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Development and application of key technologies for Guide Dog Robot: A systematic literature review

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ABSTRACT

In the current situation of many visually handicapped people worldwide, yet the corresponding number of guide dogs is quite rare. It activates the application of advanced technology to broaden their horizons and allow them to embrace the world. This paper will review the research state of the Guide Dog Robot (GDR) for people with visual impairment and present some views. According to the application scenes, we have divided the GDR into two categories: specific scene applicable type and universal scene applicable type, with the description of different performances under various scenes. Then the current research focuses are elaborated, including localization and navigation technology, recognition of traffic signs, human–robot interaction (HRI), speed coordination, and walking structure design. Subsequently, the studying directions and challenges of GDR are discussed, and collaborative human–robot mode is believed to become the research mainstream. Finally, we conclude this review and explain why few GDR has realized commercialization. The limitations of current studies and some recommendations for future research are presented.

1. Introduction

Vision is the most critical and intuitive approach for people to perceive the external world because more than 85% of external information can directly be obtained by the vision system [1]. It is a consensus that visual experience plays a crucial role in developing spatial perception, which is fundamental for numerous human activities [2]. There is no doubt that the visual impression is of vast significance to each individual. The absence of this competence will inevitably lead to severe livelihood problems [3], even depression and anxiety happening to the elderly with visual impairment [4].

Recently, the WHO (World Health Organization) survey reported that: In 2015, approximately 253 million people had suffered from vision impairments, from whom roughly 217 million had a slight vision, whereas an estimated 36 million were blind [5]. Due to the increasing population of visually handicapped people, guide dogs have shown an enormous demand in recent years. However, few guide dogs can be got to service visually handicapped people worldwide. This phenomenon is especially prominent in China [6]. In 2014, there were only 67 guide dogs of legal service in China. Even at present, no more than 200 guide dogs can be obtained. It is an unfriendly phenomenon for visually handicapped individuals. The lack of guide dogs has isolated them from the external world. They deserve to have the choice to embrace the colorful world.

Various factors cause the scarcity of guide dogs. On the one hand, not all dogs are suitable to be trained as guide dogs [7]. An only rare breed of dogs, such as Golden Retriever, Labrador, and German Shepherd, coupled with good qualities of smartness, obedience, persistence, and friendliness, may have the opportunity to be competent for this job [8]. On the other hand, it is a challenge to train the selected dogs to become professional guide dogs, for it will consume a long training period and high training cost. Typically, it will take 1.5 to 2 years to train a qualified guide dog. The corresponding price is about 12000–20000 dollars, undoubtedly a considerable expense. Moreover, their official service time is only about five years [9]. These factors profoundly explain the inherent imbalance between the increasing number of visually impaired people and the scarcity of guide dogs.

In recent decades, as artificial intelligence and automated technology develops rapidly, the guide dog robot (GDR) has come into existence as the alternative to the guide dog, impacting this situation. Its primary structural forms include small electronic blind guidance device, guide cane, wearable blind guidance device, and mobile blind guidance device.

GDR is described as a robot that holds the vital features of guide dogs. Combined with sensor technology, intelligent algorithms, or other advanced technologies, visually handicapped

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individuals will be provided with safe path guidance by GDR. Up to now, most functions that the guide dog specifics have been realized by GDR. Beyond that, GDR can even be competent for the missions that traditional guide dogs cannot complete, such as navigation to unknown places. Sensors can play the role of the dog's eyes by detecting surrounding road conditions. The sensor information is processed, and then the corresponding command will be transmitted to GDR. Once the surrounding information is captured by the sensors, combined with a path planning algorithm, the optimal route to the destination will be selected. In this paper, the GDRs that are referred to mainly focus on mobile GDR because the mobile GDR's function has excellent potential for expansion and can reduce the probability of blind people being injured. It is the mainstream direction for the development of blind assistive devices.

As an independent power device of blind guidance, the mobile GDR is the closest to the well-trained guide dog in use characteristics, and the related research has been carried out early. In 1978, Tachi et al. of MEL (Mechanical Engineering Laboratory) made the first mobile guide robot called MELDOG MARK I [10]. Furthermore, they put forward four main functions that the GDR should be equipped: Obey the master's instructions (turn left and right, straight, stop, etc.), intelligent disobedience in dangerous situations, coordinate with the master's walking speed, automatic guidance by setting the start point code and the destination code. Among them, walking speed coordination was achieved by detecting the relative distance between the blind person and GDR through the ultrasonic sensor. Then the feedback would be conveyed to GDR to maintain a constant distance. Subsequently, in MELDOG Mark II, III, and IV, they successively carried out the test experiments of navigation based on landmark and map, obstacle detection based on camera, map error compensation based on landmark data or other functions [11–13].

In contrast, the research focus of GDR in China was on guide cane in the early stage, while the research of mobile GDR was carried out relatively late. According to literature research, until 2005, Zeng et al. [14] designed a mobile GDR based on the commercial robot and successfully carried out relevant function tests. However, at that time, it remained a gap in the functional exploration of human–robot interaction compared with the international level. Recently, due to the development of the mobile GDR to the multi-intelligence direction and user's demand for functional diversity, the research focus in China is gradually inclined to the tip of autonomous mobile GDR.

The GDR reviewed in this paper is a new type of promising service robot. Among them, mobile GDR is our primary research goal, which served as the multi-functional integration goal of the blind guidance device. In terms of some key technologies such as navigation, obstacle avoidance, and interaction, other types of blind guidance aids have strong commonality with mobile GDR, so they are also partly covered in this review to arouse enlightenment.

This paper is organized as follows. Section 2 presents the classification and development status of GDR, while Section 3 describes the current research focus of GDR. Current challenges and directions are proposed in Section 4. Finally, the paper is concluded in Section 5, coupled with limitations of the recent studies and some recommendations for future research.

2. Classification and development status of mobile GDR

Up to now, a clear division of blind guidance aids has been carried out, but the classification of mobile GDR is still blank. According to the application scene, we divide them into specific scene applicable type and complex scene applicable type.

Different application scenes result in various technical priorities. For example, GPS localization is not available in indoor environments, outdoor navigation is based on global path planning and local path planning, and specific scenes need to be equipped with unique functions, etc. However, on the whole, mobile GDR has not yet developed a prominent faction due to relatively immature research. The characteristics of the reported mobile GDR are not distinct, and the vision here is for the convenience of elaboration.

2.1. Specific scene applicable type

In this review, the term specific scene applicable GDR means a kind of mobile GDR applied in relatively fixed sets, mainly indoor environments. In detail, it refers to the mobile GDR, which can provide route guidance and obstacle avoidance for blind people in typical indoor environments, supermarkets, hospitals, stations, or other scenes.

Table 1 has given an overview of numerous mobile GDRs applied in the specific scene and concluded their main technologies and performance characteristics. In addition to the technical differences, it is also listed why they are suitable to be defined as "indoor special usage GDR" from the perspective of researchers. What can be seen is that navigation will be the priority of the mobile GDR for better performance in indoor environments.

2.1.1. GDR applied in the indoor environment

GDR applied in the indoor environment is a comprehensive control system that integrates multiple functions, including environment perception, localization and navigation, and autonomous obstacle avoidance. As shown in Table 1, different GDRs applicable in this situation demonstrated various main features for why they are called "indoor applied GDR". Hence, the classification here is not based on distinct features of mobile GDR but to promote the comprehensiveness of indoor mobile GDR technology.

The most prominent feature of this kind of GDR is the difference in localization system where it does not rely on GPS due to the mask to GPS signal. Instead, RFID, ultrasonic sensor, deep camera, etc. is often for indoor localization. More details will be found in Section 3.1, including indoor navigation modes. However, errors in the accuracy of indoor localization will occur inevitably. To solve it, a Kalman filter method is often used to correct the position for its excellent performance in state estimation. The indoor walking aid robot designed by Luo [17] is to provide walking aid services for visually handicapped people indoor. Through the combination of the encoder and the electronic compass, the short distance and high precision localization were realized. Meanwhile, the ultrasonic network was used to correct the localization system for its local high-precision localization by extended Kalman filter, thus avoiding the error accumulation of the long-distance localization.

Moreover, interactive performance is also valued in indoor navigation. Huang et al. [19] designed an indoor navigation service robot system for visually handicapped people where the Kinect was used to obtain the user's skeleton data. Once getting the relative position of the user to the robot, the commands would generate to instruct the robot and the user to adjust their movements accordingly. Kulkarni et al. [15] proposed an indoor mobile GDR called "Pioneer 3DX robot" to enhance user's experience in helping deploy a user-friendly interactive system. Else, other demands in indoor navigation for blind people, such as robust navigation [28], object recognition [23].

For the indoor environment, leading visually handicapped individuals to take the elevator is a significant challenge. Feng et al. [29] developed a mobile GDR which can guide the user to the front of the elevator button panel and then tell the user the button to push according to the demand. It is also an unavoidable problem to guide people with visual impairment up and

Table 1
Overview of mobile GDR in specific scene application.

Study	Localization mode	Navigation way	Unique function	Features for indoor usage
Kulkarni et al. [15]	–	–	Equipped with a database for user information	Diverse interaction ways
Chen et al. [16]	RSSI based on RFID signal intensity	Repeated learning ideas for path planning	RFID tags both for localization and object recognition	Multi-room wide-range navigation, multi-sensory interaction, object recognition function
Luo [17]	Dead reckoning combined with ultrasonic network	Inertial navigation (Electronic compass and encoder for dead reckoning)	–	No GPS, replaced with correction for localization
Nguyen et al. [18]	Off-line map / Vision-based localization for unobservable position	A* algorithm for path planning	Vehicle travel reconstruction using visual odometry technique	Environment representation, user localization, navigation, and interaction
Huang et al. [19]	–	–	The skeleton data capture to get the relative position	Vibration tactile feedback
Kassim et al. [20]	RFID tags, coupled with a digital compass for localization	Using passive RFID transponders mounted on the floor	–	Indoor navigation system
Alhmiedat et al. [21]	Digital encoders	Dijkstra's algorithm	–	Navigation in an indoor known environment
Kulyukin et al. [22]	RFID identification	Standard breadth first search (BFS) for a desired path	–	Navigation in structured indoor environments
Du et al. [23]	–	–	Obstacle recognition	High recognition rate of obstacles in indoor environments
Khanh et al. [24]	Wi-Fi-based indoor positioning system	Cloud-based navigation system	Navigation using a fixed edge cloud and wireless access point	Indoor robot navigation
Nanavati et al. [25]	–	A* Graph Search	–	Indoor autonomous navigation system
Kayukawa et al. [26]	Using an RGB-D camera	Based on the ROS navigation stack	Empty chair detection, 2D map creation	Local navigation
Capi et al. [27]	–	–	Recognition of obstacles, steps and stairs	Indoor navigation and object recognition

down stairs in an indoor environment. For that, Huang et al. [30] proposed a method to detect the rising and descending stairs in depth image in their indoor obstacle detection system for visually handicapped individuals. They also researched the detection success rate and failure rate in an indoor environment under sufficient/insufficient light, which brought inspiration for GDR applied in the indoor environment.

Additionally, Luis et al. [31] presented an indoor navigation system for visually handicapped individuals, which identified the position of a person by letting the developer graphically create room and calculated the velocity and direction of the user's movements. Nevertheless, the limitation exists in that this localization method is suitable for places that do not frequently change. If an object in the environment is moved, the map also needs to be refreshed. Combined the visual marker and ultrasonic sensors, the wearable system [32] was proposed for blind users in the indoor environment. The visual markers were used to identify the points of interest in the indoor environment, while ultrasonic sensors were to raise the environmental perception and avoid possible obstacles.

2.1.2. GDR applied in the supermarket

It is common knowledge that a guide dog does well in micro navigation, such as obstacle avoidance. However, it is not good at performing macro navigation which requires a topological understanding of the environment [33]. The advantage of a guide dog, micro navigation, can hardly play a role in searching for the target product in the supermarket. Besides, visually impaired individuals cannot convey their demand for purchasing goods to the guide dog, let alone assisted in completing a series of processes, including product selection and payment. Duarte et al. have ever done comprehensive research on this topic, and more details can be obtained in [34]. Overall, it is challenging to allow visually handicapped individuals to move safely and perform their target commodity independently in the supermarket.

Domingo MC et al. [35] proposed a comprehensive theoretical plan for a blind guidance system in the supermarket scene (Fig. 1): Stick RFID tags with product name, description and price on corresponding product, then rely on RFID tag reader of guide cane for information transmission. The monitor station (smartphone) maintains a Bluetooth connection with the user's

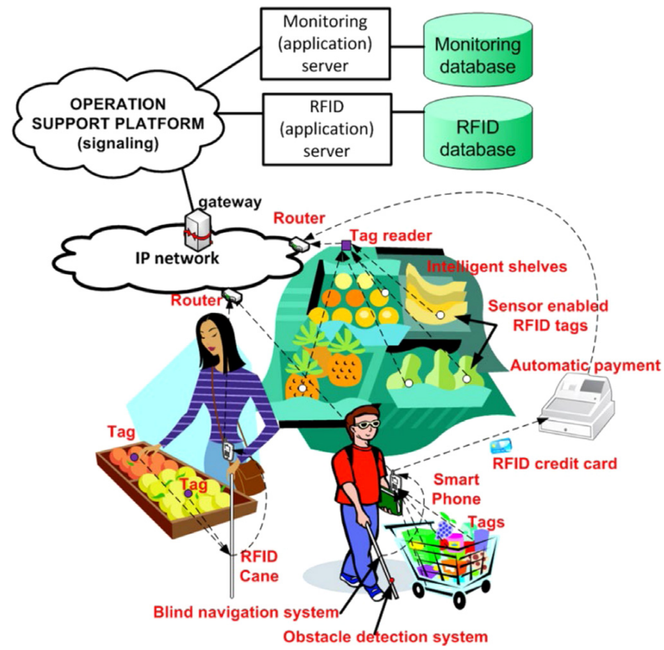

Fig. 1. Shopping scenario [35].

RFID reader (guide cane) so that it can use a tag with navigation information to identify the map at any time. Meanwhile, blind people can interact with the monitoring station by voice and reach the target area according to the voice navigation information prompted. In addition, payment can also be performed using RFID. Although this research is not direct for mobile GDR, it has particular reference significance for the function development of currently immature supermarket applied GDR.

Rumipamba et al. [36] ever proposed a prototype of a differential type dragging GDR for supermarket application. It can follow the route identified by a black line on the ground, equipped with ultrasonic sensors to avoid collisions. However, this navigation method seems to be not flexible enough due to the fixed route. RoboCart [33,37,38], a proof-of-concept prototype of GDR, relies on RFID tags deployed in various supermarket positions for localization and laser range finder for navigation. Users can allow destination input by the haptic feedback on a hand-held keyboard. Robocart will autonomously guide users to the destinations and cue them of the environment salient features through synthetic speech and a portable barcode reader. Up to now, the reported mobile GDRs for the supermarket are only the above two. Supermarket-applied GDR may be more inclined to the development of portable and easy-to-detect guidance aids. ShopTalk [39,40], a wearable small-scale system assisting visually handicapped people in retrieving required products, composed of a barcode reader, a computation device, and a numeric keypad for user data entry. Among them, a portable barcode reader attached to the stabilizer is easier to align with shelf barcodes. Besides, develop a cell phone application as a virtual GDR for visually handicapped people is also a promising choice. It usually needs a navigation function and barcode scanner for commodity recognition [41,42].

2.1.3. GDR applied in the hospital

For visually handicapped individuals, to move efficiently in the hospital is an uneasy challenge, for it sits in an ample space with a complex spatial layout. Besides, many hospitals have regulated that animals are not allowed to enter for hygiene reasons [43]. It brings great restrictions to the movement of guide dogs with visually handicapped individuals.

To alleviate this problem, NSK Ltd. [43,44] developed a mobile GDR called LIGHBOT to provide blind guidance in a large hospital. To some extent, it is equal to an intelligent autonomous car for visually handicapped individuals. As the user walks with the robot handle held, LIGHBOT will recognize walls and obstacles around it and guide the user to the destination through barriers. Through the robot's obstacle sensor (laser range finder), the user can avoid obstacles along the way, by which "intelligent disobedience" proposed by Tachi [10] is minimal. Moreover, the LIGHBOT was equipped with a 4-axis force sensor in the handle. Once the handle is turned to the target direction, LIGHBOT will move in the same direction. Tobita et al. also proposed that GDR structure applied in barrier-free environments such as large hospitals should be modified in hardware in two aspects: The button should be set for destination input for visually impaired people, and the height should be adjusted to a suitable height for the elderly. Capi [27,45] presented a GDR guiding visually handicapped people in public buildings such as hospitals, offices, etc. Similarly, it can detect obstacles and convey the surrounding information with visual sensor and LRF (laser range finders).

GDR applied in the hospital seems to be more concerned about recognizing particular obstacles, such as stairs and steps. The infrared distance sensor of LIGHBOT is equipped at the front of the lower part to detect and avoid a significant drop of steps in the forward direction. Capi also noticed that stairs and steps in hospitals presented a danger for visually handicapped people. Thus, they developed algorithms to recognize the steps and stairs using the LRF in the vertical plane, solving the problem commonly encountered in indoor navigation. Moreover, guiding blind people to take the elevator in the hospital is also a vital consideration. LIGHBOT supports this function with a person pushing the elevator button. It will be more intelligent given communication with the elevator system.

Relatively speaking, rare GDRs applied in the hospital have been developed up to now. Besides, it does not show such distinctive features in function compared with GDR applied in indoor environments. Hospital is a place where people move densely, and the spatial arrangement is complicated. Considering the characteristics of the hospital, two main points are presented: one is the need for static and dynamic obstacle avoidance, mainly to avoid hospital facilities, pedestrians, and moving objects. The other is the need for mature path planning technology. It will be better to store the hospital map so that the users can find the target medical department easily.

2.1.4. GDR applied in the station

A design scheme of GDR which aims to help visually handicapped individuals to move conveniently in an urban rail station was introduced in [46]. This kind of GDR design scheme was verified technically feasible. However, the design scheme was just proposed. Even up to now, the prototype applied in this scene has not been developed. Chen et al. [47] ever put forward relative ideas that in the field of station application: set the RFID chip in some places with signs in the station, the RF reader mounted on the GDR can identify and then voice-tell the blind people. Besides, he suggested that a particular passage for blind people be set up in the station, so the rest of the passengers will not affect and interfere with GDR and blind people. Undoubtfully, it brings us enlightening ideas.

Besides, specific scene applicable GDR like in a museum [48], library and exhibition hall has also been referred to, which share similarities in technology with the GDR in the indoor environment. It is expected that the characteristics in different indoor scenarios and corresponding demand can be fully considered for the specialization of the GDR function.

2.2. Complex scene applicable type

Since the focus of mobile GDR for specific scenes was generally put on the indoor environment, its performance in the outdoor environment is not satisfactory enough. Therefore, mobile GDR that can freely adapt to the outdoor working environment is particularly essential. Based on the idea, we define the GDR working in changeable scenes as the complex scene applicable GDR. Compared to specific scene applicable GDR, complex scene applicable GDR tends to cope with more diverse environmental information, such as typical object recognition, dynamic obstacle analysis, both for outdoor and indoor environment, etc.

In outdoor guidance, the type of object is quite various. It is helpful to recognize them and inform the user. Bruno et al. [49] applied transfer learning in the deep learning network YOLO in their mobile GDR "Robot Bart ", which is geared to urban outskirts. By recognizing representative obstacles in urban environments, the blind user can be informed of the obstacle type in front of him. In addition to diverse objects, complex environments always include moving objects, should be more sensitive to collision detection. Tsinghua University [50] developed the mobile GDR "Doogo". The detection range of Doogo is about 25–30 m, with an accuracy of 3 cm, which can accurately detect and sense obstacles in the surrounding environment. By capturing the relative speed and trajectory between the blind user and the surrounding moving objects, the proposed conflict analysis algorithm will analyze whether the dynamic obstacles can avoid blind users by carrying out a real-time risk assessment. It is expected that when faced with a complicated situation, Doogo cannot respond effectively, the user will get online feedback by taking pictures of the surrounding environment. Further, since GDR should navigate and guide blind people in complex environments where there exist many moving obstacles, such as pedestrians, Kang et al. [51] ever made a GDR "Guide Mobile Robot" with front ultrasonic sensors to infer obstacle's intention by calculating the angle change between the direction of the GDR's movement and the line formed by the CLA's (Centroid of the Largest Area).

Some studies have integrated GDR indoor and outdoor navigation into the system to broaden the application range, which is manifested by different localization methods, not only limited to mobile GDR. Xiao et al. [52] developed a wearable walking aid device that can guide visually handicapped individuals in most scenes due to its operational modes of indoor mode and outdoor mode. In the indoor mode, since most buildings lack accessible features, the proposed system used computer vision technology to detect objects and recognize signs, etc., then the navigation map will be built up for guidance. While in the outdoor mode, due to the GPS errors, this system will build a personalized navigation map to benefit the users. Similarly, Yelamarthi et al. [53] designed a Smart-Robot (SR) for visually handicapped persons based on an integrated navigation system including RFID and GPS, suitable for indoor and outdoor navigation. Ran et al. [54] also focused on the integrated indoor/outdoor blind navigation system, while their solution included OEM ultrasound localization for indoor location measurement and DGPS for outdoor location. In urban environments, the characteristics of environments change in a wide range. Based on the previous work that was focused on GDR indoor navigation, Capi et al. [55] focused on GDR navigation algorithms of the four most frequent types of urban environments, including narrow and wide pedestrian walkways, junctions, and open squares. It is also noteworthy that to complex scene applicable GDR, the road situation is to be considered. Megalingam et al. [56] designed an affordable low-cost mobile GDR prototype both for indoor and outdoor environments where a high amount of torque is prepared to overcome the friction caused by the tar road.

The adjustment of mechanical structure is also conducive to dealing with complex scenes. Ogawa et al. [57] developed a guidance robot which is convenient for its two work modes, including guiding and carrying. The GDR can perform well in most situations for its flexible structure. It can be folded and carried by hand on the stairs.

In contrast, complex scene applicable GDR tends to be faced with more technique problems. Except for the above issues, intelligent interaction in a noisy environment, emergency response, etc., should also be considered. We can expect that the complex scene applicable GDR will be a carrier that integrates multiple advanced technologies.

3. Current research focus

3.1. Localization and navigation technology

As one of the main tasks of the navigation problem, localization is the process of determining the robot pose relative to a previous position, to the environment, or a map [58]. The localization and navigation technology of GDR performs differently in indoor and outdoor, known and unknown environments.

It is common for GDR applied in indoor environments to face navigation issues in limited space. Darius et al. [59] have done detailed research on indoor navigation systems for blind people, of great reference value. In this case, higher localization accuracy tends to be given priority, and GPS with poor localization accuracy is out of choice in this scene. Instead, RFID, Kinect, ultrasonic sensor, or other hardware are often used for better navigation performance. The RFID system can obtain centimeter-level localization accuracy within a few milliseconds, coupled with the advantages of strong environmental adaptability, wide transmission range, and low cost, which is suitable for indoor localization of mobile GDR. For example, the mobile GDR, called RG-I, with RFID tags embedded in the environment to position and avoid obstacles [22]. Kassim et al. [60] developed a GDR in the form of electronic cane with the RFID reader/ writer module installed at the bottom to easily detect the RFID tag. Chen et al. [61] innovatively proposed an indoor GDR localization method based on the combination of high and low frequency RFID for higher localization accuracy and fewer redundant paths in indoor environments. Na et al. [62] implemented the Blind Interactive Guide System (BIGS) to support the navigation of visually handicapped people. With several RFID tags deployed on the floor, the user's current location can be recognized by an RFID reader, then the user's direction will be calculated. The author also supplemented two primary limitations of RFID-based solutions: (1) It involves more time and effort to reconfigure the localization area. (2) It is relatively rigid that the user has to be guided through the predefined paths. Additionally, except for localization, RFID chips can also store information of the target objects to inform blind users. The same solutions are provided in [20,63].

Currently, most GDRs applied in the indoor environment tend to use RFID localization system, considering its advantages referred to before. Meanwhile, it is inevitable that the UHF RFID system still suffers from a certain degree of environmental interference. Some random errors are added in the localization accuracy in the experiment. Various communication conflicts, sampling errors, and time accumulation effects also exist, so there will exist some errors in localization and obstacle detection. Therefore, improving the GDR localization accuracy from the perspectives of algorithm optimization, signal value stabilization, and hardware performance enhancement has always been a concern.

Compared with RFID localization technology, GDR navigation using visual sensors shows more flexibility and intelligence due to its comprehensive and real-time environmental information detection. Since the beginning of the 21st century, visual sensors have been widely used in blind guidance systems, especially in mobile GDR. Nguyen et al. [18] proposed a mobile vision-based way-finding system for visually handicapped individuals in indoor environments. Two cameras were equipped in the image acquisition system, one to capture the surrounding environment while the other to capture the travel route. To build reliable travel routes, the study adopted the visual odometry technique to the indoor environment by scattering markers (or stickers) along the whole journey to detect more feature points. Representative scenes along travel routes were used to represent an indoor environment, which was more convenient to cope with the repetitive and ambiguous structures of the indoor environment. The test validated the feasibility of the approach where visually handicapped individuals could find a suitable way to the target destination. Currently, the depth camera has been widely applied in GDR navigation. Based on the photo recognition function of ordinary cameras, the depth camera can obtain extra surrounding information, including the position and size of obstacles. Li et al. [64] developed an efficient strategy for obstacle detection and avoidance based on an onboard RGB-D camera for depth information, coupled with a wide-angle camera for visual motion tracking. Lee et al. [65] presented a novel wearable RGB-D camera-based navigation system for visually handicapped individuals, of which the glass-mounted RGBD camera performed real-time 6-DOF feature extraction of blind users, further built a 3D voxel map in the indoor environment.

Moreover, the phenomenon including multi-path and reflection of indoor sensor signals is quite severe, and it will bring challenges to indoor localization accuracy [66].

As for outdoor localization of GDR, Meliones et al. have described in detail in [67], mainly introducing the integrated blind guide system based on the GPS system, including the earliest blind and visually handicapped users' satellite navigation system-Loadstone GPS [68], iOS platform application See Eye GPS [69], etc. The GPS system served as an outdoor system for blind people also deserves particular optimization, added with the traffic information required by the blind guidance. Balata [70] combined GIS database and GPS localization technology to customize a unique sidewalk map for blind people, significantly improving navigation efficiency.

Islam et al. [71] reviewed the navigation system for visually impaired individuals developed by different sensors. In some cases, two-dimensional sensors, such as lidar, can only obtain environmental information in a certain plane but cannot meet three-dimensional environmental information demand. For more comprehensive map information, Liu [72] combined the two-dimensional lidar with the three-dimensional Kinect. The multi-sensor fusion method is a term referring to the integration of local data resources collected by multiple homogeneous or different types of sensors arranged in different locations. Then the computer technology will be used to analyze, eliminate the contradiction and redundancy between the sensor data information and reduce uncertainty, which is often selected to obtain more information available in the environment. Different sensors were implemented for different functions [73]: vision sensor 1 for tracking and identification of a zebra crossing, vision sensor 2 for identification of traffic lights and ultrasonic sensors used for obstacle avoidance, the fused data was to make GDR more intelligent and provide a guarantee for the safe navigation of visually handicapped individuals, other researches on multi-sensor fusion example of GDR shown in [23,74].

From the above content, it is a significant trend to combine indoor localization technology and outdoor localization technology to enhance the intelligent degree and application range of GDR.

Path planning is one of the most critical links in the navigation of the GDR. Its task is to find a non-collision path from the initial state (including position and attitude) to the target state (including position and attitude) according to certain evaluation criteria in the environment with obstacles. Nowadays, the path planning of GDR can be divided into global path planning and local path planning. Global path planning is based on the known map, while local path planning is on the contrary. The accuracy of the global path planning depends on the accuracy of the environment acquisition. The primary forms are taken: grid method, free space method, V-graph method, etc., while the means of local path planning mainly include fuzzy logic algorithm, proximity graph method, genetic algorithm, neural network algorithm, artificial potential field method, etc.

Intelligent search algorithms, such as genetic algorithm and ant algorithm, A^* algorithm are extensively applied to the path planning of GDR. Shyam [75] dealt with the motion of the two-wheeled mobile robot (TWMR) serviced for visually handicapped individuals from point to point, moving towards its destination with ant algorithm. Because the DWA algorithm is not timely, coupled with an unsmooth turning path and unreasonable planning path, Liu et al. [76] proposed an improved DWA algorithm where the impact of the environment on DWA parameters had been reduced, thus presenting a smoother trajectory and more timely collision avoidance of their GDR. Li et al. [64,77] presented the Intelligent Situation Awareness and Navigation Aid (ISANA) system for visually handicapped individuals, using A^* algorithm as the path planner to find the most suitable route to the destination based on the global 2D traversable grid map layer in the semantic map. Further, it realized real-time dynamic path planning through obstacle detection and motion estimation, which brought safe and flexible guidance for users. Therefore, this kind of path planning which depends on the real-time data captured by sensors, is also called online planning.

The path planning methods mentioned above are classified as local path planning, while GDR can carry out off-line planning of path navigation according to the actual mathematical model of surrounding paths. Zhang et al. [78,79] developed an indoor navigation system for visually handicapped users, in which the user can scan and extract the floor plan with the head-mounted camera and digitalize it into a grid map. According to the room numbers and corners extracted from a floor plan, the landmarks and waypoints can be inferred. Chen et al. [80] proposed a path planning algorithm combined with V-graph method and A^* algorithm in an indoor environment for visually handicapped individuals, the usage of heuristic method enhanced the adaptability of the V-graph method to the environment and the real-time performance of the algorithm. In the same obstacle environment, the performance of this algorithm and the V-graph method based on the Dijkstra search algorithm are compared, and the higher search efficiency of this algorithm was verified.

Besides, it also supplemented that most existing path-planning methods generate sharp turn-by-turn paths connecting corner or feature anchors, which will bring unbearable experiences to users in [81]. The experience of the user is especially taken seriously, and it is expected to solve this question in further study. Further, the real-time performance of path planning is also one of the contents to be considered. I am convinced that it is necessary to combine global path planning and local path planning to improve the globality of path planning and the noise robustness of the environment model.

3.2. Recognition of traffic signs

As the "eyes" of blind people, mobile GDR naturally needs to identify what it sees and then inform the user. Based on the YOLO algorithm, which is suitable for the requirements of simultaneous detection of multiple obstacles, Wang et al. [82] tested their GDR, and the cups, laptops, potted plants, and chairs were accurately identified in the real scene. However, the identification of these objectives may not be helpful enough for blind users. Significant objective recognition is focused on the traffic signs for it is related to the navigation task. One of the most prime difficulties to hinder the mobile GDR from putting into use is failed to recognize the traffic sign accurately under the complicated traffic circumstances. The traffic signs to identify majorly includes zebra crossing, blind path, traffic light, etc. No doubt, it is not easy to capture critical traffic information when faced with a complex environment and interpret it accurately.

The research [83] involves object detection, traffic cone detection, and traffic light detection of mobile GDR. Comprehensive research was conducted on traffic signs visual recognition technology of mobile GDR, using the image processing toolbox in Matlab [84]. In the aspect of traffic light recognition, the color recognition and extraction of preprocessed images constitute the primary operation. The traffic light of red and green colors received preliminary extraction based on RGB color difference. Further, the identification of green shade should be added with restrictions on aspect ratio due to the great disturbance by leaves and other figures. Additionally, this feature can be realized by the deep neural network. With 1000 images from different distances and angles about the traffic light collected and corresponding labels, a deep neural network was trained for performing the traffic light detection task [85]. A fast detection approach using the Adaboosting algorithm and Template matching algorithm to classify pedestrian light was proposed [86]. The method emphasized the detection speed, with a certain value in the application of actual scenarios. By separating traffic lights from other parts utilizing the Adaboosting algorithm, the matching time will subsequently decrease.

Aiming at the significant characteristic that many parallel line segments with small length in blind track, blind track images will be detected through a series of procedures, including preprocessing, clustering, target region extraction, etc. According to the deviation degree of the blind person's travel direction from the blind track, the mobile GDR will choose whether to issue an alarm signal to ensure that the visually handicapped people travel along the blind path. In the field of zebra crossing detection, Hough Transform is often applied for the marking of a straight line on the edge [84,86]. The identification of zebra crossing is mainly based on the apparent characteristics of black and white. Using the detected zebra crossing features to guide the movement of blind people better is also an inspiring idea. Tang et al. [84] applied the successive iteration method to calculate the average slope of the zebra crossing. The walking direction of blind people would be adjusted based on these data.

Currently, there still exist certain deficiencies in GDR's recognition technology of traffic signs. For instance, many irregular or incomplete blind tracks, zebra crossing, and traffic lights in the environment have brought difficulties in recognition. The recognition performance will be affected in the presence of a large number of disturbances such as glare, headlight, plenty of pedestrians and vehicles, etc. Correlate image processing and identification algorithms need to be optimized in the future to relieve this problem. Mancini [87] ever processed the athletic tracks images in the presence of strong sunlight and shadow, their parameters for thresholding algorithm derived from paper [88], which could increase the accuracy of the binarized image when faced with large areas filled with black or white. Further, it is convinced that the traffic sign recognition applied to mobile GDR should be distinguished from common traffic sign recognition. The focus is that traffic information ought to be provided for better navigation service. For example, the green light suddenly turns into a red light when crossing the road, mobile GDR has to recognize traffic signs in real-time [89] and promptly remind them how to move next.

3.3. Human–robot interaction

As the bridge to exchange information between GDR and visually handicapped person, the interactive effect will directly affect the overall experience of GDR. Furthermore, HRI (human–robot interaction) is the most prominent feature of GDR, distinguished from other automatic navigation robots, presenting a broad development prospect in human–robot integration time.

Since the service object of GDR is visually handicapped people, the way of HRI is relatively limited. For them, the main channel to obtain external information relies on touching and hearing. Given this feature, the interaction with visually handicapped persons should mainly focus on auditory interaction, tactile interaction, and force interaction.

Table 2 has listed the HRI way, corresponding feedback device, and interactive content. As shown in Fig. 2, this paper divides the interaction mode of the GDR into three main types: auditory interaction, tactile interaction, and force interaction. Auditory interaction relies on verbal feedback and non-verbal form feedback, which can transmit rich content in the interaction process, but its performance may be unsatisfactory in a noisy environment. Tactile interaction is usually based on button feedback, specific vibration sequence feedback, braille display feedback, which is characterized by fast response and high reliability of command transmission. Force interaction is both instantaneous and directional, making the HRI process concise and efficient. Besides, multi-modal interaction, which integrates the above interaction modes meanwhile, is also applied for a better experience.

Common auditory interaction ways mainly contain verbal and non-verbal form feedback. Aditi et al. developed a mobile GDR called pioneer 3DX robot, which applied simple text-to-speech (TTS) software installed on the robot's laptop for voice output. A similar scheme was used in [83]. Soveny et al. [106] applied auditory interaction intending to warn blind people of surrounding threats. Based on several indicators of the detected obstacle, the traffic analysis module will set a threat level in which frequency is positively correlated with the sound scheme, while the sound volume is inversely proportional to the distance. Once the threat is away from the user's current movement trajectory, the user will be informed of the stereo balance of the sound scheme, coupling with the relative position of the threat.

Compared with auditory interaction, the haptic interaction shows more diversity in hardware form. Vibration feedback is a common way of haptic interaction for its fast and reliable feedback. Adriano et al. [87] made their haptic device formed with a set of two gloves, on which the circuits were developed to the interface BLE device and vibration motor. A visually handicapped person can clearly understand the meaning it informed according to the vibration sequence, which is generated with a specific schema. For instance, the increase of frequency and intensity in the left glove means "quickly go to right", vice versa. Similarly, Katzschmann et al. [107] applied strong frequent pulses of specific direction on the blind guidance belt to indicate that obstacle in this direction is approaching. Lee et al. [108] applied five vibration motors connected with the user's fingers to convey the motion direction intuitively. Wang et al. [91] used the vibration belt cooperating with the mobile GDR to achieve HRI. The difference is that this study maps the depth image space to the haptic space and encodes the motor vibration to prompt the orientation. For example, motor 1, 2, 9, 10 vibration means moving to direction 1, which brings intuitive guidance effect and detailed direction.

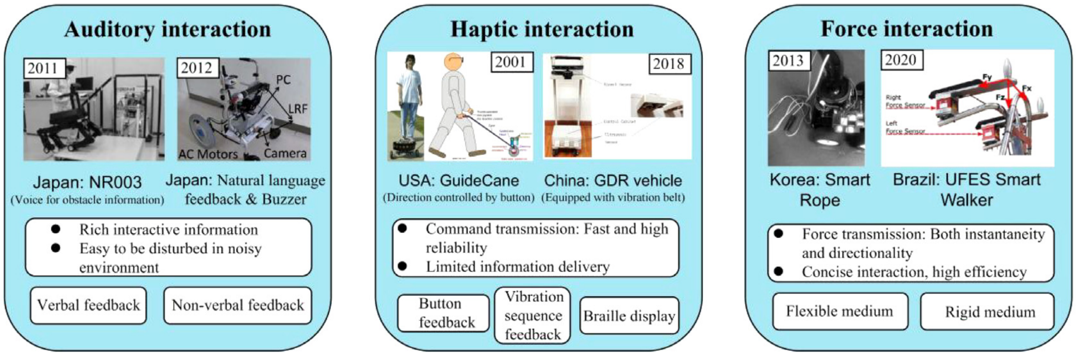

Fig. 2. Typical interaction modes and classification of GDR: Auditory interaction [27,45], haptic interaction [90,91] and force interaction [92,93].

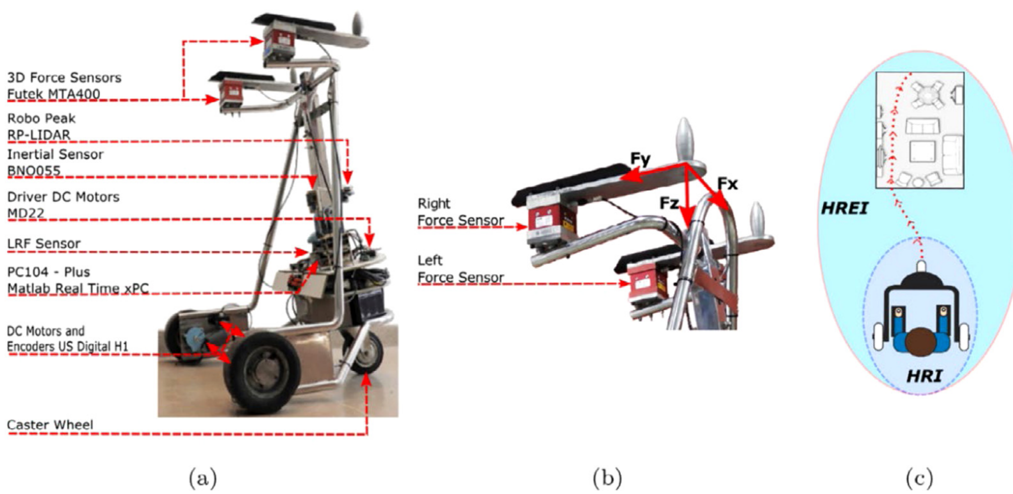

Fig. 3. (a) Smart Walker of UFES/Brazil. (b) Physical interaction system based on force sensors. (c) Interaction layers [92].

In addition to motor vibration feedback, hardware for haptic interaction also includes button and braille display, etc. The button-based HRI tends to be characterized by simple structure and quick response, but the information amount is limited by the button number, such as specific direction [9], position selection [109]. Thus it is difficult to complete the interaction task only by button. It adopted a suitcase handle with vibro-tactile feedback in mobile GDR called CaBot [110], where it was equipped with speed up/down button and vibrator for navigation directions. In this aspect, Braille display reveals more environmental information. Zeng et al. [111] implemented an obstacle detector and a planar tactile display. When the obstacle is closer than 2 meters away from the user, the Wiimote will be vibrating to warn users, coupled with unique information warnings of the Braille display. To render the surrounding obstacles in detail, the study designed a specific layout on the tactile display, attached with tactile obstacle symbols, which represent three attributes about obstacles: type, width, height. Compared with the above motor vibration feedback, it can bring obstacle description, but also increases user's understanding burden to a certain extent.

As a special haptic interaction way, force interaction can transmit key navigation information succinctly and efficiently, even realize the recognition of the walking state of blind people, which has a promising prospect. UFES Smart Walker [92], a mobile GDR for guiding visually handicapped individuals along the desired path (Fig. 3). Under the forearm supporting platforms, it was equipped with a pair of 3D force sensors to detect the user's motion intention. The physical interaction between the user and the UFES Smart Walker was input to the controller to provide haptic feedback hinting the following path. HapticRein [112], an interactive haptic rein for a mobile GDR, it can realize acceleration, deceleration and turning of GDR by detecting the force value fluctuation of the force sensor on handle. A mobile GDR that can be steered by users through a joystick was developed by Dae et al. [96]. Blind people can convey their motion intention by adjusting the direction offset of the joystick. The study points out that users will feel obvious discomfort in their hands and shoulders when walking fast or turning sharply. Therefore, a new Decision of Angular Velocity algorithm (DAV) is proposed to determine the rotation of GDR according to the user's rotation intention. The above interactive media are rigid, while the force interaction based on the rigid medium is not flexible enough. When the movement state of GDR switches, the user's hand will be impacted. Wei et al. [93] proposed a smart rope of bidirectional interaction. Its central part is a hall-sensor joystick which was connected with a rope held by the blind people. As the distance between the master and GDR extends, the force will generate from the rope's tension to the joystick, so as to achieve the dynamic balance of travel speed. Through this rope-connected joystick, GDR can also sense the user's state and motion command.

However, the force value that GDR relies on is inevitably affected by gait-induced disturbances, meaningless motion, and uneven road. F. Jiménez et al. [92] applied a Fourier Linear Combiner (FLC) algorithm to estimate and cancel cadence component of an input signal/ a Weighted-Frequency Fourier Linear Combiner (WFLC) algorithm to remove gait-induced disturbances; Dae et al. [96] proposed New Fuzzy Logic Control (NFLC) to reduce noise signal that is caused by meaningless motion; Wei et al. [93]

Table 2
GDR with corresponding interaction way.

Author	Year	Interaction way	Feedback device	Interactive content
Nguyen et al. [18]	2017	Vibration interaction	A smart phone;	Four vibrations signals
Aditi et al. [15]	2016	Audio interaction	Text-to-speech (TTS) software installed on the robot's laptop	Voices with differing gender, ages, and nationalities
Huang et al. [19]	2017	Vibro-tactile interaction	Vibro-tactile bracelet device	Nine vibration codes which represent the regions of user
Genci et al. [27]	2012	Voice interaction	Speaker	Natural language or beep signal
Runze Chen et al. [94]	2018	Voice interaction	Voice assistant	Synthesis voice
H. Mori et al. [95]	2004	Vibration and voice interaction	Handle with vibrators, speaker	Directional vibration, synthesis voice
Dae et al. [96]	2009	Force interaction	Joystick	Force signals in different directions
Zhang et al. [78]	2015	Speech–audio interaction	Speaker	Synthesis voice
Li et al. [64]	2018	Multi-modal human–machine interaction	Speaker, two vibration motors	Speech–audio, vibration direction and intensity
Lacey et al. [97]	1997	Multi-modal interaction	Joystick, switch that was mounted on the handrail, speaker	Audio feedback, joystick force direction
Kassim et al. [60]	2016	Multi-modal interaction	Braille keypad, headphone, handle	Synthesis voice, braille input
Zhang et al. [98]	2019	Force interaction, voice interaction	Active rolling tip (ART), Bluetooth earphone	The desired direction guided by the active rolling tip, audio messages
Lee et al. [99]	2013	Haptic interaction, voice interaction	Stick with tactile sensor, microphone, speaker sound receiver	Speech information, tactile signal
Cosgun et al. [100]	2014	Haptic interaction	A vibro tactile belt	Two classes of vibration patterns depending on the intended motion
Ulrich et al. [9,90]	2001	Haptic interaction	Thumb-operated mini joystick	Button for motion direction
Zhu et al. [83]	2019	Voice interaction	Speaker	Vocal commands in natural manner
Wu et al. [101]	2016	Voice interaction	Voice broadcast system	The direction to walk and information of surrounding environment
Gomez et al. [102]	2012	Haptic feedback, force feedback	Speaker, joystick	Synthetic speech, force
Yelamarthi et al. [53]	2010	Haptic feedback, voice feedback	Small speaker, a glove with vibration motor	Synthetic speech, the force of middle and ring fingers
Kotani et al. [103]	1996	Haptic feedback, voice feedback	A command bar with a braille key, speaker	Braille key, synthesis voice
Bhatlawande et al. [104]	2014	Intuitive vibration, audio or voice feedback	Two micro-vibration dc motors, speaker	Voice message, vibration of different directions
Liu et al. [105]	2016	Haptic feedback	Vibration tactile wristband device	Vibration motor code representing different directions

applied a fuzzy logic controller to distinguish between small involuntary force and the intended navigational movement.

Generally speaking, a single way of interaction is difficult to meet the demand of the practical application. Usually, a hybrid interaction solution tends to be a good choice. Zöllner et al. [113] have done as follows: micro navigation realized by locating the vibe boards on different directions of the user's waist, macro navigation based on the synthesized voice feedback mechanism. It is reasonable in that rapid vibration is suitable for micro navigation such as obstacle avoidance, synthesized voice can convey macro navigation instructions in detail. The interaction ways involved in multimodal interaction will also be divided into primary and secondary. In this study [114], speech–audio is the primary interaction modality, while in noisy environments, the two vibration motors of SmartCane will instruct the direction of turning, and the vibration intensity will decrease as the target direction approaches. PAM-AID [115] also applied hybrid interaction where the user can indicate their target direction via a joystick and the feedback to the user is transmitted by audio. With multi-modal and multi-task features, HRI is developing to pHRI (physical Human–robot interaction) gradually, showing the potential and feasibility of robot systems for active and safe collaboration with humans [116,117].

More details about the HRI of GDR can be obtained in [118]. Generally speaking, a single interaction way has limitations on the speed and content of information transmission: Auditory interaction can transmit abundant information but with delay, while the information transmission of haptic and force interaction is limited but with fast response and high reliability. The combination of multiple interaction solutions can achieve a comprehensive interactive experience. Besides, how to make GDR actively identify the walking state of the blind and conduct intelligent interaction will be the future trend. We expect to see that after meeting the basic interaction demand, GDR can improve the richness and intelligence of voice interaction, perform greetings, monitor user's physical condition with corresponding feedback, etc.

3.4. Speed coordination

HRI is a two-way interaction between GDR and the blind, while speed coordination, related to the intelligence of GDR, should be defined as a one-way interaction of GDR. Like a guide dog, the walking speed of GDR should coincide with that of their master to ensure the guidance process is coordinated and natural. The advantage of this technology is that GDR actively cooperates with the user's movement process, which reduces the travel burden of visually handicapped individuals to a certain extent.

If speed coordination is maintained unilaterally by blind people, it will bring some inconvenience. H. Mori [95] ever equipped the mobile GDR called RoTA with a start/stop switch and a high/low-speed control switch to meet users' feelings. Nevertheless, some deficiencies inevitably accompany in this solution. First, the state of GDR is entirely controlled by blind users, and the demand to achieve the desired speed is difficult to reach by the switch. The second is that the switch control is not intelligent enough. It must be manually operated to achieve the speed change effect. The function of speed coordination can only be realized by the mobile GDR.

Early on, Tachi et al. [10] have noticed this problem and set up a safety zone detected by ultrasonic sound in their mobile GDR. It is necessary to know the speed of blind people for speed coordination. Several methods were proposed to get it. To keep pace with visually handicapped individuals, Saegusa et al. [119,120] proposed an algorithm to detect walking companions. The study defined a dark blue dashed rectangle area as the footing-recognizing area to monitor the led-person's walking speed. Besides, the user can predefine the distance between the body center and the LRF. Then the GDR can intelligently maintain at this distance. Based on the GDR speed, the relative velocity between the person and the GDR will be used as the criterion for GDR acceleration and deceleration. The speed v_{rz} of GDR in this study is determined as the following rule:

$$v_{rz} = \begin{cases} v_{max} & (d_{fz} < d_{near}) \\ \frac{v_{max}}{d_{stop}-d_{near}}\left(d_{stop} - d_{fz}\right) & (d_{near} < d_{fz} < d_{stop}) \\ 0 & (d_{stop} < d_{fz}) \end{cases} \quad (1)$$

Where v_{max}, d_{fz}, d_{near}, d_{stop} are maximum leading speed of the mobile GDR, the real-time distance between the follower and the GDR, the set distance between the follower and the GDR when the robot reaches v_{max}, the set distance between the follower and the GDR when the GDR needs to stop to wait for the follower, respectively.

There are also speed sensors installed on users to detect their movement status. While complying with the user's walking requirements, mobile GDR also needs to autonomously monitor the user's walking state to determine the walking demand. In this way, it will be more intelligent. As is mentioned earlier, the smart rope coupled with the hall-sensor joystick [93] can also complete this mission, while the difference is that this study applied the force fluctuation to transmit the acceleration/ deceleration demand of the visually handicapped users, rather than relative speed change. Further, Cho et al. [121] developed the "intelligent lead" for the mobile GDR to acquire a stable distance and control speed. The critical point is that it can adjust the movement state according to the position of the user's hand, in line with the habit of people holding dogs. Actually, it fused the data acquired through the serial linkage, Kinect and IMU sensor with the Extended Kalman Filter EKF for acquiring hand position.

Desai et al. [122] proposed a leader–follower control model which is widely used in multi-robot formation control, providing the theoretical basis for the speed coordination of mobile GDR.

3.5. Walking structure design

Due to the complex path situation, mobile GDR has to be faced with whether to avoid or cross the obstacle. Worse, considering the frequent work on rugged blind tracks, mobile GDR must adapt to various pavement shapes. It inevitably puts forward higher demand for its structural performance. The traditional wheel structure is prone to cause bumps and even rollover of GDR when faced with obstacles, while on the flat road surface, the moving effect of legged GDR is not so smooth as the wheeled GDR, coupling with a more significant technical challenge. Hence, optimization of the GDR walking structure has become necessary to cope with the uncertainty of the road condition. Here, we have concluded several typical structures of mobile GDR.

Combined with the wheeled type and the legged type, the wheel-leg structure of mobile GDR was published [123]. As shown: four mecanum wheels are assembled for convenient turning. Each leg with 6 degrees of freedom can be driven by steering gear. The wheel-leg structure GDR can freely turn into a switch between the two working modes according to the road condition. In detail, when crossing the flat road section, the wheel mode will be adopted, while the uneven road section strewn with obstacles will be switched to four legs. Based on this structure, mobile GDR can even achieve the operation of going up and down stairs, such as a guide-dog style robot developed by NSK [124]. Equipped with a sensor*2, when ascending and descending a staircase, it can limit contact with uneven terrain with a secure stop for stable movement and safe guidance. The following walking mechanism designed [125] is described as three wheel-bodies structure. When encountering the low obstacle, the wheel frame will rotate relative to the wheel axis under the obstruction of an obstacle. The result is that the rear wheel body rotates to the top while the top wheel body rotates to the bottom. Duan et al. [126] applied a kind of walking structure in mobile GDR that can walk on complicated streets. The adopted walking structure was an anti-overturning crawler mechanism, equipped with the anti-drop chain device, with the structural feasibility verified. The mechanism structure effectively lowers the gravity center of the robot for higher stability. Hence it can climb over-100 mm-high obstacles and gullies smaller than 200 mm wide, ensuring the robot's ability to pass through complex terrain and smoothness of movement.

Similarly, the GDR walking structure equipped with two kinds of convertible crawlers was designed for climbing ladders [127]. However, it seems that the crawler mechanism is suitable for the soft terrain, while the advantage in the city environment seems not to be noticeable. Further, a mobile chassis [128] for GDR equipped with shock absorber for smaller collision vibration and longer life is protective for its structure.

Besides, a self-lifting obstacle-crossing GDR [129] that can walk quickly and safely on a flat road has been proposed. The mobile GDR adopted a new type of linkage mechanism. When the height of the obstacle is more than 200 mm, the GDR will retreat L to ensure that its medium body does not collide with the shoulder in the process of crossing the shoulder. Then the front and rear obstacle surmounting mechanism will press down under the drive of the motor, resulting in the action of supporting the ground, with the gravity center of the robot body raised accordingly. By taking advantage of the high maneuverability, good stability, and smooth operation of the four rotors, blind guidance navigation was established [130]. It can achieve all-around, high-precision, and perfect obstacle avoidance navigation. The test indicated that blind users could almost rely on the four rotors navigation system to complete outdoor travel. The movement of InviGBot is realized with three legs, decreasing the cost of the materials and power consumption. This design feature allows for effective movement on uneven surfaces where the wheeled structure poses more difficulties [131].

So far, most mobile GDRs have adopted the wheeled structure for its relatively simple technology and mature control. Yet, it reduces the appearance features of mobile GDR for more similarity to a smart car. Except for appearance, the groundbreaking structural optimization will allow GDR to run smoothly on most road surfaces, furtherly enhances the operational reliability of mobile GDR. It is feasible to choose a suitable mechanism based on different situations. If the mobile GDR is often allowed to guide the user up and down stairs, undoubtedly, leg structure is a better choice. Nevertheless, it is not ruled out that the task of moving GDR up and down stairs can be realized through the wheel structure, Campos et al. [132] proposed a conceptual design of mobile GDR showing the climbing stairs task. The optimization design of the structure has reduced the difficulty of robot climbing-stairs technology to some extent.

To some extent, it shares similarities with other autonomous vehicles in structure design, such as autonomous agricultural vehicles. It is enlightening to take the indexes of ground pressure, the complexity of design and development, maneuverability, and so on as additional considerations [133].

4. Directions and challenges

As the alternative to the guide dog, GDR can naturally realize the primary features of a guide dog. According to the preliminary study [134], the main features of a guide dog can be described as follows:

(1) Walk, turn and avoid obstacles;
(2) Guide visually handicapped person to the destination;
(3) Have the interaction function to understand the user's ideas and inform them of the road situation;
(4) Keep the pace coordinated with their masters;
(5) Be alert to dangerous environments;
(6) Obey masters' orders (except in particular situation);
(7) Understand and assist the master in using transportation facilities such as bus and elevator;
(8) Essential ability including attention, environmental adaptability, ability to remember the familiar segments and emergency response capability.

From the above content, it is visible that existing GDR can indeed complete major missions of a guide dog, even with the features that guide dogs do not have. To a certain extent, the maturity of GDR development has been affirmed. Yet functional integrity cannot be directly equal to the performance of GDR. The real-time performance of obstacle avoidance function, the fluency of HRI, the accuracy of target recognition, and so on are worthy of concern, for more perfect the function of GDR, more likely visually handicapped individuals to integrate into the society independently. There is no doubt that no blind people want to be guided by a rigid robot. Therefore, it is the general trend to promote the intellectualization of the GDR blind guidance system.

Nowadays, collaborative human–robot mode plays an even more critical role in the new generation of intelligent robots [135]. For GDR, to realize harmonious coexistence, except for navigating to the desired destination, comfortability and adaptation is especially worth focus. It means that GDR will judge the user's current status and motion intention from sensor data, such as force signal, vision, natural language, then the action it imposes has to conform with the cognitive habits of people. It will be paid attention to that GDR should actively understand people.

4.1. Intelligent interactive performance

A general concern about HRI is to keep the pace of mobile GDR and visually handicapped people coordinated, which is the most humanized feature of a guide dog in work. Making blind and visually handicapped people feel secure is the potential task of GDR. Relative solutions have been proposed to solve this problem, as referred to in Section 3.4.

Besides maintaining speed coordination, the interactive experience in navigation during walking should be as natural and concise in key information convey as possible. In this regard, the force interaction based on cable is a good choice, which cannot only simulate the traction state of the guide dog naturally but also transmit the motion demand flexibly. A similar study has been involved. The aerial vehicle proposed by [136] was capable of safely guiding the human to the desired position or along a desired path by pulling the tether.

Inspired by relevant research, an interactive solution will be proposed where a flexible cable is used as a bridge between mobile GDR and blind people. In the process of common navigation, just like a guide dog, users can express acceleration, deceleration, turning, or other demands through the transmission of force signals. This kind of HRI is not easy to be affected by the environment and responds quickly. Also, the flexible structure promotes a comfortable interactive experience. Based on the deep neural network, the flexible cable can convey the user's movement intention and speculate the user's movement state and mood by analyzing the fluctuation law of the force signal. It is a promising interaction mode. Hopefully, in the process of revising this manuscript, Xiao et al. [137] proposed the leash-guided mobile GDR and built end-to-end hybrid physical human–robot interaction (hybrid-pHRI) framework, including taut mode and slack mode. The flexible interaction mode physically helps guide the person with a safe and efficient trajectory in a narrow space.

Another necessity is the interactive content and method need to be enriched, for it is directly related to the intelligence of GDR, the interaction of GDR should include the following aspects [47]. Firstly, it should consider multi-modal input/output. Multiple input methods including voice, handwriting, gesture, sight, expression, and braille keyboard, while multiple output methods include voice, text, graphics, and expressions, etc. Secondly, an intelligent interface agent, the media of HRI described as humanized software entity, is expected to realize the interaction task between blind people and GDR. Then, it is necessary to rich the

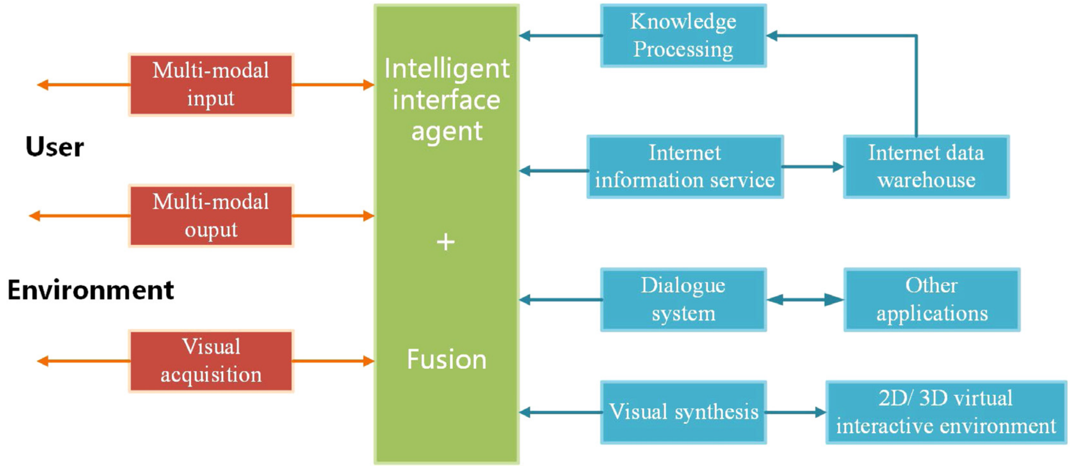

Fig. 4. Intelligent interactive system architecture diagram proposed by Chen [47].

voice interaction content where the scene in front of the blind people can be described in detail, which can make up for the blind person's lack of surrounding information perception. To a certain degree, it can restore the function of the eyes as much as possible, not just navigation, it can make blind people envision the surrounding world. Further, it is also feasible to capture the facial expressions and gestures of the dialog person to inform the user when he is chatting, which is beneficial to improve the social skills of visually handicapped people. A complete GDR intelligent human–computer interaction model should be as shown in Fig. 4.

4.2. Real-time information collection

Additionally, for the safety of blind navigation, it is necessary for GDR to send real-time information of the visually handicapped people to the upper computer, to monitor their body condition in real-time and ensure their safety.

Further, real-time data can also enhance safety. If the user falls, is hit, or other accidents occur, GDR should alarm in time to get help from the surrounding environment and inform the family of the current situation in time. It is expected that GDR can develop into a travel assistant for visually handicapped people in the future, for instance, real-time monitoring of the user's travel information, health status, as a reminder of travel conditions and weather, etc., to bring convenience to personalized services. A service robot integrated with various features based on big data analysis will be the goal of GDR development.

Some popular technologies will assist GDR in enriching user information collection and shape a more intelligent service robot. Emotion recognition, a relatively high level of intelligence, can be explicitly available, including extrinsic (such as voice, gesture, and facial expression) and intrinsic (such as heartbeat, pulse, breathing, and body temperature) information. But it is difficult to match such expression signals with emotional characteristics and then determine the proportions of different emotional information. Hence, realizing real-time emotion monitor by GDR is quite a challenge in the distant future. Nowadays, it is more feasible to obtain some physical indicators and walking intentions of blind people through GDR in real-time.

4.3. Blind guidance in public transportation

Even with the consistent focus on the realization of GDR functions, most researches on GDR tend to dismiss the research for mobile GDR to assist the users to take transportation like bus and elevator, etc. The explanation is that the spital layout of the vehicle environment is quite complex and often accompanied by the flow of multiple people.

Moreover, the operation of getting on and off the bus and the steps, etc., poses a great challenge to the high-quality mobile GDR. Cai et al. [138] proposed a GDR with its alarm system for public transportation in the form of a cane. When in danger, it can also alert the surrounding people in time for help or send alarm information to the alarm management platform. However, it does not solve the problem of leading blind people to get on and off. Mobile GDR leading blind people to take transportation facilities, whether bus subway or stairs, has to step over the threshold, so it ought to have the competence to climb the stairs. First, the stairs need to be identified accurately, distinguished from the sidewalk, relying on the accurate camera and advanced recognition algorithm. Then, some distinctive structure designs such as leg structure can effectively target the scene of climbing stairs. The built-in anti-shake algorithm is also needed to effectively solve the problem of visual jitter caused by the motion of the body, thus ensuring the robustness and safety of the GDR's autonomous movement. Meanwhile, the change of gravity center position of GDR should also be considered in the design stage. It has to be said that how to make GDR up and down stairs is such a challenging and promising technology for the combination of multiple technologies. Another solution is to reduce the weight of mobile GDR so that blind people can carry it up and down stairs. While the richness of function is bound to lead to an increase in weight, keeping the balance is the key.

4.4. Multi-GDR collaboration and information exchange

Nowadays, only limited environmental information can be observed by a single GDR. As the range of position environment extends, it is quite challenging to detect such a vast space due to the limitation of the sensor's observation range. Therefore, multi-robot cooperative SLAM is relatively easy to solve this problem, which will become a focus of subsequent research. This idea was first proposed by Chen and his research group of Jiangsu University of Science and Technology [47].

It is expected that a GDR information coverage community will be built in the future. In this case, data exchange and collaboration will be carried out among multiple GDRs within the community to expand the blind area and guide area of a single GDR, ultimately improving the accuracy and efficiency of guidance, realizing data exchange and mutual learning between GDRs. However, the advantage of a multi-GDR system is based on the cooperation between single GDRs, so there exists coupling between GDR individuals and the critical technology is more complicated than a single GDR system.

In the future, mobile GDR will become a part of smart transportation in the city. Based on the Internet of the vehicle system, mobile GDR can exchange information with running vehicles. On the one hand, GDR can avoid some visible obstacles through its environment detection system. On the other hand, the traffic data obtained through the Internet of vehicles, including the speed, distance, traffic light conditions of nearby vehicles, etc., can be calculated and processed by mobile GDR according to the traffic information to make safe and efficient guidance. In addition to the traffic information of vehicles, as mentioned above, the guidance information of multiple GDRs can also be interconnected, which will be of great benefit to the building of the cooperative GDR traffic system.

As 5G technology develops, it has achieved a significant leap in data transmission speed. It means that plenty of traffic data information will be transmitted to the cloud by 5G technology for storage and processing, effectively solving the problems of limited storage capacity and slow calculation speed of a single GDR.

4.5. Intelligent disobedience

As mentioned before, one feature that the guide dog perceives is to obey master's orders except in particular situations, defined as intelligent disobedience. Intelligence does not only mean that the GDR will abide by the user's command absolutely but also shown as disobedience to the invalid or dangerous command.

Since visually handicapped people's perception of the world is not comprehensive enough, it is inevitable when he gives wrong instructions to GDR. For example, if the user allows the GDR to cross the street based on his auditory judgment of no running cars, but the traffic light is red, at this time, the mobile GDR needs to disobey his command and explain the situation in detail. As to the order concerning personal safety, it is absolutely not feasible for GDR to execute fully.

As an essential function of a guide dog, this point has not attracted enough attention so far. The main reason may be that the interaction technology of GDR is not yet mature enough to communicate with blind people fluently. Once the HRI level between blind people and GDR reaches a certain level, it will lead to the above contradiction. Hence, it is likely to be a big challenge shortly and a problem that must be considered in robot development.

5. Conclusion

Based on GDR-related research, a review is presented combined with objective descriptions and subjective comments. After several years of development, GDR has been verified feasible to serve in the indoor environments and a series of complex outdoor environments. The key technologies were elaborated in detail: localization and navigation technology, recognition of traffic signs, HRI, speed coordination, and walking structure design. Among them, HRI and speed coordination will be the research trend as the unique characteristic of GDR. Many effective results in this aspect have been achieved so far. In the end, current challenges and directions are expounded. It is expected to trigger some enlightening thoughts on promoting the development of GDR. In the future, collaborative human–robot mode and multi-GDR collaboration will be the development trend. Hence, real-time information of blind users is required to infer their state for better service.

Indeed, evaluating the work presented in the paper, the existing GDR can already complete most of the missions of a guide dog. However, most GDRs have not been put into use, mainly due to the following reasons:

(1) Visually handicapped, especially blind groups, generally do not get enough attention from the external world.
(2) To a certain extent, many GDRs definitely obtain the function of a guide dog, while in terms of performance, such as dynamic obstacle avoidance ability, coordinated guidance ability, technical reliability, etc., they may not be as good as a traditional guide dog.
(3) Few studies considered setting up an emergency procedure for GDR in danger. It will make users feel uneasy. Attention should be paid to the detection and solution of accidents such as fall, collision and machine failure, etc.
(4) Like self-driving cars, some ethical problems at the engineering level are hard to cope with, such as the division of responsibilities after the accident of GDR navigation.

Further, compared with a guide dog, GDR has a bright future not only for low cost and easy to produce but also for its irreplaceable function. GDR can realize the navigation to unknown locations, while common guide dogs cannot. GDR can transmit state information of blind people to their family in real-time through the online platform, which is more secure, in contrast, a guide dog cannot provide such a guarantee. Also, it is no need to consider the problems of GDR attention and environmental adaptability. Even when it comes to interaction effect in some scenarios, GDR will perform better than a guide dog to some extent, for a guide dog cannot communicate with the blind in human language after all. It is expected to build an equal, non-discriminatory, and friendly world for blind people based on the maturity of GDR function in the future.

Declaration of competing interest

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References

[1] M.H. Hu, et al., An overview of assistive devices for blind and visually impaired people, Int. J. Robot. Autom. 34 (5) (2019) 580–598.
[2] M. Gori, et al., Devices for visually impaired people: High technological devices with low user acceptance and no adaptability for children, Neurosci. Biobehav. Rev. 69 (2016) 79–88.
[3] I. Sielicki, Z. Bartkowski, J. Bartkowska, Significance of colors and contrasts in the life of visually impaired, optical sensing for public safety, Health Secur. 4535 (2001) 41–44.
[4] J.R. Evans, A.E. Fletcher, R.P.L. Wormald, Depression and anxiety in visually impaired older people, Ophthalmology 114 (2) (2007) 283–288.
[5] R.R.A. Bourne, et al., Magnitude, temporal trends, and projections of the global prevalence of blindness and distance and near vision impairment: A systematic review and meta-analysis, Lancet Global Health 5 (9) (2017) E888–E897.
[6] C. Yifei, Application status of guide dogs in China, China Work. Dog (11) (2016) 54–56.
[7] J.A. Murphy, Describing categories of temperament in potential guide dogs for the blind, Appl. Anim. Behav. Sci. 58 (1–2) (1998) 163–178.
[8] L.S. Batt, et al., Factors associated with success in guide dog training, J. Vet. Behav. Clin. Appl. Res. 3 (4) (2008) 143–151.
[9] I. Ulrich, J. Borenstein, The GuideCane-applying mobile robot technologies to assist the visually impaired, IEEE Trans. Syst., Man Cybern. A : Syst. Hum. 31 (2) (2001) 0–136.
[10] S. Tachi, et al., Study on guide dog (seeing-eye) robot, I. Basic plan and some experiments with MELDOG MARK I, Bull. Mech. Eng. Lab. (32) (1978) 1–12.
[11] S. Tachi, Guide dog robot, in: International Symposium of Robotics Research, 1984.
[12] Guide Dog Robot (MELDOG). Available from: https://tachilab.org/en/projects/meldog.html#point04.
[13] S. Tachi, et al., Electrocutaneous communication in a guide dog robot (MELDOG), IEEE Trans. Bio-Med. Eng. 32 (7) (1985) 461.
[14] Z. Jingjing, et al., Design and implementation of guide dog robot, Mechatronics (04) (2005) 22–25.

[15] A. Kulkarni, et al., Robotic assistance in indoor navigation for people who are blind, 2016.
[16] C. Chen, Z. Jin, Z. Yang, Integrated design of a RFID-based interior voice guide seeing eyes robot, J. Jiangsu Univ. Sci. Technol. (Natural Science Edition) (05) (2012) 494–499.
[17] L. Yang, Research on Navigation Technology for Indoor Walking Aid Robot, Harbin Institute of Technology, 2014.
[18] Q.H. Nguyen, et al., Developing a way-finding system on mobile robot assisting visually impaired people in an indoor environment, Multimedia Tools Appl. 76 (2) (2016) 1–25.
[19] P. Huang, G. Song, Y. Jian, An indoor navigation service robot system based on vibration tactile feedback, Int. J. Soc. Robot. 9 (3) (2017) 331–341.
[20] A.M. Kassim, et al., Indoor navigation system based on passive RFID transponder with digital compass for visually impaired people, Int. J. Adv. Comput. Sci. Appl. 7 (2) (2016).
[21] T.A. Alhmiedat, A. Abutaleb, G. Samara, A prototype navigation system for guiding blind people indoors using NXT mindstorms, Int. J. Online Eng. 9 (5) (2013) 52.
[22] V. Kulyukin, et al., Robot-assisted wayfinding for the visually impaired in structured indoor environments, Auton. Robots 21 (1) (2006) 29–41.
[23] D. Du, J. Xu, Y. Wang, Obstacle recognition of indoor blind guide robot based on improved D-S evidence theory, J. Phys. Conf. Ser. 1820 (1) (2021) 012053, 5pp.
[24] T.T. Khanh, et al., The practice of cloud-based navigation system for indoor robot, in: 2020 14th International Conference on Ubiquitous Information Management and Communication, IMCOM, 2020.
[25] A. Nanavati, X.Z. Tan, A. Steinfeld, Coupled indoor navigation for people who are blind, in: Companion of the Acm/Ieee International Conference, 2018.
[26] S. Kayukawa, et al., BlindPilot: A Robotic local navigation system that leads blind people to a landmark object, in: CHI '20: CHI Conference on Human Factors in Computing Systems, 2020.
[27] G. Capi, Development of a new robotic system for assisting and guiding visually impaired people, in: IEEE International Conference on Robotics & Biomimetics, 2012.
[28] M. López, et al., A navigation system for assistant robots using visually augmented POMDPs, Auton. Robots 19 (1) (2005) 67–87.
[29] C. Feng, S. Azenkot, M. Cakmak, Designing a robot guide for blind people in indoor environments, in: 10th Annual ACM/IEEE International Conference on Human-Robot Interaction, HRI 2015, March 2, 2015 - March 5, 2015, IEEE Computer Society, Portland, OR, United states, 2015.
[30] H. Hsieh-Chang, H. Ching-Tang, Y. Cheng-Hsiang, An indoor obstacle detection system using depth information and region growth, Sensors 15 (10) (2015) 27116–27141.
[31] L.A. Guerrero, F. Vasquez, S.F. Ochoa, An indoor navigation system for the visually impaired, Sensors (2012).
[32] W. Simões, V. Lucena Jr., Blind user wearable audio assistance for indoor navigation based on visual markers and ultrasonic obstacle detection, 2016.
[33] V. Kulyukin, C. Gharpure, J. Nicholson, RoboCart: Toward robot-assisted navigation of grocery stores by the visually, in: Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on, 2005.
[34] K. Duarte, J. Cecílio, P. Furtado, Overview of assistive technologies for the blind: Navigation and shopping, in: International Conference on Control Automation Robotics & Vision, 2015.
[35] M.C. Domingo, An overview of the internet of things for people with disabilities, J. Netw. Comput. Appl. 35 (2) (2012) 584–596.
[36] .J.A. Rumipamba, et al., Prototype of guide robot using marks in dynamic environments for visually impaired people, in: 2019 International Conference on Image and Video Processing, and Artificial Intelligence, 23-25 Aug. 2019, SPIE, USA, 2019.
[37] V. Kulyukin, C. Gharpure, D. Coster, Robot-assisted shopping for the visually impaired: Proof-of-concept design and feasibility evaluation, Assist. Technol. 20 (2) (2008) 86–98.
[38] V. Kulyukin, Robot-assisted shopping for the blind: Haptic and locomotor spaces in supermarkets, 2006.
[39] V. Kulyukin, J. Nicholson, D. Coster, Shoptalk:toward independent shopping by people with visual impairments, in: International Acm Sigaccess Conference on Computers & Accessibility, 2008.
[40] J. Nicholson, J.c. Edu, V. Kulyukin, ShopTalk: independent blind shopping=verbal route directions+ barcode scans, 2007.
[41] T. Trongwongsa, et al., Shopping navigation system for visual impaired people based on proximity-based technology, in: International Joint Conference on Computer Science & Software Engineering, 2015.
[42] D. López-de Ipia, T. Lorido, U. López, Indoor navigation and product recognition for blind people assisted shopping, in: Ambient Assisted Living - Third International Workshop, IWAAL 2011, Held At IWANN 2011, Torremolinos-MáLaga, Spain, June (2011) 8-10. Proceedings, 2011.
[43] Kazuteru, et al., Examination of a guidance robot for visually impaired people, J. Robot. Mechatronics (2017).
[44] K. Tobita, et al., Structure and examination of the guidance robot LIGHBOT for visually impaired and elderly people, J. Robot. Mechatronics 30 (1) (2018) 86–92.
[45] G. Capi, H. Toda, A new robotic system to assist visually impaired people, in: Ro-Man, 2011.
[46] X. Zuohua, H. Bing, Research and analysis of blind guide robot in urban rail station, Sci. Technol. Inf. (14) (2013) 6.
[47] C. chen, Positioning and Path Planning Technology of Blind Guidacne Robot, National Defense Industry Press, 2015.
[48] M.A. Yousuf, et al., Social interaction with visitors: mobile guide robots capable of offering a museum tour, IEEJ Trans. Electr. Electron. Eng. 14 (12) (2019).
[49] D.R. Bruno, M.H. De Assis, F.S. Osorio, Development of a mobile robot: Robotic guide dog for aid of visual disabilities in urban environments, in: 16th Latin American Robotics Symposium, 7th Brazilian Symposium on Robotics and 10th Workshop on Robotics in Education, LARS/SBR/WRE 2019, October 23, 2019 - October 25, 2019, Institute of Electrical and Electronics Engineers Inc., Rio Grande, Brazil, 2019.
[50] To develop electronic guide dog, Doogo wants to make it easier for blind people to travel. Available from: https://36kr.com/p/1721261735937.
[51] D.O. Kang, et al., Multiobjective navigation of a guide mobile robot for the visually impaired based on intention inference of obstacles, Auton. Robots 10 (2) (2001) 213–230.
[52] J. Xiao, et al., An assistive navigation framework for the visually impaired, IEEE Trans. Hum.–Mach. Syst. 45 (5) (2015) 635–640.
[53] K. Yelamarthi, et al., RFID and GPS integrated navigation system for the visually impaired, in: 53rd IEEE International Midwest Symposium on Circuits and Systems, MWSCAS 2010, August 1, 2010 - August 4, 2010, Institute of Electrical and Electronics Engineers Inc., Seattle, WA, United states, 2010.
[54] L. Ran, S. Helal, S. Moore, Drishti: An integrated indoor/outdoor blind navigation system and service, in: Proceedings - Second IEEE Annual Conference on Pervasive Computing and Communications, PerCom 2004, March 14, 2004 - March 17, 2004, Institute of Electrical and Electronics Engineers Computer Society, Orlando, FL, United states, 2004.
[55] G. Capi, M. Kitani, K. Ueki, Guide robot intelligent navigation in urban environments, Adv. Robot. 28 (15) (2014) 1043–1053.
[56] R.K. Megalingam, et al., Autonomous path guiding robot for visually impaired people, in: International Conference on Cognitive Informatics and Soft Computing, CISC 2017, December 20, 2017 - December 21, 2017, Springer Verlag, Hyderabad, India, 2019.
[57] H. Ogawa, et al., A guidance robot for the visually impaired: System description and velocity reference generation, 2014.
[58] Y. Yasuda, L. Martins, F. Cappabianco, Autonomous visual navigation for mobile robots, ACM Comput. Surv. 53 (1) (2020) 1–34.
[59] Plikynas, et al., Indoor navigation systems for visually impaired persons: Mapping the features of existing technologies to user needs, Sensors 20 (3) (2020) 636.
[60] A.M. Kassim, et al., Indoor navigation system based on passive RFID transponder with digital compass for visually impaired people, Int. J. Adv. Comput. Sci. Appl. 7 (2) (2016) 604–611.
[61] C. Chao, J. Zuguang, T. Jian, Navigation and localization strategy of seeing eyes robot using LF and UHF RFID tags, China Mech. Eng. 25 (8) (2014) 1059–1064.
[62] J. Na, The Blind Interactive Guide System using RFID-Based Indoor Positioning System, Springer Berlin Heidelberg, 2006.
[63] C. Loconsole, et al., An IMU and RFID-Based Navigation System Providing Vibrotactile Feedback for Visually Impaired People, Springer, Cham, 2016.
[64] Bing, et al., Vision-based mobile indoor assistive navigation aid for blind people, IEEE Trans. Mob. Comput. (2018).
[65] Y.H. Lee, G. Medioni, Wearable RGBD indoor navigation system for the blind, in: European Conference on Computer Vision, 2014.
[66] Y. Shang, et al., Localization from connectivity in sensor networks, 2004.
[67] A. Meliones, D. Sampson, Blind MuseumTourer: A system for self-guided tours in museums and blind indoor navigation, Technologies 6 (1) (2018).
[68] Loadstone GPS. Available from: http://www.loadstone-gps.com.
[69] Seeing Eye GPS. Available from: http://www.senderogroup.com/products/shopseeingeyegps.html.
[70] J. Balata, Z. Mikovec, P. Slavik, Landmark-enhanced route itineraries for navigation of blind pedestrians in urban environment, J. Multimodal User Interfaces 12 (3) (2018) 1–18.
[71] M.M. Islam, et al., Developing walking assistants for visually impaired people: A review, IEEE Sensors J. 19 (8) (2019) 2814–2828.
[72] L. Zhi, Simultaneous Localization and Mapping for Guide Robot Based on Multisensor (Master thesis), Jiangsu University of Science and Technology, 2017.
[73] C. Yu, S. Li, Q. Li, Study on blind-guiding robot based on STM32 embedded systems, 2016.

[74] Y. Zhao, R. Huang, B. Hu, A multi-sensor fusion system for improving indoor mobility of the visually impaired, in: 2019 Chinese Automation Congress, CAC, 2019.
[75] S.R.S. Krishnan, Robotic wheelchair to guide elderly and visually impaired people, in: IEEE International Conference on Technologies for Practical Robot Applications, 2009.
[76] Liu, et al., Local path planning algorithm for blind-guiding robot based on improved DWA algorithm, in: The 31st Chinese Control and Decision Conference, 2019CCDC.
[77] L. Bing, et al., ISANA: Wearable Context-Aware Indoor Assistive Navigation with Obstacle Avoidance for the Blind, Springer International Publishing, 2016.
[78] X. Zhang, et al., A SLAM based semantic indoor navigation system for visually impaired users, in: 2015 IEEE International Conference on Systems, Man, and Cybernetics, SMC, 2015.
[79] X. Zhang, A wearable indoor navigation system with context based decision making for visually impaired, Int. J. Adv. Robot. Autom. 1 (2016) 1–11.
[80] C. Chao, et al., A path planning algorithm fbr seeing eye robots based on V-Graph, Mech. Sci. Technol. Aerosp. Eng. (04) (2014) 28–33.
[81] X. Zhang, et al., An ARCore based user centric assistive navigation system for visually impaired people, Appl. Sci. 9 (5) (2019).
[82] W. Zhengbo, M. Xing, M. Chunyang, Research on intelligent speech guide robot control method based on machine vision, in: 2019 3rd International Conference on Artificial Intelligence Applications and Technologies, AIAAT 2019, 1-3 Aug. 2019, IOP Publishing, UK, 2019.
[83] J. Zhu, et al., An edge computing platform of guide-dog robot for visually impaired, in: 14th IEEE International Symposium on Autonomous Decentralized Systems, ISADS 2019, April 8, 2019 - April 10, 2019, Institute of Electrical and Electronics Engineers Inc., Utrecht, Netherlands, 2019.
[84] T. Zhichao, et al., Research on traffic sign visual recognition technology of guiding robot, Comput. Technol. Dev. 000 (9) (2014) 23–27.
[85] Q. Chen, et al., Traffic light and moving object detection for a guide-dog robot, in: 3rd Asian Conference on Artificial Intelligence Technology, ACAIT 2019, July 5, 2019 - July 7, 2019, Institution of Engineering and Technology., Chongqing, China, 2020.
[86] Y. Wei, M. Lee, A guide-dog robot system research for the visually impaired, in: 2014 IEEE International Conference on Industrial Technology, ICIT 2014, February 26, 2014 - March 1, 2014, Institute of Electrical and Electronics Engineers Inc., Busan, Korea, Republic of, 2014.
[87] A. Mancini, E. Frontoni, P. Zingaretti, Mechatronic system to help visually impaired users during walking and running, IEEE Trans. Intell. Transp. Syst. 19 (2) (2018) 649–660.
[88] F. Cocchioni, et al., Visual based landing for an unmanned quadrotor, J. Intell. Robot. Syst.: Theory Appl. 84 (1–4) (2016) 511–528.
[89] R. De Charette, F. Nashashibi, Real time visual traffic lights recognition based on spot light detection and adaptive traffic lights templates, in: 2009 IEEE Intelligent Vehicles Symposium, June 3, 2009 - June 5, 2009, Institute of Electrical and Electronics Engineers Inc., Xi'an, China, 2009.
[90] S. Shoval, Navbelt and the guidecane, IEEE Robot. Autom. Mag. (2003) 10.
[91] R. Wang, X. Li, T. Chen, A walking assistant system for the visually impaired based on tactile perception, J. Shanxi Datong Univ. (Natural Science Edition) 34 (05) (2018) 16–19.
[92] M.F. Jimenez, et al., Assistive locomotion device with haptic feedback for guiding visually impaired people, 2020.
[93] Y. Wei, X. Kou, C.L. Min, Smart rope and vision based guide-dog robot system for the visually impaired self-walking in urban system, in: IEEE/ASME International Conference on Advanced Intelligent Mechatronics, 2013.
[94] R. Chen, et al., Construction of a voice driven life assistant system for visually impaired people, in: 2018 International Conference on Artificial Intelligence and Big Data, ICAIBD 2018, May 26, 2018 - May 28, 2018, Institute of Electrical and Electronics Engineers Inc., Chengdu, China, 2018.
[95] H. Mori, et al., The matching fund project for practical use of robotic travel aid for the visually impaired, Adv. Robot. 18 (5) (2004) 453–472.
[96] D.Y. Kim, K.Y. Yi, A user-steered guide robot for the blind, in: 2008 IEEE International Conference on Robotics and Biomimetics, ROBIO 2008, February 21, 2009 - February 26, 2009, IEEE Computer Society, Bangkok, Thailand, 2008.
[97] G. Lacey, Evaluation of robot mobility aid for the elderly blind, 1997.
[98] H. Zhang, C. Ye, Human-robot interaction for assisted wayfinding of a robotic navigation aid for the blind, in: 12th International Conference on Human System Interaction, HSI 2019, June 25, 2019 - June 26, 2019, IEEE Computer Society., Richmond, VA, United states, 2019.
[99] M.-F.R. Lee, F.H.S. Chiu, C. Zhuo, Novel design of a social mobile robot for the blind disabilities, in: 2013 6th IEEE/SICE International Symposium on System Integration, SII 2013, December 15, 2013 - December 17, 2013, IEEE Computer Society, Kobe, Japan, 2013.
[100] A. Cosgun, E.A. Sisbot, H.I. Christensen, Evaluation of rotational and directional vibration patterns on a tactile belt for guiding visually impaired people, in: 2014 IEEE Haptics Symposium, HAPTICS, 2014.
[101] T.-F. Wu, et al., Intelligent wheeled mobile robots for blind navigation application, Eng. Comput. (Swansea Wales) 34 (2) (2017) 214–238.
[102] J.V. Gomez, F.E. Sandnes, RoboguideDog: Guiding blind users through physical environments with laser range scanners, Procedia Comput. Sci. 14 (Complete) (2012) 218–225.
[103] S. Kotani, H. Mori, N. Kiyohiro, Development of the robotic travel aid 'HITOMI', Robot. Auton. Syst. 17 (1–2) (1996) 119–128.
[104] S. Bhatlawande, et al., Design, development, and clinical evaluation of the electronic mobility cane for vision rehabilitation, IEEE Trans. Neural Syst. Rehabil. Eng. 22 (6) (2014) 1148–1159.
[105] Z. Liu, et al., Mobile robotic navigation system for human based on vibro-tactile perception, J. Southeast Univ. (Natural Science Edition) 46 (5) (2016) 1013–1019.
[106] B. Soveny, G. Kovacs, Z.T. Kardkovacs, Blind guide - a virtual eye for guiding indoor and outdoor movement, in: Cognitive Infocommunications, 2015.
[107] R. Katzschmann, B. Araki, D. Rus, Safe local navigation for visually impaired users with a time-of-flight and haptic feedback device, IEEE Trans. Neural Syst. Rehabil. Eng. PP (99) (2018) 1.
[108] D. Li, J. Lu, Tactile navigation system using a haptic device, Inst. Control, Robot. Syst. (ICROS) (2014) 160–161.
[109] G.A. Mutiara, G.I. Hapsari, R. Rijalul, Smart guide extension for blind cane, in: 4th International Conference on Information and Communication Technology, ICoICT 2016, May 25, 2016 - May 27, 2016, Institute of Electrical and Electronics Engineers Inc., Bandung, Indonesia, 2016.
[110] J. Guerreiro, et al., CaBot: Designing and evaluating an autonomous navigation robot for blind people, in: ACM SIGACCESS Conference on Computers and Accessibility, ASSETS, 2019.
[111] L. Zeng, D. Prescher, G. Weber, Exploration and avoidance of surrounding obstacles for the visually impaired, in: 14th International ACM SIGACCESS Conference on Computers and Accessibility, ASSETS 2012, October 22, 2012 - October 24, 2012, Association for Computing Machinery, Boulder, CO, United states, 2012.
[112] L. Zeng, et al., HapticRein: Design and development of an interactive haptic rein for a guidance robot, in: International Conference on Computers Helping People with Special Needs, 2018.
[113] M. Zöllner, et al., NAVI – a proof-of-concept of a mobile navigational aid for visually impaired based on the microsoft kinect, in: Human-Computer Interaction, INTERACT 2011, Springer Berlin Heidelberg, Berlin, Heidelberg, 2011.
[114] B. Li, et al., Vision-based mobile indoor assistive navigation aid for blind people, IEEE Trans. Mob. Comput. 18 (3) (2019) 702–714.
[115] G. Lacey, K.M. Dawson-Howe, Application of robotics to a mobility aid for the elderly blind, Robot. Auton. Syst. 23 (4) (1998) 245–252.
[116] X. Teng, et al., Progress and prospects of multimodal fusion methods in physical human–robot interaction: a review, IEEE Sensors J. 20 (18) (2020) 10355–10370.
[117] S. Haddadin, E. Croft, Physical human–robot interaction, in: B. Siciliano, O. Khatib (Eds.), Springer Handbook of Robotics, Springer International Publishing, Cham, 2016, pp. 1835–1874.
[118] Y. Zhao, Y.H. Mao, Features and situation of man-machine interaction for the blind, Comput. Appl. (2005).
[119] S. Saegusa, et al., Development of a guide-dog robot: Leading and recognizing a visually-handicapped person using a LRF, J. Adv. Mech. Des., Syst. Manuf. 4 (1) (2010) 194–205.
[120] S. Saegusa, et al., Development of a Guide-Dog Robot: Human–Robot Interface Considering Walking Conditions for a Visually Handicapped Person, Springer Verlag, 2011.
[121] K.-B. Cho, B. Lee, Intelligent lead: A novel HRI sensor for guide robots, Sensors (Basel, Switzerland) 12 (2012) 8301–8318.
[122] J.P. Desai, J.P. Ostrowski, V. Kumar, Modeling and control of formations of nonholonomic mobile robots, IEEE Trans. Robot. Autom. 17 (6) (2002) 905–908.
[123] S. Songquan, et al., A kind of blind guidance robot with wheel leg structure and its use method. CN105997447A.
[124] NSK Develops a Guide-Dog Style Robot. Available from: https://www.nsk.com/company/news/2011/press111027b.html#.
[125] X. Changxiong, S. Yilei, A kind of electronic guide dog. CN205083960U.
[126] D. Wei, W. Yuangang, C. Yue, Design of walking mechanism in a blind guiding robot, Mech. Eng. (11) (2015) 48–49.
[127] L. Da, et al., A kind of guide dog robot. CN206285242U.
[128] Q. Jian, Mobile chassis for guide dog robot. CN210384357U.
[129] H. Dazhi, W. Xiaoli, S.T. Liufang, The design of self-lifting obstacle crossing guide robot, Mach. Tools Hydraul. 46 (11) (2018) 33–37.
[130] X. Qian, X. Debin, L. Yishuai, Design of blind navigation system based on quadrotor, China Sci. Technol. Inf. (13) (2018) 73–74.

[131] J.A. Garcia, J. Poncela, Results of mobility and obstacles detection of an experimental three-legged prototype for blind and deafblind people. DBLP, 2011.
[132] G. Campos, et al., Stair climbing robot based on convolutional neural networks for visual impaired, in: 2019 International Conference on Mechatronics, Electronics and Automotive Engineering, ICMEAE, 26-29 Nov. 2019, IEEE, Piscataway, NJ, USA, 2019.
[133] A. Roshanianfard, et al., A review of autonomous agricultural vehicles (The experience of Hokkaido University), J. Terramech. 91 (2020) 155–183.
[134] C.A.o.t. Blind, et al., Guide dog, 2018, p. 16, State Administration for Market Regulation; Standardization administration.
[135] T.M. Wang, Y. Tao, H. Liu, Current researches and future development trend of intelligent robot: A review, Int. J. Autom. Comput. (2011).
[136] M. Tognon, R. Alami, B. Siciliano, Physical human-robot interaction with a tethered aerial vehicle: Application to a force-based human guiding problem, IEEE Trans. Robot. (2021) 1–12.
[137] A. Xiao, et al., Robotic guide dog: Leading a human with leash-guided hybrid physical interaction, 2021.
[138] C. Shengben, et al., A blind guidance robot and its blind alarm system for public transportation. CN107411941A.

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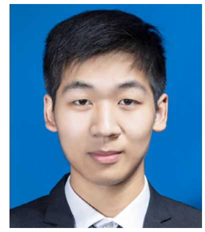

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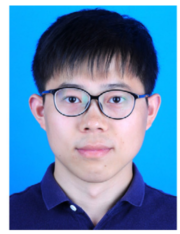

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