.

PERSEUS (Personal Help for Blind Users) developed by Vítek et al. [25] also uses a stereo camera and wearable computer, and additionally incorporates input from a sighted individual. The visually impaired user wears protective acrylate glasses fitted with two cameras and an acoustic transducer. At times of distress, the user signals the navigation center which then alerts a sighted operator. A stereoscopic video stream of the user's view transmitted to the navigation center via public WiFi is used by the operator to guide the blind user by providing audio instructions.

Kaiser et al. [26] designed a wearable navigation system that uses SLAM targeted at both indoor and outdoor environments. This custom device to be carried by the user has a short-range laser, inertial measurement unit (IMU), headphones and a wearable computer. SLAM is used to build a map of the environment that is being explored while at the same time keeping track of the user's position in that environment. The system uses the constructed map to guide the user to the desired destination using audio instructions.

2.2. Wheelchair Users

Wayfinding and navigation are critical to help ensure the full participation of wheelchair users (WCU) in society. WCU indicate the environment as the second most important factor which limits access to the community and transportation [45], second only to the user's wheelchair. Wayfinding and navigation technology can play an important role by mitigating these environmental factors by routing WCUs around these environmental barriers.

The functionality of the wayfinding technology required for WCU and B/VI is similar. Namely, as discussed in the previous section, the system must perform one or more of the following functions: familiarization, localization, route planning, and communicating with the user in a meaningful manner through an accessible interface. The key difference for WCU is that a dynamic map shown on a smartphone is accessible, but not for many B/VI travellers.

Design considerations for personalized wayfinding and navigation technology for WCU were discussed in [31] but no comprehensive system has been developed yet. Key considerations of the design include: requirements that the map database include location-based accessibility features, such as sidewalk conditions; personalized route planning algorithms that can be accomplished based on the users functional level and preferences; and positional accuracy within 3 meters.

These design considerations have been investigated by researchers and demonstration projects are in place on several university campuses and a few cities. Multicity and publicly available services are available to support wheelchair navigation, but none could be considered a comprehensive wayfinding or navigation service. In the following section, we provide an overview of these services and research topics.

2.3. Multicity and publicly available services

Wheelmap (wheelmap.org) and AXSmap (axsmap.com) are two publicly available, multi-city services which both provide wayfinding services tailored for wheelchair users. Both services focus on the first design consideration described above (location-based

accessibility features) which are crowdsourced from members.

Wheelmap is built on the OpenStreetMap service [30], which is structured to permit user-generated content to be shared among members. Wheelmap provides location-based information about whether a location is ‘wheelchair accessible’, has ‘limited accessibility’ or is ‘not wheelchair-accessible’ through a web-based or mobile application interface. Locations are broken into the following categories, which can be included or removed from the map by the user: public transportation, food, leisure, bank-post, education, shopping, sport, tourism, accommodation, and government and health. As of June 2014, Wheelmap claims the following achievements (<http://wheelmap.org/en/about/>):

- 400,000 crowdsourced data entries since 2010
- ~ 35,000/month
- Availability in 21 languages
- Most extensive data collection on the wheelchair accessibility of public places

Wheelmap has several important limitations. First, all of the sites assessed are currently located in either Europe or the UK, limiting the usefulness to wheelchair users who live in those areas. Wheelmap does not provide navigation support, only location-base accessibility indicators, and thus the user would have to plan routes on their own. No validation of the accuracy of the site assessments have been performed, so the reliability of the data is unclear. Finally, the three levels of accessibility (accessible, limited accessibility and non accessible) provides only a generic assessment which does not include the level of detail commonly noted to be necessary for wheelchair route planning [31] and [42].

AXSmap (www.axsmap.com) is built on the Google Maps API and functions similarly to Wheelmap by providing location-based assessments of accessibility. As of June 2014, 5364 places had been assessed and the target audience is in the United States. Similar to Wheelmap, there are three levels of accessibility which users can report: accessible, poor and not accessible. The same limitations listed for Wheelmap apply to AXSmap.

Google Maps offers wayfinding support for pedestrians, including route planning. Non-road routes, such as through parks, are also present in some regions, which provides additional functionality to pedestrians. Unfortunately, Google Maps does not include information relevant to the accessibility of a pedestrian path. Furthermore, there is no way to tailor Google Maps based on preferences that would be relevant to wheelchair users.

2.4. Single-site wayfinding systems for Wheelchair Users

U-Access was a web-based wayfinding navigation system developed on the University of Utah campus which was tailored for the needs of people with disabilities, including wheelchair users [41]. U-Access included features which address all three of the design considerations discussed in

[31]. An ‘individuals physical ability level’ was codified as either peripatetic, aided mobility, or wheelchair user. And depending on the ability level, the user could interact (i.e., overcome) ‘environmental objects’ which included attributes related to curb-cuts, ramps, sidewalks, entrances and parking. Depending on users ability level and their desired route, U-Access could generate routes based on a shortest path algorithm ([46]) which would be displayed through a web-browser. The pedestrian network map was developed from several data sources including data from the University of Utah’s Facility Management and Center for Disability Services. Using this data, the pedestrian routes maps were generated for each of the three physical ability levels, and then based on the user’s profile and origin and destination, a shortest path route would be generated. Users evaluated the U-Access system, but there is no information as to whether the system was fully implemented or widely used at the University of Utah or other sites.

The Personal Accessibility Location Services (PALS) is a wayfinding system tailored to people with disabilities, including wheelchair users that has been prototyped on the University of Pittsburgh Campus. The system includes three components [34]:

- A Personalized Accessibility Map, which includes locations of accessible entrances, shortest paths between buildings, and optimized paths based on the users’ preferences [36] and [37].
- A social navigation network which is a location-based network that allows PALS users to manipulate a map of their surrounding area, and to recommend and request services to or from others using PALS [34].
- A pedestrian navigation service that provides navigation guidance to PALS users [35].
- The pedestrian network data was collected manually [38]. The system has been prototyped and assessed by students who use wheelchairs [39].

Mobile Pervasive Accessibility Social Sensing (mPASS) [43] provides a conceptual overview to gather accessibility reports from users and uses a mash-up of existing services to provide route planning. For instance, the mPASS app for Andriod relies on Google Maps and Foursquare, and allows users to configure their profile, insert an ‘accessibility’ report, receive notifications to validate the accessibility barriers, view past report logs, and search for the best route.

EasyWheel [40] includes a routing service, a social community service (via Facebook), and a mapping system via OpenStreetMap. The system was in a prototype phase in 2011 but it is unclear whether it has been developed further.

RouteCheckr [44] was a wayfinding service prototyped at the Technical University of Dresden which provides route calculation which are tailored based on a users profiles. A unique characteristics of this service was the ability for the RouteCheckr to perform ‘multimodal annotation’ based on both direct annotation by the user, as well as automatically generated

information based on the users' location, orientation, and movement).

3. Enhancing Wayfinding And Navigation With Social Navigation Networks

Most wayfinding and navigation technology solutions to date are "compute-centric," based on maps, models, and algorithms. Karimi *et. al.* [32] presented a new concept for wayfinding and navigation for pedestrians called "experience-centric," where people share their wayfinding experiences with others (members) via SoNavNet [33], a Social Navigation Network. In this paper, we extend that concept for the wayfinding and navigation needs and preferences of PWDs, and propose a hybrid solution that enhances compute-centric approaches with experience-centric benefits via a social navigation network. The following sections examine the strengths and limitations of compute-centric and experience-centric approaches focusing on an example solution in each category, and outlines our proposed hybrid solution that harnesses the power of social networks to enhance wayfinding and navigation technology for PWDs.

An example compute-centric approach is the dynamic guidance tool in the NavPal system developed by Kannan et al. [27] shown in Figure 5. This Android smartphone-based indoor wayfinding and navigation tool was developed for B/VI users and integrates indoor localization [29], sparse map-representation [27], and an accessible user interface [28]. Specifically, this navigation solution combines dead reckoning (DR) and Wi-Fi signal strength fingerprinting with enhanced route-planning algorithms to account for the constraints of B/VI users to efficiently plan routes and communicate the route information with sufficient resolution. The localization component uses a small wheeled robot to initially map the indoor environments and build a database of Wi-Fi fingerprints. This P3DX robot was retrofitted with a laser rangefinder for obstacle detection and mapping, and fiber optic gyroscope for localization. The robot is remotely operated to roam a building carrying a smartphone and thereby constructs a Wi-Fi signal strength map that corresponds to the building map generated by the robot's sensors. The smartphone app is then able to use this Wi-Fi map to localize the user during navigation. The interface uses simple on-screen gestures and a combination of voice and vibration feedback to allow B/VI users to interact with the tool.



Figure 1: Initial prototype of NavPal dynamic guidance tool implemented on a smartphone

This NavPal tool represents the map of an indoor environment using a variation of hierarchical maps to accommodate dynamic changes while maintaining a compressed representation suitable for a smartphone. **Error! Reference source not found..** Indoor locations were represented on a map as nodes on a graph and the map was split into sub-graphs. A variation of the D* algorithm was used to efficiently plan and re-plan routes dynamically despite the limited computing power available on the smartphone. **Error! Reference source not found..** In this hierarchical map representation, low-level maps, which are used for higher-resolution navigation within rooms and hallways, represent individual rooms with significant spatial detail without having to represent the spatial relationships to other rooms. Complementarily, high-level maps, which are used to generate plans for coarse navigation between floors and rooms, represent larger areas of a building while omitting detailed spatial relationships of individual locations inside rooms and corridors. In this implementation, high-level maps were represented as graphs and low-level maps as grids. The high-level route planner first searches for an optimal path on the graph and provides a restricted set of nodes to the low-level route planner. This grid planner then traverses the provided nodes and generates a higher-resolution path to the destination.

While the NavPal dynamic guidance tool and other compute-centric approaches have yielded positive results in many scenarios, they require complex modeling of the environment and additional constraints in route planning algorithms to address the needs of PWDs. This approach is therefore unlikely to scale in a manner that is universally useful, given the range of needs and the diversity of PWDs. Next we examine experience-centric approaches which focus on user experiences, collaboration, and communication, instead of maps and route planning algorithms.

PWDs who experience ineffective wayfinding and navigation solutions to meet their specific needs and preferences using current technologies, are often willing to share their wayfinding experiences with others with similar needs and preferences using relevant tools such as SoNavNet [33]. Sharing wayfinding experiences among PWDs have several benefits, most important of which are:

- there is no need for capturing and quantifying parameters;
- there is no need for developing models;
- wayfinding experiences can be shared with and without sidewalk network maps;
- wayfinding experiences can be easily and equally shared in both outdoors and indoors;
- there is more trust in wayfinding experiences of other PWDs with similar needs and preferences than computer models and algorithms; and
- there is no need to compute routes.

Taking the SoNavNet approach, PWDs can share following experiences:

- a route between an origin and destination that is accessible, safe, and/or efficient ;
- a route between an origin and destination that is not accessible, safe, and/or efficient;
- a route to avoid the challenges it poses; and
- a segment of a sidewalk path or a floor plan that is closed due to construction or other obstacles.

SoNavNet is built based on the principle of the experience-centric approach and is made possible through communication and collaboration. The possibility of annotating routes is perhaps the most important feature of the experience-centric approach for PWDs in that wayfinding experiences can be detailed at both group level and individual level. For example, the suitability of a route for wheelchair users may be annotated with further details to indicate that the route could be more difficult to travel on, perhaps due to slope, for users with manual wheelchairs compared to those who use electric powered wheelchairs. SoNavNet is based on the experience-based approach and through communication (as an online social media) and collaboration (sharing and exchanging experiences), PWDs can find suitable routes both in outdoors and indoors that can meet their specific needs and preferences. SoNavNet, as an online social navigation network system, facilitate sharing and exchanging experiences on points of interest (POIs), routes of interest (ROIs), and areas of interest (AOIs).

POIs are very important for wayfinding of PWDs in that they need to be accessible as origin and destination locations. For example, in finding a suitable route to reach a restaurant, the restaurant building (destination) must have accessible entrance/exit doors to facilitate the wheelchair traveler. PWDs can annotate POIs in SoNavNet for their accessibility and specific details about specific needs and preferences. ROIs can be annotated in SoNavNet based on personalized experiences with different mobility challenges. For example, an annotation on a ROI in SoNavNet could indicate its suitability for individuals who are blind or visually impaired it avoids high traffic intersections. Such annotations may lead to different routes, which may be partially or fully different, between the same pair of origin and destination location for an individual who is blind, an individual who is visually impaired, and an individual who uses wheelchair. AOIs are also important for wayfinding of PWDs in that they can be annotated for their accessibility or otherwise in SoNavNet. For example, a certain floor may be inaccessible to B/VI temporarily due to decorations. Another example is when passage by wheelchair users may be impeded in a certain area (e.g., park) due to a flood.

As SoNavNet is made available and PWDs annotate POIs, ROIs, and AOIs, it is possible that several PWDs with the same mobility challenges annotate a given route differently. To distinguish between these differences, a set of algorithms must be designed and developed that can find and match accessibility features indoors and outdoors that meet the specific needs and preferences of an

individual with disability. Table 1 shows wayfinding features, accessibility on features, and example annotations on wayfinding features in SoNavNet.

Table 1. Wayfinding features and annotation in SoNavNet.

Feature	Accessibility	Example Annotation
POI	Accessible to enter/exit	Outdoor: A restaurant with a long ramp Indoor: An accessible restroom on a different floor
ROI	Each segment of a route to be accessible with respect to safety and comfort	Outdoor: A pedestrian path with even surface Indoor: A hallway with least traffic
AOI	Areas marked as accessible/inaccessible permanently or temporarily	Outdoor: A set of sidewalk segments blocked due to construction Indoor: A floor closed for water maintenance

Figures 1-4 are screenshots of SoNavNet. Figure 1 is the main page of SoNavNet where members can sign up onto the system with a map showing the current location. Figure 2 is a screenshot showing how a POI is selected and annotated. Figure 3 is a screenshot showing how a ROI is selected and annotated. Figure 4 is a screenshot showing how an AOI is selected and annotated.

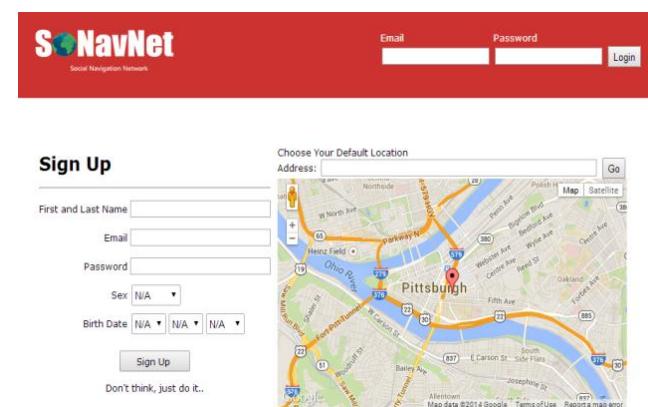


Figure 1. Main page of SoNavNet.

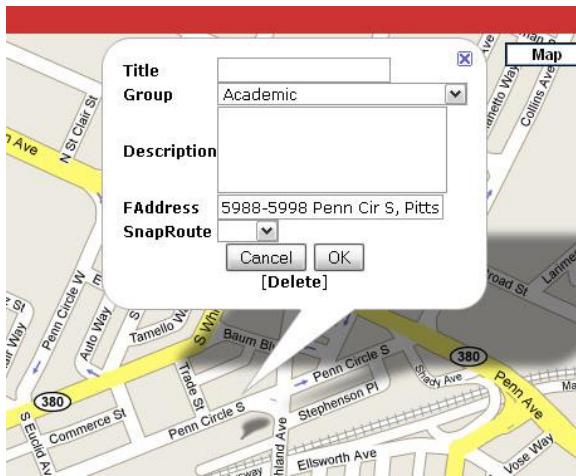


Figure 2. Example POI selection and annotation in SoNavNet.

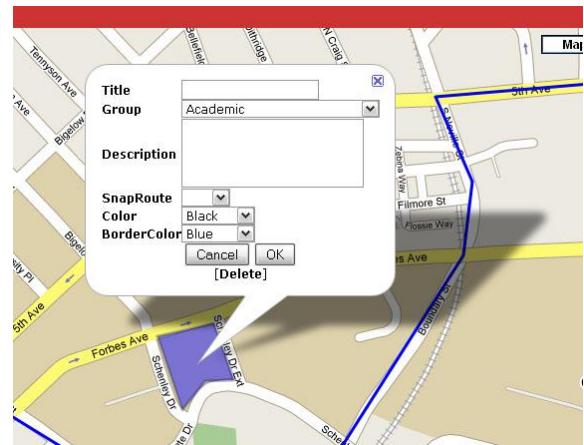


Figure 4. Example AOI selection and annotation in SoNavNet.

Table 2. Principal differences between the compute-centric and experience-centric approaches

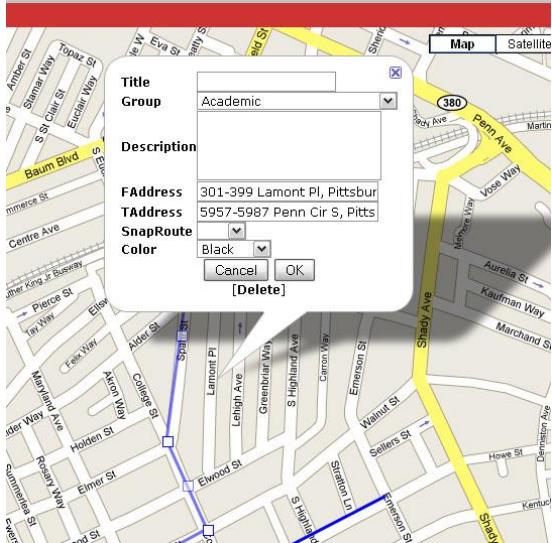


Figure 3. Example ROI selection and annotation in SoNavNet.

Having examined examples of both compute-centric and experience-centric approaches to wayfinding and navigation for PWDs, we can now compare and contrast these methodologies and present our proposed hybrid approach.

Table 2 shows the main differences between compute-centric approaches (such as NavPal) and experience-centric approaches (such as SoNavNet) from the perspective of what each needs to provide wayfinding and navigation solutions. As shown in the table, the compute-centric approach is possible (compatible) both outdoors and indoors only if the required items are available, whereas the experience-centric approach can recommend wayfinding options without such requirements.

Environment	Compute-Centric	
	Compute	Requirements
Outdoor	A route between O-D based on desired criteria	<ul style="list-style-type: none"> • Sidewalk map database • Model/algorithm/code • Specified criteria
Indoor	A route between O-D using desired criteria	<ul style="list-style-type: none"> • Floors map of a building • Model/algorithm/code • Specified criteria
Environment	Experience-Centric	
	Recommend	Requirements
Outdoor	A route between O-D	<ul style="list-style-type: none"> • An annotated route between O-D • Check annotation for accessibility match
Indoor	A route between O-D	<ul style="list-style-type: none"> • An annotated route between O-D • Check annotation for accessibility and match

Some of the notable differences between these two approaches are:

- a suitable navigation database with appropriate data is a must in the compute-centric approach, to search for locations (e.g., destinations), display maps, compute routes, among other things, whereas the experience-centric approach can operate without such a database.
- b) Wayfinding in the compute-centric approach depends on the availability of appropriate routing algorithms, which are based on specific models, whereas in the experience-centric approach practical wayfinding experiences are shared without a need to routing algorithms.
- c) In the case of real-time update, such as road closure or construction, the navigation database in the compute-centric approach needs to be updated, which is possible but usually with delay, whereas such updates

- can easily and immediately be shared through the experience-centric approach.
- d) In the compute-centric approach, different strategies and algorithms must be designed and developed for wayfinding in outdoors and wayfinding in indoors, whereas in the experience-centric approach wayfinding in outdoors and indoors can be shared similarly.
 - e) Routes in the compute-centric approach are presented to users once they are computed without the feedback of others, whereas routes shared in the experience-based approach can be annotated by highlighting specific experiences of users.

It is clear from these items above that while data and algorithms constitute the foundation of the compute-centric approach to compute routes, the experience-centric approach relies on communication and collaboration to share routes. While all the differences above must be considered in developing online social navigation networks (e.g., SoNavNet), the last two items (d and e) are of particular importance to PWDs.

Despite their many strengths, experience-centric approaches, however, are not without their limitations. Experience-centric approaches, in their reliance on user data, must successfully deal with three major challenges. First, these approaches need user input. Attracting sufficient participation from relevant sources of wayfinding information is often difficult. Moreover, all participants may not be qualified to evaluate routes for different disabilities. For example, the average sighted person is not usually capable of giving relevant navigation instructions to a blind person. Second, different types of wayfinding/navigation information have different lifespans. Examples where the data rapidly becomes stale includes maintenance detours, emergency evacuation, and congestion due to irregular events such as parades or festivals. In contrast, the addition of a new ramp to a building has a much longer lifespan of accuracy. Finally, all experience-centric systems will at some point (and sometimes frequently) encounter bad data. This typically originates from user error and occasionally from malicious sources. While the former is often due to inadvertent mistakes (for example, pressing the wrong button or clicking on the wrong spot of a map), the latter is a real concern for PWDs. For these reasons, experience-centric approaches tend to be better suited to wayfinding tasks and are often less reliable than compute-centric approaches for navigation tasks.

We propose that the most effective wayfinding and navigation solution for PWDs therefore, is to combine the best of both of these approaches, and enhance compute-centric approaches with the advantages of social navigation networks used in the experience-centric approaches. In this hybrid approach, compute-centric approaches will fill in the gaps when available for locations where user data is sparse or unreliable. Universal design is a proven way to expand value to all users, not just those willing to help PWDs. Orientation and navigation help has universal value, so it should be

possible to create a crowd experience that attracts users without disabilities to contribute relevant wayfinding information. The system will however need to use relevant compute-centric algorithms to use information provided by different users, and extract relevant information that meets the needs of specific users (especially PWDs who may have different constraints or preferences). Another example of this universal design concept is to design wayfinding tools for PWDs in a manner that enables PWDs to effectively seek assistance as needed from available sources. For example, a graphical map view on the NavPal dynamic guidance tool will enable a sighted bystander to provide assistance to a B/VI traveller more easily since the bystander can simply click on the relevant location on the map to indicate a place of interest. The proposed hybrid approach can address the lifespan of wayfinding/navigation information by tagging information with estimated lifespans, and treating this data accordingly in both algorithms and user interaction. Finally, the presence of error requires system designers to use good interaction design, error checking, and heuristics to identify, verify, and correct erroneous data. This will require a combination of compute-centric algorithms for data analysis and error prediction, and experience-centric information from trusted sources for error identification and data verification.

4. Future Research Directions

In this section, we identify key topics for future research directions in using social networks for enhancing wayfinding for PWDs.

- **Group-Individual.** Research is needed to identify specific features for systems and services (such as SoNavNet) based on experience-centric approaches that can effectively assist PWDs with wayfinding at two levels: group and individual. Distinguishing between the features for each level is important in that, while the wayfinding challenges and issues of PWDs at the group level overlap those at the individual level, each individual may have specific unique needs and preferences that may not be addressed at the group level.
- **Group-Group.** Research is needed to determine whether there should be differences between the features of wayfinding and navigation tools for people who use wheelchairs and people who are B/VI. Distinguishing between the required features for each group is important in that while there could be overlapping wayfinding challenges and issues among different groups, each group has its own specific needs and preferences.
- **Annotation.** Research is needed to find suitable ways for annotating POIs, ROIs, and AOIs, develop algorithms for evaluating annotations, and develop algorithms for matching annotations with specific wayfinding needs and preferences of PWDs.

- **Environment.** Research is needed to find the similarities and dissimilarities between the wayfinding and navigation challenges and issues of PWDs in outdoors and indoors through services such as SoNavNet.
- **Collaboration.** Research is needed to develop methodologies and algorithms that facilitate collaboration of wayfinding experiences among users of social navigation networks such as SoNavNet.
- **Metrics.** Research is needed to evaluate the effectiveness of various tools for assisting PWDs with wayfinding and navigation.
- **Data Quality:** Research is needed to determine how experience-centric gathered data can be used to update the sidewalk map data used for compute-centric approaches (e.g., when a construction project begins), and how compute-centric data can be used to validate experience-centric information.
- **Participation.** Research is needed to determine strategies to encourage PWDs and other trusted sources to participate in the experience-based components of navigation and wayfinding solutions for PWDs.

5. Summary

While wayfinding and navigation systems and services are playing an important role in enabling the mobility of people, they are not able to address the mobility challenges of PWDs. In this paper, we argue that this is largely due to the compute-centric nature of these systems and services where models and algorithms along with a map of the environment are needed to assist people in wayfinding and navigation. In contrast to compute-centric approaches, experience-centric approaches do not depend on models, algorithms, and map databases and are particularly of interest to PWDs where they can share and exchange their unique mobility experiences with other members of social navigation networks. However, since the experience-centric approach has shortcomings of its own, we propose a hybrid approach utilizing the benefits of both compute-centric and experience-centric approaches. We believe that this hybrid approach will provide a new means for wayfinding and navigation for PWDs in outdoors and indoors, and also provide richer solutions in wayfinding and navigation technology for all.

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