AN OVERVIEW OF ASSISTIVE DEVICES FOR BLIND AND VISUALLY IMPAIRED PEOPLE

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Abstract

Across the world, there are approximately 253 million people with vision impairments, and assistive devices have constantly been in demand. Advanced research has led to the development of numerous assistive devices for blind people and visually impaired people (VIP) to improve their quality of life. An overview of these different types of assistive devices such as canes, glasses, hats and gloves is presented in this survey. A FCBPSS (F: function, C: context, B: behaviour, P: principle, S: state, S: structure) architecture of visual impairment assistance system is preliminarily proposed to allow other researchers to design the assistive devices with the good experience and the high performance for blind people and VIPs in the future. As VIPs and blind people may have different behaviour patterns, a criterion for classifying different types of vision impairments is presented. Subsequently, we classify the substitutive senses for visual perception into five categories: vision enhancement, audition, somatosense, visual prosthesis, and olfactory and gustation. Two commonly used feedback forms, namely audition and vibration, are elaborated. Based on literature survey, we also present a summary prospective of the development of assistive devices: add more sensing and feedback modules, use the knowledge of perception mechanism and behaviour pattern as the design guideline and design more reliable validation experiments.

Key Words

Assistive device, perception, electronic mobility aids, vision impairments

1. Introduction

Statistics recently reported by the World Health Organization show that there are approximately 253 million people with vision impairments, among whom 36 million

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are blind and 217 million have moderate-to-severe vision impairments [1]. The vision system is critical for humans to perceive the external world as more than 85% of external information can be obtained through the vision system. It largely influences our cognition and the progress of shaping spatial perception [2]. Due to its vast significance for every individual, the absence of vision will reduce individuals' proficiency in various skills [3], which in turn may lead to severe livelihood problems [4], [5]. Owing to the ever-increasing blind and visually impaired population, assistive devices have constantly been in a huge demand for recent years [6]. For instance, as a traditional mobility aid, the white cane is the most popular among blind and visually impaired people (VIP) [7]. However, the performance is far from satisfactory as common white canes indicate limited information of obstacle position. For this reason, numerous state-of-the-art assistive devices have been developed, serving to gather more helpful clews of any obstacle, such as its category, volume and distance for VIPs and blind persons.

Research on assistive technology for VIP and blind people spans across different disciplines, including computer science, communications engineering, mathematics and mechanical engineering. Thanks to the advances in these disciplines in recent years, the development of assistive technology for VIP and blind people has also been promoted, with devices helpful to complete activities of daily living and even execute specific tasks such as print access [8]. Varied classifications of assistive devices exist. First, assistive devices can be divided into two categorizations, namely wearable and portable devices [9]. Wearable assistive devices allow completely hands-free interaction or minimize the use of hands when utilizing the device. In view of the fact that portable assistive devices usually require the users to get involved in the operation, most devices are designed to be more compact and lightweight. Moreover, assistive devices can be divided into three other categories, which are vision enhancement, vision replacement and vision substitution [6], [10]. For vision enhancement-based assistive techniques, they process visual signals from a camera and then display output signals on a screen. With the help of vision replacement-based assistive techniques, visual information is possible to be directly sent to the
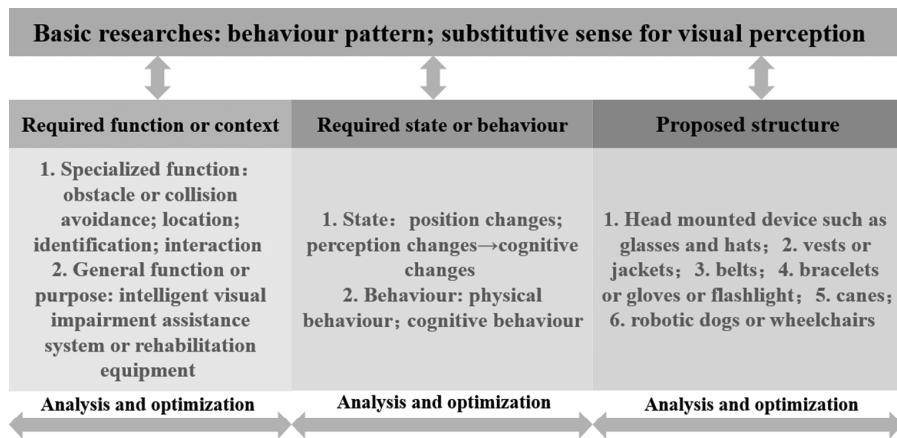
Figure 1. FCBPSS architecture of visual impairment assistance system.

human brain's visual cortex through implantable visual prosthesis [11]. Furthermore, vision substitution-based assistive devices, belonging to sensory substitution devices (SSDs), provide feasibility to leverage the obtained information from a variety of sensors and then give a feedback to the user *via* the nonvisual senses such as tactus and audition. The basic principle behind visual SSDs is that some other sensory modalities (*e.g.* audition) are used to provide environmental information normally by vision sense for VIPs and totally vision-deprived people [12]. From the view of image processing, the purpose of image processing for vision replacement and vision substitution is to convert the visual information into the spatially resolved electrical signals and nonvisual signals, respectively. Based on the feedback forms, we can conclude that the vision enhancement and vision replacement are, respectively, suitable for VIPs and blind people, while the vision substitution can be used for both VIPs and blind people. The assistive devices are always sorted into four groups based on the feedback types offered to end users. This classification does not emphasize the hardware and software architecture of assistive devices [13]. Therefore, in the current review, we classify the assistive devices based on the form of the final product or the technical construction of the device.

The remainder of this review is organized as follows. Section 3 introduces the classification of VIPs and blind persons. Section 4 lists the substitutive senses for visual perception. In Section 5, we elaborate assistive devices for VIPs and blind persons. The review is concluded in Section 6.

2. FCBPSS Framework of Visual Impairment Assistance System

FCBPSS (F: function, C: context, B: behaviour, P: principle, S: state, S: structure) is a general framework for designing the systems [14], and it can serve as an excellent architecture to guide the design of visual impairment assistance system. Function, context, behaviour, state and structure refer to the role a system plays, the condition and environment under which a function is played by a system, the input (stimuli)–output (response) relationship and a set of components with their connection,

respectively. Based on Zhang *et al.* [15], this framework can be applicable to any system including but not limited to the enterprise system and the engineering system. Some engineering problems have been solved on the basis of the FCBPSS framework [16]. Nonetheless, to the best of our knowledge, there is no framework for the development of visual impairment assistance system. For the purpose of allowing other researchers to design the better assistive devices for blind people and VIPs in the future, we preliminarily propose an FCBPSS architecture specific to the visual impairment assistance system according to the design concept described by Zhang *et al.* [14].

Figure 1 demonstrates the FCBPSS architecture of visual impairment assistance system. As shown in Fig. 1, the specialized functions of visual impairment assistance system contain the obstacle or collision avoidance, the location, the identification and the interaction. The general function or the purpose is to develop the intelligent visual impairment assistance system or rehabilitation equipment. The states include the changes in position, perception and cognitive (described in Section 4). Two behaviour types, namely the physical behaviour and the cognitive behaviour, have to be considered during the design process (described in Section 3). The proposed structure includes but is not limited to head-mounted devices such as glasses and hats, vests or jackets, belts, bracelets or gloves or flashlight, canes, robotic dogs or wheelchairs. This part has been reviewed in Section 5. It should be noted that the basic researches such as the studies on behaviour pattern and substitutive sense for visual perception are helpful for solving the engineering problems.

The design concepts of the current visual impairment assistance systems are relatively shallow, and we believe that the designed systems using the FCBPSS framework will have a very good experience and high performance. There is one review in the field of human–computer interaction, and the author of this review stated that the intelligent human–machine interactions can be divided into six levels and eight dimensions [17]. The visual impairment assistance system is also a kind of human–computer interaction equipment. Researchers in this field require to divide the systems to be established into several levels or dimensions according to the specific needs of the task and
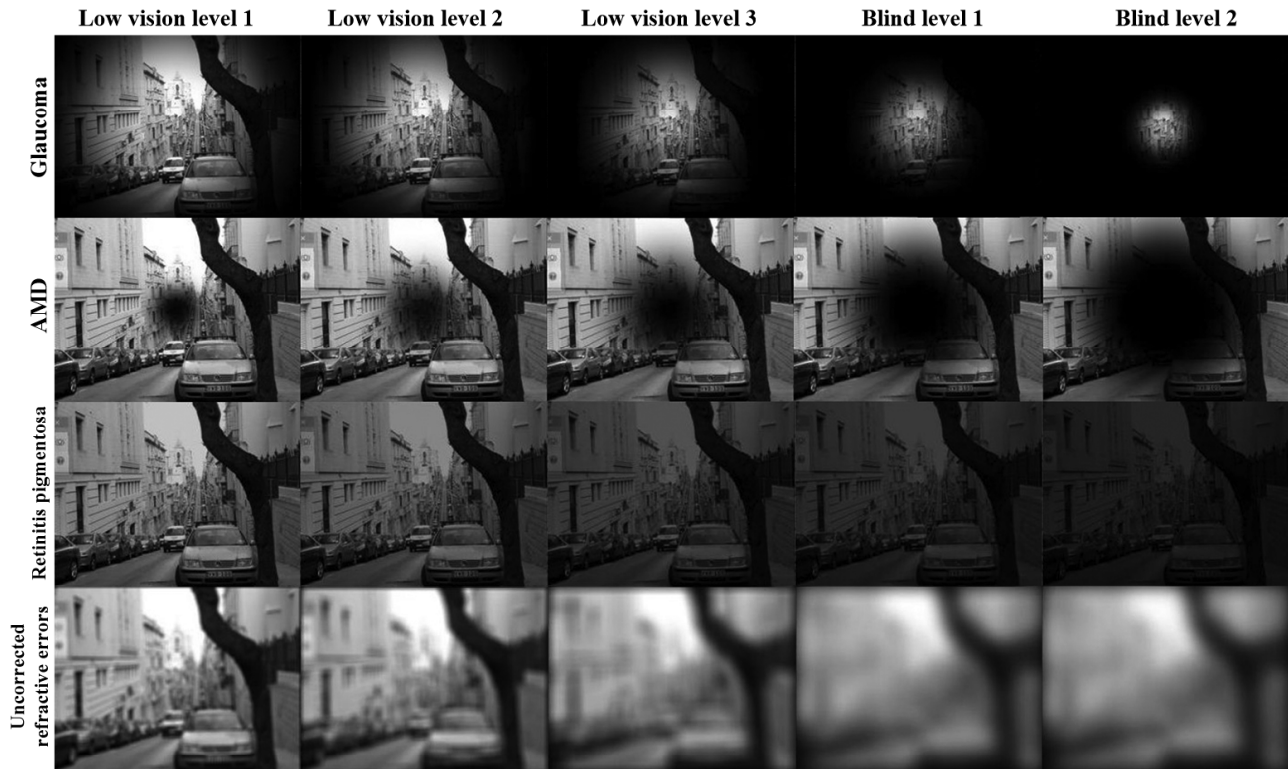
Figure 2. Classification of vision function based on the type of vision impairments (images are simulated by the custom-built software).

then design the appropriate FCBPSS framework to guide the development of the systems with good experience and high performance.

3. Classification of VIPs and Blind People

Why do we introduce the classification of VIPs and blind people for assistive devices at the beginning of this review? This arrangement is considered to be necessary for the reason that VIPs and blind people have different behaviour patterns due to the variations among individuals. Based on the literature evidence, the change of mentality caused by the altered sensory way of the outside world may have an impact on a person's behaviour pattern [18].

Some researchers have spent an adequate amount of time investigating the behaviour patterns of VIPs and blind people. Experimental results of a recent research conducted by Mihailovic *et al.* [19] showed that glaucoma severity was associated with several gait parameters, such as step length. Turano *et al.* [20] found that the gaze strategies of persons with normal vision and persons with retinitis pigmentosa (RP) were significantly different. For example, walking persons with RP fixate over a larger area of the environment. In light of the experimental results, Aspinall *et al.* [21] reported that the fixation counts were significantly higher for persons with age-related macular degeneration (AMD) compared with normally sighted persons during navigation. The changes in the learning process reveal that VIPs and blind people exhibit different behaviour patterns at different stages. An important difference lies between those who are congenitally or early

blind and those who are late blind, particularly in terms of sensory and cognitive abilities and preferences. A relevant review by Pasqualotto and Proulx [22] noted that the common classification of 'early' blind may be a misnomer as even a year or two of visual experience can lead to brain development akin to a late blind or indeed a sighted person. The late blind most often resembles the sighted in their sensory and cognitive profile. For congenital blindness, they indeed have superior auditory memory abilities [23].

The major global causes of vision impairments and blindness are uncorrected refractive errors, cataract, AMD and glaucoma. According to the International Classification of Diseases, the vision function is classified into four broad categories: normal vision, moderate vision impairments, severe vision impairments and blindness [1]. On the basis of overall visual ability, the grades of vision function consist of five levels by the WTO in 1973, which are low vision level 1, low vision level 2, low vision level 3, blind level 1 and blind level 2.

The use of classification based on the type of vision impairments can provide a better guidance for the design and development of assistive devices. By counselling clinical ophthalmologists and examining literature, we summarize the categorization in line with the type of vision impairments as follows: (1) decrease in the sensitivity of the light, (2) blurred vision (caused by retinal anomaly or refractive error), (3) vision loss and (4) total blindness. One eye disease may lead to multiple kinds of vision impairments at the same time, so we generate the simulated images in the computer and summarize them in Fig. 2. As shown in the first line of Fig. 2, people with glaucoma in the early

stage lose their peripheral visual field, and then a tubular vision slowly appears as the disease deteriorates. The second line of Fig. 2 demonstrates that visual impairment of AMD is mainly manifested as central vision loss. RP is an incurable eye disease, and the eyesight of persons with RP will get worse as the disease progresses (the third line of Fig. 2). Uncorrected refractive errors can be corrected by the use of a diopter lens (the last line of Fig. 2). The reason for the exclusion of cataract in Fig. 2 is that the cataract can be treated. These simulated images (Fig. 2) can provide the guidance for the design and development of assistive devices.

4. Substitutive Sense for Visual Perception

Vision impairments will alter the perception mechanism of VIP and blind people. Due to the total or partial absence of visual perception function, VIPs and blind people will be more dependent on other senses such as somatosense and audition.

Based on the literature survey, we summarize a tree diagram to demonstrate the existing substitutive senses for visual perception (Fig. 3). VIPs can see the outside world by means of the vision-enhancement techniques. One research group in the Harvard University focused on vision-enhancement techniques and used them to expand the visual field of VIPs [24], [25]. Hu *et al.* [26] attempted to develop a see-through glass associated with threshold-based enhancement algorithm to assist the people with night blindness. The visual prosthesis, one of the substitutive senses, directly displays the feedback information on the visual cortex in the human brain by the use of phosphene phenomenon [27], [28]. We will not discuss this feedback form as it involves some issues of medical researches, which is beyond the purpose of this survey. Readers can refer to the literature [29] for more information with respect to visual prosthesis. Thermal feedback, one of the somatosenses, can take advantage of temperature fluctuation on the human body surface to remind users of changes in the external environment. Lécuyer [30] designed a virtual reality system for VIPs to explore virtual environments. They used thermal feedback generated by 12 infrared lamps to simulate the virtual sun. Thermal feedback is highly influenced by ambient temperature, and, therefore, it is difficult to be perceived by users in some circumstances. Olfactory and gustation are two rare chemical feedback approaches, and they are seldom applied in assistive devices. VIPs and blind people mainly adopt the audition and tactus to take in information from the outside world and then process it to shape a right worldview that helps them understand life and make wise decisions. The majority of assistive devices use the audition and tactus among all feedback methods. In the following sections, we will emphatically review these feedback ways.

Spatial reference frames are of importance due to their relevance to navigation and mental mapping for VIPs and blind people [31]. We can refer to Hall's extra-personal space definition [32] to select the suitable substitutive sense for visual perception. Figure 4 illustrates the sensing ranges of these substitutive senses at different spatial scales [33].
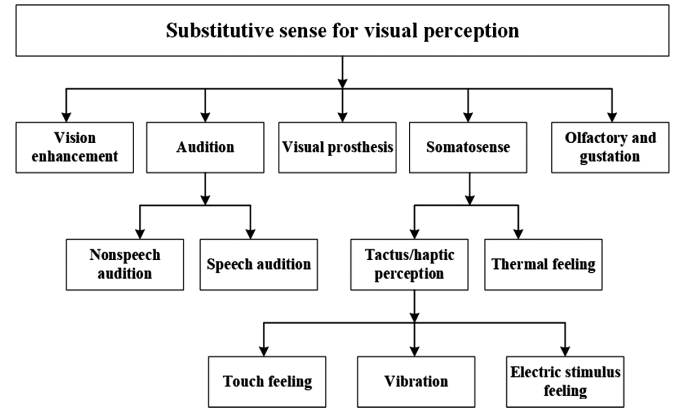

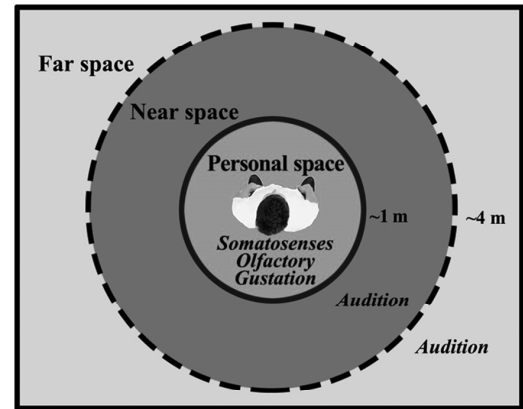Figure 3. Tree diagram of substitutive sense for visual perception.

Figure 4. Hall's extra-personal space definition with minor revision for personal space.

Furthermore, Tversky [34] concluded more complex and efficient spatial thinking models. In one of her reports, she stated that there was a mental space except for the external space. Mental space is constructed from what we perceive, aided by what we think and infer, in the service of action in the world or imagined in the mind [35]. Spatial thinking in mental space can help VIPs and blind people create representations of a real-world space. More detailed work conducted by Pasqualotto *et al.* [36] showed differences between congenitally blind and late-blind people in their spatial reference frame preferences. Moreover, the same research group gave visual-like exposure to those who cannot see a room and thus provided allocentric reference frame information using auditory devices [37]. Hence, the understanding of mental space may be beneficial to the design of assistance devices.

4.1 Audition

The term audition is used to conclude all auditory perception means in assistive devices. This summative term may be incomprehensible, but it can be applied for reference by relevant researchers and interested readers. The sound processing speed of VIPs and blind people is faster than that of sighted people [38]. Moreover, auditory memory

and retrieval abilities of congenitally blind people are superior to those of sighted people [39]. Survey results of the questionnaire showed that blind people of Iran are more inclined to use audio media rather than other media to access or utilize information [40]. Similar research was conducted by Kolarik *et al.* [41]. They found that VIPs outperformed sighted people in three cases: (1) when following the conversation switched from one person to another, (2) when locating the multiple speakers and (3) when separating the speech from music.

Findings of the previous literature evidence are in accordance with the perceptual enhancement hypothesis, that is VIPs and blind people will attempt to develop the ability of other senses to compensate for visual impairment [42], [43]. A recent survey concluded that complete blind people at an early stage show the superior performance in spatial hearing in the horizontal plane, but the performance in the vertical plane is unsatisfactory [44]. The spatial sound resolution ability of blind people is relatively low when they use the allocentric frame of reference. Besides, compared to early-onset blind individuals, late-onset blind people perform better in terms of spatial hearing. This indicates that the early visual experience is of great significance for the development of spatial hearing. Although VIPs and blind individuals exhibit better auditory processing ability, their brain region related to language processing is degraded [45]. This may be attributed to the fact that they seldom participate in social activities. The improvement of audio ability of VIPs and blind people is targeted, and it requires lengthy time to learn how to perceive the outside world using audition instead of vision.

In Fig. 3, we classify the auditory feedback into two categories viz. speech and nonspeech. The principle of speech feedback is to convert the ambient information into linguistic information [46], and subsequently, VIPs and blind people receive speech instructions *via* the earphone or speaker. Speech feedback is simple and intuitive, and the user can understand it without any learning process. Nevertheless, in some situations, speech feedback takes a longer time to describe the surrounding circumstances. There is no doubt that the user will feel annoyed and irritated [47]. Furthermore, delays in receiving information can even cause some irreversible accidents. The nonspeech feedback alerts the user using the music, environmental sounds or some artificial sounds [48]. In recent years, investigators have designed a variety of nonspeech cues such as spindex [49], spearcons [50] and audemes [51] to meet different application requirements. Although there is a learning process for nonspeech interface, this instruction can quickly convey information to users, which can address deficiencies of speech feedback. Researches carried out by Hussain *et al.* have validated the previous statement [52]–[54].

4.2 Tactus

Tactus or haptic perception [55], one of the somatosenses, can be further separated into three parts, namely touch feeling, vibration and electric stimulus feeling (Fig. 3).

It is difficult to distinguish concepts of touch feeling and vibration. In our opinion, the touch feeling means the feeling given by the texture of an object in contact when we stroke or touch this object. The vibration means the feeling caused by external forces. Because the stimulation amount of touch feeling is less than that of vibration, few investigators have applied the touch feeling as feedback in assistive devices. Our research group used an electrical compass and a servo-driven pointer to develop an indoor localization system [56]. This system can give the direction information to the user with touch stimulation. In terms of electric stimulus feeling, it is arisen by electrical stimulation and can be used for a visual prosthesis. Like audition, tactus is also commonly used in a feedback interface for assistive devices.

Heller *et al.* [57] systematically investigated the haptic pattern perceived by blind individuals. They stated that the tactus is a crucial sense, which can be used to substitute for vision. Results of the experiments conducted by Occelli *et al.* [58] show that people with early-onset blindness reflect greater haptic sensitivity than the sighted. They also validated the hypothesis that people losing vision early can recognize objects by their haptic perception regardless of spatial transformations. Picard *et al.* [59] invited children, adolescents and young adults to compare their haptic memory capacities. The result demonstrated that the haptic memory ability is an age-related skill. Carpio *et al.* [60] found that there is no significant difference between blind and sighted school students in content acquisition or aesthetic appreciation of images. This indicates that the blind people can experience the world through their haptic perception and eventually reach the same cognitive level of sighted people. The research findings of Puspitawati *et al.* [61] showed that, compared to VIPs with slight visual impairment, the people with total blindness have the faster speed of processing haptic information. This may further illustrate that, for VIPs and blind people, dependence on tactile perception increases with the severity of visual impairment. Therefore, a feedback module of an assistive device can be designed to meet the needs of the people with varying degrees of visual impairment.

5. Assistive Devices for Blind and Visually Impaired Persons

Assistive technology, one of the information accessibility technologies, has attracted considerable attention worldwide owing to its remarkable social significance [4], [62]. Over the past decade, a variety of assistive devices have been developed for functional assistances of VIPs and blind people. We summarize these devices in the following sections. In Tables 1 and 2, although several assistance devices offer the same functionality, there exist differences in types of sensors used, feedback modes, hardware frameworks and data processing algorithms. Validation experiments are important for assistance devices, and, therefore, investigators design different experiments, aiming to verify their feasibilities and reliabilities of completing the specific task.

Table 1

Summary of Assistive Canes for VIPs and Blind People about Sensors Used and Feedback Produced as well as Validation Methods

Study	Sensor	Feedback	Functionality	Validation
Gupta *et al.* [76]	Ultrasonic sensor; GPS receiver	Audition	Navigation	Tested in computer
Fan *et al.* [86]	Ultrasonic sensor; GPS receiver; RGB-D camera	Audition; vibration	Navigation	Tested in outdoor open area
Silva and Dias [90]	Ultrasonic sensor; inertia measurement unit	Audition	Obstacle detection	Tested by obstacles in the path
Kumar *et al.* [75]	Ultrasonic sensor	Audition	Obstacle and potholes detection	Tested by 10 volunteers
Majeed and Baadel [73]	RGB camera with 270° lens	Audition	Facial recognition	Tested in database
Satpute *et al.* [91]	Ultrasonic sensor; GPS receiver	Audition; vibration	Navigation; obstacle detection	None
Rizzo *et al.* [92]	Adaptive mobility devices	Vibration	Drop-off and obstacle detection	Tested by 6 adults
Shah *et al.* [77]	Ultrasonic sensor	Audition	Navigation; obstacle and potholes detection	None
Sharma *et al.* [78]	Ultrasonic sensor	Audition; vibration	Static and dynamic obstacles detection	Tested in real-time environment
Krishnan *et al.* [81]	Ultrasonic sensor; GPS receiver; RGB camera	Audition	Navigation; obstacle detection	Tested in database
Bolgiano and Meeks [70]	Laser	Audition; vibration	Obstacle detection	None
Sugimoto *et al.* [93]	Ultrasonic sensor; GPS receiver	Vibration	Navigation; obstacle detection	Tested in preset scenarios
Wankhade *et al.* [94]	Infrared sensor	Audition; vibration	Obstacle detection	None
Kassim *et al.* [88]	RFID network; digital compass	Audition	Indoor navigation	Tested by the mobile robot and human subject
Vera *et al.* [71]	RGB camera; laser pointer	Vibration	Obstacle detection	Tested by 16 sighted persons
Alwis and Samarawickrama [95]	Ultrasonic sensor	Audition; vibration	Obstacle detection	None
Pisa *et al.* [89]	FMCW radar	None	Obstacle detection	Tested by obstacle with different distances
Buchs *et al.* [80]	Infrared sensors	Audition; vibration	Waist-up obstacles detection	Tested by the trained blind participants

(*continued*)

Table 1
Continued

Pinto *et al.* [96]	Ultrasonic sensor; GPS receiver	Audition; vibration	Obstacle detection	Tested by obstacle with different distances
Ye *et al.* [74]	3D camera	Audition	Obstacle detection; pose estimation	Validated by data from various indoor scenes
Dang *et al.* [72]	Linear laser; RGB camera; inertial measurement unit	Audition	Obstacle detection and recognition	Validated by the obstacles with various heights, types, distances
Niitsu *et al.* [82]	Ultrasonic sensor; infrared sensor; compass; tri-axial accelerometer	Audition (bone conduction)	Obstacle detection	Examined in 20 times by 1 user
Takizawa *et al.* [87]	Kinect sensor	Vibration	Object recognition	Tested by 2 blindfolded persons
Jeong and Yu [97]	Ultrasonic sensor	Vibration	Obstacle detection	Tested by 4 blind folded and 10 blind persons
Bay Advanced Technologies Ltd. [79]	Ultrasonic sensor	Audition; vibration	Obstacle detection	None
Scherlen *et al.* [83]	Infrared sensor; brilliance; water sensors	None	Object recognition	None
Kim *et al.* [84]	Ultrasonic sensor; colour sensor; Cds photo resistor	Audition; vibration	Obstacle detection	Validate the usability by 7 types of criteria
Shim and Yoon [85]	Ultrasonic sensor; infrared sensor; contact sensor (two antennas)	Audition	Obstacle detection	None

Nearly all assistive devices listed later belong to SSDs. SSDs have been around for 40 years. The vibrotactile sensors were usually placed on the back to develop assistive device [63]. Subsequently, some investigators put an artificial sensor on the tongue [64]. The latter is the antecedent to the commercial BrainPort that is cited in Table 3. More recent, and highly promising, is the auditory device The vOICe [65]. It has been studied extensively for localization [66] and object identification [67]. There have been numerous neuroscience studies showing that The vOICe activates visual cortex in the blind as they perform tasks with images – suggesting that one can truly 'see' with the sound output of the device [68]. These devices in early stages have been widely validated in various tasks, settings and user groups. Thus the success and use are more easily ascertained than many devices cited in Tables 1 and 2.

5.1 Vision Substitution by Assistive Canes

The use of assistive cane is critical in reducing the risk of collision, which can help VIPs and blind people to walk more confidently. Table 1 summarizes some assistive canes designed for VIPs and blind people.

In general, an assistive cane is developed by mounting sensing and feedback modules on a classic white cane. Subsequently, the assistive cane acquires information with respect to surroundings and transmits raw or (pre-)processed data to users *via* predefined feedback approach [69]. Bolgiano and Meeks [70] first put a laser into a cane to detect obstacles in the traveling path, and audio and vibratory signals were available when VIPs and blind people approach the obstacle.

Vera *et al.* [71] used an RGB camera and a laser pointer in combination to develop a virtual white cane for

Table 2
Summary of Assistive Glasses for VIPs and Blind People about Sensors Used and Feedback Produced
as well as Validation Methods

Study	Sensor	Feedback	Functionality	Validation
Sadi *et al.* [98]	Ultrasonic sensor	Audition	Obstacle detection	Tested in lab conditions
Kassim *et al.* [99]	Ultrasonic sensor	Audition; vibration	Obstacle detection	Validated by blind spot evaluation experiment
Yi and Tian [100]	RGB camera	Audition	Text reading from natural scene	Tested by 10 blind persons
Everding *et al.* [102]	RGB camera	Audition	Obstacle detection	Tested by 2 experiments (11 and 5 persons, respectively)
Wang *et al.* [103]	RGB camera	Audition	Navigation; way finding	Evaluated in databases
Hassan and Tang [101]	RGB camera	Audition	Text recognition	Tested by several sample texts
Pundlik *et al.* [104]	Google Glass	Vision	Smartphone screen magnification	Evaluated by 8 sighted and 4 visually impaired persons
Neto *et al.* [105]	RGB-D camera	3D audition	Face recognition	Validated in databases and by both blindfolded and visually impaired users
Stoll *et al.* [106]	RGB-D camera	Audition	Indoor navigation	Validated by 2 performance metrics *i.e.* travel time and error
Hicks *et al.* [107]	RGB-D camera	Vision	Scene recognition and analysis	Tested by 4 sighted and 12 visually impaired participants
Wu *et al.* [108]	Pico projector; optical lenses	Vision	Vision enhancement	In simulated stage
Lan *et al.* [112]	RGB camera	Audition	Public sign recognition	Tested by some common public signs
Hu *et al.* [26]	RGB camera	Vision	Night vision enhancement	Evaluated on custom-built databases

VIPs and blind people. In their device, the RGB camera in smartphone captures the laser beam reflection, and the distance from the cane to the obstacle is calculated using active triangulation. Through the personalized vibration generated by smartphone, the user will be warned if possible obstacles are located in traveling path. Furthermore, the magnitude of vibration is applied for the quantization of distance. Results of validated experiments demonstrated that the travel time of virtual white cane is less than that of the traditional white cane. The assistive cane equipped with the point laser may fail to detect the potholes and the obstacles in small and tiny size.

Dang *et al.* [72] proposed an assistive cane using a linear laser, an RGB camera and an inertial measurement unit as sensors to classify the type of obstacle and estimate the distance from the obstacle to the user. The inertial measurement unit is an electronic device that measures a user's angular rate to determine spatial coordinate frames.

The inertial sensor tracks the position of laser stripe in the navigation coordinate frame, and the subsequent analysis of the laser point coordinates in regard to the original laser stripe can divide obstacles into walls, stairs and blocks. The information gathered is transmitted to the user *via* a simple nonspeech feedback. The performance of this assistive cane is easily influenced by the strong illumination, thereby limiting the application scope of this assistive cane.

Due to the limited detecting or scanning range when using the laser as a sensor, we can only detect objects located in the region where the laser illuminates. To overcome this shortcoming, we need to leverage spatial information recorded by RGB camera. Majeed and Baadel [73] integrated an RGB camera with 270° lens into an assistive cane, thus allowing us to capture much of environmental information. The proposed smart cane can help VIPs and blind people to dodge obstacles placed at the

Table 3

Summary of Some Assistive Glasses Which Are Available on the Market

Name	Company	Launch date	Functionality	Brief description
Google Glass [113]	Google Inc.	2012	Direction recognition	It is equipped with the RGB camera and gyroscope and has all the functions of mobile phone. As feedback, it can transmit the information to the user *via* the bone-conduction earphone and display screen. Google Glass is not designed for visual assistance of the VIPs and blind people, but we can do secondary development based on it
eSight 3 [114]	eSight Co.	2017	No specific function description	It is mainly designed for the individuals who are not completely blind. A high speed and quality camera is loaded in this glass to capture what the user is browsing. The obtained videos are first subjected to image-enhancement processing and then shown in two OLED screens. From the display way, eSight 3 is something like the virtual reality display device
OrCam [115]	OrCam Technologies Ltd.	2015	Text reading; face recognition; product and money identification	OrCam mainly consists of the RGB camera and portable computer. It can be fixed on any eyeglass frame and informs the user outside information *via* the audio signals
Enchroma [116]	Enchroma, Inc.	2013	Colour contrast enhancement	Enchroma is designed for the colour blindness. It does not leverage any digital processing technology. Enchroma alters the original waves using the specially designed lenses to help the persons of colour vision deficiency see the real colour
Intoer [117]	Hangzhou KR-VISION Technology Co., Ltd.	2017	Obstacle detection; scene, money, puddle, staircase, traffic signal and zebra crossing recognition; navigation	It uses the infrared binocular camera to record the environmental information illuminated by the natural and structural light. It produces the special encoded stereo to inform the user *via* the bone-conduction earphone
BrainPort® V100 [118]	Wicab, Inc.	2015	Obstacle detection; scene recognition	BrainPort® V100 is mainly composed of the RGB camera mounted on a pair of glasses, hand-held controller and tongue array containing 400 electrodes. The outside information is converted into electrical signals that are sent to the tongue array on the tongue of the user. Before using this device, there is a training phase

maximum distance of 10 m, and moreover, it can be utilized to recognize different persons' faces.

Ye *et al.* [74] used a three-dimensional (3D) camera as a sensor to develop an assistive cane, aiming to estimating pose and recognizing obstacle. The type of 3D camera used in their study is SwissRanger SR4000, which is a small-sized $(65 \times 65 \times 68 \, \text{mm}^3)$ 3D time-of-flight camera. The speech feedback module serves as the communication media between human and cane. This assistive cane was validated by data collected from a variety of indoor scenes. Results demonstrated that the proposed cane could estimate pose and recognize objects with satisfactory

performance. In their article, developers stated that they were working with orientation and mobility specialists as well as blind trainees of the World Service for the Blind in Arkansas to refine functions of their assistive cane.

Apart from the laser and RGB camera, the ultrasonic sensor is one of the widely used sensors in assistive device owing to its high-price/performance ratio. The ultrasonic sensor emits ultrasonic waves in the air, and then the reflected sound is received by the sensor. This sensor is always applied for detecting objects and measuring distance. Kumar *et al.* [75] developed an ultrasonic cane for aiding the blind people to navigate. This ultrasonic cane

is equipped with three pairs of ultrasonic trans-receivers, thus enabling the blind people to know aerial and ground obstacles as well as potholes in front of them *via* audio warnings. The maximum working range of this ultrasonic cane is 1.5 m, which is much less than that of the cane developed by Majeed and Baadel.

Gupta *et al.* [76] used an ultrasonic sensor and a GPS receiver together in classic canes. The addition of GPS module allows VIPs and blind people to travel outdoors using satellite network. Audio signals generated by Pygame module, a programming module to create games and animations, were used as the feedback to remind users. The range of distance measured by the attached ultrasonic sensor in cane is from 0.05 to 2 m, which is slightly larger than that of the device developed by Kumar *et al.*

Several investigators reported that they used an ultrasonic sensor to establish assistive canes. Shah *et al.* [77] arranged four ultrasonic sensors in a stick. Among these ultrasonic sensors, three ultrasonic sensors are applied for obstacle detection and the remaining one for pothole detection. Their experimental results showed that maximum detection distances of the ultrasonic stick were 1.45, 0.6 and 0.82 m when the obstacles located on the front, left-front and right-front, respectively. A similar smart stick was reported by Sharma *et al.* [78]. They stated that this smart stick was able to perceive obstacles of any height in front of or slightly sideways to users. Bay Advanced Technologies Ltd. [79] developed an ultrasonic sensor-based assistive cane named 'K' Sonar, and this cane was available on the market.

Infrared sensor is also a very popular sensor selected by investigators for the development of the smart cane. It is an electronic sensor, which works by using a specific light sensor to detect a selected light wavelength in the infrared spectrum. This sensor can detect infrared light radiating from objects in its view field to detect object and measure distance. Buchs *et al.* [80] mounted two infrared sensors on a white cane. One infrared sensor was parallel to the horizontal plane while the other was approximately 42° with respect to the horizontal plane. Such arrangement of infrared sensors allows this smart cane to detect waist-up obstacles. The detection range of this cane is only 1.5 m. The addition of RGB camera can increase the detection range of developed smart cane. Krishnan *et al.* [81] applied an ultrasonic sensor and an RGB camera in the sensing mode of smart cane, and the testing result demonstrated that the maximum detection range was 3 m.

Infrared sensor is usually used in conjunction with other types of sensors to form the multi-mode sensing array. Niitsu *et al.* [82] put four sensors viz. ultrasonic sensor, infrared sensor, compass and tri-axial accelerometer together on a classic cane. In this smart cane, a bone-conduction headphone was used for human–cane interaction in such a way that the feedback information could be passed to users unobtrusively. This assistive cane based on multi-mode sensing array can achieve the detection accuracy of 100% for wide obstacles, crossing and approaching persons, while 95% for thin obstacles. It should be noted that the bone conduction may have interference with several brain functions. Scherlen *et al.*

[83] leveraged an infrared sensor, a brilliance sensor and a water sensor in combination to develop a smart cane named 'RecognizeCane', which was capable of recognizing objects and their constituent materials. At present, four materials, namely metal (steel), glass, cardboard and plastic, can be successfully recognized. Also, the 'RecognizeCane' can distinguish the zebra crossing and water puddle using brilliance and water sensors, respectively. The brilliance sensor was also adopted by Kim *et al.* [84] in their smart cane to measure environmental brightness information. To detect obstacles in front accurately, two antennas used as the contact sensors, an ultrasonic sensor and an infrared sensor, were attached to a sensing unit of a smart cane by Shim and Yoon [85]. With the aid of contact sensors, this smart cane can effectively complement for ultrasonic and infrared sensors for detection of short-range obstacles.

Fan *et al.* [86], respectively, applied an RGB-D camera and an ultrasonic sensor to acquire dynamic visual environmental information and detect obstacles around. The RGB-D camera is able to obtain synchronized videos of both colour and depth. To implement outdoor navigation, they added a GPS module into the sensing unit. Results of validation experiments conducted in the open area demonstrated that the assistive cane installed in this sensing unit can help VIPs and blind people to travel outdoors safely. However, this cane cannot process the image data captured by RGB-D camera in real time. Takizawa *et al.* [87] also used an RGB-D camera in their sensing unit, and they called this developed cane as the Kinect cane. By the use of RGB-D camera, the Kinect cane can recognize different types of indoor obstacles, including chair, staircase and floor. Two blindfolded persons were invited to test the performance of proposed cane, and obtained results showed that the average search time by Kinect cane was significantly shorter than that by classic white cane.

Some other sensors are also used in sensing unit of assistive cane. Kassim *et al.* [88] mounted radio frequency identification (RFID) transponders on the floor and then installed an RFID reader at the end of cane. RFID is a technology that records the presence of an object using radio signals. When walking, the RFID reader reads RFID tags arranged on the floor in advance, and the addresses of these tags are sent for map processing. Subsequently, the auditory interface emits voice commands such as 90° turn left after digital compass calibration. Results of small-sample experiment containing two human subjects showed that the RFID-based smart cane has a potential to help VIPs and blind people to walk independently in indoor environments. Frequency-modulated continuous wave (FMCW) radars and antennas were housed in a classic white cane by Pisa *et al.* [89] for obstacle detection. The result showed that this cane could receive reflections from a metallic panel up to 5 m. FMCW radar is a short-range measuring radar set capable of determining the distance of object in its view field.

The assistive cane belongs to the portable assistive device. It is compact and lightweight, thus it is easily taken by users. Despite these advantages, the assistive cane needs to interact with users constantly.

5.2 Vision Substitution by Assistive Glasses

Assistive glass is one of the wearable assistive devices. In Table 2, some assistive glasses designed for VIPs and blind people are presented. The assistive glass in general fixes sensing and feedback modules on a classic glass. Unlike the assistive cane, the assistive glass in general uses the visual signal as the feedback for users.

Sadi *et al.* [98] embedded an ultrasonic sensor in a traditional glass to develop a smart glass for walking assistance. The sensing region of attached ultrasonic sensor covers 3 m distance and 60° angle. Processed information that corresponds to the distance of obstacle is sent to users *via* audio signals. Validation experiments carried out in the lab showed that detection accuracies of proposed glass were all beyond 93%. Kassim *et al.* [99] compared the performance of three sensors inclusive of an ultrasonic sensor, an infrared sensor and a laser range by taking several metrics such as accuracy, size and weight into account. Finally, they selected ultrasonic sensors for the development of their assistive glass. As feedback, two warning modes viz. audition and vibration were designed in their device and users could switch the warning mode based on her or his preference or environment around. Kassim *et al.* gave an example: when a user comes to a noisy environment such as bus terminal or market, he or she can use the vibration mode instead of auditory mode, thus allowing the audio sense to hear ambient sounds. A blind spot evaluation experiment demonstrated the effectiveness of proposed smart glass.

Except for the ultrasonic sensor, the RGB camera is also commonly used in the sensing unit of assistive glass, and there are four publications that used RGB cameras to obtain outside information in Table 2. Yi and Tian [100] applied an RGB camera equipped on a glass for assisting VIPs to access text information in their daily lives. They reported that the further study should focus on improving the detection accuracy of scene text hidden in cluttered background. One possible solution for this is to explore more effective feature representations to establish more robust models, and subsequently, we write the obtained model into a processing unit of smart glass. A similar research was conducted by Hassan and Tang [101]. Their smart glass is only suitable for recognizing the text on hardcopy materials. Inspired by the principle of human visual perception, Everding *et al.* [102] deployed two RGB cameras on a classic glass to imitate two human retinas. The performance of their smart glass is satisfactory when subjects are static. For moving tests, the performance is still unknown. Wang *et al.* [103] embedded a saliency map algorithm into an RGB camera-based smart glass for the detection of indoor signs. Experimental results on their databases containing indoor signs and doors showed the usability of their glass. The output information of four abovementioned publications is all delivered to users using the audio form.

Pundlik *et al.* [104] did the secondary development for Google Glass to magnify the screen content of smartphone, thereby helping VIPs to easily access information displayed on the screen. They invited eight sighted and four VIP to employ calculator and music player apps on smartphone with the aid of proposed glass and built-in screen zoom app of phone. Comparison results showed that the assistive glass based on Google Glass outperformed the built-in screen zoom software in improving the ability of VIPs to read screen content.

As the RGB-D camera can acquire both colour and distance information, it has been widely used in assistive glass. Neto *et al.* [105] directly tied a Microsoft Kinect sensor to the user's head, and this assistive device informed the user outside information *via* 3D audio signal. This hardware architecture is somewhat abrupt. The similar hardware framework was adopted by Stoll *et al.* [106]. After validation experiments on 21 blindfolded young adults with 1-week interval, they deemed that this system was promising for indoor use, but still inefficient for outdoor scenarios. Hicks *et al.* [107] improved the hardware architecture and made it more like glass. They converted scene data obtained by RGB-D camera into a depth map that nearby objects were rendered into brighter. Subsequently, processed depth images were displayed on two OLED screens. With the validation experiment, for VIPs, the average detection distance was approximately 3 m. Hence, further work needs to be done for increasing the detection distance of objects. The possible solution to this is to change the mechanical architecture of the glasses as the see-through display.

Wu *et al.* [108] designed a compact see-through near-eye display system that could be used for the persons who are hyperopic. Unlike most assistive devices, this system does not use any digital processing technologies. The main principle of this system is that the light emitted by objects at a distance goes through preset aspherical surfaces, and the user can see the relatively clear image of object. According to their simulated results, the final image provided for users is nearly identical to the original image. However, the reduced brightness and distortion in image corners are also observed. This glass that can enhance vision ability of people with presbyopia is still in design phase.

Hu *et al.* [26] attempted to develop a see-through glass to assist the persons who suffer from the nyctalopia. They first analysed the vision model of night blindness and then derived the relationship between luminance levels and RGB grey scale of the image to develop the enhancement algorithm. Experimental results showed that the brightness of raw dark image could be significantly improved by the use of proposed algorithm. After the spatial distance and camera lens calibrations, the processed image is able to perfectly align with the view seen by users.

Apart from previous assistive glasses which are still at an engineering or concept stage, several assistive glasses have been available on the market. These commercialized glasses for visual assistance are summarized in Table 3. Google Glass is usually used for the secondary development, and many assistive glasses not listed in our survey are developed based on Google Glass [109], [110]. Targeting ends of eSight 3 are VIPs, and therefore, developers place two OLED display screens in front of user's eyes to play processed videos. Sensors of OrCam and Intoer

Table 4
Summary of Some Assistive Devices with Various Forms

Study	Modality	Sensor	Feedback	Functionality	Validation
Wang *et al.* [119]	None	RGB-D camera	Audition	Detection of stairs, pedestrian crosswalks and traffic signs	evaluated on databases
Satue and Miah [120]	None	Ultrasonic sensor	Nerve stimulation; audition; vibration	Obstacle detection	Tested in predefined environments
Sekhar *et al.* [121]	None	Stereo cameras	Audition	Obstacle detection	Compared with the other systems
Rao *et al.* [122]	None	Laser device; RGB camera	None	Pothole and uneven surface detection	Validated by the performance metric
Gharani and Karimi [123]	None	RGB camera	None	Context-aware obstacle detection	Compared with the other two algorithms using different performance metrics
Pattanshetti *et al.* [128]	Hat	Ultrasonic sensor; GPS receiver; RGB camera	Audition; vibration	Currency recognition; obstacle detection; Navigation	None
Reshma [125]	Belt	Ultrasonic sensor	Audition	Obstacle detection	Tested by 4 blind folded persons
Wattal *et al.* [126]	Belt	Ultrasonic sensor	Audition	Obstacle detection	Compared the measured and actual distance and position of obstacle
Mocanu *et al.* [127]	Belt	Ultrasonic sensor; RGB camera	Audition	Obstacle detection and recognition	Tested by 21 visually impaired subjects
Froneman *et al.* [138]	Belt	Ultrasonic sensor	Vibration	Obstacle detection	Evaluated by various common static household obstacles
Bhatlawande *et al.* [129]	Bracelet	Ultrasonic sensor	Audition; vibration	Way-finding; obstacle detection	Tested by 2 blindfolded persons
Rangarajan and Benslija [130]	Robotic dog	Force sensor; RGB camera	Audition	Obstacle detection; word recognition	Tested on flat ground and slope
Lin *et al.* [131]	Smartphone	RGB camera	Audition	Obstacle detection and recognition	Tested by 4 visually impaired persons
Lee *et al.* [132]	Jacket	Ultrasonic sensor; GPS receiver; RGB camera; magnetic compass sensor	Audition; vibration	Navigation; obstacle detection	Tested with various device configurations in different environments
Kim and Song [133]	Wheelchair	Ultrasonic sensor	None	Obstacle detection	Tested at different moving speeds
Altaha and Rhee [137]	Cane; jacket; glove	Ultrasonic sensor	3D audition	Obstacle detection	Tested by the blind person

(continued)

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Table 4
Continued

Mekhalfi et al. [139]	Jacket	Laser sensor; RGB camera	Audition	Indoor scene description	Tested in databases
Bhatlawande et al. [135]	Bracelet; Belt	Ultrasonic sensor; RGB camera	Audition; vibration	Obstacle detection	Tested by 15 trained blind persons
Sivagami et al. [136]	Glasses; belt	Ultrasonic sensor	Audition	Obstacle detection	Tested by the blindfolded persons
Wu et al. [140]	Wheeled robots	Ultrasonic sensor; RGB camera; RFID reader	None	Indoor navigation	Tested on the predefined path
Spiers and Dollar [141]	Hand-held cube	UWB transmitter	Shape-changing tactus	Indoor navigation	Tested by the sighted persons
Fang et al. [134]	Flashlight	RGB camera; structured light	Audition	Obstacle detection	Evaluated on custom-built databases

are an RGB camera and an infrared binocular camera, respectively. These two products both use the audio signal as feedback to inform users. Enchroma is designed for the assistance of colour blindness. Like the study conducted by Wu et al. [108], this product achieves its functionality (here is colour contrast enhancement) using a specially designed lens, instead of any digital processing technologies. The sensing unit of BrainPort® V100 is similar to above-mentioned products, and the only difference is that it leverages the electric stimulus feeling as feedback. Developers of BrainPort® V100 consider that the tongue is extremely sensitive to electric stimulus, and hence, they place the tongue array which contains 400 electrodes in the user's tongue. This indicates that the resolution of BrainPort® V100 is 20×20 pixels. The intensity of stimulation represents the pixel intensity of the image obtained by RGB camera. In addition, due to the low resolution of tongue array, the background of the raw image requires to be eliminated [111].

5.3 Vision Substitution by Other Forms of Assistive Devices

Table 4 summarizes some assistive devices with various forms except for canes and glasses.

Several investigators only provide a core component of assistive device. By the use of an RGB-D image, Wang et al. [119] developed an imaging processing algorithm-based Hough transform for detection and recognition of stairs, pedestrian crosswalks and traffic signals. Results tested on their RGB-D databases showed the effectiveness of this system. Satue and Miah [120] applied an ultrasonic sensor to detect obstacles and then combined the electric stimulus, audition and vibration to warn the blind people of dangerous situations. As feedback, they placed the nerve stimulator unit on the wrist, and this unit would give an electric shock below the safe limit of human nerve stimulation according to the distance of obstacle. Sekhar et al. [121] used a real-time stereo vision algorithm written in FPGA to detect obstacles. A matching algorithm called zero-mean sun of absolute differences can maximize the hardware utilization, and therefore, their system is applicable to real-time applications. Rao et al. [122] combined a laser and an RGB camera in their assistive system to realize the pothole and uneven surface detection. From their study, we find that the laser can be served as the structural light for detecting various obstacles. Gharani and Karimi [123] calculated the optical flow between two consecutive RGB images and extracted feature points based on the texture of object and movement of the user. Experimental results showed that the combined use of optical flow and point track algorithms was capable of detecting both moving and stationary obstacles which were close to the RGB camera.

There existed the assistive devices in the other modalities:

Belt is a widely used modality for assistive device [124]. Reshma [125] furnished five ultrasonic sensors around the belt. This spatial arrangement of sensors allowed us to detect obstacles within the circle of 5 m in diameter. A similar assistive belt was reported by Wattal et al. [126] and the maximum detection distance was also 5 m. Mocanu et al. [127] used one RGB camera and four ultrasonic sensors in their visual assistive belt. A total of 21 VIPs were involved in the evaluation experiment, and results demonstrated that the developed assistive belt could recognize both static and moving objects in highly dynamic urban scenes. Besides, each subject expressed a good experience.

Pattanshetti et al. [128] developed an assistive hat, which consisted of an ultrasonic sensor and an RGB camera for obstacle detection and currency identification,

respectively. To achieve the outdoor navigation, they leveraged a GPS module in mobile phone.

Bhatlawande *et al.* [129] developed an ultrasonic bracelet for independent mobility of VIPs and blind people. With on-demand hand movements, this bracelet can warn the user of the obstacles in the range from 0.2 to 6 m. Alerting signals were then sent to users *via* audition and vibration.

Rangarajan and Benslija [130] reported a voice recognition robotic dog that could guide VIPs and blind people to the destination avoiding obstacles and traffic. This robotic dog had been successfully tested on the flat ground and slope. Lin *et al.* [131] directly used a built-in RGB camera of smartphone to detect and recognize obstacles. However, the recognition accuracy of obstacle in their study was only 60%. In the real world, this is insufficient for VIPs and blind people to avoid obstacles around them.

Lee *et al.* [132] put an ultrasonic sensor array, a GPS receiver, an RGB camera and a magnetic compass sensor on the jacket to help VIPs and blind people to travel outdoors. This assistive jacket had been tested with various device configurations in different environments, and results demonstrated that the sensor and receiver network had a potential ability to guarantee the safe outdoor navigation.

Kim and Song [133] extended the functionality of a classic wheelchair by adding multiple ultrasonic sensors, and the wheelchair can therefore execute efficient obstacle searching. The excellent performance had been observed when the updated wheelchair was tested at different moving speeds.

An assistive flashlight was designed by Fang *et al.*, who used an RGB camera and a structured light generated by a laser array to detect obstacles [134]. The laser of high refresh rate was used to achieve a visual bifurcation effect so that people around could not perceive the laser light but the camera could capture it. Therefore, the flashlight can operate in an unobtrusive pattern.

To further improve the performance of assistive device, some investigators simultaneously used several modalities of assistive devices to reach the specific assistive purposes. Bhatlawande *et al.* [135] installed an RGB camera and an ultrasonic sensor on a belt and a bracelet, respectively, for assisting the blind people in walking. Based on results of evaluation experiment with 15 blind people, the dual-mode assistive device exhibited excellent performance: 93.33% participants expressed satisfaction, 86.66% comprehended its operational convenience and 80% appreciated the comfort of the system. Sivagami *et al.* [136] also developed dual-mode assistive devices containing two modalities viz. glasses and a belt for VIPs and blind people to travel under unknown circumstances. Altaha and Rhee [137] proposed three different modalities viz. jacket, glove and cane for obstacle detection. They arranged three ultrasonic sensors on the front, left and right sides, respectively, thus allowing us not only to detect the presence of nearby objects but also to measure the distance of objects from users. We suggest that they can in future use these three assistive devices in combination to increase the detection range and distance.

6. Conclusion and Prospective

Although numerous assistive devices are available, they are not yet effectively adopted by VIPs and blind people. One reason is that these assistive devices can only act in a restricted spatial range due to their limited sensors and feedback modes. The other reason is that the performance of these assistive devices is not effectively validated. As shown in the aforementioned tables, in many cases, only blindfolded sighted subjects were invited to validation experiments. Actually, cognitive strategies observed in VIPs and blind people are significantly different from those in blindfolded sighted subjects.

In this section, we will next discuss three prospectives for assistive devices to conclude this survey: (1) increase the diversity of input and output information to guarantee the reliability of assistive device, (2) develop the assistive device based on perception mechanism and behaviour pattern of VIPs and blind people and (3) design more reliable experiments to validate the feasibility of assistive device.

The diversity of feedback can increase the reliability of final assistive devices. The multimodal feedback, including audition, thermal and vibration was embedded into the virtual reality system, which allows VIPs and blind people to explore and navigate inside virtual environments [30]. Simultaneously, the use of sensor fusion framework for assistive device allows us to obtain more important information about the surrounding environment. Rizzo *et al.* [142] found that the depth information extracted from a stereoscopic camera system could ignore specific potential collision hazards, and the addition of infrared sensors could offer a reliable distance measurement to remove this inconsistency of depth inferred from stereo images. Hence, for the specific task, if used sensors give inconsistent measurements, the alternate sensing modality can be chosen to remedy this inconsistency.

Study of changes in the connectivity of the functional areas of the human brain can help us understand the change in perception mechanism of VIPs and blind people [143]. Because congenitally blind people rely more on audition or tactus information, the connectivity of multisensory brain areas of them will be more complicated [144]. Therefore, the introduction of brain imaging is essential for the design of assistive devices. Luckily, there are some reviews available in a recent special issue of 'Neuroscience and Biobehavioral Reviews' that cover the spectrum of SSDs and their relevance for understanding the human brain (http://www.sciencedirect.com/science/journal/01497634/41). In addition, we can develop better assistive devices according to the idea of bionics [145].

Currently, the performance of assistive devices is rarely or inadequately validated by VIPs and blind individuals. As cognitive strategies of VIPs and sighted people are significantly different, it is not guaranteed that the performance validated by sighted blindfolded people represents that by VIPs and blind people [69]. Therefore, it is very necessary to invite numerous VIPs and blind people from different blind associations to test the performance of developed assistive device. Furthermore, real-world

scenarios are far more complicated, and testing environments should fully cover any possible application scenario.

Acknowledgement

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