Heliyon 10 (2024) e31825

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

A comprehensive review of navigation systems for visually impaired individuals

Mustufa Haider Abidi [a,b,*], Arshad Noor Siddiquee [b,c], Hisham Alkhalefah [a,b], Vishwaraj Srivastava [b,d]

[a] Advanced Manufacturing Institute, King Saud University, Riyadh, 11421, Saudi Arabia
[b] King Salman Center for Disability Research, Riyadh, 11614, Saudi Arabia
[c] Department of Mechanical Engineering, Jamia Millia Islamia, New Delhi, 110025, India
[d] National Centre for Flexible Electronics, Indian Institute of Technology-Kanpur, India

ARTICLE INFO

Keywords:
Visual impairment
Sensors
Artificial intelligence
Assistive technologies

ABSTRACT

Background: This review explores the evolutionary trajectory of navigation assistance tools tailored for the visually impaired, spanning from traditional aids like white canes to contemporary electronic devices. It underlines their pivotal role in fostering safe mobility for visually impaired individuals.

Objectives: The primary aim is to categorize and assess the plethora of navigation assistance solutions available. Emphasis is placed on technological advancements, particularly in electronic systems employing sensors, AI, and feedback mechanisms. Furthermore, the review underscores the emerging influence of smartphone-based solutions and navigation satellite systems in augmenting independence and quality of life for the visually impaired.

Methods: Navigation assistance solutions are segmented into four key categories: Visual Imagery Systems, Non-Visual Data Systems, Map-Based Solutions, and 3D Sound Systems. The integration of diverse sensors like Ultrasonic Sensors and LiDAR for obstacle detection and real-time feedback is scrutinized. Additionally, the fusion of smartphone technology with sensors to deliver location-based assistance is explored. The review also evaluates the functionality, efficacy, and cost-efficiency of navigation satellite systems.

Results: Results indicate a significant evolution in navigation aids, with modern electronic systems proving highly effective in aiding obstacle detection and safe navigation. The convenience and portability of smartphone-based solutions are underscored, along with the potential of navigation satellite systems to enhance navigation assistance.

Conclusions: In conclusion, the review advocates for continued innovation and technological integration in navigation tools to empower visually impaired individuals with increased independence and safe access to their surroundings. It accentuates the imperative of ongoing efforts to enhance the quality of life for those with visual impairments through futuristic technological solutions.

---

[*] Corresponding author. Advanced Manufacturing Institute, King Saud University, Riyadh, 11421, Saudi Arabia.
E-mail address: mabidi@ksu.edu.sa (M.H. Abidi).

https://doi.org/10.1016/j.heliyon.2024.e31825
Received 18 February 2024; Received in revised form 8 April 2024; Accepted 22 May 2024

1. Introduction

Individuals with visual impairments frequently encounter a multitude of challenges in their routine activities. These difficulties encompass issues like identifying physical barriers, walking across unfamiliar routes, safely crossing streets, and utilizing public transportation. Moreover, they also face obstacles when maneuvering within indoor spaces, reading printed materials, and engaging in social interactions [1]. Unfortunately, these challenges are compounded by the inconsistent availability of assistive technology and the absence of universally accessible design standards in their surroundings [2]. Furthermore, adapting to changing weather conditions and the emotional troll of navigating a world primarily designed for sighted individuals further exacerbate these difficulties. Despite these hurdles, many visually impaired individuals rely on a combination of their skills, mobility aids, and assistive tools to foster their independence, underscoring the significance of raising public awareness and promoting inclusive design in urban planning, transportation, and technology to enhance their overall well-being [3].

Navigation systems hold a pivotal role in enhancing the independence and mobility of individuals with visual impairments [4]. To begin with, these systems instill a significant boost in self-assurance by providing real-time information about their surroundings and guiding them through routes, enabling them to confidently explore new territories and maneuver unfamiliar settings, consequently leading to better self-reliance in their daily routines [5]. Additionally, these systems bolster the safety of visually impaired individuals during their journeys, providing vital auditory cues and guidance to help them circumvent obstacles, safely traverse on streets, and adeptly navigate intricate public transportation networks, thereby diminishing the likelihood of accidents and injuries, rendering both outdoor and indoor mobility more secure and manageable [6–8].

Efficiency in charting optimal routes constitutes another integral facet of navigation systems. They adeptly compute the most efficient pathways to desired destinations, affording users the ability to economize time and energy [9–11]. This efficacy proves especially invaluable in urban landscapes where intricate layouts and densely populated areas may otherwise pose overwhelming challenges, ensuring smoother and more streamlined journeys [12]. Furthermore, navigation tools facilitate the visually impaired in accessing crucial services like healthcare facilities, educational institutions, and employment opportunities with greater ease. This increased accessibility, advances their integration into society, empowering them to more effectively pursue their aspirations and careers [13–15]. The social dimension of inclusion is also positively impacted by navigation systems, as they guide users to recreational venues, dining establishments, cultural events, and other social gatherings, thus mitigating feelings of isolation and augmenting their overall quality of life [16–18]. Navigation systems make significant contributions to fostering a sense of independence among visually impaired individuals [19–22]. By providing guidance and real-time information, they reduce their dependence on others for transportation and daily navigation tasks, thereby not only empowering them but also preserving a greater degree of control over their lives [23,24]. Furthermore, navigation systems alleviate the stress and anxiety associated with travel, assuring users that they possess a reliable tool to offer guidance in unfamiliar surroundings, thereby facilitating a more comfortable and enjoyable experience [25]. They also adapt seamlessly to changing environmental conditions, such as fluctuating weather or construction sites, delivering real-time updates to ensure safe navigation and bolster confidence in dynamic settings [26].

Many navigation apps and devices incorporate customization options, enabling users to personalize the interface and settings to align with their specific needs and preferences. This adaptability ensures that the system remains a highly tailored and functional tool [27–29]. Finally, navigation systems promote continuous learning by assisting visually impaired individuals in memorizing new routes and gaining familiarity with their surroundings over time. This ongoing learning process further heightens their independence and capability to navigate their environments effectively [30]. Navigation systems stand as invaluable tools for individuals with visual impairments, affording them the capacity to traverse the world with heightened ease, security, and self-sufficiency [31–33]. They play a pivotal role in fostering inclusivity, advancing access to education and employment, enriching social engagement, and ultimately

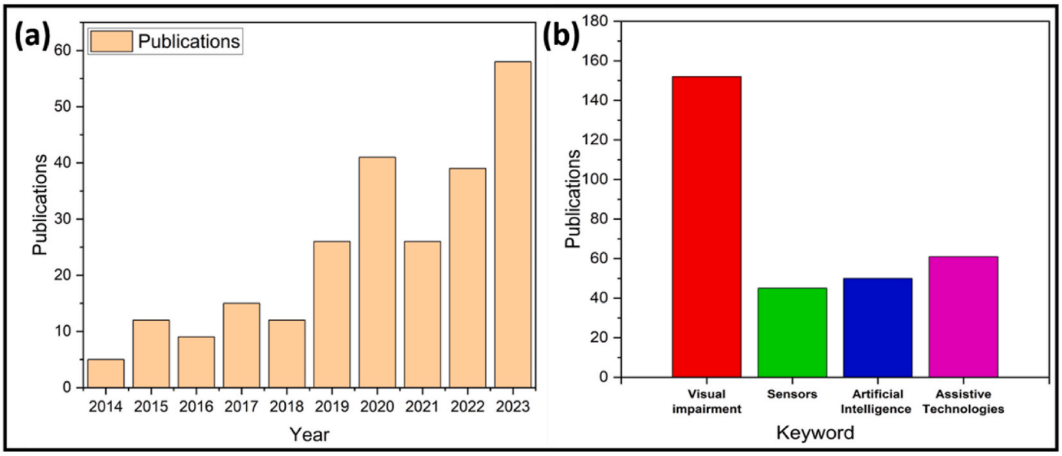

Fig. 1. *(a) year wise publication on* "Navigation Systems for Visually Impaired" *(b) publications on* " Visual impairment ", " sensors", "artificial intelligence", and " assistive technologies" *from the year 2014 to year 2023.*

enhancing the lives of those grappling with visual impairments. But these navigation systems are insufficiently studied thus constituting a research gap. Based on this research gap, the research questions (RQs) are.

- RQ1: What are different types of navigation systems for visually impaired persons
- RQ2: How do navigation systems integrate with existing assistive technologies and mobility aids used by visually impaired individuals?

Based on these questions the objective of this review paper is to analyze and compare various navigation systems designed for visually impaired persons.

The keyword 'Navigation Systems for Visually Impaired" was searched for Articles 'topic', 'abstract', and 'keywords' in the SCOPUS database within a time span of 10 years between 2014 and 2023. The search resulted in 1261 articles from database. In the second stage the results were refined via "search within results" by using keywords "Visual impairment", "sensors", "artificial intelligence", and "assistive technologies" which resulted in 152, 45, 50 and 61 articles respectively as shown in Fig. 1(a and b).

Furthermore, the network map of co-occurrence keywords is presented in Fig. 2. It intuitively reveals the relationship of keywords of "Navigation Systems for Visually Impaired". The node size corresponds to the keyword occurrence frequency, wherein a greater frequency results in a larger node size.

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart was utilized to illustrate the article selection process (refer to Fig. 3). It encompassed articles initially identified in the search (n = 308) and those remaining after screening (n = 102). While this significant number of articles is employed for quantitative analysis, not all are included in qualitative analysis.

In Section 2, wearable and non-wearable navigation systems are discussed. Section 3 delves into the integration of Red-Green-Blue-Depth (RGB-D) cameras with tactile sensor-based systems. Following this, Section 4 explores navigation stick-based systems. Section 5 addresses systems designed for obstacle avoidance and navigable path generation. Moving forward to Section 6, various algorithms pertinent to navigation are discussed. Section 7 focuses on user experience considerations and the application of human-centered design principles in the development of navigation systems. Lastly, Section 8 presents the concluding remarks.

2. Wearable and non-wearable navigation systems

Wearable technology has an impact, on the lives of its users. These devices are embedded in clothes, watches or accessories. Wrist worn devices have become quite popular due to ease in use. They offer access to information and can be used for various type of signals useful for navigation [34]. The wearable navigation systems as shown in Fig. 4, employ sensors positioned on multiple body areas like the feet, knees, thighs, or waist, utilizing various sensor types such as accelerometers, gyroscopic sensors, magnetometers, force sensors, extensometers, goniometers, active markers, electromyography, and others to capture diverse signals associated with human gait. Wearable computers are a type of device that can be worn on the body although there is no definition for them. They can be

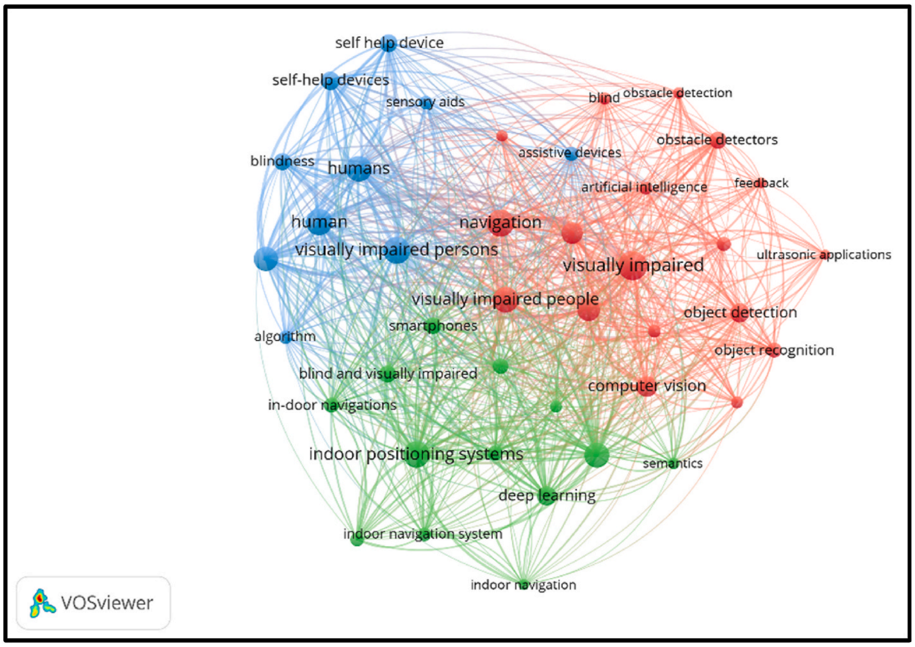

Fig. 2. The network of co-occurring keywords with VOS viewer.

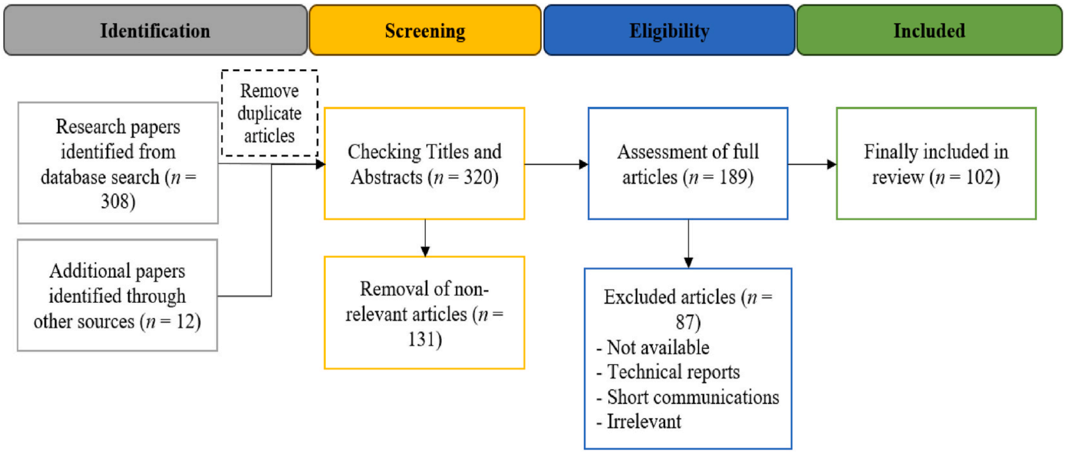

Fig. 3. PRISMA flowchart for systematic screening of literature.

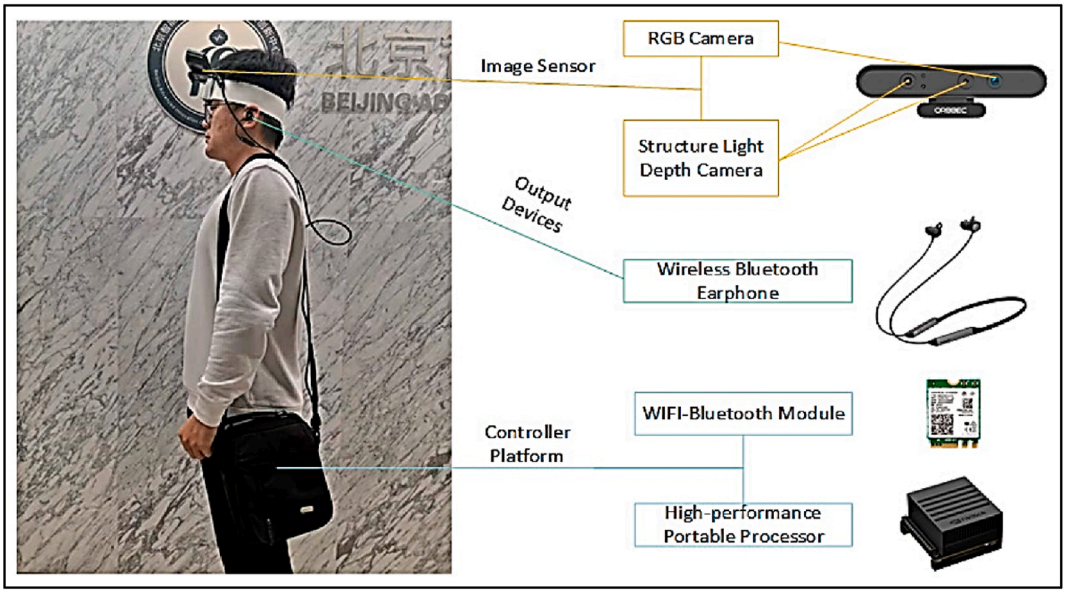

Fig. 4. *The wearable navigation system platform* [30].

characterized by specific features. The field of computing encompasses computer science, electrical engineering and psychology [35]. Within computer science there are branches such as intelligence, human computer interaction (HCI) and hardware design. HCI is closely related to psychology while hardware design has its roots, in engineering. When it comes to computer interfaces they are primarily associated with HCI and psychology than electrical engineering [34]. Examples of wearable systems: Smart glasses, haptic vests, and wearable sensors.

Wearable systems offer advantages such as transparent analysis and continuous monitoring of gait during daily activities and over the long term, cost-effectiveness, versatility in deployment, availability of compact sensors, improved usability through wireless technology, and empowerment of patients in clinical gait analysis by promoting autonomy and active involvement [36].

The disadvantages of wearable systems include limitations imposed by power consumption and battery life, the need for complex algorithms to estimate parameters from inertial sensors, a restricted capacity for analyzing gait parameters, and vulnerability to noise and external interference not under the control of specialists.

Non-wearable systems (NWS) necessitate controlled research environments equipped with sensors to collect gait data from individuals walking on designated pathways [37]. NWS systems can be divided into two categories: image processing (IP) and floor sensors (FS). IP systems employ optic sensors like cameras, laser range scanners, and infrared sensors to objectively measure various gait parameters through digital image processing. On the other hand, FS systems use sensors embedded in the floor to capture gait data. NWS-based methods are typically conducted in controlled laboratory conditions with devices like cameras, laser sensors, or Time-of-Flight (ToF) cameras on clearly defined walkways. These conditions offer advantages like isolation from external influences, ensuring precise analysis of gait parameters and achieving high levels of repeatability and reproducibility [37]. Examples of non-wearable systems: Navigation sticks, handheld devices, and auditory-based systems. The advantages of NWS include simultaneous analysis of multiple gait parameters from various approaches, extended data collection due to no power constraints, non-intrusive systems, higher precision and measurement capacity in complex analysis, better repeatability in controlled environments, and real-time control by specialists, while the disadvantages encompass potential alterations to normal gait patterns due to space restrictions, higher equipment and testing costs, and the inability to monitor real-life gait outside of instrumented environments.

3. Red-Green-Blue-Depth (RGB-D) camera coupled with tactile sensor-based systems

RGB-D typically denotes data obtained from RGB-D sensors, which includes Red, Green, Blue color information along with depth data. An RGB-D image contains depth information for each pixel, precisely matched with the corresponding image pixels. This depth-derived image channel represents distances between the image plane and objects in the RGB image. Incorporating depth data into a standard RGB image enhances both data accuracy and density. Fig. 5 illustrates an example of information captured by an RGB-D sensor [38].

Depth information is primarily acquired through two methods: triangulation and ToF techniques. Triangulation can be passively implemented via stereovision, a process that calculates depth by capturing the same scene from multiple viewpoints. This mimics the way human vision works, where depth is determined by the disparity between images from different angles. Achieving this requires understanding camera geometry and necessitates calibration whenever the system configuration changes. An active approach involves structured light, which projects an infrared light pattern onto the scene and gauges disparity based on the variations in object depth. Additionally, ToF and Light Detection and Ranging (LiDAR) scanners measure the time it takes for light to reach an object's surface and return to the sensor. LiDAR employs mechanical components in its setup, while ToF accomplishes distance calculations using integrated circuits [21,31]. The majority of consumer RGB-D sensors utilize structured light or ToF techniques. These RGB-D sensors encounter noise and data distortions, which are addressed through specially crafted algorithms. However, ToF offers superior depth resolution compared to other methods, achieving accuracy at the scale of a few millimeters. Furthermore, structured light systems are unsuitable for outdoor environments due to the strong interference of sunlight with infrared cameras. Human activity recognition (HAR) tasks that do not demand extremely high depth resolution and precision can be effectively executed using both structured light sensors and ToF devices. These devices present an excellent compromise between affordability, performance, and ease of use, enabling the development of inconspicuous and privacy-preserving solutions.

3.1. *Tactile sensor-based systems that use both touch and depth information*

The human skin serves as the body's largest sensory system and houses a sophisticated network of mechanoreceptors responsible for detecting tactile sensations. It is well-documented that these mechanoreceptors become active when touched, transmitting signals to the central nervous system for interpretation and feedback.

Once the fundamental principles of tactile sensing were understood, these principles could be employed to enable robotic systems to engage with objects in their surroundings in a manner akin to humans. This means that machines can analyze objects by considering their physical attributes, including factors like pressure, dynamic strain, surface texture, and shear, for the purposes of recognition and interaction [40].

The activation of tactile systems relies on the development of effective strategies for perceiving tactile information, the technological characteristics of sensory devices, and the implementation of efficient methods for tactile learning [41]. Numerous tactile sensing systems have been suggested and created, integrating various principles that encompass piezo resistive, piezoelectric, capacitive, and optical technologies [42].

Tactile sensing is a crucial sensor mode for robots as it is central to their interactions with the surroundings. These sensors offer a varied and comprehensive array of data signals, which encompass intricate details obtained from the interactions between the robot and its surroundings as represented in Fig. 6. Importantly, this data extends beyond individual contacts and can be harnessed to derive a broad spectrum of insights about the objects within the environment and the robot's actions during these interactions [43].

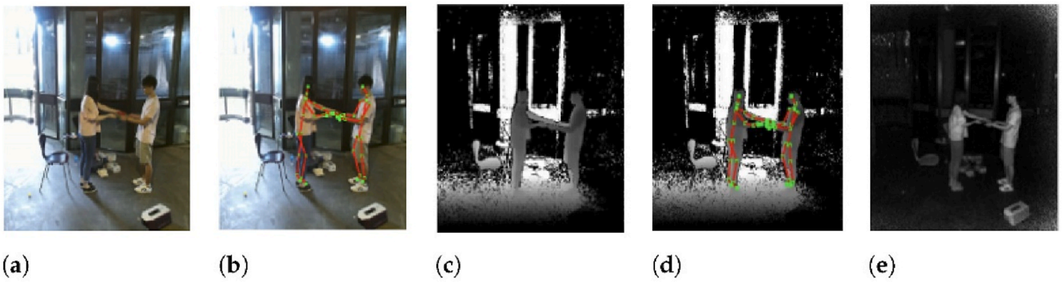

Fig. 5. Example data captured by an RGB-D sensor as taken from the NTU RGB-D dataset [39] in (a) RGB, (b) RGB + Skeleton Joints, (c) Depth, (d) Depth + Skeleton Joints, and (e) IR modalities [38].

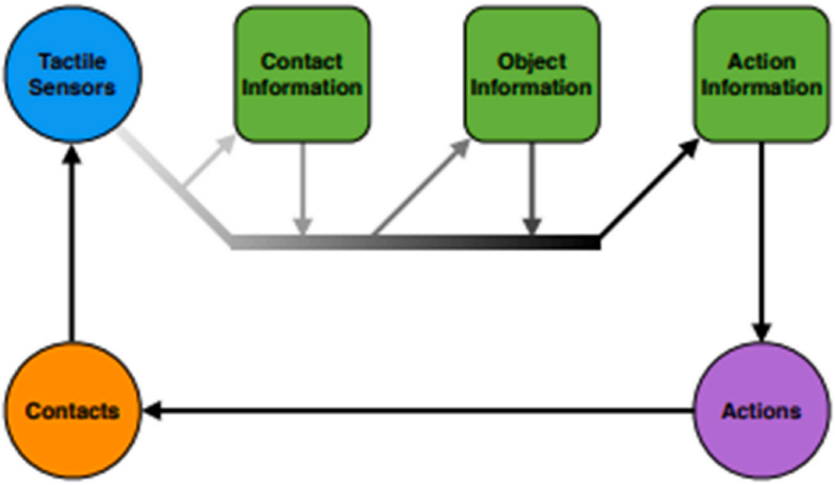

Fig. 6. Perception-action loop for tactile information extraction and control [43].

3.2. Case studies of systems that combine RGBD cameras and tactile sensors to aid navigation

As per the World Health Organization's report from 2012, there were approximately 285 million individuals with visual impairments, 39 million among them experiencing blindness. In this context, wearable systems known as "navigation assistance for visually impaired" (NAVI) have the potential to enhance or supplement human capabilities, thereby facilitating improved interaction with the surrounding environment [18]. RGB-D sensors have gained popularity because they offer a substantial volume of data, are cost-effective, and hold promise for miniaturization. These devices furnish distance data through active infrared sensors and capture intensity images using a passive sensor like a regular camera. A research study introduced a dependable NAVI system designed for safe navigation in unfamiliar environments [44]. The study employed an affordable RGB-D system that combines range data with color information to identify obstacle-free routes. The system initially identifies key structural elements in the scene using range data, which is then expanded upon using color information from images. This system underwent real-world testing and was assessed against a publicly available dataset, yielding impressive results for floor segmentation with a precision rate of 99 % and a recall rate of 95 %. Notably, the algorithm exhibited robustness in the face of lighting variations, glare, and reflections. Furthermore, the researchers made the dataset they used in their study available to serve as a benchmark for evaluating NAVI systems utilizing RGB-D data. In a separate research project available in the ACM Digital Library, a wearable device was proposed. This device was composed of an RGB-D sensor (specifically, the Asus Xtion Pro Live camera) and an ultrasonic sensor affixed to glasses with a slight tilt toward the ground. Both sensors simultaneously collected data, which was then processed by their algorithm. The implementation was carried out using the Python programming language, utilizing the OpenCV2 and Open Natural Interaction 2 (OpenNI2) libraries [45]. Each captured image was segmented into three zones - left, middle, and right, contingent upon the positioning of the visually impaired individual. The system employed auditory cues to provide the user with directional guidance for optimal obstacle avoidance. This research paper introduced a precise indoor navigation solution tailored for individuals with visual impairments, leveraging computer vision and sensor-based methodologies. The algorithm proposed for object detection effectively addresses issues related to detecting small and transparent obstructions in the path of visually impaired individuals. Audio feedback is employed to alert users with visual

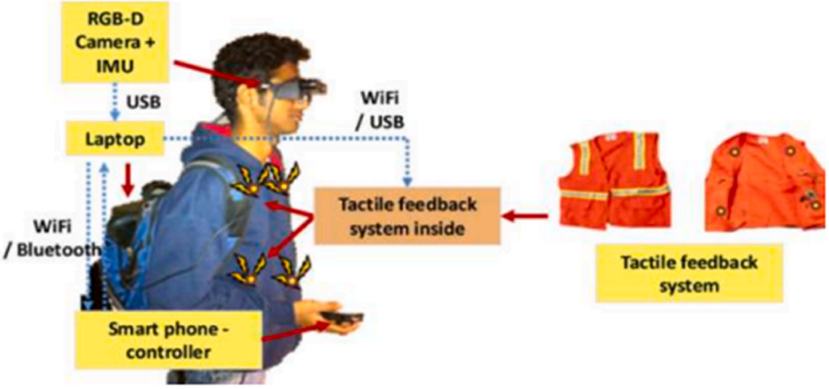

Fig. 7. Overview of the proposed system: A head-mounted camera + IMU sensor, a smartphone user interface, and tactile interface system [46].

impairments about the presence of obstacles via earphones. Furthermore, the system is portable, cost-effective, sufficiently rapid, and functions in real-time conditions. Extensive testing was conducted in real-world scenarios across various indoor environments, irrespective of the object's height.

In another study, an innovative wearable RGB-D camera-based indoor navigation system for individuals with visual impairments was introduced (as illustrated in Fig. 7) [46]. This system facilitates guiding visually impaired users from one location to another without the need for pre-existing maps or GPS data. The core components of such a system include precise real-time egomotion estimation, mapping, and obstacle-aware path planning. To achieve accurate 6-DOF egomotion estimation in real-time, the system relies on sparse visual features, dense point clouds, and ground plane data obtained from a head-mounted RGB-D camera. Additionally, the system constructs a 2D probabilistic occupancy grid map for efficient analysis of traversability. This map serves as the foundation for dynamic path planning and obstacle avoidance. Furthermore, the system can store and retrieve maps created during travel, continually expanding the navigable area. The system generates the shortest path between the starting point and the destination and continually updates this path as the user moves. Tactile feedback cues are generated and relayed to a haptic feedback vest to guide visually impaired users to the designated waypoints. The proposed wearable system prototype consists of multiple modules, including a head-mounted RGB-D camera, a standard laptop running navigation software, a smartphone user interface, and the haptic feedback vest. This system delivers real-time navigation performance, averaging 28.6 Hz on a laptop, enhancing the range of activities and improving orientation and mobility for visually impaired users in complex environments.

The newly proposed pose estimation algorithm, which utilizes sparse features and dense 3D point clouds with guidance from the ground plane, demonstrates superior performance compared to one of the leading pose estimation algorithms based on sparse features. In a walking scenario, the proposed algorithm achieved an absolute error of 2.661 m for a 49.0 m trajectory with a blindfolded subject guided by a sighted person, outperforming the alternative algorithm with an absolute error of 3.674 m.

The proposed pose estimation algorithm exhibits real-time capabilities when processing QVGA (320 x 240) image and depth streams. Performance evaluation, involving four blind subjects, yielded an impressive average error of 0.88 m over trajectories averaging 13.93 m in length. In the context of human navigation, where the subject's pose and surrounding environment may change, dynamic path planning in the presence of obstacles is crucial. To enhance the practicality of the shortest path algorithm and facilitate cue generation for blind users, the proposal involves generating waypoints based on the shortest path algorithm and the chamfer distance map of the occupancy grid. Pilot studies have shown that the system-generated waypoints closely approximate the trajectories of sighted individuals, with fewer intermediate locations compared to the shortest path generated by the D* Lite algorithm.

When used in conjunction with a white cane, mobility experiments involving the proposed system improved the average mobility performance of blindfolded subjects by 57.77 % compared to using the white cane alone [46].

3.3. Benefits and challenges of integrating these technologies

RGB-D sensors and tactile sensors play crucial roles in robotics and automation, enabling machines to perceive and interact with their environment. Integrating these two sensor technologies offers several benefits and challenges:

Benefits.

1. **Enhanced Perception**: Combining RGB-D and tactile sensors provides a more comprehensive perception of the environment. RGB-D sensors capture visual information, while tactile sensors offer information about touch and contact, improving object recognition and manipulation capabilities [47].
2. **Improved Object Manipulation**: Integration allows robots to handle objects more delicately and adapt their grip based on tactile feedback, reducing the risk of damaging fragile items or achieving a more secure grasp [48].
3. **Robustness**: RGB-D sensors can be affected by lighting conditions, while tactile sensors provide reliable information regardless of lighting, contributing to robustness in various environments [49].
4. **Safety**: Tactile sensors have the capability to identify unforeseen physical contact or impacts, allowing robots to swiftly respond to prevent accidents, thus enhancing their safety during interactions with humans [50].

Challenges.

1. **Data Fusion**: The integration of data from both RGB-D and tactile sensors demands advanced algorithms for fusing this information. The complexity and computational intensity stem from the necessity to align and draw meaningful conclusions based on data collected from a variety of sensors [51].
2. **Calibration and Synchronization**: Accurate calibration and synchronization of both sensor types pose a significant challenge. Any misalignment or synchronization issues can lead to inaccuracies in perception and manipulation [52].
3. **Cost**: The integration of these sensor technologies can result in elevated overall costs in robotic systems, potentially restricting their affordability for specific applications [53].
4. **Integration Complexity**: Incorporating multiple sensors into a robotic system necessitates meticulous hardware and software design, subsequently increasing the intricacy of development and maintenance [54].

In brief, the amalgamation of RGB-D and tactile sensor technologies presents significant advantages in terms of robot perception, manipulation, and safety. However, it also introduces challenges related to data fusion, calibration, cost, and complexity. Overcoming these challenges is crucial for unlocking the complete potential of integrated sensor systems in the realm of robotics and automation.

4. Navigation stick based systems

The white cane is a classic and extensively utilized navigation tool for individuals who are blind. It is cost-effective, dependable, effective, straightforward, and empowers users to directly sense the ground for tactile feedback. The white cane improves the sensory awareness of blind individuals, enabling them to employ techniques like obstacle detection, echolocation, and shore lining to gain a deeper understanding of their surroundings [19].

Obstacle Detection: Users can detect obstacles within a range of up to 1.2 m from the ground by sweeping the cane from side to side while walking. This aids in identifying steps, drop-offs, curbs, and other obstructions.

Tactile Techniques: Through dragging and tapping the white cane, users can discern characteristics of objects, such as their shape, hardness, and dimensions. This helps them create mental maps of their surroundings [55].

Echolocation: Blind individuals employ echolocation to identify objects with sound-reflecting surfaces, like walls and parked cars. This technique provides information about the object's location, dimensions, and density based on variations in sound.

Shore lining: It involves tracking along the edge of one's travel path, which is beneficial for finding specific items or locations, maintaining contact with landmarks, and avoiding open spaces [56].

However, white canes do have limitations. They cannot detect obstacles at trunk and head levels or overhanging objects, and physical contact with obstacles is required to detect them. To address these limitations, researchers are developing technology-based aids for navigation and orientation, falling into three categories:

Electronic Travel Aids (ETAs): These use sensors to collect sensory data for navigation, enhancing the basic functionality of the white cane by providing more comprehensive information about the environment [57].

Electronic Orientation Aids (EOAs): EOAs offer orientation assistance, aiding users in understanding their surroundings and navigating more effectively [57].

Position Locator Devices (PLDs): PLDs leverage technologies like GPS for localization and tracking, helping users better understand their precise location and providing additional data for navigation. These technology-based aids are designed to complement and improve upon the traditional white cane, offering blind individuals enhanced tactile information about the ground, potential hazards, and their immediate surroundings [58].

4.1. Evolution of navigation sticks into electronic devices with additional sensors and feedback mechanisms

Navigation aids for visually impaired individuals have evolved significantly, transitioning from basic tools like white canes and tactile paving to advanced electronic devices equipped with sensors and feedback mechanisms. Early solutions relied on auditory cues and simple obstacle detection, while recent advancements have integrated sophisticated technologies. Initially, ultrasonic and infrared sensors were incorporated, providing feedback through sound and tactile means. Electronic travel aids (ETAs) emerged at a later stage, employing ultrasonic or infrared technology to either create a sound field or detect reflections from objects, thereby enhancing navigation capabilities. The widespread proliferation of smartphones has spurred the development of navigation applications that leverage GPS and a range of sensors to furnish location-based information [57]. Wearable devices have also gained popularity, employing a combination of sensors to provide precise feedback through methods like vibrations, auditory cues, or haptic sensations. Furthermore, the integration of artificial intelligence and machine learning has expanded the functionalities of navigation aids, enabling features such as object recognition, text reading, and context-aware information delivery. Augmented reality (AR) glasses and sensory substitution devices are emerging as well, offering a more immersive and informative navigation experience for individuals with visual impairments [59]. The progression of navigation tools for the visually impaired underscores a shift from basic mechanical aids to advanced electronic devices that harness sensors, artificial intelligence, and diverse feedback mechanisms to enhance mobility and promote independence. Ongoing research and technological advancements continue to drive progress in this field, aiming to improve the lives of individuals with visual impairments. These innovations have not only made navigation more accessible but have also paved the way for a future where visually impaired individuals can interact with and understand their environments in increasingly profound and independent ways, ultimately promoting greater inclusion and participation in society.

These systems employ diverse core technologies, each with its own advantages and limitations. The following classification categorizes electronic travel aids considered in this review based on their underlying technology.

4.1.1. Visual imagery systems

Vision-based navigation employs computer vision algorithms and optical sensors, such as cameras, to extract visual features from the environment. These systems detect obstacles using these features and provide directions to ensure safe navigation [60]. Various visual imaging devices/technologies have been explored, including stereo cameras, IP camera networks, and RGB-D cameras. Vision-based navigation, or optical navigation, leverages computer vision algorithms and optical sensors, such as cameras, to extract visual features from the environment. These systems aim to detect obstacles using these visual features and provide directions for safe navigation. Different technologies and devices, including stereo cameras and IP camera networks, have been employed in these systems.

4.1.1.1. Stereo camera. One approach utilizes stereo cameras, as exemplified by the Tyflos system. Tyflos employs two vision cameras to capture images of the 3D environment, which are then converted into verbal descriptions to communicate with the user.

A different system, designed for outdoor use, combines a binocular camera, inertial measurement unit (IMU), and earphones into a bike helmet. When an object is found in a particular location, it is converted into a sound source and transmitted to the user via earphones using a technique called binaural rendering.

4.1.1.2. IP camera network. Some navigation systems use IP cameras installed in indoor environments (as presented in Fig. 8. Kuriakose et al. [21] proposed a system with cameras placed on room ceilings. The system takes pictures with the cameras and uses computer vision algorithms to process them remotely. Users can interact with the system through a mobile app on their smartphones to reach their destinations. However, the main challenge with this approach is the cost of installing many IP cameras in indoor spaces.

4.1.1.3. Visual simultaneous localization and mapping (VSLAM). Visual simultaneous localization and mapping (VSLAM) is a technology that uses images from a camera to estimate the device's location and orientation. It is gaining popularity in navigation system design because it can operate effectively with just a single camera sensor. One example of a VSLAM-based navigation system is described by Bai et al. [61]. This system addresses the challenges of indoor localization and path planning for the visually impaired by using VSLAM to create virtual navigation paths and dynamically selecting sub goals to avoid obstacles. Another example is a system described by Bai et al. [62]. This system integrates a helmet with stereo cameras, an Android smartphone, a web application, and a cloud computing platform as presented in Fig. 9. It shows promise, but evaluations indicate room for improvement in object detection and recognition accuracy. Overall, VSLAM technology is a promising approach for navigation system development due to its ability to operate with a single camera sensor and potential to enhance navigation assistance for the visually impaired.

4.1.1.4. RGB-D cameras. The Intelligent Situational Awareness and Navigation Aid (ISANA), as presented in Ref. [63], represents an electronic prototype known as SmartCane. This innovative system leverages the Google Tango [64] tablet as its mobile computing platform. ISANA employs an onboard RGB-D camera to facilitate an efficient obstacle detection and avoidance mechanism based on the Kalman filter algorithm, specifically the TSM-KF algorithm.

Additionally, ISANA incorporates a multimodal human-machine interface (HMI) that encompasses speech-audio interaction and robust haptic interaction. This interface is seamlessly integrated into the electronic SmartCane, providing users with a comprehensive means of interacting with the system.

Xiao et al. [65] has introduced a cyber-physical system that employs an RGB-D sensor for the purpose of object detection and scene comprehension. This system offers users the flexibility of utilizing both auditory and vibrotactile feedback modes. It should be noted that the system relies on internet access for its computational functions; however, it is capable of functioning effectively in both indoor and outdoor environments.

The system proposed by Ref. [46] also agrees that RGB-D camera plays a central role in enabling indoor navigation for individuals with visual impairments in this system. The comprehensive system setup includes essential components such as a standard laptop running specialized navigation software, a user interface accessible via smartphone, and a haptic feedback vest.

The system is equipped with the capability to determine both the user's initial location and their desired destination through voice

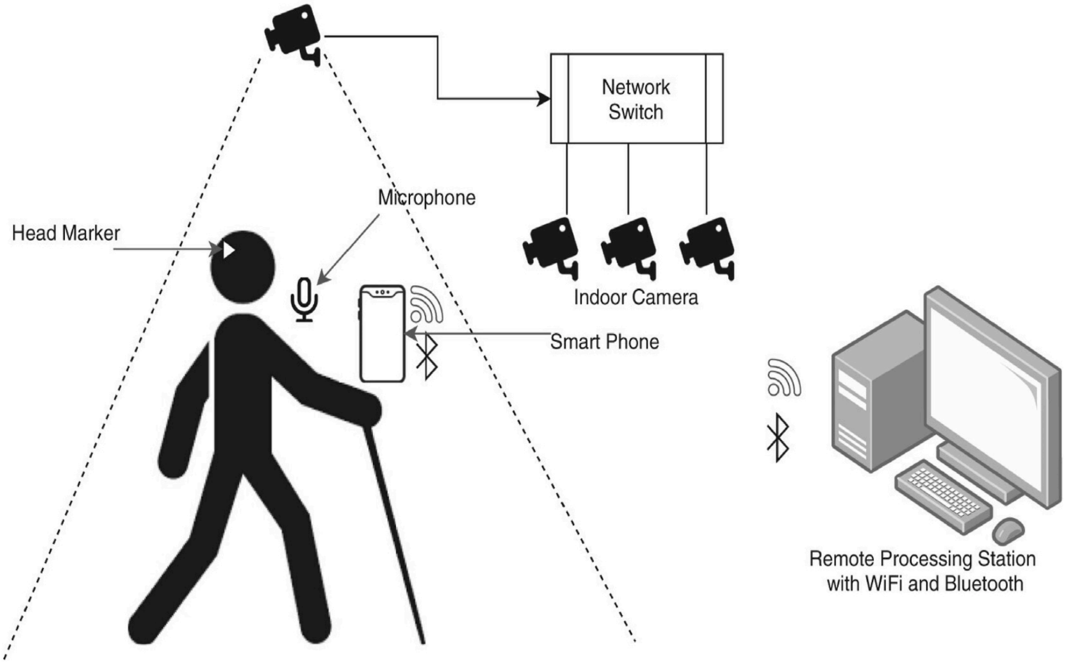

Fig. 8. *Architecture of IP-camera based system* [21].

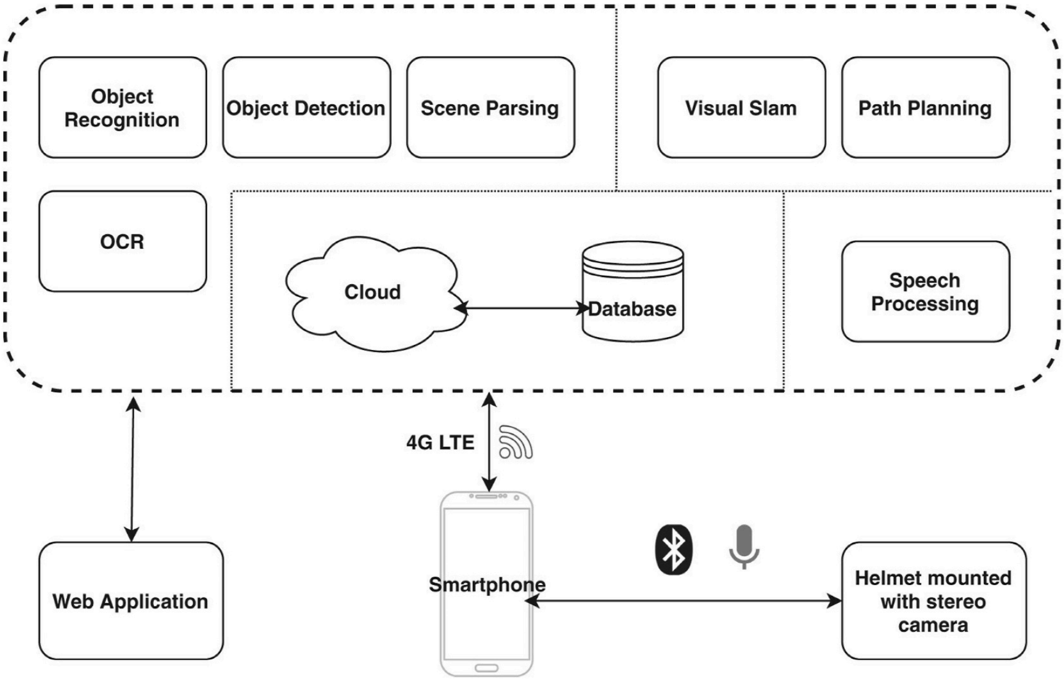

Fig. 9. Cloud and vision-based navigation system [61].

instructions. Furthermore, it transcends the conventional approach of relying solely on pre-existing maps. Instead, it has the capacity to dynamically generate maps in real-time as the user travels, enhancing the navigation experience.

4.1.1.5. Microsoft Kinect. The Microsoft Kinect, categorized as an RGB-D camera, has garnered substantial interest among researchers for its potential application in designing navigation systems for the visually impaired [6]. It is worth noting the recent developments in Kinect-based navigation systems. The Kinect, a motion sensing input device from Microsoft, can be used to detect objects, making it a valuable tool for navigation assistance. It also has a wide range of features and works well in low-light environments.

One system proposed by Ref. [66] utilized an algorithm that leverages input data from the Microsoft Xbox Kinect 360. This approach enables the creation of a 3D map of indoor spaces and facilitates the detection of obstacle depths, including humans. Similarly [67], introduced an obstacle avoidance system designed for individuals with visual impairments, employing a Kinect depth camera. In this system, depth images captured by the Kinect camera underwent processing using a windowing-based mean method, enabling the detection of various obstacles. Upon recognizing an obstacle, the system provides voice feedback to the user via earphones.

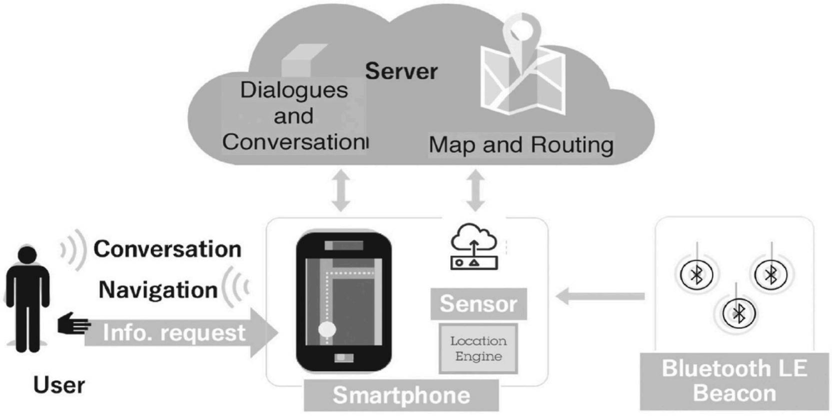

Fig. 10. An overview of Navcog3 system [73,74].

4.1.2. Non-Visual Data Systems

Non-visual data systems rely on alternative sensory data sources, such as sound or haptic feedback, to aid navigation [68].

4.1.2.1. BLE beacons. Numerous instances of literature have documented the use of Bluetooth beacons in various systems [69,70]. It's noteworthy to delve into a few of these systems in more detail. Nair et al. [71] introduced a hybrid approach for positioning and navigation that combines Bluetooth Low Energy (BLE) beacons and Google Tango, leveraging the strengths of both technologies while mitigating their respective weaknesses. Another system, the Guide Beacon [72], employs a smartphone to interact with Bluetooth-based beacons strategically placed in different indoor locations to provide users with navigation guidance. An overview of Bluetooth based navigation system 'Navcog3 system' is presented in Fig. 10.

4.1.2.2. IoT based. The Internet of Things (IoT) represents the seamless communication between diverse systems capable of exchanging data over a network autonomously, eliminating the need for human or machine interventions. Navigation systems built upon the IoT concept have become a recurring topic in the literature, gaining prominence after the widespread adoption of IoT for various applications [75,76].

4.1.2.3. Ultrasonic sensors. Navigation systems that rely on ultrasonic sensors have emerged as a popular alternative in design, especially following visual (camera) based solutions. These systems, which utilize technology like Raspberry Pi or Arduino boards [77], operate in tandem with ultrasonic proximity sensors and GPS modules. As an example of a significant advancement, consider the development of a remarkable ultrasonic smart cane. This device features customizable sensitivity settings and integrates both an ultrasonic proximity sensor and a GPS module [78].

4.1.2.4. 4.1.2.4. IR sensors. Within the field of navigation system development, infrared (IR) sensors are becoming increasingly popular due to their benefits, including lower power consumption and cost-effectiveness when compared to ultrasonic sensors. Researchers have delved into the possibilities offered by IR sensors, resulting in notable innovations such as a smart assistive cane that utilizes IR technology, as detailed in Ref. [70]. Furthermore, IR sensors have been seamlessly integrated with other technologies such as Google Tango and Unity, expanding their potential to enhance navigation systems even further [79].

4.1.3. Map-based systems

Individuals with visual impairments commonly employ tactile aids like raised point maps, small-scale models, or magnetic boards after receiving orientation and mobility (O&M) training. These multimodal maps serve the purpose of assisting visually impaired individuals in navigating and acquiring spatial knowledge when visual information is lacking. Nevertheless, these tools come with limitations, including the inability to update map content. To address these constraints, interactive maps designed for accessibility have been developed. In an attempt to offer a solution, in a study researchers adopted a participatory design approach to craft an augmented reality map tailored for use in O&M instruction [72]. This innovative prototype integrates features such as projection, audio feedback, and tactile elements, empowering individuals with visual impairments to effectively explore and construct maps [80].

4.1.4. Systems with 3D sound

The Sound of Vision system, is a wearable sensory substitution device designed to aid visually impaired individuals in navigating their surroundings. It achieves this by generating and conveying auditory and tactile representations of the environment to the user. While offering both audio and haptic feedback, it's worth noting that the system requires enhancements in terms of usability and accuracy.

4.1.5. Smartphone-based solutions

Navigation solutions based on smartphones provide users with the advantages of portability and convenience.

4.2. Modern electronic navigation sticks with built-in obstacle detection and navigation assistance features

In the modern navigation tools, smart cane is an electronic assistive device that incorporates image capturing and recognition capabilities through the use of Artificial Intelligence technology. It comprises the following components.

4.2.1. Raspberry Pi

The Raspberry Pi 3 is a microcontroller board within the Pi series, serving as a single-board computer that supports the LINUX operating system. It offers notable features like wireless LAN and Bluetooth, rendering it suitable for advanced applications. This versatile board provides ports for connecting touch LCD displays and cameras. It operates on a 5V voltage and can be powered via USB, batteries, or an AC-DC adapter. One significant application of the Raspberry Pi 3 in this context is its integration with the Smart Cane app. This app incorporates an AI-based algorithm for image tagging based on context, content, and recognized actions within the images. The process of image tagging with the Smart Cane app entails sending authorized web requests to the subscription endpoint and receiving data in JSON format.

4.2.2. Ultrasonic sensors

The smart stick incorporates four HC-SRC04 ultrasonic sensors. One of these sensors is specialized in detecting obstacles in front of the user, while the remaining three are responsible for identifying obstacles around the stick's sides. These sensors' function based on the principle of sound wave detection, much like the sonar or radar systems. They emit high-frequency sound waves and measure the time it takes for the echo signals to return, allowing them to determine the distance to objects. Each HC-SRC04 ultrasonic sensor comes with four pins: ground, Vcc (providing voltage), trigger (initiating the pulse), and echo (receiving the reflected signal). These sensors possess a useful detection range that extends from 2 to 400 cm.

4.2.3. Raspberry Pi camera module

The Raspberry Pi Camera Module features an 8-megapixel camera capable of recording video in 1080p30 and 720p60 modes, delivering high-resolution images at 3280×2464 pixels. It serves the purpose of capturing images, with a primary focus on object identification. Located at the front end of the device, it detects and records images of objects, which are then transmitted to the microcontroller using either Bluetooth or a wireless network connection. Subsequently, the microcontroller initiates authorized web requests to a subscription endpoint, where object identification is accomplished through image tagging within the application.

4.2.4. Voice playback module

This device communicates information regarding detected obstacles to the user using a microphone or a set of headphones. It employs the WTV-SR IC recognition module for voice playback. Furthermore, it possesses the ability to both record and replay voices, offering a range of control options. Notably, it is recognized for its cost-effectiveness and effectiveness in fulfilling this particular function.

4.2.5. GPS/GSM module

The GPS module is furnished with a memory chip that enables users to save different locations, which can be set using voice commands. This module aids users in finding their chosen destinations by utilizing the saved data. Additionally, the GSM modem plays a vital role in transmitting emergency notifications to predefined contact numbers when the user initiates an emergency call. This ensures rapid assistance can be requested when necessary.

4.3. Evaluation of the effectiveness of navigation stick-based systems

A thorough assessment of navigation satellite systems (NSS) is carried out using a comprehensive approach, concentrating on three primary areas of evaluation: functional performance, the efficacy of the regulatory framework (RS), and economic efficiency. Various methodologies are applied to each of these areas.

1. *Evaluation of Functional Performance:* This aspect is appraised through a performance-oriented methodology. It involves scrutinizing how well the navigation satellite system executes its intended functions and responsibilities. This assessment typically takes into account factors like precision, coverage, signal robustness, and reliability to gauge the system's effectiveness in supporting navigation and positioning tasks.
2. *Assessment of Regulatory System (RS) Effectiveness:* The appraisal of the regulatory system governing the navigation satellite system relies on a well-established standardized vocabulary and a logical information system model. This evaluation entails an examination of how effectively the regulatory framework and policies facilitate the operation and management of the NSS. It may also encompass considerations related to spectrum management, licensing, and compliance.
3 *Examination of Cost Efficiency:* The cost efficiency of the navigation satellite system is gauged using tailored econometric models and an economic description system specifically tailored for navigation systems (NSs). This evaluation centers on the economic aspects of the NSS, including the expenses associated with its development, deployment, maintenance, and operation. Its objective is to determine whether the NSS offers value for money and if cost-effective strategies are in place.

In essence, this comprehensive evaluation approach delves into the functional, regulatory, and economic facets of navigation satellite systems, providing an all-encompassing appraisal of their effectiveness and efficiency [81].

5. Systems for obstacle avoidance and navigable path generation

The human eyes serve as the primary sensory organ, providing crucial visual information for various tasks in our environment. However, this reality poses significant challenges for individuals with visual impairments, potentially leading to their isolation from society. It is common for good sighted individuals, to offer help to the visually impaired. However, rushing to assist without inquiry can inadvertently make visually impaired individuals feel disempowered, compromising their independence and, consequently, their emotional stability. Therefore, it is imperative to empower visually impaired individuals to support themselves, fostering greater autonomy and social integration. Unfortunately, limited access to information remains a barrier to their independence. One more formidable difficulty faced by those with complete vision loss, is the navigation of physical spaces while avoiding obstacles to ensure their safety. One potential solution to this challenge is the development of an artificial vision system capable of detecting obstacles and providing warnings to the visually impaired individuals, aiding them in obstacle avoidance. This involves employing a system that can identify obstacles by detecting objects, with the primary purpose of providing alerts [82].

5.1. *Systems that use various sensors (ultrasonic, LiDAR, etc.) to detect obstacles and provide feedback*

5.1.1. *Sensing system of environmental perception technologies for driverless vehicle*

Self-driving cars rely on sophisticated smart driving systems to navigate safely. These systems use a variety of sensors to perceive the environment around the car, including cameras, LIDAR, and ultrasonic sensors.

5.1.1.1. Vision sensing. Vision sensing uses cameras to capture images of the surroundings. These images are then processed to identify objects and features, such as roads, lanes, other vehicles, and pedestrians.

5.1.1.2. Laser sensing (lidar). Lidar uses lasers to measure the distance to objects in the surroundings. This information is used to create a 3D map of the environment, which can be used to help the car navigate and avoid obstacles.

5.1.1.3. Ultrasonic sensing. Ultrasonic sensors emit high-frequency sound waves and measure the time it takes for the waves to echo back from objects. This information is used to detect obstacles that are close to the car. Each of these sensors has its own advantages and disadvantages.

Vision sensing is relatively inexpensive but can be affected by lighting conditions. Lidar is more expensive but is less affected by lighting conditions. Ultrasonic sensors are also relatively inexpensive but have a limited range [83].

5.1.2. *Embedded sensors, communication technologies, computing Platforms and machine Learning for UAVs*

Unmanned aerial vehicles, or drones, have become increasingly popular in recent years due to their versatility and affordability. Drones are equipped with a variety of sensors, hardware platforms, and software technologies that enable them to perform a wide range of tasks.

5.1.2.1. Sensors. Drones typically use vision-based sensors, such as RGB-D cameras, to capture images and depth information. Drones may also use thermal cameras to detect heat signatures, lidar sensors to create 3D maps, mmWave radar sensors to detect objects in adverse weather conditions, and ultrasonic sensors for altitude control and close-range obstacle detection. Inertial measurement units (IMUs) are also used to measure the drone’s orientation and motion.

5.1.2.2. Computing modules. Drones are equipped with onboard computers or processors that handle data processing, sensor fusion, and decision-making tasks. These computers are often designed to be lightweight and energy-efficient.

5.1.2.3. Communication technologies. Drones rely on a variety of communication technologies to exchange data with ground control stations and other devices. Common communication technologies include Wi-Fi for short-range communications, LoRa for long-distance, low-power data transmission, and LTE-M for cellular connectivity.

5.1.2.4. Machine learning algorithms. Drones often incorporate machine learning algorithms for tasks such as object detection, tracking, path planning, and autonomous navigation. These algorithms enable drones to make real-time decisions based on sensor data. The specific components used in a drone depend on its mission and requirements. As sensor technology, computing power, and communication capabilities continue to advance, drones are becoming increasingly valuable across a variety of industries [84].

6. Algorithms for various aspects of navigation

The mobility and spatial awareness of visually impaired people are supported through a blend of hardware and software solutions, incorporating diverse algorithms [85]. Researchers led by Dunai [86] introduced a navigation system that employed CMOS time-of-flight sensors and RFID components. Nevertheless, these systems were often costly, and the wired nature of CMOS time-of-flight sensor-based navigation made it less user-friendly. Additionally, RFID-based systems carried the risk of data loss during data retrieval. In a different approach, Bai et al. [61] put forth a cloud and vision-based navigation system, which incorporated features like speech recognition, simultaneous localization, mapping, and path planning through deep learning. This system could interact via voice commands. Sivan and Darsan [87] focused on ambient assisted living and employed mobile technology along with ultrasound systems. They collected, organized, and detected data, converting it into voice for transfer to mobile phones. Setiadi et al. [88] used neural networks to assist the visually impaired. They employed two cameras for pedestrian path detection and Light Detection and Ranging (LiDAR) for environmental sensing. Their system captured images and provided audio feedback. Ismail et al. [89] proposed an effective solution involving speech recognition for patients, elderly individuals, and those with disabilities. They utilized low-cost, easily controlled IoT devices and enhanced their system using the Support Vector Machine (SVM) and Dynamic Time Warping (DTW) algorithm.

Yang et al. [90] developed wearable smart glasses called “inteor” featuring an RGB-D sensor and bone-conducting headphones. They aimed to enhance terrain awareness in real-time. Their approach employed a Fully Convolutional Network (FCN) for pixel-wise semantic segmentation, allowing for real-time image assembly. However, the system’s coverage range is limited and requires further testing. Kumar et al. [91] proposed a cost-effective, user-friendly 2-module navigation system for the visually impaired. The first module used smartphone technology and an ultrasonic accessory unit for intelligent navigation, including text-to-speech and

GPS-based audio guidance. The second module, named “Blind Perceptron,” employed a neural network for image preprocessing, summarization, and classification. It achieved 95 % accuracy for obstacle identification but had limitations in face detection for moving faces. Niu et al. [92] developed an indoor navigation system using the YOLO v2 algorithm, which detected doors, door handles, and hands. The system included a portable camera, GPU, and Bluetooth headset. Their model utilized a deep neural network (DNN) with 22 layers and achieved fast object detection, although it had issues with hand image processing and was limited to door-opening tasks. Lin et al. [93] employed the YOLO algorithm for a smartphone-based navigation system. The system featured online and offline modes, with varying object recognition modules (Fast R–CNN and YOLO). The experiment achieved a 60 % recognition rate, but the accuracy seemed relatively low, especially for partially impaired individuals. Bhandari et al. [94] conducted an analysis of deep learning systems applied to assistive navigation tools for individuals with visual impairments, and they made a comparative assessment of the current deep learning systems used in this context. Fig. 11 illustrates the comprehensive procedure for object detection. The key elements include data, feature extraction, classifiers, object detection and recognition, and the output (feedback) phase. Users activate the device using either a touch or sound interface and direct the camera to capture images of objects in front of them. For a detailed insight into the overall architecture and design of the object detection and object recognition system, please refer to Table 1.

7. User experience and human-centered design principles in navigation system development

User experience (UX) and human-centered design (HCD) principles are paramount in navigation system development. Here are insights from research papers emphasizing their importance:

Nakic et al. [98] discussed User-Centered Design as a method for engaging users in the design process, ensuring their perspectives guide system development. The authors recognize the utilization of User-Centered Design (UCD) techniques in the swift creation of prototypes and product delivery, as well as in the development of geo-visualization applications. In this context, UCD methods are employed to align user tasks with data representations and interactions. This approach can also be extended to navigation systems. The paper emphasizes the importance of usability in crafting data visualizations, indicating its significance in the development of navigation systems. Usability, as defined by ISO, pertains to how effectively, efficiently, and satisfactorily a system, product, or service can be employed by specified users to attain predefined objectives within a specified usage context. Furthermore, the paper underscores UCD as an iterative process encompassing design, implementation, and evaluation. This suggests the iterative refinement of a design to improve user experience is crucial. Evaluation methods can include end users (usability testing) or HCI experts, thus incorporating user feedback directly in the process could enhance a navigation system’s user experience.

Ngoc et al. [99] presents a case study review emphasizing Human-Centered Design in the context of industry 4.0, underscoring its relevance in modern technology development. Considering user experience and human-centered design principles in developing navigation systems is crucial for several reasons. Firstly, traditional technology-oriented designs which force users to adapt to the interface can result in lower system performance and higher error rates. Hence, placing humans at the center of interface design (human-machine interface or HMI) allows for better understanding and operation of the technology in a straightforward and user-friendly manner. Additionally, designing for HMI requires several disciplines, including cognitive psychology, industrial design, information processing graphics, human factors, and ergonomics, ensuring a well-rounded and user-friendly design that considers all

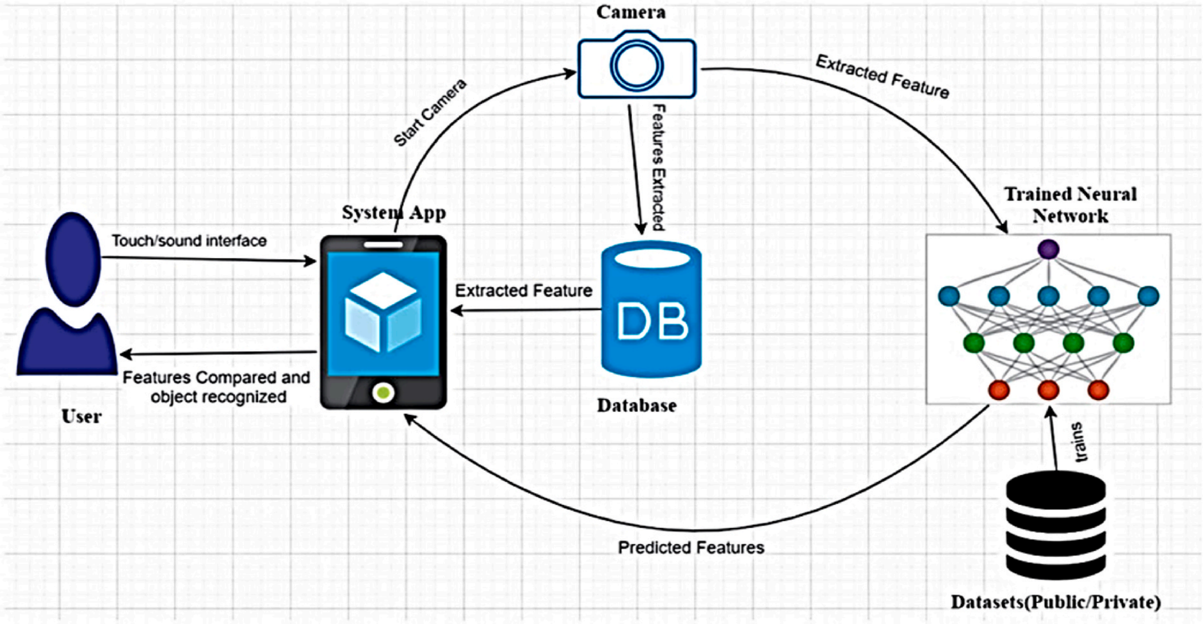

Fig. 11. Overall architecture and design of the object detection and object recognition system [94].

Table 1
Deep learning architecture used for the object detection and recognition process.

Authors	Method used	Objectives	References
Ismail et al.	Support Vector Machine (SVM) and Dynamic Time Warping (DTW) algorithm.	Speech recognition for patients	[89]
Yang et al.	SegNet	Curve negotiation and traversability awareness along the pathway of VI people	[90]
Kumar et al.	Artificial neural network	Intelligent face recognition and navigation system	[91]
Niu et al.	CNN	Door knob detection and real time feedback	[92]
Lin et al.	Faster RCNN and YOLO algorithm	Solving the navigation problem for VI people and achieving obstacle avoidance	[93]
Poggi et al.	LeNet architecture	Obstacle avoidance and proper guidance for the visually impaired people	[95]
Berriel et al.	CNN	Crosswalk detection for VI pedestrian	[96]
Trabelsi et al.	Complex-valued neural network	Indoor object detection	[97]

aspects of the human experience. Moreover, an important metric to understand the effectiveness of the HMI design is its usability. This includes factors such as usefulness, efficiency, effectiveness, and the learning curve of the user interface. Finally, the concept of user multidimensional experience, a core idea of user-centered design (UCD), is garnering increasing attention. This perspective tallies users' emotional and psychological responses, further reinforcing the need for user centrism in the design process. UCD focuses on enhancing user acceptance and acceptability, thereby improving their overall experience with the product or service.

Velsen et al. [100] explores the limitations of User- and Human-Centered Design, providing critical insights into areas that need improvement while emphasizing the continued significance of these principles. The paper concerns the limitations of using Human-Centered Design (HCD) in developing eHealth services and doesn't specifically talk about the importance of incorporating user experiences and HCD into the development of navigation systems. However, the authors do discuss a couple of projects where they included end-users in the design process, such as designing tools for people with dementia and a smart wearable for children with breathing issues. They emphasize that including end-users in the design process made the final products more acceptable, highlighting a general importance of considering user experience in the design process, which could be applicable to navigation system development. It's also mentioned that involving a diverse group of stakeholders, including experts by experience and professionals, is beneficial but can lead to challenges in data interpretation and participant selection.

7.1. Case studies highlighting successful user-centered design approaches in navigation systems

Some of the case studies pertaining to UCD approaches are summarized below:

Roth et al. [101] discusses user-centered design (UCD) in the context of interactive mapping and GIScience, with a specific case study on the GeoVISTA CrimeViz system. While not directly about navigation systems, the insights from this case study might be applicable to them as well. GeoVISTA CrimeViz is a web-based mapping tool designed for interactive visual data analysis of criminal incidents over both space and time. The User-Centered Design (UCD) approach played a pivotal role in enhancing the concept and interface of GeoVISTA CrimeViz through an iterative process. This involved a sequence of cycles involving users, utility, and usability, including.

1. Collecting input and feedback from the intended users regarding their needs and design preferences. This can be done through surveys, interviews, and usability testing.
2. Incorporating these insights into the conceptualization and functional requirements of the interface. This step involves designing the system to be easy to use and navigate, and to provide users with the information and feedback they need in a clear and concise way.
3. Developing new iterations and prototypes of the interface for further assessment and refinement. This allows the designers to get feedback from users early and often, and to make changes to the system based on that feedback.

The Wayfinding app is a good example of a navigation system that has been designed using a UCD approach. The app was developed in close collaboration with visually impaired users from the beginning, and it has been extensively tested by visually impaired users to ensure that it is easy to use and navigate [102].

The NavVis Mobility Kit and the KNFB Reader are two other examples of navigation systems that have been designed using a UCD approach. Both systems have been shown to be effective in helping visually impaired individuals to navigate more independently and confidently.

Here are some general principles of UCD that can be applied to the development of navigation systems for visually impaired individuals.

- Early user involvement: Involve visually impaired users in the design process from the beginning.
- Iterative design: Design and refine the system through a series of iterative cycles.
- Accessibility testing: Test the system extensively with visually impaired users to ensure that it is easy to use and navigate.

- Provide clear and concise feedback: The system should provide users with clear and concise feedback about their surroundings.
- Make the system customizable: Allow users to customize the system to meet their individual needs.

By following these principles, designers can create navigation systems that are both effective and accessible to visually impaired individuals.

8. Conclusions

An in-depth literature review revealed current state and challenges in the navigation systems for visually impaired people. Navigation systems play a role, in enhancing the independence and mobility of people with impairments. These systems provide real time information ensuring safety, efficiency and accessibility. Ultimately, they promote inclusivity and enhance the quality of life for individuals with visual impairments. Navigation systems can be categorized into two types; wearable and non-wearable options. Wearable systems like glasses and head mounted displays offer the advantage of being hands free and portable. However, they may be bulky and uncomfortable when used for periods. On the other hand, non-wearable systems such as smartphones and portable GPS devices are more discreet and lightweight but demands users to carry them actively and interact with them. An exciting technology for navigation systems involves combining RGB-D cameras with sensors. This combination improves perception, object manipulation, robustness and safety. However, there are challenges associated with this approach such as data fusion, calibration, cost considerations and complexity. The field of navigation aids for impaired individuals has seen advancements in recent years. Traditional aids like canes and tactile paving have been complemented by electronic devices equipped with sensors and feedback mechanisms that offer greater independence and mobility.

Different types of technologies, such, as systems for imagery, non-visual data, maps and 3D sound have been combined in these navigation aids. Each technology has its strengths and weaknesses. For example, visual imagery systems provide information about the surroundings but may not be dependable, in low light or difficult situations. Data systems that don't rely on visuals, like LiDAR sensors can work in any lighting situation. However, they may not offer the level of detail as visual imagery systems. Smartphone based solutions have become popular by utilizing the capabilities of smartphones and different sensors to provide location-based information and guidance. To sum it up the field of navigation for impaired individuals is constantly evolving with advancements in technology and solutions. The integration of both hardware and software solutions along with the use of algorithms plays a role in improving mobility and spatial awareness for those with visual impairments. Recent innovations aim to make these systems more accessible and user friendly while addressing challenges, like costs and limited user-friendliness. These innovations prioritize effectiveness and user friendliness by following user centered design principles specifically tailored for impaired individuals. All the challenges mentioned in the current navigation systems can be explored for future research work to make the life easier and better for visually impaired people.

Declaration

The authors declare that AI-based tool has been used for language and grammatical corrections.

CRediT authorship contribution statement

Mustufa Haider Abidi: Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Arshad Noor Siddiquee:** Writing – review & editing, Writing – original draft, Resources, Conceptualization. **Hisham Alkhalefah:** Writing – review & editing, Supervision, Conceptualization. **Vishwaraj Srivastava:** Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:MUSTUFA HAIDER ABIDI reports financial support was provided by King Salman Center for Disability Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors extend their appreciation to the King Salman center For Disability Research for funding this work through Research Group no KSRG-2023-451.

References

[1] G. Kbar, et al., Utilizing sensors networks to develop a smart and context-aware solution for people with disabilities at the workplace (design and implementation), Int. J. Distributed Sens. Netw. 12 (9) (2016) 1550147716658606, https://doi.org/10.1177/1550147716658606.

[2] N. Tyagi, et al., Assistive navigation system for visually impaired and blind people: a review, in: 2021 International Conference on Artificial Intelligence and Machine Vision (AIMV), 2021, https://doi.org/10.1109/AIMV53313.2021.9670951. Gandhinagar, India.

[3] J. Akilandeswari, et al., Design and development of an indoor navigation system using denoising autoencoder based convolutional neural network for visually impaired people, Multimed. Tool. Appl. 81 (3) (2022) 3483–3514, https://doi.org/10.1007/s11042-021-11287-z.

[4] M.D. Messaoudi, B.J. Menelas, H. McHeick, Review of navigation assistive tools and technologies for the visually impaired, Sensors 22 (20) (2022).

[5] F.E.-z. El-taher, et al., A systematic review of urban navigation systems for visually impaired people, Sensors 21 (9) (2021) 3103.

[6] A.M.B. Dourado, E.C. Pedrino, Towards interactive customization of multimodal embedded navigation systems for visually impaired people, Int. J. Hum. Comput. Stud. 176 (2023) 103046, https://doi.org/10.1016/j.ijhcs.2023.103046.

[7] S. Real, A. Araujo, Navigation systems for the blind and visually impaired: Past work, challenges, and open Problems, Sensors 19 (15) (2019), https://doi.org/10.3390/s19153404.

[8] V. Isazade, Advancement in navigation technologies and their potential for the visually impaired: a comprehensive review, Spatial Information Research 31 (5) (2023) 547–558, https://doi.org/10.1007/s41324-023-00522-4.

[9] F. Scalvini, et al., Outdoor navigation assistive system based on robust and real-time visual–auditory substitution approach, Sensors 24 (1) (2024) 166.

[10] N. Fernando, D.A. McMeekin, I. Murray, Route planning methods in indoor navigation tools for vision impaired persons: a systematic review, Disabil. Rehabil. Assist. Technol. 18 (6) (2023) 763–782, https://doi.org/10.1080/17483107.2021.1922522.

[11] A.S. Martinez-Sala, et al., Design, implementation and evaluation of an indoor navigation system for visually impaired people, Sensors 15 (12) (2015) 32168–32187, https://doi.org/10.3390/s151229912.

[12] G. Kbar, et al., A University-based smart and context aware solution for people with disabilities (USCAS-PWD), Computers 5 (3) (2016) 18.

[13] A. Bhowmick, S.M. Hazarika, An insight into assistive technology for the visually impaired and blind people: state-of-the-art and future trends, Journal on Multimodal User Interfaces 11 (2) (2017) 149–172, https://doi.org/10.1007/s12193-016-0235-6.

[14] A.T. Parker, et al., Wayfinding tools for people with visual impairments in real-world settings: a literature review of recent studies, Frontiers in Education 6 (2021), https://doi.org/10.3389/feduc.2021.723816.

[15] H.S. Kang, M. Exworthy, Wearing the future-wearables to empower users to take greater responsibility for their Health and care: scoping review, JMIR Mhealth Uhealth 10 (7) (2022) e35684.

[16] R. Velázquez, et al., An outdoor navigation system for blind pedestrians using GPS and tactile-foot feedback, Appl. Sci. 8 (4) (2018) 578, https://doi.org/10.3390/app8040578.

[17] S. Martínez-Cruz, et al., An outdoor navigation assistance system for visually impaired people in public transportation, IEEE Access 9 (2021) 130767–130777, https://doi.org/10.1109/ACCESS.2021.3111544.

[18] L. Raja, R. Santhosh, Experimental study on shoe based navigation system for the visually impaired, Mater. Today: Proc. 45 (2021) 1713–1716, https://doi.org/10.1016/j.matpr.2020.08.615.

[19] N.S. Patankar, et al., An intelligent IoT based smart stick for visually impaired person using image sensing, in: 2023 14th International Conference on Computing Communication and Networking Technologies (ICCCNT), 2023, https://doi.org/10.1109/ICCCNT56998.2023.10306645. Delhi, India.

[20] J. Ducasse, A.M. Brock, C. Jouffrais, Accessible interactive maps for visually impaired users, in: E. Pissaloux, R. Velazquez (Eds.), Mobility of Visually Impaired People: Fundamentals and ICT Assistive Technologies, Springer International Publishing, Cham, 2018, pp. 537–584, https://doi.org/10.1007/978-3-319-54446-5_17.

[21] B. Kuriakose, R. Shrestha, F.E. Sandnes, LiDAR-based obstacle detection and distance estimation in navigation assistance for visually impaired, in: Universal Access in Human-Computer Interaction. User and Context Diversity, Springer International Publishing, Cham, 2022, https://doi.org/10.1007/978-3-031-05039-8_35.

[22] M. Kahraman, C. Turhan, An intelligent indoor guidance and navigation system for the visually impaired, Assist. Technol. 34 (4) (2022) 478–486, https://doi.org/10.1080/10400435.2021.1872738.

[23] P. Chanana, et al., Assistive technology solutions for aiding travel of pedestrians with visual impairment, J. Rehabil. Assist. Technol. Eng. 4 (2017) 2055668317725993, https://doi.org/10.1177/2055668317725993.

[24] C.K. Lakde, P.S. Prasad, Navigation system for visually impaired people, in: 2015 International Conference on Computation of Power, Energy, Information and Communication (ICCPEIC), IEEE, Melmaruvathur, India, 2015, https://doi.org/10.1109/ICCPEIC.2015.7259447.

[25] P.J. Duh, et al., V-eye: a vision-based navigation system for the visually impaired, IEEE Trans. Multimed. 23 (2021) 1567–1580, https://doi.org/10.1109/TMM.2020.3001500.

[26] A. Bhowmick, et al., IntelliNavi: navigation for blind based on Kinect and machine learning, in: Multi-disciplinary Trends in Artificial Intelligence, Springer International Publishing, Cham, 2014, https://doi.org/10.1007/978-3-319-13365-2_16.

[27] P.E. Ponchillia, et al., Developing an indoor navigation application: identifying the needs and preferences of users who are visually impaired, J. Vis. Impair. Blind. (JVIB) 114 (5) (2020) 344–355, https://doi.org/10.1177/0145482X20953279.

[28] V. Nair, et al., ASSIST: evaluating the usability and performance of an indoor navigation assistant for blind and visually impaired people, Assist. Technol. 34 (3) (2022) 289–299, https://doi.org/10.1080/10400435.2020.1809553.

[29] H.-E. Chen, et al., BlindNavi: a navigation app for the visually impaired smartphone user, in: Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems, Association for Computing Machinery, 2015, pp. 19–24, https://doi.org/10.1145/2702613.2726953, conf-loc>, Seoul, <country>Republic of Korea</country>, </conf-loc>.

[30] Z. Chen, et al., A wearable navigation device for visually impaired people based on the real-time semantic visual SLAM system, Sensors 21 (4) (2021) 1536, https://doi.org/10.3390/s21041536.

[31] M. Jain, W. Patel, Review on LiDAR-based navigation systems for the visually impaired, SN Computer Science 4 (4) (2023) 323, https://doi.org/10.1007/s42979-023-01735-y.

[32] B. Kuriakose, R. Shrestha, F.E. Sandnes, Tools and technologies for blind and visually impaired navigation support: a review, IETE Tech. Rev. 39 (1) (2022) 3–18, https://doi.org/10.1080/02564602.2020.1819893.

[33] B.K. Asiedu Asante, H. Imamura, Towards robust obstacle avoidance for the visually impaired person using stereo cameras, Technologies 11 (6) (2023) 168, https://doi.org/10.3390/technologies11060168.

[34] R.M. Al-Eidan, H. Al-Khalifa, A.M. Al-Salman, A review of wrist-worn wearable: sensors, models, and challenges, J. Sens. 2018 (2018) 5853917, https://doi.org/10.1155/2018/5853917.

[35] H. Witt, Fundamentals of perception and cognition, in: H. Witt (Ed.), User Interfaces for Wearable Computers: Development and Evaluation, Vieweg+Teubner, Wiesbaden, 2008, pp. 21–35, https://doi.org/10.1007/978-3-8351-9232-4_3.

[36] D.M. Peters, et al., Utilization of wearable technology to assess gait and mobility post-stroke: a systematic review, J. NeuroEng. Rehabil. 18 (1) (2021) 67, https://doi.org/10.1186/s12984-021-00863-x.

[37] A. Muro-de-la-Herran, B. Garcia-Zapirain, A. Mendez-Zorrilla, Gait analysis methods: an overview of wearable and non-wearable systems, highlighting clinical applications, Sensors 14 (2) (2014) 3362–3394, https://doi.org/10.3390/s140203362.

[38] M.B. Shaikh, D. Chai, RGB-D data-based action recognition: a review, Sensors 21 (2021), https://doi.org/10.3390/s21124246.

[39] J. Liu, et al., Ntu RGB+D 120: a large-scale benchmark for 3D human activity understanding, IEEE Trans. Pattern Anal. Mach. Intell. 42 (10) (2020) 2684–2701, https://doi.org/10.1109/TPAMI.2019.2916873.

[40] Y. Al-Handarish, et al., A survey of tactile-sensing systems and their applications in biomedical engineering, Adv. Mater. Sci. Eng. 2020 (2020) 4047937, https://doi.org/10.1155/2020/4047937.

[41] A. Pawar, et al., Smartphone based tactile feedback system providing navigation and obstacle avoidance to the blind and visually impaired, in: 2022 5th International Conference on Advances in Science and Technology (ICAST), 2022, https://doi.org/10.1109/ICAST55766.2022.10039535. Mumbai, India.

[42] M. Bouzit, et al., Tactile Feedback Navigation Handle for the Visually Impaired (2004) 1171–1177, https://doi.org/10.1115/IMECE2004-60450.

[43] Q. Li, et al., A review of tactile information: perception and action through touch, IEEE Trans. Robot. 36 (6) (2020) 1619–1634, https://doi.org/10.1109/TRO.2020.3003230.

[44] A. Aladrén, et al., Navigation assistance for the visually impaired using RGB-D sensor with range expansion, IEEE Syst. J. 10 (3) (2016) 922–932, https://doi.org/10.1109/JSYST.2014.2320639.

[45] H. Hakim, A. Fadhil, Navigation system for visually impaired people based on RGB-D camera and ultrasonic sensor, in: Proceedings of the International Conference on Information and Communication Technology, Association for Computing Machinery, Baghdad, Iraq, 2019, pp. 172–177, https://doi.org/10.1145/3321289.3321303.

[46] Y.H. Lee, G. Medioni, RGB-D camera based wearable navigation system for the visually impaired, Comput. Vis. Image Understand. 149 (2016) 3–20, https://doi.org/10.1016/j.cviu.2016.03.019.

[47] P.d.l. Puente, et al., RGB-D sensor setup for multiple tasks of home robots and experimental results, in: 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2014, https://doi.org/10.1109/IROS.2014.6942915. Chicago, IL, USA.

[48] L. Chumbley, et al., Integrating high-resolution tactile sensing into grasp stability prediction, in: 2022 19th Conference on Robots and Vision (CRV), 2022, https://doi.org/10.1109/CRV55824.2022.00021. Toronto, ON, Canada.

[49] N. Navarro-Guerrero, et al., Visuo-haptic object perception for robots: an overview, Aut. Robots 47 (4) (2023) 377–403, https://doi.org/10.1007/S10514-023-10091-Y.

[50] A. Bicchi, M.A. Peshkin, J.E. Colgate, Safety for physical human–robot interaction, in: B. Siciliano, O. Khatib (Eds.), Springer Handbook of Robotics, Springer Berlin Heidelberg, Berlin, Heidelberg, 2008, pp. 1335–1348, https://doi.org/10.1007/978-3-540-30301-5_58.

[51] P. Kolar, P. Benavidez, M. Jamshidi, Survey of datafusion techniques for laser and vision based sensor integration for autonomous navigation, Sensors 20 (8) (2020) 2180, https://doi.org/10.3390/s20082180.

[52] G. Trinidad Barnech, et al., Enhancing robotic perception through synchronized simulation and physical common-sense reasoning, Sensors 24 (7) (2024) 2249, https://doi.org/10.3390/s24072249.

[53] A. Buerkle, et al., Towards industrial robots as a service (IRaaS): flexibility, usability, safety and business models, Robot. Comput. Integrated Manuf. 81 (2023) 102484, https://doi.org/10.1016/j.rcim.2022.102484.

[54] B. Suslu, F. Ali, I.K. Jennions, Understanding the role of sensor optimisation in complex systems, Sensors 23 (18) (2023) 7819, https://doi.org/10.3390/s23187819.

[55] Z. Yang, M. Gao, J. Choi, Smart walking cane based on triboelectric nanogenerators for assisting the visually impaired, Nano Energy 124 (2024) 109485, https://doi.org/10.1016/j.nanoen.2024.109485.

[56] S. Prathibha, et al., Ultra-modern walking stick designed for the blind, in: 2023 International Conference on Networking and Communications (ICNWC), 2023, https://doi.org/10.1109/ICNWC57852.2023.10127473. Chennai, India.

[57] I.-J. Kim, Recent advancements in indoor electronic travel aids for the blind or visually impaired: a comprehensive review of technologies and implementations, Univers. Access Inf. Soc. (2024), https://doi.org/10.1007/s10209-023-01086-8.

[58] I. Khan, S. Khusro, I. Ullah, Technology-assisted white cane: evaluation and future directions, PeerJ 6 (2018) e6058, https://doi.org/10.7717/PEERJ.6058.

[59] K.M. Masal, S. Bhatlawande, S.D. Shingade, Development of a visual to audio and tactile substitution system for mobility and orientation of visually impaired people: a review, Multimed. Tool. Appl. 83 (7) (2024) 20387–20427, https://doi.org/10.1007/s11042-023-16355-0.

[60] S. Badrloo, et al., Image-based obstacle detection methods for the safe navigation of unmanned vehicles: a review, Rem. Sens. 14 (15) (2022) 3824, https://doi.org/10.3390/rs14153824.

[61] J. Bai, et al., A cloud and vision-based navigation system used for blind people, in: Proceedings of the 2017 International Conference on Artificial Intelligence, Automation and Control Technologies, Association for Computing Machinery, Wuhan, China, 2017 22, https://doi.org/10.1145/3080845.3080867.

[62] J. Bai, et al., Virtual-blind-road following-based wearable navigation device for blind people, IEEE Trans. Consum. Electron. 64 (1) (2018) 136–143, https://doi.org/10.1109/TCE.2018.2812498.

[63] B. Li, et al., Vision-based mobile indoor assistive navigation aid for blind people, IEEE Trans. Mobile Comput. 18 (3) (2019) 702–714, https://doi.org/10.1109/TMC.2018.2842751.

[64] Marder-Eppstein, E., Project Tango, in ACM SIGGRAPH 2016 Real-Time Live! 2016, Association for Computing Machinery: Anaheim, California. p. Article 40, Doi: https://doi.org/10.1145/2933540.2933550.

[65] J. Xiao, et al., An assistive navigation framework for the visually impaired, IEEE Transactions on Human-Machine Systems 45 (5) (2015) 635–640, https://doi.org/10.1109/THMS.2014.2382570.

[66] M. Sain, D. Necsulescu, Portable monitoring and navigation control system for helping visually impaired people, 1:121-9, in: 4th International Conference of Control, Dynamic Systems, and Robotics (CDSR'17), 2017, p. 121, https://doi.org/10.11159/cdsr17.121. Toronto, Canada.

[67] Z. Zhang, Microsoft Kinect sensor and its effect, IEEE MultiMedia 19 (2) (2012) 4–10, https://doi.org/10.1109/MMUL.2012.24.

[68] S. Swaminathan, et al., From tactile to NavTile: opportunities and challenges with multi-modal feedback for guiding surfaces during non-visual navigation, in: Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, Association for Computing Machinery, 2021 36, https://doi.org/10.1145/3411764.3445716 conf-loc>, Yokohama, <country>Japan</country>, </conf-loc.

[69] M. Castillo-Cara, et al., Ray: smart indoor/outdoor routes for the blind using Bluetooth 4.0 BLE, Procedia Comput. Sci. 83 (2016) 690–694, https://doi.org/10.1016/j.procs.2016.04.153.

[70] T. Ishihara, et al., Beacon-guided structure from motion for smartphone-based navigation, in: 2017 IEEE Winter Conference on Applications of Computer Vision (WACV), 2017, https://doi.org/10.1109/WACV.2017.91.

[71] V. Nair, et al., A hybrid indoor positioning system for blind and visually impaired using Bluetooth and Google Tango, Journal on technology and persons with disabilities 6 (2018). Medium: X, https://par.nsf.gov/biblio/10065143.

[72] S.A. Cheraghi, V. Namboodiri, L. Walker, GuideBeacon: Beacon-based indoor wayfinding for the blind, visually impaired, and disoriented, in: 2017 IEEE International Conference on Pervasive Computing and Communications (PerCom), 2017, https://doi.org/10.1109/PERCOM.2017.7917858.

[73] Sato, D., et al., NavCog3: An Evaluation of a Smartphone-Based Blind Indoor Navigation Assistant with Semantic Features in a Large-Scale Environment, in Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility. 2017, Association for Computing Machinery: Baltimore, Maryland, USA. p. 270–279, Doi: https://doi.org/10.1145/3132525.3132535.

[74] E. Hoggan, S.A. Brewster, J. Johnston, Investigating the effectiveness of tactile feedback for mobile touchscreens, in: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Association for Computing Machinery, Florence, Italy, 2008, pp. 1573–1582, https://doi.org/10.1145/1357054.1357300.

[75] V.B. Krishna, K. Aparna, Iot-based indoor navigation wearable system for blind people, in: Artificial Intelligence and Evolutionary Computations in Engineering Systems, Springer Verlag, 2018, pp. 413–421, https://doi.org/10.1007/978-981-10-7868-2_40.

[76] N.S. Mala, S.S. Thushara, S. Subbiah, Navigation gadget for visually impaired based on IoT, in: 2017 2nd International Conference on Computing and Communications Technologies (ICCCT), 2017, https://doi.org/10.1109/ICCCT2.2017.7972298. Chennai, India.

[77] S. Gupta, et al., Advanced guide cane for the visually impaired people, in: 1st International Conference on Next Generation Computing Technologies (NGCT), IEEE, Dehradun, India, 2015, https://doi.org/10.1109/NGCT.2015.7375159.

[78] A. Sen, K. Sen, J. Das, Ultrasonic blind stick for completely blind people to avoid any kind of obstacles, in: IEEE SENSORS, IEEE, New Delhi, India, 2018, https://doi.org/10.1109/ICSENS.2018.8589680.

[79] R. Jafri, et al., 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 6 (2018) 443–454, https://doi.org/10.1109/ACCESS.2017.2766579.

[80] J. Albouys-Perrois, et al., Towards a multisensory augmented reality map for blind and low vision people: a participatory design approach, in: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, Association for Computing Machinery, Montreal QC, Canada, 2018, p. 629, https://doi.org/10.1145/3173574.3174203.

[81] A.I. Bolkunov, M.N. Krasil'shikov, V.V. Malyshev, Comprehensive assessment of the effectiveness of navigation satellite systems, J. Comput. Syst. Sci. Int. 61 (3) (2022) 430–446, https://doi.org/10.1134/S1064230722030030.

[82] T. Schwarze, et al., A camera-based mobility aid for visually impaired people, KI - Künstliche Intelligenz 30 (1) (2016) 29–36, https://doi.org/10.1007/s13218-015-0407-7.

[83] Q. Chen, et al., Sensing system of environmental perception technologies for driverless vehicle: a review of state of the art and challenges, Sensor Actuator Phys. 319 (2021) 112566, https://doi.org/10.1016/j.sna.2021.112566.
[84] A.N. Wilson, et al., Embedded sensors, communication technologies, computing platforms and machine learning for UAVs: a review, IEEE Sensor. J. 22 (3) (2022) 1807–1826, https://doi.org/10.1109/JSEN.2021.3139124.
[85] A. Lo Valvo, et al., A navigation and augmented reality system for visually impaired people, Sensors 21 (9) (2021) 3061, https://doi.org/10.3390/s21093061.
[86] L. Dunai, et al., 3D CMOS sensor based acoustic object detection and navigation system for blind people, in: IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society, 2012, https://doi.org/10.1109/IECON.2012.6389214. Montreal, QC, Canada.
[87] S. Sivan, G. Darsan, Computer vision based assistive technology for blind and visually impaired people, in: Proceedings of the 7th International Conference on Computing Communication and Networking Technologies, Association for Computing Machinery, Dallas, TX, USA, 2016 41, https://doi.org/10.1145/2967878.2967923.
[88] B. Setiadi, et al., Navigation and object detection for blind persons based on neural network, International Journal of Applied Technology Research 1 (1) (2020) 56–65, https://doi.org/10.35313/ijatr.v1i1.24.
[89] A. Ismail, S. Abdlerazek, I.M. El-Henawy, Development of smart healthcare system based on speech recognition using support vector machine and dynamic time warping, Sustainability 12 (6) (2020) 2403, https://doi.org/10.3390/su12062403.
[90] K. Yang, et al., Unifying terrain awareness for the visually impaired through real-time semantic segmentation, Sensors 18 (5) (2018) 1506, https://doi.org/10.3390/s18051506.
[91] P.M. Kumar, et al., Retracted article: intelligent face recognition and navigation system using neural learning for smart security in Internet of Things, Cluster Comput. 22 (4) (2019) 7733–7744, https://doi.org/10.1007/s10586-017-1323-4.
[92] L. Niu, et al., A wearable assistive technology for the visually impaired with door knob detection and real-time feedback for hand-to-handle manipulation, in: 2017 IEEE International Conference on Computer Vision Workshops (ICCVW), 2017, https://doi.org/10.1109/ICCVW.2017.177. Venice, Italy.
[93] B.-S. Lin, C.-C. Lee, P.-Y. Chiang, Simple smartphone-based guiding system for visually impaired people, Sensors 17 (6) (2017) 1371, https://doi.org/10.3390/s17061371.
[94] A. Bhandari, et al., Object detection and recognition: using deep learning to assist the visually impaired. Disability and Rehabilitation, Assist. Technol. 16 (3) (2021) 280–288, https://doi.org/10.1080/17483107.2019.1673834.
[95] M. Poggi, L. Nanni, S. Mattoccia, Crosswalk recognition through point-cloud processing and deep-learning suited to a wearable mobility aid for the visually impaired, in: New Trends in Image Analysis and Processing – ICIAP 2015 Workshops, Springer International Publishing, Cham, 2015, https://doi.org/10.1007/978-3-319-23222-5_35.
[96] R.F. Berriel, et al., Automatic large-scale data acquisition via crowdsourcing for crosswalk classification: a deep learning approach, Comput. Graph. 68 (2017) 32–42, https://doi.org/10.1016/j.cag.2017.08.004.
[97] R. Trabelsi, et al., Indoor object recognition in RGBD images with complex-valued neural networks for visually-impaired people, Neurocomputing 330 (2019) 94–103, https://doi.org/10.1016/j.neucom.2018.11.032.
[98] J. Nakić, I.N. Kosović, A. Franić, User-centered design as a method for engaging users in the development of geovisualization: a use case of temperature visualization, Appl. Sci. 12 (17) (2022) 8754, https://doi.org/10.3390/app12178754.
[99] H. Nguyen Ngoc, G. Lasa, I. Iriarte, Human-centred design in industry 4.0: case study review and opportunities for future research, J. Intell. Manuf. 33 (1) (2022) 35–76, https://doi.org/10.1007/s10845-021-01796-x.
[100] L. van Velsen, G. Ludden, C. Grünloh, The limitations of user-and human-centered design in an eHealth context and how to move beyond them, J. Med. Internet Res. 24 (10) (2022) e37341, https://doi.org/10.2196/37341.
[101] R.E. Roth, K.S. Ross, A.M. MacEachren, User-centered design for interactive maps: a case study in crime analysis, ISPRS Int. J. Geo-Inf. 4 (2015) 262–301, https://doi.org/10.3390/ijgi4010262.
[102] E. Krajnc, J. Feiner, S. Schmidt, User centered interaction design for mobile applications focused on visually impaired and blind people, in: HCI in Work and Learning, Life and Leisure, Springer Berlin Heidelberg, Berlin, Heidelberg, 2010, https://doi.org/10.1007/978-3-642-16607-5_12.