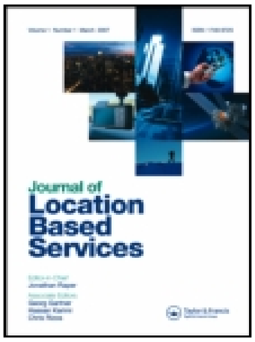

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Indoor navigation for people who are blind or vision impaired: where are we and where are we going?

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Despite over a decade of intensive research and development, the problem of delivering an effective indoor navigation system to blind and/or vision impaired (BVI) persons remains largely unsolved. In an attempt to strengthen and improve future research efforts, we define a set of criteria for evaluating the success of a potential navigation device. The requirements analysis has been broken down into the subcategories of positioning accuracy, robustness, seamlessness of integration with varying environments and, perhaps the most critical aspect, the nature of information that is provided to a BVI user. We need apply this evaluation framework to significant examples of research in this area before concluding the paper by presenting and evaluating our own system. The results of this paper clearly prove the need for a new focus and user-centred design attitude in relation to this problem – one which incorporates universal and inclusive design principles, recognises the uniqueness of the audience and understands the challenges associated with the systems/devices intended environment of use.

Keywords: indoor navigation; blind and/or vision impaired; human–computer interaction; user requirements; universal design; location information; user interface; user experience; inclusive design

1. Introduction

The task of designing an indoor navigation system for a person who is blind and/or vision impaired (BVI) is an incredibly daunting challenge, yet one that has shown is worth tackling. The complexity lies in the task of fully understanding and appreciating the uniqueness of the BVI community's varied requirements for such a device/system. Indeed, although the physical surroundings of all human beings remain the same, the internal perception of these surroundings by a person with limited or no sight is remarkably different to our own (Golledge 1993; Arditi, Holtzman, and Kosslyn 1988).

The design of a navigation device for this audience involves of course research and development in the indoor navigation field but more importantly must absolutely focus on the audiences' specific user requirements. In order to direct current and future research efforts towards this common goal, we have defined a set of criteria for evaluating the suitability and performance of a potential navigation solution. We then proceed to apply

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these criteria to some of the most significant examples of research and development over the past decade. Finally, we present our own system and the output of a session of tests conducted with 10 people who are BVI. The output of these tests is then used to objectively assess our solution against the framework defined in this paper.

It is with this exercise that we aim to summarise the best of our achievements so far as a scientific community, and to subsequently identify the areas of research which deserve further attention. It is our goal that this work provides a constructive pathway and solution towards solving the problem of a truly accessible environment which has been long attempted and has affected so many members of our global society.

2. Problem background

It is estimated that over 285 million people worldwide are vision impaired (Taylor and Bilgrami 2020). In Australia, as in most developed countries, this figure is rising at a significant rate due to a rapidly ageing population. Recent studies have estimated that vision disorders cost the country AUD 16.6 billion per annum, of which the largest portion (AUD 4.2 billion) is dedicated towards carers, assistive aids, lost earnings, and welfare and tax payments (Taylor and Bilgrami 2020). With this in mind, there can be little doubt that the development of an effective and low cost indoor navigation device would serve to meet one of Australia's major economic challenges over the next few decades.

Navigation and mobility assistance is of integral importance to the global BVI community, as it provides a means of achieving independence and social equity (WHO 2012). To this day, the most widely used and successful mobility aids are the long cane and guide dog (WHO 2012). It is due to the simplicity, popularity and adaptability of these aids that we do not strive to replace their functionality, but rather complement their use. The majority of research efforts share this objective (Liu et al. 2007; Dedes and Dempster 2005; Angin, Bhargava, and Helal 2010; Ohkubo et al. 2005). There is, however, significantly less focus on how this decision influences the functional requirements of a secondary navigation device. It is of critical importance that we understand the limitations of the long cane (or trained guide dog) with respect to the task of navigating an indoor environment.

The theories of inclusive and universal design provide significant motivation towards the adoption of a new direction in research and design practices involving disabled communities particularly in engineering disciplines. These theories advocate the need for such communities to not only be considered but also to be physically involved with the research and design processes. This is in order to facilitate the realisation of products which are accessible to a vast collection of potential users, irrespective of their abilities or handicaps. We recognise these theories as providing the most appropriate direction towards advancing the outcomes of research into navigation and orientation assistance for people who are BVI, and our research and technical work is strongly grounded in inclusive and universal design principles.

3. Methodology

A thorough evaluation of assistive indoor navigation solutions should cover all aspects relating to the end users' intended usage of the device, the environments within which the device/system will need to operate and the performance characteristics of the product. Using these considerations, our proposed criteria are broken up into the following four categories:

(1) Accuracy of the device.
(2) Robustness (or reliability) of the device.
(3) Ability to integrate with a varying environment.
(4) Quality/usefulness of information provided to the user.

The requirements of each category have been determined through an examination of existing research related to indoor positioning technology and surveys with people who are BVI.

3.1. *Accuracy*

The accuracy of a navigation system is the principal concern for both the end user and the developer. Accuracy refers to the distance offset (or error) of a system's approximated location value with reference to the true location value. Research into the improvement of location accuracy for indoor navigation systems primarily involves the integration of additional sensor data (such as accelerometers and magnetometers; Liu et al. 2007; Dedes and Dempster 2005). Other techniques involve real-time filtering, cross reference with step-detection algorithms or multiplication of reference points (Liu et al. 2007; Fallah et al. 2012; Li et al. 2005; Gallagher et al. 2010). When used in indoor environments, such techniques have proven to achieve accuracies of up to 1 m (Liu et al. 2007).

Improving the accuracy of an indoor navigation system involves significant design trade-offs which can compromise power consumption and processing complexity. As an example, the energy required to obtain a GPS signal on an Android mobile device has been measured to be within the range of 2000–9000 mJ, compared with a range of 500–650 mJ to obtain a Wi-Fi signal (Lin et al. 2010). The energy and processing demands placed on a portable location device such as a smartphone directly result in a significant compromise in battery life. Although researchers have investigated this issue, see Gallagher et al. (2011) for instance, it still needs to be taken into account when designing a positioning system. Another factor which must be brought into play is the rate in which the location signal is updated, providing a new location estimate. This variable directly influences power consumption and can result in a perceivable 'lag' of positioning results given to the user.

With these trade-offs in mind, it becomes essential to evaluate the importance of each factor in relation to the unique situation of each BVI user. As indicated by Jacquet, Bellik, and Bourda (2006), a person with limited or no sight is greatly dependent on the accuracy of a navigation system, as they do not possess the ability to visually confirm the correctness of the provided information. The long cane provides a method of acquiring localised information about the 'regularities of an environment' (Hersh and Johnson 2008) such as the user's proximity to nearby walls and furniture, and a guide dog is able to help locate doorways and stairs. BVI users are, however, at a great disadvantage when acquiring context-based information such as office numbers or building names which are typically publicised with textual signs. Even with the introduction of standards stating that accessible services must be indicated using Braille notices, the underlying facts are that BVI persons still need to be able to find those signs and that only approximately 2% of the BVI population actually read Braille, rendering those signs meaningless and ineffective to the majority of BVI persons (Arditi and Brabyn 2000).

Without a way of acquiring contextual information, a BVI user is limited to the range of localised information obtainable from assistive technology or a primary mobility aid such as a long cane. The long cane is the most popular, typically spanning a length equal to the height of the user's breastbone (Hersh and Johnson 2008). In order to allow a BVI user to perform an effective comparison between their perceived environment and the information provided to them, the navigation device must be able to provide an accuracy which complements the limits of their perceived environment. This implies a strict accuracy guideline of less than 2 m for the majority of users.

An alternative to this constraint requires an additional functionality of the navigation device, allowing for a detailed description of the objects within a user's immediate environment, which could be particularly useful for the users of guide dogs. This option has been explored in recent research efforts which are further discussed in Section 4.

3.2. *Robustness*

The robustness of a navigation device refers to the level of consistency in providing reliable and accurate positioning values in areas where signal strength and/or data acquisition may be compromised. This is an important measure when considering the application of an assistive navigation device, particularly when the technology relies on real-time signal acquisition (such as GPS, wireless or cellular-based information).

Common variations within an indoor environment (such as the presence of concrete or steel, nearby buildings or underground areas which affect the line of sight with a signal provider or metallic lift shafts which interfere with compass readings) make it difficult to provide a guaranteed consistency of range in positioning systems. The most effective solution to this problem is to allow the system to intelligently compare various signal types and make an informed judgement on the associated error for a determined location value. An extreme case of this involves an integration of object-recognition technology through the utilisation of a video camera. This is one of various examples which will be discussed further in Section 4.

We propose the following requirement involving the robustness of a navigation device for BVI users: that the user must be informed, to the best extent of the device's capabilities, of the estimated error associated with each position value. Note that this does not enforce a particular degree of accuracy or consistency of error, but rather works on the notion that the user deserves to receive navigation information in the most truthful form available. This is particularly appropriate for devices relying on real-time signal acquisition, and allows the user to form an independent judgement of their position by understanding the reliability of the device's current output.

There are obviously cases where the above criterion is almost impossible to achieve, and it would be more prudent to provide a guaranteed error for the system. Examples of these are systems which incorporate the use of infrared (IR) or radio-frequency identification (RFID) technology. The majority of modern indoor positioning technologies do, however, incorporate the acquisition of wireless or satellite signals with varying degrees of error.

3.3. *Integration with the intended environment*

A potential navigation solution for people who are BVI must be judged in respect of its applicability to the intended indoor (and outdoor) environment of use. This includes a robust analysis of the portability and extensibility of the technology used as well as an examination of the various environmental conditions under which it will operate.

In addition to this, it is important to evaluate the potential limitations that may be incurred by a BVI user when operating the device within an indoor environment. An Orientation and Mobility Environmental Complexity Scale has been developed and can be used as a starting point when considering the devices' intended user and environment of use (Deverell 2011).

Despite the proven accuracy of systems which rely on additional infrastructure to be incorporated within the environment (such as passive RFID technology), they have proved to be largely infeasible. The inflicted cost, installation time and maintenance requirements of such systems leave them inappropriate for large scale or wide-spread implementations. It also must be noted that the range of passive RFID tags is typically limited to 1–2 m (Kaur et al. 2011). We do, however, recognise the positive outcomes that have resulted from research efforts into RFID technology. Accuracies of less than 1 m can be attained with far less variation in signal strength than that of wireless signal acquisition (Kaur et al. 2011). Possible hybrid and integrated applications of RFID technology for assisting navigation are discussed further in the next section.

Regardless of the methods utilised for acquisition of location-specific information, we propose that no navigation solution should impact a BVI user's personal environment, in other words their ability to interact with a primary mobility aid. The greatest concern with respect to the above consideration is in allowing the user at least one hand free for the control of a long cane, guide dog or other primary mobility aids. The user must be able to compare and relate information from both technologies in order to reach a successful understanding of the characteristics of their surrounding environment and undertake the task of navigation without compromising his/her personal safety. These criteria must be imposed without leniency and without compromising. Figure 1 shows the optimum use of such a device.

Similar to their reliance on a primary mobility aid, a person who is BVI depends heavily on various forms of somatic-sensory information in order to achieve mobility and perceive and interpret their surrounding environment. Thus, the above criterion can be extended to enforce that a navigation solution must not limit a user's ability to receive external audio, tactile or olfactory information from the immediate environment. We will discuss the available technology which addresses this concern in Section 4.

3.4. *Providing information to the user*

This section provides insight into the nature in which a BVI user cognitively perceives and interacts with his/her environment when navigating. This will aid the development of design criteria for instructing the way information should be provided to a BVI user, as well as the most appropriate information content to provide.

A great quantity of research has been undertaken on the cognitive mapping process of BVI users when attempting to navigate an unfamiliar environment. It has been found that associating landmarks with such areas is generally the most effective means of developing spatial awareness and remembering a route or set of directions (Arditi et al. 1999). It is suggested in Golledge et al. (1998) that landmarks were mental checkpoints for BVI users which were often recognised by their distinct sound, scent or tactile properties. Landmarks could also have prominent visual properties (such as colour contrast) for people with limited vision, or be characterised by the level of activity in the area. An ongoing survey of BVI individuals conducted at the University of New South Wales, Sydney, has found that common indoor landmarks include cinemas, supermarkets, cafes/restaurants, lifts and

Figure 1. Operation of the SIMO system while maintaining use of a primary navigation aid.

large staircases (Li et al. 2009). The prominence of landmarks has been recognised in Wang et al. (2012) for instance. Researchers must recognise the importance of incorporating (or assisting) contextual and relevant landmark identification when designing a navigation system as a means of providing the most useful form of spatial information to the intended user.

The format of outputted information must also be considered with respect to a BVI audience. A study conducted in Loomis, Golledge, and Klatzky (1998) found that ‘virtual acoustic displays’ which used modulations in volume and binaural emphasis to convey a sense of direction and distance were more effective than audio verbal descriptions in improving the travel time for users along a specified route. The study also noted the disadvantages of imploring spatial sound as a primary information display, as it requires the user to have accurate (and equal) hearing, to wear headphones and incurs additional hardware requirements. With this in mind, we propose that a navigation system for BVI users should allow for at least a basic audio description of the environment as the primary output of information. It is suggested that the researcher aims to investigate the possibility of including alternative output formats in order to allow for some level of user personalisation.

The preferred measurements of direction and length also vary among the BVI community. A survey by Kalia conducted in Kalia et al. (2010) found that BVI users were able to conduct navigation tasks with great confidence when distances were specified in the measurement of steps as opposed to metres (or feet). The determination of preferred measurement of direction is more ambiguous. The advantage of virtual acoustic displays, in which the perceived direction and volume of audio instructions varied with the user’s heading and distance from a specified target location, is reported in Loomis, Golledge, and Klatzky (1998). In a survey of 10 BVI users, 7 performed navigation tasks best when provided this mode of information. The participants also performed relatively well when provided a bearing of direction to the next waypoint or target (such as '80° left'). There was a strong preference for both forms of directional information when compared with the 'no compass' mode, in which users received directional information with reference from their starting position or previous waypoint. In summary, the research has proven a clear need for egocentric directional information, as opposed to external or standardised directional information which does not consider the user's heading.

The above requirements are closely related to the cognitive load theory within the area of usability analysis. The BVI individual is at an acute disadvantage when undertaking orientation and navigation activities, as they must constantly utilise their perceptual skills in order to make sense of their environment and compensate for a lack of sight in varying forms. These activities are often combined with the mental load of operating a guide dog or cane and the interpretation of surrounding information. It is obvious from the above statements that an effective navigation solution for the BVI must require minimal cognitive effort.

Table 1 represents the proposed criteria for evaluation of an indoor navigation device for BVI users. It is important to note that while these criteria have been carefully constructed and delivered with respect to the most relevant findings in both the human–computer interaction and indoor navigation areas, it is only intended as an initial attempt. We hope this will inspire further refinement of the design criteria and collaboration amongst other researchers in this area.

4. Evaluation

GPS, or more generally GNSS (Global Navigation Satellite Systems), has been used to navigate persons who are BVI since the late 1990s (Yelamarthi et al. 2010; Holland, Morse, and Gedenryd 2002; Makino, Ishii, and Nakashizuka 1996) outdoors. However, indoor navigation is a more challenging problem and GNSS cannot be utilised, due to lack of availability or degraded accuracy. Therefore, alternative technologies have been developed to fill the shortcomings of GNSS indoors. In a system developed by Altini et al. (2011), a Bluetooth localisation service based on multiple neural networks for indoor localisation is presented. A magnetometer was used to provide the user orientation. Five tiny motors were attached on the shoulders and chest of the user to instruct him/her to turn left, turn right or go ahead. GuideCane is an electronic travel aid developed by Ulrich and Borenstein (2001). It is equipped with 10 ultrasonic sensors to detect obstacles and a servomotor to steer two wheels on the tip of the cane. When the sonar detects obstacles, a built-in computer instructs the servo to steer the wheels in order to avoid the obstacle, guiding the user. Hesch and Roumeliotis introduced an indoor localisation aid for the BVI in 2007 (Hesch and Roumeliotis 2007). Their prototype portable device consisted of a foot-mounted pedometer and a standard white cane, on which a laser range finder and a 3-axis gyroscope had been mounted. The position of the user was estimated using the heading estimates from the gyroscope, the linear velocity measurements from the pedometer and the relative coordinates of known corner features detected by the laser scanner. Tests showed that the system worked well in a laboratory environment with a low uncertainty in the position estimate (max $\sigma = 0.16\,\mathrm{m}$). In Guerrero, Vasquez, and Ochoa (2012), IR triangulation is applied to determine a user's position in an indoor environment.

Table 1. The summary of criteria.

	Considerations	Proposed requirements
Accuracy	Allow user to utilise and compare the information received from both primary mobility aid (e.g. cane) and the navigation device.	Deliver accuracy which complements the immediate perceptual range from primary mobility device. Suggested accuracy of less than 2 m.
	Power consumption/computational complexity.	Reduce computational load on any portable device which relies on battery source.
Robustness	User relies heavily on device and cannot always confirm correctness of information provided.	If error varies with the environment, provide an estimate (best effort) of the error or provide a guaranteed error which applies to all readings.
Integration with environment	Feasibility of external infrastructural requirements.	To be kept minimal, to ensure extensible systems.
	Impact on user's ability to operate a primary mobility aid.	Must allow for at least one hand free, preferably both.
	Impact on user's ability to obtain sensory information from the environment.	Must not inhibit user's ability to receive audio, olfactory or tactile information (this relates primarily to use of gloves and/or earphones).
Information outputted to user	BVI users often use landmarks to identify with the environment, as opposed to building names or other textual references.	Incorporate description and identification of landmarks.
	The most promising output modalities (in terms of user performance) have been determined as audio descriptions and audio tones (such as sonar-like beeps to describe virtual direction and distance).	Allow for at least an audio output description of the environment and directions/instructions. Suggest integrating additional modalities such as tactile interfaces or tones/beeps to provide users to select their preference.
	Distances and directions are often understood better by BVI users when described in egocentric measures.	Distances should be expressed in steps rather than metres/feet.
		Bearings should be expressed with reference to user's current heading as opposed to the external environment.
	The reliance on external sensory information, combined with the concurrent usage of one or more mobility aids/devices, places a large cognitive load on a BVI user.	Minimise additional cognitive load due to use of the device, to allow users to apply more focus on their preferred mobility techniques and practices.

A white cane equipped with several IR LEDs acts as the transmitter and two IR cameras installed at known locations capture the signals and send the measurements to a computer via Bluetooth. The user's position is then estimated and instructions are generated and sent to the user's smartphone trough Wi-Fi. In Chumkamon, Tuvaphanthaphiphat, and Keeratiwintakorn (2008), a simple RFID-based navigation system for the blind is introduced. A large number of RFID tags have to be deployed along a pathway. An RFID scanner installed in a white cane can detect these tags to locate the user.

The rest of this section presents an evaluation of significant research examples in indoor navigation for BVI users spanning the last decade. Of each, we discuss the specific attributes which directly relate to the proposed criteria. As we focus on indoor navigation, systems using GNSS are not evaluated here, although the criteria defined in the previous section can also be applied to outdoor navigation systems with minor modifications.

4.1. *Drishti*

The Drishti project, conducted in the early 2000s by Ran, Helal and Moore at the University of Florida (Ran, Helal, and Moore 2004), was an early example of an indoor navigation solution for the BVI, and laid a solid foundation for future research by considering the differences in environmental requirements for an indoor system as opposed to existing outdoor systems. Drishti was also developed to investigate the issue of seamless transition between indoor and outdoor navigation modes – a novel approach which sought to effectively provide an 'all-in-one' navigation and orientation solution for users.

Drishti consisted of a wearable computer, headset and ultrasound positioning beacons (to be worn on the shoulders) to provide location information and route guidance to a user in the form of a text-to-speech audio description. The system boasts a user-friendly interface, which incorporates common expressions such as 'where am I?' and provides an object-based description of the user's environment (such as the presence of chairs, tables and toilets). With respect to the proposed criteria in Section 3, the most notable aspects of the system interface are (a) the instructional information describes turns in the measure of degrees (egocentric) and distances in steps and (b) the calculation of optimal routes which is evaluated on the presence of detectable hazards.

Despite its promising interface and impressive indoor accuracy of 22 cm, there are aspects of the Drishti system which limit the possibility of wide-scale implementations. The system requires the installation of multiple ultrasound pilots around the intended environment in order to provide positioning accuracy to the user. In an indoor setting consisting of four rooms, a total of four pilots were required. The researchers also noted the presence of 'dead spots' within the environment where location information was unattainable due to signal blocking. These results indicate the need for a large number of pilots to be installed in various locations in order to provide a useable system. This scheme, similar to the proposed RFID systems, has severe limitations, notably a large monetary cost in the initial installation – and potentially large on-going maintenance costs, which restricts its applicability to wide-scale implementation.

The system also requires the use of headphones and a mounted computer. Whilst the researchers demonstrate the ability for the hardware to be condensed into a more portable and easily carried form (which is achievable with today's computing power), the speech–input interface may restrict the use of the device in noisy environments. The researcher's intent to employ a mobile phone as the primary device would certainly enhance the portability of the system. Additional integration of alternative input methods (such as tactile or with haptic feedback buttons) would further increase the range of conditions under which the system can be used.

4.2. *RG-I*

RG-I is the name of a robotic guide prototype. It is the outcome of a collaborative project conducted by two departments within Utah State University started in 2003 (Kulyukin et al. 2006). Their objective was 'to alleviate localization and navigation problems of completely autonomous approaches by instrumenting environments with inexpensive and reliable sensors that can be placed in and out of environments without disrupting any indigenous activities'. Clearly, this objective is consistent with our criteria listed in the previous section.

RG-I was built on top of a commercially available robotic platform. A Wayfinding Toolkit was mounted on top of the platform and powered from the on-board batteries. The toolkit included a laptop connected to the platform's microcontroller, a laser range finder and an RFID reader. The laser range finder was used to create potential fields for obstacle avoidance and RFID tags had to be deployed densely for positioning purposes. There was no clear description of the size of the prototype; however, from the picture of a RG-I leading a guide dog user, one can see the RG-I was approximately 50 cm by 60 cm with a height of about 100 cm. The height of the prototype is linked to the height of installation of the RFID tags as the antenna of the RFID scanner was installed on the top of the platform. The user interface (UI) has two input modes: haptic and speech; the output modes use speech synthesis or audio icons. BVI individuals told RG-I their desired destination and RG-I used its path planner to find the best path (connectivity graph was generated based on the RFID tags). Then, the users followed RG-I by holding onto a dog leash attached to the platform. A pilot experiment showed that RG-I could successfully guide all five BVI volunteers to various destinations in a laboratory environment. All these participants used a wireless wearable microphone to interact with the robot. BVI volunteers were quite satisfied with the design and with the fact that it was used to complement and enhance the performance of traditional methods. With the assistance of laser scanning, the RFID-based positioning system worked reasonably well. RG-I could also provide some basic location-based information when the user requested it.

However, several problems have also been identified. RG-I is an expensive piece of equipment. This is an additional barrier to adoption of the system by institutions and corporations. It does not work in all indoor environments such as a large foyer, because the range of RFID is limited. In addition, deploying and managing a large number of RFID tags is a non-trivial task. RFID tags need to be installed at every door, every potential destination and every turn. In fact, to make sure that the positioning accuracy met the requirement, RFID tags had to be fixed on the walls every 2–3 m. Deploying the system in two indoor test beds (4270 and 6590 m^2) took about 70 h and 140 tags were used.

It was reported that most complaints were about the human–robot interaction aspects of the system. The usability of speech as input/output was then evaluated more systematically. It found that speech appears to be a better output medium than input. However, the experiments did not give a clear answer as to whether BVI individuals prefer to be notified of obstacles/navigation events via speech or audio icons. We believe that the latest speech recognition technology would work much better now.

4.3. *Navatar*

A current project being undertaken at the University of Nevada, Reno, relies on the input from a user to confirm location estimates. The research team has developed a navigation solution known as 'Navatar' which can be run on an Android mobile device, making it portable, cost-effective and easy to upgrade (Fallah et al. 2012). The system utilises a dead-reckoning technique by comparing a predetermined representative map of an indoor environment with step-detection estimates, achieved via particle filtering. The system has the advantages of being a low-cost solution which requires no additional infrastructure within the intended environment. Due to the inaccuracy of such dead-reckoning techniques, the user is implored to 'confirm' the presence of each landmark whilst navigating. This confirmation from the user is utilised in a Bayesian particle filter in order to adjust positioning values. In other words, the system makes use of the 'user as a sensor', allowing for the positioning estimates to be re-calibrated based on the user's input.

There are consequences to the aforementioned scheme which directly contradict the guidelines of our criteria, concerning the robustness of a navigation device and the consideration of a user's mental load when operating the device. It is mentioned in Fallah et al. (2012) that 'The user had to confirm the successful execution of a direction before receiving the next one'. In response to this, consider a situation in which a user was unable to locate and confirm the target landmark. The cause of this error cannot be determined – it may lie in the user's inability to recognise the landmark or it may be due to the inaccuracy of the position estimate. In addition, in this context, the user would be forced to 'confirm' in order to proceed with navigation. This false confirmation could potentially introduce a new source of error into the positioning algorithm, resulting in subsequent positioning estimates to be farther off course. In a worst-case scenario, this may lead a user into an unsafe and potentially dangerous situation.

The Navatar system directly conflicts the proposed requirements concerning the robustness of a navigation device. Not only does the estimated error vary without informing the user, but the user's operation of the device can also lead to indeterminable variance of accuracy.

It is also important to consider the mental load placed on the user when operating the Navatar. The task of detecting specific landmarks such as hallways, intersections or stairs in unfamiliar environments limits the level of focus that a user can apply to other necessary aspects of navigation, orientation and mobility (O&M) such as hazard detection. Whilst it can be argued that landmark recognition is an integral part of navigation, which the user would practice regardless of the device(s) being used, it is the notion of the system *strictly requiring* confirmation which enforces the user to focus predominantly on this task. This has the potential to limit the user's ability to engage with his/her environment in a way which best suits their unique strengths and techniques of perceptual mobility and orientation.

5. SIMO system

In this part we will present and evaluate SIMO (simplified information for mobility and orientation), an indoor navigation and orientation system specifically created for BVI users and co-designed with people who are BVI at the University of New South Wales, Sydney, Australia.

5.1. *Overview of SIMO*

Conceptually, SIMO can be approximately divided in two parts; first an indoor positioning engine that is responsible for computing the user's position and second an interface specifically designed in collaboration with BVI users which delivers this information in the most accessible and meaningful way.

When this project conceptual design was realised in 2006, the vision was one of a custom-made device with four or five large tactile buttons to control the system and no screen, cutting manufacturing costs and extending battery life. A custom PCB would host all the required sensors, and haptic and audio feedbacks would be the only types of feedback provided. However, with the launch of the iPhone by Apple in 2007, we quickly came to the conclusion that a smartphone was a more sensible and cost-effective approach to the problem. Indeed, a smartphone may host all the sensors and type of outputs required and most importantly, it is relatively cheap to acquire and does not stigmatise the BVI user by forcing him/her to wear a bulky device. Moreover, an ever increasing number of BVI people now know how to use a touchscreen device and thus potential users will not be required to learn how to operate a completely new and different device.

5.1.1. *Interface*

When designing the interface, we did our best to respect all the proposed requirements in Section 3, and especially those in the following categories: 'Integration with the environment' and 'Information outputted to the user'. In this paper, we will only present the interface when the device is in navigation mode, i.e. the user has already selected a destination and the task of the device is to assist him/her into reaching this destination.

Figure 2 presents three prototype screenshots of the application, guiding a user in three different colour contrast schemes (more colour contrast schemes may easily be added).

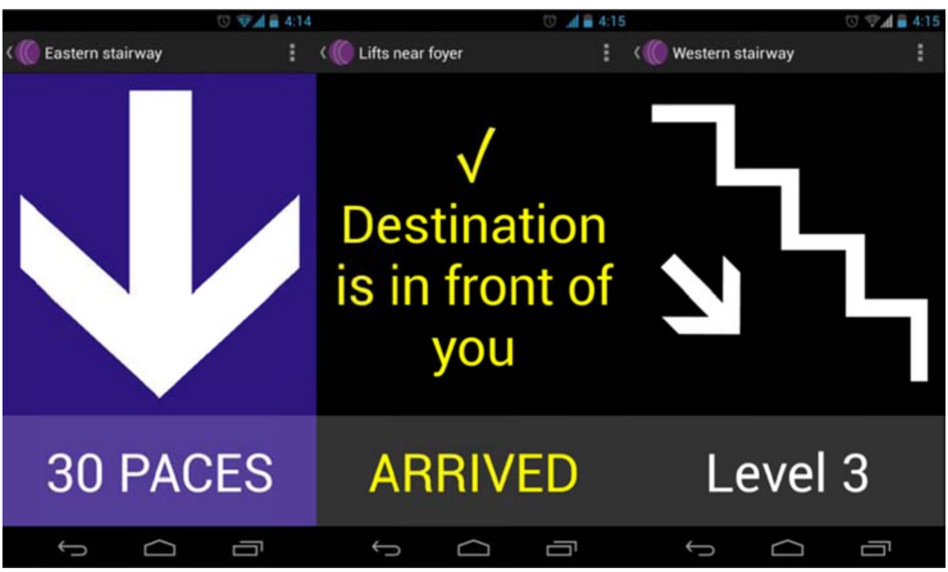

Figure 2. Screenshots of SIMO operating in navigation mode on an Android system.

A minimal interface was designed in order to include people with low-vision who do not necessarily need any other form of feedback. A maximum of two out of three UI elements can be displayed at any one time: a directional element expressed in a large arrow pointing in the direction the user should follow, a distance element in paces/metres until the next instruction, and a textual representation of the current instruction.

Distances are given in paces when they are less than 50 paces and in metres when above; this can be altered depending on the user preference. This helps the user to build a mental estimate of how long the travel time is until the next waypoint where he/she will need to utilise his/her O&M skills and the system to find the correct path to the destination.

When accessibility options on the device are turned on, the third UI element is deactivated. In that case, any tap or double-tap on any part of the screen will trigger the current instruction as well as the next instruction to be read aloud by the phone. Note here that a tap or double tap is a simple enough gesture that it can be executed with only one hand, leaving the other hand free to use a primary mobility aid. The system also does not give any unsolicited voice feedback in order to not overload the senses of the user. To notify the user about a new instruction, the device vibrates briefly; the user may then choose to ask for audio feedback if he/she feels the need for it.

A fault in the operation of our system is that it requires the user to hold the device in one hand with the front of the smartphone pointing in the same direction as the users' body. This is of course so that the embedded compass actually aligns with the direction of travel to give a correct estimate of the users heading to the positioning engine. We are fully aware that this may be somewhat impractical in certain situations and propose further and future research in this area.

5.1.2. *Positioning engine*

A detailed report on SIMO's positioning engine can be found in Gallagher et al. (2012). The overall architecture of the positioning engine is shown in Figure 3. The output of the positioning engine is a 3D position (x, y, l) where (x, y) are the coordinates of the user on level l of the building. A Kalman filter is responsible to estimate the 2D component of the user's position (x, y). A level finder module that relies on a calibrated barometer embedded

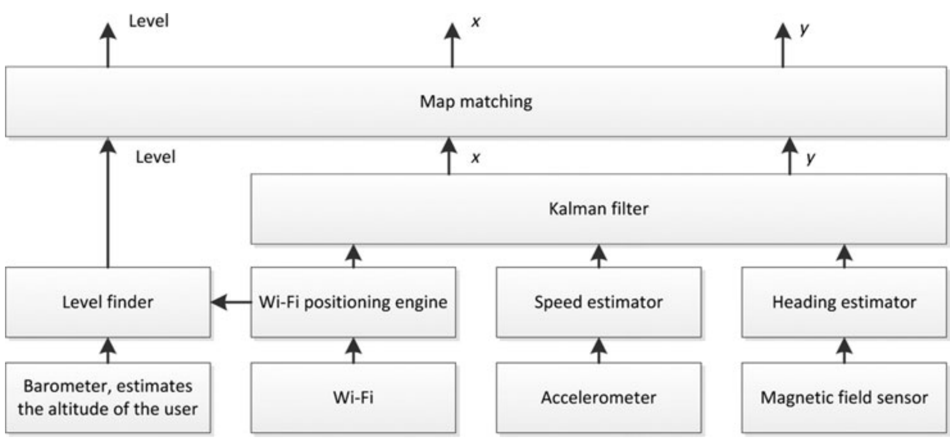

Figure 3. Architecture of SIMO's indoor positioning engine.

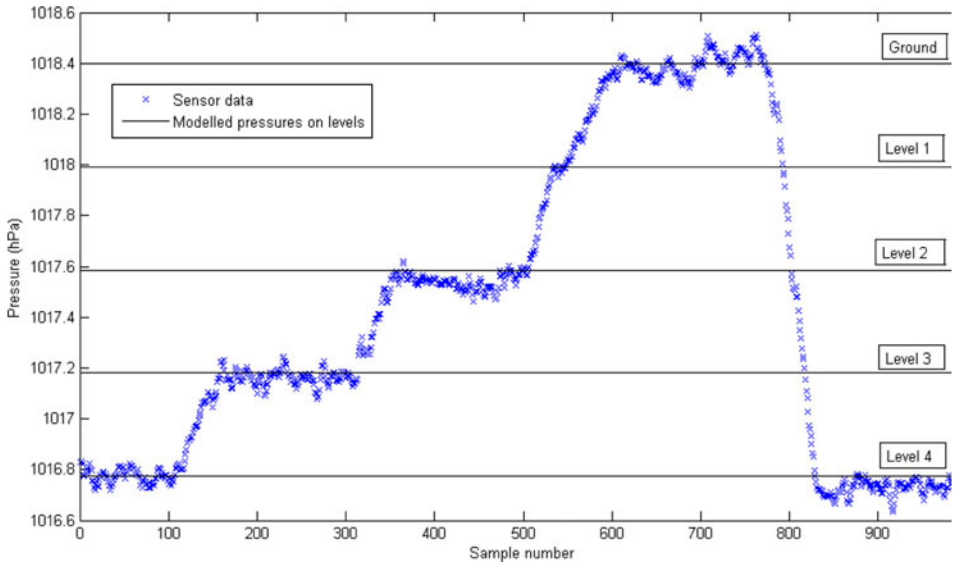

Figure 4. Test of the barometer as a level decision tool. Height difference between two levels is 3.5 m.

on the phone is responsible for estimating the level of the user. The noise in the barometer's pressure measurements is low enough as to easily distinguish altitude differences of 3 m, which we estimate is the minimum altitude difference between two levels in a typical building (see Figure 4).

A motion model of the user containing speed and heading values is constantly updated in order to feed the Kalman filter's prediction stage. The speed value is computed every 500 ms using an FFT-based step frequency estimation algorithm, the step length is then computed using a model obtained empirically that takes into account the height and gender of the user as well as the step frequency. An update rate of 15 Hz was empirically chosen for the heading data, this value is high enough for our application and could probably be lowered to reduce the computational complexity of our software.

The update stage of a Kalman filter iteration is done by using an absolute 2D position measurement. A new position is computed using the now well-known Nearest Neighbour algorithm applied to Wi-Fi fingerprints. Finally, once an iteration of the Kalman filter is completed, the computed position is matched against a representation of the level's walls and corridors in order to prevent the position of moving into non-covered areas.

5.1.3. *Positioning engine tests*

Extensive tests of the positioning engine's accuracy were conducted in a controlled environment and the detailed results are presented in Holland, Morse, and Gedenryd (2002). Three different users were asked to walk along a pre-defined path at a constant speed while using the software. Ground truth was obtained by recording timestamps and assuming the users do their best to walk at constant speed (an assumption that holds given the final level of accuracy reached). Each user was asked to walk along the path three times. The path was roughly 60 m long with several sharp turns along the way. The final average accuracy of the SIMO system obtained was of 3.0 m, an increase of 41% over using the Wi-Fi Nearest Neighbour algorithm only (5.8 m average accuracy). Most importantly, the standard deviation of the error was much smaller when using the Kalman filter, which leads to a more robust position.

5.2. *Navigation usability test*

In this part, we will summarise the output of a test campaign we conducted at Vision Australia NSW branch building, located in Enfield, NSW. The focus here is on the navigation component of the application rather than on the interface usability. The SIMO software was installed and configured on a Samsung Nexus S smartphone.

5.2.1. *Testing procedures*

We contacted and recruited participants through Vision Australia and our database of volunteers. A total of 10 persons with different vision impairments agreed to participate in the tests. All the participants are registered blind, most having very limited to no residual vision. Each individual test session lasted approximately 1 h. During the session, some related basic information of the use, such as demographics, pre-existing navigation and orientation skills, and experiences with assistive technology, was collected first.

Then before the test began, the administrator conducted a short orientation and training session. This was used to explain to the participants what the software attempted to do and to let them familiarise themselves with the operation of the device and software. A participant was then asked to navigate to multiple points of interests within the building, in a single-level scenario. Two administrators were following the participant at all times to ensure complete safety of the participant and to record the devices' operability. Once all the navigation tasks were completed, the participant was asked to provide feedback on the Software using three sets of questionnaires:

(1) System usability test scores.
(2) Overall system ratings.
(3) Open-ended questions.

For brevity purposes, only feedback from the last questionnaire will be analysed in this paper. Using this feedback, we will also assess the performance of our software in relation to the set of criteria defined in the previous sections of this paper and is summarised in Table 1.

5.2.2. *Analysis of participants' feedback*

When asked about their opinions about specific features and interactions during the test, participants provided their feedback around several themes which are summarised in Table 2.

5.2.2.1. *Positives*. On analysing participants overall satisfaction, we found that 100% of the participants agreed (i.e. agreed or strongly agreed) that the software not only helped them navigate, but also enabled them to navigate faster by providing instant voice feedback when approaching turning points. All users would use the software again and found that it was suitable in that context. Moreover, all of them were able to quickly learn how to operate the device and did not really need any additional assistance to select

Table 2. Summary of open-ended discussion output.

Experience	• Overall satisfaction • Agrees that it contains enough information to help form a travel strategy • Easy to learn how to operate
System accuracy	• Understands that it is accurate up to a certain level but still requires the user to use traditional O&M skills • Satisfied that the system could guide them to the destination within a certain radius • Limited accuracy makes it hard to rely on the system to find the destination at the end of the journey (e.g. lift button, specific door when several other doors are very close)
Personalisation	• Unable to moderate the amount of information delivered to users based on familiarity and environment. Most users recommended we add levels of personalisation based on user needs (more or less information outputted during the journey)
User interaction	• Interacting with the device too often is detrimental to users' guide dogs' concentration as the dog does not like to start and stop very often • Touchscreen surface lacks sensitivity • Taxing to interact with screen while walking (when repeating turn-by turn instructions or selecting a new route) • Found haptic feedback very useful
Voice interaction	• Should be able to personalise voice speed and type
Liked most	• Voice and haptic feedback, information about the point of interest
Liked least	• Interacting with the phone while navigating • Lack of personalisation options

destinations and navigate to them during the test. Most participants found that the vibration feedback was useful during the trip and that it was good design practice not to have the device automatically speak as that would overload their senses. Most praised the accuracy of the system and the very fast update rate, hearing the paces going down as they walked down a corridor greatly improved their confidence in the systems' accuracy.

5.2.2.2. *Negatives*. A minor negative point is that some users had trouble double tapping on the screen to get voice feedback. However, this feedback mostly came from users who barely used any touchscreen device before. At the end of the session, their ability to operate the device had already greatly improved. We believe the double-tapping gesture is easy enough to learn and that with a bit more training, the majority of potential users will be able to master it. Regarding BVI people relying on guide dogs for mobility purposes, some found that the device gave them too little information at a time, forcing them to start and stop often to double tap on the screen to access the information required. This had some detrimental effects on the dog's concentration. A guide dog is trained in a specific way and does not like to start and stop often. A planned solution is to personalise the feedback and amount of information delivered in this case to give more instructions at a time, so that the dog is not required to stop so often. Most users were also disappointed with the lack of customisation options in our software such as changing the speed or type of voice or tuning the level of details the software outputs while in navigation mode. Some users also expressed the desire to be able to put the phone anywhere, like in their pocket for instance. In terms of accuracy, the biggest complaint was about heading information. Indeed, the low quality of the magnetic field sensors on the phone coupled with possibly

Table 3. Evaluation of the SIMO system against the set of criteria defined in Table 1.

Requirement	Element	Comments
Accuracy	Value	The goal of reaching 2 m 100% of the time has still not been reached. Roughly, SIMO is expected to be within 5 m 95% of the time.
Robustness	Perceived robustness	Heading information is less robust than the position itself. The user training will focus on making sure the user is aware that the position is accurate within 5 paces 95% of the time, but that heading information could be quite unreliable.
Integration with environment	Infrastructure requirement	Only infrastructure needed are Wi-Fi accesspoints, which are already deployed in most public spaces.
	One-handed operation with long cane orguide dog	One hand is left free to operate a primary mobility aid. In the future, the device will be able to be placed in the users' pocket or backpack to free the second hand. A level of personalisation will be included to improve the experience for guide dog users.
	Impact on other senses	The device does not impact the user's ability to obtain sensory information from the environment. The device can output audio via the phones' speaker or a pair of headphones depending on the users' preference.
Information outputted to user	Landmarks	Landmarks can be saved and personalised by the user for easy retrieval. The user can instantly position himself/herself in relation to a landmark as the device outputs a distance and heading relative to the user's current position. In the future, the user will be able to record audio snippets associated with a landmark.
	Type of feedback	Voice and haptic feedback have been included. Voice feedback is triggered only on demand by the user and not automatically as to not overload the user's senses.
	Format of distances and headings	Distances are displayed as paces for distances less than 50 m and then in metres. Due to inaccuracies in the heading measurements, heading information is egocentric and expressed as four cardinal directions (in front of you, to your left, to your right, behind you).
	Amount of information outputted	Default amount of information is kept to a minimum (slight haptic feedback, not automatic voice feedback) as to not overload the senses. In the future, personalisation options will allow the user to change this amount.

high interference from metal in a building's structure can result in large heading errors. This will be fixed in future iterations of the software by fusing magnetic field data with gyroscope data to stabilise the output of the heading estimator.

5.2.3. *Evaluation of SIMO against the set of criteria previously defined*

Table 3 details the evaluation of the SIMO device against the set of criteria we defined earlier in this paper. The main failure of SIMO is in the accuracy requirement where it fails to get above the required 2 m threshold. However, this requirement is currently unreachable without the help of dedicated hardware on both the infrastructure and client side (e.g. UWB or laser ranging systems). The robustness of the solution, especially of the heading value, is also problematic as an upper bound on the accuracy of the heading cannot be provided. In terms of positioning error, it is safe to assume an upper bound of 10–15 m. The user must therefore be made aware of this limitation and is advised not to place 100% of his/her trust in the system's solution, but rather use it as a guidance and information tool up to the close vicinity of his/her destination, and then continue with proven and trusted mobility skills. In terms of interface and feedback design, SIMO does much better, especially in the way it delivers distance and heading information, and by setting a good balance between too little and too much feedback. More customisation options in the future will improve the user experience in this area. It can be said that a usable interface that does not require significant mental energy to operate can increase the perceived robustness of the system.

6. Conclusion

In this paper, we proposed a set of criteria for evaluating the effectiveness of an indoor navigation solution for people who are BVI. These criteria have been constructed from collective research efforts in understanding the BVI community's O&M requirements. The paper also examines recent efforts in the delivery of navigation systems with reference to these proposed criteria, in an attempt to highlight their achievements thus far as well as stress the remaining issues which demand further attention. With this examination, we have identified two all-encompassing issues:

- The need to consider the applicability of a navigation solution to a varying indoor environment and usage requirements.
- The critical importance of fully understanding the specific needs, desires and capabilities of the people who are BVI and their respective communities around the world.

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