An Astute Assistive Device for Mobility and Object Recognition for Visually Impaired People

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***Abstract*—To provide autonomous navigation and orientation to visually impaired people, this article proposes a new electronic assistive device called the NavCane. The device helps people find obstacle-free paths in both indoor and outdoor settings. The NavCane also aids in the recognition of objects in an indoor setting. The advantage of the NavCane device is that it provides priority information about obstacles in the path without causing information overload. The priority information deduced by the system is transmitted to the user using tactile and auditory communication methods. Unlike existing electronic travel assistance systems which are limited to obstacle detection and path finding, the NavCane also helps users by recognizing objects in known indoor settings. The developed prototype is low cost and as a low power embedded device for obstacle detection and obstacle identification, it is an alternative to machine vision systems. It has a radio-frequency identification reader, ultrasonic sensors, a global system for mobile communication module, a global positioning system module, vibration motors, a gyroscope, a wet floor sensor, and a battery. To test the usefulness of the NavCane in mundane commuting, object recognition, and rehabilitation for visually impaired people, we assessed it with the help of 80 visually impaired people from a blind school and a home for elderly people. All the assessments were executed in controlled indoor and outdoor test environments with both a NavCane and a white cane. The experimental results show that the NavCane is an effective device for detecting of obstacles, ascending and descending staircases, navigating wet floors, and object recognition in environments that are known and unknown to the user. In addition, our evaluation results indicate that the NavCane improves the performance of obstacle-free navigation compared to a white cane.**

***Index Terms*—Assistive technology, distance measurement, feedback communications, indoor navigation, man–machine systems, object detection, object recognition, radio-frequency identification (RFID) tags, rehabilitation, tactile sensors, ultrasonic transducers.**

I. Introduction

VISION is one of the important human senses for gaining knowledge of the surrounding environment. The absence of vision makes unassisted navigation, object identification, and orientation in unfamiliar settings a challenging task. According to a report by the World Health Organization (WHO), 314 million people worldwide suffer from visual impairment. The reason for visual impairment is typically eye disease or uncorrected refractive errors. Out of the 314 million visually impaired people, 45 million are blind [20]. Blindness is an issue that is prevalent and ever increasing due to the aging population. In older people, there is a higher risk of visual impairment that increases the difficulty of autonomous mobility.

For many people with visual impairments, assistance plays an important role in social participation. The absence of appropriate assistive devices for people with visual impairments makes them too dependant on their family members. In addition, the cost of rehabilitation might not be affordable for people in low-income countries due to a lack of employment [33]. Assistive technologies are powerful tools for rehabilitation, which improve the functioning, participation, and independence of visually impaired people.

According to the World Health Organization's International Classification of Functioning, Disability, and Health (ICF), human functioning problems for visually impaired people are categorized as activity limitations and participation restrictions. To overcome these limitations, visually impaired people often use a white cane to aid them in navigation. White canes are less expensive and can detect obstacles up to knee level. However, a white cane requires continuous and conscious effort from its user to detect obstacles in the surrounding environment. Furthermore, it is not useful in detecting raised obstacles such as ladders and scaffoldings, which may pose the risk of collision with the obstacle and cause injury to them. Thus, a white cane does not sufficiently meet the needs of visually impaired people.

Guide dogs are used by visually impaired to assist them in navigation and obstacle avoidance, however, to assist visually impaired people, the guide dogs need to be trained, and fully trained guide dogs are costly. Additionally, owning a dog is much more of a commitment than owning a white cane, and it may not even be possible for some economically disadvantaged people to own a dog. Furthermore, it is a challenging responsibility for a blind person to appropriately take care of a guide dog. The main challenges in indoor navigation and orientation are a lack of knowledge of known landmarks, obstacle detection, object recognition, and hazards.

Safe and independent mobility is still a challenging task for blind people. In this modern age, technology has revolutionized

Manuscript received October 17, 2018; revised March 10, 2019 and May 27, 2019; accepted June 18, 2019. Date of publication August 15, 2019; date of current version September 14, 2019. This article was recommended by Associate Editor M. Neubert. *(Corresponding author: Kailas Patil.)*

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Digital Object Identifier 10.1109/THMS.2019.2931745

the way people live and can also be used to help people. Some electronic travel aids (ETAs) have been proposed by researchers to assist visually impaired people with mobility and to increase their speed while navigating. According to a report [17] from USA, assistive technologies for mobility reduce the need for support services. The different forms of existing ETAs are wearable devices, smart canes, and handheld devices. NavGuide [23], GuideCane [27], K-Sonar [11], Ultracane [28], and electronic mobility cane (EMC) [3] are ETAs that make use of ultrasonic sensors to detect objects in the surrounding environment. However, they are limited to knee-level obstacle detection and fail to detect descending staircases.

Although ETAs are available to help visually impaired people, the acceptance of ETAs is low [4]. However, the low acceptance rate does not mean that visually impaired people resist adopting electronic assistive devices; instead, it indicates that there is a need for further research to improve the adaptability and usability of ETAs.

The existing ETAs are less popular among potential users because they have poorly designed user interfaces and are limited to navigation purposes, functionally complex, heavy to carry, costly, and lack object identification functionality, even in known indoor environments. In addition, the existing ETA systems are limited to helping individuals avoid obstacles. For example, a person might be looking for a sofa to sit on; however, the existing ETA systems are limited to finding an obstacle free path and do not provide information on indoor settings. One of the reasons for the lower acceptance of existing ETAs is the lack of communication between the users of ETAs and their developers.

The following factors play an important role in designing appropriate and suitable assistive devices for visually impaired people.

1) *Suitability for the environment*: A large number of assistive devices are donated to low-income countries by the international community without providing the required services. They are rejected because they are not able to address the needs of visually impaired people in their environment.
2) *Suitability for the user*: End user involvement in requirement analysis research and assessment of needs is a critical factor to minimize the rejection of a device due to a mismatch between the device functionality and user needs. In addition, involving rehabilitation workers, social workers, or community workers in planning and designing a system increases the probability of acceptance of the assistive system [19].

According to the principles of the United Nations Convention on the Rights of Persons with Disabilities (CRPD), user-centered services are recommended, so that visually impaired people will also be involved in the design decisions about the support or assistance required by them. Therefore, we gathered the user requirements and expectations by conducting a survey in a school for the blind. We interviewed a total of 210 visually impaired people and caretakers. We asked all the participants the same set of questions regarding their requirements for ETAs. We also asked what type of feedback they would prefer for the detection of obstacles. The people interviewed were mostly white cane users. Of the interview participants, 93.21% of them confirmed that a white cane did not provide information about the surrounding environment. Close to 84.52% of the participants felt the need to detect scaffolds and head level obstacles to avoid injuries. A total of 42.11% of the participants acknowledged that a white cane did not provide knowledge of descending staircases. They mentioned that, compared to climbing up staircases, climbing down staircases was more difficult for them as it is difficult to judge the stairs using a white cane while stepping down. Overall, 83.45% of all the participants mentioned that they had suffered from injuries due to slipping on wet floors; hence, they felt the need for the sensing of wet floors. Close to 95% of the participants felt the need to have some facility to contact their relatives or caretakers in the case of an emergency in an outdoor environment. In all, 90% of the participants preferred using ETAs that are easy to carry and light weight. A total of 73% of the participants acknowledged the need to identify objects and colors. Overall, 88% of the participants felt that the assistive device should be cost effective and provide audio feedback to them about obstacles. In addition, a U.S. survey reports that there are a considerable number of unmet needs for assistive technologies [9].

The gaps and limitations in existing ETA systems motivated us to design the NavCane, an electronic travel aid for visually impaired people. The NavCane enables visually impaired people to travel in indoor and outdoor environments without the help of caretakers. The NavCane detects obstacles at the foot, knee, waist, and chest levels and scaffold objects up to the chest level. It also detects wet floors and identifies objects in indoor environments. The NavCane users are provided with appropriate tactile(vibration) and audio feedback for detected obstacles. These reference points help visually impaired people calculate the optimum number of movements to navigate from one point to another. The NavCane system helps users identify indoor objects by using an radio-frequency identification (RFID) reader and RFID tags. The identification of an object allows a blind person to efficiently and autonomously move from one place to another. This article covers the design, implementation, experimental evaluation, and statistical analysis of the NavCane.

The rest of this article is organized as follows. Section II summarizes the existing literature for obstacle detection and safe mobility. Section III presents the design of the NavCane. Section IV provides the experimental setup details. Further, Section V summarizes the experimental results of the NavCane and Section VI describes the performance of the NavCane using statistical analysis. Section VII discusses the possible limitations of the system. Finally, Section VIII concludes the article with the scope of future research.

II. Literature Review

We categorized the techniques for assisting visually impaired people into four different groups based on the methods used for mobility and obstacle recognition tasks.

A. Range-Based Techniques

The C-5 laser cane [16] emits infrared pulses that are reflected by objects in front of it and are detected by a photodetector. The distance of the obstacle can be calculated based on the angle made by the reflected pulse. The Ultracane [28] was a step forward in assistive technology. It detects objects in front of and at shoulder or head height of the user. It informs the user about detected obstacles through tactile feedback. The GuideCane [27] is a robotic cane that has a passive wheel at the bottom. The wheel is useful during its regular operation but it adds extra weight to the cane. It cannot detect overhanging obstacles or sidewalk borders. The technique by Ando *et al.* [2] and the EMC [3] use tactile and audio feedback mechanisms to warn users about obstacles detected in the surrounding environment. The device is limited to detecting only floor-level and knee-level obstacles. In addition, the performance of the EMC in detecting obstacles is hindered whenever it is slanted or used diagonally.

Echolocation [12] is a portable cane. It detects head-level obstacles and notifies the user through an audio feedback mechanism. However, it is a costly device and does not detect slippery floors.

B. Image Processing Techniques

Zhang *et al.* [32] proposed robotic navigation aids (RNAs) for the independent mobility of visually impaired people. This technology used a three-dimensional (3-D) camera for obstacle-free indoor wayfinding for visually impaired people. In addition, to locate the device user in an indoor location, it uses the floor plan of the building. It provides audio feedback to the user to announce the reference points and navigational commands. An object recognition method for blind people is implemented by Ye *et al.* [31] using a robotic navigation aid. It allows the real-time detection of indoor obstacles.

Tyflos [5] is a device used for mobility within premises and is also used to read text. It embeds an RFID reader, a global positioning system (GPS) device, a proximity sensor, two small cameras, and a microphone to collect the input from the surrounding environment. Vibrating devices and speech synthesizers are used as output devices to convey the calculated distance to the user. This information is useful to the user to identify objects in front of him. The vOICe [18] device provides audio feedback to its users about obstacles. It uses machine vision techniques to identify the obstacles. The system is built by attaching a digital camera to eyeglasses, and headphones are used to provide audio feedback. Ye *et al.* [30] presented a corobotic cane (CRC) that uses robotic techniques to provide navigational assistance. The CRC system is useful in an indoor environment. It uses a 3-D camera for object recognition. It suffers from camera-based systems that are limited in the field of view.

C. Artificial Intelligence Techniques

Artificial intelligence technology has been applied to aid visually impaired people. Ramiro [29] *et al.* designed a computer-based device that is useful for assessing assistive devices for blind people. The system is able to simulate several eye disease conditions in human vision. Rao *et al.* [25] used artificial neural network techniques for the recognition of characters and conversion of text into speech as a reading aid for the blind. The authors used a dictionary-based approach for the announcement of prerecorded voice data. Rajam and Balakrishnan [24] developed a camera-based system for the detection of sign images to convert them into speech. The work mainly focused on Tamil sign alphabets and sign detections. However, our research focuses on different types of obstacle detection and the generation of voice feedback to users for safe and independent navigation.

D. Haptic and Wearable Computing Technologies

Katzschmann *et al.* [14] proposed a wearable system that is capable of detecting scaffold obstacles. It uses infrared light to measure the distance from the user to the surrounding obstacles. Ando *et al.* [1] proposed a multisensor system to assist visually impaired people in performing urban mobility tasks.

Flores *et al.* [10] presented a vibrotactile belt system for guiding blind walkers. It uses an external localization system instead of GPS-based navigation to measure the position and orientation of the user. In the study by O'Modhrain *et al.* [21], all the researchers are visually impaired and they presented important issues to the designers of media for blind users. The study considers the impact of human factors on the effectiveness of tactile, vibrotactile, and haptic methods of rendering maps and graphs. Park *et al.* [22] proposed an assistive robotic system using a novel haptic exploration framework for real-time remote exploration. In particular, it aims to help visually impaired people explore public places such as art galleries and museums. The information acquired by the system is provided using a forced feedback platform that gives a real-time 3-D haptic rendering of the item.

The CyARM [13], sonic torch [15], and kaspa systems [6], [7] are handheld devices that use echolocation to detect obstacles. These systems require the user's constant conscious effort to actively scan the surrounding environment. The NavBelt [26] is a portable, wearable assistive system that has embedded ultrasonic sensors. It requires users to make a conscious effort to comprehend the audio cues.

The NavGuide [23] is a wearable device that detects obstacles up to the knee level in the front, left, and right directions. However, it is limited to obstacle detection, and it does not provide object identification. There are six major differences between the NavGuide and NavCane. First, the NavCane provides the unique facility of a panic button. When a visually impaired person needs assistance or help, by pressing the panic button, the NavCane sends an alert message and e-mail to the preconfigured caretakers in the system. Second, the NavGuide is limited to detecting only foot and knee-level objects, whereas the NavCane can detect obstacles and scaffolds up to the chest level. Third, the NavGuide fails to detect a descending staircase, whereas the NavCane detects both descending staircases and slopes. Fourth, by using RFID technology, the NavCane is capable of identifying objects in an indoor environment, and if an RFID tag is attached to clothing, it can help identify the color and the type of clothing, e.g., a red shirt, a black pant, etc. Fifth, the NavGuide is limited to obstacle detection only, whereas the NavCane provides both obstacle detection and obstacle identification features. Sixth, the NavGuide is a wearable device, whereas the NavCane can be integrated into existing white cane systems.

III. Architecture of the NavCane

The NavCane design is motivated by the principles of universal design, such as: 1) *flexibility* to accommodate a range of features and skills and 2) *the communication* of priority information in a variety of situations. The primary goal of designing an electronic navigation aid is to assist blind, limited vision, and elderly people in obstacle finding, obstacle identification, and safe navigation. The NavCane uses range-based sensing technology for detecting obstacles. The NavCane is designed to have the following eight functionalities. First, assisting visually impaired people in the detection and avoidance of obstacles at different levels, such as foot, knee, waist, and chest levels and scaffolds up to chest level. Second, assisting in way finding in indoor and outdoor environments. Third, identifying the presence of water on the floor. Fourth, allowing a user to press a contact button to send auto alerts through SMS and e-mail to caretakers about emergency situations. Fifth, identifying objects and the colors of clothes. Sixth, providing tactile feedback using vibration and auditory feedback using wired or wireless headphones. Seventh, providing a low-battery alarm to users, and eighth, assisting users in the detection of descending and ascending staircases.

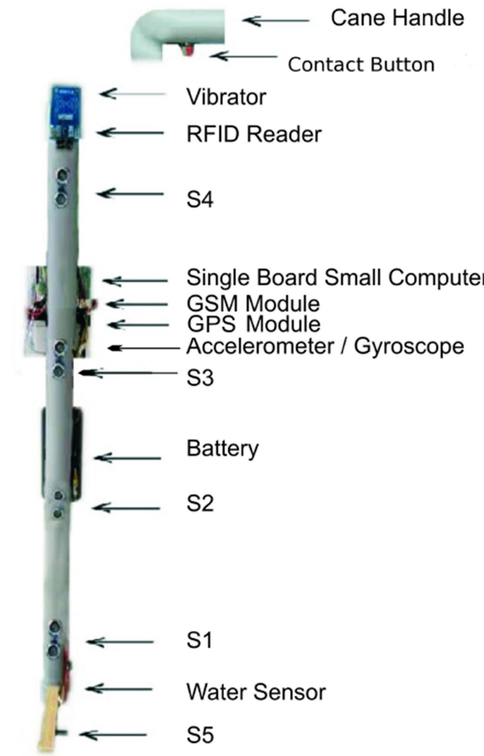

Fig. 1. Assembled NavCane showing the placement of system components.

The NavCane detects obstacles in the forward direction by using ultrasonic sensors. In an indoor environment, it identifies obstacles by using an RFID reader. By identifying the presence of obstacles in the forward direction and gathering the information from the sensors, the NavCane makes a user aware of the reference points in the surrounding environment. Using this information, it aids users in navigation. The NavCane provides appropriate feedback about obstacles in the surrounding environment to the user via tactile and auditory feedback mechanisms. The availability of this information plays a vital role in the safe movement of a user. Range-based sensors are used in the NavCane to gather surrounding information.

The NavCane consists of five ultrasonic sensors, a wet floor detection sensor, an accelerometer, an RFID reader, a contact button, a vibration motor, a global system for mobile communication (GSM) module, a GPS module, a single board small computer (SBSC), and a battery for the power supply. Among the five ultrasonic sensors, S1, S2, S3, and S4 are the front-facing sensors, while S5 faces the ground, as shown in Fig. 1. All five sensors are wide beam ping sensors. Ultrasonic sensors S1, S2, S3, and S4 are used for detecting ascending staircases, foot, knee, waist, and chest-level obstacles and scaffolds up to the chest level. S5, the ground facing sensor, is used to detect slopes and descending staircases. A wet floor sensor is used to detect wet floors. A novel algorithm named *obstacle-free path finding with object recognition* is proposed in the NavCane system for way finding and obstacle detection. The algorithm works in two parts—one part is for obstacle detection and the other part is for obstacle identification. The algorithm gathers information from the environment by using range-based sensors. The gathered information is prioritized, and the user is given feedback accordingly.

The obstacle detection part of the algorithm uses ultrasonic sensors and a wet sensor placed on the NavCane. The obstacles in front are detected when the NavCane is held straight ahead by the user. The orientation angle of the NavCane is calculated using an accelerometer. In case the NavCane is tilted either in the *x-axis* or the *y-axis*, the user is prompted to hold the stick straight via an audio feedback. The foot, knee, waist, and chest-level obstacles and chest-level scaffolds are detected by an obstacle detection algorithm. On the detection of obstacles in the navigation path, tactile and audio feedback is provided to the user.

Low vision or visually impaired people face problems in identifying objects. The obstacle identification subalgorithm identifies objects using an RFID reader placed on the NavCane. It is used to identify objects by using the RFID tags that are attached to them. The objects are identified by an RFID reader which reads the information stored in the RFID tags attached to the objects. The information stored in the RFID tags includes the names of objects, such as sofas, chairs, and tables. We also configured the RFID tags to store the color of clothing, such as shirts and pants. The RFID tags are then attached to the clothing, which helps the user identify the color and type of their clothing and accordingly choose which color clothes to wear. Upon reading the information associated with the object, it is conveyed to the user in the form of audio feedback.

TABLE I
DISTANCE OF ULTRASONIC SENSORS FROM THE GROUND

Ultrasonic Sensor ID	**Distance from Ground (cm)**	**Sensing Direction**
S1	10	Front
S2	35	Front
S3	55	Front
S4	90	Front
S5	3	Ground

A. *Obstacle Detection Algorithm*

The obstacle detection algorithm gathers the information from the sensors that are placed at different levels as shown in Table I. The information gathered using the sensors is prioritized by the obstacle detection algorithm based on the distance of the obstacle. Obstacles up to hundred cm are detected. When an obstacle is detected, the level of the obstacle and the distance from the NavCane user are conveyed to the user with appropriate audio and tactile feedback.

The sensors are arranged on the NavCane considering the average height of an adult human as per the standards. Obstacles at foot, knee, waist, and chest level as well as chest-level scaffolds and ascending staircases are detected using sensors S1, S2, S3, and S4. Sensor S5 is used to detect descending staircases and slopes.

The ultrasonic sensors detect the obstacle by sending a high-frequency sound pulse, which is obstructed when there is an obstacle in the path. When there is an obstacle ahead, the high-frequency waves sent by the sensor are reflected back and received by the receiver in the sensor. The distance to the obstacle from the user is calculated using

$$D = s \times t \tag{1}$$

where D is the distance traveled, s is the speed of sound, and t is the time elapsed. The speed of sound is approximately 343.2 m/s in dry air. The distance between the sensor and the obstacle is one-half the distance traveled by the sound wave. Hence, the distance in (1) becomes

$$D = \frac{(343.2 \text{ m/s}) \times \Delta t}{2}. \tag{2}$$

The distance D to the obstacle is calculated by each ultrasonic sensor using (2). The detailed descriptions of different obstacle detections is given as follows.

1) Orientation Angle Calculation: An accelerometer is used to measure the tilt or change in inclination of the NavCane by a user. The diagonal or slanted usage of the NavCane changes the angle of the ultrasonic sensor beam used to detect objects, hence, reducing the obstacle detection accuracy. To identify the orientation of the NavCane and infer reliable results for detecting obstacles, it is important to detect the inclination angle. Inclination sensing uses the gravity vector and its projection on the axes of the accelerometer to determine the tilt angle. The tilt of the NavCane is measured using the x- and y-axis inclination of the accelerometer. The inverse sine of the *x-axis* and inverse cosine of the *y-axis* is computed to convert the acceleration measured by the accelerometer to the inclination angle, as shown

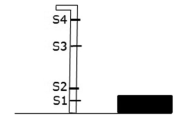

Fig. 2. Foot-level obstacle.

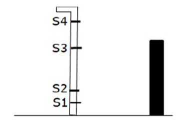

Fig. 3. Knee-level obstacle.

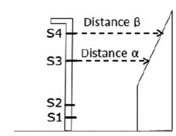

Fig. 4. Knee-level and waist-level backward slanting obstacle detection.

in (3). The ratio of the two values is taken as shown in (4), where θ is the inclination angle in radians

$$\frac{Ax_{\text{out}}}{Ay_{\text{out}}} = \frac{1g \times \sin(\theta)}{1g \times \cos(\theta)} = \tan(\theta) \tag{3}$$

$$\theta = \tan^{-1}\left(\frac{Ax_{\text{out}}}{Ay_{\text{out}}}\right). \tag{4}$$

2) Foot-Level Obstacle Detection: A foot-level obstacle, considering the average height of an adult human, is detected using the ultrasonic sensor S1. Fig. 2 shows that when there is a foot-level obstacle in the forward direction, it is detected by sensor S1.

3) Knee-Level Obstacle Detection: A knee-level obstacle, considering the average height of an adult human, is detected using ultrasonic sensors S1, S2, and S3. Fig. 3 shows that when there is a knee-level obstacle in the forward direction, it is detected using sensors S1, S2, and S3.

4) Knee-Level Backward Slanting Obstacle Detection: A knee-level obstacle in the backward slanting direction is detected if the distance D measured by ultrasonic sensor S3 is greater than distance D measured by ultrasonic sensors S1 and S2, as shown in Fig. 4.

5) Knee-Level Forward Slanting Obstacle Detection: A knee-level slanting obstacle in the forward direction is detected if the distance D measured by ultrasonic sensor S3 is less than the distance measured by ultrasonic sensors S1 and S2.

6) Waist-Level and Chest-Level Obstacle Detection: The average height of an adult human is used to detect waist-level and chest-level obstacles using ultrasonic sensors S1 to S4, as shown in Fig. 5.

7) Waist-Level Backward Slanting Obstacle Detection: Fig. 4 shows that a waist-level obstacle in the backward slanting direction is detected if the distance D measured by ultrasonic sensor S4 is more than the distance measured by ultrasonic sensors S1, S2, and S3.

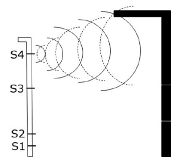

Fig. 5. Waist-level obstacle detection.

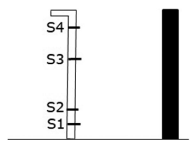

Fig. 6. Scaffold obstacle.

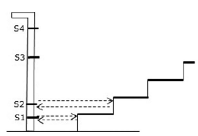

Fig. 7. Ascending stair detection.

8) Waist-Level Forward Slanting Obstacle Detection: A waist-level obstacle in the forward slanting direction is detected if the distance *D* measured by ultrasonic sensor S4 is less than the distance measured by ultrasonic sensors S1, S2, and S3.

9) Chest-Level Scaffold Obstacle Detection: A chest-level scaffold obstacle in the forward direction is detected using sensor S4. If there are no signals received from S1, S2, or S3 but only from S4, as shown in Fig. 6, then, that signal is used to calculate the distance to the chest-level scaffold from the user.

10) Ascending Staircase Detection: The arrangement of sensors S1 and S2 on NavCane is determined as per the International Residential Code (IRC) for staircase construction [8]. As per the IRC, the dimensions for stair width, tread depth, and riser height are 91.4, 25, and 19.6 cm, respectively. The riser refers to the distance you lift your foot from one stair to an adjacent stair and the tread refers to the horizontal distance from the front edge of a stair to the back part where it stops. The tread is also called the run of the stairs. Suppose that T_d represents the tread depth and α is a threshold value of ± 5 cm. An ascending staircase is detected when the difference in the distances $Ds2$ and $Ds1$ is approximately equal to the tread depth. An ascending staircase is detected by measuring the difference between the distances obtained from the ultrasonic sensors S2 and S1 and then comparing the calculated difference with the tread depth, as shown in Fig. 7. If the difference in the measurements of S2 and S1 is equal to the tread depth, then an ascending staircase is detected.

11) Descending Staircase Detection: Sensor S5 is used to detect slopes and descending staircases. As per the IRC standards, the riser height (R_h) is 19.6 cm for a staircase. Equation (5) is used to detect descending staircases, where δ is the distance of the S5 sensor from the ground (3 cm) and $Ds5_{t1}$ and $Ds5_{t2}$ are the distances calculated by S5 sensor at time $t1$ and $t2$, respectively, at an interval of 100 ms. Fig. 8 shows how the S5 sensor is used to detect a descending staircase

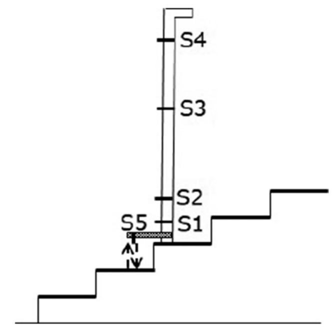

Fig. 8. Descending stair detection.

$$\left[\left(\frac{Ds5_{t1}+Ds5_{t2}}{2}\right)\approx(R_h+\delta+\alpha)\right]. \qquad (5)$$

12) Slope Detection: The Americans with Disabilities Act (ADA) recommends a 1:12 slope, which means that every one inch of vertical rise requires at least 12 inches of slope length (i.e., 5 degrees of incline). Suppose that S_d is the vertical distance from the S5 sensor to the slope, excluding δ, and $Ds5_{t1}$ and $Ds5_{t2}$ are the distances calculated by sensor S5 at time $t1$ and $t2$, respectively, at an interval of 100 ms. Equation (6) is then used to identify the slope

$$\left[\left(\frac{Ds5_{t1}+Ds5_{t2}}{2}\right)\approx(S_d+\delta+\alpha)\right]. \qquad (6)$$

13) Wet Floor Detection Sensors: A liquid contact sensor is placed at the bottom of the NavCane to detect the presence of liquid on the floor.

14) Feedback: It is crucial to provide only the priority information about detected obstacles and identified objects to the users to assist them in way finding and obstacle avoidance. The NavCane provides feedback to the user using audio and tactile output methods. The audio samples to be played are stored in an SD card connected to the SBSC. Table II lists the various audio feedbacks provided to the users in different situations. The user is provided tactile feedback as well via a vibration motor. On detection of obstacles, the vibration motor placed on the internal surface of the NavCane handle rotates at a speed of 12 000 r/min. In addition, the NavCane is equipped with a contact button, and GSM and GPS modules. A user can press the contact button in an emergency situation or when he or she needs help. Pressing the contact button sends SMS and e-mail alerts to the configured caretaker's account. The e-mail notification to the preconfigured caretaker contains the message—"panic button pressed by user from location." The location information of the user is deduced by the GPS.

B. Object Identification Algorithm

The second part of obstacle-free path finding with object recognition is object identification. In the case of a familiar indoor environment, object identification can be performed using

TABLE II
VOICE FEEDBACK PROVIDED TO USERS BY NAVCANE

Sr.No.	Scenario	Voice Feedback
1	Foot-level Obstacle Ahead	Foot-level
2	Knee-level Obstacle Ahead	Knee-level
3	Backward Slanted Knee-level Obstacle Ahead	Backward Slated Knee-level
4	Forward Slanted Knee-level Obstacle Ahead	Forward slanted Knee Level
5	Waist-level and chelst-level obstacle Ahead	Waist-level and Chest-level
6	Backward Slanted Waist-level Obstacle Ahead	Backward slanted Waist-level
7	Forward Slanted Waist	Forward Slanted Waist-level
8	Scaffold Ahead	Scaffold
9	Ascending Staircase Detected	Ascending Staircase
10	Descending Staircase Detection	Descending Staircase
11	Wet floor detected	Wet floor
12	Panic Button Pressed	Panic request sent
13	Slope Detected	Slope
14	Chair Detected	Chair
15	Sofa Detected	Sofa
16	Low system Battery	Low Battery

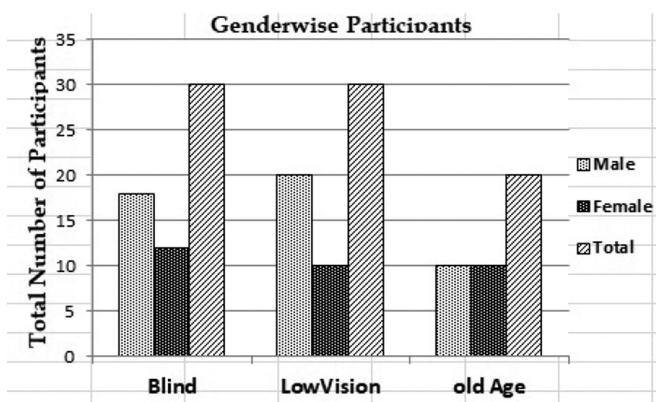

Fig. 9. Genderwise Participants.

an RFID reader mounted on the NavCane handle and the RFID tags attached to objects. The RFID tags are configured with the name of indoor objects, such as sofas, chairs, and tables. The RFID tags are also configured with the color of clothes so that the user can choose the color of the attire he or she wants to wear.

IV. EXPERIMENTAL SETUP

The usability and performance of the NavCane were tested by performing indoor and outdoor experiments. A total of 80 visually impaired people participated in the experiments. Out of the 80 participants, there were 30 participants who were totally blind, and 30 participants had low vision, that is, their visual acuity was 20/70 or poorer and there were 20 participants who were elderly, as shown in Fig. 9. The participants initially used a white cane or a regular cane for navigational purposes and were well versed with using it.

To perform the experiments, we involved physiotherapists, rehabilitation workers, and social workers. They provided the

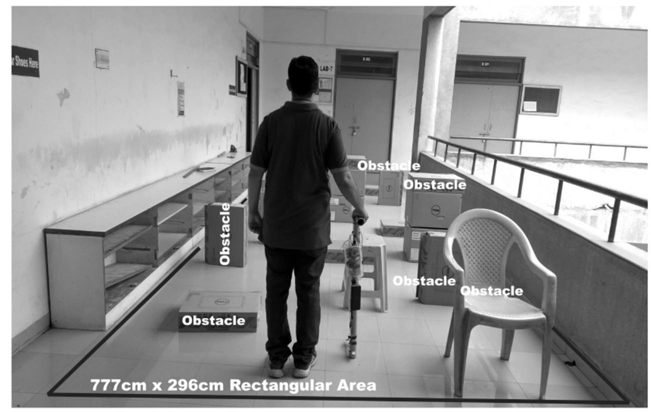

Fig. 10. Indoor environment scenario with obstacles at random locations.

inputs for conducting the training for visually impaired people. A short training period of 12 h divided over four days was conducted for the participants. During the training, the use of the NavCane and its utility was explained to the participants.

The users were told to hold the NavCane straight while navigating; if they held it in a tilted position, they were prompted to hold the cane straight via the audio feedback. They were instructed that holding the cane straight facilitates obstacle detection in the forward direction. The users learned about the various audio feedback given to them in case of obstacle detection at different levels in the forward direction, as listed in Table II. First, the users practiced holding the NavCane in the correct position. The users also felt the tactile feedback given by the vibration motor placed on the inner surface of the NavCane handle. The users were trained to press the panic button placed below the NavCane handle and were explained that in case of an emergency, they can press it to transmit a panic signal to their caretaker. After practicing holding the NavCane correctly, the users were confident in using it for navigation. After completing the training of the participants, six experiments were performed in controlled environments to test the accuracy of obstacle detection and obstacle identification by NavCane users. Objects of varying sizes were created artificially in the indoor environments.

A. Indoor Environment

The first experiment was performed in a controlled indoor environment. The indoor environment comprised a total of 15 obstacles, including 5 foot-level, 5 knee-level, and 5 waist-level obstacles. The obstacles were arranged in rectangular blocks with a length 777 cm and width 296 cm. The user had to start from one end of the path and reach the other end by crossing the obstacles in the path, as shown in Fig. 10.

B. Outdoor Environment

The second experiment was performed in a controlled outdoor environment that consisted of a total of 45 obstacles. There were 15 foot-level, 15 knee-level, and 15 waist-level obstacles in the outdoor environment. They were placed on a cement concrete

Fig. 11. Experimental setup for ascending and descending staircase scenario.

Fig. 12. Experimental setup for wet floor scenario.

road, which was 2000 cm long $\times$ 630 cm wide. The participants had to start from one end of the road and reach the other end by avoiding the obstacles on the road.

C. Ascending and Descending Staircases

The third experiment was conducted to detect ascending and descending staircases, as shown in Fig. 11. In the experiment, there were 23 steps. Each step of the staircase had a tread depth of 25 cm, a width of 150 cm, and a riser height of 20 cm. All of the participants climbed up and down the steps using a normal white cane and then, a NavCane.

D. Wet Floor Detection

The fourth experiment was performed to detect a wet floor. It was performed in an outdoor environment as shown in Fig. 12. Each of the participants had to start at one end of the path and reach the other end by avoiding the wet floor area. This experiment was performed using both the white cane and NavCane. The NavCane provided alerts when a wet floor was detected, thus, making the user aware of a wet floor; hence, they crossed it carefully by avoiding it.

E. Slope Detection

The fifth experiment was performed for slope detection. The participants had to start from one end of the slope and reach the end of the slope as shown in Fig. 13. The experiment was conducted using both the NavCane and white cane.

Fig. 13. Experimental setup for slope scenario.

Fig. 14. Experimental setup for scaffold scenario.

(a) (b)

Fig. 15. Experimental setup for object identification. (a) Sofa. (b) Chair.

F. Scaffold Detection

The sixth experiment was performed for scaffold detection. The participants had to start from one end of a path and reach the other end of the travel path. The travel path had a chest-level scaffold, and the participant was able to detect the scaffold, as shown in the Fig. 14, and reach the other end of the travel path by avoiding it.

G. Object Identification Experiment

The seventh experiment was performed for object identification. The object identification experiment was performed in an indoor environment, as shown in Fig. 15. In the object identification experiment, the users correctly identified objects such as indoor furniture (sofa, bed, kitchen counter, table, etc.) and the color of clothes.

V. Results

This section performs analyses of user safety using the NavCane in the avoidance of obstacle collisions, and compares the

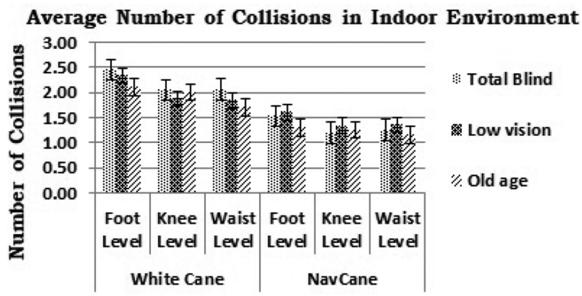

Fig. 16. Number of objects collided in indoor environment.

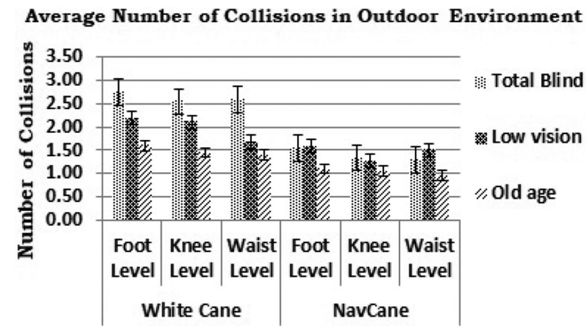

Fig. 17. Number of objects collided in outdoor environment.

results to those of the white cane, including the time required by the user for all the experiments and a power consumption analysis of the NavCane system.

A. User Safety Analysis

One of the major objectives of the NavCane is to improve the safety of the user during path finding. To achieve this objective, we measured the number of collisions during the movement of a user in indoor and outdoor environments and compared the results with those of a white cane. The NavCane provides safe navigation assistance to users. In our controlled environment, the participants traveled from the starting point to the endpoint of both the indoor and outdoor scenarios using the white cane and NavCane. All of them were familiar with white cane usage, whereas, we trained all the participants on how to hold, use the NavCane, and interpret the feedback provided by the NavCane system.

1) Object Collision in an Indoor Environment: The indoor environment contained total of 15 obstacles that comprised 5 foot-level, 5 knee-level, and 5 waist-level obstacles in an area of 777 cm $\times$ 296 cm. Fig. 16 shows the number of obstacles that the participants collided with by using the white cane and NavCane. According to the results of the experiments, as reported in Fig. 16, the users collided more with obstacles when they used the white cane, whereas the number of collisions using the NavCane was less. Once the users become accustomed to handling the NavCane, even fewer collisions will occur.

2) Object Collision in an Outdoor Environment: The outdoor environment contained a total of 45 obstacles that comprised 15 foot-level, 15 knee-level, and 15 waist-level obstacles in an area of 2000 cm $\times$ 630 cm. Fig. 17 shows that in the outdoor environment, there were fewer collisions by the visually impaired people using the NavCane compared to that with the white cane. This shows that the NavCane improves the safety of users during way finding. Once the users become accustomed to handling the NavCane, even fewer collisions will occur.

3) Slippage Due to a Wet Floor: The wet floor detection experiment was performed in an area of 250 cm $\times$ 300 cm. The participants were supposed to start at one end of the path and reach the other end, avoiding the wet floor. The number of slippages due to the wet floor were higher with white cane than with the NavCane.

Next, we provide the comparative time analysis for the experiments performed in controlled environments. All 80 users participated in the experiments. The performance of the users was closely observed and analyzed.

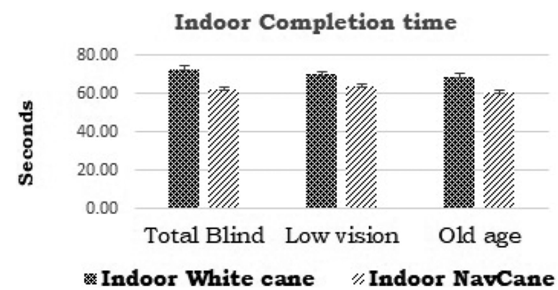

Fig. 18. Indoor environment completion time.

B. Completion Time Analysis

This section provides a completion time analysis of all the experiments for the white cane and NavCane.

1) Indoor Environment Completion Time: Fig. 18 shows a graph indicating the time required by participants to move from one end of the indoor environment to the other. The participant traveled the 777 cm $\times$ 296 cm area using both the white cane and NavCane. The completion time of the participant was compared. Using the NavCane, the participants required less time to reach the other end of the prescribed area.

2) Outdoor Environment Completion Time: The second experiment was performed in an outdoor environment in an area of 2000 cm $\times$ 630 cm. The users started from one end and reached the other end using both the white cane and NavCane. With the NavCane, the users found it comfortable to move along the path as the NavCane provided both voice and tactile feedback. Fig. 19 shows the average completion time of the users. The time required using the NavCane was less than that required using the white cane.

3) Ascending and Descending Staircase Completion Time: The third experiment was conducted to determine the time required by the users to climb up and down the ascending and descending staircase. The users used both the white cane and NavCane for navigating the stairs. Fig. 20 shows the average completion time of the users for the staircase. The time required using the NavCane was less than that required using a white cane.

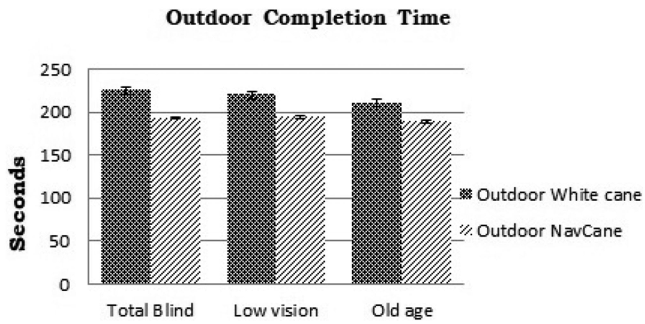

Fig. 19. Outdoor environment completion time.

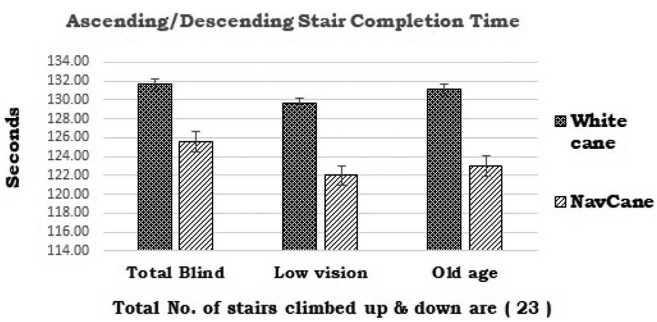

Fig. 20. Ascending and descending staircase completion time.

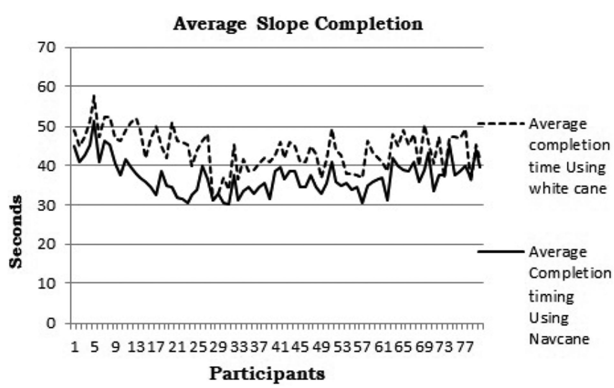

Fig. 21. Slope completion time.

4) Slope Completion Time: The participants were asked to climb up and down a slope of length 405 cm. Fig. 21 shows the average completion time of slope climbing using the NavCane and white cane.

C. Power Consumption Analysis

The energy consumption in milliamperes (mA) of each component used in the NavCane is listed in Table III.

1) Energy Consumption in an Ideal State: When the NavCane is not in use by the user, that is in situations where the NavCane user is relaxing and not moving around and the NavCane sensors are put into sleep mode, the current consumption of the NavCane is the energy consumed by the single board Raspberry Pi 3 computer, which is 400 mA in inactive state.

TABLE III
INDIVIDUAL COMPONENT CURRENT CONSUMPTION

Component	Current	Quantity	Total Current
Vibration Motor	50	1	50
Ultrasonic Sensor	15	5	75
Water Sensor	20	1	20
RFID reader	26	1	26
Accelerometer	0.5	1	0.5
Raspberry Pi	2500	1	2500
GPS Module	45	1	45
GSM Module	500	1	500

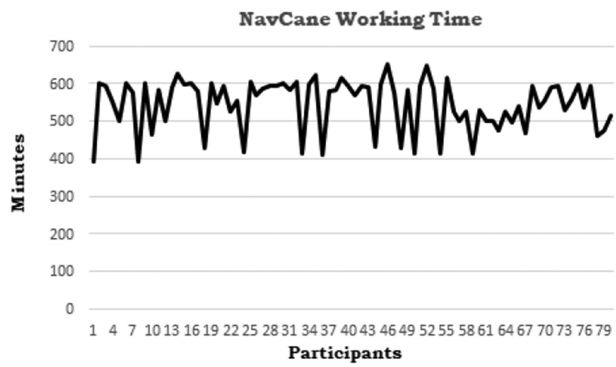

Fig. 22. Working time of NavCane.

2) Energy Consumption When the System Has a Partial Load: When the NavCane user holds the NavCane in a horizontally straight position, then all the ultrasonic sensors, and wet floor detectors become activated, and the SBSC becomes active and starts consuming energy. Upon the detection of obstacles, the vibrator motor starts giving tactile feedback to the user, and it also consumes energy.

3) Continuous Working Time: The participants were provided with a fully charged NavCane, and they were asked to use it continuously until the power source was drained. The working time of the NavCane was noted for 80 participants. Fig. 22 shows the working time of the NavCane. The participants used the NavCane in various environments, and if there were many obstacles detected or if the user used it multiple times for obstacle identification or pressed the panic button several times, the working time of NavCane decreased. When the user rested or kept the NavCane in a vertical position, all the sensors and devices are put into sleep mode in this position. Hence, the working time of the NavCane varies according to the battery usage by the SBSC. If the usage of the battery by SBSC is less then it works for a longer time and *vice-versa*.

4) Continuous Energy Consumption: We measured the continuous energy consumption of the NavCane in various environments for periods of over 600 minutes. The current consumed at different intervals of time is shown in Fig. 23. While measuring the energy consumption in various environments, whenever there were no obstacles in the path, the NavCane would go into sleep mode, hence reducing the energy consumption. The different sensors become active only when needed; for example, the ultrasonic sensors become active when there were obstacles, stairs, or slopes in the path. The RFID reader is active when it is close to some obstacle that has to be identified. Hence, at

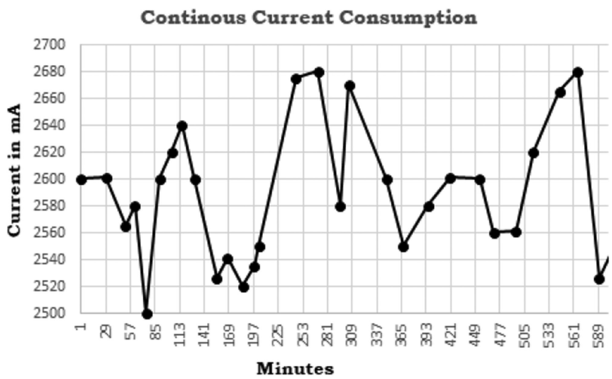

Fig. 23. Continuous current consumption details for NavCane.

different time intervals, the energy consumption of the NavCane varies.

VI. Statistical Analysis of the Performance of the NavCane Using Independence Test

The objective of doing independence test is to check whether the performance of NavCane is dependent on user gender or not. Two tests will be carried out, one for indoor usage and the second for outdoor usage. In each case, we test the following.

H_0: *The number of collisions that a blind person has with obstacles in his way while using the NavCane and gender are independent.*

H_1: *The number of collisions that a blind person has with obstacles in his way while using the NavCane and gender are not independent.*

For this purpose we will use contingency tables. A contingency table is an array having r rows and c columns. Each row of the array contains information on the distribution of given characteristics of a subgroup of a population. In this study, the subgroups of interest are male and female visually impaired persons, while the characteristics in whose distribution we are interested is the distribution of the number of collisions that a visually impaired person has with obstacles in their way while using the NavCane. We carry out the test using the χ^2 statistic given as follows:

$$\chi^2 = \sum_{i=1}^{r}\sum_{i=1}^{c}\frac{(o_{ij}-e_{ij})^2}{e_{ij}} \tag{7}$$

where o_{ij} is the observed frequency for the ijth cell of the contingency table and e_{ij} is the expected frequency for the ijth cell of the contingency table given in the following:

$$e_{ij} = \frac{\left(\sum_{k=1}^{r} o_{kj}\right)\left(\sum_{k=1}^{c} o_{ik}\right)}{n} \tag{8}$$

where n is the sample size, i.e., number of male + number of female. In our case for the test of independence, $r = 2$. The value of χ^2 obtained from the data (contingency) table is compared with the value of $\chi^2_{(r-1)(c-1)}(\alpha)$ where α is the significance level and $(r-1)(c-1)$ is the number of degrees of freedom to make a decision to reject the null hypothesis or not. We have grouped the data in each case so that the expected frequency in each cell of the contingency table is at least five.

A. Indoor: Test of Independence of Gender and NavCane Performance

$\chi^2 = 0.696325$
$\alpha = 0.1$
$\chi^2_1(0.1) = 2.706$

The value of the test statistic is 0.696325 which is less than the critical value $\chi^2_1(0.1) = 2.706$, and hence, falls in the non-rejection region. We, therefore, fail to reject the null hypothesis and state that the performance of NavCane and gender are independent.

B. Outdoor: Test of Independence of Gender and NavCane Performance

$\chi^2 = 0.043045$
$\alpha = 0.1$
$\chi^2_1(0.1) = 2.706$

The value of the test statistic is 0.043045 which is less than the critical value $\chi^2_1(0.1) = 2.706$, and hence, falls in the non-rejection region. We, therefore, cannot reject the null hypothesis and conclude that for outdoor use, the performance of NavCane and gender are independent.

VII. Discussion

We acknowledge that the current implementation of the NavCane may have three limitations. The first is that it is unable to aid in object recognition in unfamiliar indoor environments and in head-level obstacle detection. The second limitation of the NavCane is that it aids in the identification of descending staircases as well as slopes, only if the NavCane is held upright, forming an approximately 90^0 angle with the floor plane. An angle of 75^0–90^0 provides reliable results. However, the NavCane can misclassify descending staircases and slopes when used at less than 75^0 angles. Sensor S5 is used to detect descending staircases and slopes. The distance is calculated by measuring the signals from sensor S5 at time $t1$ and $t2$ with an interval of 100 ms. If the distance measured by sensor S5 is equal to the riser height (19.6 cm), then it is a descending stair case, and if the distance is less than the riser height and greater than S_d (the vertical distance from S5 to the slope), then it is a slope. The NavCane has a tolerance factor of ± 5 for calculating either the descending staircase or slope. This approach leads to misclassifying staircases versus slopes when the NavCane is used in a diagonal or slanted position. The third limitation of the NavCane is the accuracy of the distance measurement for detected obstacles. We observed a deviation of 4% between the actual and NavCane detected distance measurements of obstacles. The NavCane detects floor-level obstacles with a height of (at least) 4 cm.

VIII. Conclusion and Future Work

The loss of vision makes a person totally dependent on others for performing their mundane activities. They lack the means of independent mobility. This research article described a novel solution, the NavCane, for visually impaired people. The NavCane contributes to addressing seven fundamental limitations of the existing assistive devices: 1) NavCane is able to detect wet floors, which helps reduce slipping accidents; 2) it detects obstacles at different levels, such as foot, knee, waist, and chest levels and scaffolds up to chest level; 3) it provides simplified feedback to the user for obstacles in the surrounding area using tactile and audio mechanisms; 4) it is a low-cost device; 5) it generates SMS and e-mail alerts to caretakers, and the e-mail contains information about the user location; 6) it provides a low-battery alert to the user; and 7) it assists users in the recognition of objects using RFID readers in familiar environments.

The evaluation of the NavCane with visually impaired people shows the usability and effectiveness of the NavCane for people with low vision, totally blind people, and the elderly.

In the future, machine learning algorithms can be integrated with cameras for obstacle detection to improve the distance measuring accuracy. Additionally, the machine learning algorithms can be integrated into the proposed system to profile the user behavior and trigger priority alerts accordingly. Knowledge and attitudes are important environmental factors that affect a person's social life. The NavCane can also help users find paths to outdoor destinations and help them navigate through the route. A haptic display can be integrated with the system to provide an improved user interface. It is important to investigate techniques that raise awareness and challenge negative attitudes to create more accessible environments for persons with disabilities.

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