Developing Walking Assistants for Visually Impaired People: A Review

Md. Milon Islam, Muhammad Sheikh Sadi, *Senior Member, IEEE*, Kamal Z. Zamli, *Member, IEEE*, and Md. Manjur Ahmed

***Abstract*— The development of walking assistants for visually impaired people has become a prominent research area due to the rapid growth of these individuals in recent decades. Although numerous frameworks have been developed to aid visually impaired people, a considerable portion of these is limited in their scopes. In this review, we exhibit a similar review of walking assistants for visually impaired people to demonstrate the advancement of such technologies. This review discusses the recent innovative technologies developed for the visually impaired to aid them in walking with their merits and demerits. With the help of this review, a schema is drawn for upcoming development in the field of sensors, computer vision, and smartphone-based walking assistants. This review aims to present the majority of the issues of such frameworks to serve as a basis for different researchers to develop walking assistants that ensure movability and safety of visually impaired people.**

***Index Terms*— Visually impaired people, walking assistants, computer vision, sensors, smartphone, electronic travel aid, navigation, review.**

I. Introduction

PEOPLE influenced by visual deficiency and visual ailments need assistance to triumph over daily assignments, such as moving and exploring unfamiliar environments [1]. Recent statistics from the World Health Organization have shown that approximately 253 million people in the world are visually impaired, from which 217 million have a slight vision, whereas 36 million are blind [2]. The problem is becoming a matter of concern because the number of visually impaired is increasing by 2 million per decade. An estimation has shown that the number of blind people may be doubled in 2020 [3].

Blindness is the imbalance of physiological or neurological components that is called the condition of lacking discernment. Despite numerous evolutions in innovation, blindness remains a critical issue [4], [5]. Researchers have been focusing on this issue to develop supportive tools or assistants for visually impaired people. A few navigation tools and frameworks are accessible for blind people. The most important tools are guide dogs and white canes. However, their performance is limited by speediness, coverage, and capacity, which are generally accessible to persons having eyes for navigation [6]. Walking assistants have been acquainted with taking care of the daily issues associated with navigation and location aids that are involved with mobility support since the 1960s. The assistants aid the visually impaired people by detecting and locating the obstacles around them using the sensors that take the sense from the exterior situation [7].

Visual assistance technology comprises three parts, namely, vision enhancement, substitution, and replacement [8]–[11]. The first two categories are nearly the same in functionality. The captured image is processed, and the output is displayed in a monitoring device in vision enhancement, whereas the production of the vision substitution is taken through vibration or with the aid of alarming devices that can generate a sound, which has inferior information capability rather than vision. Vision replacement handles medical technology and is comparatively more complicated than the others. The information is displayed straight to the humanoid intelligence through the optic nerve.

Many walking assistants have been developed based on the visual assistance technology to solve the problems of visually impaired people. Among them, white cane [12] can only provide location information but cannot find the shortest path. Guide dogs [37] provide information of the shortest path. GuideCane [13] can detect the floor level in front of users and sideways' difficulties. K-Sonar canes [7], which can identify floor- and head-level hindrances, use adjustable frequency sound forms to deliver the distance of barriers. CyARM [14] is a handheld obstacle recognition system. Most of walking assistants have been developed on the basis of obstacle detection with feedback signal [15]–[19].

The purpose of our review is to focus on the vision substitution that includes electronic travel aid (ETA) [20], electronic orientation aid [21], and position locator devices [8], [9]. Among them, ETA, which collects information from the interior environment and transfers it using sensors, cameras, and smartphones, is the most promising in the review. A few ETAs are available in a wearable format, and few others are available in handheld format depending on the users' nature. This review discusses the challenges met by blind people and the real-life solutions to the problems. The recent technologies

Manuscript received December 6, 2018; accepted December 21, 2018. Date of publication January 1, 2019; date of current version March 18, 2019. This work was supported by the Ministry of Higher Education, Malaysia, through the Fundamental Research Grant Scheme (FRGS) under Grant RDU170103 and Grant RDU190184. The associate editor coordinating the review of this paper and approving it for publication was Prof. Tarikul Islam. *(Corresponding author: Md. Manjur Ahmed.)*

M. M. Islam and M. Sheikh Sadi are with the Department of Computer Science and Engineering, Khulna University of Engineering and Technology, Khulna 9203, Bangladesh (e-mail: milonislam@cse.kuet.ac.bd; sadi@cse.kuet.ac.bd).

K. Z. Zamli is with the Faculty of Computer Systems and Software Engineering, Universiti Malaysia Pahang, Gambang 26300, Kuantan, Malaysia (e-mail: kamalz@ump.edu.my).

M. M. Ahmed is with the Department of Computer Science and Engineering, University of Barishal, Barishal 8200, Bangladesh (e-mail: manjur_39@yahoo.com).

Digital Object Identifier 10.1109/JSEN.2018.2890423

adopted in this field for aiding the visually impaired people for safe mobility are also explained.

A survey was conducted in [55] to measure subjects' requirements and expectations from walking assistants. A total of 57 visually impaired people, their care patrons, and rehabilitation specialists participated on the interview. The participants were asked about their favored usable functions, carry techniques, user and physical interfaces, and visual characteristics for a walking assistant. The movement complications and appropriateness of their present assistance were also inquired. The common requirements from walking assistants that were observed from the survey were proper information of the surroundings, light weight, low cost, safety, modest user interface, simple carry technique, and cosmetic suitability. Nearly all the systems that were reviewed provide surrounding information in different directions (e.g., front, left, right, and so on); however, not a single system can fulfill the user requirements. Most of the systems worked in fewer directions. Lightweight and low-cost systems were proposed in [1], [47], [48], [50], [52], [55], [56], [59], [81], [83], [84], [87]–[89], [106], and [108]–[110]; and the systems proposed in [51], [53], [54], and [57] were low cost but bulky. A simple user interface was provided in [54] and [110]. General, lightweight systems are easy to carry.

A comparative study with existing review articles in this field is conducted to prove the novelty of our review. Dakopoulos and Bourbakis [8] reviewed the wearable obstacle avoidance prototypes, which were developed generally with different types of sensor. The authors categorized the systems by focusing primarily on feedback interface. The reviews related to the techniques that are used in those systems, the environment where the systems work, the detection range that the systems cover, the capturing devices the systems use, and the cost required by the systems were illustrated in this review. Elmannai and Elleithy [9] reviewed the sensor-based assistive devices for the visually impaired. Nonetheless, few prevailing areas, such as computer vision- and smartphone-based approaches were somehow overlooked in their review. Bhowmick and Hazarika [10] reviewed the relevant research; however, they did not analyze the comparison of performances among the mentioned systems in their review. Fernandes *et al.* [11] and Hakobyan *et al.* [105] reviewed different types of walk-in assistants (e.g., obstacle avoidance, navigation, object recognition, and speech typing). However, these types were limited to mobile platforms only. Hakobyan *et al.* [105] categorized the assistants based on detection range (i.e., near, intermediate, and far distances) in their review; however, other areas, such as those based on feedback signal, coverage area (indoor/outdoor), weight, and cost, were somehow overlooked. Leo *et al.* [71] and Terven *et al.* [78] reviewed the assistive technologies for the visually impaired people based on computer vision, which can assist visually impaired individuals in different directions; however, the performance of each assistive technology was not demonstrated. Nearly all the reviewed systems are in fewer directions. Some of them are in only sensor-based, some are computer vision-based, and some are on only in mobile platforms. Large gaps remain in the domain of reviewing the

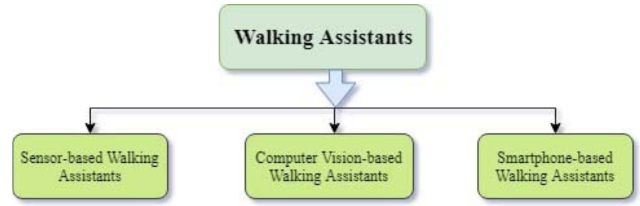

Fig. 1. Taxonomy of the reviewed walking assistants for visually impaired people.

literature related to the development of walking assistants for the visually impaired. Hence, in this review, we cover the relevant research that includes nearly all sensor-, computer vision-, and smartphone-based approaches and analyze the performance of each approach.

The remainder of this review is presented as follows. Section II discusses the literature on developing assistants, including the taxonomy and performance analysis for the assistants. Section III reviews the sensor-based walking assistants. Section IV demonstrates the computer vision-based walking assistants. The smartphone-based walking assistants are reviewed in Section V. Section IV presents the detailed discussion and summary. Section V concludes this review.

II. Literature on Developing Walking Assistants

Several assistants have been developed to guide visually impaired people for easy walking. Many organizations have been working for an extended period to make low-cost and well-organized tools for them. We exhibit the most recent and most vital schemes (range has been considered at 2012–2018) with the description considering:

i) introducing the scheme,
ii) working procedure of the scheme, and
iii) critical analysis of the techniques.

A. Taxonomy of the Reviewed Walking Assistants

Walking assistants are generally developed based on some techniques. For example, some systems are designed by combining different techniques. However, in this review, the categorization is performed on the basis of priority, that is, which method contributes more than the others. Therefore, on the basis of the existing methods, the developed walking assistants can be divided into three categories as follows.

(A) Sensor-based walking assistants
(B) Computer vision-based walking assistants, and
(C) Smartphone-based walking assistants.

The taxonomy of the reviewed walking assistants is depicted in Fig. 1, in which the works associated with the previously described criteria are outlined.

B. Performance Analysis

The performance of a walking assistant for the visually impaired depends on some features. The features that we consider here are the types of capturing device used, types of feedback signal provided, the coverage area, the weight, and the cost. These features are key concerns for measuring the efficiency and reliability of any walking assistant that is developed for visually impaired people. The performances

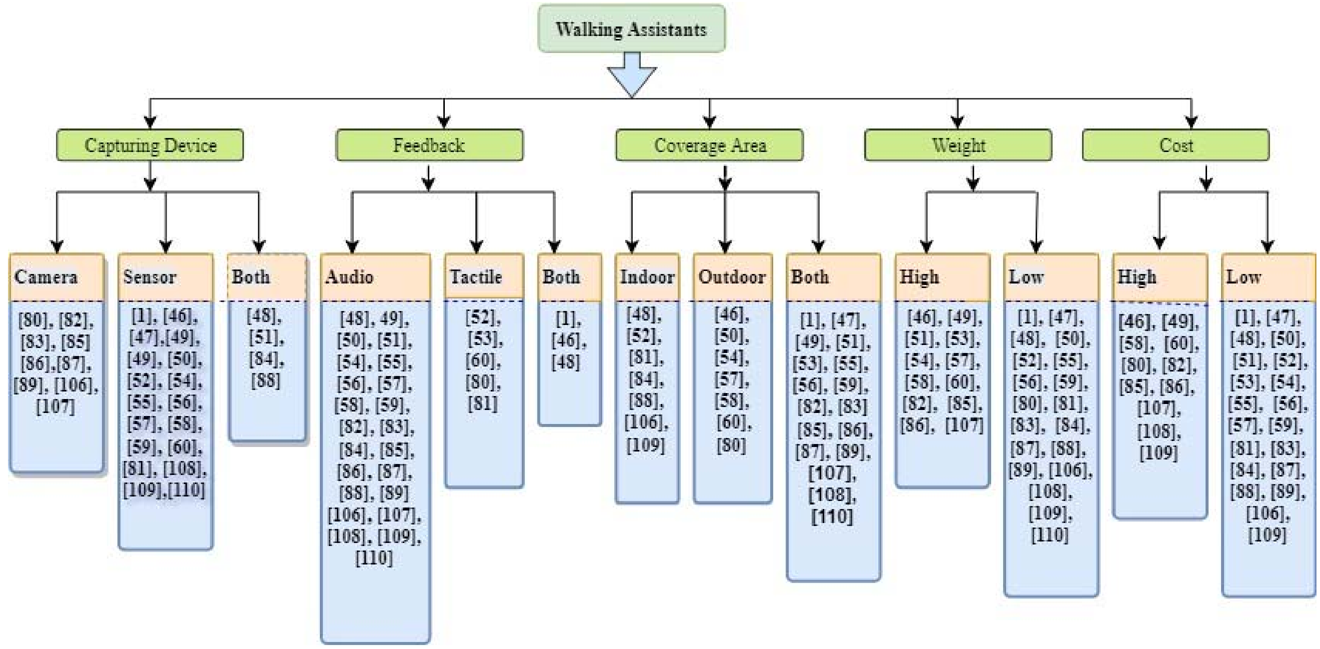

Fig. 2. Properties of the performance evaluation of reviewed walking assistants for visually impaired people.

of the reviewed walking assistants are drawn in Fig. 2 by considering the previously described features. From the Fig. 2, no system offers all features to a reasonable degree. Each framework offers something unique over the others but cannot address every feature because a perfect framework ought to have every one of the features and numerous functionalities. The most significant conclusion is that no framework can fully assist visually impaired people.

The developed systems cannot fulfill user demand perfectly because some of the systems are in their early stage or research stage, and some of them take a long time to perform an experiment with a real-time environment; moreover, some of them are unwearable, heavy, and costly.

Furthermore, the progress and maturity of a navigation assistance system can be measured by how much the system assists the users. Given many hindrances (e.g., front, left, and right obstacles; pothole and hump on roads; and staircases) on the way of walking, most of the systems work in fewer directions. Some of them can detect obstacles in front of the users, some can detect only potholes or humps on the road, and some can detect knee- or head-level obstacles. However, no article thus far has covered all or majority of the hindrances on the way of walking. Hence, we argue that most of the systems are at the early stage of problem solving in relation to this area.

The prototypes mentioned in [48], [82], [84], and [86] used cameras and sensors as capturing devices. Some systems provide tactile feedback [52], [55], [56], [81], [89], and some provide audio and tactile feedback [1], [46], [47]. The framework developed in [55] works in outdoor scenarios but is unsuitable indoors. The system can detect static obstacles within a 5 m distance but is inappropriate for dynamic obstacles. Some systems provide indoor coverage, whereas some provide outdoor coverage. Nevertheless, the user demand is indoor and outdoor.

In accuracy comparison, the highest and lowest accuracies achieved by the system in [53] were approximately 98.8% when the obstacle was close (5 cm) to users and 62.8% when the obstacle was far (350 cm) away from the users. The highest and average accuracies obtained by the system proposed in [59] were approximately 98% and 96%, respectively. In [83], most of the pixel-wise accuracy within different ranges was over 90%. The results in [84] revealed that an avoidance algorithm without ultrasonic sensor had an accuracy of 98.93% in case of frosted glass but had extremely low accuracy in case of pure transparent glass. The detection rate obtained in [87] was 94.4%. Hence, the developed walking assistants have achieved sufficient accuracy when obstacles are close to users.

III. Sensor-Based Walking Assistants

Sensor-based walking assistants provide surrounding information to visually impaired people through audio signal, vibration, and/or both [22]. These frameworks depend on the gathered information to recognize an obstacle and avoid it by calculating the distance between the users and obstacles using the velocity of the obstacles. The system architecture of sensor-based walking assistants for visually impaired people is illustrated in Fig. 3. Several sensors are used to construct different types of assistant to provide various services. Among the different sensors, ultrasonic sensors are widely used. Most of the walking assistants for visually impaired people are developed using ultrasonic sensor [23]–[36]. Some of the walking assistants are developed on the basis of other sensor-based technology, such as infrared (IR) [37]–[40], laser [41], dynamic vision [42], [43], Ubisense compass [44], and time-of-flight distance [45] sensors. The system developed by different types of sensors are reviewed and these are outlined in Fig. 2.

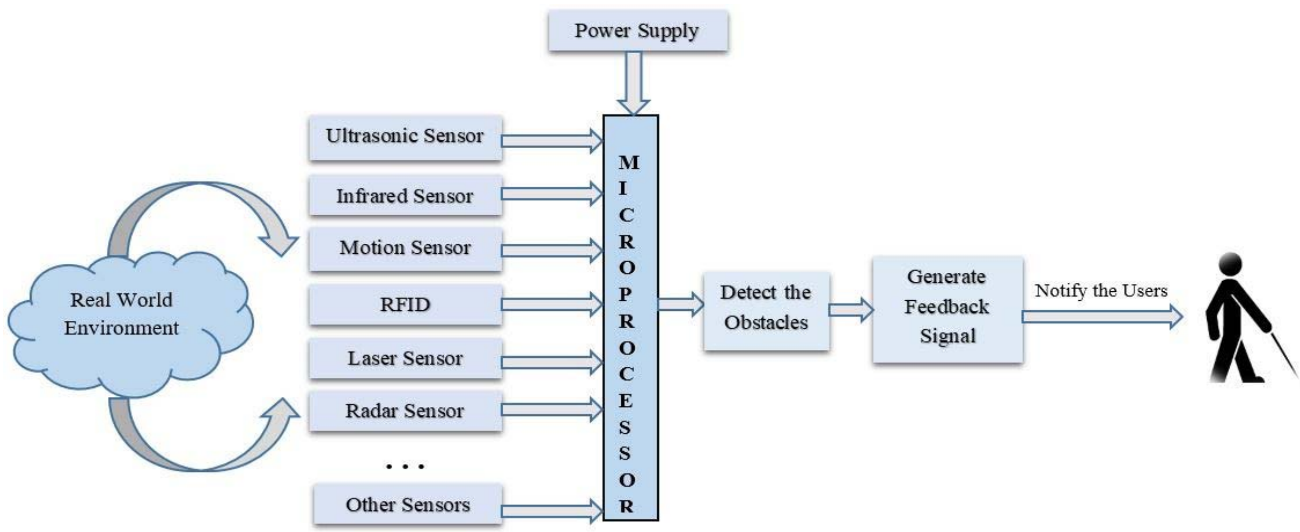

Fig. 3. System architecture of sensor-based walking assistants for visually impaired people.

A. Radar-Based Navigation Device

Cardillo *et al.* [1] proposed an electromagnetic sensor device using a microwave radar that aids visually impaired people by notifying the presence of obstacles in the way. The system comprises TX and RX antennas and stigma. The TX and RX antennas are connected to the transceiver board. The target distance is calculated by digitizing and applying the Fourier transform on the output of the homodyne receiver. The system is noise tolerant and small in size. However, the subunits of the system are not integrated into a single circuit board and cover a short range of radar system.

Kwiatkowski *et al.* [46] investigated a radar-based navigation tool for blind people in unfamiliar surroundings. The tool perceives the environment information and transfers the distance into a 3D acoustic signal that is used as feedback. The sensor includes Frequency Modulated Continuous Wave (FMCW) radar with a center frequency and bandwidth of 80 GHz and 24 GHz, respectively. The system is partitioned into three parts. The data are collected through the sensor unit and fed to the processing unit. The initial radar data are evaluated and compared with the sensor data, and a virtual map of objects is found. The virtual map is converted into a 3D audio signal, which alerts the blind person for the presence of obstacles. The system is beneficial for visually impaired people for wayfinding; however, the design of the antenna is a critical issue and makes the system bulky.

B. Wearable Navigation Device

Patil *et al.* [47] proposed an ETA named NavGuide to aid the visually impaired and blind people in their navigation by avoiding the obstacles on the way. The system comprises six ultrasonic sensors, four vibration motors, a wet floor detector sensor, microcontroller circuits, a step-down button, and a battery. The ultrasonic sensor emits high-frequency sound waves and calculates the time for the reflected sound waves. The distance of an obstacle is calculated using the speed of the waves and the total time elapsed. The data collected from the environment are sent to the logical map construction unit. This unit includes microcontroller circuits that decide on the position of the obstacles. The wet floor detector sensor senses any fluid dropped on the floor on the users' walkways. The system alerts the users by generating vibration and audio alert signal as feedback. Moreover, the NavGuide can detect knee- and floor-level obstacles, as well as the condition of the floors. However, the system cannot detect human impediments that communicate in the form of motion and touch.

Bai *et al.* [48] proposed a new wearable device for aiding visually impaired people to reach the destination and avoid the collisions with obstacles during navigation by using a dynamic subgoal selection strategy. The device consists of a depth camera, a fisheye, an embedded CPU board, an earphone, an ultrasonic rangefinder, and a pair of optical see-through (OST) glasses. The rendering unit generates the audio signal that alerts visually impaired people of the presence of obstacles. The visual simultaneous localization and mapping part builds the virtual-blind-road using the RGB and depth image. The system detects the shortest path from the source to the destination using a point-of-interest graph, which is formed by an A*-based way-finding algorithm. The device proposed by the authors is low cost, small in size, and easy to wear. However, the ultrasonic sensor readings change with temperature and humidity, which may misguide the users.

Rizvi *et al.* [49] presented a technique for blind people, which can be helpful in their daily living by detecting the obstacles using voice feedback and haptic. The system is used by blind people for navigation and locate their position using global positioning system (GPS) and global system for mobile communications (GSM). The main hardware components used are sequentially as follows: Arduino UNO, sonar sensor, LV-MaxSonar-EZ, VoiceBox Shield, GSM SIM900 and GPS modules, and Buzzer and DC motor. In the described scheme, the microcontroller sends a signal to the ultrasonic sensor, and the sensor transmits the command and receives a pulse in the form of Pulse Width Modulation (PWM). Meanwhile, the microcontroller calculates the distance of obstacles and generates an alert signal using alert modules. The technique does not only provide information on the obstacles but also locates the user position. However, the weight and size of the wearable globe become comparatively large.

Prattico *et al.* [50] developed an ETA using IR–ultrasonic sensors to aid visually impaired and blind people in their navigation. The system consists of two IR sensors, an ultrasonic sensor, a microcontroller, and four vibrating motors. The microcontroller is used to receive the input signs and decide. The vibrator motors are used to reply feedback signs to the user with the presence of obstacles. All the apparatuses are combined in a belt. Although, the device is comfortable, it is not wearable. Moreover, the system can detect positive and negative obstacles.

Vera *et al.* [51] proposed a framework called Blind Guide for visually impaired people to navigate them in interior and exterior environments using wireless sensor networks. The system consists of various wireless sensors that can be utilized in various portions of the body. The sensors can detect obstacles and provide an audio signal as feedback. The hardware components used in the scheme are the external sensor; ultrasonic sensor; Wi-Fi microcontroller; and a central device that includes a camera module, a Raspberry Pi, and a speaker. An audio signal is sent to the central device when an object is detected. The primary device then captures an image of the object with the aid of the camera module, and the image is sent to the cloud image recognition service. The system can identify chairs, tables, doors, walls, and ordinary objects in the interior environment and avoid the common obstacles in the exterior environment. However, the system cannot label the images for processing.

Tsirmpas *et al.* [52] proposed an excellent and sophisticated construction of an indoor navigation system for visually impaired people. The system can detect the position of the user and provide suggestions for self-movement by perceiving the obstacles from the surroundings. The system uses Bluetooth, ultra-wide band, Wi-Fi, or radio frequency identification (RFID) technologies. The information from the environments is gathered through micro-electromechanical sensors (MEMS), and the data are processed using microcontroller ATmega328. The system covers a distance between 1 m and 2 m in indoor surroundings. The system can localize the position of the user and detect the obstacles in indoor environments. However, it does not work in outdoor environments because the RFID tags provide a small range of coverage.

C. Smart Stick

Sharma *et al.* [53] developed a smart stick that is low cost but durable and assists visually impaired people in their movements. The stick provides pure knowledge about the distance and the location of the obstacle through vibration and audio in hand and ear, respectively. Bluetooth dongle has been used to establish a connection between the earphone and the smart stick. The proposed scheme can detect static and dynamic obstacles, downstairs, and upstairs. The main hardware components used in the system are a microcontroller, an ultrasonic sensor, and HC-05 master–slave Bluetooth modules. However, the smart stick cannot detect objects in all surroundings, that is, it can only detect obstacles in front of users, and the error rate becomes high with the increment in distance.

Kaushalya *et al.* [54] developed a walking assistant called AKSHI to aid visually impaired people. The system uses Raspberry Pi 2, ultrasonic sensor, GSM module, and RFID reader and tags. The RFID reader is attached with the bottom part of the stick that can detect the obstacles using RFID tags. The ultrasonic sensor is placed below the circuit box on the track of 45° angles. Another box, including Raspberry Pi, GSM, and GPS modules, is attached to the stick. A mobile application was also developed to keep track of the user location using GSM and GPS modules. Users can access the GPS location interface that displays the current location of the visually impaired. However, the RFID tags work within a short range, and the stick cannot work in dirty and muddy environments.

D. Electronic Mobility Cane

Bhatlawande *et al.* [55] proposed an electronic mobility cane for wayfinding and obstacle detection of visually impaired people. The system constructs a logical map of the surroundings and maintains them based on priority. The system provides the priority information to users by using feedback signals, such as voice, vibration, or audio, and detects staircase and floor statuses. The system consists of ultrasonic sensors, liquid, metal detection sensor, wireless transceivers, battery, and microcontroller circuits. Furthermore, the system collects and categorizes the information of surroundings. However, the system cannot identify overhanging obstacles and requires excessive training that might be expensive for visually impaired people.

O'Brien *et al.* [56] discussed a low-cost electronic tool integrated with a conventional cane that provides an alarm signal when obstacles are detected. A custom-built printed circuit board embedded with a microcontroller drives the sensor and the motor. Its weight with battery is approximately 110 g. The system calculates the distance during the notification of obstacles. An alarm signal is generated when the calculated distance is between 0.2 m and 0.6 m, and another signal is generated when the distance is between 0.6 m and 1 m. Moreover, the system searches for another obstacle when no obstacles are observed between 0.2 m and 1 m.

E. Smart Virtual Eye

Zhou *et al.* [57] developed a smart system called Smart Eye to aid visually impaired people by providing them with information on the surroundings. The system has two modules, namely, embedded wearable sensor and smartphone modules. The wearable sensor module consists of power (9 V DC battery), CPU (32 b mbed NXP LPC1768), sensors (ultrasonic and motion sensors), and communication (Bluetooth or Wi-Fi chip) parts. An Android application was developed to provide distance notification to users that is returned by using an ultrasonic sensor. The embedded module and smartphone communicate through Bluetooth or Wi-Fi. The developed application is vigorous and detects obstacles at approximately 10 ft away. This process is conducted in a laboratory and cannot interact with the real world along with real-time obstacles.

Sohl-Dickstein *et al.* [58] presented a tool called Sonic Eye based on ultrasonic echolocation and spatial hearing principles that aid visually impaired people for their safe mobility. The tool comprises an ultrasonic emitter, stereo microphones, and a wearable headset. The resonance of ultrasonic pulses is noted, and a feedback signal (human auditory range) is then provided to the users with the presence of obstacles. The tool can be used efficiently to observe the surroundings, and the human auditory structure may swiftly adapt to artificial echolocation signals. However, the system is not precisely contactless as the users should wear the echolocation device.

Sadi *et al.* [59] proposed a system for visually impaired people to aid them in walking by identifying an object and creating an audio signal as per the distance of the object. The system is designed similar to a spectacle and can detect obstacles under 3 m distance and 60° angle. The spectacle consists of an ultrasonic sensor, a microcontroller, and an alarm generator. The ultrasonic sensor generates an ultrasound wave that is reflected to the sensor by observing the obstacle's location within 3 m. The microcontroller measures the distance by manipulating the time between the back and forth travel of ultrasound from the obstacle. A signal is transferred to the alarm generator with the presence of obstacles, and it generates an alarm based on the signal from the microcontroller. The ultrasonic sensor is positioned at the middle of the spectacle, and the microcontroller, alarm generator, and battery are attached to the temple. The developed scheme is a low-cost and straightforward strategy but bulky. Temperature, density, and weight also limit the ultrasonic sensor. Moreover, system accuracy varies at near and far distances.

Bharambe *et al.* [60] introduced a low-cost and supportive tool for visually impaired people that can be used as an artificial eye. The embedded tool in the proposed system is used to detect obstacles using ultrasonic sensors, and vibrator motors generate the feedback. An Android device is used for navigation. An Android application is used to track the position of blind people using GPS and General Packet Radio Services (GPRS) and guide them in the proper direction. The system is used to detect and locate obstacles. However, the system is only a prototype in the laboratory.

Table I summarizes the aforementioned sensor-based walking assistants for visually impaired people and evaluates some of the important parameters, such as capturing and feedback devices, major hardware components, and their detection/coverage range, weight, and cost effectiveness.

In the cost analysis, some systems provide numerical and relative values. The costs of the proposed systems in [54], [55], [56], and [59] are approximately \$290, \$280, \$40, and \$10, respectively, and they are treated as low-cost systems. The cost of the system in [60] is approximately \$1790 and is treated as a high-cost system. Therefore, from the state of the arts, we consider the system having the cost greater than \$300 as high cost. The same concept is applied for Tables I–III.

IV. Computer Vision-Based Walking Assistants

At present, computer vision [61]–[79] has attracted considerable attention for the development of different types of walking assistant for visually impaired people. The systems developed based on computer vision technology provide exact and flexible services. The system architecture of computer vision-based walking assistants for visually impaired people is shown in Fig. 4. In these approaches, different types of camera are used to capture the images from real-world environment, and computer vision-based algorithms are used to detect obstacles. However, computer vision-based systems are affected with soft real time. A hard-real time system guarantees that critical tasks are completed on time, whereas a soft real-time system prioritizes a critical real-time task over other tasks and retains that priority until its completion. A computer vision system requires time to capture images, process the images, and generate an alert signal. However, a hardware system uses the input from the real-time environment and provides the results within a few instances. Result analysis requires time to solve the problem, which should be considered. The walking assistants developed based on computer vision technology in recent years are as follows.

A. Wearable Navigation Tool

Mancini *et al.* [80] introduced a monocular vision-based system to aid visually impaired people in walking, running, and jogging. The authors presented some algorithms to extract lines/lanes to follow. The system comprises a camera, a board, and two gloves equipped with vibration motors. The system detects the right track with speed greater than 10 km/h by using the gloves. An RGB camera captures the images, a processing unit processes the images and extracts the lines/lanes, and a haptic device generates an alert signal and provides the command to users to move left or right. However, the system is unsuitable in crowded scenarios.

Aladrén *et al.* [81] introduced a novel navigation system for blind or slightly blind people by using an RGB-D camera that collects visual and range information from the surroundings. The developed system not only detects obstacle-free paths but also classifies them, which is valuable for the safe navigation of visually impaired people. The sound map created by stereo beeps and voice commands is used as a feedback signal to alert the users with the presence of obstacles. The system uses a floor-based segmentation technique. In the system, the camera is attached on the user's neck, and the laptop is stored in the user's backpack. The developed tool is light and easy to wear for blind people. However, the system only operates in indoor environment, and its performance is degraded in sunlight, that is, during daytime because the readings of RGB-D camera vary with sunlight.

Kammoun *et al.* [82] developed a system called NAVIG project to aid visually impaired people. The system localizes particular objects in the surroundings. It is composed of stereoscopic cameras, GPS, sensors, microphone, headphones, and a computer stored in a backpack. The system also uses a head-mounted stereoscopic camera to capture images from the environment. The captured images are processed by using machine learning approaches, such as object localization algorithms. The NAVIG operates under indoor and outdoor environments.

TABLE I

SUMMARY OF SENSOR-BASED WALKING ASSISTANTS FOR VISUALLY IMPAIRED PEOPLE

Authors	Year	Capturing Devices	Feedback Devices/ Types	Major Hardware Components	Coverage Area	Detection Range	Weight	Cost
Cardillo et al. [1]	2018	Radar sensor	Vibrational and/or acoustic warning	TX and RX antennas and stigma	Indoor and outdoor	1–5 m	A few hundreds of grams	Low cost
Kwiatkowski et al. [46]	2017	Radar sensor	Hearing device	Stepper motor, FMCW radar, and slippery ring	Outdoor	N/A	Bulky	High cost
Patil et al. [47]	2018	Ultrasonic and wet floor detector sensors	Vibration and audio signal	Four vibration motors, microcontroller circuits, a step-down button, and a battery	Indoor and outdoor	0.26–3 m	Lightweight	Low cost
Bai et al. [48]	2018	Depth camera and ultrasonic sensor	Audio signal	A fisheye, an embedded CPU board, an earphone, and a pair of OST glasses.	Indoor	0.26–1.34 m	Lightweight	Low cost
Rizvi et al. [49]	2017	Ultrasonic and sonar sensors	Buzzer	Arduino UNO, microcontroller, GSM and GPS modules, and DC motor	Indoor and outdoor	0.09–0.20 m	Bulky but wearable	High cost
Prattico et al. [50]	2013	IR sensors and ultrasonic sensor	Vibrating motors	Microcontroller and filters	Outdoor	0.2–1.5 m	Lightweight	Low cost
Vera et al. [51]	2017	Peripheral sensor, ultrasonic sensors, and camera	Speaker	Wi-Fi microcontroller and Raspberry Pi 3	Indoor and outdoor	1–2.5 m	Bulky	Low cost
Tsirmpas et al. [52]	2015	RFID tags	Voice controller	Microcontroller ATmega8	Indoor	1.2–2 m	Lightweight	Low cost
Sharma et al. [53]	2017	Ultrasonic sensors	Vibration motor	Microcontroller and Bluetooth modules	Indoor and outdoor	0.05–3.5 m	Heavyweight	Low cost
Kaushalya et al. [54]	2016	Transducer sensor	Voice signal	Raspberry Pi 2, 5 V and 2 V rechargeable batteries, GSM module, RFID reader and tags	Outdoor areas, such as pedestrian crossing	0.05–0.07 m	Bulky	Low cost
Bhatlawande et al. [55]	2014	Ultrasonic sensor	Audio and vibration or voice signal	Liquid and metal detection sensor, wireless transceivers, battery, and microcontroller circuits.	Indoor and outdoor	1–4 m	Weight (0.503 kg)	Low cost
O'Brien et al. [56]	2014	MB1200 sensor	Pulsed vibration	Microcontroller, motor, and 9 V battery	Indoor and outdoor	0.2–1 m	110 g	Low cost
Zhou et al. [57]	2016	Ultrasonic sensor	Text-to-speech (TTS)	Power, CPU, and Bluetooth chip	Outdoor	0.30–3.048 m	Bulky	Low cost
Sohl-Dickstein et al. [58]	2015	Ultrasonic emitter	Stereo microphones	Artificial pinna, ultrasonic microphone and speaker, and a chip	Outdoor	N/A	Heavyweight	High cost
Sadi et al. [59]	2014	Ultrasonic sensors	Alarm generator	Microcontroller and lithium-ion battery	Indoor and outdoor	0.1–3 m	Approximately 165 g	Low cost
Bharambe et al. [60]	2013	Ultrasonic sensors	Vibrator motors	Microcontroller, registered divider, operational amplifier, 5 V power supply, oscilloscope, and voltage regulator	Outdoor	2–3 m	Lightweight	High cost

*** Not Appropriately defined: N/A**

B. Smart Guiding Glasses

Yang *et al.* [83] proposed a wearable tool that utilizes pixel-wise semantic segmentation to aid visually impaired people. The system notifies individuals about traversable areas, stairs, water hazards, and sidewalks. In addition, the prototype avoids fast-approaching pedestrians, short-range hindrances, and vehicles. The system uses an in-depth learning approach with an encoder that generates down-sampled feature maps and a corresponding decoder that up-samples the feature maps to match the input resolution. ADE20K dataset, which incorporates indoor and outdoor images, is used to train the system. The system comprises an IR camera, an RGB camera, and a RealSense image processor. However, the system cannot work in zebra crosswalks, traffic lights, hazardous curbs, and water puddles.

Bai *et al.* [84] developed a smart guiding tool similar to an eyeglass to aid visually impaired people for their safe movement. The system comprises a pair of display glasses and some developed sensors that are cost effective. The developed system comprises a depth camera to gather information from the surroundings, ultrasonic sensor and microprogrammed control unit for obstacle distance measurement, and a CPU for image processing and sound analysis. Audio instructions are provided as feedback with the presence of obstacles. The system is

TABLE II

SUMMARY OF COMPUTER VISION-BASED WALKING ASSISTANTS FOR VISUALLY IMPAIRED PEOPLE

Authors	Year	Capturing Devices	Feedback Devices/ Types	Major Hardware Components	Coverage Area	Detection Range	Weight	Cost
Mancini et al. [80]	2018	Camera	Vibration	BLE device and vibration motor	Outdoor	2–3 m	Lightweight	High cost
Aladrén et al. [81]	2016	RGB-D sensor	Stereo beeps and voice commands	Laptop	Indoor	0–3 m	Lightweight	Low cost
Kammoun et al. [82]	2012	Stereoscopic cameras	Audio-augmented reality	GPS, sensors, microphone, headphones, and laptop equipped with an Intel i7 quad-core processor	Indoor and outdoor	N/A	Bulky	High cost
Yang et al. [83]	2018	RGB and IR cameras	Stereo sound and audio signal	RealSense image processor and bone conduction headphones	Indoor and outdoor	N/A	Lightweight	Low cost
Bai et al. [84]	2017	Depth camera and ultrasonic sensor	Audio signal	Microprogrammed control unit and embedded CPU	Indoor	0.952–2.692 m	Lightweight	Low cost
Kang et al. [85], [86]	2017,2015	Vision camera	Stereo	Bluetooth chip, Wi-Fi module, laptop, and earphone	Indoor and outdoor	N/A	Bulky	High cost
Yang et al. [87]	2016	RGB-D sensor and IR camera	Audio signal	RealSense R200, processor, attitude sensor, and bone-conducting headphone	Indoor and outdoor	N/A	Lightweight	Low cost
Mekhalfi et al. [88]	2016	Camera and IMU sensor	Speech synthesis module	Dell laptop with 4 GB RAM	Indoor	N/A	Lightweight	Low cost
Sövény et al. [89]	2015	Logitech QuickCam Pro 9000 USB cameras	Audio module	Laptop computer with Intel Core i5 3210M 2.5 GHz processor and 8 GB RAM	Indoor and outdoor	N/A	Lightweight	Low cost

*** Not Appropriately defined: N/A**

TABLE III

SUMMARY OF THE SMARTPHOE-BASED WALKING ASSISTANTS FOR THE VISUALLY IMPAIRED PEOPLE

Authors	Year	Capturing Devices	Feedback Devices/ Types	Major Hardware Components	Coverage Area	Detection Range	Weight	Cost
Cheraghi et al. [106]	2017	Camera	Smartphones	Beacon	Indoor	N/A	Lightweight	Low cost
Ţepelea et al. [107]	2017	Camera and MEMS sensors	Audio module	Light sensor, orientation sensor, GPS sensor, accelerometer, GSM module, touchscreen, Arduino nano board, and Raspberry Pi board	Indoor and outdoor	N/A	Lightweight	Low cost
Alghamdi et al. [108]	2013	RFID tags	Audio of tag locations	Mobile reader and smartphone	Indoor and outdoor	0–0.5 m	Lightweight	High cost
Nakajima and Haruyama [109]	2013	Geomagnetic sensor	Feedback sound	LED lights and headphone	Indoor	1–4 m	Heavyweight	High cost
Tanveer et al. [110]	2015	Ultrasonic sensors	Bengali/ English voice commands	Bluetooth module HC-05 and GPS module	Indoor and outdoor	0.02–1 m	Lightweight	High cost

*** Not Appropriately defined: N/A**

evaluated in home, office, and supermarket environments. The proposed glass is efficient and supports the eye vision of visually impaired people in indoor environment. However, the system cannot provide the location information and does not have wayfinding and way-following functionalities.

Kang *et al.* [85], [86] proposed a new obstacle detection modality in a deformable grid (DG) structure to aid visually impaired people. The proposed modality perceives an obstacle in danger of a crash due to the level of DG deformation. The system uses a vision camera that captures video sequence with 320×240 resolution at 30 fps. The captured sequences are sent to a laptop via a Wi-Fi module. The system notifies the users of the obstacle's position before 2 s. The output signal is conveyed to the user's earphone by using a Bluetooth module. Kang *et al.* [85] used a vertex deformation function to improve the performance of [86] in terms of accuracy and processing time. The developed method is comparatively better than the previous one. However, the system cannot detect obstacles that are closed to a door or a wall.

Yang *et al.* [87] also proposed a wearable prototype to assist visually impaired people by using an RGB-D sensor and an Intel RealSense R200 that expands the detection of

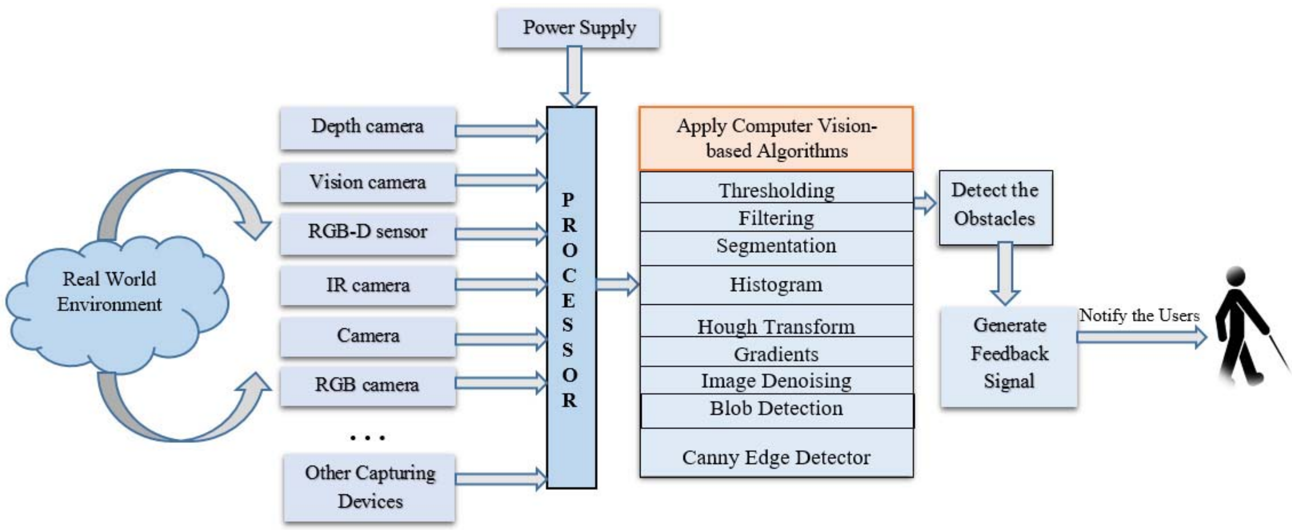

Fig. 4. System architecture of computer vision-based walking assistants for visually impaired people.

the traversable area. An RGB image-guided filtering is used to enhance the real sense of the depth image. In addition, random sample consensus segmentation and surface normal vector estimation are used to cover the traversable area. The system comprises RealSense R200, IR camera, RGB camera, processor, attitude sensor, and bone-conducting headphone. The proposed wearable prototype operates on indoor and outdoor environments. However, its operation is not optimized because the proposed wearable prototype has low speed and only covers a short area.

C. Eye Sight

Mekhalfi *et al.* [88] developed a prototype for blind people that automatically moves and recognizes objects in indoor environment. The system is integrated into a module with a headset, camera, marker, inertial measurement unit (IMU), and laser sensors that are positioned on the user's chest. The system is divided into different modules, such as egomotion, path planning, object detection, and object recognition modules. Communication between the prototype module and users is performed through speech recognition and synthesis modules. The system uses machine learning approaches for recognition. On this basis, some image datasets are trained with machine learning approaches. The laser sensor provides information about the distance to be covered. The camera captures the scenes and sends it for navigation or recognition. The prototype module avoids static and dynamic obstacles.

Sövény *et al.* [89] designed a wearable tool to aid visually impaired people in interior and exterior navigations by perceiving the environment. The system can detect traffic lamps, street crossings, cars, and other obstacles located on the street. The scheme uses real-time data by using camera and sensors and generates audio signals with the presence of obstacles. A motion vector is used to identify the obstacles. A label based on the key track of the obstacle is acquired by fitting a route on the basis of the obstacle's size, movement speed, and its location in the image. A slow movement speed is recognized as a pole by using a vertical key track. An object with a fast movement speed and same property as before is recognized as a passerby. An obstacle with horizontal key track and high motion vector is recognized as a vehicle. The data processing unit (DPU) in the current prototype is limited to video inputs, and the system is loud and obsolete.

Table II summarizes the aforementioned computer vision-based walking assistants for visually impaired people and evaluates some important parameters, such as capturing and feedback devices, major hardware components, and their detection/coverage range, weight, and cost-effectiveness.

V. Smartphone-Based Walking Assistants

The advancement of smartphones has created a new era of research in different fields. Currently, smartphones have become common toward nearly all types of people. Thus, walking assistants developed based on smartphones [90]–[105] are flexible and user friendly. The system architecture of smartphone-based walking assistants for visually impaired people is shown in Fig. 5. In these approaches, different types of smartphone camera or sensor are used to capture data from real-world environment, and the processors of smartphone are used to process the data and generate alert signals in detecting obstacles/objects. The walking assistants developed based on smartphones are as follows.

A. GuideBeacon

Cheraghi *et al.* [106] developed a system called GuideBeacon, which can be used for indoor wayfinding of visually impaired people to assist them in navigation within interior surroundings. A smartphone application declares the name of interior space and directs the user in the desired goal for the first time. However, the system is not wearable similar to spectacles, and GuideBeacon is not configured with respect to users' demand.

B. Head-Mounted Device

A smartphone-based navigation system for blind people was presented in [107]. The system utilizes MEMS that are integrated in a smartphone. Other sensors are also used to perceive

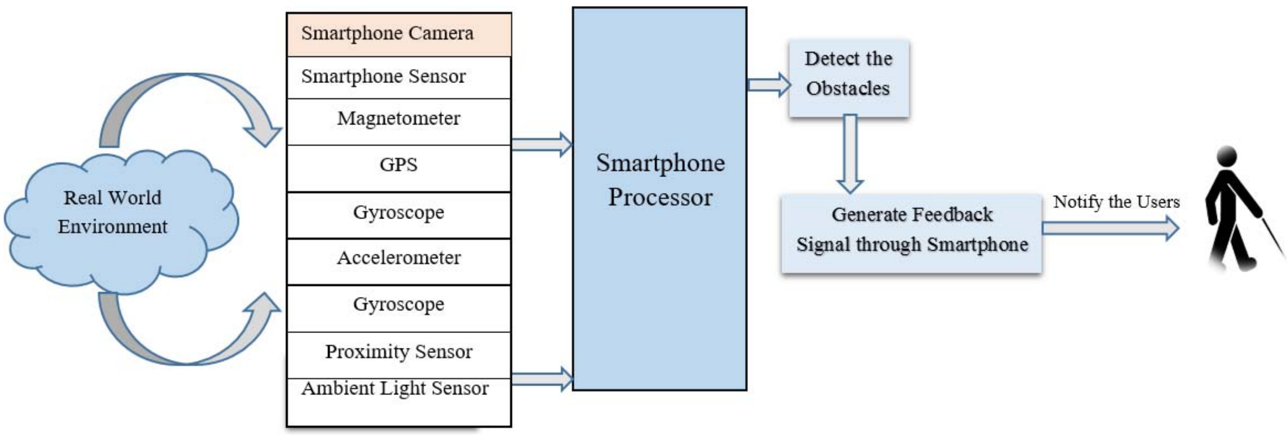

Fig. 5. System architecture of smartphone-based walking assistants for visually impaired people.

information from environments. The smartphone communicates with external modules through Bluetooth and Wi-Fi. Communication between users and mobile application is performed through TTS. A battery with 3800 mAh rating is attached to the smartphone as a backup, and external sensors are connected with a solar charged battery with 5600 mAh rating. The proposed portable system is efficient, low cost, and small in size. The application enables book reading, easy setup of phone calls, and date and time searching. However, the proposed system is not evaluated in buildings and outdoor environments.

Alghamdi *et al.* [108] presented a novel technique for visually impaired and blind people to aid them in their indoor and outdoor navigations by demonstrating their position and guiding them to reach their goal. The system is based on RFID technology and approximately covers 0.5 m distance. The system aids in finding offices, laboratories, and theaters. The system comprises a smartphone, a mobile RFID reader, and an earpiece. The RFID reader is linked to the smartphone through Bluetooth. Communication between the smartphone and RFID reader is performed through Wi-Fi to obtain tag locations. The successful detection rate obtained by the system is 93.5%, and the false positive rate is only 1%. However, RFID tags work within a short range. Thus, users cannot obtain an alert signal for obstacles that are in long distances.

Nakajima and Haruyama [109] proposed an indoor mobility system for blind people. A visible light ID is transmitted to a portable tool that is worn by a blind person through LEDs. The ID receives the latitude and longitude information for blind people. The system is evaluated in an interior navigation system by using LED lights and a geomagnetic sensor combined with a smartphone. The test outcomes show an accuracy of 1–2 m acquired by the proposed framework. However, an accuracy detection method of the system is not well-defined.

C. EyeMate

Tanveer *et al.* [110] introduced a walking assistance tool for blind people. The system allows blind people to navigate by using a spectacle interfaced with a smartphone. The smartphone application generates Bengali/English voice signals with the detection of the obstacle's location. Visually impaired people establish a voice call to a fixed number by clicking the headset button. Latitude and longitude are measured through GPS, and tracking of blind people is handled by using another application based on Google maps. The overall error rate is approximately 5% for concrete and floor tiles. However, this system fails to perform in certain circumstances, such as elevations.

Table III summarizes the aforementioned smartphone-based walking assistants for visually impaired people and evaluates some important parameters, such as capturing and feedback devices, major hardware components, and their detection/coverage range, weight, and cost-effectiveness.

VI. Discussions and Future directions

A. Discussions

The review summary is organized with some properties, such as capturing devices, feedback devices/types, hardware components, coverage area, detection range, weight, and cost effectiveness. The previously described criteria are used because they measure the quality of a system. From the Tables I-III (Sections III-V), nearly all of the systems can provide feedback to alert visually impaired people. Some systems can detect obstacles within a short range, whereas some of them can detect obstacles within a long range; some of them provide only indoor or outdoor coverage, whereas some provide both; some are bulky, whereas some are lightweight; and some are low cost, whereas some are expensive. As shown in Table I, the system described in [1] covers the highest detection range (1–5m) with small weight and cost. The sensor-based walking assistant with the highest cost ($1790) was developed in [60], which only functions in outdoor environment. Most of the computer vision-based systems, such as [64], [80], [82], [85], and [86], have high costs, as illustrated in Table II. Furthermore, systems developed based on smartphone technology cover indoor and outdoor navigations, as shown in Table III [106], [108], [109]. The systems proposed in [107] and [110] only cover indoor environment. On the basis of the above discussion, no single system can properly fulfill the user requirements.

This review emphasizes the omitted properties of most important walking assistants for visually impaired people.

Only the recent developed walking assistants are investigated because covering all would be a challenging task due to the rapid growth of modern technology. The performances of the developed assistants are analyzed, and our review is summarized in Tables I–III, which incorporate the technical perception factors that are useful in evaluating the assistants' performances. The sensors used in the development of walking assistants may cause disadvantages when they are misused. The accomplishments of the systems that are developed based on ultrasonic sensor [47], [53], [55], [57], [59] may be affected with environmental factors whether they are altered or not [111]. However, the detection range of this type of sensor is approximately 200–400 cm. In addition, the systems that are developed based on the concept of IR techniques [50] show low performance in daytime due to ultraviolet sensitivity to sunshine [112]. From the review, computer vision-based techniques show poor performance due to some factors experienced by walking assistants, such as vagueness of objects, perspective consequence, low visibility of the obstacles, shadows, incomplete occlusions, brightness, and light reflection. Smartphone-based walking assistants cannot perform well in long-distance obstacles, the audio feedback signal generated by the smartphone becomes blurry in noisy environments, and visually impaired people experience difficulty in operating smartphones.

This review provides an arrangement of fundamental rules for outlining assistive tools and required features that should be included in the tools to obtain better performance.

The rules are expressed as follows

1) *Simple:* The simple design of a system enables easy usage without the aid of any external devices.
2) *Low cost:* A prototype with acceptable cost should be designed. Otherwise, majority of the people cannot use the prototype.
3) *Lightweight:* Lightweight design makes the system wearable for users with flexibility.
4) *Reliable:* The device should be compatible in terms of software and hardware specifications.
5) *Coverage area:* The device should fulfill the user requirements in indoor and outdoor scenarios.

B. Recommendations for Future Research

Although several works have been conducted to aid visually impaired people, studies on this research area have been rarely reported. In a radar-based navigation tool, the use of multi-static systems can be invoked because they have spatially distributed transmitter and receiver capabilities and illuminate the area of interest from various angles. In [1], the suitability of the tool could be improved by combining all the subunits in a single circuit board. An appropriate antenna design could avoid the limitations in [46], in which the weight of the system would be light, thereby making it wearable.

The NavGuide [47] could be improved by using artificial intelligence that enables the prediction of human health disorders and provides signals. The system could be integrated with RFID readers and tags that can identify obstacles, as developed in [52], [54], and [108]. The accuracy of wearable glove [49] could be improved by combining additional distance sensors positioned on different angles or by using an updated sensor, such as LiDAR. The prototype in [82] includes a computer in a backpack, which is bulky. For the number of marker optimizations, the processing unit is replaced with a tablet or smartphone or Raspberry Pi to minimize its size and weight; moreover, verbal guidance instructions should be substituted with haptic technology for improving the user interface to enhance the possibilities of [88]. The work in [80] could be enhanced by reducing the overall size and weight of the prototype. A vision-based system with other sensors (e.g., small RADAR and compact RTK L1 GPS receiver) can detect obstacles along the path. In outdoor environments, the use of an L1 RTK receiver reduces the probability to track a wrong path. To gain a high user experience, vibration bracelets may be evaluated to appraise the users' sensitivity to vibration. In addition, a wireless charging circuit could be integrated to simplify battery charging of bracelets. The size and weight of the prototype could be condensed by utilizing slight form of processors, such as Arduino nano, ESP32 chip, and Raspberry Pi, which are demonstrated in [51], [54], and [107], respectively.

Various types of cameras could be used to solve the illumination problem in [51]. The current system cannot provide the description of the surroundings. The progress of cognitive mapping of the surroundings can provide users considerable confidence in finding new areas, which will be investigated in future research. The limitation of [81] is that the performance of the system is degraded during sunlight (i.e., during daytime) because the readings of RGB-D camera vary with sunlight. Hence, alternative solutions with respect to used cameras and/or advanced cameras, which are independent from environmental conditions, could be used. RF energy gathering methods should be investigated to improve the system proposed in [52] to confirm the essential energy and powering of additional sensors in the placement of RFID tags. However, RFID tags work within a short range. Thus, users cannot obtain an alert signal for obstacles that are in long distances [108]. The scope of this prototype is to find a suitable service discovery method.

The prototype in [53] can detect obstacles that are in front of users rather than detecting all objects in the surroundings. The system proposed in [110] only provides a forward direction and maintain a record of users' locations by using a GPS module. Thus, the current version of the prototype can be improved by adding sensors in left and right directions to maintain the users in the right track. The system developed in [47] and [55] would be the possible solution for the future study of [53] and [110]. The future extension of [50] should focus on the use of suitable filters to make the tool quick in object detection. Reduction on the amplitude of noise and delay period makes the system fast. The work of AKSHI stick [54] could be enhanced by developing a prototype that includes the tractability of users, and the weight of the stick could be reduced. The electronic mobility cane developed in [55] could focus on increasing the number of real-life tests and measurements in terms of its future enhancement.

Furthermore, the smart virtual eye developed in [57] should focus on applying the application scheme outside of a controlled boundary. Open scopes exist to emphasize the daily user interactions and object recognition in real time. Frame-by-frame video processing could be introduced in further enhancement. The work in [58] could be extended to evaluate the prototype for visually impaired individuals, which is a vital research direction. Few systems, proposed by Bai *et al.* [48], O'Brien *et al.* [56], and Sadi *et al.* [59], have a strong dependency on weather conditions. However, the readings can be changed with the change of the environment (temperature or humidity). In this regard, the variations among the sensors could be investigated to avoid that type of dependency.

The work in [60] could be enhanced by developing a plane extraction algorithm in OpenCV integrated with mobile application, which can detect potholes or any step during walking. Future research could use 2D array of motors that can provide detailed information as a feedback. In the future, the used algorithm could be modified to avoid smash [87]. In addition, a cross-modal stereo-matching structure between IR and RGB images would be effective to expand the perceiving range intrinsically. Pixel-wise polarization approximation and multimodal sensual awareness should be combined to make prototype in [83] effective against cross-season scenarios. Deep learning techniques can efficiently increase the RGB-D perception in high dynamic surroundings. Zebra crosswalks, traffic lights, hazardous curbs, and water puddles would be covered in the road crossing context and traversability-related semantic perception. In addition, panoramic semantic segmentation would be accurate for providing great assistive awareness. The drawback of the system [85] is that it fails to detect the obstacles closed to a door or a wall. Future research could focus on inspecting an image segmentation-based method to resolve the hindrance introduced in [81], [83], and [87]. The proposed framework in [86] smashes recognition in a region where the motion vector fails to compute, such as in walls and doors. The integration of mobile data communication module and SIM card in the DPU enables the prototype to link to facilities of public transport systems and could be a possible future extension of the research proposed in [89].

The next improvement of the system [106] could be related on the user interface and navigation units (e.g., reducing voice distortion and timing of given instructions). In addition, the accuracy of compass should be improved when smartphones are apprehended in several locations. In future studies, powerful and high-cost smartphones could be developed, which would lead to the efficient assistance of [107]. An azimuth accuracy detection method could improve the current version by covering considerable detection ranges of the prototype [109].

Nearly all the systems that are reviewed consider the obstacles in front of the users. However, no single system can categorize the obstacles, which are essential for visually impaired people during navigation. Some critical hindrances that are faced by blind people are pothole on the road surface, staircase situation, road surface smoothness, water on the road surface, and different roads. Thus, the development of walking assistants considering the previously described issues may contribute in the novel research for aiding visually impaired people during navigation.

VII. Conclusions

This article presents the modern assistive technologies for visually impaired people in the area of computer vision, embedded system, and mobile platforms. The goals of the developed system are to generate an audio signal and/or vibration with the presence of obstacles for indoor and outdoor surroundings. Although all the studied tools are in their early stages, many of them are interpreted into everyday life with the use of recent technologies (i.e., mobile phones). On the basis of the review, sufficient explanation of the major features that should be incorporated in any framework that can assist visually impaired people is provided. Evidently, the actual goal is achieved when physicians and computer scientists develop an assistive technology for visually impaired people in the future. Hopefully, this review will assist researchers who are enthusiastic in developing walking assistants for visually impaired people in the future.

Acknowledgments

The authors would like to acknowledge their colleagues and friends who made valuable comments that enhanced the quality of the study.

References

[1] E. Cardillo *et al.*, "An electromagnetic sensor prototype to assist visually impaired and blind people in autonomous walking," *IEEE Sensors J.*, vol. 18, no. 6, pp. 2568–2576, Mar. 2018.

[2] R. R. A. Bourne *et al.*, "Magnitude, temporal trends, and projections of the global prevalence of blindness and distance and near vision impairment: A systematic review and meta-analysis," *Lancet Global Health*, vol. 5, no. 9, pp. e888–e897, Sep. 2017.

[3] R. Velázquez, "Wearable assistive devices for the blind," in *Wearable and Autonomous Biomedical Devices and Systems for Smart Environment* (Lecture Notes in Electrical Engineering), vol. 75. Berlin, Germany: Springer, 2010, pp. 331–349.

[4] S. L. Joseph *et al.*, "Being aware of the world: Toward using social media to support the blind with navigation," *IEEE Trans. Human-Mach. Syst.*, vol. 45, no. 3, pp. 399–405, Jun. 2015.

[5] M. Bousbia-Salah, M. Bettayeb, and A. Larbi, "A navigation aid for blind people," *J. Intell. Robot. Syst.*, vol. 64, nos. 3–4, pp. 387–400, 2011.

[6] B. B. Blasch, W. R. Wiener, and R. L. Welsh, *Foundations of Orientation and Mobility*, 2nd ed. New York, NY, USA: AFB Press, 1997.

[7] M. A. Hersh and M. A. Johnson, *Assistive Technology for Visually Impaired and Blind People*. London, U.K.: Springer-Verlag, 2008.

[8] D. Dakopoulos and N. G. Bourbakis, "Wearable obstacle avoidance electronic travel aids for blind: A survey," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 40, no. 1, pp. 25–35, Jan. 2010.

[9] W. Elmannai and K. Elleithy, "Sensor-based assistive devices for visually-impaired people: Current status, challenges, and future directions," *Sensors*, vol. 17, no. 3, pp. 565–606, Mar. 2017.

[10] A. Bhowmick and S. M. Hazarika, "An insight into assistive technology for the visually impaired and blind people: State-of-the-art and future trends," *J. Multimodal User Interfaces*, vol. 11, no. 2, pp. 149–172, Jan. 2017.

[11] H. Fernandes, P. Costa, V. Filipe, H. Paredes, and J. Barroso, "A review of assistive spatial orientation and navigation technologies for the visually impaired," *Univ. Access Inf. Soc.*, vol. 2017, pp. 1–14, Aug. 2017.

[12] H. Zhang and C. Ye, "An indoor wayfinding system based on geometric features aided graph SLAM for the visually impaired," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 9, pp. 1592–1604, Sep. 2017.

[13] I. Ulrich and J. Borenstein, "The GuideCane-applying mobile robot technologies to assist the visually impaired," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 31, no. 2, pp. 131–136, Mar. 2001.

[14] K. Ito *et al.*, "CyARM: An alternative aid device for blind persons," in *Proc. Conf. Hum. Factors Comput. Sci.*, 2005, pp. 1483–1486.

[15] F. Penizzotto, E. Slawinski, and V. Mut, “Laser radar based autonomous mobile robot guidance system for olive groves navigation,” *IEEE Latin Amer. Trans.*, vol. 13, no. 5, pp. 1303–1312, May 2015.

[16] Y. H. Lee and G. Medioni, “Wearable RGBD indoor navigation system for the blind,” in *Proc. ECCV Workshops*, Zürich, Switzerland, 2014, pp. 493–508.

[17] M. M. Kamal, A. I. Bayazid, M. S. Sadi, M. M. Islam, and N. Hasan, “Towards developing walking assistants for the visually impaired people,” in *Proc. IEEE Region 10 Humanitarian Technol. Conf. (R10-HTC)*, Dhaka, Bangladesh, Dec. 2017, pp. 238–241.

[18] M. F. Saaid, A. M. Mohammad, and M. S. A. M. Ali, “Smart cane with range notification for blind people,” in *Proc. IEEE Int. Conf. Autom. Control Intell. Syst. (I2CACIS)*, Selangor, Malaysian, Oct. 2016, pp. 225–229.

[19] A. J. Ramadhan, “Wearable smart system for visually impaired people,” *Sensors*, vol. 18, no. 3, p. 843, Mar. 2018.

[20] J. Liu, J. Liu, L. Xu, and W. Jin, “Electronic travel aids for the blind based on sensory substitution,” in *Proc. 5th Int. Conf. Comput. Sci. Educ. (ICCSE)*, Hefei, China, Aug. 2010, pp. 1328–1331.

[21] S. Kammoun, M. J.-M. Macé, B. Oriola, and J. Christophe, “Toward a better guidance in wearable electronic orientation aids,” in *Proc. IFIP Conf. Hum.-Comput. Interact.*, Lisbon, Portugal, Sep. 2011, pp. 624–627.

[22] W. M. Elmannai and K. M. Elleithy, “A highly accurate and reliable data fusion framework for guiding the visually impaired,” *IEEE Access*, vol. 6, pp. 33029–33054, 2018.

[23] F. Shaikh, V. Kuvar, and M. A. Meghani, “Ultrasonic sound based navigation and assistive system for visually impaired with real time location tracking and Panic button,” in *Proc. 2nd Int. Conf. Commun. Electron. Syst. (ICCES)*, Coimbatore, India, 2017, pp. 172–175.

[24] R. F. Olanrewaju, M. L. A. M. Radzi, and M. Rehab, “iWalk: Intelligent walking stick for visually impaired subjects,” in *Proc. IEEE 4th Int. Conf. Smart Instrum., Meas. Appl. (ICSIMA)*, Putrajaya, Malaysia, Nov. 2017, pp. 1–4.

[25] Z. Saquib, V. Murari, and S. N. Bhargav, “BlinDar: An invisible eye for the blind people making life easy for the blind with Internet of Things (IoT),” in *Proc. 2nd IEEE Int. Conf. Recent Trends Electron., Inf. Commun. Technol. (RTEICT)*, Bengaluru, India, May 2017, pp. 71–75.

[26] A. Dastider, B. Basak, M. Safayatullah, C. Shahnaz, and S. A. Fattah, “Cost efficient autonomous navigation system (e-cane) for visually impaired human beings,” in *Proc. IEEE Region 10 Humanitarian Technol. Conf. (R10-HTC)*, Dhaka, Bangladesh, 2017, pp. 650–653.

[27] D. Shahu, I. Shinko, R. Kodra, and I. Baxhaku, “A low-cost mobility monitoring system for visually impaired users,” in *Proc. Int. Conf. Smart Syst. Technol. (SST)*, Osijek, Croatia, 2017, pp. 235–238.

[28] N. S. Mala, S. S. Thushara, and S. Subbiah, “Navigation gadget for visually impaired based on IoT,” in *Proc. 2nd Int. Conf. Comput. Commun. Technol. (ICCCT)*, Chennai, India, 2017, pp. 334–338.

[29] E. Zahir, M. S. Hossain, M. W. Iqbal, I. Jalil, and S. M. Kabir, “Implementing and testing an ultrasonic sensor based mobility aid for a visually impaired person,” in *Proc. IEEE Region 10 Humanitarian Technol. Conf. (R10-HTC)*, Dhaka, Bangladesh, Dec. 2017, pp. 453–456.

[30] R. V. Jawale, M. V. Kadam, R. S. Gaikawad, and L. S. Kondaka, “Ultrasonic navigation based blind aid for the visually impaired,” in *Proc. IEEE Int. Conf. Power, Control, Signals Instrum. Eng. (ICPCSI)*, Chennai, India, Sep. 2017, pp. 923–928.

[31] H. M. U. Munir, F. Mahmood, A. Zeb, F. Mehmood, U. S. Khan, and J. Iqbal, “The voice enabled stick,” in *Proc. 20th Int. Conf. Comput. Inf. Technol. (ICCIT)*, Dhaka, Bangladesh, 2017, pp. 1–5.

[32] R. Agarwal *et al.*, “Low cost ultrasonic smart glasses for blind,” in *Proc. 8th IEEE Annu. Inf. Technol., Electron. Mobile Commun. Conf. (IEMCON)*, Vancouver, BC, Canada, Oct. 2017, pp. 210–213.

[33] Ş. Aymaz and T. Çavdar, “Ultrasonic assistive headset for visually impaired people,” in *Proc. 39th Int. Conf. Telecommun. Signal Process. (TSP)*, Vienna, Austria, 2016, pp. 388–391.

[34] K. Laubhan, M. Trent, B. Root, A. Abdelgawad, and K. Yelamarthi, “A wearable portable electronic travel aid for blind,” in *Proc. Int. Conf. Elect., Electron., Optim. Techn. (ICEEOT)*, Chennai, India, 2016, pp. 1999–2003.

[35] S. A. Pullano, A. S. Fiorillo, N. Vanello, and L. Landini, “Obstacle detection system based on low quality factor ultrasonic transducers for medical devices,” in *Proc. IEEE Int. Symp. Med. Meas. Appl. (MeMeA)*, Benevento, Italy, May 2016, pp. 1–4.

[36] A. Jayakody, C. I. Meegama, H. U. Pinnawalage, R. M. H. N. Muwenwella, and S. C. Dalpathado, “AVII [assist vision impaired individual]: An intelligent indoor navigation system for the vision impaired individuals with VLC,” in *Proc. IEEE Int. Conf. Inf. Automat. Sustainability (ICIAfS)*, Galle, Sri Lanka, Dec. 2016, pp. 1–6.

[37] R. Jafri, R. L. Campos, S. A. Ali, and H. R. Arabnia, “Visual and infrared sensor data-based obstacle detection for the visually impaired using the Google project tango tablet development kit and the unity engine,” *IEEE Access*, vol. 6, pp. 443–454, 2018.

[38] A. B. Yadav, L. Bindal, V. U. Namhakumar, K. Namitha, and H. Harsha, “Design and development of smart assistive device for visually impaired people,” in *Proc. IEEE Int. Conf. Recent Trends Electron. Inf. Commun. Technol.*, Bengaluru, India, May 2016, pp. 1506–1509.

[39] A. A. Nada, M. A. Fakhr, and A. F. Seddik, “Assistive infrared sensor based smart stick for blind people,” in *Proc. Sci. Inf. Conf. (SAI)*, London, U.K., 2015, pp. 1149–1154.

[40] A. S. Al-Fahoum, H. B. Al-Hmoud, and A. A. Al-Fraihat, “A smart infrared microcontroller-based blind guidance system,” *Active Passive Electron. Compon.*, vol. 2013, Jun. 2013, Art. no. 726480.

[41] G. Capi, “Development of a new robotic system for assisting and guiding visually impaired people,” in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Guangzhou, China, Dec. 2012, pp. 229–234.

[42] L. Everding, L. Walger, V. S. Ghaderi, and J. Conradt, “A mobility device for the blind with improved vertical resolution using dynamic vision sensors,” in *Proc. IEEE 18th Int. Conf. e-Health Netw., Appl. Services (Healthcom)*, Munich, Germany, 2016, pp. 1–5.

[43] V. S. Ghaderi, M. Mulas, V. F. S. Pereira, L. Everding, D. Weikersdorfer, and J. Conradt, “A wearable mobility device for the blind using retina-inspired dynamic vision sensors,” in *Proc. 37th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Milan, Italy, Aug. 2015, pp. 3371–3374.

[44] A. S. Martinez-Sala, F. Losilla, J. C. Sánchez-Aarnoutse, and J. García-Haro, “Design, implementation and evaluation of an indoor navigation system for visually impaired people,” *Sensors*, vol. 15, pp. 32168–32187, Dec. 2015.

[45] R. K. Katzschmann, B. Araki, and D. Rus, “Safe local navigation for visually impaired users with a time-of-flight and haptic feedback device,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 3, pp. 583–593, Mar. 2018.

[46] P. Kwiatkowski, T. Jaeschke, D. Starke, L. Piotrowsky, H. Deis, and N. Pohl, “A concept study for a radar-based navigation device with sector scan antenna for visually impaired people,” in *IEEE MTT-S Int. Microw. Symp. Dig.*, Gothenburg, Sweden, May 2017, pp. 1–4.

[47] K. Patil, Q. Jawadwala, and F. C. Shu, “Design and construction of electronic aid for visually impaired people,” in *IEEE Trans. Human-Mach. Syst.*, vol. 48, no. 2, pp. 172–182, Apr. 2018.

[48] J. Bai, S. Lian, Z. Liu, K. Wang, and D. Liu, “Virtual-blind-road following-based wearable navigation device for blind people,” *IEEE Trans. Consum. Electron.*, vol. 64, no. 1, pp. 136–143, Feb. 2018.

[49] S. T. H. Rizvi, M. J. Asif, and H. Ashfaq, “Visual impairment aid using haptic and sound feedback,” in *Proc. Int. Conf. Commun., Comput. Digit. Syst. (C-CODE)*, Islamabad, Pakistan, 2017, pp. 175–178.

[50] F. Prattico, C. Cera, and F. Petroni, “A new hybrid infrared-ultrasonic electronic travel aids for blind people,” *Sens. Actuators A, Phys.*, vol. 201, pp. 363–370, Oct. 2013.

[51] D. Vera, D. Marcillo, and A. Pereira, “Blind guide: Anytime, anywhere solution for guiding blind people,” in *Proc. World Conf. Inf. Syst. Technol.* Cham, Switzerland: Springer, 2017, pp. 353–363.

[52] C. Tsirmpas, A. Rompas, O. Fokou, and D. Koutsouris, “An indoor navigation system for visually impaired and elderly people based on radio frequency identification (RFID),” *Inf. Sci.*, vol. 320, pp. 288–305, Nov. 2015.

[53] S. Sharma, M. Gupta, A. Kumar, M. Tripathi, and M. S. Gaur, “Multiple distance sensors based smart stick for visually impaired people,” in *Proc. IEEE 7th Annu. Comput. Commun. Workshop Conf. (CCWC)*, Las Vegas, NV, USA, Jan. 2017 pp. 1–5.

[54] V. S. S. Kaushalya, K. D. D. P. Premarathne, H. M. Shadir, P. Krithika, and S. G. S. Fernando, “‘AKSHI’: Automated help aid for visually impaired people using obstacle detection and GPS technology,” *Int. J. Sci. Res. Publications*, vol. 6, no. 11, pp. 579–583, Nov. 2016.

[55] S. Bhatlawande, M. Mahadevappa, J. Mukherjee, M. Biswas, D. Das, and S. Gupta, “Design, development, and clinical evaluation of the electronic mobility cane for vision rehabilitation,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 22, no. 6, pp. 1148–1159, Nov. 2014.

[56] E. E. O'Brien, A. A. Mohtar, L. E. Diment, and K. J. Reynolds, "A detachable electronic device for use with a long white cane to assist with mobility," *Assist Technol.*, vol. 26, no. 4, pp. 219–226, May 2014.

[57] D. Zhou, Y. Yang, and H. Yan, "A smart 'virtual eye' mobile system for the visually impaired," *IEEE Potentials*, vol. 35, no. 6, pp. 13–20, Nov./Dec. 2016.

[58] J. Sohl-Dickstein *et al.*, "A device for human ultrasonic echolocation," *IEEE Trans. Biomed. Eng.*, vol. 62, no. 6, pp. 1526–1534, Jun. 2015.

[59] M. S. Sadi, S. Mahmud, M. M. Kamal, and A. I. Bayazid, "Automated walk-in assistant for the blinds," in *Proc. Int. Conf. Elect. Eng. Inf. Commun. Technol.*, Dhaka, Bangladesh, 2014, pp. 1–4.

[60] S. Bharambe, R. Thakker, H. Patil, and K. M. Bhurchandi, "Substitute eyes for blind with navigator using Android," in *Proc. Texas Instrum. India Educators, Conf.*, Bengaluru, India, 2013, pp. 38–43.

[61] K. Qian, W. Zhao, Z. Ma, J. Ma, X. Ma, and H. Yu, "Wearable-assisted localization and inspection guidance system using egocentric stereo cameras," *IEEE Sensors J.*, vol. 18, no. 2, pp. 809–821, Jan. 2018.

[62] K. Yang, K. Wang, H. Chen, and J. Bai, "Reducing the minimum range of a RGB-depth sensor to aid navigation in visually impaired individuals," *Appl. Opt.*, vol. 57, pp. 2809–2819, Jun. 2018.

[63] S. Lin, K. Wang, K. Yang, and R. Cheng, "KrNet: A kinetic real-time convolutional neural network for navigational assistance," in *Computers Helping People With Special Needs* (Lecture Notes in Computer Science), vol. 10897, K. Miesenberger and G. Kouroupetroglou, Eds. Cham, Switzerland: Springer, 2018, pp. 55–62.

[64] E. E. Pissaloux, R. Velázquez, and F. Maingreaud, "A new framework for cognitive mobility of visually impaired users in using tactile device," in *IEEE Trans. Human-Mach. Syst.*, vol. 47, no. 6, pp. 1040–1051, Dec. 2017.

[65] K. Yang, K. Wang, R. Cheng, W. Hu, X. Huang, and J. Bai, "Detecting traversable area and water hazards for the visually impaired with a pRGB-D sensor," *Sensors*, vol. 17, no. 8, p. 1890, Aug. 2017.

[66] K. Yang *et al.*, "IR stereo RealSense: Decreasing minimum range of navigational assistance for visually impaired individuals," *J. Ambient Intell. Smart Environ.*, vol. 9, pp. 743–755, Nov. 2017.

[67] R. Cheng *et al.*, "Crosswalk navigation for people with visual impairments on a wearable device," *J. Electron. Imag.*, vol. 26, p. 053025, Oct. 2017.

[68] R. Cheng, K. Wang, K. Yang, N. Long, J. Bai, and D. Liu, "Real-time pedestrian crossing lights detection algorithm for the visually impaired," *Multimedia Tools Appl.*, vol. 77, no. 16, pp. 20651–20671, Aug. 2017.

[69] E. Ko and E. Y. Kim, "A vision-based wayfinding system for visually impaired people using situation awareness and activity-based instructions," *Sensors*, vol. 17, p. 1882, Aug. 2017.

[70] N. Botezatu, S. Caraiman, D. Rzeszotarski, and P. Strumillo, "Development of a versatile assistive system for the visually impaired based on sensor fusion," in *Proc. 21st Int. Conf. Syst. Theory, Control Comput. (ICSTCC)*, Sinaia, Romania, 2017, pp. 540–547.

[71] M. Leo, G. Medioni, M. Trivedi, T. Kanade, and G. M. Farinella, "Computer vision for assistive technologies," *Comput. Vis. Image Understand.*, vol. 154, pp. 1–15, Jan. 2017.

[72] S. Caraiman *et al.*, "Computer vision for the visually impaired: The sound of vision system," in *Proc. IEEE Int. Conf. Comput. Vis. Workshops (ICCVW)*, Venice, Italy, Oct. 2017, pp. 1480–1489.

[73] Z. Fei, E. Yang, H. Hu, and H. Zhou, "Review of machine vision-based electronic travel aids," in *Proc. 23rd Int. Conf. Automat. Comput. (ICAC)*, Huddersfield, U.K., 2017, pp. 1–7.

[74] K. Chaccour and G. Badr, "Computer vision guidance system for indoor navigation of visually impaired people," in *Proc. IEEE 8th Int. Conf. Intell. Syst. (IS)*, Sofia, Bulgaria, 2016, pp. 449–454.

[75] S. Khade and Y. Dandawate, "Hardware implementation of obstacle detection for assisting visually impaired people in an unfamiliar environment by using raspberry Pi," in *Proc. Int. Conf. Smart Trends Inf. Technol. Comput. Commun.* Singapore: Springer, 2016, pp. 889–895.

[76] S. M. Jonas *et al.*, "IMAGO: Image-guided navigation for visually impaired people," *J. Ambient Intell. Smart Environ.*, vol. 7, no. 5, pp. 679–692, Apr. 2015.

[77] R. Jafri, S. A. Ali, H. R. Arabnia, and S. Fatima, "Computer vision-based object recognition for the visually impaired in an indoors environment: A survey," *Vis. Comput.*, vol. 30, no. 11, pp. 1197–1222, Nov. 2014.

[78] J. R. Terven, J. Salas, and B. Raducanu, "New opportunities for computer vision-based assistive technology systems for the visually impaired," *Computer*, vol. 47, no. 4, pp. 52–58, Apr. 2014.

[79] Y. Tian, X. Yang, C. Yi, and A. Arditi, "Toward a computer vision-based wayfinding aid for blind persons to access unfamiliar indoor environments," *Mach. Vis. Appl.*, vol. 24, no. 3, pp. 521–535, Apr. 2013.

[80] A. Mancini, E. Frontoni, and P. Zingaretti, "Mechatronic system to help visually impaired users during walking and running," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 2, pp. 649–660, Feb. 2018.

[81] A. Aladrén, G. López-Nicolás, L. Puig, and J. J. Guerrero, "Navigation assistance for the visually impaired using RGB-D sensor with range expansion," *IEEE Syst. J.*, vol. 10, no. 3, pp. 922–932, Sep. 2016.

[82] S. Kammoun *et al.*, "Navigation and space perception assistance for the visually impaired: The NAVIG project," *IRBM*, vol. 33, no. 2, pp. 182–189, Apr. 2012.

[83] K. Yang *et al.*, "Unifying terrain awareness for the visually impaired through real-time semantic segmentation," *Sensors*, vol. 18, no. 5, p. 1506, May 2018.

[84] J. Bai, S. Lian, Z. Liu, K. Wang, and D. Liu, "Smart guiding glasses for visually impaired people in indoor environment," in *IEEE Trans. Consum. Electron.*, vol. 63, no. 3, pp. 258–266, Aug. 2017.

[85] M.-C. Kang, S.-H. Chae, J.-Y. Sun, S.-H. Lee, and S.-J. Ko, "An enhanced obstacle avoidance method for the visually impaired using deformable grid," *IEEE Trans. Consum. Electron.*, vol. 63, no. 2, pp. 169–177, May 2017.

[86] M.-C. Kang, S.-H. Chae, J.-Y. Sun, J.-W. Yoo, and S.-J. Ko, "A novel obstacle detection method based on deformable grid for the visually impaired," *IEEE Trans. Consum. Electron.*, vol. 61, no. 3, pp. 376–383, Aug. 2015.

[87] K. Yang, K. Wang, W. Hu, and J. Bai, "Expanding the detection of traversable area with realsense for the visually impaired," *Sensors*, vol. 10, no. 4, p. 1954, Nov. 2016.

[88] M. L. Mekhalfi, F. Melgani, A. Zeggada, F. G. B. De Natale, M. A.-M. Salem, and A. Khamis, "Recovering the sight to blind people in indoor environments with smart technologies," *Expert Syst. Appl.*, vol. 46, pp. 129–138, Mar. 2016.

[89] B. Söveny, G. Kovács, and Z. T. Kardkovács, "Blind guide: A virtual eye for guiding indoor and outdoor movement," *J. Multimodal User Interfaces*, vol. 9, no. 4, pp. 287–297, Dec. 2015.

[90] R. Velázquez, E. Pissaloux, P. Rodrigo, M. Carrasco, N. I. Giannoccaro, and A. Lay-Ekuakille, "An outdoor navigation system for blind pedestrians using GPS and tactile-foot feedback," *Appl. Sci.*, vol. 8, no. 4, p. 578, Apr. 2018.

[91] A. Als, A. King, K. Johnson, and R. Sargeant, "BluKane: An obstacle avoidance navigation app to assist the visually impaired," in *Computers Helping People With Special Needs* (Lecture Notes in Computer Science), vol. 10897, K. Miesenberger and G. Kouroupetroglou, Eds. Cham, Switzerland: Springer, 2018, pp. 36–43.

[92] M. Murata, D. Ahmetovic, D. Sato, H. Takagi, K. M. Kitani, and C. Asakawa, "Smartphone-based indoor localization for blind navigation across building complexes," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. (PerCom)*, Athens, Greece, Mar. 2018, pp. 1–10.

[93] J. P. Gomes, J. P. Sousa, C. R. Cunha, and E. P. Morais, "An indoor navigation architecture using variable data sources for blind and visually impaired persons," in *Proc. 13th Iberian Conf. Inf. Syst. Technol. (CISTI)*, Caceres, Spain, 2018, pp. 1–5.

[94] Y. Tao, L. Ding, and A. Ganz, "Indoor navigation validation framework for visually impaired users," *IEEE Access*, vol. 5, pp. 21763–21773, 2017.

[95] R. Kasthuri, B. Nivetha, S. Shabana, M. Veluchamy, and S. Sivakumar, "Smart device for visually impaired people," in *Proc. 3rd Int. Conf. Sci. Technol. Eng. Manage. (ICONSTEM)*, Chennai, India, 2017, pp. 54–59.

[96] B.-S. Lin, C.-C. Lee, and P.-Y. Chiang, "Simple smartphone-based guiding system for visually impaired people," *Sensors*, vol. 17, no. 6, p. 1371, Jun. 2017.

[97] S. Patel, A. Kumar, P. Yadav, J. Desai, and D. Patil, "Smartphone-based obstacle detection for visually impaired people," in *Proc. Int. Conf. Innov. Inf., Embedded Commun. Syst. (ICIIECS)*, Coimbatore, India, 2017, pp. 1–3.

[98] R. A. Asmara, F. Al Huda, B. S. Andoko, and A. N. Handayani, "Optimized walking straight guidance system for visually impaired person that use Android smartphone," in *Proc. Int. Conf. Sustainable Inf. Eng. Technol. (SIET)*, Malang, Indonesia, 2017, pp. 332–336.

[99] S. Mukherjee *et al.*, "Android based personal travelling assistant using turning algorithm," in *Proc. Int. Conf. Energy, Commun., Data Anal. Soft Comput. (ICECDS)*, Chennai, India, 2017, pp. 3161–3165.

[100] S. Al-Khalifa and M. Al-Razgan, "Ebsar: Indoor guidance for the visually impaired," *Comput. Elect. Eng.*, vol. 54, pp. 26–39, Aug. 2016.
[101] A. Alnafessah, M. Al-Ammar, S. Al-Hadhrami, A. Al-Salman, and H. Al-Khalifa, "Developing an ultra wideband indoor navigation system for visually impaired people," *Int. J. Distrib. Sens. Netw.*, vol. 12, no. 7, p. 6152342, Jul. 2016.
[102] K. K. Kim, S. H. Han, J. Park, and J. Park, "The interaction experiences of visually impaired people with assistive technology: A case study of smartphones," *Int. J. Ind. Ergonom.*, vol. 55, pp. 22–33, Sep. 2016.
[103] Á. Csapó, G. Wersényi, H. Nagy, and T. Stockman, "A survey of assistive technologies and applications for blind users on mobile platforms: A review and foundation for research," *J. Multimodal User Interfaces*, vol. 9, no. 4, pp. 275–286, Dec. 2015.
[104] M. C. Rodriguez-Sanchez, M. A. Moreno-Alvarez, E. Martin, S. Borromeo, and J. A. Hernandez-Tamame, "Accessible smartphones for blind users: A case study for a wayfinding system," *Expert Syst. Appl.*, vol. 41, no. 16, pp. 7210–7222, Nov. 2014.
[105] L. Hakobyan, J. Lumsden, D. O'Sullivan, and H. Bartlett, "Mobile assistive technologies for the visually impaired," *Surv. Ophthalmol.*, vol. 58, no. 6, pp. 513–528, Nov./Dec. 2013.
[106] S. A. Cheraghi, V. Namboodiri, and L. Walker, "GuideBeacon: Beacon-based indoor wayfinding for the blind, visually impaired, and disoriented," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. (PerCom)*, Kona, HI, USA, Mar. 2017, pp. 121–130.
[107] L. Ţepelea, I. Gavriluţ, and A. Gacsádi, "Smartphone application to assist visually impaired people," in *Proc. 14th Int. Conf. Eng. Mod. Electr. Syst. (EMES)*, Oradea, Romania, 2017, pp. 228–231.
[108] S. Alghamdi, R. van Schyndel, and I. Khalil, "Accurate positioning using long range active RFID technology to assist visually impaired people," *J. Netw. Comput. Appl.*, vol. 41, pp. 135–147, May 2014.
[109] M. Nakajima and S. Haruyama, "New indoor navigation system for visually impaired people using visible light communication," *EURASIP J. Wireless Commun. Netw.*, vol. 2013, no. 1, p. 37, Dec. 2013.
[110] M. S. R. Tanveer, M. M. A. Hashem, and M. K. Hossain, "Android assistant EyeMate for blind and blind tracker," in *Proc. 18th Int. Conf. Comput. Inf. Technol. (ICCIT)*, Dhaka, Bangladesh, 2015, pp. 266–271.
[111] AIRMAR. *Technology Overview for Applying Ultrasonic Technology (AirducerTM Catalog)*. Accessed: Sep. 4, 2018. [Online]. Available: https://www.airmar.com
[112] H. Photonics. *Characteristics and Use of Infrared Detectors*. Accessed: Sep. 4, 2018. [Online]. Available: https://www.hamamatsu.com/resources/pdf/ssd/infrared_kird9001e.pdf

Md. Milon Islam received the B.Sc. degree in computer science engineering (CSE) from the Khulna University of Engineering and Technology, Khulna, Bangladesh, in 2016, where he is currently pursuing the M.Sc. degree in CSE. In 2017, he joined the Department of Computer Science and Engineering, Khulna University of Engineering and Technology, as a Lecturer. His research interests include computer vision, embedded system, and machine learning.

Muhammad Sheikh Sadi (M'04–SM'18) received the Ph.D. degree from the Department of Electrical and Computer Engineering, Curtin University, Australia, in 2010. His Ph.D. dissertation was on "Towards Minimizing the Risks of Soft Errors at the Design Level of Embedded Systems." He was also a Visiting Research Scholar with the Dependable Embedded Systems and Software Research Group, TU Darmstadt, Germany. He has been a Professor with the Department of Computer Science and Engineering, Khulna University of Engineering and Technology, Bangladesh, since 2013. He is a DAAD Research Scholar with the University of Koblenz and Landau, Germany, until 2019. He has published more than 56 research papers in peer-reviewed journals and conferences. His areas of research interests are soft errors tolerance, hardware redundancy for fault tolerance, humanitarian technology, and Internet of Things. He is a reviewer for several reputed journals.

Kamal Z. Zamli (M'17) received the B.Sc. degree in electrical engineering from the Worcester Polytechnic Institute, USA, in 1992, the M.Sc. degree in real-time software engineering from Universiti Teknologi Malaysia in 2000, and the Ph.D. degree in software engineering from Newcastle University, Newcastle upon Tyne, U.K., in 2003. He is currently the Dean and a Professor with the Faculty of Computer Systems and Software Engineering, Universiti Malaysia Pahang.

He is a member of MySEIG. His main research interests include search-based software engineering, combinatorial software testing, and computational intelligence.

Md. Manjur Ahmed received the B.Sc. degree in computer science and engineering from Khulna University of Engineering and Technology, Bangladesh, in 2009, and the Ph.D. degree in computational intelligence from Universiti Sains Malaysia in 2016. He is currently a Senior Lecturer with Universiti Malaysia Pahang. His current research interests include fuzzy information granule, intelligent systems for data stream, and applications of computational intelligence.