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A Highly Accurate and Reliable Data Fusion Framework for Guiding the Visually Impaired

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ABSTRACT The world has approximately 253 million visually impaired (VI) people according to a report by the world health organization (WHO) in 2014. Thirty-six million people are estimated to be blind. According to WHO, 217 million people are estimated to have moderate to severe visual impairment. An important factor that motivated this research is the fact that 90% of VI people live in developing countries. Several systems were designed to improve the quality of the life of VI people and support their mobility. Unfortunately, none of these systems are considered to be a complete solution for VI people and these systems are very expensive. We present in this paper an intelligent framework for supporting VI people. The proposed work integrates sensor-based and computer vision-based techniques to provide an accurate and economical solution. These techniques allow us to detect multiple objects and enhance the accuracy of the collision avoidance system. In addition, we introduce a novel obstacle avoidance algorithm based on the image depth information and fuzzy logic. By using the fuzzy logic, we were able to provide precise information to help the VI user in avoiding front obstacles. The system has been deployed and tested in real-time scenarios. An accuracy of 98% was obtained for detecting objects and 100% accuracy in avoiding the detected objects.

INDEX TERMS Assistive wearable devices, computer vision systems, data fusion algorithm, obstacle detection and obstacle collision avoidance, sensor-based networks, visual impairment, blindness, and mobility limitation.

I. INTRODUCTION

In 2014, statistics of 253 million VI people worldwide were reported by The World Health Organization (WHO) [1]; 36 million people are completely blind. In the USA, approximately 8.7 million people are VI, whereas approximately 1.3 million people are blind [2]. Both the National Federation for the Blind [2] and the American Foundation for the Blind [3] reported that 100,000 of VI people are students. During the last decade, the accomplishment of public health performance was a decrease in the number of diseases that cause blindness. Ninety percent of VI people are low-income and live in developing countries. In addition, 82% of VI people are older than 50 years old [1]. This number is estimated to increase approximately 2 million per decade. By 2020, this number is estimated to double [4].

VI people encounter many challenges when performing most natural activities that are performed by human beings, such as detecting static or dynamic objects and safely navigating through their paths. These activities are highly difficult and may be dangerous for VI people, especially if the environment is unknown. Therefore, VI people use the same route every time by remembering unique elements.

The most popular assistance method used by VI people to detect and avoid obstacles through their paths is a white cane; a trained dog is used for navigation service [5]. These methods are limited with regard to the information that they provide in real-time scenarios; this information cannot ensure safe mobility and a clear path to the user as it would for a sighted person [6], [7]. A white cane is designed to detect close objects with physical contact requirements. A white cane can also alert people to the presence of VI people and enable sighted people to yield the path to VI people. However, a white cane cannot detect head level barriers and their danger levels. A dog is a good navigation solution compared to the white cane but it is an expensive solution. Intensive training is required for dogs that serve as guide dogs.

Therefore, developing an independent, effective, and assistive device for VI people that provides real-time information with fine recognition of the surrounding environment within a reasonable range of detection and indoor and outdoor coverage during day or night becomes a critical challenge.

Many electronic devices (wearable and portable) were introduced to assist VI people in providing navigational information, such as ultrasonic obstacle detection glasses, laser canes, and mobile applications using smart phones. However, the majority of available systems have two issues: these offered devices are very expensive, whereas VI people predominantly belong to the low-income group and the capacities and services of these proposed systems are limited. Therefore, a complete design of a framework that integrates all possible and useful sensors with computer vision methods can overcome these limitations.

We have investigated several solutions that assist VI people. A fair taxonomy was the result of our intensive study to provide a technical classification to compare any system with other systems. This taxonomy is presented in a literature survey paper that was recently published in [8]. None of these studies provides a complete solution that can assist VI people in all aspects of their lives. Thus, the objective of this work is to design an efficient framework that significantly improves the life of VI people. The framework can overcome the limitations of previous systems by providing a wider range of detection that works indoors and outdoors and a navigational service.

The focus of this paper is to design a novel navigation assistant and wearable device to support VI people in identifying and avoiding static/dynamic objects by integrating computer vision technology and sensor-based technology. An innovative approach, which is referred to as a proximity measurement method, is proposed for measuring distance. This approach is based on an image's depth. The system has been deployed and tested in real-time scenarios. This system enables the user to detect and avoid obstacles by providing navigational information to recover his/her path in the case of obstacles. The novelty of this work arises from multisensory integration and a proposed data fusion algorithm with the help of computer vision methods. The combination of different data resources improves the accuracy of the output. Our platform was evaluated for different scenarios. The validated results indicated accurate navigational instructions and effective performance in terms of obstacle detection and avoidance. The system consistently sends warning audio messages to the user. Thus, this system is designed to assist normal walkers.

The organization of the paper is as follows: section 2 presents a background about assistive technologies for VI people. A study of the state-of-the art assistive technologies for VI people is presented in section 3. The proposed framework is described in section 4. Real-time scenarios and experimental results are presented in section 5. Section 6 concludes the paper with a discussion, comparison, and perspectives of future directions.

II. BACKGROUND

Assistive technology was introduced in the 1960s to solve problems associated with transmitting information [9] and mobility assistance, such as orientation and navigation [10], [11].

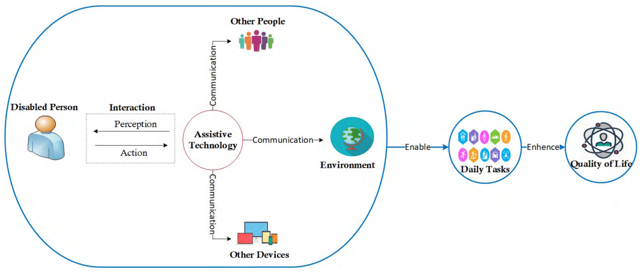


FIGURE 1. Demonstration of the interaction between the assistive technology and the user [13].

Assistive technology includes all services, systems, appliances, and devices that are used to assist disabled people in their daily lives to facilitate their activities and ensure their safe mobility [12]. Figure 1 demonstrates the services and capabilities that are afforded to a disabled person by interaction with assistive technology. The user can communicate and take actions toward other people, devices, and the surrounding environment using either sensors or computer vision technologies that have been employed by assistive technology. The user with a disability can individually accomplish his/her daily tasks and experience an enhanced quality of life that enables him/her to feel connected to the outside world [13].

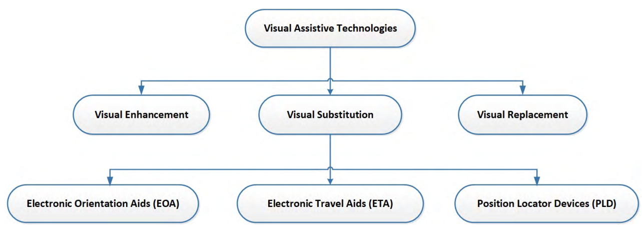


FIGURE 2. The taxonomy of assistive technology.

Figure 2 shows the three main subcategories of visual assistive technology: vision enhancement, vision substitution, and vision replacement [14], [15]. Using the functions of sensors, this technology became available to users in terms of electronic devices and applications. These systems provide different services, such as object localization, detection, and avoidance. Navigation and orientation services are offered to provide users with a sense of their external environment. Sensors help VI people with their mobility tasks based on identifying an object's properties [6], [16].

The most complex category in this taxonomy is the vision replacement category, which is related to medical and technology issues. In terms of the vision replacement category, the results or information to be displayed will be sent to the brain's visual cortex or sent via a specific nerve [14]. Vision replacement and vision enhancement are comparable with a slight difference. The processed data that was sensed by a sensor in the vision enhancement category will be displayed. The results in the vision substitution category will not be displayed. Alternatively, the output is either auditory or tactile by may consist of both auditory or tactile outputs based on touch and hearing senses and the option that is more convenient to the user.

The visual substitution category, which is our main focus, is subdivided into three other categories: Electronic Travel Aid (ETAs), Electronic Orientation Aid (EOAs), and Position Locator Devices (PLDs). Each of these categories provides a particular service to enhance the user's mobility with a slight difference. Table 1 describes each subcategory of the visual substitution category and their services.

TABLE 1. Visual substitution subcategories.

Category Name	Description	Services
ETA	Devices that collect and sense data about enclosed and surrounding areas and then send it via sensors, laser or sonar to the user or remote server [17, 18].	Identify the surrounding obstacles. Information about the textures and gaps of the movement surface can be provided. Finding items that surround the obstacles. Determining the distance between the user and the obstacle. Identifying remarkable locations. Obstacle avoidance information is provided to improve the self-orientation throughout the area.
EOA	Devices that give pedestrians guidelines and instructions about his/her path [19, 20].	Best path is defined for the user; Calculating the user's position by tracking the path. To develop a mental map for the user about the area and guide him/her, clear directions and path signs are given.
PLD	Devices that identify the user's location; for example, the global positioning system (GPS).	Route guidance from one point to another point is provided.

III. RELATED WORK

Although several solutions were proposed in the last decade, none of these solutions is a complete solution that can assist VI people in all aspects of their lives. The following subsections present some of the work that has been performed.

A. SENSOR-BASED ETA

Sensor-Based ETAs are techniques or systems that provide the VI person with information about their surrounding environment via vibration, audio messages or both vibration and messages using sensors. These systems primarily rely on the collected data to detect an object and avoid it by measuring the velocity of the obstacle and the distance between the user and the obstacle. Different devices use different types of sensors and provide different services. Ultrasonic sensors are the most popular sensors.

Wahab *et al.* developed an obstacle detection and avoidance system that is based on the ultrasonic technology in [21]. A number of ultrasonic sensors are attached to a cane. However, a timer for the water detector's buzzer is needed. In addition, [22] proposed an embedded device using an android application to navigate the user through his/her path. Modified GSM was introduced in this study. A multi-sensor system was designed and installed on a stick to detect and avoid front obstacles in three different directions [23]. An electronic cane was designed as a mobility aid to detect front obstacles with the help of haptics and ultrasonic technology [24]. An ultrasonic cane was presented in [25] as a development to the C-5 laser cane [26] to detect both ground objects and aerial objects. The authors of [27] introduced an ultrasonic headset as a mobility aid for VI people that detects and avoids obstacles.

Other systems use different types of sensors and devices to provide VI people with navigational services. A navigational system that is based on a laser light and sensors was proposed in [28] to support the mobility of VI people. A low-cost navigator for pedestrians was designed using the Raspberry Pi device and Geo-Coder-US and Mo Nav modules in [29]. An assistive navigator was suggested in [30] to guide the user through his/her unknown path by adapting GPS and GSM technologies.

An obstacle avoidance system was proposed in [31] using a Kinect depth camera and an auto-adaptive thresholding strategy. The largest peak threshold is defined using the Otsu method [32]. The idea of the navigator belt, including the number of cells around the belt, was introduced in [33] based on the Kinect depth sensor. This belt is designed to detect and avoid obstacles that are represented in a 3D model. Each cell represents a different warning message.

Using ultra-wide technology, the SUGAR system was introduced as an indoor navigator to VI people. This system navigates the user through an enclosed place that was mapped in advance [34].

Using a retina-inspired dynamic vision camera, [35] improved the mobility of VI. The system represents the environmental information as an audio landscape using 3D sound [36]. The premise is a dynamic vision camera that resembles the human retina [37], [38].

B. SENSOR SUBSTITUTION-BASED ETA

Sensor substitution-based systems are designed to be an alternative to multi-sensory systems. A small wireless device that is placed on the user's tongue was proposed to navigate VI people [39]. The wireless communication between the glasses (camera placed on the glasses) and the device is established using the designed dipole antenna in [40]. Using radio frequency technology, the Radio Frequency Identification Walking Stick was introduced in [41] to ensure safe mobility; the user does not walk beyond the sidewalk boundaries.

A virtual cane was designed in [42] for obstacle detection and avoidance for VI and handicapped people using laser rangefinder and haptics. An H3DAPI plate form was employed [43].

A mobile crowd assistant was implemented in [44] to navigate the user to his/her desired destination. The user's information and volunteer feedback are transferred through the crowd server.

C. ETA SENSORY-BASED COMPUTER VISION METHODS

Recently, we noticed a rapid propagation of assistive systems due to the improvement and progress of the computer vision techniques that add more value and services with flexibility.

Fusion of artificial vision and map matching [46] and GPS introduced an enhanced navigational system that supports VI people in their mobility [45]. The SpikNet recognition algorithm was employed for image processing [47]. GPS, modified a geographic information system (GIS) [48] and vision-based positioning are used to provide the properties of obstacles.

Cognitive guidance device is designed by integrating the Kinect sensor's output, vanishing points and fuzzy decisions to navigate the VI person through a known environment [49]. Spatial landmarks are not detected by the system.

An independent mobility aid was proposed in [50] for indoor and outdoor obstacle avoidance [51] for static/dynamic object detection. Lucas-Kanade, RANSAC, adapted HOG descriptor, Bag of Visual Words (BoVW), and SVM are employed for object detection and recognition.

Aladren *et al.* [52] introduced an object detection system using an RGB-D Sensor and computer vision techniques. The classification target is to classify the object as either a floor or an obstacle. The classification process was based on the use of a canny edge detector [53], the Hough Line Transform and RANSA, which are applied on the RGB-D's output.

Integrating both ultrasonic-based technology and computer vision algorithms presented an obstacle detection and recognition system [54]. SIFT, Lucas-Kanade, RANSAC and K-means clustering were applied to a mobile camera's output. The recognition part was limited to classifying the object as either normal or urgent. According to their paper, the users' feedback indicates that the system is not sufficiently reliable to be a replacement for the white cane.

Details about the systems presented in this section are provided in [8]. Based on the study and literature review presented in [8], no system could fully satisfy all of the user's needs to provide him/her with safe mobility indoors and outdoors. The above-mentioned systems are not fully satisfying the user's needs due to the limitation of used techniques in these proposed systems [8]. Systems that are based on both sensors and computer vision provide better solutions. However, there is no single technique that can be considered a robust or complete solution to replace a white cane and provide safe mobility both indoors and outdoors with a wide range of object detection.

Due to this observation, we propose a novel system that integrates both sensor-based techniques and computer vision techniques to provide a complete solution for VI people indoors and outdoors with other complementary features. The proposed approach is described in the following section.

IV. PROPOSED FUSION OF SENSOR-BASED DATA USING COMPUTER VISION

In this paper, we integrate both computer vision and sensor-based technologies to facilitate the user's mobility indoors and outdoors and provide an efficient system for the VI person. The system is affordable for both the blind and low vision people. Figure 3 illustrates the developed device.

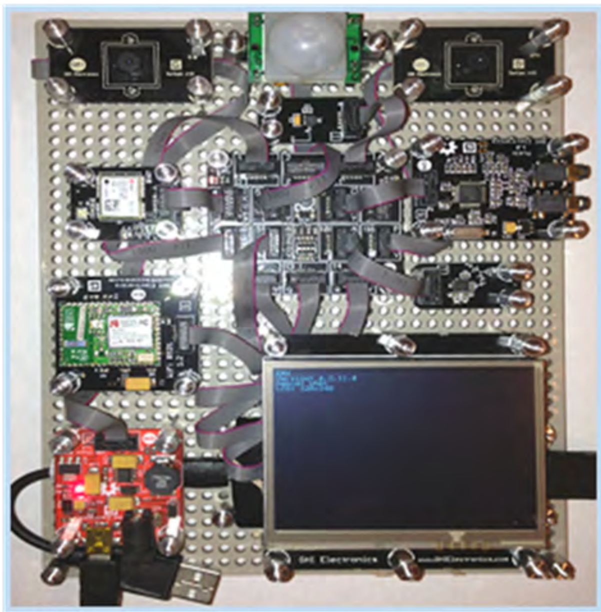


FIGURE 3. Designed prototype for proposed system.

This section discusses the object detection and the proposed novel and unique obstacle avoidance technique that is based on the depth of an image to provide the user with navigational information in an audio format using a headset. The results of the proposed obstacle avoidance approach and the proposed data fusion algorithm shows a significant improvement and qualitative advancement in the collision avoidance field, which increases its accuracy compared with other existing systems. The anticipated obstacle avoidance technique is based on the depth of an image, which is considered a challenging area for many researchers. Therefore, the majority of researchers prefer to use ultrasonic sensors-based technology instead of the depth of an image despite the implicit limitations of the ultrasonic sensor-based technology. Details about the proposed approach are provided in this section.

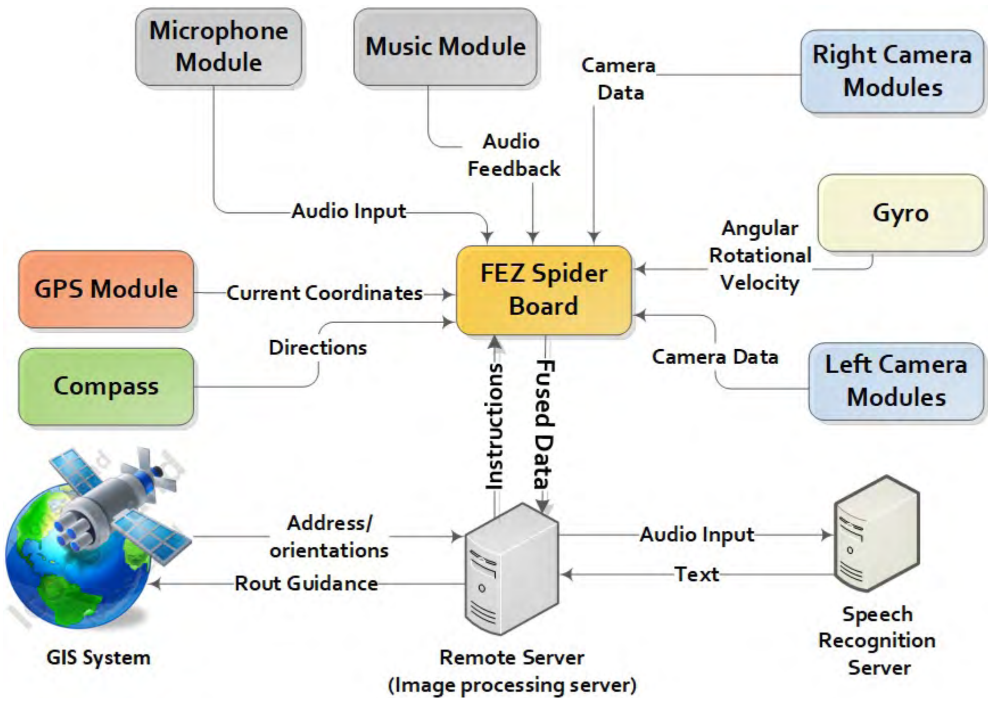


FIGURE 4. Proposed methodology of the interaction process among the hardware components.

We propose a framework that significantly improves the life of the VI person. This framework supports the following features: obstacle detection [55], [56], navigational guidance, and the proposed distance measurement approach to provide an accurate collision avoidance system. The system performs well both indoors and outdoors. Additional features can be implemented in the future, including locomotion [45], [49], [57]–[63], character recognition and text reading [64], [65], identifying currency bills [66], note taking [67], [68], traffic signal detection [69], barcode scanning, product information retrieval [70], finding lost items [71], localizing specific objects [72], [73], and mobile vision [74].

A. PROPOSED METHODOLOGY AND FLOWCHART OF THE DATA FUSION ALGORITHM

The proposed framework includes hardware and software components. The hardware design is composed of two camera modules, a compass module, a GPS module, a gyroscope module, a music (audio output) module, a microphone module, and a wi-fi module.

However, the aim of the software is to develop an efficient data fusion algorithm that is based on sensory data to enhance and provide a highly accurate object detection/avoidance and navigational system with the help of computer vision methods to provide safe mobility. Figure 4 demonstrates the interaction between the hardware components for the navigational system and the fused data that are received by the microcontroller board (FEZ Spider) from multiple sensors and transferred to the remote server.

The system is designed to navigate the user to the desired location and to avoid any obstacle in front of the user after it is detected. Based on fused data from multiple sensors and computer vision methods, the user will receive feedback in an audio format. Two camera sensors are used for object detection, which is processed using computer vision methods. The remote server handles the image processing. Based on the depth of the image, we can approximately measure the distance between the obstacle and the VI person. A compass is employed for orientation adjustment. A gyro sensor is employed for rotation measurement in degrees. A GPS provides the user's location. All components are connected with the microcontroller board, which communicates with a remote server. Route guidance is provided by a GIS. Thus, we use a gyro, compass, and GPS to track the user's directions, locations and orientations to provide accurate route guidance information.

Figure 5 demonstrates the flow of the anticipated data fusion algorithm's work and the method of using the fused data that was received from multiple sensors and processing it to provide accurate real-time information.

The proposed system has three modes, as shown in the flowchart of Figure 5. Mode zero indicates that the system is booting. Mode 1 represents the static and dynamic obstacle detection and avoidance system. Mode 2 is the data fusion model of obstacle detection/ avoidance and the navigation system. Once the system is on and the device is placed in the right position, the right and left cameras start to transfer the token frames to the remote server through the FEZ Spider board. The static and dynamic

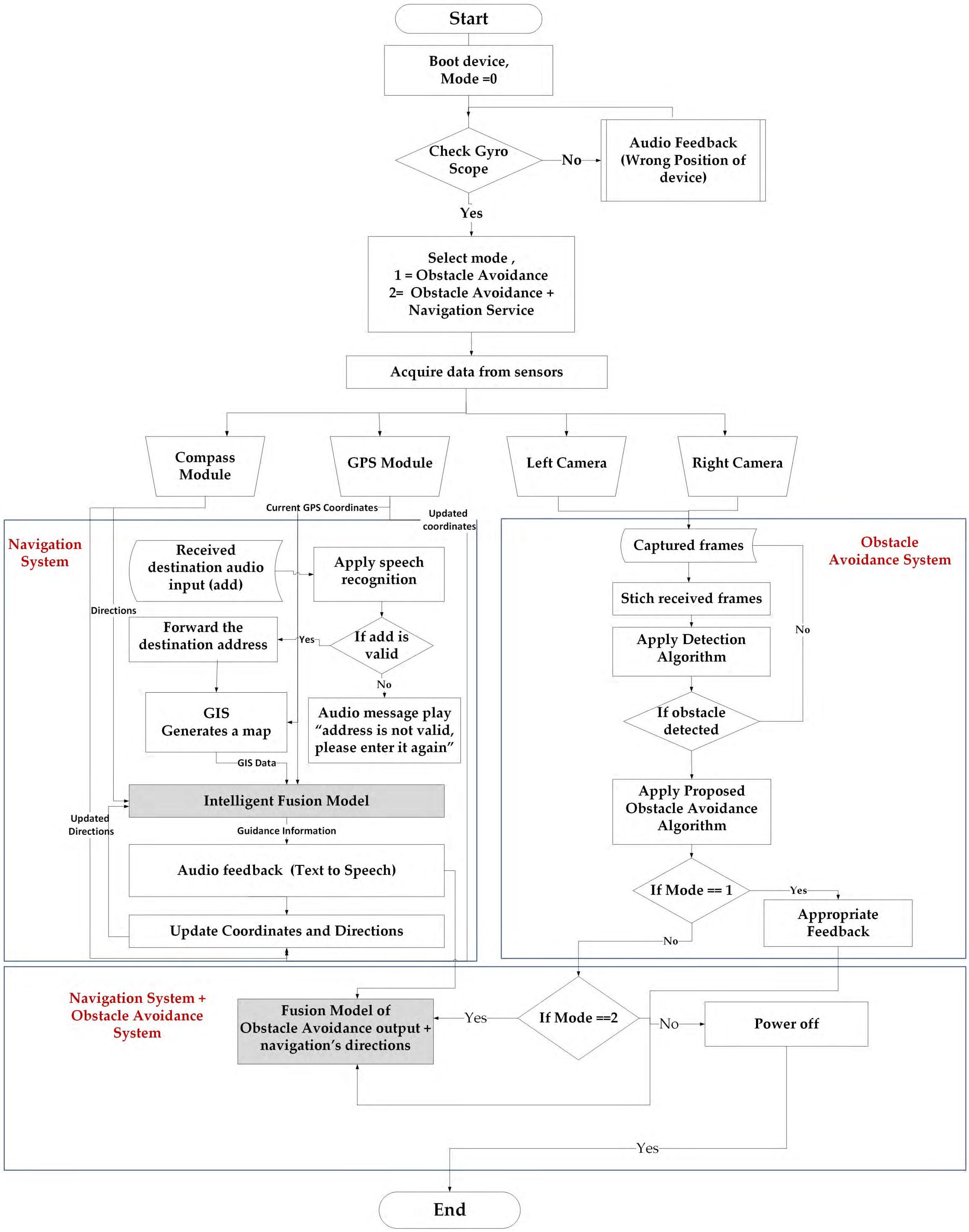


FIGURE 5. Flowchart of the proposed data fusion algorithm using multiple sensors.

object detection and proposed avoidance system will be applied.

As the object is detected, the remote server will trigger the appropriate audio message and the FEZ Spider board will send a signal to play the message through the audio module in the case of mode 2. If the user selected mode 3, the user will ask for the destination address through the microphone module. The desired address will be sent to the speech recognition server through the FEZ Spider board and validated.

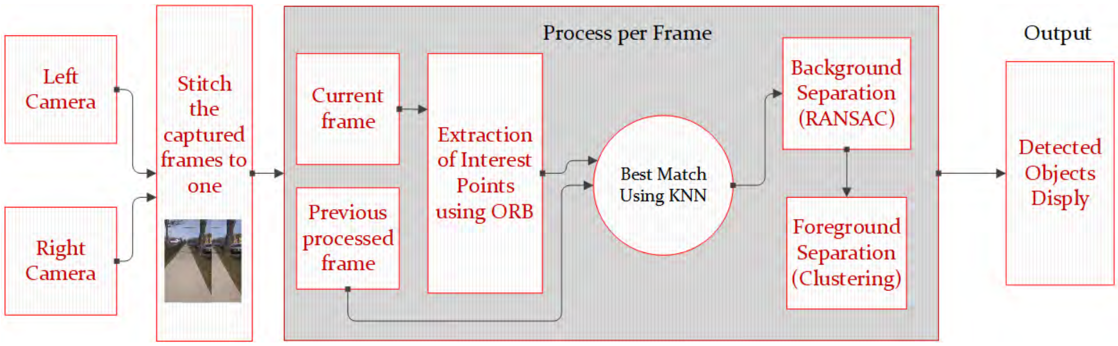


FIGURE 6. The block diagram of static/dynamic object detection process.

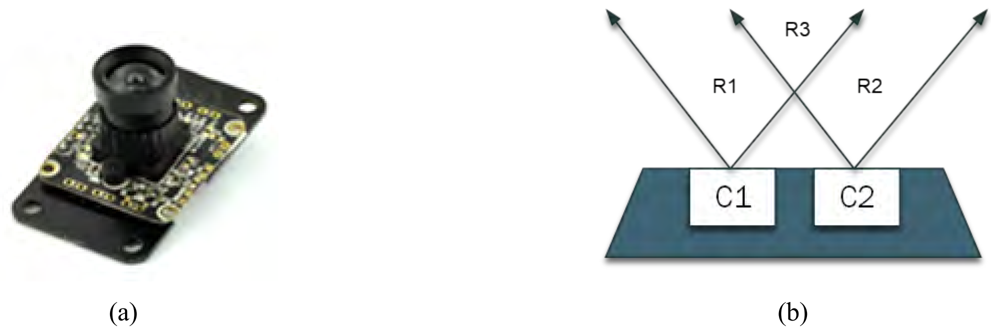


FIGURE 7. (a) Camera Module for object detection, (b) The camera view range.

Information about the user's location and orientation will be retrieved from the GPS, gyroscope, and compass sensors. The three-axis gyroscope is used to provide information about the changes of the user's movement and orientation. Hence, we use the gyroscope as a black box to determine the orientation and tilt of the user from 90-degree angle to measure if the camera is tilted enough so that it is slightly facing the floor. We need the camera slightly facing down so it captures only a small area within few meters. As an example, when the user is walking outside and the camera might captures 100 m ahead, which is unnecessary information during that time. We have determined capturing 9 meters in front is enough to control the used resources. Otherwise, the system will be slower in processing the captured data and it will not be energy efficient. The output of this multi-sensory data will be fed into the GIS to generate a map and provide guidance information using audio messages. In the scenario in which an obstacle appears in this scene and the user should receive navigational information, both messages will be combined into one message and then sent to the user. However, the obstacle avoidance warning message will precede the navigational information in order and be combined with the word "then"; for example, "slight left, then, turn right". Thus, the proposed system performs indoors as a static/dynamic obstacle detection and avoidance system and outdoors as a combination of a static/dynamic obstacle detection and avoidance system and navigator.

B. STATIC/ DYNAMIC OBSTACLE DETECTION USING CAMERA MODULES AND COMPUTER VISION TECHNIQUES

1) EXTRACTION OF INTEREST POINTS USING THE COMBINATION OF ORIENTED FAST AND ROTATED BRIEF (ORB) ALGORITHM

Figure 6 illustrates the process of the object detection systematically using computer vision methods. The camera displayed in Figure 7 (a) is from GHI Electronics [75]; it is a serial camera with a resolution of 320×240 and a maximum resolution of 20 fps. We use two camera modules in our framework to cover a wider view of the scene and then stitch the various camera views into one view. Figure 7 (b) demonstrates the use of two cameras to detect objects on edges and objects that cannot be noticed when using one camera.

The Oriented FAST and Rotated BRIEF (ORB) is the approach that we applied for static/dynamic object detection. ORB is characterized by a fast computation for panorama stitching and low power consumption. The ORB algorithm is an open source that was presented by Ethan Rublee, Vincent Rabaud, Kurt Konolige and Gary R. Bradski in 2011 as a suitable alternative of SIFT due to its effective matching performance and low computing cost [76]. Unlike other extraction algorithms, ORB has a descriptor. Therefore, ORB is an integration of the modified Features from Accelerated Segment Test (FAST) detector [77] and the modified Binary

Robust Independent Elementary Features (BRIEF) descriptor [78]. FAST was chosen because it is sufficiently fast for real-time applications compared with other detectors. The modified version of FAST is termed oriented FAST (oFAST). Key points are selected by FAST [77].

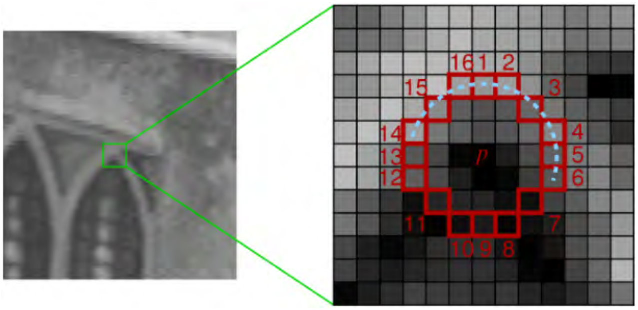


FIGURE 8. **Segments test detector [80].**

As demonstrated in Figure 8, P is the candidate point. I_p is the intensity of the candidate point. An appropriate threshold is selected as t. A circular of 16 pixels around the centroid point is referred to as a neighborhood. Consecutive N pixels need to satisfy the following equation (1) of the 16 pixels:

$$\left|I_x - I_p\right| > t \tag{1}$$

I_x is the value of surrounding consecutive pixels. N top points are filtered by the Harris corner measure [79].

The strength-weighted centroid C will be calculated with a located corner at the center to make the FAST rotational invariant. The moments are calculated as (x, y) in a circular with radius r and $-r$ as follows:

$$m_{pq} = \sum x^p y^q I(x, y) \tag{2}$$

In addition, centroid C can be calculated by applying (2):

$$C = \left(\frac{m_{10}}{m_{00}}, \frac{m_{01}}{m_{00}}\right) \tag{3}$$

The orientation is calculated based on the vector's direction from the corner point to the centroid point as shown in (4):

$$\theta = atan2\left(m_{01}, m_{10}\right) \tag{4}$$

BRIEF is a binary string representation of an image patch P [78]. τ is a binary test of n pairs of pixel points that can be defined as shown in (5):

$$\tau\,(\mathrm{p;\,x,\,y}) := \begin{cases} 1: & p\,(x) < p(y) \\ 0: & p\,(x) \geq p\,(y) \end{cases} \tag{5}$$

The strength of P at the point x is $P(x)$. τ represents one binary test, whereas f_n represents n binary tests. In (6), f_n represents n vector length binary strings, which is the descriptor of the feature point:

$$f_n\,(p) := \sum_{1 \leq i \leq n} 2^{i-1} \tau(\mathrm{p};\, x_i, y_i) \tag{6}$$

BRIEF can change the directions based on the orientation. For each set of n binary tests of features at location (xi, yi), we determine a matrix of size $2xn$:

$$S = \begin{pmatrix} x_i, \ldots\ldots, x_n \\ y_i, \ldots\ldots, y_n \end{pmatrix} \tag{7}$$

Where S stores the set of pixels' coordinates, and S_Θ is the rotation of S using the orientation of patch Θ. The steered version can be determined as follows:

$$S_\Theta = S * R_\theta \tag{8}$$

The modified version of BRIEF can be denoted as (9):

$$g_n\,(p, \Theta) := f_n(P) | (xi, yi) \in S_\Theta \tag{9}$$

Each angle is a multiple of 12 degrees. The lookup table of pre-processed BRIEF is created. If the key point orientation Θ is constant in all directions, the precise set of points S_Θ will be used to compute its descriptor [80].

The descriptors of extracted features will be the output of this step, which will be fed to the descriptor matcher KNN.

2) DESCRIPTOR MATCHING USING K-NEAREST NEIGHBOR (KNN) ALGORITHM

We employed the K-Nearest Neighbor (KNN) algorithm to match the descriptors of extracted interest points between two frames to an object's presence. In this paper, we use the Brute Force matcher, which is the simple version of the KNN. In our case, the Brute Force will match the closest K corresponding descriptors of extracted points with the descriptor of selected interest points in a frame by trying each corresponding descriptor of interest points in the corresponding frame. The Hamming Distance method is applied between each two pairs since the descriptor of ORB is a binary string. Each descriptor of an interest point will be represented as the vector f, which was generated by BRIEF. If the descriptors of two interest points are equal, the result is 0; otherwise, the result is 1. The Hamming distance will ensure correct matching by counting the difference between the attributes, in which the pair of two instances differ.

Let $K = 2$, that is, for each extracted point p_i, KNN needs to find the corresponding two neighbor matched points t_{i1}, t_{i2} in the next frame. We chose $k = 2$ because we are running the algorithm on stream video, where objects are possibly shifted slightly from the reference frame to the next frame. The distance between p_i and t_{i1}, t_{i2} is d_{i1}, d_{i2}. We retain p_i, t_i if a significant difference between d_{i1}, d_{i2} is observed; if the difference is close, then we eliminate the points as mismatches [80]. The corresponding interest points will be counted as a correct match, if the $ratio_i$ of $\frac{d_{i1}}{d_{i2}}$ is less than 0.8 [81].

The K-Nearest Neighbor Algorithm finds the best match of the descriptor of an extracted interest point to the corresponding descriptor. However, RANSAC reduces the false positive match when the presence of an object is determined but an actual object does not exist.

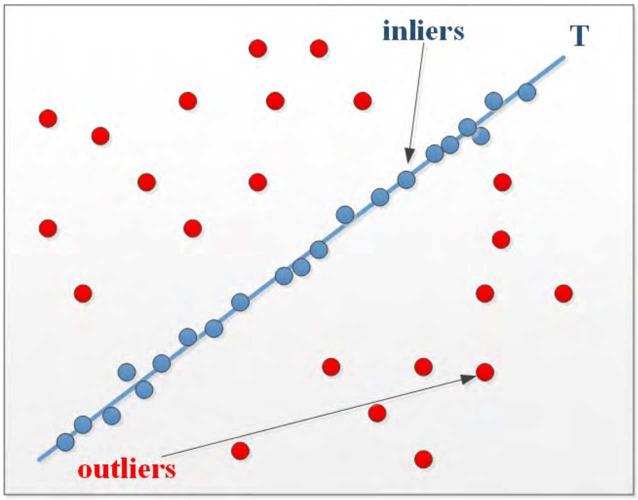


FIGURE 9. The performance of RANSAC for line fitting [82].

3) ELIMINATING FALSE MATCH USING RANDOM SAMPLE CONSENSUS (RANSAC)

We employed RANSAC to eliminate false matches, which are termed outliers. RANSAC is a highly estimated robust algorithm for estimating and eliminating outliers, even a significant number (more than 50%) of outliers. The outliers in Figure 9 are denoted by red dots; they did not have any influence on the results, which are represented in blue color.

RANSAC's assumption that at least one set will satisfy a certain model and the data distribution of a set of outliers does not satisfy a certain model. Therefore, RANSAC improves the dataset by guessing the factors of the model that involves the highest number of best matches [82].

The threshold distance t is calculated by assuming that the probability of inlier points in a set of points is α and that the distribution of the inlier point is known. In addition, the value of the threshold t can be computed if the distribution of inlier points justifies the variance σ of Gaussian circulation and the mean is equal to zero.

Based on the squared sum Gaussian variant, d^2 is the square distance of two points to obey the chi-square distribution (x_m^2) with m degrees of freedom. The random variable, which follows the rules of a chi-square distribution, has the probability of being lower than the integral upper limit. This variable can be represented as follows:

$$F_m\left(k^2\right) = \int_0^{k^2} x_m^2(\xi)\, d\xi < k^2 \tag{10}$$

The threshold distance is computed as follows:

$$t^2 = F_m^{-1}(\alpha)\sigma^2 \tag{11}$$

In addition, outliers and inliers can be classified as effective or non-effective points, which are represented as follows:

$$\begin{aligned} &\text{Inlier: } d^2 < t^2 \\ &\text{Outlier: } d^2 \geq t^2 \end{aligned} \tag{12}$$

N is the number of iterations; it needs to be sufficiently high to obtain the probability P such that at least one set does not have an outlier. Assuming that the probability of the outlier is $v = 1 - u$, for the minimum of points, N iterations are giving as follows:

$$1 - p = (1 - u^m)^N \tag{13}$$

Thus, N is expressed as

$$N = \frac{\log(1-p)}{\log[1-(1-\text{v})^m]} \tag{14}$$

RANSAC is randomly iterated N times to determine the inliers and outliers.

K-Means clustering will be applied to valid points to create a cluster for each object based on the detected corners.

4) FOREGROUND OBJECTS EXTRACTION USING MODIFIED K-MEANS CRUSTING

We employ the K-Means clustering technique to cluster n extracted points of a particular frame. The K-Means clustering technique is a well-known clustering analysis. Many approaches prefer the K-means technique for clustering due to its simplicity and suitability for large datasets. The purpose of the K-Means technique in this paper is to assign n extracted points $p_1, p_2, \ldots.., p_n$ to k clusters $\{s_1, s_2, \ldots.., s_k\}$, whereas K is the maximum number of clusters and $k < n$:

$$\sum_{i=0}^{n} D\left(p_i, Center\left(S_k\right)\right), \quad where\ p_i \in |S_k \tag{15}$$

The $Center\left(S_j\right)$ is the centroid point of S_i; it is calculated as the means of linked data points and depends on the number of desired clusters. The centroid points will be randomly selected. Each feature point will be assigned to the closest centroid based on the calculated distance D. Groups will be formed and distinguished from each other. In this study, we establish $k = 6$ for each frame based on our observations.

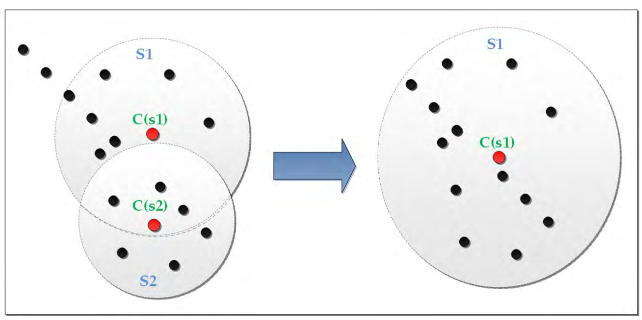


FIGURE 10. Demonstration of merging two clusters into one cluster.

However, more than one cluster may represent the same object. Therefore, a merging method needs to be applied in the case of any intersections among the clusters. Figure 10 represents the modification that we made to the K-Means clustering technique.

FIGURE 11. **Representation of the proposed object detection technique; (a) original frame, (b) the frame after applying proposed sequence of algorithms for object detection and (c) the frame after applying K-means clustering and merging to identify each object.**

Algorithm 1 Modified K-Means Clustering Algorithm

Input: A set of points $p_1, p_2, \ldots\ldots, p_n$
Output: A set of K clusters $s_1, s_2, \ldots\ldots, s_k$

N ← number of interest points
K ← number of clusters
C_s ← centroid point
While (K < N)
  Assign all points to closest centroid to form K clusters
  Recomputed the centroid of each cluster
End while
While (true)
 For (i = 0; i <= k; i++)
 For (j = i + 1; j <= k; j++)
   only if $((S_j \cap S_i)$^$(C_{S_j}$ within $S_i)$
    Merge S_j into S_i
   End if
  End for
 End for
End while

Algorithm 1 shows the steps for clustering the closest neighbors of each centroid and merging the clustered. Two clusters can be merged into one cluster if $(S_1 \cap S_2)$ AND the centroid C_{S_2} within S_1 and then merges S_2 to S_1. Otherwise, merging does not occur even if $(S_1 \cap S_2)$.

The result of the combination of adopted algorithms is represented in Figure 11. The two green dots, which are represented on the floor in Figure 11 (b), denote the detection range from where the user is standing.

C. PROPOSED PROXIMITY MEASUREMENT METHOD FOR A RELIABLE COLLISION AVOIDANCE SYSTEM

Existing systems use sensors to measure the distance between the user and the obstacle; a technique that supports distance measurement for this type of system is not available. In this section, we propose a proximity measurement methodology to approximately measure the distance between the user and the obstacle using mathematical models. The proposed approach is based on the camera that faces a slight angle down to have a fixed distance between a VI person and the ground. This view enables us to have a reference to determine whether an object is an obstruction. We have determined that the average distance between a VI person and the ground is 9 meters with the device facing down on an angle. This result enables us to identify an obstacle within a 9-meter range; however, a VI person would only need to react to an object within the 3-meter range. Our proposed method divides the frame into three areas—left, right, and center—as shown in Figure 12.

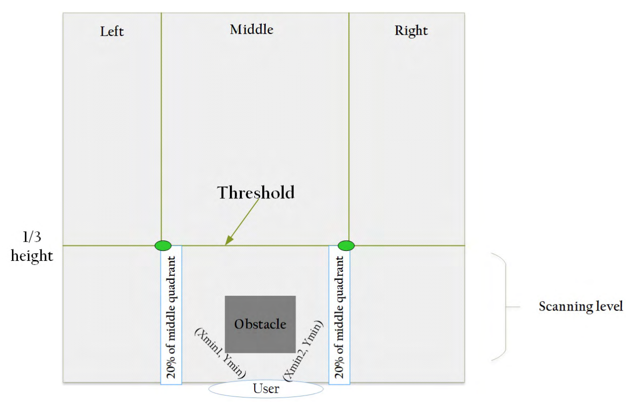


FIGURE 12. **Approximate distance measurement for object avoidance.**

We have assumed that an object in the upper part of the frame is further away than on object in the lower half and that an object detected in the lower half is an obstruction to the VI person. We can represent the frame in an $xy-coordinate\ system$. Let W be the width and H be

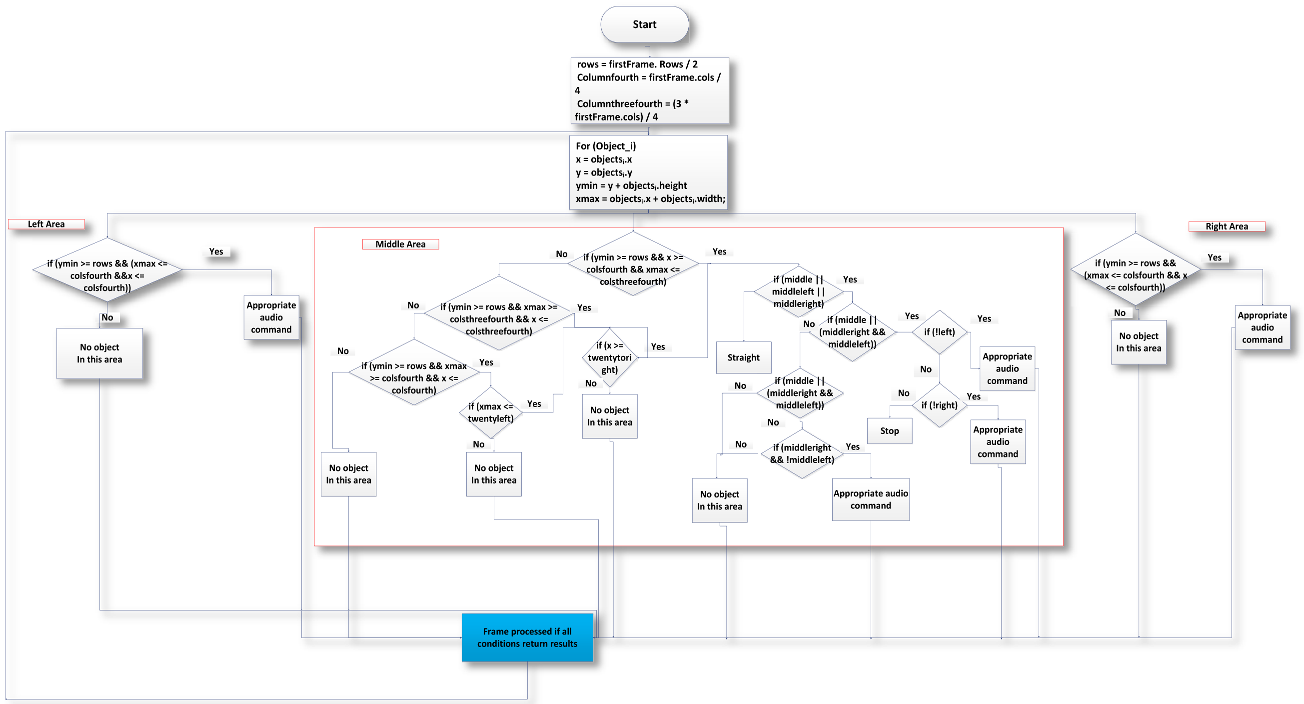


FIGURE 13. Flowchart of the collision avoidance algorithm.

the height. The calculation of the right and left is expressed as follows:

$$(\frac{1}{3}H, \frac{2}{5}W) \; \& \; (\frac{1}{3}H, \frac{3}{5}W) \tag{16}$$

Equation (16) represents the corners of the middle area, where we detect objects and inform the VI person that an obstacle is in front of them. Two green dots, which are equal to $\frac{1}{3}H$ of the frame, represents the threshold of the free collision area. Objects between the two green dots and the start point must be avoided. An object is deemed an obstruction if and when the lower corners of the objects represented by (x_{min1}, y_{min}) & (x_{min2}, y_{min}) enter below the area of equation (16). If an object exists in front of the VI person, an alternative path is required. We determine this path by searching for an object on the left or right of the area enclosed by (16). If no objects are detected on the left side of equation (16), the system issues a turn left and go straight command to the VI person. If an object on the left is detected, then the system searches for an object on the right. If an object on the right is not detected, then a turn right and go straight command is issued to the VI person. If objects are detected on the left and right sides and middle, the system issues a stop and wait command until a suitable path is identified for the VI to continue. We calculated 20% of the middle quadrat to provide accurate information to the user. If the obstacle exists within 20% of the middle quadrat, he/she does not need to move to other sides as long as the object appears in one of the 20% of the middle quadrat but not both.

Figure 13 displays a flowchart of the collision avoidance system. Each preprocessed frame is divided into left, middle, and right parts. Figure 13 shows the parallel process of simultaneously applying a free collision approach to the three areas at same time. Although the proposed approach is applied to the middle area (where free collision path is needed), a quick scan is being run on both the right area and left area to ensure a free path for the user in case any obstacle appears in front of the user in the middle area. An audio feedback is the output of this algorithm. Previous studies indicated that audio feedback is a better choice than a tactile feedback because the user becomes familiar with tactile feedback and loses their sense of a particular body's area. This algorithm will be recursively applied for each frame compared with the previous frame. The algorithm considers the previous frame as the reference frame. Tactile feedback is a suitable option for people who are hearing impairment.

Table 2 represents the conditions and the audio feedback that the user will receive. We decided to use a left area as the default direction if the obstacle appears in the middle; however, both left areas and right areas are free to avoid any confusion.

Algorithm 2 demonstrates the proposed distance measurement approach for collision avoidance.

1) FUZZY LOGIC CONTROLLER

In order to implement the abovementioned strategy, we use fuzzy logic to determine the precise decision that the user will take in order to avoid front obstacles based on multiple inputs. Figure 14 shows the fuzzy controller system for obstacle avoidance algorithm which includes: fuzzier that converts the inputs to number of fuzzy sets based on the

TABLE 2. Audio feedback of the obstacle avoidance system based on certain conditions.

Condition	Feedback
Obstacle detected in front in near proximity to the VI person, and the left and right areas are free.	"Move left"
Obstacle detected in front in near proximity to the VI person and in the left area; the right area is free.	"Move right"
Obstacle detected in front in near proximity to the VI person and in the right area; the left area is free.	"Move left"
Detected object is within 20% of the middle quadrant of the left side.	"Slight right, then straight"
Detected object is within 20% of the middle quadrant of the right side.	"Slight left, then straight"
No objects detected.	"Go straight"

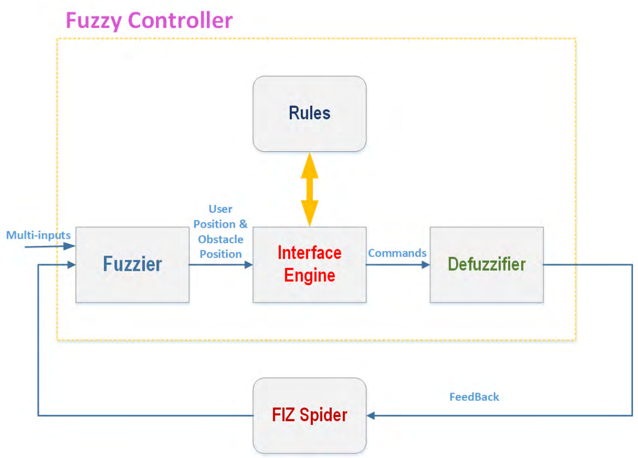


FIGURE 14. The Fuzzy structure for obstacle avoidance system.

defined variables and member functions; interface engine which generates fuzzy results based on the fuzzy rules; Each fuzzy output will be mapped by member functions to get the precise output the user should seek [83]. We used Mathlab R2017b software just in order to implement the rules of the fuzzy logic.

Step 1 (Input and Output Determination): The input variables for the proposed system are seven inputs. Those inputs are based on the position of the detected obstacles, the obstacle range {far, near} and the user position {the user's location within the frame}. They are donated as: {ObsRange, UserPosition, ObsLeft, Obs20%LeftMid, ObsMiddle, Obs20%RightMid, and ObsRight}. The output is the feedback that the user needs for a path to the endpoint (audio feedback that is sent through headphones).

Step 2 (Fuzzification): We have divided each input into membership functions. Since the user is wearing the devices on his/her chest, there are only three options in term of the user's position which are: {Left, middle, and right}.

Algorithm 2 Object Avoidance Algorithm

Input: An array of detected objects
Output: Warning message in audio format

```
rows ← firstFrame. Rows / 3
Xcorner1 ← 2 *firstFrame.cols / 5
Xcorner2 ← 3 * firstFrame.cols / 5
For.parallel (Objectsi)
  x ← objectsi.x
  y ← objectsi.y
  ymin ← y + objectsi.height
  xmax ← objectsi.x + objectsi.width;
  If (ymin >= rows && x >= Xcorner1 && xmax <=
  Xcorner2)
    Middle ← true
  Else if (ymin >= rows && xmax >= Xcorner2
  && x<=Xcorner2)
    twentypercenttoright=Xcorner2-twenty
    If(x>=twentypercenttoright)
      MiddleRight ← true
Else if (ymin >= rows && xmax >= Xcorner1 && x<=
Xcorner1)
    twentypercenttolefft=Columnfourth+twenty
    If(xmax<=twentypercenttolefft)
      MiddleLeft ← true
Else if (ymin >= rows && (xmax <= Xcorner1 && x<=
Xcorner1))
    Left ← true
  Else if (ymin >= rows && (x >= Xcorner1 &&
  xmax>= Xcorner1))
    Right ← true
  End If
End For
For.parallel (Objectsi)
If (Middle || MiddleLeft || MiddleRight)
   If (Middle || (MiddleRight && MiddleLeft))
    IF(!LEFT)
Output: "move left"
Else if (! Right)
   Output: "move right"
Else
  Output: "Stop"
......... \\More if statements
......... \\More if statements
End If
  Else If(MiddleLeft && !MiddleRight)
      Output: "Slight Right then straight"
End For
```

However, since we are using two cameras; and the processed frames of those two cameras are stitched every time as one, the user's position is going to be always in middle. Therefore, the membership function of the user's position is donated as shown in Figure 15. The range of this membership function is 300cm as it is considered to be the width of the scene.

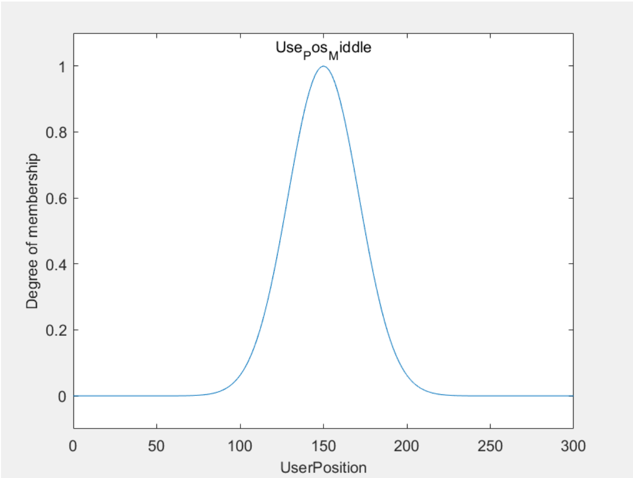


FIGURE 15. Membership function for the user's position.

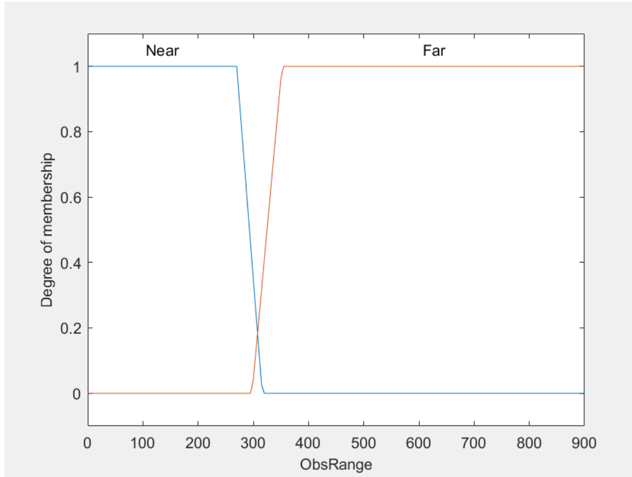


FIGURE 16. Membership function of object presentence in two ranges of the scene.

TABLE 3. Audio feedback of the obstacle avoidance system based on certain conditionsd.

Term	Meaning	Range
Left	User is in the left	0 – 1/3 of scene's width [0:50:100]
Middle	User is in the middle	1/3 of the scene's width to 2/3 of scene's width [100:150:200]
Right	User is in the right	last 1/3 of the scene's width [200:250:300]

The used membership function is Gaussian Function. Gaussian function is represented in (17) using the middle value m and $\sigma > 0$. As σ gets smaller, the bell gets narrower.

$$G(x) = \exp\left[\frac{-(x-m)^2}{2\sigma^2}\right] \quad (17)$$

Table 3 describes the terms of user's position. Obstacle's position is described in Table 4. However, the obstacle's range is divided into two membership functions {Near, Far} within the scene's height which is [0 -900cm]. The threshold is set to be 300cm. Consequently, the obstacle is near if it exists within the range of [0 – 300cm], however, the obstacle is far if it is far than 300cm. Fig. 16 represents the membership function of the obstacle's range within the height of the scene (frame or view). In addition, the obstacle's position is divided into {ObsLeft, Obs20%LeftMid, ObsMiddle, Obs20%RightMid, ObsRight}. However, in order to have more control on the fuzzy rules, we had to divide each part of the obstacle's position into two membership functions that exist or does exist {ObsEx, Obs_NEx}.

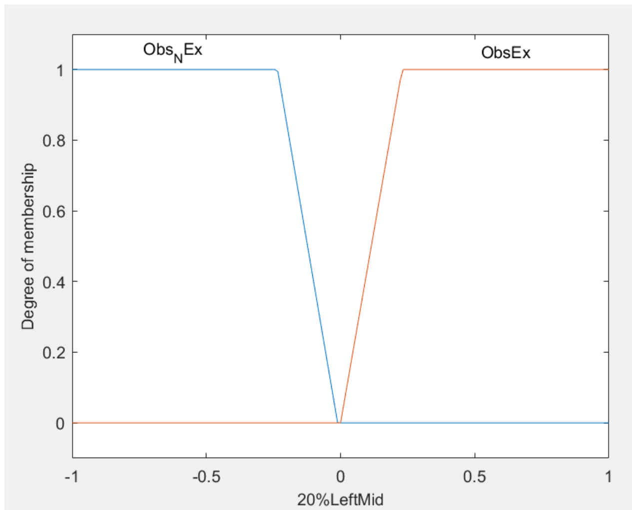


FIGURE 17. Membership function for obstacle's position in the left side.

Figure 17 represents the membership function of the obstacle's position in the left side of the scene. Same function will be presented for the remaining inputs for the obstacle's position. The negative values indicates that the obstacle does not exist in that side, whereas, the positive values exemplifies the existence of the obstacle in that side. Assume the value of the obstacle's position is x and in R range, where $x \epsilon R$. Consequently, four parameters [i, j, k, l] are used to express the Trapezoidal-shaped membership function in the following equation (18):

$$\mu_{trap}(x : i, j, k, l) = \max(\min\left(\frac{x-i}{j-i}, 1, \frac{l-x}{l-k}, 0\right)) \quad (18)$$

The output is divided into six membership functions that are based on the fused input variables. The output can be: {MoveLeft, SlightLeftStraight, GoStraight, SlightRightStraight, MoveRight, and Stop}. We used the Trapezoidal-shaped membership function for MoveRight and

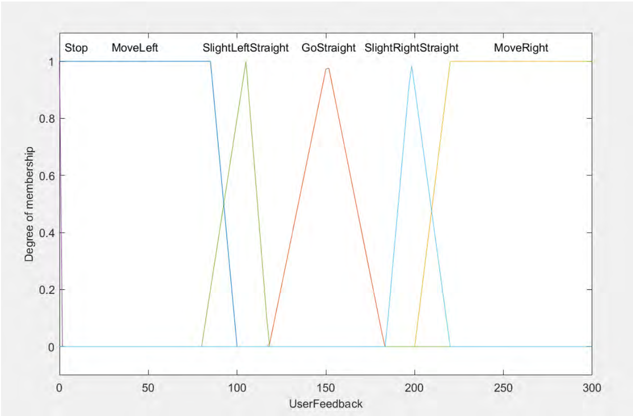


FIGURE 18. Membership function of the output (feedback/directions).

MoveLeft membership values. However, we used Triangular membership function as shown in Fig. 18 to represent {SlightLeftStraight, GoStraight, SlightRightStraight, MoveLeft, MoveRight, and Stop}. The model value, lower limit a and upper limit b, can define the Triangular membership function; where a < m < b. This function can be expressed in (19):

$$A(x) = \begin{cases} 0 & if\ x \leq a \\ \dfrac{x-a}{m-a} & if\ x \epsilon (a, m) \\ \dfrac{b-x}{b-m} & if\ x \epsilon (m, b) \\ 0 & if\ x \geq b \end{cases} \quad (19)$$

Step 3 (Creating Fuzzy Rules): The fuzzy rules can be produced based on observing and employing the Knowledge that was introduced in Table 3 and Table 4, member function and variables. The rules were implemented using five conditions of the obstacle's position, the obstacles' range, and user's position. There are 18 rules for the fuzzy controller system. The implemented 18 rules are presented in Appendix A.

TABLE 4. Definition of the obstacle position's variables.

Term	Meaning
ObsLeft	Left [0-100] cm
ObsRight	Right [200-300] cm
ObsMiddle	Middle [100 – 200] cm
Obs20%LeftMid	Obstacle is the left side, yet it is within the 20% of middle quadrant from left side. [75 -125] cm
Obs20%RightMid	Obstacle is in the right side yet it is within the 20% of middle quadrant from right side. [175 – 225] cm

We have used the union operation to connect the membership values. AND is a representation of minimum result between two values, whereas, OR is the representation of maximum result between two values. Let μ_γ and μ_δ are two membership values, thus, the fuzzy AND is described as following (20):

$$\mu_\gamma AND \mu_\delta = \min(\mu_\gamma, \mu_\delta) \quad (20)$$

Step 4 (Defuzzification): Defuzzification is the last step of the fuzzy controller system. The output is produced based on the set of inputs, membership functions and values, and the fuzzy rules. The defized effect of the user's position and the obstacles' position on the feedback is calculated using the defuzzification method the Large Of Maximum (LOM) method. Figure 19 illustrates the surface viewer that displays the boundary of the differences and combination of obstacle's position and user's position. The user will be allowed to receive the accurate and precise feedback in order to avoid front obstacles based on the combination of the described membership values.

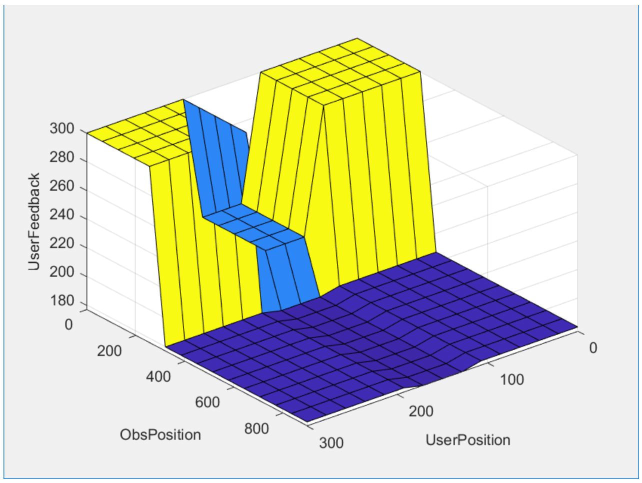


FIGURE 19. The Surface Viewer that examines the output surface of an FIS for obstacle's position and user's position using fuzzy logic toolbox.

Furthermore, fuzzy logic is used to assist the VI person from colliding with front obstacles in front of them. The proposed system was built based on the user's position, obstacle's position and one output. After the device's initialization step occurs, the information of the obstacle and user position will be fed to the fuzzy controller. Then the decision will be made based on the 18 fuzzy rules. This feedback will be sent to the user through their headphones. The whole process will be recursively employed. In case an obstacle does not exist, user will continue his/her path (straight) with no change.

V. IMPLEMENTATION AND EXPERIMENT SETUP

The aim of the developed device is to detect static and dynamic objects, obstacle avoidance and provide a navigational information. This section describes experience setup and test plan.

TABLE 5. calculation of the power consumption for the components

Module Name	Current (mA)	Power (mW)
Fez Spider	160 (active mode)	528
Camera (right)	55	181.5
Camera (left)	55	181.5
Compass	1	3.3
GPS	70	231
Gyroscope	1	3.3
Music	16	52.8
PIR Motion	10	33
wi-fi	40	132
Display	150	495
Total power without display		1346.4
Total power with display		1841.4

A. DESIGN STRUCTURE OF THE PROPOSED SYSTEM

The device was designed to facilitate the user's mobility by providing appropriate navigational information. We used C# programing language. Table 5 shows the power consumption for all modules. The system is built using the .NET Gadgeteer compatible mainboard and modules from GHI Electronics [76].

The software implementation is built on top of the following SDKs using Visual Studio 2013:

- NETMF SDK 4.3
- NETMF and Gadgeteer Package 2013 R3

Microsoft introduced .Net Gadgeteer as an open source to design electronic devices by taking advantage of object-oriented programming and integrating Visual Studio and .NET Micro Framework [84]. Net Gadgeteer is considered to be a tool for connecting a mainboard with electronic components. A well-known company that offers a variety of mainboards and modules is GHI Electronic.

The FEZ Spider Mainboard is a .NET Gadgeteer-compatible mainboard from GHI Electronics. The board supports the features of the .NET Micro Framework core, USB host, RLP and wi-fi. The mainboard is shown in Figure 20.

The FEZ Spider Mainboard is a .NET Gadgeteer-compatible mainboard from GHI Electronics. The board supports the features of the .NET Micro Framework core, USB host, RLP and wi-fi. The mainboard is shown in Figure 20.

B. IMPLEMENTATION AND TEST PLAN

The complete design of our wearable navigational device is shown in Figure 21. All sensors modules are connected to the FEZ-Spider mainboard.

We have employed two camera modules for static dynamic obstacle detection and avoidance. The previous studies emphasized that wearable devices are more convenient than portable devices for VI people. The wearable device is worn

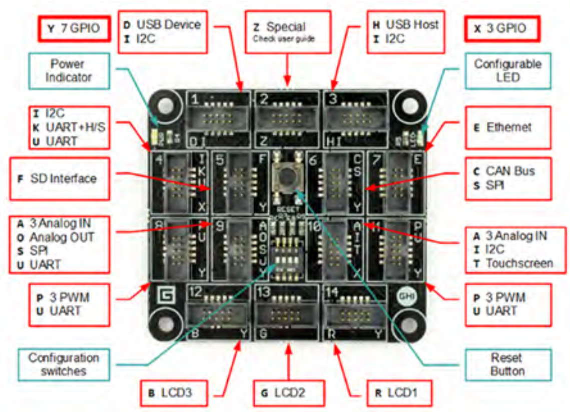


FIGURE 20. GHI Electronics FEZ Spider Mainboard [76].

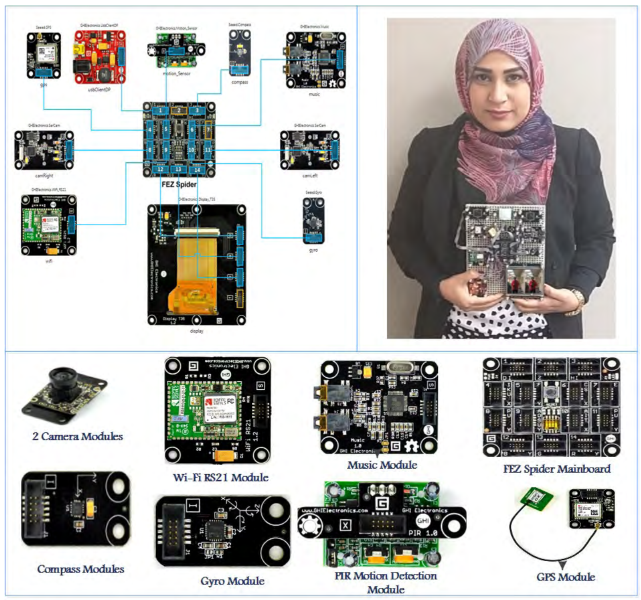


FIGURE 21. Hardware architecture.

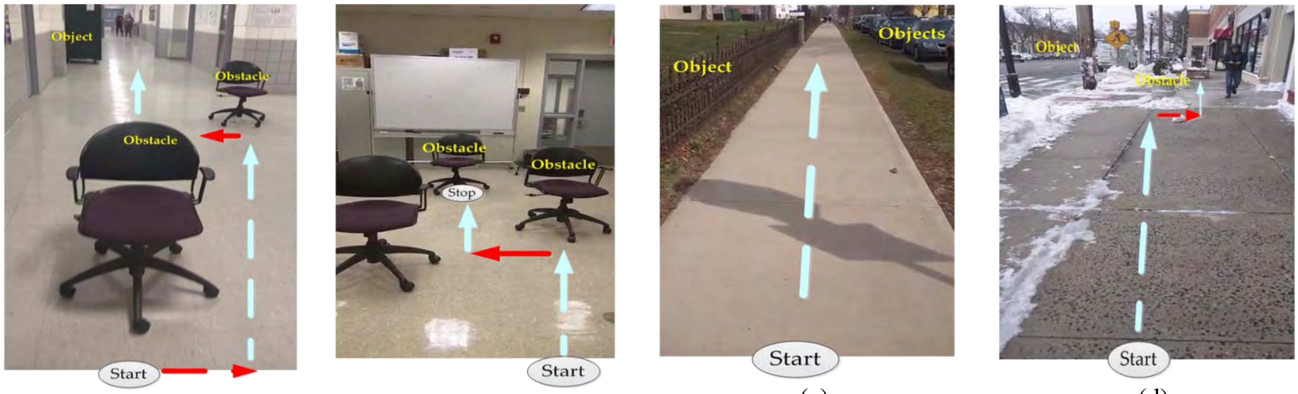
on the user's chest. The location of the device on this area of the user's body will ensure two things: 1) the device will have a stable position and will be connected by two belts: the first belt is on the neck side, and the second belt is on the waist side. Therefore, the device will not move from its position, 2) this location of the device will enable our system to address the obstacles under waist level and at head level.

The device was tested in indoor and outdoor scenarios. The number and shape of the obstacles differed by scenario. Our system was also tested on a video dataset that was directly fed to the system. A video of the testing experiments was added to as external material to this paper.

VI. REAL TIME EXPERIMENTS AND RESULTS

A. REAL TIME SCENARIOS

A set of experiments was performed on the designed device in indoor and outdoor environments. Simultaneously, frames



(a) (b) (c) (d)

FIGURE 22. **This figure illustrates different real scenarios that were tested. (a): A snapshot of the first real-time experiment when two objects exist, (b): A snapshot of the second real-time experiment to avoid dynamic and static objects in a complex environment, (c): A snapshot of the third real-time experiment for outdoor navigation, (d): A snapshot of the fourth real-time experiment for outdoor navigation using a complex path setup.**

will be transmitted to the server using an HTTP request to the device through the IP address. The GHI system has a built-in web server that can respond to HTTP requests. When the HTTP request is made, the device responds with the videos taken by the two camera modules, which are mounted on our device.

We grouped the objects in each scene into two subgroups because we realized that some objects should not be considered as obstacles unless they are located in front of the users or are blocking his/her path; otherwise, the object is considered to be an object. The two groups are as follows: the first group contains objects that are located in a frame in a particular video but do not create an obstruction to the user, which are termed objects. The second group contains any object with which the user can collide, which we termed obstacles. Once the obstacles are detected, our proposed measurement method will be applied for obstacle avoidance.

Each frame of the streamed video will be framed to three parts: left, right, and middle areas where the user is standing. Audio messages will be produced based on the direction that the user needs to follow.

Scenario 1: the first scenario was conducted indoors to examine the detection algorithm and the proposed method for avoiding obstacles in a simple environment. The scenario was conducted in a hall of the Tech building at the University of Bridgeport. Three obstacles are detected in the scene, whereas other objects are not considered to be obstacles. While the user was walking through the hall, audio messages were produced to avoid two sequential chairs, as shown in Fig. 22 (a).

Scenario 2: this scenario was also conducted indoors to detect and avoid objects along the user's path. Multiple objects are in this scene. The objective of this scenario is to test the system for detecting obstacles in close proximity while giving navigational instructions to avoid and move between the chairs. The chairs were setup in the middle and close to each other to test the accuracy of the avoidance technique in a complex environment, where more than one obstacle is located in close proximity. The arrows in Figure 22(b) illustrate the directions that the user was proceeding while he was using the device.

Scenario 3: this scenario was conducted outdoors to evaluate outdoor navigation performance. The scenario, which was conducted outdoors at the University of Bridgeport, is shown in Figure 22 (c). The objective of this scenario is to test the sensitivity of the modules to sunlight.

Scenario 4: this scenario was conducted outdoors to evaluate the proposed avoidance algorithm, where multiple objects exist. This scenario was performed with path planning but without any setup in a complex outdoor environment with dynamic objects. The user started from a predefined point and walked along a path, as shown in Figure 22 (d), to avoid detected static and dynamic obstacles and safely proceed along his path.

B. OVERVIEW OF THE FUNCTIONAL CAPABILITY OF PROPOSED METHOD IN THE SCENARIOS

Table 6 demonstrates the capability and reliability of the static/dynamic object detection algorithm model to safely navigate the user through his/her path. The modules, the type of experiment and the output are included in this table.

C. RESULTS AND EVALUATION

The focus of this evaluation is to provide an efficient and economically accessible device that assists VI people in navigating indoors and outdoors and detecting dynamic and static objects. In this section, we represent the accuracy based on the results of real-time scenarios, which are demonstrated in Table 7. Table 8 illustrates the results of examining the designed system on a video dataset of 30 videos. Each video has numerous frames to examine the accuracy of the performance of the detection system and avoidance of dynamic and static objects.

TABLE 6. Overview of the results of the four scenarios.

Scenario	Type of Experiment/Type of Module	Experimental Platform	Results
1	Indoors using two camera modules, a wi-fi module, and a music module. All are connected with a FEZ spider main board.	In an indoor light setting environment with one moving chair and one static object located to examine the performance of detection object on frames.	The system determined any obstacle in front of the VI person using two cameras. Then, avoided any obstacle with which the user may collide.
2	Indoors using two camera modules, a wi-fi module, and a music module. All are connected with a FEZ Spider main board.	In a low-light setting with a complex environment, a number of dynamic and static objects were placed to examine the efficiency of the system in detecting and avoiding multiple objects.	The system was able to detect multiple objects in close proximity. The system was able to navigate the user through his path without colliding with any objects.
3	Outdoors using two camera modules, and a music module. All connected with a FEZ Spider main board.	In a free path, the system was tested to examine the performance outdoors and the effectiveness of sunlight.	The system was allowed to detect all surrounding objects, with the exception of the black gate due to its large size. The user received an audio message that instructed him to keep straight while the path was free.
4	Indoors using two camera modules, a wi-fi module and a music module. All were connected with a FEZ spider main board.	In an indoor light setting environment with one moving chair and one static object located to examine the performance of the detection object on frames.	The system was allowed to determine any obstacle in front of the VI person using two cameras. Then, avoid any obstacle which with the user may collide.

The experiments were run on Windows 7, core i7, and the resolution of the camera is 320 × 240 with a maximum resolution of 20 fps. More intensive testing can be performed with a larger dataset. Our sequence of algorithms to detect dynamic and static objects, especially obstacles, yields very promising results and high accuracy compared with other algorithms. We have tested our algorithm on a sequence of videos that is considered to be a challenge for other systems. The processing time is dependent on the resolution of the camera; a higher resolution consumes a larger amount of time. Therefore, we chose a GHI camera module with a reasonable resolution to save time. An accuracy of 96.40% was obtained for our four pre-prepared scenarios and a small number of objects. An accuracy of 98.36% was achieved based on examining the proposed algorithm on a higher number of videos and a higher number of objects per frame. This finding indicates that our algorithm adequately performs for crowded environments with a larger dataset. As shown in Table 7, scenario 3 has a number of objects that the user does not encounter and that are not considered to be obstacles. This scenario was presented to test the sensitivity of the sensors to sunlight and to test the outdoor performance of our device. The user was safely guided by the device through his/her path. Clear and short audio messages were produced within a reasonable time.

Table 9 describes the matching level of the microcontroller's decision based on the proposed avoidance algorithm's process. The results of our tests indicate that the results are promising and accurate for avoiding any obstacles that may cause a collision with the user and navigating him/her through his/her path to ensure safe mobility.

Figure 23 shows two real-time indoor scenarios that we recorded while the user employed the system. Figure 24 represents a real-time outdoor scenario. Snapshots of some frames at different times were taken to show different outputs. The figure represents the performance of the system indoors and outdoors. A blindfolded person was wearing the device. The system started to give instructions based on detected obstacles. The user followed the instructions, which were given through a headset within a reasonable time based on the user's report. The user mentioned that the device was light and easy to use and the instructions were clear; he did not need any previous knowledge about the surrounding environment.

D. COMPUTATIONAL ANALYSIS

The collision avoidance approach is used in this framework to avoid the detected obstacles that the user may collide with. The user is provided with the avoidance instructions in predefined distance (1/3 height of a frame). Therefore, we have one scanning level (from the frame start to 1/3 height) where we scan for a free path to the user. This scanning level is moving as the user walks.

The scanning level is divided to three areas: left, right and middle as shown in Figure 25. The searching approach in each area is based on the fuzzy logic under one "for loop". We first search for the detected obstacles. If there is no obstacle within the scanning level, the user will continue straight. If there is an obstacle, the fuzzy rules will be applied. Thus, the

TABLE 7. Evaluation results of the proposed framework.

Video	Average Number of Frames	Average Number of Objects per Video	Average Number of Obstacles per Video	Average Number of Detected Objects per Video	Average Number of Detected Obstacles per Video	Accuracy per Video For Detected Objects	Accuracy per Video for Detected Obstacles	Processing Time per Frame
video1 of scenario 1	288	36	20	32	20	88.89%	100.00%	17.5 ms
video2 of scenario 2	237	15	15	15	15	100.00%	100.00%	18 ms
video3 of scenario 3	862	50	-	44	-	88.32%	-	36 ms
video4 of scenario 4	590	35	17	34	17	97.14%	100.00%	26.66 ms
Accuracy of Detection Algorithm = 96.40%								

TABLE 8. Evaluation results for the tested dataset.

No. of Videos	Average Number of Frames per Video	Detection Rate for Detected Objects	Detection Rate for Detected Obstacles	Average Accuracy
30	700	Worst: 85.71% Average: 96.72% Best: 100%	100.00%	98.36%

proposed obstacle avoidance approach has a complexity of linear time O(n); n is the number of detected front obstacles and need to be avoided). Every time the user pass the threshold (1/3 height of the frame), a new window (1/3 height) will be calculated.

In order to get the time complexity of the whole system, we need to add the time complexity of the detection algorithm and the time complexity of the obstacle avoidance algorithm. Most obstacle avoidance algorithms are applied after SIFT or SURF algorithms for object detection. Our obstacle avoidance approach is applied after ORB algorithm for object detection, which requires less memory and computation time than other systems [76]. According to [85] and [86], the time complexity of ORB algorithm is almost half of the time complexity of SIFT and SURF. This conclude that our overall all system provide a faster and reliable obstacle avoidance system.

Figure 26 represents the taken time to process five frames; each frame includes number of obstacles. Furthermore, Figure 26 describes the actual taken time to detect obstacles, avoid obstacles as well as sending the audio feedback to the user through the headphone. This Figure demonstrates the taken time for detection / avoidance algorithm, establishing HTTP request and playing the audio feedback. Thus, the complete processing time is increasing proportionally to the number of detected objects with a time complexity of $O(n^2)$

The required processing time for 50 obstacles in one frame is 0.35sec. The used serial camera has a resolution of 320 × 240 and a maximum resolution of 20 fps. Thus, our system is capable to process more than three frames within a second. That indicates the proposed system is a real time system as we designed it for the pedestrians.

E. DISCUSSION

The objective of this study is to overcome the limitation of the reviewed systems by designing a new system that supports missing features in an effective and autonomous design. Table 10 represents a comparison between the previous systems that were reviewed in section III and the proposed system; this comparison is based on the user's needs and the engineers' perspectives.

Table 10 focuses on the performance of the systems. The parameters in Table 10 were chosen based on our in-depth study [8]. The unavailability of these features can negatively influence the performance of the systems. The main concerns of the user are the analysis type (real-time or non-real-time), weight, cost, and performance (outdoors, indoors). The main concerns of engineers are the type of detected objects, the range of the detection, and the total accuracy of the system. Other parameters can be added to Table 10, and some of the listed parameters can be conjoined for both users and engineers.

However, the type of the sensors and the techniques that we discussed in section 3 may explain the limitations. For example, infrared technology is sensitive to sunlight, which indicates that systems based on infrared technology are not suitable for outdoor use [87]. The scope limitation of radio frequency technology makes it less preferable in this field because the installation of tags is required in surrounding areas [88]. In addition, systems based on the Kinect sensor demonstrate a small detection range because

FIGURE 23. The proposed system is applied to indoor real-time scenarios.

the accuracy of the Kinect sensor decreases when the distance between the object and the camera increases [89], [90]. The change in the environmental parameters can have a significant impact on the performance of ultrasonic sensors [91]. Thus, ultrasonic sensors have a small detection range.

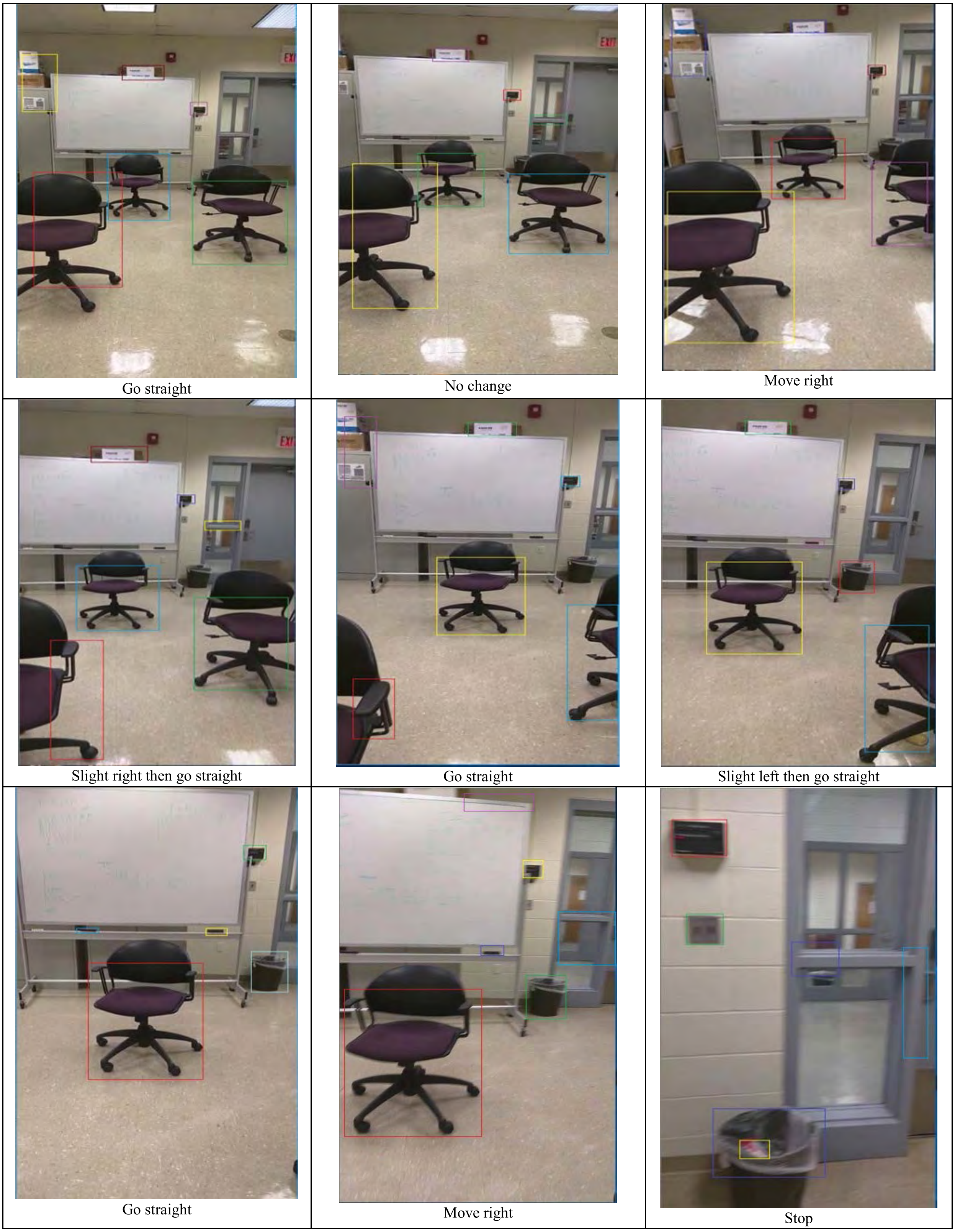


FIGURE 24. The proposed system is applied to outdoor real-time scenarios.

As shown in Table 10, systems [31], [32], and [41] do not operate in real time, which indicates that they are in the research phase. These systems include Silicon Eyes, RFIWS, and Path Force belts. Approximately 70% of the reviewed techniques do not fully satisfy the benchmark table (Table 10). For instance, [22] does not provide indoor

TABLE 9. The evolution of the proposed obstacle avoidance approach.

Time	Expected Decision	Actual Decision by the FEZ Spider Board	Reason
t0	Move left Or move right	Move left	Obstacle detected in front in near proximity to the VI person, and the left and right areas are free.
t1	Move Right	Move right	Obstacle detected in front and to the left in near proximity to the VI person
t2	Go straight,	Go straight	Obstacle detected in front but not in near proximity to the VI person
t3	Go straight	Go straight	No objects detected
t4	Move left or slight left then go straight	slight left and go straight	The detected object is within 20% of the middle quadrant of the right side; the object does not create an obstruction to the user.
t5	Move right, slight right and go straight	slight right and go straight	The detected object is within 20% of the middle quadrant of the left side; the object does not create obstruction to the user
t6	Move left or move right	Move left	Obstacle detected in front near proximity to the VI person, and only the left area is free.
t7	Go straight, move left or move right	Go straight	Object detected in front but not in near proximity to the VI person.
t8	Move left or slight left and go straight	slight left and go straight	The detected object is within 20% of the middle quadrant of the right side; the object does not create obstruction to the user
t9	Stop	Stop	Obstacle detected in front near proximity to the VI person. The left and right areas are occupied.
t10	Move right	Move right	Obstacle detected in front near proximity to the VI person. However, the right area is free.
t11	Move right or move left	Move left	Two obstacles are detected in front near proximity to the VI person. Both the left and right areas are free. However, the proposed algorithm will produce move left audio message as if it is free even if the right area is also free.

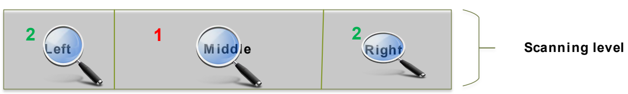


FIGURE 25. The searching area for obstacle avoidance approach.

performance, and the detection range is small due to the use of ultrasonic sensors. The integration of both sensor-based and computer vision technologies is a solution to these issues since sensor-based systems have limitations due to the sensors' limitations and unpredictable behavior due to the environment's influence on these systems, which are usually unpredictable too. Hence, systems that are based on computer vision technology can also have limitations.

Furthermore, we have surveyed a large number of published articles including that present the rules of O&M [92] for visually impaired people. All the published work agreed on one point that the guidance of the visually impaired requires precise instructions and accurate positioning as well as needs to be economically accessible [92]. We have designed a system that integrate sensor-based and computer vision system. The used sequence of algorithms (computer vision-based) provide us with an efficient multi object detection system. As we are able to locate the user's position and the obstacle's coordinates, the accurate positioning condition is applied.

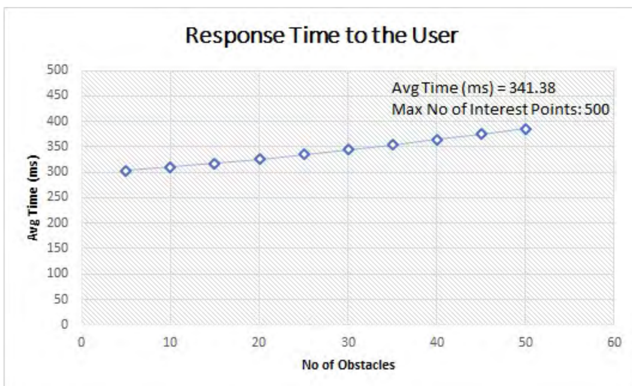


FIGURE 26. The cost of the proposed approach as a time function for avoiding number of obstacles in each frame.

TABLE 10. Comparison between the previous systems that were analyzed in section 3 and the proposed system based on the user's needs.

	System	User's Perspective			Performance		Engineer's Perspective: Object Classification		Detection Range	Accuracy
		Cost	Weight	Real Time	Indoor	Outdoor	Static	Dynamic		
Sensor-Based ETA	[21]	-	-	✓	-	✓	✓	-	1 m–1.5 m	-
	[22]	$1790	light	✓	-	✓	✓	-	2 m–3 m	-
	[23]	-	-	✓	-	✓	✓	-	0 m–2 m in front	-
	[24]	-	170 gram	✓	-	✓	✓	-	Close objects over the waistline	80% → 0.5 m–5 m
	[25]	-	Light	✓	✓	-	✓	-	5 – 150 cm	-
	[27]	-	light	✓	✓	✓	✓	-	3 cm – 4 m	N/A
	[28]	-	-	✓	✓	✓	✓	-	0.5 m–5 m	80% → 0.5 m–5 m < 80% → R > 5 m
	[29]	$138	-	✓	-	✓	✓	-	-	Good accuracy within residential area only
	[30]	-	-	-	-	-	✓	✓	2.5 cm – 3.5 m	N/A
	[31]	-	-	✓	✓	-	✓	✓	0.8 m – 4 m	N/A
	[33]	-	-	-	-	✓	✓	✓	Short	N/A
	[34]	-	-	✓	✓	✓	✓	-	50 m – 60 m	-
	[35]	low	Light	✓	✓	-	✓	✓	0.5 m–8 m	99% ± for object detection system
Sensor Substitution-Based ETA	[39]	low	Light	✓	-	✓	✓	-	-	Different parts of the tongue, (1,2,3,4) 100% (7) 10% (5,6,8) 50%
	[41]	-	-	-	-	✓	✓	-	1 m–3 m	-
	[42]	-	-	✓	-	✓	✓	-	20 m with 3 cm error	-
	[44]	-	-	✓	✓	-	✓	✓	-	-
Computer Vision Methods and Sensor-Based ETA	[45]	low	-	✓	-	✓	✓	✓	2 m–10 m	Accurate results for user position
	[49]	-	-	✓	✓	-	✓	-	1.5 m–4.0 m	N/A
	[50]	low	-	✓	✓	✓	✓	-	Up to 10 m	High Accuracy
	[52]	low	-	✓	✓	-	✓	-	> 3 m	95%
	[54]	Low	750 gram	✓	✓	✓	✓	✓	2 < R ≤ 5 m	N/A
	Proposed System	**$ 242.41**	**180 gram**	✓	✓	✓	✓	✓	**0 m < R <= 9 m**	**96.40 ± 2; 98.36% with larger data set ; 100% for obstacle avoidance system.**

With this study, O&M instructions and the benchmark Table 8, we suggest that the proposed system stands out in this comparison based on its features and the ability to satisfy expectations of both the user and the engineer with high accuracy using both sensor-based technology and computer vision technology.

VII. CONCLUSION

In this study, we developed a hardware and software implementation that provides a framework for a wearable device that can assist VI people. The system was implemented using a .NET Gadgeteer-compatible mainboard and modules from GHI Electronics. This novel electronic travel aid facilitates the mobility of VI people indoors and outdoors using computer vision and sensor-based approaches.

At the hardware level, the proposed system includes modules such as GPS, camera, compass, gyroscope, music, microphone, wi-fi, and a FEZ spider microcontroller. At the software level, the system was designed based on multi-sensory data and computer vision approaches to support a navigational system and produce accurate information.

The proposed measurement method enables us to approximately measure the distance between the user and the object. This method enables the user to safely traverse his/her path without any collisions depending on the change in the size and bottom (x, y) coordination of this object in a particular frame.

An accuracy of 96.40±2% for the static and dynamic detection system is achieved based on the proposed sequence of well-known algorithms. Our proposed obstacle avoidance system enabled the user to traverse his/her path and avoid 100% of the obstacles when they were detected. We conducted numerous experiments to test the accuracy of the

TABLE 11. Fuzzy rules for proposed obstacles avoidance system.

Rule	User's Position	Obstacle's Range	ObsLeft	Obs20% LeftMid	ObsMiddle	Obs20% RightMid	ObsRight	Feedback
1	Middle	Near	ObsEx	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	GoStraight
2	Middle	Near	ObsEx	Obs_NEx	Obs_NEx	Obs_NEx	ObsEx	GoStraight
3	Middle	Near	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	ObsEx	GoStraight
4	Middle	Near	ObsEx	ObsEx	Obs_NEx	Obs_NEx	Obs_NEx	SlightRightStraight
5	Middle	Near	Obs_NEx	Obs_NEx	Obs_NEx	ObsEx	ObsEx	SlightLeftStraight
6	Middle	Near	ObsEx	ObsEx	Obs_NEx	ObsEx	ObsEx	stop
7	Middle	Near	ObsEx	Obs_NEx	ObsEx	Obs_NEx	Obs_NEx	MoveRight
8	Middle	Near	Obs_NEx	Obs_NEx	ObsEx	Obs_NEx	ObsEx	MoveLeft
9	Middle	Near	ObsEx	Obs_NEx	ObsEx	Obs_NEx	ObsEx	Stop
10	Middle	Far	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	GoStraight
11	Middle	Far	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	GoStraight
12	Middle	Far	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	GoStraight
13	Middle	Far	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	GoStraight
14	Middle	Far	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	GoStraight
15	Middle	Far	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	GoStraight
16	Middle	Far	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	GoStraight
17	Middle	Far	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	GoStraight
18	Middle	Far	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	Obs_NEx	GoStraight

system. The proposed system exhibits outstanding performance when comparing the expected decision with the actual decision.

Based on the extensive evaluation of other systems, our system exhibits accurate performance and an improved interaction structure with VI people. The following summary describes the properties of the proposed system:

Performance: the device satisfies the parameters represented in Table 10, which need to be supported in any device that assists VI people.

Wireless connectivity: using a wi-fi sensor, the device is wirelessly connected.

Reliability: designed device satisfies the software's and hardware requirements.

Simplicity: the proposed device has a simple interface that is user-friendly and does not require previous knowledge (speech recognition and audio feedback for navigational instructions).

Wearable: from a previous study and review [8], the proposed system can be worn rather than carried, which is more convenient.

Economically accessible: since most blind people are from low-income backgrounds, the designed system is an economic solution, because the current implementation costs less than $250.

The proposed collision avoidance system can be implemented in different applications such as automotive applications, self-driving vehicles, and military applications.

VIII. FUTURE DIRECTIONS: OBSTACLE DETECTION USING SENSOR NETWORKS

Walls and large doors may not be detected due to their size of representation into the frame, which may consume half of the frame. In this case, distinguishing between the foreground and the background can be difficult. Therefore, ultrasonic sensors may be the solution. In addition, the ultrasonic module is a reliable source of obstacle detection that can measure distance if it is integrated with computer vision techniques. Therefore, additional ultrasonic sensors can increase the accuracy.

APPENDIX A

See Table 11.

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