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Indoor Navigation for the Blind and Vision Impaired: Where are we and Where are we Going?

Elyse Wise, Binghao Li, Thomas Gallagher, Andrew G. Dempster, Chris Rizos
School of Surveying and Geospatial Engineering, UNSW
Sydney, Australia
bviproject@unsw.edu.au

Euan Ramsey-Stewart
Ramsey-Stewart Industrial Design
Sydney, Australia
euan@rsid.com.au

Daniel Woo
School of Computer Science and Engineering, UNSW
Sydney, Australia

Abstract—**Despite over a decade of intensive research and development, the problem of delivering an effective indoor navigation system to the blind and vision impaired (BVI) 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. In order to give complete coverage, the Requirements Analysis has been broken down into the subcategories of positioning accuracy, robustness, seamlessness of integration with varying environments and the nature of information that is outputted to a BVI user. We then apply this framework to a number of existing navigation solutions for the BVI, drawing upon the notable achievements that have been made thus far and also the crucial issues that remain unresolved or are yet to receive attention. It was found that these key issues, which existing designs fail to overcome, can be attributed to the need for a new focus and user centred design attitude – one which incorporates universal design, recognises the uniqueness of its audience and understands the challenges associated with the systems/devices intended environment.**

Keywords- indoor navigation; blind vision impaired; human-computer interaction; user requirements; universal design; location information;

I. Introduction

The task of designing an indoor navigation system for a blind or vision impaired (BVI) user is an incredibly daunting challenge, yet one that 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.

Although the physical surroundings of all human beings remains the same, the internal perception of these surroundings by a person with limited or no sight is remarkably different to our own [1][2].

The design of a navigation device for this audience involves a study of Geospatial Engineering as well as a user requirements analysis. 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 these criteria to some of the most significant examples of research and development over the past decade. 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 path towards solving a problem which has been long attempted and has affected so many members of our global society.

II. Problem Background

It is estimated that over 285 million people worldwide are visually impaired [3]. 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 [3]. With this in mind, there can be little doubt that the development of an effective 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 [4]. To this day, the most widely used and successful mobility aids are the long cane and guide dog [4]. 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 [5][6][7][8]. 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 theory of Universal Design provides significant motivation towards the adoption of a new direction in research and design practices involving disabled communities. This theory advocates 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, irrespectively of their abilities or handicaps. We recognise this theory as providing the most appropriate direction

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towards advancing the outcomes of research into navigation and orientation assistance for the blind and vision impaired, and our work is strongly grounded in universal design principles.

III. 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:

a. Accuracy of the device

b. Robustness (or reliability) of the device

c. Ability to integrate with a varying environment

d. 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 vision impaired persons.

The products which illustrate a significant design or research perspective(s) within the above categories have been chosen for further discussion in section IV. The overall selection spans the last decade of significant research efforts and covers a wide variety in the given product's platform, physical characteristics and interface design.

A. 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) [5][6]. Other techniques involve real-time filtering, cross reference with step-detection algorithms or multiplication of reference points [5][9][10][11]. When used in indoor environments, such techniques have proven to achieve accuracies of up to 1 metre [5].

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 2000-9000mJ, compared with a range of 500-650mJ to obtain a Wi-Fi signal [12]. 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 [13] 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 trades-off in mind, it becomes essential to evaluate the importance of each factor in relation to the unique situation of the BVI user. As indicated by [14], 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 provided information. The long cane provides a method of acquiring localised information about the “regularities of an environment” [15] such as the user's proximity to nearby walls and furniture. The BVI user is, however, at a great disadvantage to 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 to the majority of the BVI persons [16].

Without a way of acquiring contextual information, a blind user is limited to the range of localised information obtainable from a primary mobility aid. The long cane is the most popular of these aids, typically spanning a length equal to the height of the user's breastbone [15]. 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 metres 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 IV.

B. 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. It 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 IV.

We propose the following requirement involving to the robustness of a navigation device for the BVI: 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 infra-red (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.

C. Integration with the Intended Environment

A potential navigation solution for the BVI must be judged in respect of its applicability to the intended indoor (and outdoor) environment of use. This includes an analysis of the portability and extensibility of the technology 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 incurred by the 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 [17].

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 metres [18]. We do however recognise the positive outcomes that have resulted from research efforts into RFID technology. Accuracies of less than 1 metre can be attained with far less variation in signal strength than that of wireless signal acquisition [18]. Possible applications of RFID technology for assisting navigation is 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 the 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 BVI user at least one hand free for the control of a long cane or guide dog. A BVI 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. Fig. 1 shows the optimum use of such a device.

Similar to their reliance on a primary mobility aid, a BVI person 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 IV.

D. Providing Information to the End 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 [19]. It is suggested in [20] that landmarks were mental checkpoints for BVI users which were often recognised by their distinct sound, scent or tactile properties. Landmarks could also have

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

prominent visual properties (such as colour contrast) for users with limited vision, or be characterised by the level of activity in the area. An ongoing survey of blind and vision impaired individuals conducted at the University of New South Wales, Sydney, has found that common indoor landmarks include cinemas, supermarkets, cafes/restaurants, lifts and large staircases [21]. The prominence of landmarks has been recognised in [22] for instance. Researchers must recognise the importance of incorporating (or assisting) 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 [23] 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 the BVI should allow for at least an audio description of the environment as the primary output of information. It is suggested that the researcher aim 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 population. A survey conducted in [24] 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 by Loomis in [23]. In a survey of ten BVI users, seven 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 degrees left"). There was a strong preference for both forms of directional information when compared to 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. 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 the BVI. 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.

TABLE I. 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 an accuracy which compliments the immediate perceptual range from primary mobility device. Suggested accuracy of less than 2 metres.
Accuracy	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.
Integration with Environment	Impact on user's ability to operate a primary mobility aid.	Must allow for at least one hand free, preferably both.

Integration with Environment	Impact on user's ability to obtain sensory information from 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.
Information outputted to user	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 environment and directions/instructions. Suggest integrating additional modalities such as tactile interfaces or tones/beeps to provide user's to select their preference.
Information outputted to user	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.
Information outputted to user	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 user to apply more focus on their preferred mobility techniques and practices.

IV. Evaluation

This section presents an overview of significant research examples in indoor navigation for BVI users spanning the last decade. Of each, we discuss the specific attributes of each project which directly relate to the proposed criteria.

A. *Drishti*

The Drishti project, conducted in the early 2000s by Ran, Helal and Moore at the University of Florida [25] 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 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 III, 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 22cm, 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 proposed RFID systems, has severe limitations, notably a large monetary cost in the initial installation, 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 buttons) would further increase the range of conditions under which the system can be used.

B. *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 have 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 [9]. 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 [9] 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. Additionally, 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 a potentially unsafe 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 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.

C. *Content-based applications*

A traffic lights detector developed at Purdue University, USA, is proposed as the initial application as part of a proposed context-aware navigation system which implores Cloud Computing capabilities and existing internet resources [7]. The project is based on the premise that many existing navigation solutions are reliant on additional infrastructures, which severely limit their application to a real-world environment.

The proposed system is intended to make use of existing map data, coordinate and route-finding information and object recognition software on order to provide real-time, context-specific information about a user's environment and the state of dynamic objects within the environment (such as current traffic light signals). The advantages of a “cloud-computing” architecture are but not limited, to the wide variety of available information, the architecture also allows complex algorithms and optimisation techniques to take place remotely. This dramatically reduces the processing demands placed on the remote device itself, potentially reducing battery drain.

The system is intended to be deployed on smartphones (such as Android phones and iPhones) and will be able to utilise local information captured by the device (in particular, the system will interpret information from the device's integrated camera and compass). This scheme allows for a comparison of local and external information about the user's environment and thus portrays location-specific information, object-recognition information and route guidance in both indoor and outdoor environments.

The integration of a video camera for providing environmental information (and in this specific case, the state of traffic lights) is a current cause of short battery life when used on a smartphone platform. The researchers intend to incorporate image-reduction technology and use existing information about the location of traffic lights (and other objects of interest) to ensure video capture is used sparingly. This though, will still deplete battery power and is not an ideal solution.

The adaptability and extensibility of this system are clear advantages when compared to other existing solutions. It is important to note, however, that the system relies on a wireless internet connection at all times – a service which is not yet guaranteed in all urban environments and can be quite costly and restrictive in terms of bandwidth. The upload and download speed of the network connection are most likely to cause delays in sending and receiving the necessary information such as video recordings of the environment and route information. The core limitations of the scheme are, however, conditions which are likely to improve over the coming decades as mobile wireless technologies and reliance on distributed computing services advance.

V. CONCLUSION

In this paper, we proposed a set of criteria for evaluating the effectiveness of an indoor navigation solution for the BVI. These criteria have been constructed from collective research efforts in understanding the BVI community's orientation and mobility requirements. It is our intention that these criteria form the initial basis for further exploration into an indoor navigation system for BVI users and help clarify the requirements of the BVI. 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. The evaluation revealed shortcomings in all set criteria:

Drishti - Whilst the Drishti system provides an impressive 22cm accuracy, it does not give the user a reasonable level of estimation reliability. More importantly, the required infrastructure severely limits the possibility of wide-scale implementations.

Navatar - The need for users to confirm the correctness of the system's estimated location increases the cognitive load significantly, limiting the user's ability to engage with his/her environment in a way that is natural to them.

Context-Aware Navigation System (Purdue University) – Explores the alternative of cloud-based infrastructure, giving clear advantages in system adaptability and extensibility. Whilst the associated problems of reliance on this system (such as signal coverage and battery life) are presently affecting its wide-scale applicability, these are issues which will resolve organically given the forecasted trends in technology.

Overall, this examination has found the presence of two all-encompassing issues:

- the need to consider the applicability of a navigation solution to a varying indoor environment
- the critical importance of fully understanding the specific needs, desires and capabilities of the Blind and Vision Impaired communities around the world

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