Mobile Assistive Technologies for the Visually Impaired

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Abstract

There are around 285 million visually-impaired people worldwide, and around 370,000 people are registered as blind or partially sighted in the UK[A]. On-going advances in information technology (IT) are increasing the scope for IT-based mobile assistive technologies to facilitate the independence, safety, and improved quality of life of the visually impaired. Research is being directed at making mobile phones and other handheld devices accessible via our haptic (touch) and audio sensory channels. We review research and innovation within the field of mobile assistive technology for the visually impaired and, in so doing, highlight the need for successful collaboration between clinical expertise, computer science, and domain users to realize fully the potential benefits of such technologies. We initially reflect on research which has been conducted to make mobile phones more accessible to people with vision loss. We then discuss innovative assistive applications designed for the visually impaired that are either delivered via mainstream devices and can be used while in motion (e.g., mobile phones) or are embedded within an environment that may be in motion (e.g., public transport) or within which the user may be in motion (e.g., smart homes).

Keywords. Vision loss, visual impairment, low vision, blind, IT systems, mobile computer devices, mobile technology, mobile assistive technology, handheld assistive technology

Introduction

In the UK, 20% of people aged 75 years and over are living with sight loss. Regrettably, this percentage is expected to increase in coming decades [B]. Vision loss is the most serious sensory disability, causing approximately 90% deprivation of entire multi-sense perception for an individual [28, 98]. Visual impairment has a significant impact on individuals' quality of life, including their ability to work and to develop personal relationships. Almost half (48%) of the visually impaired feel "moderately" or "completely" cut off from people and things around them [B].

Advances in information technology (IT), and in particular mobile technology, are increasing the scope for IT-based assistive technologies to support a better quality of life for individuals with disabilities, including visual impairment. Technology has the potential to enhance individuals' ability to participate fully in societal activities and to live independently [63, 95].

The domain of IT-based assistive technologies is broad, as is the range of support such technologies can provide. The past few years have seen an increasing trend for ubiquitous computing – that is, a model of human-computer interaction in which the technology fits into the natural human environment [106]. With truly ubiquitous computing, users may engage in everyday activities not even conscious that they are using IT to accomplish them. When ubiquitous computing is directed to deliver assistance to individuals with disabilities, the concept of mobile assistive technologies emerges. Mobile assistive technologies allow individuals with disabilities to benefit from portable, lightweight, discrete aids that are delivered via devices that are popular among the general population and therefore do not carry the same stigma as other, more traditional, assistive aids.

In this review, we provide a comprehensive overview of *research and innovation* within the field of mobile assistive technology to support people with visual impairment. We highlight the need for collaboration between clinical expertise and the field of computer science, as well as the how the inclusion of persons with low vision in the design process will help deliver innovative, effective, and acceptable mobile assistive technology solutions. We consider the term 'visual impairment' to incorporate any condition that impedes an individual's ability to execute typical daily activities due to visual loss. Since our aim is to present a general review of mobile assistive technologies for the visually impaired, we do not segregate low vision from total blindness and so use these terms interchangeably. Where a device or application only supports a specific type or level of visual impairment, we specify this.

Unfortunately, visual loss inevitably leads to impaired ability to access information and perform everyday tasks[15]. In today's knowledge-intensive society, information access is increasingly crucial, not just for performing daily activities, but also for engaging in education and employment. As such, for a visually-impaired person, a key function of many assistive technologies is to provide access to information[78]. Information accessibility for the visually impaired has been enhanced generally by the development of tactile- and auditory-based presentation methods as effective alternatives to traditional visual presentation of information [3,71,2]. These alternative modalities for information access are, for example, applicable to websites [e.g., 26, 67], charts and graphs [e.g., 36, 35], and facial expressions [e.g., 10]. In isolation, however, these solutions do not constitute mobile assistive technologies and so, while important and interesting, they are outside the scope of this review.

Assistive Technology: Goals and Interpretations

Assistive technologies in the broadest sense of the concept are in widespread use, and their benefits are well documented [e.g., 49, 83, 89]. The technologies have evolved significantly over the years, from a simple typewriter built in the 19th century to help blind people write legibly [C] to a mobile phone application helping visually-impaired individuals to 'see' and understand their surroundings [64]. Assistive technologies have the potential to enhance the quality of life of visually-impaired persons via improved autonomy and safety. Furthermore, by encouraging them to travel outside their normal environment and to interact socially, these technologies can decrease their fear of social isolation.

There are various definitions of assistive technology. Common to them all, however, is the concept of an item or piece of equipment that enables individuals with disabilities to enjoy full inclusion and integration in society [37, 72, 88]. Traditional assistive technologies include white canes, screen readers, walkers, etc. Modern *mobile assistive technologies* are more discrete and include (or are delivered via) a wide range of mobile computerized devices, including ubiquitous technologies like mobile phones. Such discrete technologies can help alleviate the cultural stigma associated with the more traditional (and obvious) assistive devices[D]. We interchangeably use '*mobile assistive technology'* and '*assistive technology*' to refer to mobile IT-based solutions or enhancements for facilitating the independence, safety and overall improved quality of life of individuals with visual impairment[72]. By defining assistive technology in this way we are by no means restricting our focus to assistance provided via small mobile platforms – our definition extends to include robotics as well as the accumulation of co-located and embedded technologies to create smart homes (as is discussed later).

Mobile Assistive Technology

Billi et al. [14(p 3)] observe that "mobile devices present new opportunities […] in the field of information technologies and in […] society, such as ubiquitous access [and] portability". A fundamental advantage of using mobile devices to deliver assistive technologies is the unobtrusive nature of many of the platforms. Devices that are subtle or applications that are embedded into a mainstream device such as a mobile phone can help individuals feel less stigmatized or labeled. Furthermore, assistive systems are typically adaptable across multiple mobile platforms and can support multiple disabilities.

The advent of mobile phones, in particular smartphones, has piloted a new era of connectivity where users are afforded information access "almost any time and in any place" [14]. Such devices are no longer just telephones, but now offer an impressive cluster of features in a compact, portable form [64]. Appropriately, a growing number of the visually impaired are using smartphones in their daily activities[39, 52] For the purpose of our review, "mobile" refers to any device that is itself portable and can be used while in motion (this includes mobile phones), or that is embedded within an environment that can be in motion (e.g., within public transport) or within which the user is in motion (e.g., within the home around which the user moves). We also include robotics that can either enhance or support users' mobility. We reflect on research that has been done to make standard mobile hardware more accessible to people with vision loss (e.g., mobile phones) separately from research that uses mobile devices as a platform for delivery of specialized assistive support.

Mobile Devices Made Accessible for Visually-Impaired Users

Mainstream mobile devices are typically visually and physically demanding and are, therefore, not particularly accessible to individuals with visual impairment [42]. This situation has been further exacerbated by the increasing ubiquity of touchscreen-based mobile devices that rely even more heavily on visual interaction techniques. Interestingly, however, the perceived limitations of the small keypads and screens on mobile devices, as well as their recognized inappropriateness for use within contexts where visual attention has to remain on the physical environment for safety reasons, has led to research into the use of touch and audio to enhance or replace traditional reliance on visual display resources.

Innovation in these areas has explored usage of sensory modalities other than vision – for example, speech recognition [77], non-speech auditory feedback [17], haptic (touch-based) feedback [18], and multimodal input [105, 76](which combines different sensory modalities) – to reduce dependence on visual interaction[19, 107, 21]. Recent advances in the likes of vibrotactile, text-to-speech (TTS), and gestural recognition systems have consequently opened up scope for increased accessibility to devices for persons with visual impairment.

Human-computer interaction based research is increasingly exploring the possibility of supporting truly ‘eyes-free’ interaction methods for smartphones and other handheld devices. While much of this research has been motivated by the need to preserve users’ personal safety when in environments where they cannot devote their visual resource to interacting with the device, the innovations themselves are of obvious benefit to individuals with impaired vision. *Foogue* [32] is an eyes-free interface that enables users to access and input information to mobile phones by exploiting spatial audio and gestural input. It substitutes the need for visual attention by employing audio- and haptic-based interaction techniques. Specifically, information items (e.g., mp3 files) and software applications (e.g., mp3 player) are represented audibly within the 360^{o} space around the user; sounds representing the various items, including those that are currently playing (such as an mp3 file loaded into the mp3 player), appear to originate from specific locations around the user when listened to via headphones. The user interacts with these audio representations to, for example, point to and select and open files or close a running application via physical arm/hand gestures made while holding the mobile device. By adopting the combination of audio and haptic interaction modalities, *Foogue* avoids any requirement at all for visual display and interaction.

Brewster et al.[19] proposed two novel solutions for eyes-free, mobile device use. The first presented information items to users via a 3D radial pie menu. To select an item, users were required to nod their head in the direction of the sound representing the item they wanted to use. In a current affairs application instantiation of the technique, weather, traffic, sport, and news were presented using snippets of identifiable audio – weather noises, traffic noises, the theme tune to a television show, "A Question of Sport", and the theme tune to a news channel, respectively – and the user nodded in the direction from which the sound appeared to originate in order to listen to that particular type of information. In another application, the user interacts with a music player in which musical genre, artists, albums, and tracks were represented by music snippets in a nested hierarchy which was interacted with in much the same way. Brewster et al. also developed a sonically-enhanced 2D gesture recognition system whereby a user could draw large shapes and other characters on a belt-mounted mobile device touchscreen in order to issue commands to the device. Although neither of their innovations were specifically designed for visually-impaired users, both entirely avoid visual displays and use sound- and gesture-based interaction techniques that could significantly improve the accessibility of IT devices for the visually impaired. With the rise of mobile technologies that are incorporating touch sensitive screens, we have seen a corresponding increase in research into touchscreen accessibility for the visually impaired. The biggest issue with touchscreen phones is a lack of tactile feedback that was afforded by the physical keys on older models of phones. Touchscreens provide no means of action orientation other than via the visual modality. Neff et al.[73] split the issue of touchscreen accessibility into icon presentation on one half of the screen and effective interaction with the icons on the other half of the screen. They have established a design framework which, like the work described above, is based on the use of spatialized, non-speech sounds to present icons and the use of gestures to interact with the icons. Whilst Neff et al. have provided details of their framework, no results of user studies have yet been published.

The Slide Rule [51] interface overcomes the accessibility barrier of touchscreens by providing a "talking touch-sensitive" interface – an interface that is speech-based and has no visual representation. Users navigate through and scan lists of on-screen objects by brushing their fingers down the device surface and use gestures to interact directly with on-screen objects they encounter. A set of four multi-touch gestures are used to allow users to interact with on-screen objects: (1) a one-finger scan for browsing lists (e.g., Slide Rule speaks the first and last name of each contact in a phone book as a user slides his/her finger over each contact from top of the screen to the bottom in order to find a particular contact); (2) a second-finger tap for selecting items (e.g., the user holds one finger down over the selected contact, which has already been read aloud and then taps anywhere on the screen with a second finger to select the target beneath the first finger); (3) a multi-directional flick gesture for performing additional actions (e.g., the user flicks to the left for replying to a selected message); and (4) an L-select gesture for browsing hierarchical information (e.g., in a music player application, the user first moves a finger down the screen to find the desired artist, then to the right to choose from songs by that artist).

Slide Rule was developed according to a user-centered design methodology. Specifically, formative interviews were conducted with eight visually-impaired users to elicit requirements. This was then followed by iterative prototyping of the system with three visually-impaired users. This participatory approach to design meant that direct input from target users shaped the development of a cohesive set of interaction techniques based on key issues raised by potential users. For instance, users wanted to minimize the need to search for and select on-screen items through trial-and-error; consequently, the second-finger tap gesture, described above, was developed to lessen the accuracy demands when selecting items on screen and activating other options. Subsequent pilot evaluation studies have shown that visually-impaired participants enjoyed interacting with the touchscreen and recognized its potential.

AudioBrowser [24] is a similar information access tool for touchscreens that enables users to browse stored information and system commands via a combination of both speech- and non-speech audio feedback. Users are guided by speech and non-speech audio as they move around the screen that is split in two to allow the user to differentiate the information display from the control display. As users' fingers move across the screen, non-speech audio is used to inform them when they cross a boundary. Within a given segment of the screen, speech audio informs the user of the information contained therein. A key advantage of *AudioBrowser* is that it supports a hierarchal structure that enables users to access information (e.g., webpages, personal documents, audio files, etc.) while on the move (and unable to look at the screen of their device) by following a direct, logical path.

The approach taken within *AudioBrowser* draws on the findings of a recent study investigating different approaches adopted by visually-impaired users when interacting with touchscreen user interfaces on mobile phones [53]. Participants' feedback highlighted the importance of quality of experience for visually-impaired users in comparison to task efficiency. Despite being the least time-efficient design, touchscreen interfaces based on horizontally structured hierarchies are generally preferred by users with visual impairment. This is one example of the importance of seeking and using qualitative information from end users in the design, development and evaluation of such technologies.

Aside from issues of mobile phone inaccessibility, visual impairment presents general challenges in daily life in terms of interacting with everyday appliances that support IT-based or computerized interfaces. To overcome these challenges, Nicolau et al.[75] have developed a personal mobile controller: this is an assistive application embedded within a mobile phone that is designed to allow users to interact with intelligent environments (environments that consist of computerized technology). The device was designed to meet requirements that were elicited via interviews with visually-impaired users to determine the difficulties they experience in use of ubiquitous technologies. The device downloads the appropriate interface specifications for the computerized technology within a given environment and generates a single, consistent, usable interface on a mobile phone that acts as a controlling interface for all computerized devices in the surrounding area, thus making the environment accessible via a single interactive controller for an individual to use.

The personal mobile controller is particularly useful for someone who is entering a new environment where the appliances are unfamiliar – for example, using a microwave in a new workplace. It reduces the embarrassment of having to ask others for assistance or attempt to understand the interface when there are other people around who may need to use the same appliance. Connelly et al.[25] argue that impaired users are more likely to use mobile technologies since these are deemed as non-stigmatizing and are associated with affluence and success. Having the capacity to support control of different interfaces and manifesting this control via a mobile phone as an intermediary device, the personal mobile controller exploits these positive attitudes and provides a single point of interaction with multiple complex technologies within an environment. Preliminary evaluation of the personal mobile controller revealed that users liked the controller and were able to explore and control computerized devices such as microwaves easily. Nicolau et al. propose to evaluate the personal mobile controller in field trials with members of the target user group.

As mobile technology gains sophistication and widespread use, research is on-going to make mobile phones and other handheld computer devices more efficient, cost-effective, functional, and accessible. The examples above represent just some of the work in the field of haptic interaction [94], spatial audio displays [70], and gestural recognition that is leading to the emergence of increasingly accessible means by which to interact eyes-free with mobile technologies.

In addition to more generalized innovation in the field of accessibility and usability of mobile devices discussed above, researchers have also explored the prospect of Braille displays as a specific form of haptic (touch-based) interaction for visual impairment. Whilst obviously only useful to those who have been trained in the use of Braille, research in this area represents a commitment to making mobile devices more accessible. The simplest of such approaches is *BrailleTap* [42]. Here, each mobile phone key represents a Braille character that the user can select to represent a letter of the alphabet. Using keys on the keypad as Braille cells allows the user to input text to form messages.

Jayant et al. introduced *V-Braille* [48] which, by conveying Braille through vibration on a touch screen, allows users who are Braille-literate to interact with mobile phone interfaces. The traditional Braille structure is imitated on a mobile interface by dividing the screen into six parts. When the screen is touched within these parts, vibrations of different strengths represent a character which allows users to differentiate between characters. Preliminary evaluation of V-Braille with nine potential end users showed there is scope for introducing Braille as an alternative and useful presentation paradigm.

MoBraille [9] is a novel framework for facilitating accessibility to many of the features of Android smartphones by connecting the phone to a Braille display which serves as an input/output platform. Braille displays operate by electronically raising and lowering different combinations of pins to reproduce in Braille what appears visually on a portion of the smartphone screen. *MoBraille* makes it possible for an Android application to interface with a Braille display over a Wi-Fi connection, thereby enabling Braille display users to access applications, including the compass and GPS-based facilities, on their phone. For example, *MoBraille* enables visually-impaired users to access real-time bus arrival information by displaying the information on their smartphone’s Braille display. At his current bus stop, a user points his phone towards the street that is identified based on GPS coordinates, he confirms his location via a button press, and enters the route number via his Braille display, after which the Android application displays arrival information on the Braille display. *MoBraille* was developed based on sound understanding of end users’ needs, wants, and expectations acquired as a result of conducting a series of semi-structured interviews with end users to understand the challenges they face and by engaging them in participatory design activities. As a result of a focus on the end users during design, some important findings were discovered and incorporated into the design. For instance, somewhat contrary to designers’ initial conceptions, "conciseness and training" were favored over "discoverability". Users preferred an interface requiring training and memorization as opposed to the initially proposed interface based on self-explanatory messages. Although the reported *MoBraille* proof-of-concept focused on access to bus timetable information, it has the scope to be used as a platform for many other types of applications, such as barcode scanning.

Mobile Device-Based Assistive Technology

Established research into handheld device accessibility has demonstrated that users with visual impairment can effectively interact with small keypads and screens where non-visual input and output modalities are used to compensate for the lack of visual display resources [61]. With ongoing advances in mobile technologies, it is becoming ever more feasible for the visually impaired to rely on mobile handheld devices to capture information necessary for interrogating and understanding their surroundings and to access large amounts of information that can then be used to improve their level of independence, mobility, and quality of life.

Lack of independent and safe mobility is ranked as the most significant barrier depriving individuals with visual impairment of a normal living experience [22]. Highlighting the vital impact mobile assistive technology can have in this capacity, we discuss innovation in mobile assistive technology according to key assisted-living functions designed to sustain individuals' independence. Specifically, we highlight innovation in supporting far distance tasks such as navigation and way finding [e.g., 1, 33], intermediate distance tasks such as obstacle detection [e.g.,108], space perception [e.g.,90] (which also includes near distance tasks such as reading), and independent shopping [e.g., 57]. Some of the aforementioned assisted-living functions are also supported by robotics and within smart homes and will be further discussed in these contexts.

Navigation and Way-Finding

Undoubtedly, sighted guidance is an effective means of mobility assistance for visually-impaired pedestrians [40]. Some argue that it reduces mental demand during travel [91] and, as such, also reduces levels of associated stress[80]. Consequently, researchers have attempted to combine technological solutions with sighted guidance to arrive at teleassistance systems [e.g., E, 11, 22, 40] – a remote guidance concept whereby, based on technologically recorded and transmitted environmental information, remote sighted guiders provide visually-impaired users with verbal descriptions of the users' environment as well as directional instructions. Common to all navigational teleassistance systems is the need for the visually-impaired pedestrian to carry a backpack containing a digital webcam, GPS receiver, and mobile phone with microphone and earpieces. The navigating pedestrian is guided by spoken instructions from a sighted guider who receives information – typically in the form of video images – about the pedestrian's location on a personal computer via a wireless/3G connection and provides verbal directions over the same infrastructure. Although undoubtedly useful, current teleassistance systems tend to impede individuals' sense of personal independence and privacy. Further research is therefore required into both user acceptance and development of such teleassistance systems.

In contrast to teleassistance systems, which require the involvement of sighted support operators, more truly independent mobile device-based navigation and way-finding applications are quickly becoming one of the more successful approaches for supporting unsighted mobility. One example is *Voice Maps* [96] – a system for point-to-point navigation and independent mobility for visually-impaired users in urban areas that operates on an off-the-shelf touchscreen smartphone. *Voice Maps* takes advantage of Android's text-to-speech mechanism for generating voice messages, vibration for screen accessibility, and gesture recognition for text input. An interesting feature of the system is that, besides finding the optimal route, it continuously monitors a user's direction and position. If a user deviates from the recommended path, it informs him and suggests alternative or corrective actions. No user evaluations have been carried out to date.

Sanchez and Torre [87] developed a mobile phone-based system that uses a combination of audio input/output and GPS technology to facilitate visually-impaired users' mobility in both familiar and unfamiliar environments. Users press a button on their mobile device to sign in. Based on their current GPS-detected location, they can search through destinations that are read out to them by the text-to-speech (TTS) synthesizer and hear information regarding the distance and direction required to get from their current location to their selected destination. The TTS provides directions based on a clockwise metaphor structure, whereby the user is always assumed to be facing 12:00, and turning directions are given relative to this orientation. Despite being limited by lack of support for obstacle detection and assistance with crossing streets, evaluations with visually-impaired participants showed that, with practice, the tool can be used to help visually-impaired people explore new places.

Mobility and autonomy on public transportation systems is a common difficulty that the visually impaired face. The *RAMPE* [12] system has been designed to assist visually-impaired pedestrians travelling by buses and tramways. The system is based on Wi-Fi-enabled smart handheld devices carried by the users, fixed base-stations installed at bus stops to communicate with the users' handheld devices via the Wi-Fi connection, and a central system connected to both the base-stations and buses or tramways for sending real time information about public transport to the base-stations. User needs were elicited using semi-structured interviews with end users and via direct observations of intermodal urban transit of individuals with visual impairment. The *RAMPE* application allows the user to decide on the stops he wants to connect to in order to receive relevant directions, including information about the changing environment, during transit. Once at a given stop, the user can listen to the list of the stops along a specific bus or tram line. The application adapts to the type of passenger information system available at the stations and reacts to real-time information; for example, if the static information (e.g., number of stops on a line) changes as a result of updating of the database, or an urgent event such as an accident, unforeseen disturbance, or delay, the user is informed immediately of the situation using the TTS synthesis and must acknowledge the receipt of this urgent message by pressing a button. In addition to the speech synthesis, *RAMPE* supports a dynamic keyboard depending on the state of the application: the normal mode and the urgent mode. In normal mode, each button has a specific function (e.g., the silence button puts the speech synthesis in pause), whereas in urgent mode all the buttons allow the user to acknowledge the receipt of a message. User evaluation conducted in a real urban transport environment with 23 visually-impaired participants confirmed the usefulness of the system in terms of giving rise to an accurate mental representation of the travel.

A similar mobile assistant has been developed for orienting visually-impaired people within a Metrobus environment [69]. The system consists of a smartphone, GPS, and compass device, all of which communicate via Bluetooth. The system provides an audible interface designed to assist visually-impaired users to browse through menus and options by listening to relevant information. The main purpose of the mobile assistant is to locate and orient the visually-impaired user within the Metrobus environment. For instance, the user can find out where the station exit is located by pressing a button and once the required information is received from the GPS and compass devices, relevant audio files are played to guide the user. If, for example, the exit is located towards the east, the audio file will say "*The exit is located at three o'clock*". User evaluations conducted in Metrobus stations using twenty visually-impaired participants confirmed that the mobile assistant contributes to their overall navigation performance by increasing their confidence and sense of security.

Obstacle Detection

The solutions described in the previous section focus exclusively on systems for directing users from point A to point B. Complete solutions for independent and safe navigation for visually-impaired individuals also require support for near distance tasks such as obstacle detection to warn users of the presence of potential hazards in their path.

The white cane is the most common and successful mobility aid used by the visually impaired because it helps users detect obstacles and hazards in front of them while moving [92]. Although this aid is inexpensive, it requires "substantial user training" [102 (p1)] and actively requires users to scan the area ahead and around them. To overcome these challenges, and in some cases completely remove reliance on what can be perceived as a stigmatizing cane, researchers have developed IT-based navigation devices that caution the user about hazards. Some systems focus solely on obstacle detection and some enhance navigational assistance with obstacle detection/avoidance.

SmartVision[50] is a navigation aid that electronically enhances and complements the white cane to guide users to a destination while avoiding obstacles en route. *SmartVision* supports local navigation by path tracking and obstacle detection and covers the area in front of the user and just beyond the reach of the white cane such that the system can alert users to obstacles ahead of them before their white cane would touch them. For indoor navigation, a combination of Wi-Fi with Geographic Information Systems (GIS) is employed; for outdoor use, GPS is required. As a fail-safe solution (e.g., when GPS is not available due to bad weather) users are assisted by environmentally embedded RFID (Radio Frequency Identifications) tags. An RFID reader embedded within the white cane detects such tags in the pavement, and the information from it is then automatically interpreted and used to guide the user. Further, the user is equipped with a stereo camera (that is, a camera with two lenses that stimulates human binocular vision and supports the capture of three-dimensional images) attached at chest height, a portable computer worn in a shoulder-strapped pouch or pocket, an earphone, and a small four-button device for menu navigation and option selection. An audio interface supports menu navigation and provides information about points of interest. When obstacles are detected, vibration actuators in the handle of the white cane inform users to change their direction. The prototype is still under development; researchers are actively considering the interplay between helping users avoid obstacles and remaining centered on the correct navigational path.

Calder designed a novel prototype ultrasound system for warning users about obstacles in their path [23]. The system, which has a tactile display, is hands-free and can be used as a substitute for or supplement to the cane. The system supports two modes of operation: a hands-free mode where a tactile interface (using a system of vibrational actuators or tactors) has been developed to be used on the trunk of the user's body, and an augmentative mode where tactors are attached to the handle of a modified long cane for use against the palm of the hand. Vibrations inform the user about obstacles across their path. Only where an object is detected suddenly will an audible sound complement the signal from tactors. On the basis of promising results from initial tests with visually-impaired participants, more advanced versions are under development to combat issues associated with drop-offs such as steps down or potholes in the road surface.

Zhang et al. have also developed a hands-free device to complement the white cane[108]. Their device incorporates a sensor unit installed underneath and at the front of the user's shoe for detecting road surface reflectance (e.g., black surface marking to indicate the existence of a danger zone ahead) and obstacles respectively and a small feedback unit worn on the arm for providing vibration signals based on the surfaces and obstacles detected by the sensor units. The prototype is under development, with the focus being on the hardware more than the software.

Adopting another approach, researchers at Michigan University developed the *Navbelt* [92] – a belt assembled with ultrasonic sensors to provide auditory feedback to individuals with visual impairment to enable them to avoid obstacles and navigate along a required path. When they detect obstacles, the sensors send a signal to the control unit – a portable computer carried by the user in a backpack – that processes them and converts them into audio output which is relayed to the users via headphones. Specifically, where no obstacles are detected, the audio feedback is barely audible, indicating safe and correct travel direction but where obstacles are detected, the volume of the audio feedback increases in inverse proportion to the distance to the obstacles ahead. Extensive evaluation of *NavBelt* during its 5-year long development process revealed that users were unable to understand and act on the guidance signals at a pace that kept up with their walking speed.

The *GuideCane* [85] was developed to overcome the problems associated with the *NavBelt*. It is an advanced version of the white cane that travels on wheels to support its weight. With 10 ultrasonic sensors, it is able to detect obstacles in its path and the wheels are equipped to steer in the direction dictated either by the user (via a joystick or manually) or automatically by the system via an embedded computer. When the *GuideCane*'s sensors detect an obstacle, its embedded computer analyses the environment to find a suitable alternative course and then physically guides the user along that course.

A major drawback with both *GuideCane* and *NavBelt* is that neither system is discrete. Both draw attention to users, making them potentially more vulnerable and to feel stigmatized. To combat this, alternative, discrete devices are being developed. For example, Peng et al.[81] have proposed a smartphone-based obstacle sensor for the visually impaired. With the smartphone held at a 45^{o} tilt angle, the user walks forward until the phone vibrates to indicate that the path ahead is not safe. Users have two options to identify a safe alternative path: the system provides verbal instructions to indicate which sides are safe to move toward, and the user can choose to make directional changes based on this audio feedback, or the user can point the phone in other directions until the vibration stops, signifying that it is safe to proceed in the selected direction. Although an evaluation of this system returned positive results overall, users did find it difficult to hold the phone at the required tilt angle at all times. Further limiting the usefulness of the system is its constrained means of mapping the terrain ahead, coupled with an underlying assumption that there will always be a small region in front of the user that is safe.

With the aim of guiding individuals and helping them avoid obstacles, Amemiya and Sugiyama [7] proposed the haptic direction indicator – a small, handheld mobile device based on the ‘pseudo - attraction force technique’ [6]. The method generates the force sensation by exploiting human-perception characteristics. Their prototype of a handheld force feedback device with asymmetric acceleration (accelerated more rapidly in one direction than in the other) allows the holder to experience the kinesthetic illusion of being pushed or pulled continuously in the appropriate direction. If the user takes a wrong turn, the system changes the direction of the force vector to encourage a return to the predefined route. One of the key strengths of this system – and others that use haptic force sensations – is that it prevents the overuse of audio feedback. Since the visually-impaired rely on their sense of hearing to gain information regarding their environment, it is important not to occlude or interrupt that and confuse them with too many auditory stimuli. An evaluation with twenty-three visually-impaired participants confirmed that they were able to recover the intended original route by employing the force feedback and proved that the proposed system can be used to provide navigation directions via kinesthetic sensation without any previous training [8].

Intelligent glasses are a non-invasive navigation aid[103]. Cameras mounted on eyeglasses frames detect environmental obstacles and translate this information into haptic feedback that is presented via a tactile display carried by the user. Users can carry this tactile display - which has similarities to a map - whilst they are walking and interact with it via their sense of touch (much like some of the previously discussed systems) to determine their position, path and any obstacles they might encounter.

Space Perception

"*A navigation system should not only lead a navigator, but it should also be able to deal with the dynamic environments that they navigating regardless of familiarity*" [84 (p 1649)].

Safe navigation through and presence within one’s environment involves not only knowing the appropriate path to take from point A to point B and being able to detect and avoid obstacles along that path but also being able to perceive, interpret, comprehend one’s surrounding physical space [99] and support near distance tasks such as reading. This section considers systems that have been designed to help the visually impaired with space perception.

Cognitive mapping [46] is of crucial importance for individuals in terms of creating a conceptual model of the space around them and thereby supporting their interaction with the physical environment [47]. The Haptic Sight study was designed to provide immediate spatial information to visually-impaired users [93]. Using direct observational and interview-based knowledge elicitation methods, researchers initially tried to gain an understanding of a visually-impaired person's indoor walking behavior and the information required to walk independently. They found that visually-impaired people need to be aware of their current location, the direction they are heading, the direction they need to go towards, and the path to the destination. Only after the research team had identified these parameters did they develop a handheld device-based application. The Haptic Sight interface wirelessly receives environmental information via ultrasonic and/or infrared sensors that it translates into a tactile presentation of a building layout using raised blocks on a touch surface. When holding Haptic Sight, users will be able to sense their surroundings via touch. This research is still in its early stages.

A key advantage of mobile devices, such as smartphones, is that new functions can be easily programmed and customized at the software level without the need for additional hardware. Researchers at the University of Memphis have designed a Reconfigured Mobile Android Phone (*R-MAP*) [85] to provide more independence to visually-impaired people in terms of overcoming challenges associated with everyday activities. Despite its name, *R-MAP* is essentially an auditory-based, stand-alone application for Android phones that requires no special hardware or internet connection to provide services including, but not limited to, reading food containers, labels, and envelopes. *R-MAP* uses the touchscreen of the phone. A button placed in the top right hand corner of the screen (to allow the user to adopt physical edge tracing to find the button) starts the application which is accompanied by a loud audio confirmation. A second button placed diagonally opposite this in the bottom left hand corner of the screen is used to enter data capture mode, which is announced by a low audio feedback tone. Once in capture mode, the user can click again on the top right hand button to capture the required environmental data in the form of an image. Upon capture, another audio feedback tone is used to indicate that the image is of sufficient quality for auto-interpretation. The user can then click the bottom left button again to have the system read out a description of the captured image content.

R-MAP has been evaluated both by sighted volunteers who were blindfolded and a single visually-impaired volunteer. Interestingly, the visually-impaired individual performed better than the sighted users. The users felt that *R-MAP* was generally easy to use, especially with the aid of the audio feedback. The potential to support more advanced activities such as following a route map is being studied.

Timbremap [100] is a mapping application for off-the-shelf touchscreen mobile devices. It uses audio feedback to guide a user's finger along the lines of a digitally-rendered geographical map in order to support them in developing a cognitive understanding of geometrical (representing geographical) information and thereby contextualizing their surroundings. The *Timbremap* interface provides output feedback using two non-speech sonification (audio) modes to convey or perceptualize data. The first is the line hinting mode; this guides users' touch along path segments. If a user's finger drifts off a path segment, a variety of audio feedback indicates how to return to the path to continue tracing it. The second mode is the area hinting mode; this informs the user about the number of paths around the edges of the screen, about gaps between path segments, and about the existence of any path intersections. Users can pan the map by positioning their primary finger on any spot on the map, then holding any of the four corners of the screen with a second finger and dragging the primary finger to pan the map in the direction of the second finger. To listen to points of interest (POI) markers on the map, the user holds one finger on the POI marker and double taps anywhere on the screen with a second finger. The concept of *Timbremap* is very much in line with the findings of recent research [16] that highlights the importance of understanding the cognitive maps that the visually impaired form to navigate.

MobileEye [64] aims to help the visually impaired to see and understand their surroundings during independent travel and other activities through the use of a mobile phone's camera and text- to-speech (TTS) technology. The system consists of four subsystems adapted for different types of visual disabilities: (a) a color channel mapper to help the user distinguish colors around them; (b) a software based magnifier for providing image magnification and enhancement to facilitate reading and understanding of objects; (c) a pattern recognizer for recognizing objects such as money; and (d) a document retriever for allowing access to printed materials by using only a snapshot of a page and retrieving the document from a large document database. Every operation of the software is guided by a voice message. The user activates the camera by two key presses to prevent accidental activation, and the software automatically exits after being idle for two minutes. The researchers acknowledge that further research is required to enhance the *MobileEye* concept (e.g., improved response time and evaluation of the TTS and vibrational feedback).

Shen et al. [90] have developed a similar mobile phone-based system which uses the phone's in-built camera to help the visually impaired find crosswalks and, more importantly, cross them safely. With this system, when users approach a crosswalk, they take an image of the crosswalk which is then analyzed by software run on the phone; the results of this analysis are conveyed to the users via audio feedback/instructions to assist them in crossing the crosswalk safely. The latest version of the system detects two-stripe crosswalks (these crosswalk patterns consist of two narrow white stripes bordering the crosswalk, and are much more challenging to detect due to the small number of features) in real time and helps users to stay inside the crosswalk boundaries when crossing (blind users report difficulty in maintaining direction when crossing a road due to the lack of immediate ambient features [16]). Future work will focus on further user interface development, more sophisticated functionality and further user testing.

LocalEyes [13] is a GPS-based application with a configurable multimodal interface designed for Android smartphones to facilitate visually-impaired users' navigation and awareness of their environment. It allows them to explore information about, for example, surrounding points of interest including restaurants, coffee shops, etc. Users establish their current location and orientation by simply tapping the screen and then accessing information about local points of interest by using simple gestures. Currently, information is communicated to users via speech as well as on screen via large, high-contrast text. A Braille output display and a version of *LocalEyes* for the iPhone are now being developed.

Independent Shopping

Independent and safe mobility is vital for independent shopping. Visually impaired people have ranked shopping centers as the most challenging environments through which to navigate [79], and the overall shopping experience as a "major problem" [59] because of its requirements for both near (e.g., reading labels) and intermediate distance (e.g., in-store navigation) tasks.

Researchers at Utah State University offer a comprehensive analysis of design requirements for mobile assistive technologies to assist visually-impaired shoppers and identify the main activities underpinning conventional shopping behavior as product selection and browsing before purchasing, navigating within a store, and searching for and identifying actual products [55]. On the basis of their analysis, they developed *ShopTalk* [74] to assist visually-impaired shoppers to navigate through a store and locate target products by scanning barcodes both on shelves and on individual products. *ShopTalk* consists of a set of headphones (for verbal route instructions), a barcode scanner (assembled with stabilizers designed to rest on shelves to make it easier for users to align the scanner with the barcodes), a numeric keypad, and a computational unit. *ShopTalk* guides the user in the store by issuing route instructions in two modes: location unaware mode (LUM) and location aware mode (LAM). LUM verbal route directions are generated based on a topological map built into *ShopTalk* at installation time by walking through the store, noting decision points of interest (e.g., store entrance, aisle entrances, cashier lane entrances), and then representing them in the map, and a database of parameterized route directions based on the topological map. Such guidance relies on the shopper's orientation and mobility skills, as the system itself is unaware of the shopper's actual location and orientation. The LUM mode can only be activated by pressing the *Enter* key. Conversely, LAM mode issues location-aware instructions and is activated by a barcode scan (a barcode scan also switches the mode from LUM to LAM) that informs the system about the shopper's exact location and helps the user navigate amongst the aisles. This approach relies on a barcode connectivity matrix, where product information (e.g., aisle, aisle side, shelf, section, position, description) is stored in-built from the store's inventory database. Studies of *ShopTalk* have shown a high success rate for product retrieval. The identified limitations to the system were the requirement to carry a set of hardware components and the need for the system to be able to access a store's inventory control. In recognition of these limitations, an improved version has been developed – *ShopMobile-2* [58] – which is delivered on a mobile platform and utilizes the smartphone's camera as barcode reader [56, 57]. Although user studies have been conducted, no results have as yet been published.

Further smartphone applications for grocery shopping (specifically, for searching for and identifying products) include *Trinetra* [60] that has been developed with involvement of a visually-impaired user from conception to deployment and with a goal of portability and cost-effectiveness. Tekin and Coughlan developed a similar off-the-shelf mobile phone application [101]. Both applications are barcode-based. When the user scans an item's barcode, it is checked for a product match in the database and the results are read out to the user. *BlindShopping* [65] is a similar smartphone-based system with the added advantage of guiding users through a store. In this case, users have to carry a white cane and, based on information sensed via an RFID reader attached to the tip of the white cane and RFID tags distributed throughout the aisles of the supermarket, verbal navigation instructions are provided via a headphone connected to the smartphone. Once at the target product section, the user can point the camera phone to QR (Quick Response) or UPC (Universal Product Code) codes, attached to the shelf section beneath the product, to receive verbal information about that product.

The examples outlined in the previous sections highlight the fact that mobile device-based assistive technologies can help visually-impaired users travel with greater ease and better equip them to avoid hazards when navigating based on a more comprehensive appreciation of their physical surroundings. This in turn can enhance their ability to participate fully in societal activities and increase their ability to live independently.

Smart Homes and Robotics

Designed to safeguard users' wellbeing in their own homes, robotics and smart homes (that is, homes embedded with assistive technologies) now offer the visually impaired and others with disabilities opportunities for independent living, often with added benefits in the form of facilities to reduce social isolation. Although smart homes themselves are stationary, they have been included in this review because a person living within one of these homes is mobile while using the embedded technology around them. Furthermore, development of smart homes assists users' mobility and other life activities associated with independent living. Mobile robotics is a more recent area of research in the assistive technology field. Our discussion of smart homes and robotics overlaps since the field of robotics generally incorporates the traditional concept of a robot, along with components of robotics that are used in mobility aids and smart homes.

The primary purpose of a smart home is to offer independent living and to provide a safe environment for individuals with disabilities, including visual impairment [38, 68]. The *INHOME* [104] project, which supports a number of specifically-targeted user requirements based on data from relevant literature and on feedback from health-care professionals, is designed to assist people in private residences with the aim of providing a higher degree of independence and safe living in their home environment. *INHOME* monitors individuals within their homes, enables remote control and configuration of home appliances, and provides error and status messages via an *INHOME* terminal or a TV set. For instance, while watching TV, a user may wish to receive (via the TV) status information about another home appliance (e.g., washing machine) as well as being able to remotely control and configure its operation. When the washing machine cycle has finished, for example, an alert message can be displayed on the TV screen accompanied by an audio alert.

Likewise, the user can be informed if, after switching on an oven, he/she has forgotten to place a pan over the heat. If the user does not react to the alert within a specified time interval, the oven can be switched off and interested parties previously specified by the user might be notified. Together this monitoring and level of remote control helps individuals feel safe in their own home. Furthermore, the *INHOME* mobile terminal incorporates parallel use of speech recognition and a touch screen to receive commands from users to ensure that they can maximize their feeling of control.

Virtual house calls are now possible through interactive IT-based technology. Deegan et al. [33] are exploring the concept of a robotic mobile manipulator that helps an individual with a variety of manual tasks. Part of the *ASSIST* project – a multi-institutional and interdisciplinary research project – a mobile manipulator is being developed based on sound understanding of users' special needs, lifestyles, preferences, residential geometry, and environment. Notably, focus groups revealed that elderly people with impairment are more likely to accept and use technological solutions if they understand their benefits.

Utilizing a network of camera sensors, *mobile manipulator* comprises a mobile interface to facilitate remote communication with the outside world, a microphone, and a speech synthesizer. The camera sensors continuously monitor areas where movement is most likely to occur to detect, for example, objects in the way or evidence of a fall. As discussed previously, obstacle detection is important for the visually impaired, and an individual's home is no exception. Hazards may arise when objects are moved or accidentally drop to the floor. The likelihood of falls as a result of such hazards can be eliminated by detecting and removing them. For example, if a box left in a hallway by a delivery person is detected and located using its camera sensors, the mobile manipulator is then guided autonomously using these cameras towards the object. Once the mobile manipulator determines that it is in contact with the object, it attempts to move it out of the way by applying force to the object. Not only does the mobile manipulator help individuals with manual tasks, but it can immediately contact family members or emergency medical care in the case of an accident.

Allied with the concept of independent shopping as discussed previously, *RoboCart* [54] is a robot-assisted shopping device comprising a shopping basket mounted on a polyvinyl chloride frame structure, with a small robotic base, a camera, a laser range finder, and an RFID reader. RFID tags placed at various locations in a store allow the robot to keep track of its position and guide users to their chosen vicinity, with navigation supported by the laser range finder. Repeated activity can lead to visually-impaired individuals becoming used to the space around them and, as such, increase their confidence and self-reliance. Subsequent to initial feedback from visually-impaired users, the researchers enhanced the robot by attaching a small keypad to the handle to support product selection by list browsing and to improve robot control, and a handheld wireless barcode scanner. Following these modifications, a formal longitudinal study was conducted during which visually-impaired participants successfully completed a series of trial tasks which included navigation to shelf sections, using the keypad to select grocery items, placing items into *RoboCart*'s basket, and navigating to the exit.

In addition to the mobile handheld devices outlined previously, robotic systems are also emerging as technological means for combating mobility issues. A novel robotic system has been designed to assist the visually impaired with navigation, obstacle detection, and space perception [41]. The system consists of a camera, laser range finders and a small PC placed on a trolley walker (i.e., a 4-wheeled trolled with two handles and a tray attached to the bottom to house the PC) equipped with sensors. Importantly, it has the capacity to detect hazards like stairs and steps. Additionally, the robot can distinguish between human and inanimate objects based on the camera image. When obstacles are detected, users are cautioned via beep signals or via natural language – e.g., "*be careful on the right*", or "*stairs, stairs*". Future work will involve increasing the number of sensors on the walker, using a rotating camera for detecting moving objects, and including a GPS system for outdoor environments.

Although mobile robots can now be used in healthcare (especially eldercare [20]), in smart homes, in therapy to assist individuals with manual tasks, to help decrease loneliness, or to act as a virtual interface to provide remote monitoring and communication [44], there are ethical issues concerning individuals' sense of freedom, dignity, and their human rights [82, 86], discussion of which are outside the scope of this review. In addition, because the focus of this review is on mobile assistive devices for the visually impaired, a large proportion of the published research covering smart homes and robotics has been excluded on the grounds that it is not specifically designed for the visually impaired.

Conclusions

We have reviewed research and innovation in the field of mobile assistive technologies aimed at assisting visually-impaired individuals to lead more independent lives, and the crucial role such technologies can play in substituting for a lost capability. Mobile phones and other mobile technologies can facilitate portable solutions that support users in an unobtrusive, ubiquitous capacity, aided significantly by the fact that they are discrete and non-stigmatizing. Although, all reviewed technologies are still in the research phase, we believe that many can be translated relatively easily into daily life as the majority incorporate mainstream technology such as smartphones. Table 1 summarizes the reviewed mobile device-based assistive technologies. The summary is organized according to major tasks – that is, near, intermediate, and far distance tasks.

Despite their immense potential, studies have shown that individuals will only use assistive products which serve their specific needs. Lifestyle and aspirations play an important role in the acceptance and effectiveness of assistive technology [43]. "*Every blind or visually-impaired person […] has different and specific mobility, orientation and navigational capabilities that need to be supplemented in various ways*" [98 (p24)] and, on this basis, it is essential that these individual capabilities are recognized, understood, and accommodated during innovation and design processes.

User-centered design (UCD) is a philosophical approach to technology design that places the user at the center of the design process. Designers adopting this philosophy recognize that they are not simply designing for themselves or for people with similar abilities and needs, but are instead designing for individuals who may differ in needs, capabilities, and attitudes

[25]. UCD encourages the use of user-focused design tools and practices including interviews, focus groups, surveys, usability testing, and participatory design processes [e.g., 27]. Findings suggest that the use of these UCD tools is critical to success in any technology development, but we have shown this is especially true when entering and developing for a niche market, such as assistive technologies for the visually impaired. UCD also gives vulnerable individuals a direct mechanism by which to convey their concerns with regard to what they see as negative aspects of technology designs that, if unvoiced, could result in the target user group's failure to accept the technology.

"Lack of consideration of user opinion"[83(p43)] during the design process is one of the most important factors leading to technology abandonment, especially in the field of mobile assistive technology where user needs are that bit more specialized. User comments such as "Listen to me! I know what works for me" [83(p42)] reinforce the importance of UCD.

Obviously, engaging individuals with disabilities in an empowered way can present logistical difficulties [29]. Advice from, and involvement of, domain experts such as clinicians is essential to overcome these challenges and thereby fully empower the individuals to participate in the development process. Only when the full range of stakeholders is engaged with the process can the software designers and developers be sure that they are not overlooking functionality and interactivity that is deemed essential by the user group.

In conducting this review, we noted that design methodology was often not discussed. Wherever design approaches have been mentioned, however, we have commented on them. Although we describe many laudable and exciting innovations in the field of mobile assistive technology for the visually impaired, only in a minority of cases has a user-centered design philosophy been comprehensively adopted [43, 45, 97]. We highlighted evidence of the use of individual elements of UCD, including participatory design [e.g., 26], focus groups [e.g., 52], and, most commonly, interview-based studies [e.g., 51, 11] and user evaluation studies [e.g., 64, 87, 69]. Where such methods have been adopted, they have demonstrated the extent to which they can assist designers in making informed choices in developing devices based on users' needs, wants and expectations. In particular, *MoBraille* is a clear case where functionalities preferred by users overpowered designers' initial design concepts. We suggest that the true potential for mobile assistive technologies for the visually impaired can only be fully realized if UCD approaches are more comprehensively adopted.

There is little evidence of the direct involvement of clinicians in what has been substantively research conducted in the computer science domain. We advocate strongly that the potential and beneficial reach of mobile assistive technologies can only be significantly enhanced if computer scientists and clinicians work together to adopt truly user-centered design philosophies for the development of the next generation of mobile assistive technologies.

Research	**Platform/Technology**	**Supported Tasks**		
		Near Distance	**Intermediate Distance**	**Far Distance**
Navigation and Way Finding				
Teleassistance systems [E, 11, 22, 40]	Computer and mobile phone		Obstacle avoidance	Outdoor navigation
‘Voice maps’[96]	Touchscreen smartphone			Outdoor navigation
A mobile phone-based system by Sanchez and Torre[87]	Mobile phone			Outdoor navigation
‘RAMPE’ system [12]	Smartphone		Travel information at stations	Outdoor navigation
Mobile assistant [69]	Smartphone		Travel information at stations; Navigation within Metrobus environment	
Obstacle Detection				
‘SmartVision’ system [50]	Portable computer		Obstacle avoidance; Indoor navigation	Outdoor navigation; Information about points of interest
An ultrasound system by Calder [23]	Actuators or tactors attached to cane		Obstacle avoidance	
Hands-free device by Zhang et al. [108]	A complement to the cane with sensory unit attached to the shoe			
‘Navbelt’ [92]	Belt assembled with ultrasonic sensors and portable computer		Obstacle avoidance	Outdoor navigation
‘GuideCane’ [85]	The cane built with sensors		Obstacle avoidance	Outdoor navigation
obstacle sensor by Peng et al. [81]	Smartphone		Obstacle avoidance	Outdoor navigation
Haptic direction indicator by Amemiya and Sugiyama [7]	Handheld mobile device		Obstacle avoidance	Outdoor navigation
Intelligent glasses [103]	Eyeglasses and tactile display		Obstacle avoidance	Outdoor navigation
Space Perception				
‘Haptic Sight’ study [93]	Handheld device		Obstacle avoidance	Outdoor navigation
‘R-MAP’ [85]	Smartphone	Reading (e.g., food containers, labels)		Reading (e.g., street signs)
‘Timbremap’ [100]	Touchscreen mobile device		Obstacle avoidance	Outdoor navigation; Information about points of interest
‘MobileEye’ [64]	Mobile phone	Distinguish colors; Reading; Recognizing objects (e.g., money)		
A System by Shen et	Mobile phone		Detecting and	

al.[90]			crossing crosswalks	
‘LocalEyes’[13]	Smartphone			Outdoor navigation; Information about points of interest
Independent Shopping				
‘ShopTalk’[74]	Barcode Scanner and computational unit		Navigation within a store; Searching for and identifying products	
ShopMobile-2[58]	Smartphone		Navigation within a store; Searching for and identifying products	
‘Trinetra’[60]	Smartphone		Searching for and identifying products	
‘BlindShopping’[65]	Smartphone and RFID Tags		Navigation within a store; Searching for and identifying products	
Smart Homes and Robotics				
‘INHOME’[104]	Mobile terminal and TV		Remote control and configuration of home appliances	
Mobile manipulator[33]	Camera sensors and mobile interface		Obstacle detection	Contacting family members/medical care
‘RoboCart’[54]	Robotic base, camera, laser range finder and an RFID reader		Navigation within a store; Searching for and identifying products	
Robotic system[41]	Camera, laser range finders and a small PC		Obstacle detection (including stairs and steps) Indoor navigation	

Table 1: *Summary of Reviewed Research.*

Method of Literature Search

Pertinent articles on mobile assistive technology for the visually impaired were identified using a multi-staged, systematic approach to our literature search. During the first stage, a Scopus search (covering databases including PubMed and Web of Science as well as publishers including Elsevier and Springer) for the period up until December 2011 was carried out using various combinations of the following search terms: vision loss; visual impairment; low vision; blind; assistive technology; IT systems; mobile computer devices; mobile technology; mobile assistive technology and handheld assistive technology. The first stage returned 747 research publications for review. During the second stage, all stage one articles were examined and filtered according to their applicability to this article; relevance was determined by reading the title, the abstract and skim reading the paper where necessary. Subsequent to this, a manual citation search was conducted based on the bibliographies of the retrieved articles to identify further eligible studies. During the third and final stage, 168 articles were reviewed in detail and the findings collated into this review paper. Although the literature search was not limited to the English language, all relevant articles were in English (principally as a consequence of the leading publication venues) and so no translation was required. Suitable, newly published papers identified via Scopus alerts were also included following the completion of the initial search.

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