SPECIAL SECTION ON MOBILE SERVICE COMPUTING WITH INTERNET OF THINGS

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 31, 2019, accepted April 26, 2019, date of publication May 9, 2019, date of current version June 4, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2915552

"Watch Your Step": Precise Obstacle Detection and Navigation for Mobile Users Through Their Mobile Service

MINGHUI SUN[1,2], PENGCHENG DING[3], JIAGENG SONG[2,4], MIAO SONG[5], AND LIMIN WANG[1,2]

[1]College of Computer Science and Technology, Jilin University, Changchun 130022, China
[2]Key Laboratory of Symbolic Computation and Knowledge Engineering of Ministry of Education, Jilin University, Changchun 130022, China
[3]College of Computer Science and Technology, University of Science and Technology of China, Hefei 230000, China
[4]College of Software, Jilin University, Changchun 130022, China
[5]College of Information Engineering, Shanghai Maritime University, Shanghai 200000, China

Corresponding author: Limin Wang (42600225@qq.com)

This work was supported in part by the National Natural Science Foundation of China under Grant (61872164, 61672260), in part by the Program of Science and Technology Development Plan of Jilin Province of China under Grant 20190302032GX, and in part by the Fundamental Research Funds for the Central Universities (Jilin University).

ABSTRACT Obstacle detection or navigation is useful for mobile users, especially for the visually impaired. In this paper, we propose a method for detecting obstacles precisely from mobile devices by using a depth camera. We demonstrate the system based on Google Project Tango. The system was developed by employing the Java SDK of a Google Tango mobile device. It mainly uses a built-in infrared (IR) sensor to collect data to build a perception of the surrounding environment and then constructs a matrix to record the distance information. Subsequently, the system collects data from the surrounding environment in real time and analyzes the data. If any potential risk of being exposed to injury exists, then the system delivers a warning message and indicates a safe path for the user. An experiment was designed to evaluate our system. On the basis of the experimental results, we discuss the implications for the design of the system.

INDEX TERMS Google Tango, navigation, visually impaired, obstacle detection.

I. INTRODUCTION

Data from the World Health Organization indicate that approximately 1.3 billion people suffer from vision impairment. When navigating complex indoor environments, visually impaired individuals encounter difficulties, such as detecting and avoiding obstacles and finding the right way to their intended destination. Such difficulties may undermine their autonomy, cause emotional distress, and even expose them to injury [1]–[3]. Traditionally, visually impaired individuals use a white cane or a guide dog to feel the environment and find their way. However, this method cannot provide enough information, such as distance, volume, and precise position.

With the development of mobile techniques, several systems have been developed to assist visually impaired individuals in detecting and avoiding obstacles in their daily indoor activities [4], [5]. These systems are based on different devices, including Microsoft Kinect and a miniature radar system. Some systems also use neural networks to analyze data to extract relevant features from the scene, thereby enabling the detection of possible obstacles along the way [6]. The existing systems have different characteristics. Many auxiliary systems are designed to be head-mounted, which have good auxiliary effect and can adapt to various situations. However, they are too heavy and inconvenient to wear or are too costly. By contrast, our system is developed by using Java SDK of a Google Project Tango device and is easy to carry.

Many Google Project Tango devices exist, such as a tablet and a smartphone, which are equipped with a high-performance processing chip and high-definition camera. Such devices have many useful functions, such as motion tracking, area learning, and depth perception. Applications on mobile devices use Tango's C and Java APIs to access this data and use the functions in real time. Users can hang the device around their neck and fix it on their chest, and it

The associate editor coordinating the review of this manuscript and approving it for publication was Shuiguang Deng.

does not cause discomfort unlike when a helmet is used. The system we developed uses the device to extract data from the environmental space and then establishes a data matrix to identify obstacles in all directions in space. If a potential risk is present, then the system will send a warning via audio or vibration, identify the right course, and deliver an audio instruction by loudspeaker.

This paper is structured as follows: Section II provides a brief overview on existing electronic assistive systems. Section III presents the proposed system and algorithm. Section IV discusses the experiment to evaluate the components of our method. Section V analyzes the results, and Section VI concludes this work.

II. RELATED WORK

Many systems have been developed in recent years to assist visually impaired individuals in their daily life. These systems require a set of features, including object detection, robust image captioning, text extraction, semantic understanding, and micro-navigation. Figure 1 shows the conceptual framework for the assistive system for the visually impaired.

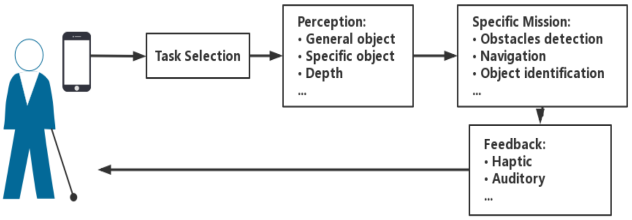


FIGURE 1. **Conceptual framework for most assistive tools for the visually impaired.**

No matter what perception they focus on, assistive systems for visually impaired individuals follow the same model. The system receives an instruction from the user, performs computations using the data from the devices, and provides feedback in different ways.

Software that have succeeded in the object detection domain include BlindTool [8], NantMobile Money Reader, and Seeing with Sound [9]. These apps can quickly detect objects, determine the face value of banknotes, or translate an image into sound. However, micro-navigation [10], or traversing the last hundred meters to a destination, is a prospective area of research that remains inchoate given that problems exist between the solution model and the sensing hardware [7].

Navigation systems for the visually impaired are divided into two main categories: infrared-enabled depth sensor-based systems and visual sensor-based systems.

Visual sensor-based systems are equipped with stereo [11]–[15] or monocular cameras [16]–[22]. These low-cost and effective systems can be installed or embedded into existing mobile computing devices. However, their performance decreases rapidly under uncontrollable conditions. Imaging factors such as motion blur, image resolution, and video noise can considerably influence performance. Moreover, their operation is limited by the high computational cost and the need for expensive cameras [23].

Infrared-enabled depth sensor-based systems detect obstacles accurately. They employ infrared tags [24] and infrared beacons [25] in the environment. These features are invisible to the naked eye, affordable, enforceable, and can operate in the dark. However, they rely on artificial infrared tagging and can be easily affected by the general thermal input from the environment [26].

Some newly emerging sensor technologies, including Microsoft's Kinect [27], Occipital's Structure Sensor [28], and Google's Project Tango Tablet Development Kit [29], can model the environment without installing any equipment therein. Their incorporated tools facilitate the development of derivative systems.

At present, most blind navigation systems are based on Kinect. They use the data from its depth sensor alone or from both its RGB and depth sensors to detect obstacles. Khan *et al.* [30] use the depth component of RGB-D data and lower the pixel for efficiency. They divide the depth image of the scene into 5 (far-left, left, middle, right, and far-right) × 3 (top, middle, and bottom) regions, calculate a metric to evaluate each region, and then inform users of the direction where obstacles are least likely to exist. The Kinect sensor is placed on the waist, the computing is conducted on a laptop, and the instruction is delivered to the user by Bluetooth. Mann *et al.* [4] employ "disparity" values, a proprietary data format provided by Kinect, to calculate the distance (0.3–5.96 m) from the user to the obstacle and use this value to detect the obstacle and determine the kind of instructions to deliver. The processing is performed on a laptop in the user's backpack. The user wears a helmet equipped with the Kinect sensor and six vibrating actuators to warn of the location of obstacles. Reference [4] develop a navigation system for the visually impaired on the basis of a waist-mounted Kinect sensor. Their system uses depth data to detect the floor and analyze the volume in front of the user to determine whether enough room is available for movement without colliding with any obstacles. Huang *et al.* [31] use least squares method to approximate ground curves, find possible stair edge points on the basis of the threshold, and transform them into an edge line by applying Hough transform. In this way, the system can detect descending stairs. Then, non-ground objects are extracted and regarded as obstacles. The user is subsequently informed of the location of obstacles and stairs in the direction the user is moving toward. In that design, the Kinect is attached to the user's helmet, chest, or waist. The processing is conducted on a laptop, and the feedback to the user is provided via text-to-speech software. Brock and Kristensson [32] develop a navigation system that reads depth data from the sensor, downsamples depth data into a low-resolution image, performs obstacle detection, and finally delivers the obstacle information to the user's headphones. The system considers the sensitive hearing of the visually impaired and converts a 3D location into sound within a given sonification volume. The horizontal and vertical positions are encoded by using the panning position and varying the pitch. Distance to the user is encoded via volume (the closer the object, the louder the volume). The processing is performed on a laptop that hangs from the user's neck with the Kinect sensor. The sonification is delivered to the headphones. The abovementioned Kinect-based solutions follow the conceptional framework (Figure 1). Other Kinect-based solutions focus on detecting specific obstacles, such as traffic and staircases [34]–[36] and even combine other technologies, such as sonar [37].

However, the Kinect is big, heavy, not wearable or hand-held but is used for gesture recognition, dumb, and uncomfortable to wear. Kinect-based systems are affixed to various parts of the body, thereby resulting in awkward, bulky contraptions. Moreover, Kinect-based systems are unappealing for the visually impaired because the cosmetic acceptability of an assistive device is even more important than its utility, as confirmed by several studies [38], [39].

The advantage of the Project Tango tablet over the Kinect is that it is small and portable, as exemplified by the phablet available in the market. As for their difference, the tablet integrates a motion tracking camera and an infrared (IR) 3D depth sensor that allows it to perform scanning [40]. Moreover, the tablet is equipped with a high-performance processor, enabling it to carry out complex computing in real time without needing to connect to a backend server.

Since the emergence of the Tango tablet, many people have tried to develop a Tango-based navigation system for the visually impaired. Li *et al.* [40] develop an indoor navigation system with three parts: a Tango device, a holder, and a white cane. The system gives advice and the user makes choices by himself. The system has an obstacle detection component, which works as follows. First, a noise filter is applied to remove the standalone points. Then, according to the pitch angle of the current pose information, a de-skewing process is performed to align the 3D point cloud with the horizontal floor plane. The Android TTS module is used to deliver instructions generated by the system. However, the system does not use the development kit provided by the Tango tablet. Jafri *et al.* [42] use the Google Project Tango Tablet Development Kit to develop a system that can track its motion and orientation in 3D space in real time. This system exploits the built-in functionalities of the Unity engine in the Tango SDK to create a 3D reconstruction of the surrounding environment, then associates a Unity collider component with the user and utilizes it to determine his interaction with the reconstructed mesh to detect obstacles. The users are warned by audio alerts. However, the usage of unity collider component is limited to detect different sizes or types of obstacles. In this paper, we propose a new method to improve the accuracy and efficiency of obstacle detection.

In summary, most related work lacks accurate obstacle details, such as obstacle position, obstacle size, and the direction in which the user can avoid the obstacle. We learn from these drawbacks and make full use of the Tango SDK to develop an advanced navigation system for the visually impaired. A quantitative experiment is designed to evaluate the performance of our proposed method.

III. STRUCTURE OF THE SYSTEM AND ALGORITHM DESIGN

The proposed system is developed on Lenovo Phab 2 Pro, the first smartphone to include the Google Tango technology. This device has a Qualcomm Snapdragon 652 processor and 6.4" big-screen Quad HD display. Its rear camera consists of a 16 MP RGB camera, depth camera, and fisheye camera. The Tango Java SDK acquires data from built-in sensors. The structure of the system is shown in Fig. 2. The processing performed by the system is divided into three steps.

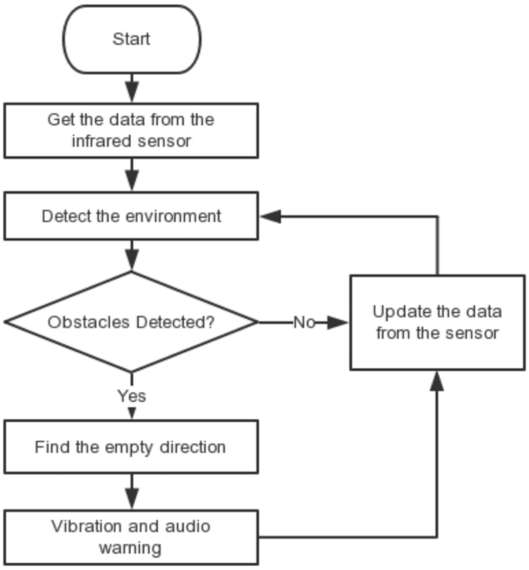


FIGURE 2. **Diagram of the proposed system.**

Step 1: The system obtains depth data via the infrared sensor and builds a 3D model of the real-world environment. The moving direction includes three main parts: left, center, and right. Each part consists of a set of grids.

Step 2: The system detects the obstacles and calculates the distance from the user to such items.

Step 3: If any possibility exists that a visually impaired individual is going to be exposed to injury, then the device will find the right path and deliver an audio warning by loudspeaker.

The details of the system, including the wearable device, data acquisition, distance calculation, the algorithm for detecting obstacles, and how the warning is delivered, are explained in the following subsection.

A. PREPARATIONS AND DATA PREPROCESSING

The Google Project Tango device is hung on the neck of the user, with the camera facing the moving direction (Fig, 3). As the device may rotate when the user is walking, we fix the device to the user and position it vertical to the

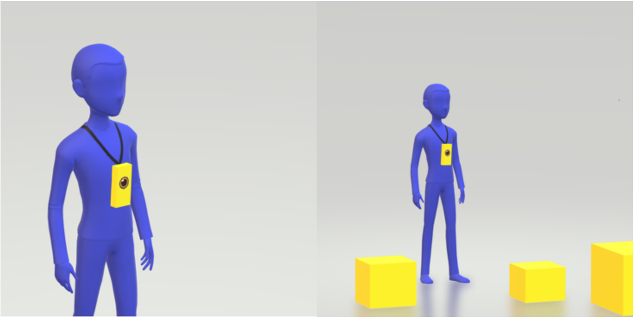


FIGURE 3. User wearing the device.

horizontal plane. Under these constraints, the camera can have a 180-degree perspective, which is enough to cover the area of the moving direction and detect obstacles in front of the user.

After fixing the device, the depth data are obtained by the depth sensor of the Google Tango device and saved in a data structure called the point cloud. The system accesses the point cloud data via the Tango Java SDK provided by Google for accessing Tango functions such as depth perception, motion tracking, and area learning. Each point of the point cloud contains three coordinate elements that indicate the location of the point and a confidence level element that reflects the accuracy of data. In our system, the program first eliminates points with confidence levels less than 90% and saves the point with x coordinate ranging from −3 to 3 m and y coordinate ranging from −1 to 1 m, which covers the direction of moving forward.

With the data acquired and preprocessed, the amount of calculation decreases and accuracy increases. Then, the system uses these data to detect obstacles and deliver prompts to users.

B. ALGORITHM FOR DETECTING OBSTACLES AND NAVIGATION

After acquiring and preprocessing data, the system gains a perspective of the surrounding environment and can easily calculate the distances of points according to depth data, which is updated in real time. An area of 6 m × 3 m is enough to detect obstacles in the way and indicate the right direction to users who can be saved from injury.

The system divides the rectangular area ahead into numeral grids, such that each point only falls into one grid which reflects the situation of a small area. We create a null matrix to mark each grid and then calculate the average distance of each grid. If the average distance of a grid is less than 2 m, then the element recording its condition will be set to 1. After these processes, we obtain a matrix to sense the presence of obstacles. Then, we execute a small matrix consisting of element 1 to detect obstacles of different sizes and shapes. The matrix with a size ranging from 2 × 2 to a higher level is designed to detect different obstacles and cover the area of moving forward. When the user walks, the data and matrix are continuously updated. If any obstacles are in the way, then the system will deliver an audio warning, detect other directions of the area, and indicate an empty location.

C. FEEDBACK TO USERS

After detecting obstacles and calculating the potentially safe way for the user to follow, the system provides users with two types of feedback: vibration and audio warning. Given that the first goal of the system is to assist visually impaired individuals in avoiding obstacles, vibration is the most direct way for a mobile phone to alert users. In a realistic scenario, when the device detects obstacles in the moving direction, it vibrates continuously to make the user aware of the presence of obstacles and stop walking immediately, thereby ensuring safety. Moreover, an audio warning would say, "Watch out! Obstacle detected, please turn left/right," thereby pointing out the safe way for users to follow. We divide the area of the moving direction into three main parts: left, center, and right. The device can evaluate the condition of every part. The audio warning will be delivered after the device calculates the average distance of every part and ascertains the location of the obstacles.

Given the particularities of users, feedback is important for a navigation system for visually impaired individuals. In this system, we combine an audio warning, which can provide more detailed information, with a vibration warning, which is felt directly. The combination of these two methods immediately reminds the users to be alert to obstacles and wait for the next instruction.

IV. EXPERIMENT DESIGN

To evaluate the validity and accuracy of the system in detecting obstacles, we design a series of experiments in different conditions, test the different functions, and construct a situation to evaluate the overall performance of the system. The related algorithm and details are shown in Section II. In our experiment, the items we used include boxes with different sizes, boards, and some furniture to construct a real indoor situation. We also chose several individuals with normal vision. Their eyes were covered, and they used a practice trail to familiarize them with behaving like the visually impaired. In all experiments, the scale parameter of every mesh was set at 0.1 cm.

A. DETECTING OBSTACLES

To evaluate the basic function of detecting obstacles with different sizes, we used boards to create different boxes whose measurements range from 10 cm × 10 cm × 10 cm to 1 m × 1 m × 1 m. All the boxes are solid and have no holes that may interfere with the data processing. The sizes of the boxes are shown in Table 1.

We chose an empty room and placed the boxes in different positions, such as the center of the room, leaning against the wall, and hanging in the center of the room so we can evaluate the obstacle detection performance. This design was selected because users often encounter complex indoor obstacles aside from furniture and walls, such as thresholds and

TABLE 1. Box sizes.

Number	Box 1	Box 2	Box 3	Box 4	Box 5
Height	5 cm	10 cm	20 cm	50 cm	80 cm
Width	5 cm	10 cm	20 cm	50 cm	80 cm
Length	5 cm	10 cm	20 cm	50 cm	80 cm

TABLE 2. Positions of obstacles.

Position Number	Details
P1	In the center of the moving direction and placed on the ground.
P2	To the left of the moving direction, aligned with a 50 cm line to the left of the user, and placed on the ground.
P3	To the right of the moving direction, aligned with a 50 cm line to the right of the user, and placed on the ground.
P4	In the center of the moving direction and hanging in the room.
P5	To the left of the moving direction, aligned with a 50 cm line to the left of the user, and hanging in the room.
P6	To the right of the moving direction, aligned with the 50 cm line in the right of the user, and hanging in the room.
P7	Leaning against the wall.

hanging items. We placed the boxes in different positions to test if the device can detect obstacles in any place and help users avoid potential risk. Seven difficult positions and their related details are shown in Table 2.

As the effective range of the depth sensor is 3 m, which covers the main environment where the visually impaired users walk around in during their daily life, we placed a box in every 0.5 m position from 1 to 3.5 m. We marked these positions with symbols: $D1 = 1$ m, $D2 = 1.5$ m, $D3 = 2$ m, $D4 = 2.5$ m, and $D5 = 3$ m. These positions are the potential areas where the users may be exposed to injury. We tested if the system can detect obstacles in these positions to evaluate whether it can help the users avoid injury.

We noted that some visually impaired individuals live alone. To ensure safety in this situation, we simulated the condition in which illumination changes during nighttime. The data from the sensor are dependent on the illumination condition, and some visually impaired individuals experience difficulty in turning lights on by themselves. Thus, we tested if the system can detect obstacles in a dark environment. We used a curtain to adjust the illumination of the room and roughly divide the illumination into three situations: totally dark (s1), dim illumination (s2), and normally bright (s3). Experiments were conducted in these situations.

The main factors that may affect the experiment were discussed above. We selected an empty room with a curtain to adjust the illumination in the room and marked some symbols to indicate the distance and position. We instructed the tester to stand at a certain point and wait for feedback, and we obtained data for the next analysis.

B. INDICATING DIRECTION

After detecting obstacles, the system may calculate the situation to the left and right to offer users a safe direction to follow. To evaluate the function of indicating directions, we chose Box 5 as the obstacle.

In this experiment, we placed the obstacles in positions P1, P2, or P3. The concrete combinations are listed in Table 3.

TABLE 3. Positions of obstacles.

Position	Direction that should be indicated
P1	Right, left
P1 , P2	Right
P1 , P3	Left
P1, P2, P3	None

The trials were conducted in a normally bright empty room except the participant and obstacles. The participant with the hanging device was supposed to walk straight toward the obstacles. A warning was delivered when the distance was reduced to a threshold value.

V. RESULT ANALYSIS

Every experiment was conducted several times, and we selected the average data as the final result. The final result and discussion are shown in this section.

A. RESULTS OF DETECTING OBSTACLES

Table 4 presents the result of the obstacle detection experiment. Three lighting conditions were used: normally bright (Lc1), dim illumination (Lc2), and totally dark (Lc3).

The experiment results indicate that the system can correctly detect the obstacles and deliver warnings to users. However, when obstacles are leaning against the wall or in the corner, the device cannot distinguish between the obstacles and the wall, so we assume that the system cannot detect them. However, this outcome does not influence the avoidance of obstacles, because we can regard the wall as an obstacle.

The system functions well for small obstacles but fails to detect obstacles with a scale less than 10 cm × 10 cm × 10 cm because the parameter we set for the mesh scale was 0.1 m, which determines the minimum obstacles the system can detect. Thus, in a real situation for visually impaired individuals, users may flexibly set the scale according to the environment and with assistance.

TABLE 4. Results of detecting obstacles in three different situations.

Distance	Position of Obstacles	Lighting Condition	Detected objects
D1	P1	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P2	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P3	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P4	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P5	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P6	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P7	Lc1	N
		Lc2	N
		Lc3	N
D2	P1	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P2	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P3	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P4	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P5	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P6	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P7	Lc1	N
		Lc2	N
		Lc3	N
D3	P1	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P2	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P3	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P4	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P5	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P6	Lc1	Boxes 2,3,4,5
		Lc2	Boxes 2,3,4,5
		Lc3	Boxes 2,3,4,5
	P7	Lc1	N
		Lc2	N
		Lc3	N

The system failed to detect any of the obstacles located at a distance over 2 m. This outcome occurred because the data collected by the device cannot be further than approximately 3 m, thereby limiting the range in which the system can work. Moreover, our system ignores points in point clouds that are over 2 m. We can change the available range by setting different parameters but not more than about 3 m.

Another finding is that illumination has no influence on the system. Thus, the system could work well in dark environments to help users avoid obstacles.

B. INDICATING DIRECTION

Table 5 lists the results of the test for indicating direction.

TABLE 5. Results of indicating direction.

Position	Message delivered
P1	Right, left
P1, P2	Right
P1, P3	Left
P1, P2, P3	Warning only

After detecting obstacles, the system correctly delivered the right message to the user about the next direction they should follow. When the environment is impassable, the system will give warnings only.

VI. CONCLUSION AND FUTURE WORK

In this paper, we present a navigation system for the visually impaired to detect obstacles in their path and ascertain a safe direction indoors. Compared with previous auxiliary equipment, this system is cheaper, lighter to carry, functions in real time, and works in indoor situations. These advantages make our system more convenient and helpful for users than prior systems.

The system cannot correctly distinguish complex situations such as obstacles leaning against a wall. Fortunately, this outcome does not influence the safety goal of the system. The system is designed in an unmapped situation. However, the Google Tango device has a function called area learning, which may help the system construct a memory of frequently passed environments and indicate where an obstacle is located. In the future, we may combine these two functions of depth sensing and area learning to help with more accurate navigation.

Data processing can also be combined with deep learning. We can train a series of models by using the collected data to enable the system to distinguish concrete types of objects. Such feature will not only help visually impaired users avoid obstacles, but also help them reach objects they want.

We hope our research would inspire the development of more assistive systems that would help visually impaired individuals with daily living, education, and entertainment.

REFERENCES

[1] R. Manduchi and S. Kurniawan, "Mobility-related accidents experienced by people with visual impairment," *AER J., Res. Pract. Vis. Impairment Blindness* vol. 4, no. 2, pp. 44–54, Feb. 2011.

[2] S. K. West *et al.*, "How does visual impairment affect performance on tasks ofeveryday life? The SEE project," *Evidence-Based Eye Care*, vol. 3, no. 4, pp. 218–219, 2002.

[3] J. S. Karlsson, "Self-reports of psychological distress in connection with various degrees of visual impairment," *J. Vis. Impairment Blindness* vol. 92, no. 7, no. 1998, pp. 483–490.

[4] S. Mann, J. Huang, R. Janzen, R. Lo, V. Rampersad, A. Chen, and T. Doha, "Blind navigation with a wearable range camera and vibrotactile helmet," in *Proc. 19th ACM Int. Conf. Multimedia*, Nov. 2011, pp. 1325–1328.

[5] L. Dunai, G. P. Fajarnes, V. S. Praderas, B. D. Garcia, and I. L. Lengua, "Real-time assistance prototype—A new navigation aid for blind people," in *Proc. 36th Annu. Conf. IEEE Ind. Electron. Soc.*, Nov. 2010, pp. 1173–1178.

[6] V. Filipe, F. Fernandes, H. Fernandes, A. Sousa, H. Paredes, and J. Barroso, "Blind navigation support system based on microsoft Kinect," *Procedia Comput. Sci.*, vol. 14, pp. 94–101, Jan. 2012.

[7] Weiss, Martin, "A survey of mobile computing for the visually impaired," 2018, arXiv: 1811.10120. [Online]. Available: https://arxiv.org/abs/1811.10120

[8] J. P. Cohen. *BlindTool—A Mobile App That Gives a 'Sense of Vision' to the Blind With Deep Learning*. Accessed: Dec. 31, 2015. [Online]. Available: https://github.com/ieee8023/blindtool

[9] P. B. L. Meijer, "An experimental system for auditory image representations," *IEEE Trans. Biomed. Eng.*, vol. 39, no. 2, pp. 112–121, Feb. 1992.

[10] J. Einsiedler, O. Sawade, B. Schäufele, M. Witzke, and I. Radusch, "Indoor micro navigation utilizing local infrastructure-based positioning," in *Proc. IEEE Intell. Vehicles Symp.*, Jun. 2012, pp. 993–998.

[11] A. Rodríguez, J. J. Yebes, P. F. Alcantarilla, L. M. Bergasa, J. Almazán, and A. Cela, "Assisting the visually impaired: Obstacle detection and warning system by acoustic feedback," *Sensors*, vol. 12, no. 12, pp. 17476–17496, Dec. 2012.

[12] J. M. S. Martinez and F. E. Ruiz, "Stereo-based aerial obstacle detection for the visually impaired," in *Proc. Workshop Comput. Vis. Appl. Visually Impaired*, Oct. 2008, pp. 1–15.

[13] H. Tang and Z. Zhu, "A segmentation-based stereovision approach for assisting visually impaired people," in *Proc. Int. Conf. Comput. Handicapped Persons*. Berlin, Germany: Springer, 2012.

[14] S.-W. Lee, S. Kang, and S.-W. Lee, "A walking guidance system for the visually impaired," *Int. J. Pattern Recognit. Artif. Intell.*, vol. 22, no. 6, pp. 1171–1186, 2008.

[15] T. Schwarze, "A camera-based mobility aid for visually impaired people," *KI- Künstliche Intell.* vol. 30, no. 1, pp. 29–36, Feb. 2016.

[16] J. Hwang, Y. Ji, and E. Y. Kim, "Monocular vision-based collision avoidance system," in *Proc. 14th Int. Conf. Hum.-Comput. Interact. Mobile Devices Services Companion*, Sep. 2012, pp. 125–130.

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

[18] S. A. Bouhamed, J. F. Eleuch, I. K. Kallel, and D. S. Masmoudi, "New electronic cane for visually impaired people for obstacle detection and recognition," in *Proc. IEEE Int. Conf. Veh. Electron. Saf. (ICVES)*, Jul. 2012, pp. 416–420.

[19] Q. Lin and Y. Han, "Safe path estimation for visual-impaired people using polar edge-blob histogram," in *Proc. World Congr. Eng. Comput. Sci.*, vol. 1, Oct. 2013, pp. 1–5.

[20] R. Tapu, B. Mocanu, A. Bursuc, and T. Zaharia, "A smartphone-based obstacle detection and classification system for assisting visually impaired people," in *Proc. IEEE Int. Conf. Comput. Vis. Workshops*, Dec. 2013, pp. 444–451.

[21] A. Caldini, M. Fanfani, and C. Colombo, "Smartphone-based obstacle detection for the visually impaired," in *Proc. Int. Conf. Image Anal. Process.* Cham, Switzerland: Springer, 2015, pp. 480–488.

[22] P. Kaur and S. Kaur, "Proposed hybrid color histogram based obstacle detection technique," in *Proc. 3rd Int. Symp. Comput. Vis. Internet*, Sep. 2016, pp. 88–97.

[23] R. Jafri and S. A. Ali, "A multimodal tablet–based application for the visually impaired for detecting and recognizing objects in a home environment," in *Proc. Int. Conf. Comput. Handicapped Persons*. Cham, Switzerland: Springer, 2014, pp. 356–359.

[24] V. Ivanchenko, J. Coughlan, W. Gerrey, and H. Shen, "Computer vision-based clear path guidance for blind wheelchair users," in *Proc. 10th Int. ACM SIGACCESS Conf. Comput. Accessibility*, Oct. 2008, pp. 291–292.

[25] K. Magatani, K. Sawa, and K. Yanashima, "Development of the navigation system for the visually impaired by using optical beacons," in *Proc. 23rd Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, vol. 2, Oct. 2001, pp. 1488–1490.

[26] R. Jafri and M. M. Khan, "Obstacle detection and avoidance for the visually impaired in indoors environments using Google's project tango device," in *Proc. Int. Conf. Comput. Helping People Special Needs*. Cham, Switzerland: Springer, 2016, pp. 179–185.

[27] *Microsoft Kinect*. Accessed: Dec. 23, 2015. [Online]. Available: https://dev.windows.com/en-us/kinect

[28] Occipital. *Structure Sensor*. Accessed: Feb. 5, 2016. [Online]. Available: http://structure.io/

[29] *Google Project Tango*. Accessed: Feb. 5, 2016. [Online]. Available: https://www.google.com/atap/project-tango/

[30] A. Khan, F. Moideen, J. Lopez, W. L. Khoo, and Z. Zhu, "KinDectect: Kinect detecting objects," in *Proc. Int. Conf. Comput. Handicapped Persons*. Berlin, Germany: Springer, 2012, pp. 588–595.

[31] (2003). *H.R. 1902-108th Congress: Medicare Vision Rehabilitation Services Act of 2003*. Accessed: Sep. 13, 2016. [Online]. Available: https://www.govtrack.us/congress/bills/108/hr1902

[32] H.-C. Huang, C.-T. Hsieh, and C.-H. Yeh, "An indoor obstacle detection system using depth information and region growth," *Sensors*, vol. 15, no. 10, pp. 27116–27141, Oct. 2015.

[33] M. Brock and P. O. Kristensson, "Supporting blind navigation using depth sensing and sonification,' in *Proc. ACM Conf. Pervasive Ubiquitous Comput. Adjunct Publication*, Sep. 2013, pp. 255–258.

[34] S. Wang, H. Pan, C. Zhang, and Y. Tian, "RGB-D image-based detection of stairs, pedestrian crosswalks and traffic signs," *J. Vis. Commun. Image Represent.*, vol. 25, no. 2, pp. 263–272, Feb. 2014.

[35] T. J. J. Tang, W. L. Lui, and W. H. Li, "Plane-based detection of staircases using inverse depth," in *Proc. Australas. Conf. Robot. Automat. (ACRA)*, Dec. 2012, pp. 1–10.

[36] A. Pérez-Yus, G. López-Nicolás, and J. J. Guerrero, "Detection and modelling of staircases using a wearable depth sensor," in *Proc. Eur. Conf. Comput. Vis.* Cham, Switzerland: Springer, 2014, pp. 449–463.

[37] K. Yelamarthi, D. Haas, D. Nielsen, and S. Mothersell, "RFID and GPS integrated navigation system for the visually impaired," in *Proc. 53rd IEEE Int. Midwest Symp. Circuits Syst.*, Aug. 2010, pp. 1149–1152.

[38] R. G. Golledge, J. R. Marston, R. James, J. M. Loomis, and R. L. Klatzky, "Stated preferences for components of a personal guidance system for nonvisual navigation," *J. Vis. Impairment Blindness*, vol. 98, no. 3, pp. 135–147, 2004.

[39] R. Jafri and S. A. Ali, "Exploring the potential of eyewear-based wearable display devices for use by the visually impaired," in *Proc. 3rd Int. Conf. User Sci. Eng. (i-USEr)*, Sep. 2014, pp. 119–124.

[40] A. A. Diakité and S. Zlatanova, "First experiments with the tango tablet for indoor scanning," *ISPRS Ann. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. 3, no. 4, pp. 67–72, May 2016.

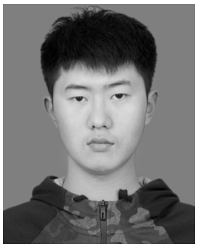
[41] B. Li, J. P. Muñoz, X. Rong, and J. Xiao, "ISANA: Wearable context-aware indoor assistive navigation with obstacle avoidance for the blind," in *Proc. Eur. Conf. Comput. Vis.* Cham, Switzerland: Springer, 2016, pp. 448–462.

[42] *Blindness and Vision Impairment*. Accessed: Oct. 11, 2018. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment

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

MINGHUI SUN received the Ph.D. degree in computer science from the Kochi University of Technology, Japan, in 2011. He is currently an Assistant Professor with the College of Computer Science and Technology, Jilin University, China. He is interested in using HCI methods to solve challenging real-world computing problems in many areas, including tactile interface, pen-based interface, and tangible interface.

PENGCHENG DING received the bachelor's degree in computer science from Jilin University, in 2017. He is currently pursuing the master's degree with the College of Computer Science and Technology, University of Science and Technology of China.



JIAGENG SONG is currently pursuing the bachelor's degree with the College of Software, Jilin University, China.

MIAO SONG received the Ph.D. degree in computer science from the Kochi University of Technology, Japan, in 2009. He is currently a Lecturer with the College of Information Engineering, Shanghai Maritime University, Shanghai, China. His research interests include image processing and signal detection.

LIMIN WANG received the Ph.D. degree in computer science from Jilin University, China, in 2005, where he is currently a Professor with the College of Computer Science and Technology. He has published innovative papers in journals, such as *Knowledge-Based Systems*, *Expert System with Applications*, and *Progress in Natural Science*. His research interests include probabilistic logic inference and Bayesian networks.

• • •