A HIGHLY ACCURATE AND RELIABLE DATA FUSION FRAMEWORK FOR GUIDING THE VISUALLY IMPAIRED

Wafa Elmannai

Under the Supervision of Dr. Khaled Elleithy

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Approvals

Committee Members

Name	Signature	Date
Dr. Khaled Elleithy		12/8/17
Dr. Elif Kongar		1/18/18
Dr. Miad Faezipour		12, 8, 2017
Dr. Xingguo Xiong		01/19/2018
Dr. Mohsen Guizani		1-10-18

Ph.D. Program Coordinator

Dr. Khaled M. Elleithy		1/18/18

Chairman, Computer Science and Engineering Department

Dr. Ausif Mahmood		1-18-2018

Dean, School of Engineering

Dr. Tarek M. Sobh		1-22 2018

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ABSTRACT

The world has approximately 285 million visually impaired (VI) people according to a report by the World Health Organization. Thirty-nine million people are estimated to be blind, whereas 246 million people are estimated to have impaired vision. An important factor that motivated this research is the fact that 90% of VI people live in developing countries. Several systems have been designed to improve the quality of the life of VI people and support the mobility of VI people. Unfortunately, none of these systems provides a complete solution for VI people, and the systems are very expensive. Therefore, this work presents an intelligent framework that includes several types of sensors embedded in a wearable device to support the visually impaired (VI) community. The proposed work is based on an integration of sensor-based and computer vision-based techniques in order to introduce an efficient and economical visual device. The designed algorithm is divided to two components: obstacle detection and collision avoidance. The system has been implemented and tested in real-time scenarios. A video dataset of 30 videos and an average of 700 frames per video was fed to the system for the testing purpose. The achieved 96.53% accuracy rate of the proposed sequence of techniques that are used for real-time detection component is based on a wide detection view that used

two camera modules and a detection range of approximately 9 meters. The 98% accuracy rate was obtained for a larger dataset. However, the main contribution in this work is the proposed novel collision avoidance approach that is based on the image depth and fuzzy control rules. Through the use of x-y coordinate system, we were able to map the input frames, whereas each frame was divided into three areas vertically and further 1/3 of the height of that frame horizontally in order to specify the urgency of any existing obstacles within that frame. In addition, we were able to provide precise information to help the VI user in avoiding front obstacles using the fuzzy logic. The strength of this proposed approach is that it aids the VI users in avoiding 100% of all detected objects. Once the device is initialized, the VI user can confidently enter unfamiliar surroundings. Therefore, this implemented device can be described as accurate, reliable, friendly, light, and economically accessible that facilitates the mobility of VI people and does not require any previous knowledge of the surrounding environment. Finally, our proposed approach was compared with most efficient introduced techniques and proved to outperform them.

DEDICATION

I dedicate this dissertation to my father's soul (Mohamed Elmannai), my mother (Soad), my sisters and brothers with a special mention to my sister (Nihal) who has been my inspiration through my life , my husband (Aymen), my beautiful daughters (Remass, Raseal, Ruba and Rubeen).

For all of your love, encouragement and support.

ACKNOWLEDGEMENTS

My thanks are wholly devoted to God who has helped me all the way to complete this work successfully.

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I would also like to thank all the committee members on their positive comments, advices, evaluation and their encouragement to me: Prof. Elif Kongar, Prof. Miad Faezipour and Prof. Xingguo Xiong. In addition, I would like to express my appreciation to Prof. Mohsen Guizani, external member of the dissertation advisory committee, for his comments, his time and his evaluation to my work.

At the end of this journey, I realize that the hard work and smartness are not enough to make you successful. The success cannot happen if you are not surrounded with great supporters. I was lucky that I have supporters at home and at school. I am truly grateful to all professors of the School of Engineering at the University of Bridgeport for their great support and encouragement. I have a great time either being working with or studying in their classes. I enjoyed the volunteer work with other professors. At the end, I learned from each one of them new things that have been a definite plus in terms of growing me up professionally.

As I owe a debt of gratitude to my family for their understanding, support and encouragement. Their love to me and their belief in my skills were my power to go through this journey. My special recognition goes to my inspiration, the kindest and strongest women on the earth my mother whose passion for the education was the reason behind my persistence to finish my education. She always tell me that I am allowed to give up anything but NOT my education. I would also thank my husband for his support, patience, and sacrifice; this will always remain my inspiration throughout my life. Moreover, I would specially thank my dearest sister Nihal for her encouragement and support in the most difficult moments.

ACRONYMS

BanknoteRec	Banknote Recognition
BoVW	Bag of Visual Words
BRIEF	Binary Robust Independent Elementary Features
C	Centroid point
CG System	Cognitive Guidance System
CMOS	Complementary Mal-oxide Semiconductor
ComVis Sys	A Computer Vision System that Ensure the Autonomous Navigation
DBG Crutch Based M-Sensors	A Design of Blind-guide Crutch Based on
ELC	An electronic Long Cane
EOA	Electronic Orientation Aid
ETA	Electronic Travel Aid
FAST	Features from Accelerated Segment Test
FAV&GPS	Fusion of Artificial Vision and GPS
FPGA	Field Programmable Gate Array
GIS	Geographic Information Systems
Global Positioning System	GPS
GPRS	General Packet Radio Service
GSM	Global System for Mobile communication
HOG	Histogram of Oriented Gradients
KNN	The K-Nearest Neighbor

LED	Light-Emitting Diode
LowCost Nav System	A Low Cost Outdoor Assistive Navigation
MobiDevice VerticleResolion	A Mobility Device for the Blind with Improved Vertical Resolution Using Dynamic Vision Sensors
Mobile Crowd Ass Nav	Mobile Crowd Assisted Navigation for the Visually-impaired
m_{pq}	Moments
Multi-sensors	
Nav RGB-D	Navigation Assistance Using RGB-D Sensor with Range Expansion
Obs Avoid using Haptics&Laser	Obstacle Avoidance Using Haptics and a Laser Rangefinder
Obs Avoid using Thresholding	Obstacle Avoidance Using Auto-adaptive Thresholding
ORB	The Oriented FAST and Rotated BRIEF
PF belt	A Path Force Feedback Belt
PLD	Position Locator Devices
RANSA	RANdom Sample Consensus
RFID	Radio-frequency identification
RFIWS	The Radio Frequency Identification Walking Stick
SIFT	The scale-invariant feature transform
Sili Eyes	Silicon Eyes
SMS	Short Message Service
t	Threshold
TED	Tongue Electro Tactile Device

Ultra Ass Headset	Ultrasonic Assistive Headset for visually-impaired people
UltraCane	Ultrasonic Cane as a Navigation Aid
Ultrasonic for ObstDetectRec	When Ultrasonic Sensors and Computer Vision Join Forces for Efficient Obstacle Detection and Recognition
UWB	Ultra-wideband
Visually-Impaired	VI

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CHAPTER 1: INRTODUCTION

In 2014, The World Health Organization (WHO) reported statistics of 285 million VI people worldwide [1]; thirty-nine million people are completely blind. In 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 [1]. 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].

The need for assistive devices for navigation and orientation has increased. The simplest and the most affordable navigators are trained dogs and the white canes [5]. Although these tools are very popular, they cannot provide the blind with required information and features for safe mobility, which are available to people with sight [6, 7].

1.1. Assistant Technology

Assistive technology was introduced in the 1960s to solve problems associated with transmitting information [5] and mobility assistance, such as orientation and navigation [6, 7].

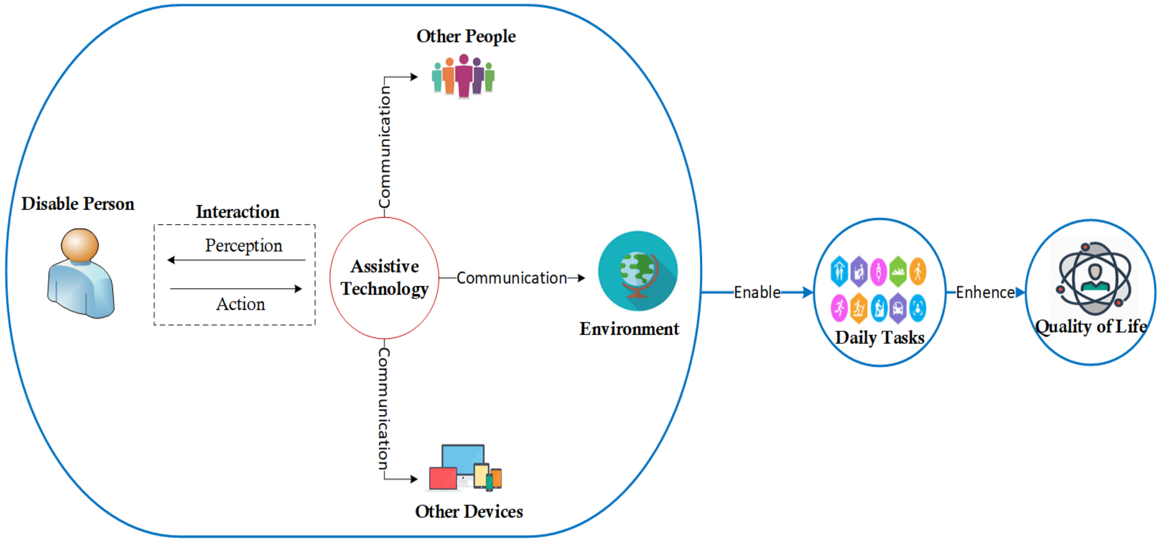


Figure 1. 1: Diagram of assistive technology [9]

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 [8]. Figure 1.1 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 [9].

Figure 1.2 shows the three main subcategories of visual assistive technology: vision enhancement, vision substitution, and vision replacement [10, 11]. 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 [12, 13].

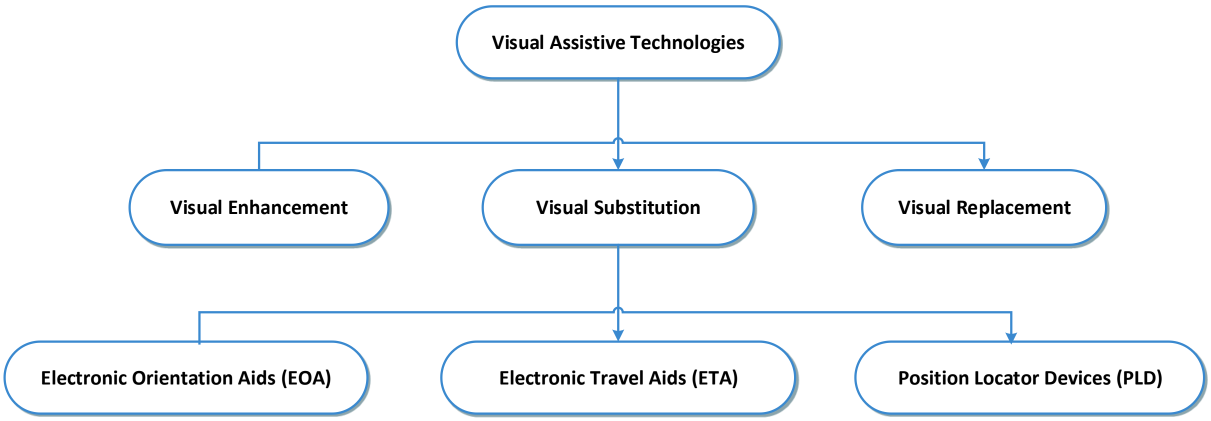


Figure 1. 2: The Hierarchy of Assistive Technology

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 [10]. 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 1.1 describes each subcategory of the visual substitution category and their services.

TABLE 1. 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 [14, 15].	Identifying the surrounding obstacles. Delivering information about the textures and gaps of the movement surface. Finding items that surround the obstacles. Determining the distance between the user and the obstacle. Identifying remarkable locations. Providing obstacle avoidance information to improve the self-orientation throughout the area.
EOA	Devices that give pedestrians guidelines and instructions about his/her path [16, 17].	Defining the best path for the user; Calculating the user’s position by tracking the path. Developing 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).	A route guidance from one point to another point is provided.

1.2. Research Problem and Scope

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 [18]. 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 [19, 20]. 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.

Even with the assistive technology revolution, users still rely on either a white cane or a trained dog. None of the existing systems are considered as a complete solution in serving, assisting the visually impaired and ensuring their safety. Researchers are aware of some important features but not all; most fundamental features that need to be included in such system do not exist in one system. According to our study, users do not consider any of the existing systems as a white cane replacement so far.

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 a good performance indoor and outdoor as well as during day or night becomes a critical challenge.

1.3. Motivation behind the Research

As the number of VI people is being increased, thus, it is very essential to ensure an independent life for them. The VI people need to communicate with the surrounding area to improve the quality of their lives. Integration of different sensors of different resources is considered as one of the represented solutions to provide robustness and efficiency. The definition of sensory data fusion or integration is a parallel process of data that is sensed by different sensors to produce an effective and accurate instructions.

For obstacle detection, avoidance, and route guidance, different types of sensors are being used such as: GPS, infrared sensor, camera modules, ultrasonic sensors. Each one has its own properties of accuracy and capability. Thus, the integration of multiple sensors can enhance the overall performance of such system.

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: (1) the offered devices are very expensive, and VI people predominantly belong to the low-income group; (2) 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 techniques can overcome these limitations.

Therefore, 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 we recently published in [20] (also in Chapter 2). 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 performs indoors and outdoors with providing a navigational service.

1.4. Potential Contributions of the Proposed Research

The focus of this work 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 and sensor-based techniques. An innovative approach, whichis referred to as a proximity measurement method, is proposed for measuring distance. This approach is based on an image's depth and fuzzy logic controller. 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 integration of multisensory devices and a proposed data fusion algorithm with the help of computer vision techniques. 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. Whereas, this system is designed to assist normal walkers. Therefore, this framework addresses the following:

Real-Time system: the system provides a real-time collision avoidance application that is fast enough to process the exchanged information between the microcontroller and sensors.

Functionality: the system supports the efficiency that provides a precise information to allow the user to safely travel through his/her path without colliding with front obstacles.

Reliability and Scalability: satisfying the hardware and software requirements in order to accommodate and handle any unpredictable fluctuations and perform as accurate as in any tested scenario. Therefore, safety is the main issue in the navigation systems.

Simplicity: the design of the framework and its use is simple for the users. Clear and understandable audio messages include warning and directions are an essential component in our system.

Cost: the design of the system supports an economical solution using efficient components**.**

CHAPTER 2: ASSISTIVE DEVICES FOR VISUALLY-IMPAIRED PEOPLE

Most electronic aids that provide services for Visually-Impaired (VI) people depend on the data collected from the surrounding environment (via either laser scanners, detected camera, or sonar) and transmitted to the user via tactile, audio or both methods. Different opinions regarding which method provides better feedback are still under discussion.

In addition, although several systems have been proposed in the past decade, none of these systems is considered a complete solution that can assist VI people in all aspects of their lives. Therefore, this chapter presents some of the work that has been performed.

However, regardless of the services that are provided by any specific system, there are some basic features required to design such a system to yield adequate performance. These features are important for measuring the efficiency and reliability of any electronic device that provides navigation and orientation services to VI people. Consequently, we present in this chapter a list of the most important and latest systems, with a brief summary including what the system is, its prototype, a brief discussion of how it works, the well-known techniques that have been used in the system, and the advantages and disadvantages.

These devices are classified in Figure 2.1.1 based on their type and in Figure 2.1.2 based on the features described in Table 2.1. The comparative results based on these features will be represented in the following section of this chapter with an answer to a very important question: which device is the most efficient and reliable?

TABLE 2.1: THE MOST IMPORTANT FEATURES THAT CORRESPOND TO USER NEEDS

Feature	Description
Analysis Type	The system needs to provide a fast processing of the exchanged information between the user and sensors. For example, a system that detects an obstacle that is 2 m in front of the user in 10 s cannot be considered as real-time system [12]
Performance	The system needs to perform as good indoor as outdoor to improve the quality of life for VI people
Time	The system should perform during the day time as well as at night time
Detection **Range**	it is the range or the distance between the user and the object to be detected by the system. The ideal minimum range is 0.5 m, and the maximum range should be more than 5 m. A larger distance is better.
Object Type	The system should avoid the sudden appearance of objects; thus, the system should detect dynamic and static objects

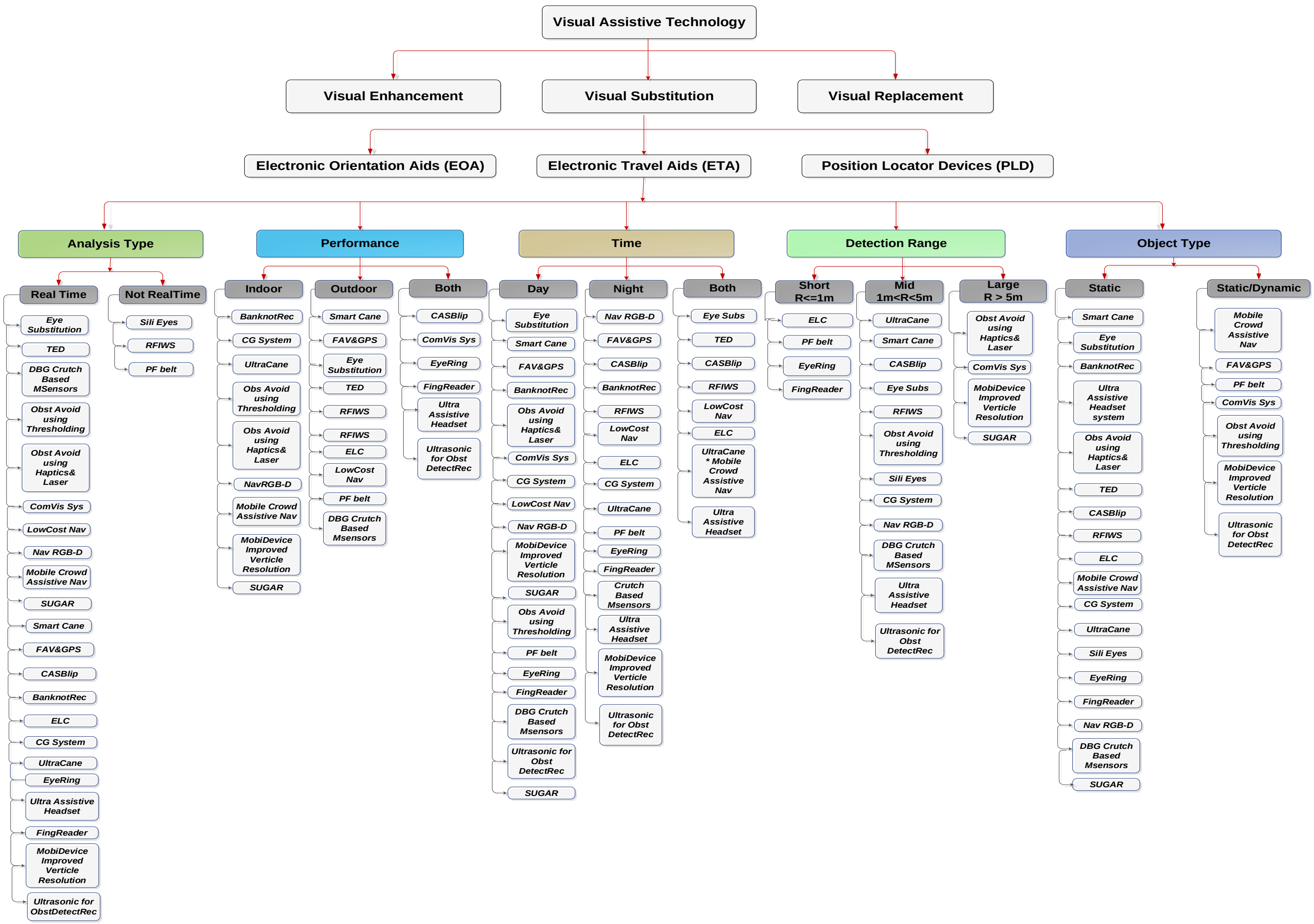


Figure 2.1.1: Classification of the assistive electronic devices based on their type

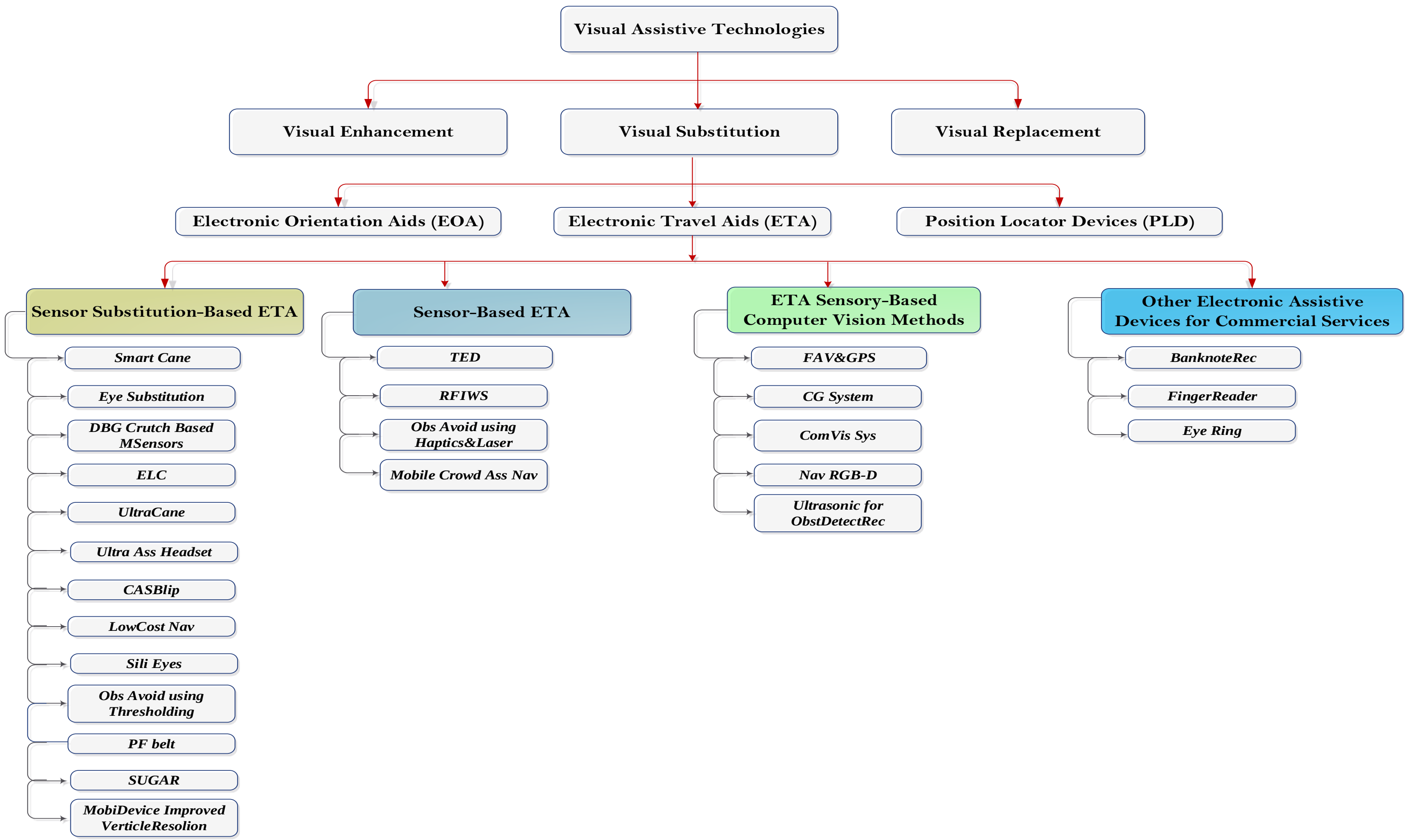


Figure 2.1.2: Classification of the assistive electronic devices based on their affordable features

2.1. **Sensor-Based ETAs**

Sensor-based ETAs are techniques or systems that provide VI people with information about their surrounding environment via vibrations, audio messages or both vibrations and messages using sensors. These systems primarily rely on 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 used in this field.

2.1.1 Smart Cane

Wahab et al. developed an obstacle detection and avoidance system that is based on the ultrasonic technology in [21]. The Smart Cane was originally presented by Central Michigan University students. The design of the Smart Cane is shown in Figure 2.2. The Smart Cane is a portable device that is equipped with a sensor system. The system consists of ultrasonic sensors, a microcontroller, a vibrator, a buzzer, and a water detector to guide VI people. The Smart Cane uses servomotors, ultrasonic sensors, and a fuzzy controller to detect the obstacles in front of the user and then provides instructions through voice messages or hand vibrations.

The servomotors are used to give precise position feedback. Ultrasonic sensors are used to detect obstacles. Hence, the fuzzy controller gives accurate decisions based on the information received from the servomotors and ultrasonic sensors to navigate the user. The output of the Smart Cane depends on gathering the above information to produce audio messages through the speaker to the user. In addition, hearing impaired people have special vibrator gloves that are provided with the Smart Cane. There is a specific vibration for each finger, and each vibration has a specific meaning.

Figure 2.1: The Smart Cane prototype [21]

The Smart Cane has achieved its goals in detecting obstacles and producing the needed feedback. As shown in Figure 2.2, the Smart Cane is easily carried and bent. However, the buzzer for the water detector will not stop before it is dried or wiped, which is very annoying. The authors of the paper have some recommendations for the tested system. They stated that to monitor the power status, it is preferable to have a power supply meter installed. Additionally, the authors recommended adding a buzzer timer to specify the period and solve the buzzer issue.

2.1.2 Eye Substitution

Bharambe et al. proposed an embedded device using an android application to navigate the user through his/her path [22]; the design of the system is illustrated in Figure 2.3.

Modified GSM was introduced in this study. Mainly, the embedded device is a TI MSP 430G2553 microcontroller (Texas Instruments Incorporated, Dallas, TX, USA). The authors implemented the proposed algorithms using an Android application. The role of this application is to use GPS, improved GSM, and GPRS to obtain the location of a person and generate better directions. The embedded device consists of two HC-SR04 ultrasonic sensors (Yuyao Zhaohua Electric Appliance Factory, Ditang Town, China) and three vibrator motors.

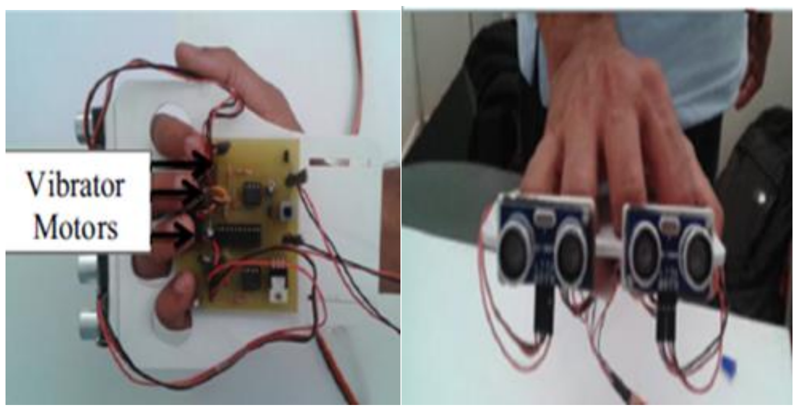


Figure 2.2: The prototype of the eye substitution device [20]

The ultrasonic sensors send a sequence of ultrasonic pulses. If the obstacle is detected, then the sound will be reflected back to the receiver, as shown in Figure 2.4. The microcontroller processes the readings of the ultrasonic sensors to activate the motors via pulse width modulation and provides low power consumption [23].

The device is light, and the design is very convenient. Furthermore, the system uses two sensors to overcome the issue of a narrow cone angle, as shown in Figure 2.5. Therefore, instead of covering two ranges, the ultrasonic devices cover three ranges. This scheme not only helps in detecting obstacles but also in locating them. However, the design could be better if the authors did not use the wood foundation that is carried by the user most of the time. In addition, the system is not reliable and is limited to Android devices.

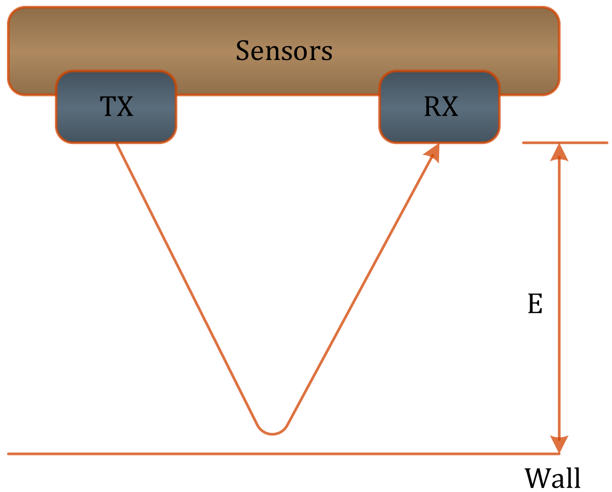


Figure 2.3: Reflection of the sequence of ultrasonic pulses between the sender and receiver

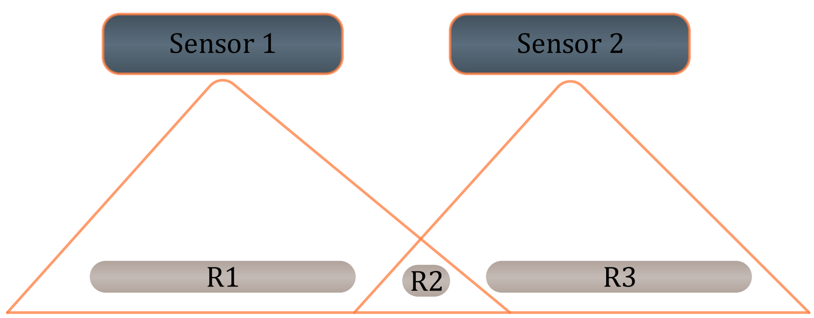


Figure 2.4: Ranges that are covered by the ultra-sonic sensors [21]

2.1.3 A Design of a Blind-Guide Crutch Based on Multisensors (DBG Crutch-Based MSensors)

A multisensory system was designed and installed on a stick to detect and avoid front obstacles in three different directions based on the ultrasonic distance measurement approach in [24]. Figure 2.6 displays the use of the crutch and the detection range of the ultrasonic system.

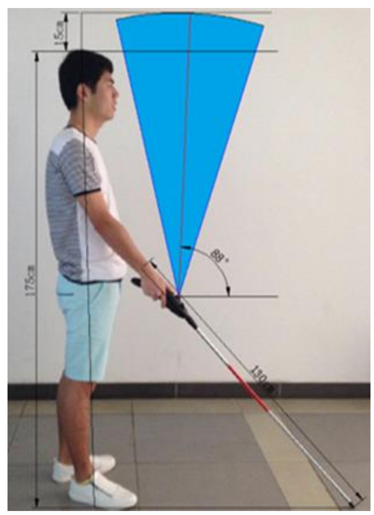


Figure 2.5: The proposed crutch with detection ranges displayed [24]

Figure 2.7 displays the replacement of the three ultrasonic sensors on the cane. The function of these sensors is to collect the distance information from different ranges; the top sensor is used for detecting the overhead obstacles, and the other two are used for the detection of front obstacles. In addition, ultrasonic transmitting and receiving modules, voice and vibration modules and a key to switch between the feedback modules are used in this system. The STC15F2K60S2 microcontroller controls the whole system.

Figure 2.6: The replacement of the three ultrasonic sensors on the cane [24]

The STC15F2K60S2 MCU controls the signals between ultrasonic transmitting and receiving modules. The travel times need to be recorded separately, such as time1, time2 and time3, when the ultrasonic signal is emitted and the echo signals are detected. If the time counter is larger than the setup threshold, then there are no obstacles present in that area. Based on the detected distance from the obstacle to the sensor, "the alarm decision-making algorithm" produces a warning message in either audio or vibrational form.

The system was successful in detecting obstacles in four directions, front, left front, right front and overhead, using three sensors. However, the detection range is small, as the maximum range was 2m. The feedback of this system only consists of warning messages regarding the obstacle location, and no directions are given to proceed forward.

2.1.4 Electronic Long Cane (ELC)

An electronic long cane (ELC) was designed as a mobility aid to detect front obstacles with the help of haptics and ultrasonic technology [25]. ELC is a development of the traditional cane to provide accurate detection of the objects around the user. The grip of the cane, shown in Figure 2.8, consists of an embedded electronic circuit that includes an ultrasonic sensor for the detection process, a micro-motor actuator as the feedback interface, and a 9-V battery as a power supplier. This grip can detect obstacles above the waistline of the blind person. Tactile feedback through vibration is produced as a warning for a close obstacle. The frequency of the feedback increases as the blind person gets closer to the obstacle. Figure 2.9 shows how the ELC can help a blind person to detect an obstacle above his/her waistline, which is considered one of the reasons for serious injury to those who are VI or completely blind.

Figure 2.7: The prototype of the grip [25]

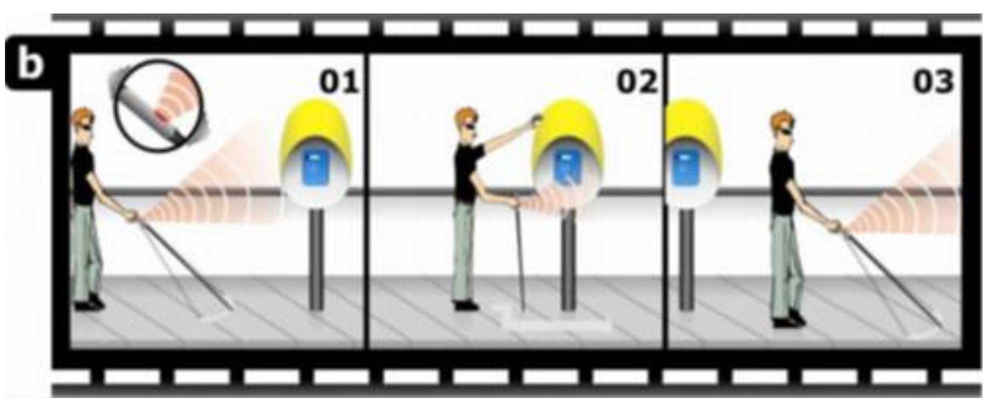


Figure 2.8: The proposed device for enhanced spatial sensitivity [25]

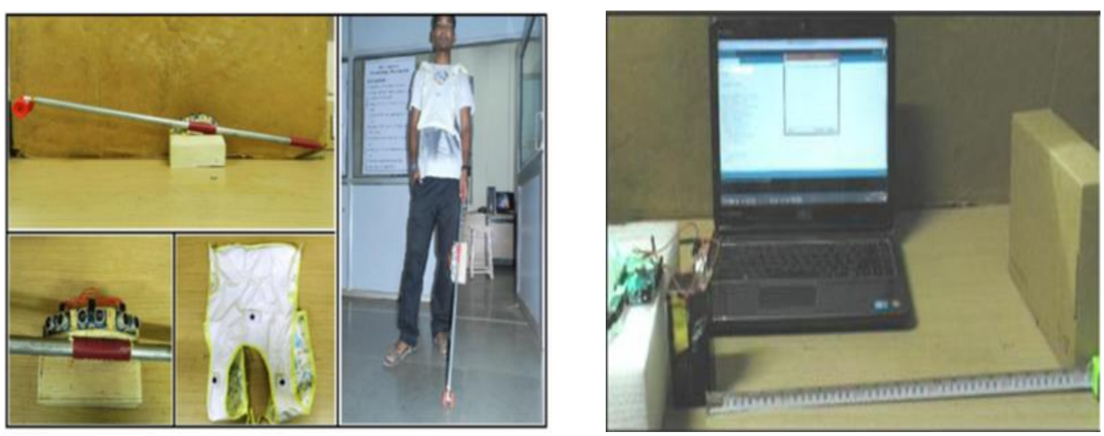
The ELC was tested on eight blind volunteers. Physical obstacles, information obstacles, and cultural obstacles were the main categories tested in the obstacle classification. The results were classified based on a quiz taken by the blind people who used the device. The results showed the efficiency of the device for physical obstacle detection above the waistline of the blind person. However, although the device helps a blind person in detecting obstacles, it does not provide orientation functionality. Therefore, the blind person still needs to identify his path himself and rely on a tradition cane for navigation, as shown in Figure 2.9.

2.1.5 Ultrasonic Cane as a Navigation Aid (UltraCane)

An ultrasonic cane was presented in [26] as a development of the C-5 laser cane [27] to detect both ground objects and aerial objects. The aim of this work was to replace the laser with ultrasonic sensors to avoid laser-associated risks. This cane can detect both ground and aerial obstacles.

The prototype of this device, as shown in Figure 2.10(a), is based on a lightweight cane, three ultrasonic trans-receivers, an X-bee-S1 trans-receiver module, two Arduino UNO microcontrollers, three LED panels, and a piezo buzzer. The goal of the three ultrasonic sensors is to detect ground and aerial obstacles in the range of 5 cm to 150 cm. Figure 2.10(b) shows the process of object detection within a specific distance. Once an ultrasonic wave is detected, a control signal is generated, and it triggers the echo pin of the microcontroller. The microcontroller records the width of the time duration of the height of each pin and transforms it into a distance. The X-bee will wirelessly transfer the control signal to the receiving unit that is worn on the shoulders. The buzzer sounds to alert the user based on the obstacle being approached (high alert, normal alert, low alert and no alert).

The authors claim that this device is a navigational aid to blind people. However, the results showed that it is only an object detector within a small range. Additionally, the detection of dynamic objects was not covered in this technique, and this issue may lead to accidents. To improve this work, tele-instructions should be given to the user for navigational aid, and the device should integrate a GPS to determine the user's position.



(a) (b)

Figure 2.9: (a) The prototype of the device; (b) Detection process of the obstacle from 5 cm to 150 cm [26]

2.1.6 Ultrasonic Assistive Headset for Visually Impaired People

The authors of [28] introduced an ultrasonic headset as a mobility aid for VI people that detects and avoids obstacles. Figure 2.11 illustrates the design of the ultrasonic headset, which contains four ultrasonic sensors. Two sensors cover each membrane to detect left and right obstacles. DYP-ME007 is the chosen type of ultrasonic sensor for a distance measurement. ISD2590 recording storage is used to record the recommended directions. There are six recorded messages, and the selected information is based on the intersection of two ultrasonic sensors if there is an obstacle.

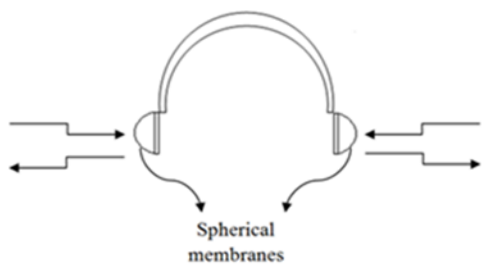


Figure 2.10: The design of the ultrasonic headset [28]

The function of this system is as follows. Each sensor has an ID that is produced as a binary code. Once the sensor receives a reflection of the ultrasonic wave, an output of “1” will be sent to the microcontroller; otherwise, “0” will be sent. Using the binary code, the microcontroller can determine which sensor is the receiver. Based on that determination, the audio feedback will be played back to the user. Figure 2.12 shows the complete design of the proposed system.

The system is a good energy-saving solution. However, the system is limited in the directions that are provided to the user. Six directions are not sufficient to guide the user indoors and outdoors. Furthermore, the headset obscures external noise, which blind people rely on to make decisions if the system fails.

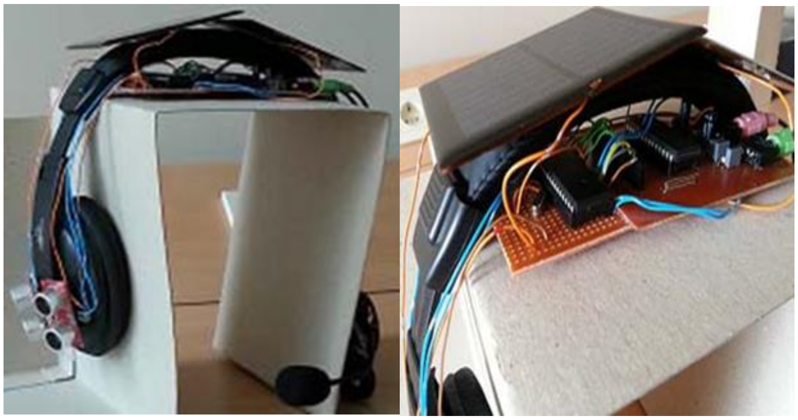


Figure 2.11: Display of the proposed ultrasonic headset with illustration of the circuit and solar panels [28]

Other systems use different types of sensors and devices to provide VI people with navigational services.

2.1.7 CASBlip

A wearable and navigational system “CASBlip” based on a laser light and sensors was proposed in [29] to support the mobility of VI people. The aims of this design are to provide object detection, orientation, and navigational services for both partially and completely blind people. This system has two important modules: a sensor module and an acoustic module. The sensor module contains a pair of glasses that include 1X64 3D CMOS image sensors and laser light beams for object detection, as shown in Figure 2.13. In addition, the sensor module includes a function that is implemented using the Field Programmable Gate Array (FPGA) that controls the reflection of the laser light beams after collision with an object to the lens of the camera, calculates the distance, acquires the data, and controls the application software. The other function of the FPGA is implemented within the acoustic module to process the environmental information, locate the object and convert this information to sounds that are received by stereophonic headphones.

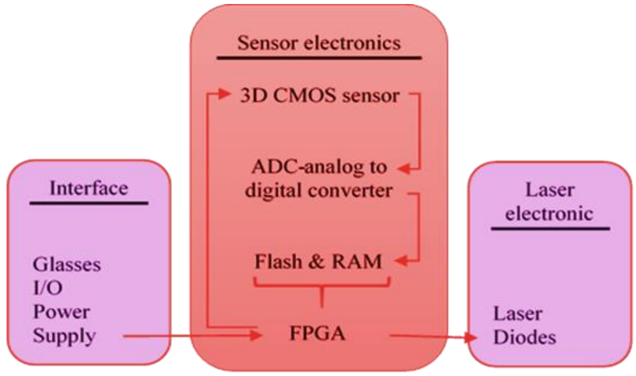


Figure 2.12: Design of the sensor module [29]

The developed acoustic system in [29] allows the user to choose the route and path after detecting the presence of the object and user. However, the small range of this device can cause serious incidents. The system was tested on two different groups of blind people. However, the results of outdoor experiments were not as good as the results of indoor experiments because of the external noise. One recommendation to further develop this system is to use stereovision or add more sensors to improve the image acquisition.

2.1.8 A Low Cost Outdoor Assistive Navigation System (LowCost Nav)

A low-cost navigator for pedestrians was designed using the Raspberry Pi device and Geo-Coder-US and Mo Nav modules in [30]. The device is placed on the user's waist and includes a Raspberry Pi device, GPS receiver and three main buttons to run the system, as shown in Figure 2.14.

Figure 2.13: The prototype of the proposed device [30]

The user can select a comfortable sound from a recorded list to receive the navigation steps in audible format. Thus, the device is provided with voice prompts and speech recognition for better capabilities. The system calculates the distance between the user and an object using a gyroscope and a magnetic compass. Furthermore, the Raspberry Pi controls the process of the navigation. Both Mo Nav and Geo-Coder-US modules are used for pedestrian route generation. Therefore, the system works as follows. The user can use the microphone to state the desired address or use one of the three provided buttons if the address is already stored in the system. The user can press the ‘up’ button to choose a stored address, e.g., home, or enter a new address by pressing the ‘down’ button and start recording the new address. The middle button is selected to continue after the device ensures that the selected address is the correct address.

The system is composed of five main modules, including the loader, which is the controller of the system; the initializer, which verifies the existence of the required data and libraries; the user interface, which receives the desired address from the user; the address query, which translates the entered address into geographic coordinates; the route query, which obtains the user's current location from the GPS; and the route transversal, which gives the audible instructions to the user to get to their destination.

This device exhibited good performance within a residential area, as shown in Figure 2.15(a). The device is also economically available for low-income people. In addition, the device is light and easy to carry. However, the device performs poorly in civilian areas where tall buildings exist due to the low accuracy of the GPS receiver, as shown in Figure 2.15(b).

(a)

(b)

Figure 2.14: (a) The results of the device's orientation in a residential area; (b) The results of the device's orientation in a civilian area [30]

2.1.9 Silicon Eyes (Sili Eyes)

An assistive navigator was suggested in [31] to guide the user through his/her unknown path by adapting GPS and GSM technologies. The assistive navigator helps the user detect their current location and then navigates the user based on haptic feedback. In addition, the user can get information about the time, date and even the color of objects in front of him/her in audio format. The proposed device is attached to a silicon glove to be wearable, as shown in Figure 2.16.

The prototype of the proposed device is based on a microcontroller that includes a 32-bit cortex-M3 to control the entire system, a 24-bit color sensor to recognize the colors of objects, a light/temperature sensor, and SONAR to detect the distance between the object and the user.

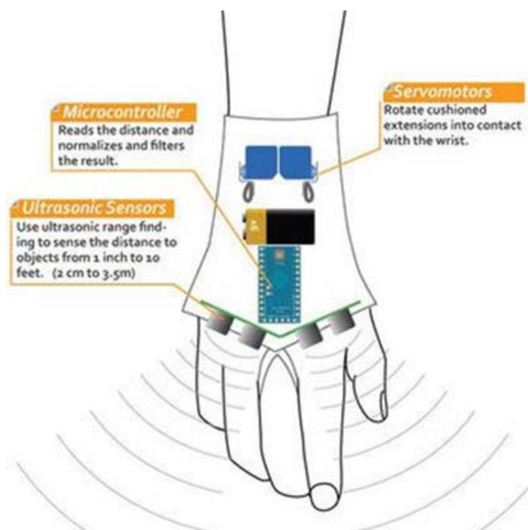


Figure 2.15: The proposed system attached on a silicon glove [31]

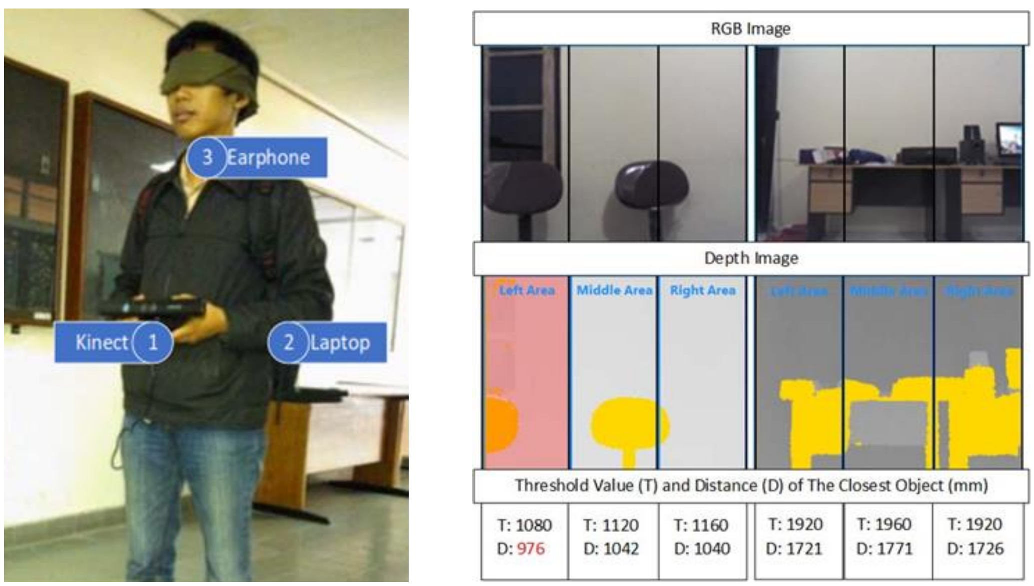
The system supports a touch keyboard using the Braille technique to enter any information. After the user chooses the desired destination, he/she will be directed along the road using an MEMS accelerometer and magnetometer. The instructions will be sent through a headset that is connected to the device via an MP3 decoder. The user will be notified by SONAR of the detected distance between the user and the closest obstacle. In the case of an emergency, the current location of the disabled user will be sent via SMS to someone whose phone number is provided by the user using both GSM and GPS technologies.

The design of the system is comfortable and wearable. In addition, the features that are provided to the user can give him/her a sense of the surrounding environment. However, the system needs a power tracker to keep track of the battery life. The emergency aid is not powerful, as the user needs to press the button in case of an emergency, and she/he must enter the phone numbers of his/her relatives, which might be a limiting factor. It would be better if the emergency features were provided using audio format.

2.1.10 Obstacle Avoidance Using Auto-adaptive Thresholding (Obs Avoid using Thresholding)

An obstacle avoidance system was proposed in [32] using a Kinect depth camera and an auto-adaptive thresholding strategy. The prototype of the proposed system is shown in Figure 2.17(a). The auto-adaptive thresholding is used to detect and calculate the distance between an obstacle and the user. A notebook with a USB hub, earphone, and Microsoft Kinect depth camera are the main components of the system.

The Kinect transfers the raw data (depth information about each pixel) to the system. To increase the efficiency, the depth range between close to 800 mm and more than 4000 mm will be reset to zero. Then, the depth image will be divided into three areas (left, middle, and right). The auto-adaptive threshold generates the optimal threshold value for each area. In each 2×2-pixel area, 1 pixel is used. Then, these data are classified and transformed to a depth histogram. The contrast function will calculate a local maximum for each depth, as shown in Figure 2.17 (b). The Otsu method is applied to find the most peak threshold values [33]. Then, an average function will determine the closest object for each area. Beeps will be generated through an earphone when the obstacle is within the range of 1500 mm. As it reaches 1000 mm, a voice recommendation will be produced for the blind person, and he/she will correspondingly take the left, middle, or right path. The low accuracy of Kinect at close range could reduce the performance of the system. Moreover, the results show that the auto-adaptive threshold cannot differentiate between objects as the distance between the user and obstacle increases.



(a) (b)

Figure 2.16: (a) The prototype of the proposed system; (b) Calculating the threshold value and the distance of the closest object [32]

2.1.11 A Path Force Feedback Belt (PF belt)

The idea of the navigator belt, including the number of cells around the belt, was introduced in [34] 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. Figure 2.18 shows the three main components of the force feedback belt design. These components are the main unit (the process) with two dual video cameras, the power supply that is packed into a pocket and the belt worn around the user's waist. The belt has number of cells that give feedback to the user. The process unit uses two video cameras to capture the video stream and generates a 3D model of the user's surrounding area, as shown in Figure 2.19.

As the processing unit in the 3D model tracks the surrounding environment of the user, the main features of the environment, such as sidewalk borders or walls, are extracted. In addition, the model will aid the blind person in her/his mobility by sending signals based on the extracted feature to the force feedback belt's corresponding cells. The corresponding cells vibrate around the belt and show the user the right path. The system is designed so that each feature has its own signature based on the vibration pattern. Therefore, each vibration frequency differentiates a specific feature or obstacle, e.g., the sidewalk border marked in blue in Figure 2.19. However, the user needs to be trained to distinguish the meaning of each frequency and multiple frequencies.

Using a 3D model within a sliding volume with continuous updating in this system provides a better and faster process of feature extraction, especially for buildings and other important and urgent objects. At the same time, it can reduce memory consumption. Otherwise, collision awareness is increased if the system is unable to capture an object, such as the floor.

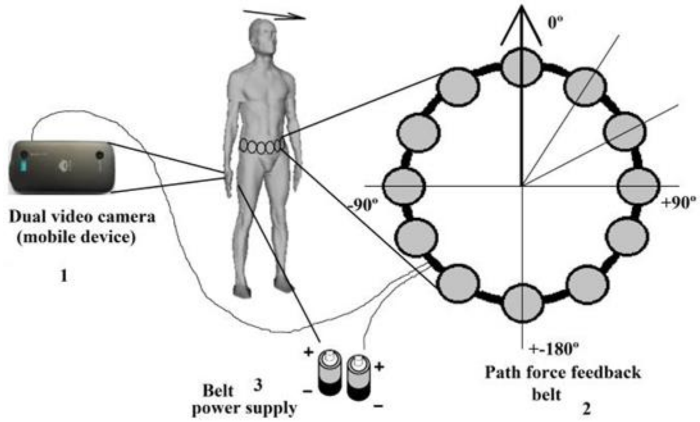


Figure 2.17: The prototype of the Path Force Feedback belt design [34]

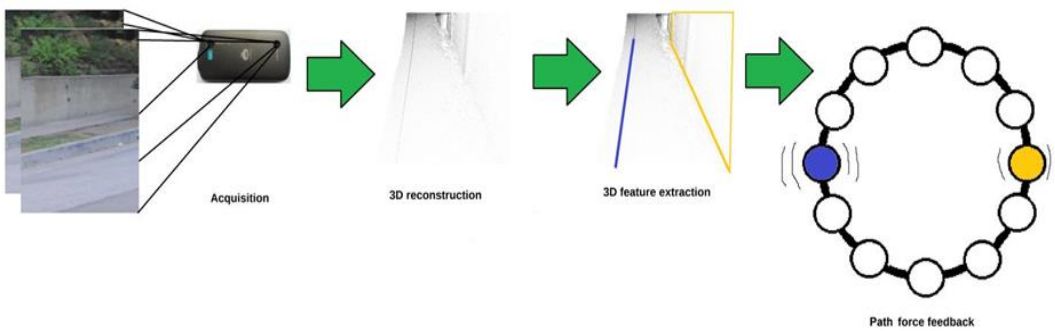


Figure 2.18: The detection process of the force feedback belt [34]

The detection range for this design is too small, and the system extracts the features of only the closest objects, as it was explained. The blind person needs to be familiar with the surrounding area to have a proper reaction. In addition, using the vibration patterns as feedback instead of audio format is not an excellent solution because the person can lose the sense of discrimination of such a technique over time, especially because there are multiple vibrations that need to be known by the user.

2.1.12 SUGAR System

Using ultra-wide technology, the SUGAR system was introduced as an indoor navigator for VI people [35]. The system requires UWB sensors, a spatial database of the environment, a server to process the collected data, a Wi-Fi connection to transmit data and a smart phone (carried by the user) to communicate with the VI person via audio feedback. The UWBs have a precision of up to 15 cm with a 95% confidence interval. UWB technology offers robustness because it does not need direct line of sight between tags and sensors. UWB technology uses UWB signals to acquire the person's location and orientation. The system also has a spatial database of the environment. This spatial database is a map of the environment being navigated by the person.

Other systems that use RIFD or NFC require the deployment of numerous devices to achieve the same accuracy as SUGAR. The installation of the devices in key locations is also an expensive process. The range of UWB sensors is 50 to 60 m, which makes them ideal for deployment in buildings with large rooms. A room with a side length of 100 m requires only four UWB sensors, but achieving the same accuracy using RFID or NFC would require the deployment of sensors every 80 cm. Figure 40 shows the physical components that are needed for the system.

We can infer the workflow of the system from the proposed architecture that is shown in Figure 2.20. The workflow starts with the UWB sensors constantly tracking the user using a tag that been carried; thiswill enable the system to build Cartesian coordinates. The smartphone compass also provides the person's orientation. From the data collected, the user's location is mapped on a graph. Once the user decides on the destination, the route planner module selects the best route. As the user navigates the room, the navigation module compares the user's location and trajectory with the previously calculated route. The smartphone receives the commands via Wi-Fi connection and plays them back through the headphones to the user.

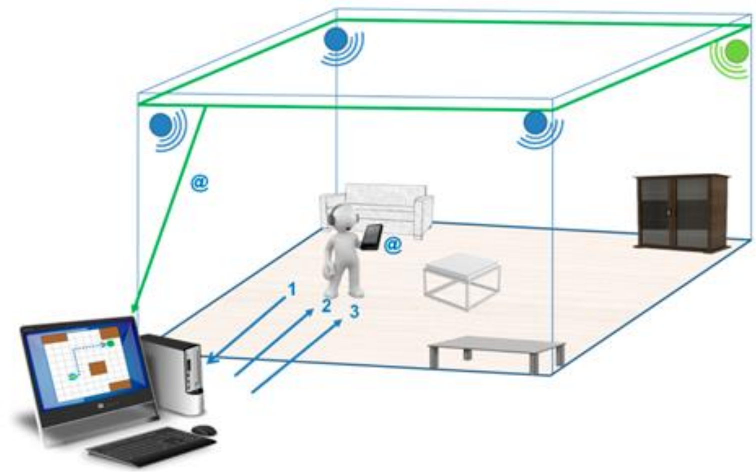


Figure 2.19: The system's installation inside a room [35]

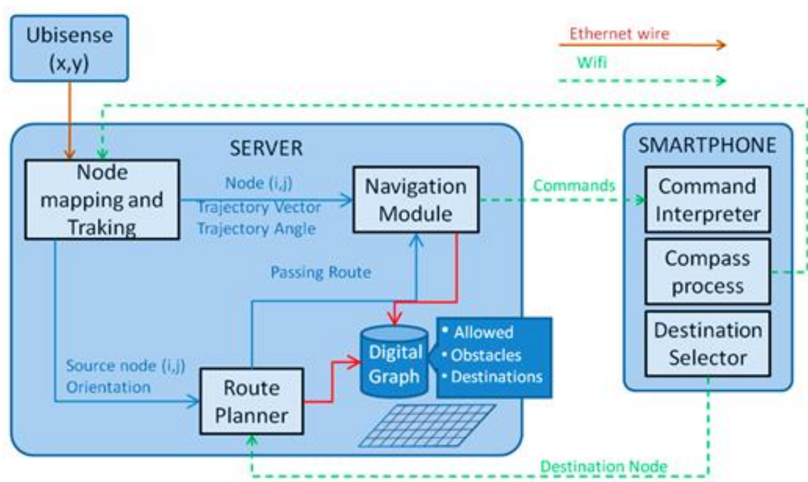


Figure 2.20: The proposed architecture of SUGAR system [35]

2.1.13 A Mobility Device for the Blind with Improved Vertical Resolution Using Dynamic Vision Sensors (MobiDevice Improved VerticalResolion)

Using a retina-inspired dynamic vision camera, [36] improved the mobility of the VI. Figure 2.22 illustrates the proposed device to be mounted on the head of the user. The system represents the environmental information as an audio landscape using 3D sound [37], such as MP3 format.

Figure 2.21: The proposed system to be mounted on the head [36]

The premise is a dynamic vision camera that resembles the human retina [38, 39]. Therefore, unlike regular cameras that are based on a fixed frame rate, DVS creates asynchronous events every time it senses an adjustment in luminance that exceeds a predefined threshold. However, the movement of the DVS can generate events at the edges of the objects or at any changed sharp textures. As a result, the accumulation of the time interval is needed to form a visual frame, as illustrated in Figure 2.23.

As shown in Figure 2.23, the colors in the output of image depth extraction are represented based on the event distance. The scene is divided into three horizontal areas based on the vertical reference of that view. The middle event will be selected. Then, the event will be displayed via simulated 3D sound. This display, in turn, will be translated to audio format for the user using the headset. The acoustic domain was used for visual information transmission. The distance to the object can be calculated via the stereo information of the DVS device.

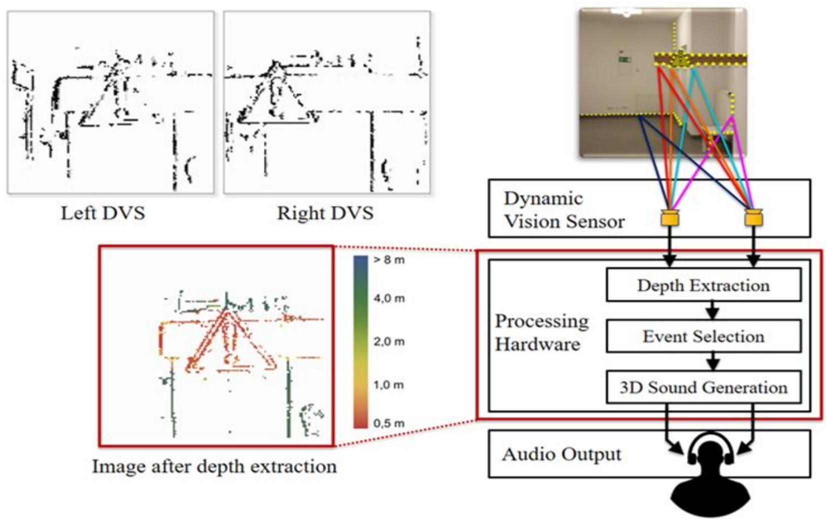


Figure 2.22: The accumulation of the interval time to form a visual frame. The entire system is illustrated (the event distance is differentiated via colors) [36].

The system was tested on two different groups to evaluate three factors: vertical position (up, down), object localization and horizontal position (left, right). The developed head-related transfer functions and the proposition of the focus area were used to promote the resolution.

Although it is not possible to assess the object avoidance performance due to the lack of information provided by the authors, the structure of the device is comfortable and light. The system provides a power consumption solution by using fewer energy consumption components than other systems.

2.2. **Sensor Substitution-Based ETA**

Sensor substitution-based systems are designed to be an alternative to multi-sensory systems.

2.2.1 **TED**

A small wireless device that is placed on the user's tongue was proposed to navigate VI people [40]. The wireless communication between the glasses (camera placed on the glasses) and the TED is established using the designed dipole antenna in [41]. The design of the antenna in front and the back is shown in Figure 2.24 (a–d). Bazooka Balun is used to reduce the effect of the cable on a small antenna [42].

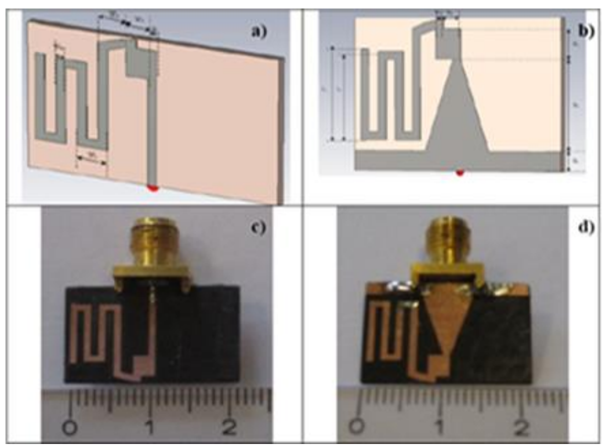


Figure 2.23: (a) The design of the antenna at the front and (b) the back; (c) fabricated antenna at the front and (d) the back [41]

The idea of a TED system was designed as a transformation of the Paul Bach-Y-Rita system into a tiny wireless system. The visual information of all video inputs is displayed using a tactile display unit.

The design of this system, as shown in Figure 2.25, is based on three main parts: sunglasses with a camera for object detection, a tongue electro-tactile device (TED), and a host computer. The device contains an antenna to support wireless communication in the system, a matrix of electrodes to help the blind sense through the tongue, a central processing unit (CPU), a wireless transmission block, an electrode controlling block, and a battery. A matrix of 33 electrodes that are distributed into 8 pulses is placed on the blind person's tongue, as shown in Figure 2.26, and the remaining components are fabricated into a circuit. Each pulse corresponds to a specific direction.

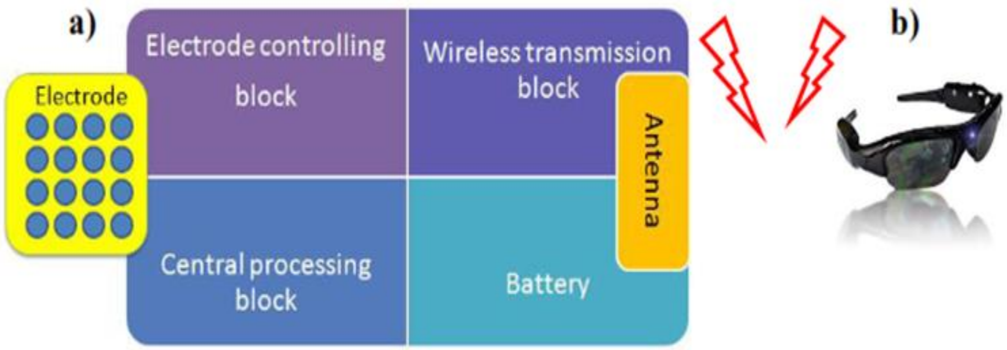


Figure 2.24: Tongue-placed electro-tactile system with sunglasses that carry an object detection camera: (a) sunglasses with an object detection camera and (b) tongue electro-tactile device [40]

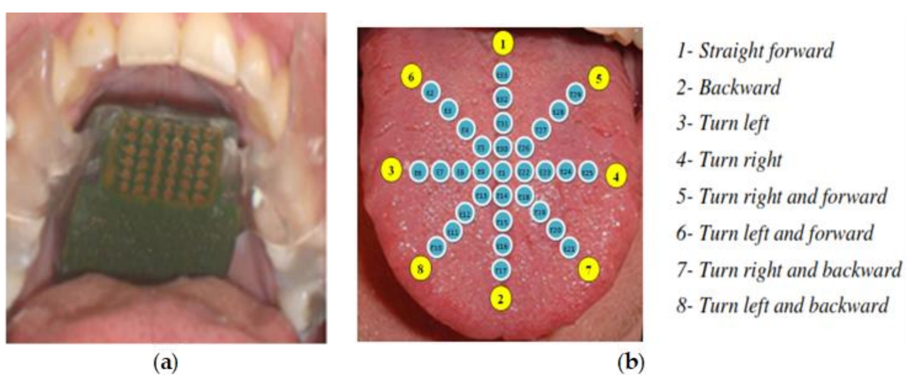


Figure 2.25: (a) Matrix of electrodes; (b) Eight different directions for the matrix of electrodes [40]

The host computer will receive the image signals that are sent from the camera to the electrode matrix first, and the signals are then transferred as interpretable information. Hence, this converted information will be received by the wireless transmission block of the TED device, as shown in Figure 2.27. Next, the image signal will be processed by the central processing block into an encoded signal that will be processed into a controlled signal by the electrode-controlling block. In the end, the controlled signal will be sent to the electrodes.

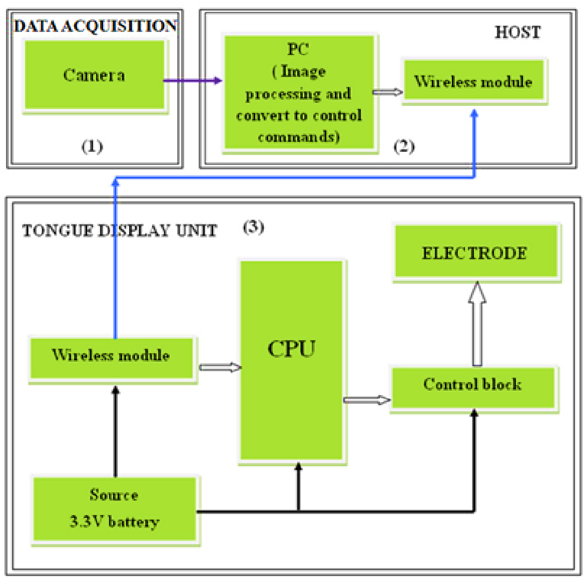


Figure 2.26: The overall design of the system [40]

Although this device meets its goal and exhibits effective performance, the results show that the antenna is not completely omnidirectional, indicating that the system is not optimized and requires further tests. The device was tested on numerous blind people. The results show that the users do not respond to some of the pulses, for example, pulse number 7, indicating that the system is not sending the pulse to that specific point.

2.2.2 RFIWS

Using radio frequency technology, the Radio Frequency Identification Walking Stick was introduced in [43] to ensure safe mobility. This system helps in detecting and calculating the approximate distance between the sidewalk border and the user. A Radio Frequency Identification (RFID) is used to transfer and receive information through the radio wave medium [44]. An RFID tag, a reader, and a core are the main components of RFID technology.

Numerous RFID tags are placed in the middle of the sidewalk with consideration of an equal and specific distance between each RFID tag and the RFID reader. The RFID is connected to the stick to detect and process received signals. Sounds and vibrations will be produced to notify the user of the distance between the border of the sidewalk and himself/herself, and the user does not walk beyond the sidewalk boundaries. Louder sounds will be generated as the user gets closer to the border. Figure 2.28 shows the distance of frequency detection (Y) and the width of the sidewalk (X). Each tag needs to be tested separately due to different ranges of detection.

RFID technology has a perfect reading function between the tags and readers, making the device reliable at the level of detection. However, each tag needs a specific range that requires extensive individual testing, leading to scope limitations. Additionally, the system can easily be stopped from working in the case of wrapping or covering the tags, which prevents those tags from receiving the radio waves.

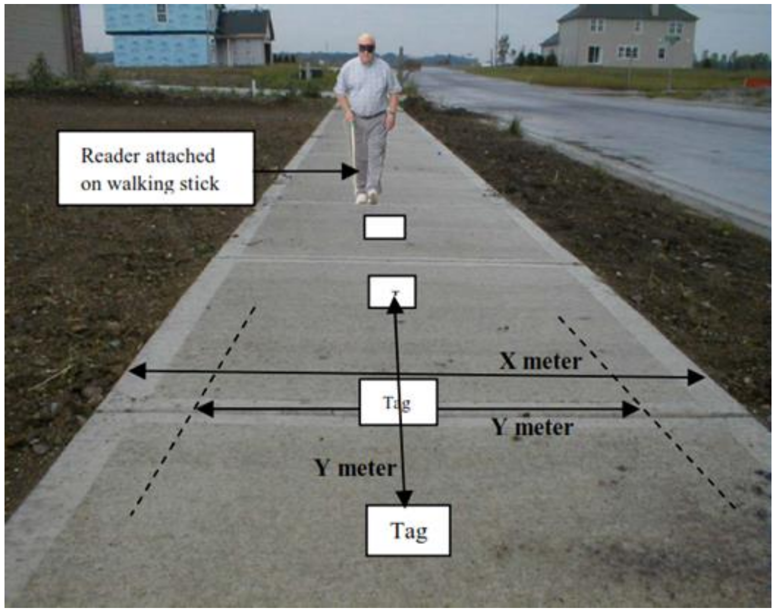


Figure 2.27: Distance of frequency detection on a sidewalk [43]

2.2.3 Obstacle Avoidance Using Haptics and a Laser Rangefinder (Obs Avoid using Haptics&Laser)

A virtual cane was designed in [45] for obstacle detection and avoidance for VI and handicapped people using a laser rangefinder and haptics. The environment is scanned by a laser rangefinder, and the feedback is sent to the user via a haptic interface. The user is able to sense the obstacle several meters away with no physical contact. The length of the virtual cane can be chosen by the user, but it is still limited. A laptop-type MSI with an Intel core i7-740 QM, a laser rangefinder type SICK, an NVIDIA graphics card type GTX460M, and a haptic display type Novint Falcone are the main components of the proposed systems, which are structured on an electronic wheelchair. Additionally, an H3DAPI plate was employed in [46].

The wheel chair is controlled by a joystick using the right hand, and environmental sensing is controlled by the Falcon (haptic interface) using the other hand, as shown in Figure 2.29. As the user starts the system, the range finder will start scanning the environment that is in front of the chair. Then, it will calculate the distance between the user and the object using laser beams. The distance information will be transmitted to the laptop to create a 3-dimensional graph using the NIVIDA card, and the graph is then transmitted to the haptic device.

Figure 2.28: Display of the proposed system mounted on a special electronic wheelchair [45]

The results showed that the precise locations of obstacles and angles were difficult to determine due to misunderstanding of the scale factor between the real and model world by the user of the haptic grip translation.

2.2.4 **Mobile Crowd Assisted Navigation for the Visually impaired (Mobile Crowd Ass Nav)**

A mobile crowd assistant was implemented in [47] to navigate the user to his/her desired destination. The aim of this framework is to offer the user accessible, efficient and flexible crowd services for VI people. A GPS, compass, accelerometer and camera are used onboard. The smartphone streams the videos and sensory information to the crowd server to be used by the volunteers.

The Crowd program gathers the volunteer feedback, and the system sends the final decision to the blind user through an audio format, a vibration or both. The video recorded by the VI user will be referred to as a room, and then each feedback of the volunteer will be weighted based on the accuracy of the information. The reason behind this aggregation process, which is shown in Figure 2.30, is to eliminate the conflict between the information received from the same query if there is more than one volunteer or if it comes from a vision algorithm machine, as shown in Figure 2.31.

Two experiments were performed to direct the user from one room to another using the proposed web app and a simple sum aggregation approach or a legion leader approach. Another experiment was done on eight blindfolded participants over an obstacle path using the simple sum aggregation approach.

The framework can be considered an economical solution for VI people. However, the system itself needs advanced experiments and evaluation with consideration of the delay and time alternatives of aggregation processes, as these factors play the main roles in the system. The authors need to test the volumes of data that can be received and aggregated and determine how to best feed this information to the VI person.

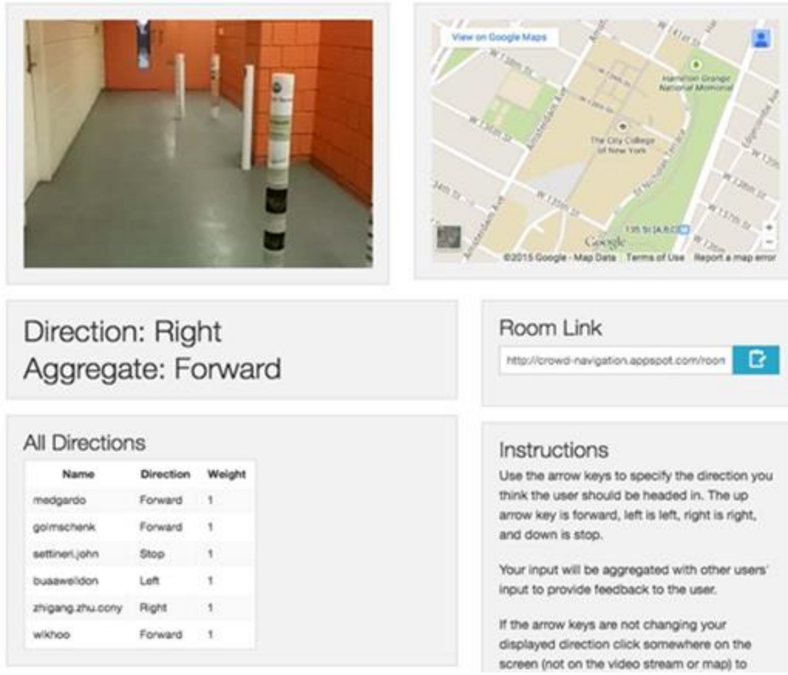


Figure 2.29: The implemented app [47]

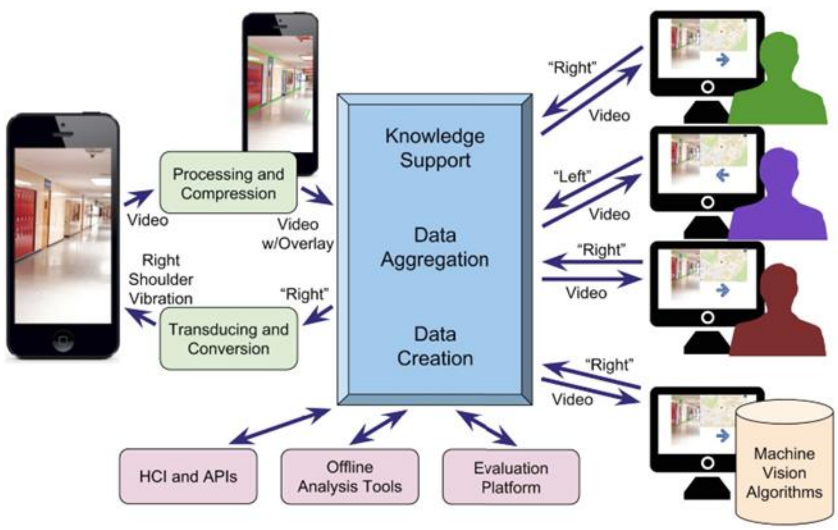


Figure 2.30: The data flow of the proposed application [47]

2.3. ETA Sensory-Based Computer Vision Methods

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

2.3.1 Fusion of Artificial Vision and GPS (FAV&GPS)

The fusion of artificial vision, map matching [48] and GPS introduced an enhanced navigational system that supports VI people in their mobility [49]. The system helps in locating the required object and allows the user to give instructions by moving her/his head toward the target. Furthermore, it supports the automatic visual detection of objects. As shown in Figure 2.32, this device is a wearable device that is mounted on the user's head, and it consists of two Bumblebee stereo cameras for video input that are installed on the helmet, GPS receiver, headphones, microphone, and Xsens Mti tracking device for motion sensing. The SpikNet recognition algorithm was employed for image processing [50].

Figure 2.31: The prototype of Fusion of Artificial Vision and GPS system[49].

GPS, a modified geographic information system (GIS) [51] and vision-based positioning are used to provide the properties of obstacles. This design can improve the performance of the navigation systems where the signal is deputized. Therefore, this system can be combined with any navigation system to overcome the issues of navigation in such areas.

Due to the lack of availability of some information regarding the consistency of pedestrian mobility by commercial GIS, this system maps the GPS signal with the adaptive GIS to estimate the user's current position, as shown in Figure 2.33. The position of the 3D target is calculated using matrices of lenses and stereoscopic variance. After detecting the user and target positions, the vision agent sends the ID of the target and its 3D coordinates.

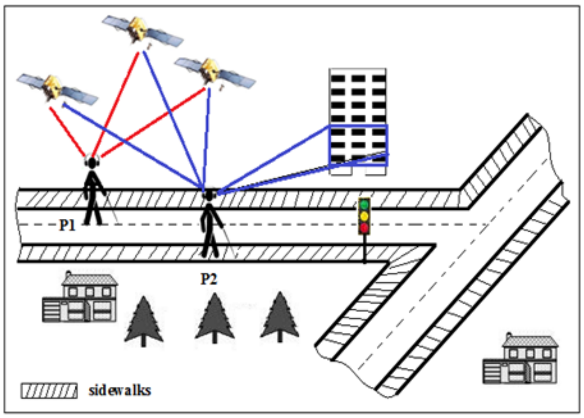


Figure 2.32: The result of mapping both commercial Geographical Information System (GIS) and Global Position System (GPS) signals is P1. P2 is the result of mapping the signals of GPS and the adaptive GIS [49].

The matrix of the rotation of each angle is multiplied by the target coordinates in the head reference frame (x, y, z) to obtain the target coordinates in the map reference (x−, y−, z−), as given in Equation (1). Then, the design uses a Geographic Information System (GIS) that contains the geolocated positions of all targets to get the longitude and latitude of landmarks. Based on this information, the user's coordinates can be computed in World Geodetic System Coordinates (WGS84). The results are in audio format through the speaker of the device.

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} . \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(yaw) & \sin(yaw) \\ 0 & \sin(yaw) & \cos(yaw) \end{bmatrix} .$$

$$\begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} . \begin{bmatrix} \cos(roll) & \sin(roll) & 0 \\ \sin(roll) & \cos(roll) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The use of the modified GIS shows positive results and better estimation of user position compared to commercial GIS methods, as shown in Figure 2.33. However, the system has not been tested on navigation systems to ensure its performance if it is integrated with a navigation system. Thus, it remains unknown whether it will enhance navigation systems or not.

2.3.2 Cognitive Guidance System (CG System)

Cognitive guidance devices are designed by integrating the output of a Kinect sensor, vanishing points and fuzzy decisions to navigate a VI person through a known environment [52]. This design uses the Kinect sensor and stereoscopic vision to calculate the distance between the user and an obstacle with the help of Mandani fuzzy decision rules and vanishing points to guide the user along the path.

The proposed system consists of two video cameras (Sony 1/3" progressive scan CCD) and one laptop. The analysis of the detection range is beyond 4 m, and is obtained using stereoscopy and Kinect to compress a cloud of 3D points to a range from 40 cm to 4 m to calculate the vanishing point. The vanishing point is used in this system as a virtual compass to direct the blind person through a structured environment. Then, fuzzy decision rules are applied to avoid obstacles.

In the first step, the system scans for planes in the range between 1.5 m and 4 m. For optimal performance, the system processes 25 frames per second. Then, the Canny filter is used for edge detection. After the edges are defined, the result is used to calculate the vanishing points. Next, the device gets the 3D Euclidean orientation from the Kinect sensor, which is projected to a 2D image that gives the direction to the goal point.

This work implemented 49 fuzzy rules that cover only 80 configurations. Moreover, the vanishing point can be computed based only on existing lines that rarely exist in the outdoors, emphasizing that the system is not ideal for outdoor use. Additionally, the perception capacities of the system need to be increased to detect spatial landmarks.

2.3.3 A Computer Vision System that Ensures the Autonomous Navigation (ComVis Sys)

A real-time obstacle detection system was presented in [53] to alert blind people and aid them in their mobility indoors and outdoors. This application works on a smartphone that is attached to the blind person's chest. Furthermore, this system focuses on a static and dynamic object detection and classification technique that was introduced in [54].

Using the detection technique in [54], the team was able to detect both static and dynamic objects in a video stream. The interesting points, which are pixels located in of the center cell of the image, are selected based on an image grid. Then, the multiscale Lucas-Kanade algorithm tracks these selected points. Next, the RANSAC algorithm is applied to these points to detect the background motion. Clusters are created to merge the outlines. The distance between the object and video camera defines the state of the object as normal or urgent.

The adapted HOG (Histogram of Oriented Gradients) descriptor was used as a recognition algorithm and integrated with the BoVW (Bag of Visual Words) framework. However, the sizes of the images are resizable based on the object type that the team chose. Then, they computed the descriptor of the extracted points of interest of each group of images and made clusters that contained the extracted features of all images. Then, they applied BoVW to create a codebook for all clusters(K): $W = \{w\_1, w\_2, , \dots., w\_k\}$. Each w is a visual word that represents the system vocabulary. The workflow is illustrated in Figure 2.34.

Each image is divided into blocks created by HOG, and these blocks are included in the training dataset and mapped to the related visual word. Finally, an SVM classifier is used for training. Therefore, each labeled piece of data is transmitted to the classifier and differentiated based on specific categories.

The implementation of the system into a smartphone is considered a great mobility aid to blind people since smartphones are light and easy to carry. In addition, using the HOG descriptor to extract the features of each set of images makes the recognition process efficient because the system not only detects the object but also recognizes the object based on its type using the clusters.

However, the fixed size of the image that is based on the category can make detecting the same object with a different size a challenge. Objects in dark places and those that are highly dynamic cannot be detected. Additionally, smartphone videos are noisy. In addition, the tested dataset of 4500 images with a dictionary of 4000 words is considered a small dataset. The system was tested, and it can only function on a Samsung S4.

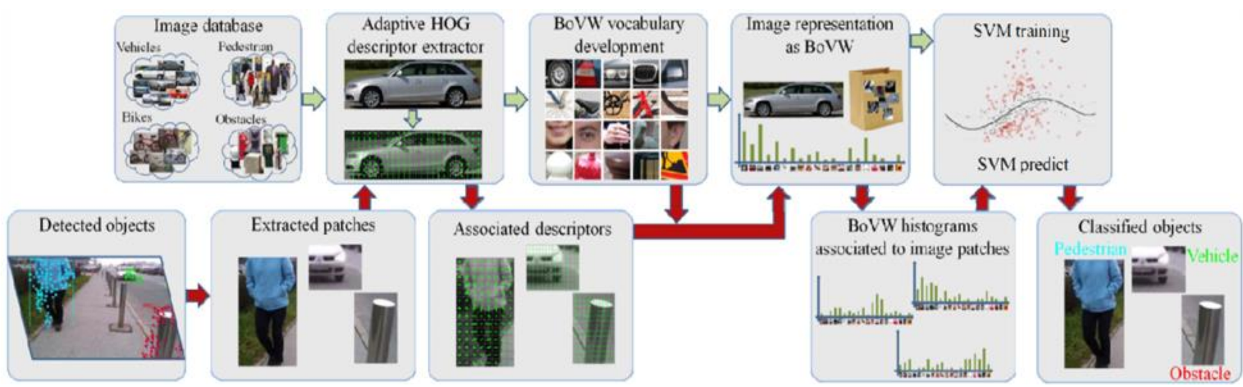


Figure 2.33: The process of the detection and recognition algorithm [53]

2.3.4 Navigation Assistance Using RGB-D Sensor with Range Expansion (Nav RGB-D)

An assistive navigator was introduced based on the integration of the range and visual information to help blind people in indoor navigation [55]. This proposed device can be more than a navigator for blind people; it can be a flashlight for anyone in a dark place. This device contains two parts: an RGB-D to obtain the color and range information between two sensors using both infrared technology and density images. The device is worn on the user's neck, as illustrated in Figure 2.35, and is connected to a laptop that is packed in a bag.

Figure 2.34: The proposed Nav RGB-D device [55]

This work tries to overcome the limitation of range information by using vision-computing techniques for further detection. Three steps will occur in this workflow after capturing the image with the RGB-D. 3D points were used to extract the main features and filter all points that are represented in each cube of the image at one point. RANdom Sample Consensus (RANSA) is the detection algorithm and is used to avoid any outliners, as follows.

$$m = \frac{\log(1 - P)}{(1 - (1 - \varepsilon)p)} \quad (2)$$

In equation 2, the number of solutions in a space is m, the dimension of the model is p, the probability of computational success is P, and the percentage of outliers is ε in the case of failure. These two steps are repeated until they produce the least number of points. Once the system reaches the step of classifying the object as either the floor or an obstacle, the vision information technique starts to analyze the extracted cloud points based on the light features, geometry and hue using the shift mean algorithm, as shown in Figure 2.36. Based on the comparison of each extracted pixel that satisfies the similarity of the above principles, valid pixels will be classified under the "floor-seed" category.

Then, both the probabilistic Hough Line Transform and Canny edge detector [56] were applied to generate a straight line between the obstacles and floors that will be represented in polygons. Hence, based on the floor division, each region will be identified as either floor or not floor. When the number of extracted lines in the comparison is too low or too high, watershed segmentation will be needed.

The system exhibits positive performance in small places by integrating both the probabilistic Hough Line Transform and Canny edge detector to classify the object as either an obstacle or the floor. However, the system does not provide good results when the area has numerous windows because of the infrared sensitivity to sunlight.

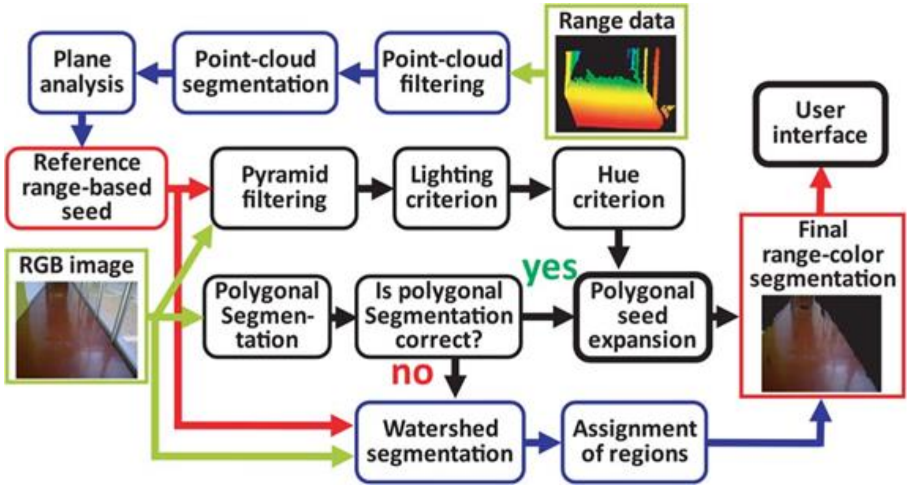


Figure 2.35: The process of the extraction and expansion of the range detection text [55]

2.3.5 When Ultrasonic Sensors and Computer Vision Join Forces for Efficient Obstacle Detection and Recognition (Ultrasonic for ObstDetectRec)

A wearable device was introduced in [57] to support the mobility of VI people in the civilian environment using sensors and computer vision techniques. Figure 2.37 illustrates the main components of the hardware architecture, where four ultrasonic sensors and a mobile video camera are the data sources and a smartphone is the processing unit. The device was able to identify both static and dynamic objects indoors and outdoors regardless of the object's characteristics using machine learning and computer vision techniques. Hence, the device provides continuous information about the surrounding area through audio feedback and beeps for unrecognized objects.

Figure 2.36: The prototype of the proposed system [60]

Figure 2.38 illustrates the process of the system, where two important modules were used: obstacle detection and recognition modules. The obstacle detection module is dependent on the information gathered from both the ultrasonic sensors and smartphone camera, which are fed to the recognition module to classify the present objects of the scene. In addition, audio feedback will be generated based on the position and distance of the object compared to the user's position.

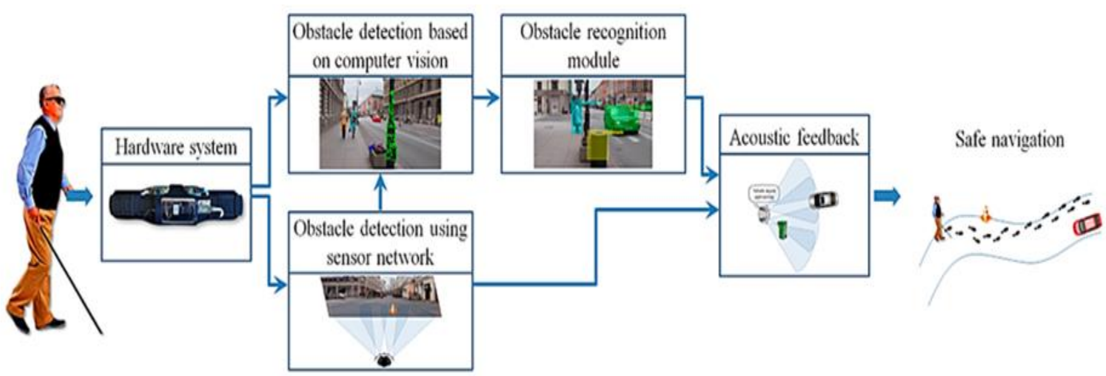


Figure 2.37: The process of the proposed navigation system [60]

The integration of the proposed filter for interesting points and the point tracker (Lucas-Kanade) reduced the exclusion time because it requires fewer resources. Hence, RANSAC was used to obtain the homographic transformation between two frames of the same scene. Then, the K-mean clustering algorithm was applied to identify various dynamic objects. The objects detected were classified as urgent or normal objects. Urgent objects are those with distances from the user of less than 2 m. Furthermore, urgent objects are the objects that are approaching the user; otherwise, they are normal objects. As a final step, the SVM classifier was integrated with a Chi Square Kernel for classification training. Two thousand five hundred images were assigned for each class (four dynamic classes for outdoors) in the training stage, which is considered a small number for producing an accurate classification rate.

The system can be considered a power consumption solution. Additionally, the integration of both the sensor network and computer vision techniques validates the robustness and reliability of the obstacle detection and recognition modules. Twenty-one VI people tested the system. As the users were more familiar with a white cane, their feedback was that the device is not trustworthy enough and needs to be combined with the white cane. In addition, the system does not provide any navigational information, and the system does not detect obstacles above waist level.

2.4. **Other Electronic Assistive Devices for Commercial Services**

Other devices were designed to serve VI people in fields that are different from navigation and to improve the quality of their lives for activities such as shopping, currency recognition, etc.

2.4.1 Banknote Recognition (BanknoteRec)

An assistive device for blind people was implemented in [58] to help them classify the types of banknotes and coins. The system was built based on three models: input (OV6620 Omni vision CMOS camera), process (SX28 microcontroller), and output (speaker) models.

The RGB color model is used to specify the type of the banknote by calculating the average red, green, and blue colors. The function of the microcontroller (IV-CAM) with the camera mounted on a chip is used to extract the desired data from the camera’s streaming video. Then, the mean color and variance data will be gathered for the next step when the MCS-51 microcontroller starts to process this gathered information. Based on the processing results, the IC voice recorder (Aplus ap8917) records the type of each kind of banknote and coin.

This system compares some samplings of each kind of banknote using the RGB model. The best matching banknote will be the result of the system. However, coins are identified based on the size by computing the number of pixels. To determine the type of the coin, the average pixel number of each coin needs to be calculated. The best-matching resultant coin is the result of the device given through the speaker.

The accuracy of the results is 80% due to two factors: the difference in the color of new and old currency and different light natural light conditions. However, the device was only tested on Thai currency. Therefore, the system is not considered reliable, and we cannot guarantee the efficiency of system performance for other types of currency. In addition, the device may not identify banknotes other than the tested banknotes if each type of banknote has a unique color, and the same may be true for coins of similar size.

Recently, similar work was presented in [59]. This device is portable and shows a reasonable accuracy in detecting Euro banknotes. The banknotes are recognized by integrating well-known computer vision techniques. However, the system has a very limited scope for a specific application, such as coins that were not considered for detection and recognition. Furthermore, fake banknotes were not detected by the system.

2.4.2 FingerReader and Eye Ring

A supportive reading solution for blind people called FingerReader was introduced by Shilkrot et al. to aid disabled people in reading printed texts with a real-time response [60]. This device is a wearable device on the index finger for close-up scanning. The device scans the printed text one line at a time, and the response comes in tactile feedback and audio format. FingerReader is designed to continuously work with EyeRing, which was presented in [61] for detecting particular objects one at the time by pointing and then scanning each item using the camera on the top of the ring, as shown in Figure 2.39.

In this design, two vibration motors with additional multimodal feedback, a dual-material case for comfort around the finger, and a high-resolution video stream are developed to expand the capacity of the FingerReader device, as shown in Figure 2.40. Haptic feedback was provided to guide the user to where he/she should move the camera.

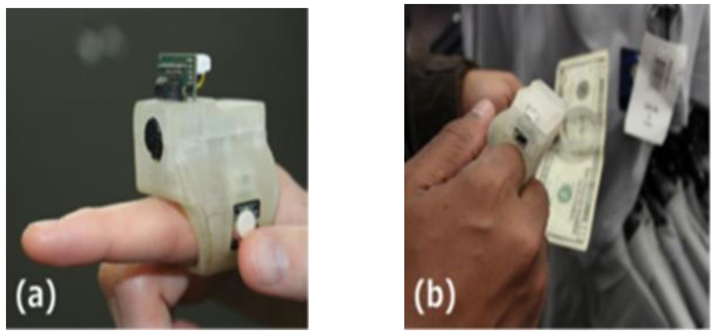


Figure 2.38: (a) The prototype of the EyeRing; (b) The process of the EyeRing device for detection and interaction applications [61]

Figure 2.39: The FingerReader prototype [60]

The team used the Text Extraction Algorithm integrated with Flite Text-To-Speech [62] and "ORC" [63]. The proposed algorithm extracts the printed text through a close-up camera. Then, it matches the cropped curves with the lines. Duplicated words are neglected by the 2D histogram. Then, the algorithm defines the words from characters and sends the words to the ORC. Those detected words are saved in a template as the user continues to scan. Hence, the algorithm will track those words for any match. The user will receive an audio and haptic feedback whenever he/she sidetracks from the current line. Furthermore, the user will receive signals through the haptic feedback to inform her/him about the end of the line if the system did not find any more printed text blocks. Figure 2.41 shows the extraction and detection process of the system.

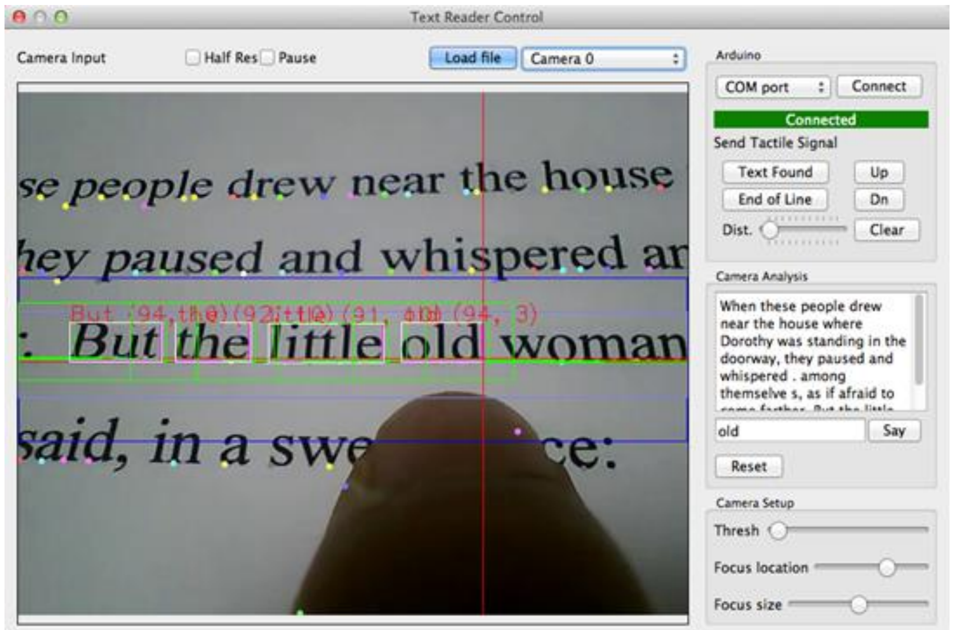


Figure 2.40: The process of the extraction and detection of printed text line [60]

The device was tested on four users after individual training that lasted 1 h. The feedback of the users indicated that the haptic feedback was more efficient than the audio response regarding the directions. In addition, there was a long stop between each word that confused the user regarding what he/she should do. However, the idea of the system is a great supportive reading solution for blind people.

2.5. Quantitative Analysis and Evaluation

In this section, we analyze the basic, yet most important, features of each device that we reviewed. These five features are described in Table 2.1. Furthermore, we present a quantitative evaluation of the reviewed systems in terms of their progress based on the main features that need to be provided by any system that offers a service for VI people.

An assistive device for a blind person needs to provide several features, including clear and concise information within seconds, consistent performance during day and night, operation indoors and outdoors, object detection from close to farther than 5 m and static and dynamic object detection to handle any sudden appearance of objects; otherwise, the user's life may be at risk.

The evaluated features are basic and fundamental features to design an assistive device for blind people who rely on their performance. Therefore, we give them the same weight of 10.0, as each feature has a significant impact on the system's performance. Based on the collected information, we gave a score for each feature of each system or device.

The value for each feature of each system is referred to as Vk. This value is between 0 and 10.0. The value of 10.0 is assigned to a fully satisfactory feature; however, prorated values will be given to the feature in the case that it does not fully satisfy the criteria in Table 2.1. For example, we gave a value of 5.00 to a system that performs only indoors, but it is supposed to perform indoor and outdoor, e.g., the Smart Cane. This strategy was applied for the analysis type, performance, detection range, time, and object-type feature. However, the assigned values for the detection range feature were applied differently; we could not give equal values for different ranges, and we emphasize devices that provide a large detection range. Therefore, a 2.5 value was given to those devices with detection ranges less than or equal to 1 m. This range is a very low range and cannot be considered a solution as a substitute for a white cane. We gave this low value to show the importance of providing large detection ranges compared to this low range.

We used the following normalization formula (equation 3) to calculate the total score for each system based on Table 2.1. The total score of each system in Table 2.2 provides a quick evaluation of each device. However, a full review is provided in Table 2.3.

$$Total\ Score = \sum_{k=0}^{N} \frac{10\ V_k}{N} + 2 \tag{3}$$

We assigned a constant value of 2 to give a clear bias in the graph and show the clear differences between the systems and supported features. N refers to the total number of features of each system, and k is the specific feature. Table 2.2 shows the evaluation for the most promising systems found in the literature.

2.6. Discussion and Comparison

Table 2.2 shows that none of the evaluated systems was 100% satisfactory in terms of the essential features. These features not only meet the user’s needs but are crucial from an engineering perspective. These features are the main building blocks to design such a device and provide services for blind people. It is remarkable that each system supports special feature(s) and might have more features than another, but none of them support all the evaluated features. Thus, we cannot consider any of them an ideal device or system that a blind person can rely on and feel confident about using.

TABLE 2.2: SCORE AND EVALUATION FOR EACH SYSTEM

System	Features					
	Analysis Type (Real Time/Not Real Time)	Performance (Indoor, Outdoor, Both)	Time (Day, Night, Both)	Detection Range (R ≤ 1 m, 1 m < R ≤ 5 m, R > 5 m)	Object Type (Static, Dynamic, Both)	Total Score
	Weight of 10					
Smart Cane	10	5	5	5	5	62
Eye Subs	10	5	10	5	5	72
FAV&GPS	10	5	5	-	10	62
BanknoteRec	10	5	5	-	5	52
TED	10	5	10	-	5	62
CASBlip	10	10	10	5	5	82
RFIWS	-	5	10	5	5	52
LowCost Nav	10	5	10	-	5	62
ELC	10	5	10	2.5	5	67
CG System	10	5	5	5	5	62
UltraCane	10	5	10	5	5	72
Obs Avoid using	10	5	5	5	10	72
Obs Avoid using	10	5	5	10	5	72
ComVis Sys	10	10	5	10	10	92
Sili Eyes	-	5	-	5	5	32
PF belt	-	5	-	2.5	10	37
EyeRing	10	10	5	Specific case	5	82
FingReader	10	10	5	Specific case	5	82
Nav RGB-D	10	5	5	5	5	62
Mobile Crowd Ass Nav	10	5	10	-	5	62
DBG Crutch Based	10	5	5	5	5	62
Ultra Ass Headset	10	10	10	5	5	82
MobiDevice Improved	10	5	5	10	10	82
Ultrasonic for	10	10	5	5	10	82
SUGAR System	10	5	5	10	5	72

Devices that have all the fundamental features will offer effective performance. The reason for this limitation is that researchers have focused on providing new features, but they never ensure that they support the fundamental features before they add new ones. Another reason is that the designers do not run enough experiments that have to be conducted with blind people in different scenarios to overcome any issue. The ideal device must not only include a new feature but also satisfy the main and basic needs of the user. The user needs to feel the sense of the surrounding environment at all times and places. The system cannot be limited to a specific case; otherwise, the design is incomplete.

Figure 2.42 shows us a full picture of the evaluation for each system with the total score for each one. Systems with higher scores demonstrate solid and improved features, such as a Computer Vision System that Ensures the Autonomous Navigation (ComVis Sys), which includes most of the features. The Path Force Feedback Belt (PF belt) and other systems that have low scores require enhancements, but that does not mean their value is less than the systems with higher scores. The PF belt has score of 37% because it is in the research stage. Currently, it is applied only outdoors and it is not suitable indoors, the detection range is 1 m, which is considered a very small range, and it is limited in scope. In this evaluation, we try to pave the road for other researchers to design devices that ensure the safety and independent mobility of VI people. The total score in Figure 2.42 reflects the values given for each feature of each system in Table 2.2. In conclusion, the performance of most of the studied systems is not 100% satisfactory for the user's needs.

Our aim in this chapter is to shed some light on the missing features of the most useful and significant devices. Since technology is advancing every day, our goal is to make this progress occur as quickly as possible. Our focus in this chapter is the performance of systems. After careful review and study of the above systems, we developed the benchmark Table 2.3, which includes technical perspective parameters that affect the performance of these systems. Notably, their unavailability might prevent the systems from offering the main and basic features that were discussed in Table 2.1. These parameters affect the performance of each system and are required to meet both the user's needs and engineers' requirements. Both the type of sensor used and the techniques used can lead to some limitations if misused. For example, systems that used infrared technology may not have performed well during the daytime due to the sensitivity of the infrared to sunlight [64]. However, systems that used Radio Frequency Identification cannot offer a large range due to the need for tag installation everywhere the system is used [65]. In addition, the Kinect sensor has a small detection range because the accuracy of the Kinect sensor decreases as the distance between the scene and the sensor increases [66, 67]. In addition, the performance of ultrasonic sensors can be affected by changes in environmental parameters [68]; hence, its maximum detection range is approximately 5 m. The limitation of each system is described individually in Table 2.3, which provides a comprehensive and technical review.

Other interesting devices for blind running athletes were reviewed but are not included in our evaluation due to their limited scope [69, 70]. The running field is a designed field that will not include general obstacles, such as stairs. In addition, the field is expected to have lines to direct the running athletes.

As a summary of our evaluation, Figure 2.43 shows, for every system, the penetration rate of each feature and its weight. For example, three out of all the presented systems are not real-time systems, which means that they are still in the research stage. These systems are Sili Eyes, RFIWS, and the PF belt. However, 72% of the systems have three features that are not fully satisfied. For instance, the Eye Subs system provides outdoor performance but not indoor, the detection range is less than 5 m due to the ultrasonic limitation, and it detects only static but not dynamic objects. In such cases, the researchers are aware of some of the fundamental features, such as real-time features, but they are not aware of other features. Therefore, some systems provide indoor performance but not outdoor, but the user will need the system service as much indoors as outdoors, possibly even more. In this review study, we hope to provide adequate descriptions of the main features that need to be included in any system that serves this group of people.

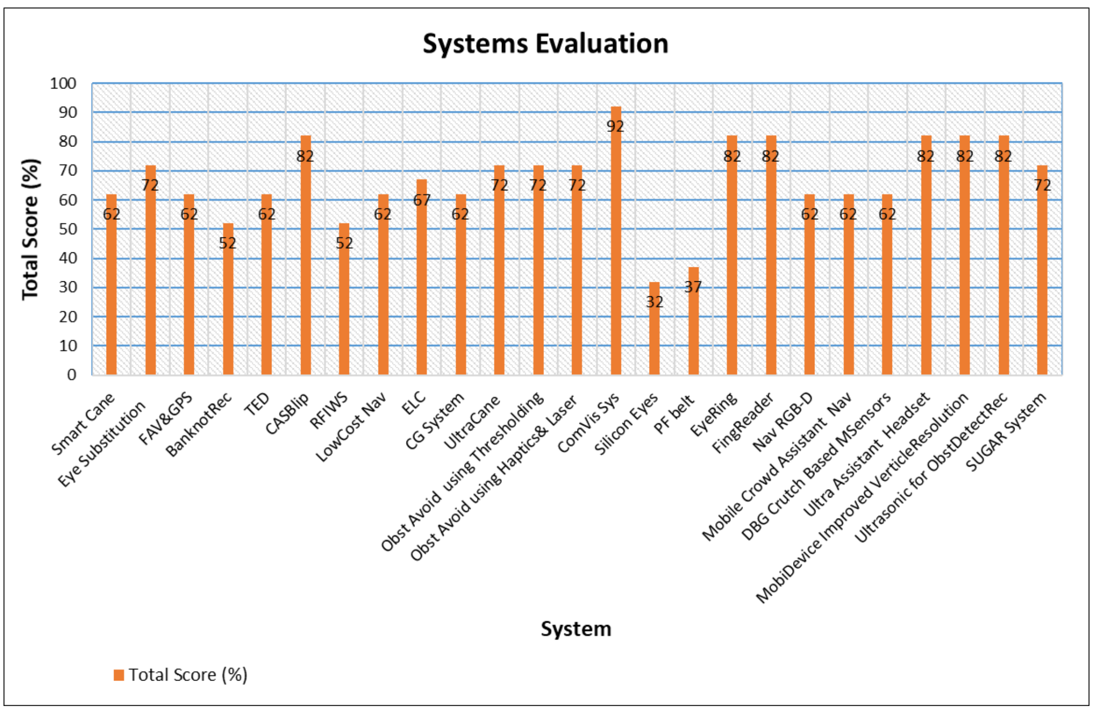


Figure 2.41: System evaluation of the total score for each system

Details about the systems presented in this section are provided in [20]. Based on the study and literature review presented in [20], no system could fully satisfy all of the user's needs and provide him/her with safe mobility indoors and outdoors. The abovementioned systems do not fully satisfy the user's needs due to the limitations of the techniques used in these proposed systems. Systems that are based on both sensors and computer vision provide better solutions. However, there is no single technique that could be considered a robust or a 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 chapter.

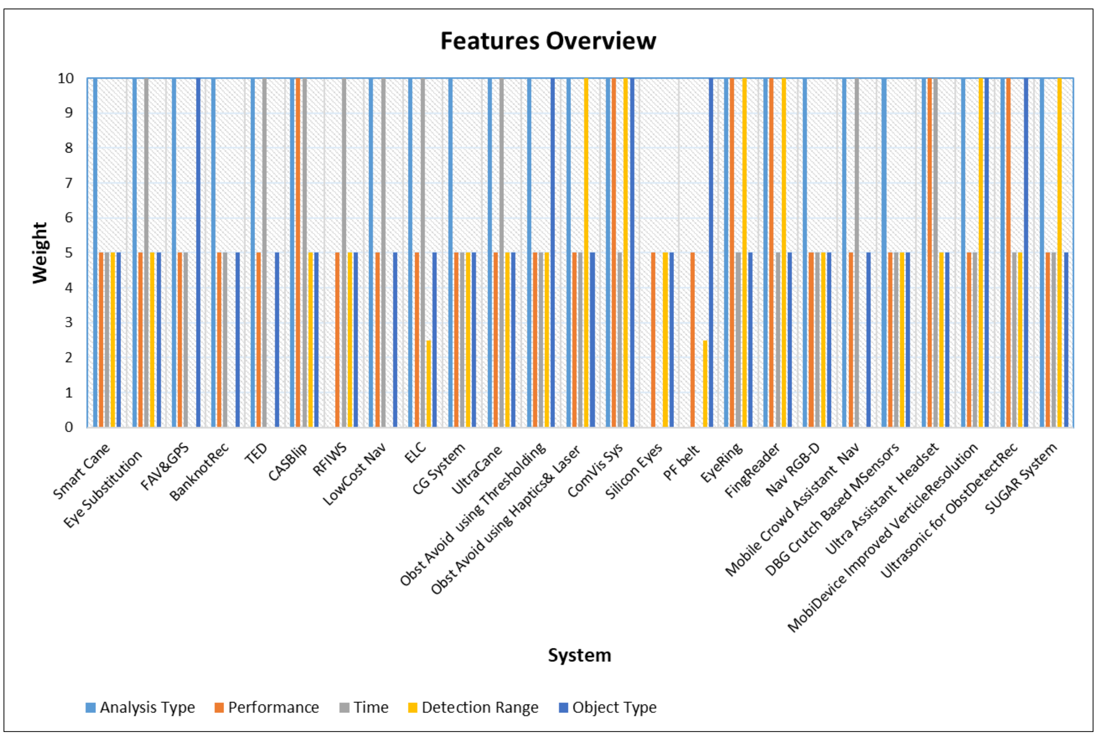


Figure 2.42: Feature overview for each system

TABLE 2. 3: EVALUATION OF REVIEWED SYSTEMS BASED ON ADDITION FEATURES THAT CAUSED THOSE LIMITATIONS OF EACH SYSTEM

Type of System	System Name	Type of the Sensors	Type of Usage	Limitation	Used Techniques for Detection, Recognition or Localization
Sensor-Based ETA	*Smart Cane*	Ultrasonic sensors Water detector	*pilot stage*	The water sensor cannot detect the water if it is less than 0.5 deep. The buzzer will not stop before it is dry. A power supply meter reading needs to be installed to track the status	Ultrasonic technology
	Eye Substitution	2 Ultrasonic Sensors Vibrator motors	*pilot stage*	The design of the system is uncomfortable due to the wood foundation which will be carried by the user most of the time as well as and the figures holes. The team used 3 motors for haptic feedback. They could use a 2-d array of such actuators that can give feedback about more details. Limited use by only Android devices	GPS, GSM, and GPRS Ultrasonic technology
	A Design of Blind-guide Crutch Based on Multi-sensors	3 Ultrasonic sensors	*deployment stage*	The detection range is small. This system is claimed to be navigation system, however, there are no given directions to the user.	Ultrasonic distance measurement approach
	ELC	Ultrasonic sensor Micro-motor actuator	*deployment stage*	It is a detector device for physical obstacles above the waistline but the navigation still relies on the blind person.	Ultrasonic sensor technology Haptics and tactile techniques
	Ultrasonic Cane as a Navigation Aid	Ultrasonic sensor (trans-receiver) Arduino UNO microcontroller wireless	*pilot stage*	Just an object detector Small detection rang Does not detect objects that suddenly appear	Ultrasonic Technology

		X-bee S1 trans receiver module			
	Ultrasonic Assistive Headset for visually-impaired people	4 Ultrasonic type (DYP-ME007) sensor obstacle detector	*pilot stage*	Limited directions are provided. The headset obscures the external noise.	Ultrasonic technology
	CASBlip	3D CMOS sensor	*pilot stage*	Small detection range Image acquisition technique needs more than 1X64 CMOS image sensor. Acoustic module needs to be improved (it can add sounds in elevation)	Binaural Acoustic module Multiple double short-time integration algorithms (MDSI)
	A Low Cost Outdoor Assistive Navigation System	3 Axial accelerometer sensors Magnetometer sensor	*pilot stage*	The accuracy of GPS receiver in high-rise building is degraded. Limited scope, the GPS receiver needs to be connected via Bluetooth to perform.	GPS technology Geo-Coder-US Module MoNav Module Bluetooth
	Silicon Eyes	24-bit color sensor SONAR obstacle detection light sensor 3-axis MEMS magnetometer 3-axis MEMS Accelerometer	*research stage*	A power supply meter reading needs to be installed to track the status. Low accuracy of GPS receiver in high-rise buildings. The haptic feedback is not efficient. Limited memory of 2 GB micro-SD card to save user information.	GPS & GSM technology

	Obstacle Avoidance Using Auto-adaptive Thresholding	Kinect’s depth camera	*pilot stage*	The accuracy of Kinect depth image decreases when the distance between the scene and sensor increase. Auto-adaptive threshold could not differentiate between the floor and the object after 2500 mm. That increases the average error of distance detection. The depth camera has to be carried which is a lot of load on the user’s hand.	Auto-adaptive Thresholding (divides equally a depth image into three areas. It finds the most optimal threshold value automatically (auto) and vary among each of those areas (adaptive).
	A Path Force Feedback Belt	IR sensor Two depth sensors (sensor 2 dual video cameras type Kinect)	*research stage*	The detection range for this design is too small. The user needs to be trained in differentiating the vibration patterns for each cell. Using vibration patterns as feedback instead of audio format is not an excellent solution as the person can lose the sense of discrimination of such techniques over the time.	Infrared technology and GPS
	SUGAR system	Ultra-wide band Sensors(UWB)	*pilot stage*	Sensors would have to be deployed in every room. The room has to be mapped beforehand. User needs to select destination beforehand. It is not suitable for outside use.	UWB positioning technique Path Finding Algorithm Time Difference of Arrival technique (TDOA)

	A Mobility Device for the Blind with Improved Vertical Resolution Using Dynamic Vision Sensors	2 retine-inspired dynamic vision sensors (DVS)	*pilot stage*	The modules are very expensive. Further intensive tests need to be done to show the performance object avoidance and navigation techniques, whereas, the test was mainly on object detection technique for the central area of the scene.	Event-based algorithm
Sensor Substitution-Based ETA	*TED*	Detective Camera	*pilot stage*	Antenna is not omni-directional. The range of voltage is not enough to supply the device. It is more difficult to recognize the pulses on the edges of the tongue.	Tongue–Placed Electro tactile Display
	RFIWS	None	*research stage*	Collision of RFID Each tag needs specific rang which needs to be tested separated (scoop limitation) The tags cannot read the radio waves if case these tags get wrapped up or covered.	Ultra-high frequency (UHF)
	Obstacle Avoidance Using Haptics and a Laser Rangefinder	Basely the system was built on the use of laser but the Novint Falcon has Encoder LED emitters and photo sensors Supplementary Sensors	*pilot stage*	Precise location of obstacles and angles were difficult to determine.	Haptics and a Laser Rangefinder

	Mobile Crowd Assisted Navigation for the Visually-impaired	Camera GPS Compass Accelerometer	*pilot stage*	The collected information is based on the volunteers' availability. There is a possibility of no input in the interval time that fails the goal of the service.	Crowd sounding service through Google engine for navigation Machine vision algorithm
ETA Sensory-Based Computer Vision Methods	*Fusion of Artificial Vision and GPS*	Optical Sensors Bumble bee Stereo Camera 3-axis Accelerometers Electronic compass Pedometer	*deployment stage*	The system was tested on the function of the object's avoidance technique. The system has not been tested or integrated with navigation systems to insure its performance; whether it will enhance the navigation systems as the authors promised or not is unknown.	Global Position System (GPS), Modified Geographical Information System (GIS) and vision based positioning SpikNet was used as recognition algorithm
	Cognitive Guidance System	Kinect sensor Video camera stereo Imaging sensor sonny ICx424 (640 × 480) RBG-D sensor for 3D point	*pilot stage*	Only 49 Fuzzy rules were covered which cover 80 different configurations. The perception capacities of the system need to be increased to detect spatial landmarks. Improve the stabilization of reconstructed walking plane and its registration through the frame.	The Canny filter for edge detection. Stereo vision, vanishing point and fuzzy rules (fuzzy logic and Mandani fuzzy decision system) to infer about the distances of objects.

	A Computer Vision System that Ensure the Autonomous Navigation	Monocular camera	*deployment stage*	Their fixed sizes of the image based on the category can make detecting the same object with different sizes a challenge. Since the proposed system is based on a smartphone video camera; if the blind person's clothes cover the video camera, then the system cannot work. The objects are in dark places and highly dynamic objects cannot be detected. The overhead and noise of smartphones videos. The tested dataset of 4500 images and dictionary of 4000 words are considered as a small dataset. The system is tested and it works only on a Samsung S4 which makes it limited in scope.	Lucas–Kanade algorithm and RANSAC algorithm are used for detection. Adapted HOG descriptor extractor, BoVW vocabulary development and SVM training are used for recognition.
	Navigation Assistance Using RGB-D Sensor With Range Expansion	RGB-D sensor	*pilot stage*	The effective of the infrared to the sunlight can negatively affect the performance of the system outdoors and during the day time.	RANdom Sample Consensus (RANSA) detection algorithm Image intensities and depth information (computer vision) Infrared technology and density images
	Ultrasonic for ObstDetectRec	4 ultrasonic sensors (Maxsonar LV EZ-0)	*pilot stage*	The system cannot detect obstacles above waist level. There is no navigational information provided. Small detection range. It is not an independent device.	Vision-based object detection module. Ultrasonic technology. SVM

CHAPTER 3: THE PROPOSED DATA FUSION ALGORITHM FOR GUIDING THE VISUALLY IMPAIRED

In this chapter, we are proposing and implementing a novel framework that is based on the integration of both computer vision-based and sensor-based technologies (multisensory data) to facilitate the user's mobility indoors and outdoors and provide an efficient system for the VI user. This integration shows a significant enhancement in the obstacle detection and avoidance field. The unique and new collision avoidance approach that makes our framework novel and effective, will be explained in details in the following chapter.

However, it is challenging to refine the fusion of the multisensory data that is received from different type of sensors, for example: GPS, gyro, compass and more in order to provide an accurate information about positioning and free path. However, this data fusion can improve the performance of the overall system.

Without any optimized system that divides the work into blocks, computation load and time can be large. Therefore, we propose a framework that significantly improves the life of the VI user. This framework supports the following features: obstacle detection [71-72], 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 [49, 52, 73 – 79], character recognition and text reading [80, 81], identifying currency bills [82], note taking [83, 84], traffic signal detection [85], barcode scanning, product information retrieval [86], finding lost items [87], localizing specific objects [88, 89], and mobile vision [90].

3.1 The Proposed Communication Methodology

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, PIR module, a music module, and a Wi-Fi module.

Moreover, we implement a software system for 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 techniques to provide safe mobility. Figure 3.1 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.

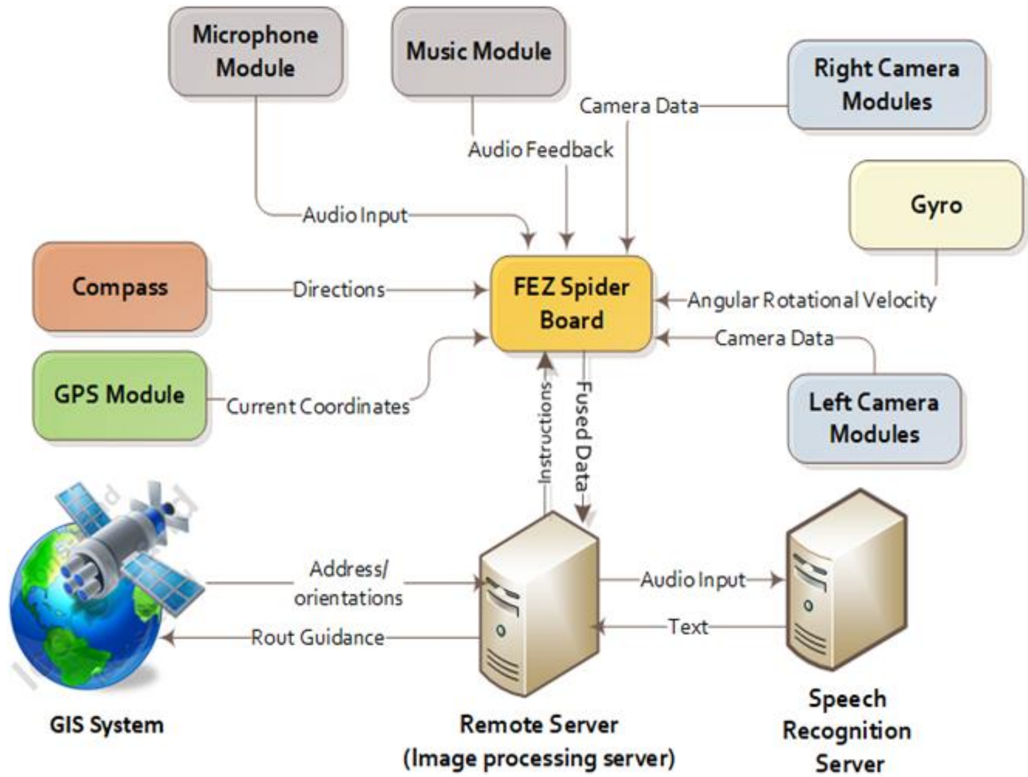


Figure 3. 1: Proposed methodology of interaction process among the hardware components

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 techniques. The remote server handles the image processing part. 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. A

GIS provide route guidance. Thus, we use a gyro, compass, and GPS to track the user's directions, locations and orientations to provide accurate route guidance information [91].

3.2 The Work Flow of the Proposed Data Fusion Algorithm

The proposed algorithm is divided into two approaches; collision avoidance and route guidance. The proposed collision avoidance will be explained in-depth next chapter.

Figure 3.2 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: mode zero indicates that the system is booting; mode 1 represents the static/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 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. 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 collision 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 [91].

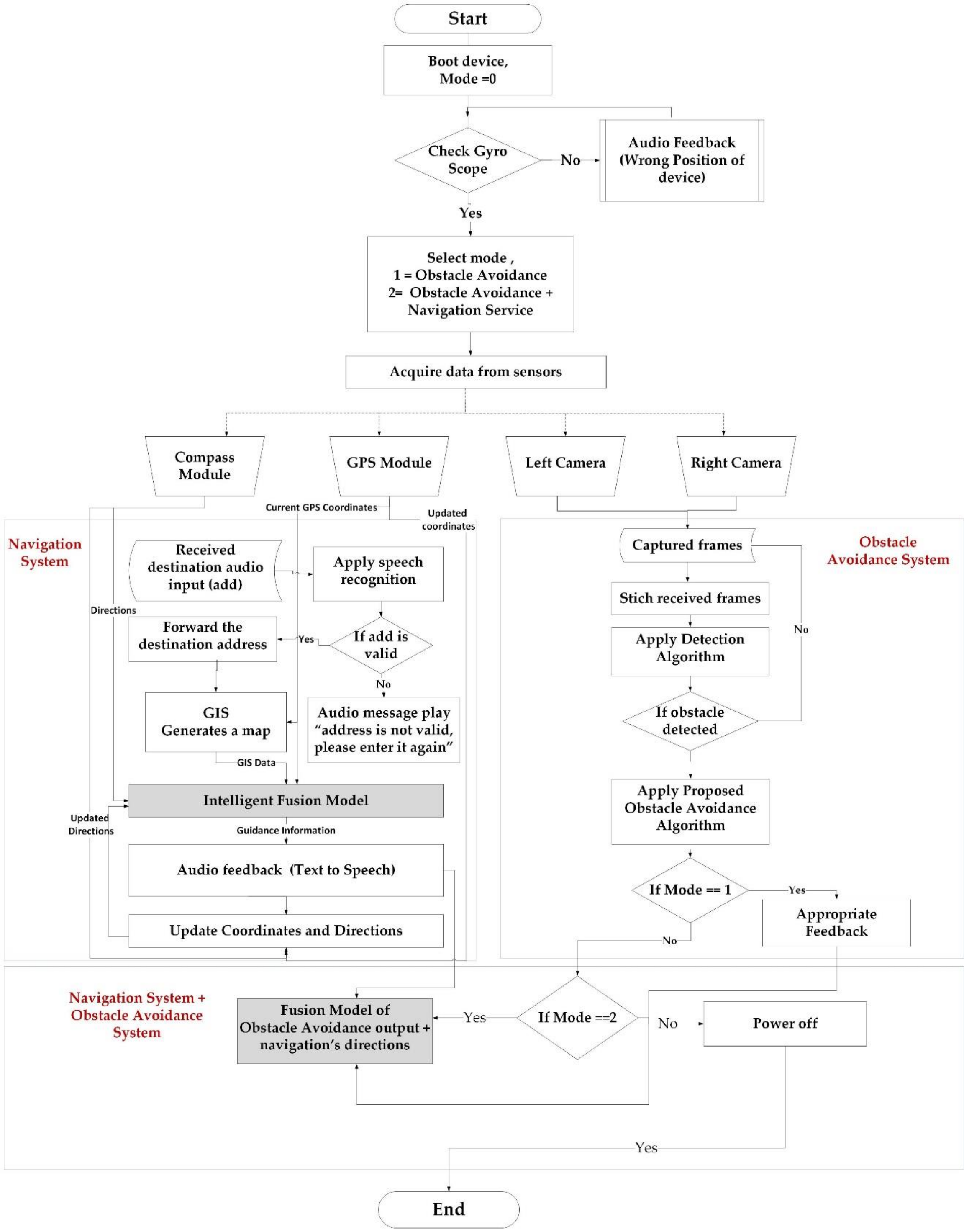


Figure 3. 2: Flowchart of the proposed data fusion algorithm using multiple sensors .

CHAPTER 4: THE STATIC/ DYNAMIC OBSTACLE DETECTION AND THE PROPOSED COLLISION AVOIDANCE APPROACH USING FUZZY LOGIC CONTROLLER

In this chapter, we will discuss the object detection and the proposed novel and unique collision avoidance approach that is based on the image depth to map the frame for better control as well as it is based on the fuzzy logic to provide the user with precise navigational information in an audio format using a headset. The results of the proposed collision 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 collision avoidance technique is based on the depth of an image, which is considered to be 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.

4.1 Static/ Dynamic Obstacle Detection Using Camera Modules and Computer Vision Techniques

The description of selected algorithms for the object detection model is provided in this section. We discussed each subsection individually as well as we explained how the output of each algorithm is handle by the following algorithm. In addition, we described the interaction of this architecture in order to get a high accuracy for the object detection model.

4.1.1 Extraction of Interest Points Using the Combination of Oriented FAST and Rotated BRIEF (ORB) Algorithm

Figure 4.1 illustrates the process of the object detection systematically using computer vision methods. The camera displayed in Figure 4.2 (a) is from GHI Electronics [92]; 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 4.2 (b) demonstrates the use of two cameras to detect objects even on edges and objects that cannot be noticed when using one camera.

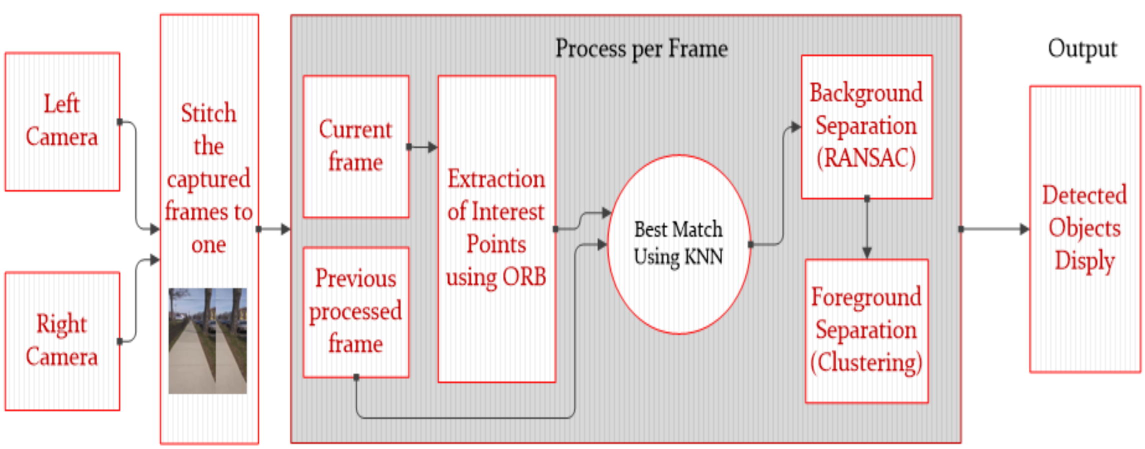
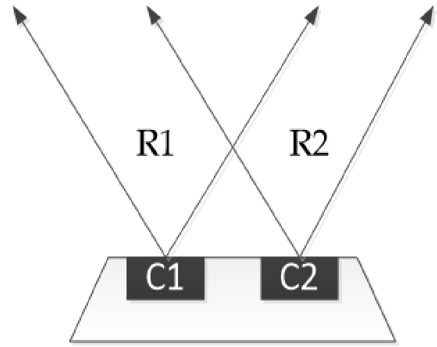


Figure 4. 1: The block diagram of the static/dynamic object detection algorithm

(a)



(b)

Figure 4. 2: (a) Camera Module for object detection, (b) The camera view range

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 [93]. Unlike other extraction algorithms, ORB has a descriptor. Therefore, ORB is an integration of the modified Features from Accelerated Segment Test (FAST) detector [94] and the modified Binary Robust Independent Elementary Features (BRIEF) descriptor [95]. 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 [94].

As demonstrated in Figure 4.3, 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:

$$\left|I_x - I_p\right| > t \quad (1)$$

I_x is the value of surrounding consecutive pixels. N top points are filtered by the Harris corner measure [96].

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:

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

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

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

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

$$\theta = atan2(m_{01}, m_{10}) \quad (4)$$

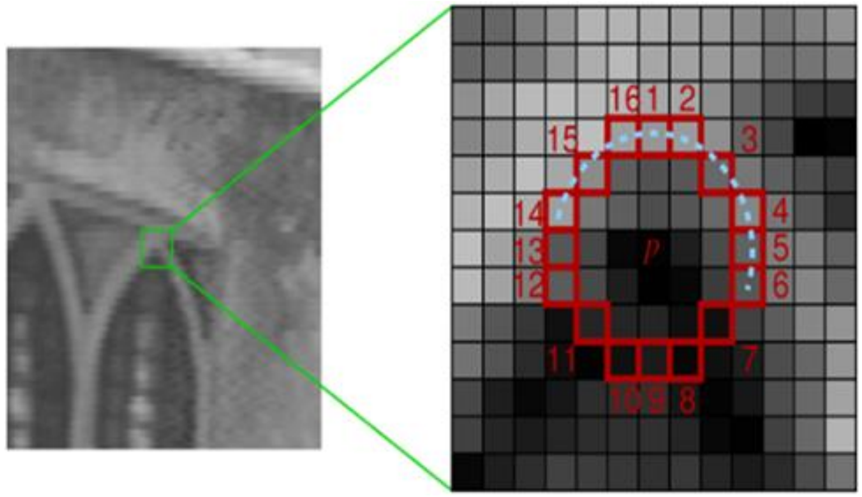


Figure 4. 3: Segments test detector [97]

BRIEF is a binary string representation of an image patch P [94]. τ is a binary test of n pairs of pixel points that can be defined as shown in (5):

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

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 $2xn$:

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

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):

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

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

4.1.2 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 for an object's presence. In this work, 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 [97]. 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 [98].

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.

4.1.3 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 4.4 are denoted by red dots; they did not have any influence on the results. Inliers are represented in blue color.

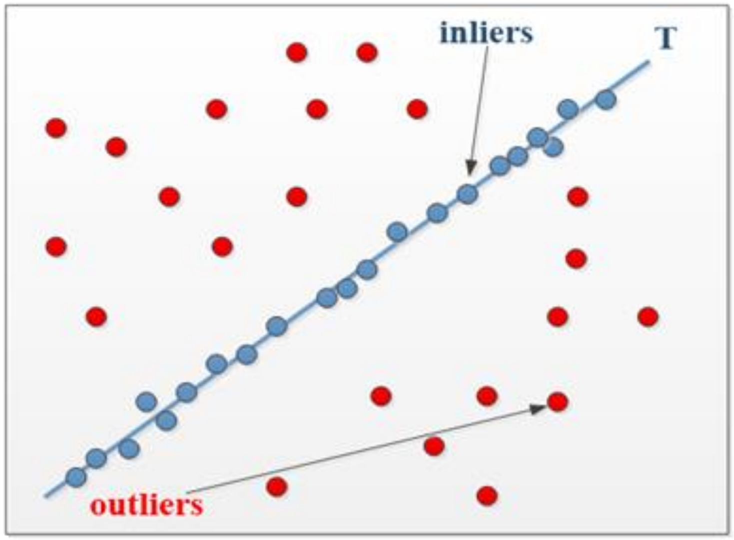


Figure 4. 4: Performance of RANSAC for line fitting [99]

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 [99].

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:

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

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

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

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.

4.1.4 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 is to assign n extracted points $\{p_1, p_2, \dots\dots, p_n\}$ to k clusters $\{s_1, s_2, \dots\dots, s_k\}$, whereas K is the maximum number of clusters and $k < n$:

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

The $Center(S_j)$ 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 $k = 10$ for each frame based on our observations.

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 4.5 represents the modification that we made to the K-Means clustering technique. 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 into S_1. Otherwise, merging does not occur even if $(S_1 \cap S_2)$.

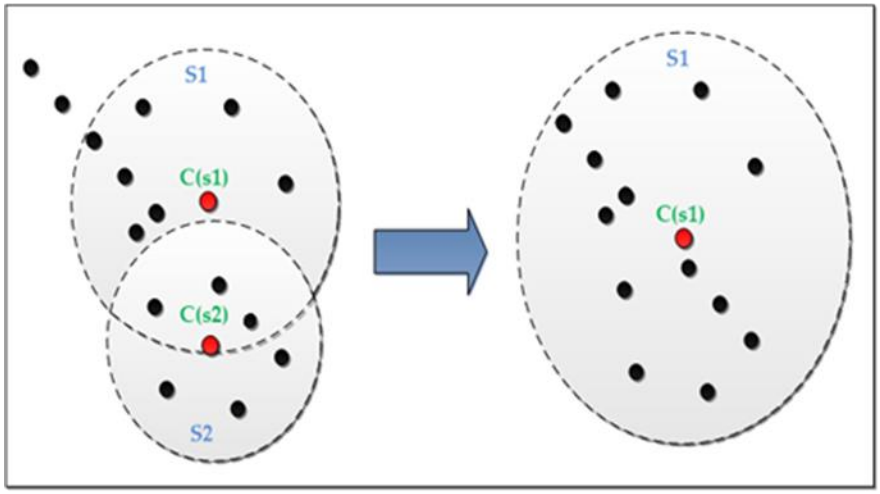


Figure 4. 5: Demonstration of merging two clusters into one cluster.

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 a cluster

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 ($(S_j \cap S_i) \wedge (C_{S_j}$ **within** $S_i)$

Merge S_j **into** S_i

End if

End for

End for

End while

The result of the combination of adopted algorithms is represented in Figure 4.6 (a). The two green dots, which are represented on the floor (the middle image) in Figure 4.6(b), denote the detection range from where the user is standing.

Figure 4. 6: 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 2 illustrates the static and dynamic object detection that applies computer vision methods on video stream by the two cameras modules.

Algorithm 2: Static/ Dynamic Obstacle Detection Algorithm

Input: Read_Frame_From_Camera_Right ^ Camera_Lift ($Frame_i$, $Frame_j$)

Output: Array of objects

Stitch($Frame_i$, $Frame_j$) into (firstFrame);

ConvertColorToGrayScale (firstFrame);

ComputeInteresstAndDescriptorsORB (firstFrame, keypointFirstFrame, descriptorsFirstFrame);

While (true)

  Read_Frame_From_Camera (nextFrame);

  ConvertColorToGrayScale (nextFrame);

  ComputeInteresstAndDescriptorsORB(nextFrame, keypointsNextFrame, descriptorsNextFrame);

  NearestNeighborBruteForceMatching (descriptorFirstFrame, descriptorNextFrame, matches,2);

  For ($matches_i$)

    If ($matches_i$ [0].distance < 0.8 * $matches_i$ [1].distance) //Lowe's ratio

      MatchedFirstFramePoint <- (keypointFirstFrame [$matches_i$ [0]])

      MatchedNextFramePoint <- (keypointsFirstFrame [$matches_i$ [0]])

    End If

  End For

  RANSAC (MatchedFirstFramePoint, MatchedNextFramePoint, Inliers)

  For ($matched1_i$)

    If (Inliers == 1) // if interest points are inliers

      InliersFirstFrame <- MatchedFirstFrame

      InliersNextFrame <- MatchedNextFrame

    End If

  End For

  NumberOfClusters=6

  CALL Modified K-Mean Clustering Algorithm

  CALL Object Avoidance Algorithm

  descriptorsFirstFrame = descriptorsNextFrame

  keypointFirstFrame = descriptorsFirstFrame

End While

4.2 Collision Avoidance Approach based on the Proposed Proximity-Measurement Method Using Fuzzy Logic Controller

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 proximity measurement methodology to measure the distance between the user and the obstacle using mathematical models and x-y coordinates system. The proposed approach is based on the camera that faces a slight angle down to have a fixed distance between a VI user 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 user 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 4.7 [91].

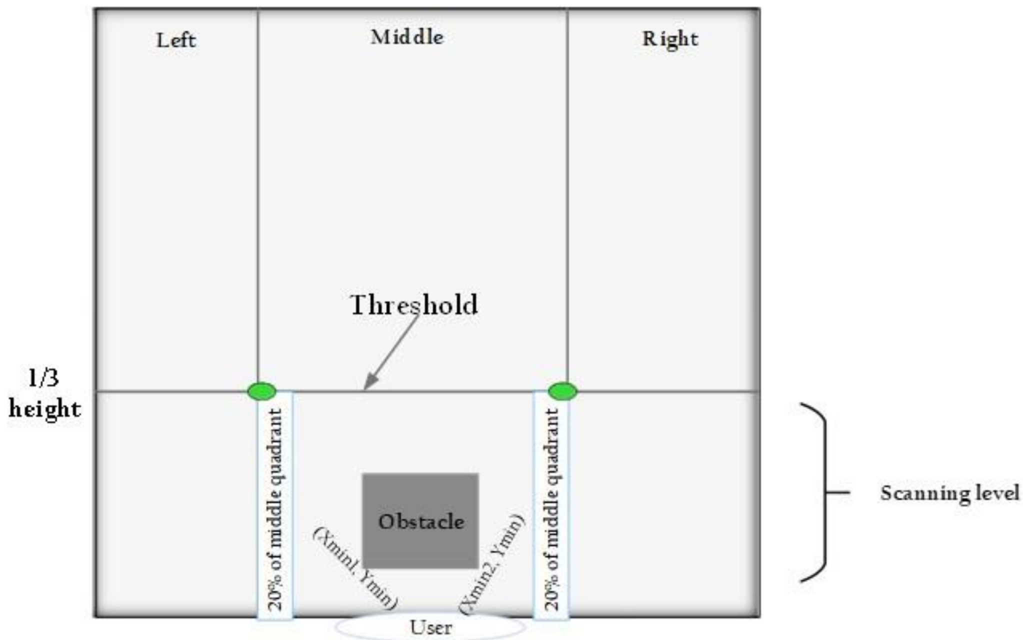


Figure 4. 7: Approximate distance measurement for object avoidance

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 user. We can represent the frame in an $xy - coordinate\ system$. Let W be the width and H be the height. The calculation of the right and left is expressed as follows:

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

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 user, 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 user. 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 quadrant to provide accurate information to the user. If the obstacle exists within 20% of the middle quadrant, he/she does not need to move to other sides as long as the object appears in one of the 20% of the middle quadrant but not both [91].

Figure 4.8 displays a flowchart of the collision avoidance system. Each preprocessed frame is divided into left, middle, and right parts. Figure 4.8 shows the parallel process of simultaneously applying a free collision approach to the three areas. 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. Tactile feedback is a suitable option for people who are hearing impairment. This algorithm will be recursively applied for each frame compared with the previous frame. The algorithm considers the previous frame as the reference frame.

Table 4.1 represents the conditions and the audio feedback that the user will receive. We decided to use a left area as the default direction to avoid any confusion if the obstacle appears in the middle; however, both left areas and right areas are free.

TABLE 4. 1: AUDIO FEEDBACK OF THE COLLISION AVOIDANCE SYSTEM 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"

Algorithm 3 demonstrates the proposed distance measurement approach for collision avoidance [91].

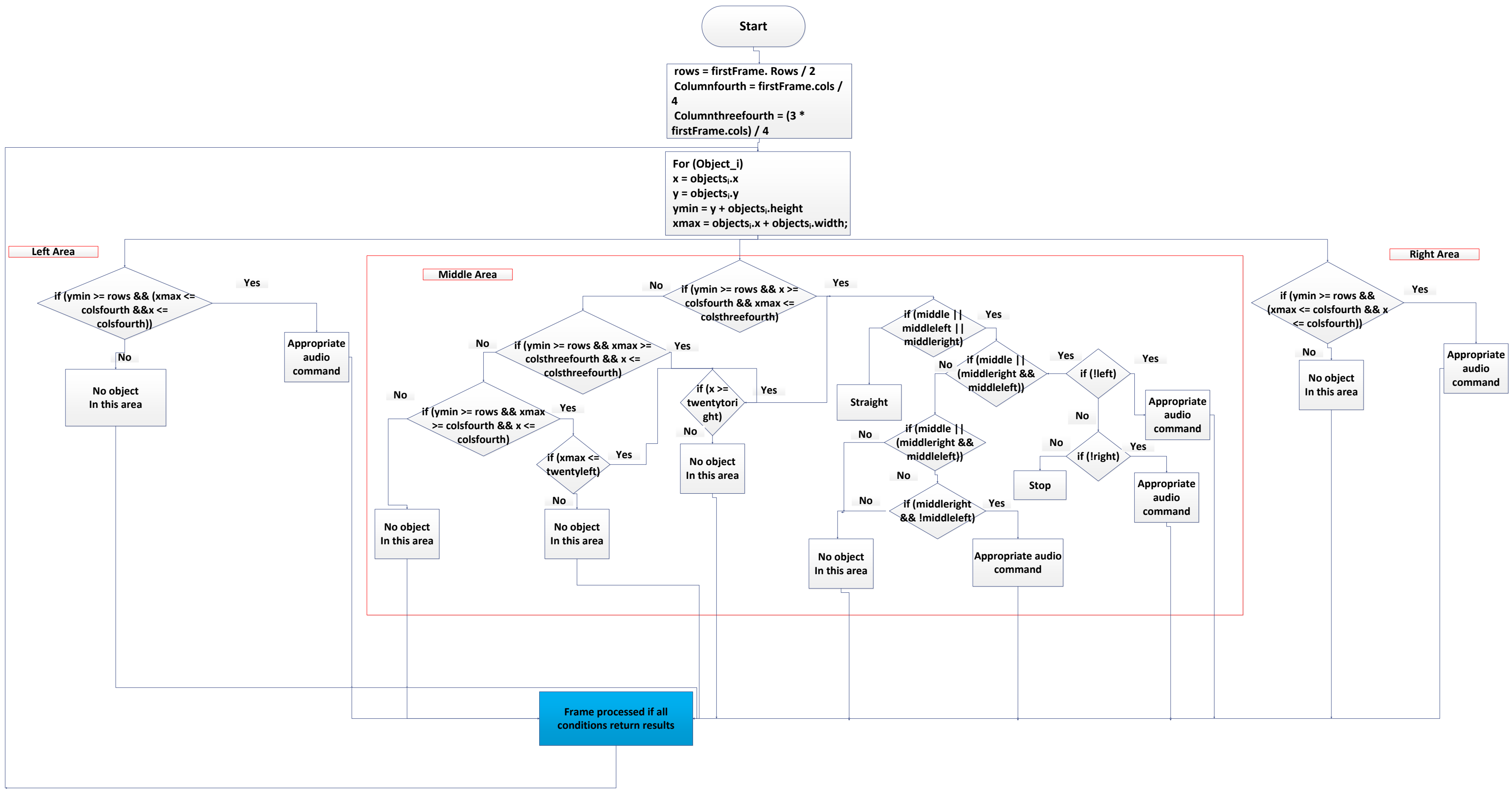


Figure 4. 8: Flowchart of the collision avoidance system

Algorithm 3: 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 (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)
      twentypercenttoleftt=Columnfourth+twenty
      If(xmax<=twentypercenttoleftt)
         MiddleLeft← true
   Else if (ymin >= rows && (xmax <= Xcorner1  && x<= Xcorner1))
      Left ← true
   Else if (ymin >= rows && (x >= Xcorner1  && xmax>= Xcorner1))
      Right← true
   End If
   If (Middle || MiddleLeft || MiddleRight)
      If (Middle || (MiddleRight && MiddleLeft))
          IF(!LEFT)
             Output:  "move left "
           Else if (! Right)
              Output: "move right "
         Else
           Output: "Stop"
   End If
   Else If(MiddleLeft && !MiddleRight)
         Output: "slight right then straight"
   Else Output: "slight left then straight"
End For
```

4.2.1 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 4.9 shows the fuzzy controller system for collision avoidance algorithm, which includes: fuzzier that converts the inputs to number of fuzzy sets based on the 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 that the user should seek [100, 101]. We used Mathlab R2017b software in order to evaluate the proposed concept.

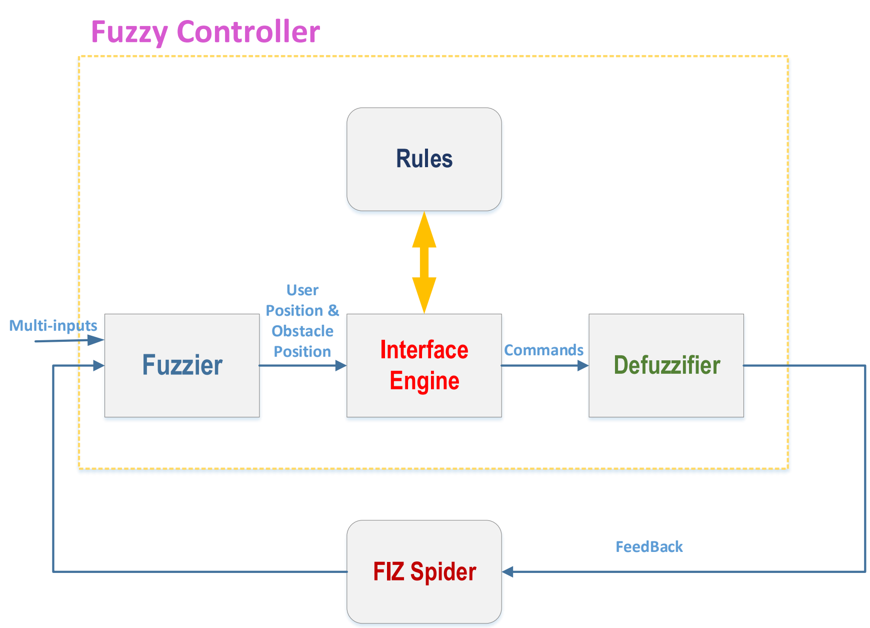


Figure 4. 9: The Fuzzy structure for collision avoidance system

4.2.1.1 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 and the user position. They are donated as {ObsRange, UserPosition, ObsLeft, Obs20%LeftMid, ObsMiddle, Obs20%RightMid, and ObsRight}. The output is the feedback that the user needs to use through his/her path to the endpoint. Figure 4.10 is a representation of applying the proposed collision avoidance (Mamdani) System using Fuzzy Inference System (FIS) in Maltlab software. The purpose of using Mathlab software is to examine the proposed collision avoidance approach before the real implementation occurs. Figure 4.11 displays the design of the fuzzy system for the collision avoidance approach, which is illustrating the inputs and their membership functions and outputs and their membership [102].

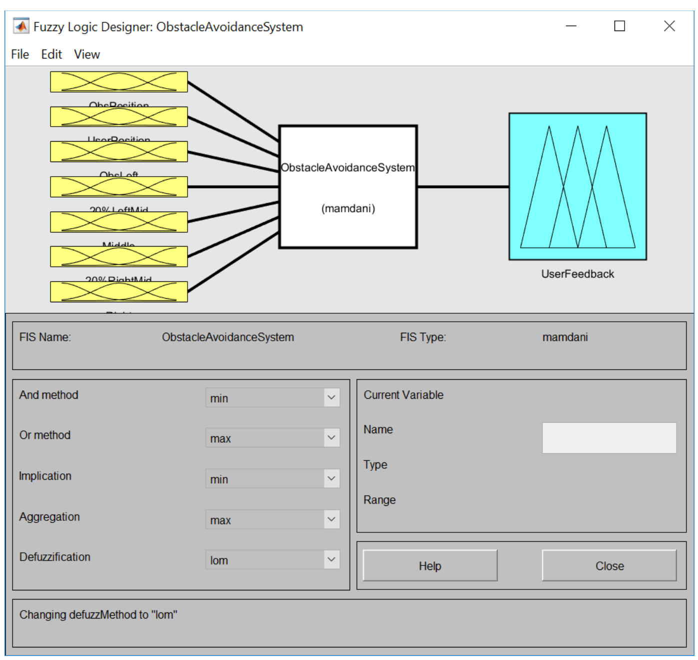


Figure 4. 10: The Fuzzy Inference System (FIS) in Maltlab for the proposed collision Avoidance (Mamdani) System

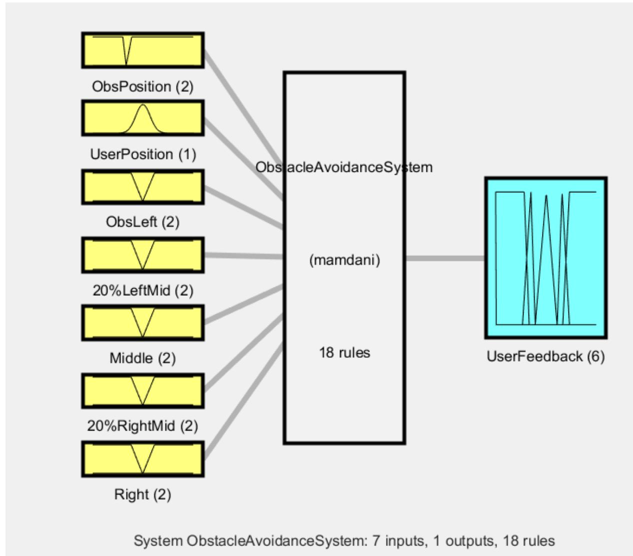


Figure 4. 11: A high-level diagram of an FIS for the proposed collision Avoidance System

4.2.1.2 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 that are: {Left, middle, and right}. Table 4.2 describes the terms of user's position. 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 4.12. The range of this membership function is 300cm as it is considered to be the width of the scene. 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.

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

Table 4.3 describes the terms of obstacle's position. 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 farther than 300cm. Figure 4.13 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} [102].

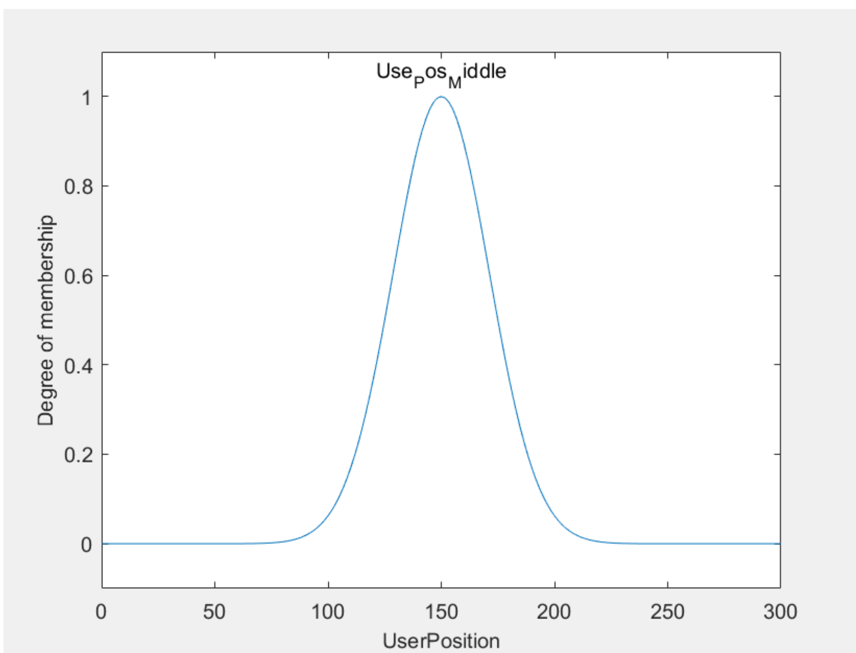


Figure 4. 12: Membership function for the user's position

TABLE 4. 2: DEFINITION OF MEMBERSHIP FUNCTION FOR USER POSITION

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]

TABLE 4. 3: 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

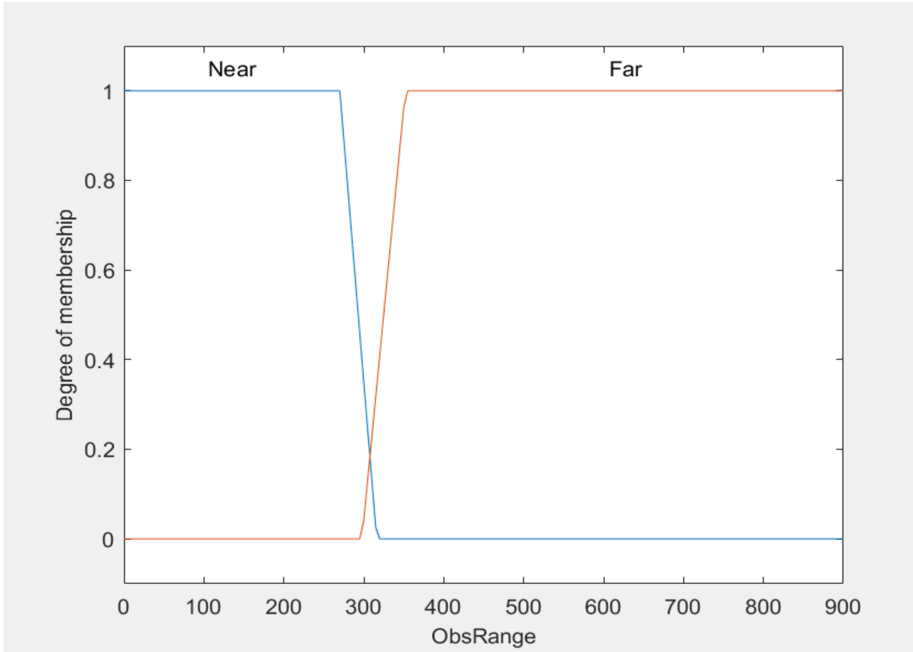


Figure 4. 13: Membership function of object presentence in two ranges of the scene

Figure 4.14 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∈R. Consequently, four parameters [i, j, k, l] are used to express the Trapezoidal-shaped membership function in the following equation (18):

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

The output is divided into six membership functions that are based on the fused input variables. The output can be: {MoveLeft, SlightLeftthenStraight, GoStraight, SlightRightthenStraight, MoveRight, and Stop}. We used the Trapezoidal-shaped membership function for MoveRight and MoveLeft membership values. However, we used Triangular membership function as shown in Figure 4.15 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):

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

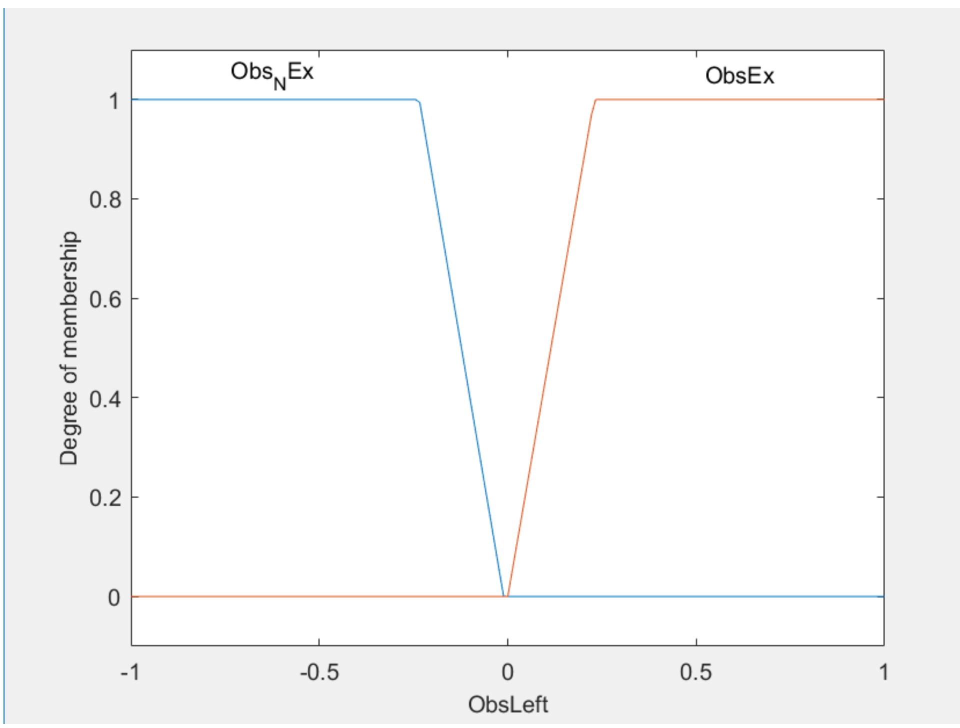


Figure 4. 14: Membership function for obstacle's position in the left side

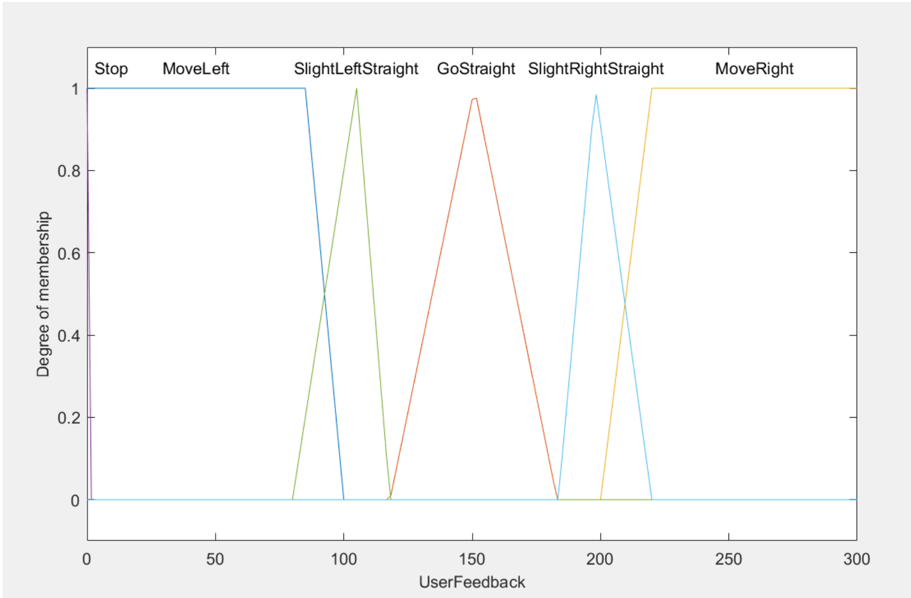


Figure 4. 15: Membership function of the output (feedback/directions)

4.2.1.3 Creating Fuzzy Rules

The fuzzy rules can be produced based on observing and employing the Knowledge that was introduced in Table 4.2, Table 4.3, member functions 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 Table 4.4.

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_Υ and μ_δ are two membership values, thus, the fuzzy AND is described as following:

$$\mu_\Upsilon \, AND \mu_\delta = \min(\mu_\Upsilon, \mu_\delta) \tag{20}$$

4.2.1.4 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.

Furthermore, fuzzy logic is used to assist the VI person from colliding with front obstacles in front of them. 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. Figure 4.16 illustrates the surface viewer that displays the feedback based on the relationship between the obstacle's position (obstacle's range) and each assigned position to the obstacle in the scene. 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 [102].

TABLE 4. 4: 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

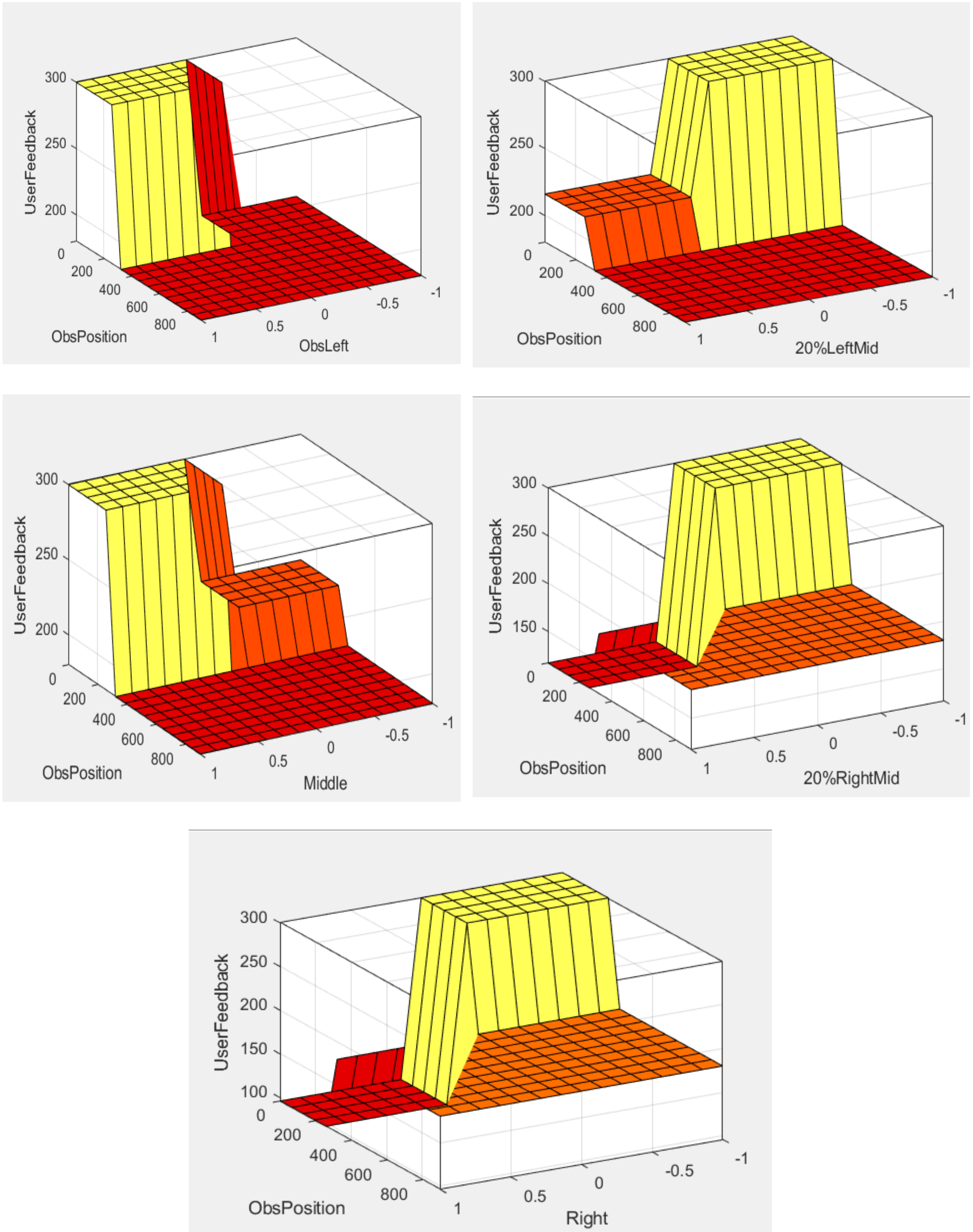


Figure 4. 16: The output of the fuzzy controller based on the position of the obstacle and the range (far or near)

CHAPTER 5: PLATEFORM AND IMPLEMENTATION

The interaction between the software and hardware has a significant influence on our experiments and results. As we stated in the previous chapters, both sensor-based and computer vision approaches have advantages and disadvantages. In order to get the most significant results and overcome the shortage of each approach, we integrated both technologies in one framework. Therefore, we examine the integration of multisensory data and the computer vison-based results in this chapter. Number of real-time experiments were performed. In addition, a video dataset was directly fed to our system to ensure the efficiency of the proposed algorithm.

This chapter outlines the implementation and testing steps of the proposed system to accomplish the expected outcomes and objectives of this work. The algorithms are implemented using the C # programming language. In addition, we will describe the overall system in which the hardware architecture was designed. We explain the function of each module and its advantages.

5.1 Design Structure of the Proposed System

The device was designed to facilitate the user's mobility by providing appropriate navigational information. Figure 5.1 illustrates the designed platform, which aims to detect static and dynamic objects, collision avoidance and provide a navigational information. We used C# programing language to implement the proposed algorithm. The system is built using the .NET Gadgeteer compatible mainboard and modules from GHI Electronics [92, 103]. Table 5.1 shows the power consumption for all modules.

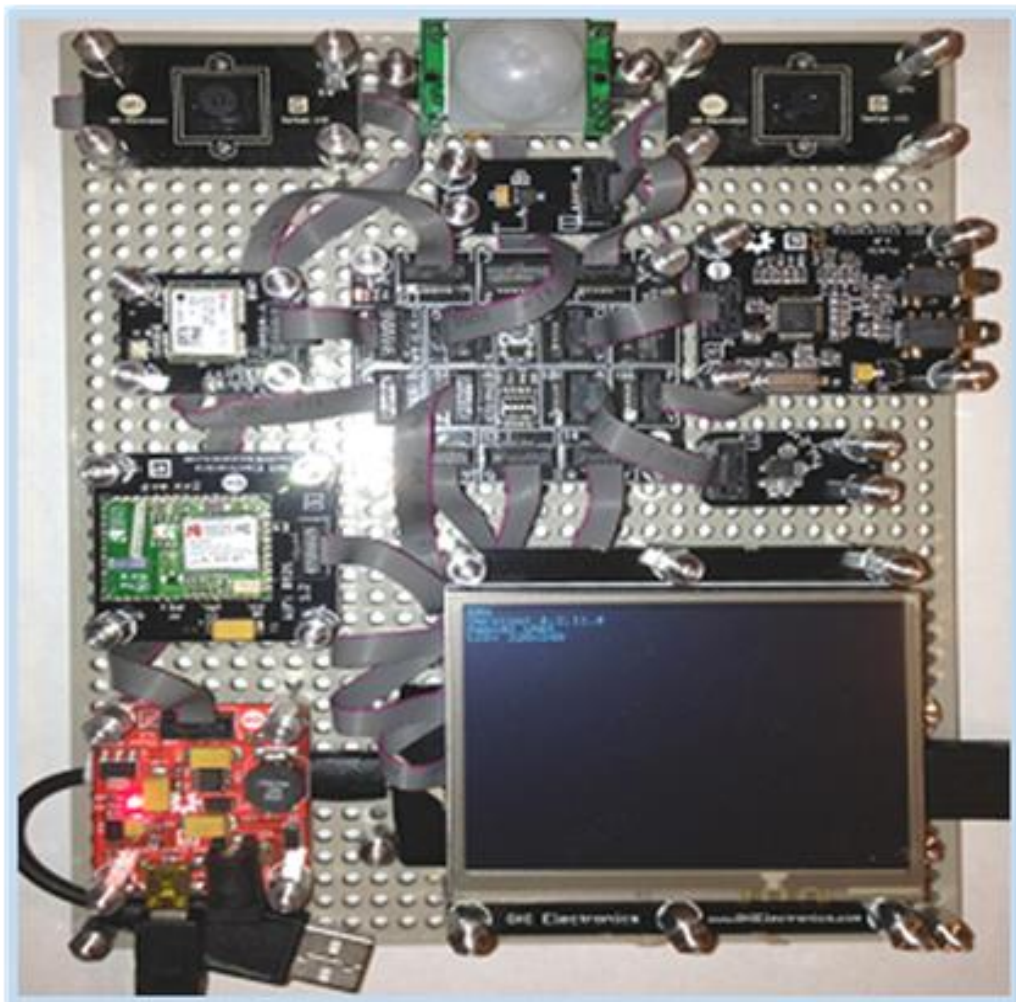


Figure 5. 1: Assistive System for the Visually Impaired

TABLE 5. 1: 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

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 is an open source to design electronic devices by taking advantage of object-oriented programming and integrating Visual Studio and .NET Micro Framework [103]. 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 following subsections presnet the used modules.

5.1.1 FEZ Spider Mainboard

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 5.2. The board has more feature as explained in [104].

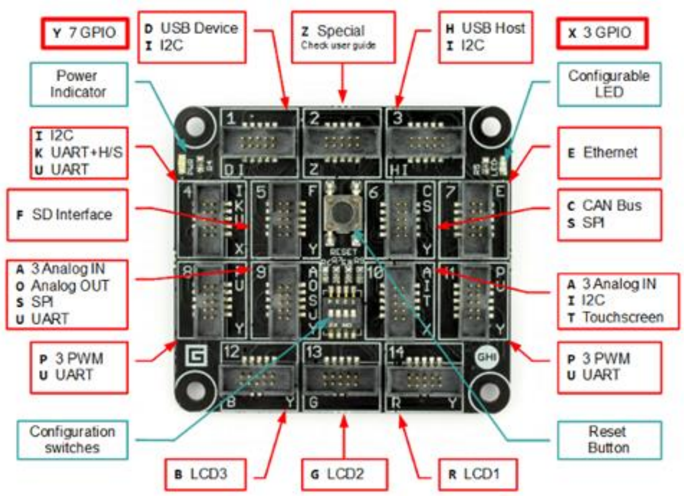


Figure 5. 2: GHI Electronics FEZ Spider Mainboard [104].

5.1.2 Camera Module

The Camera Module by GHI Electronics is a serial camera that can stream JPEG images to any Gadgeteer mainboard with socket type U. Specs of the module are demonstrated in [105]. GHI Electronics Camera Module is shown in Figure 5.3.

Figure 5. 3: GHI Electronics Camera Module

5.1.3 Compass Module

The Compass Module by GHI Electronics is designed for low field magnetic sensing with an I2C interface. It has a 1° to 2° heading accuracy. It uses a 3-axis magneto-resistive type sensor and has up to 116 Hz maximum output rate. Specs for the module are demonstrated in [106]. Figure 5.4 illustrates Compass Module.

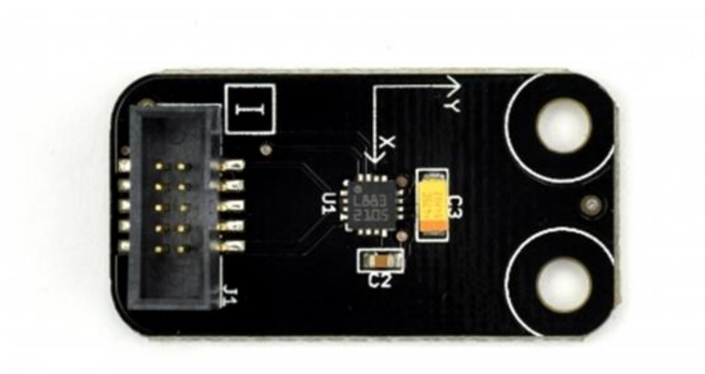


Figure 5. 4: GHI Electronics Compass Module

5.1.4 GPS Module

The GPS Module by GHI Electronics as shown in Figure 5.5 uses U-Blox Neo-6M GPS module and patch antenna connected via a U.FI connector. The module has a 1 to 5Hz update frequency. It supports NMEA and U-Blox 6 protocols. Specs for this module are demonstrated in [107].

Figure 5. 5: GHI Electronics GPS Module

5.1.5 Gyroscope Module

The GHI Electronics Gyroscope Module utilizes a 3-axis MEMS motion processing to measure 3-axis angular rate. This is useful for both motion detection and location detection applications. Specs for this module are demonstrated in [108]. The GHI Electronics Gyroscope Module is shown in **Error! Reference source not found.**.6.

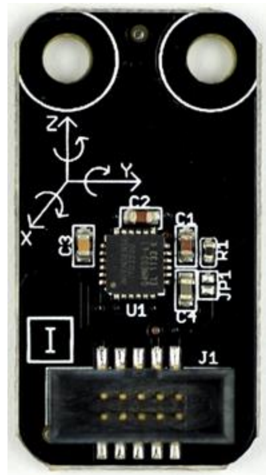


Figure 5. 6: GHI Electronics Gyroscope Module

5.1.6 Music Module

The Music Module includes an audio decoder capable of playing MP3, WMA, OGG, MIDI and WAV files. Specs for the module are demonstrated in [109]. The GHI Electronics Music Module is shown in Figure 5.7.

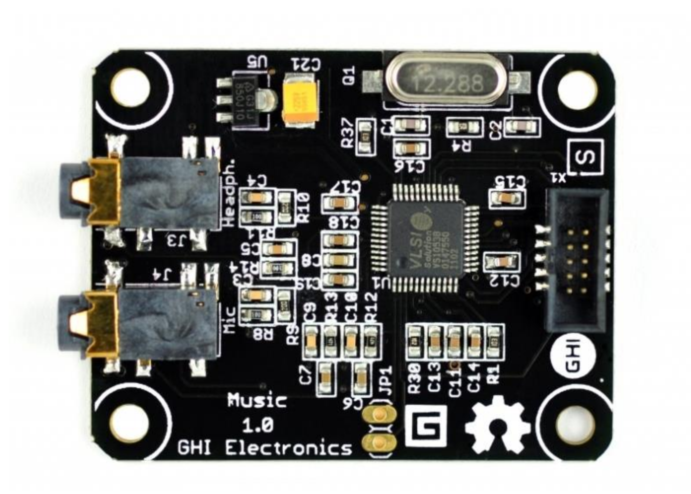


Figure 5. 7: GHI Electronics Music Module

5.1.7 PIR Motion Detection Module

The GHI Electronics PIR Motion Detection Module is a Passive Infrared sensor. It can detect motion within the module's field of view. Specs for the module are demonstrated in [110]. The GHI Electronics PIR Motion Detection Module is shown in Figure 5.8.

Figure 5. 8: GHI Electronics PIR Motion Detection Module

5.1.8 Wi-Fi Module

The GHI Electronics Wi-Fi RS21 Module can establish WiFi connections based on .NET Sockets. Specs for the module are attached below:

- Socket: S
- Size: 42mm x 42mm
- Weight: 7g
- 3.3V Consumption : 40mA
- 5V Consumption: 0mA

The GHI Electronics Wi-Fi RS21 Module is shown in Figure 5.9.

Figure 5. 9: GHI Electronics Wi-Fi RS21 Module

5.2 The Implementation and Testing Plan

The complete design of our wearable navigational device is shown in Figure 5.10. All sensors modules are connected to the FEZ-Spider mainboard.

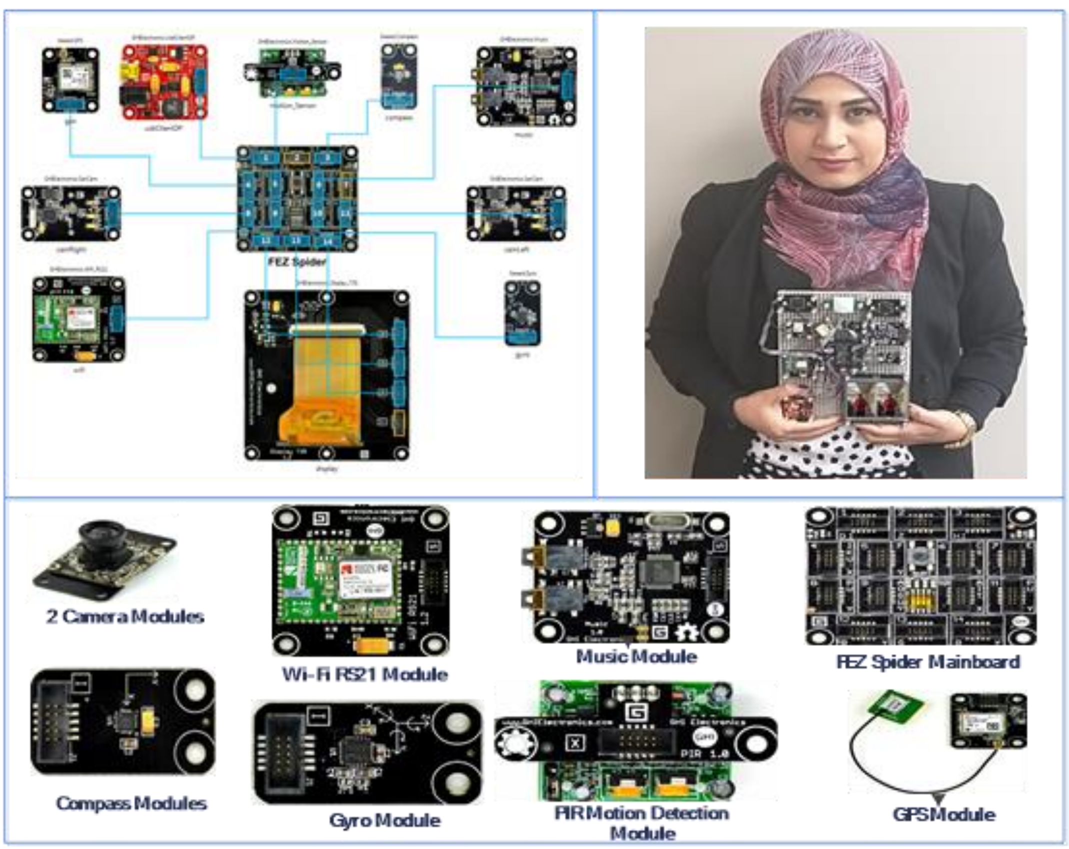


Figure 5. 10: Hardware architecture of proposed framework

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 designed device is worn 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 for indoor and outdoor scenarios. The number and shape of the obstacles are different for each scenario. Our system was also tested on a video dataset that was directly fed to the system.

5.3 Real Time Scenarios and Overview Evaluation

A set of experiments was performed on the designed device for indoor and outdoor environments. 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. We used C# programming language for implementation. For designing the framework, .net Gadgeteer framework was used. Our sequence of algorithms to detect dynamic and static objects, yields very promising results and high accuracy compared with other algorithms. This helped our proposed collision avoidance algorithm to provide the user with the most accurate and precise navigational information.

Simultaneously, frames are 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 an obstacle unless they are located in front of the users or are blocking his/her path; otherwise, the object is considered to be just an object that does not affect the user. 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 the collision avoidance. Each frame of a 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. Only four scenarios are presented in follow:

Scenario 1: the first scenario was conducted indoor to examine the detection algorithm and the proposed avoiding obstacles approach 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 and number of detected objects. While the user was walking through the hall, audio messages were produced to avoid two sequential chairs, as shown in Figure 5.11. The messages were clear and precise. The user was able to avoid both chairs by following the provided instructions.

Scenario 2: this scenario was also conducted indoor to evaluate the obstacle detection and avoidance approach 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. We tested the accuracy of the collision avoidance technique in a complex environment, where more than one obstacle is located in close proximity. The arrows in Figure 5.11 illustrate the directions that the user was proceeding while he was using the device.

Scenario 3: this scenario was conducted outdoor to evaluate outdoor navigation performance. The scenario, which was conducted outdoor at the University of Bridgeport. The objective of this scenario is to test the sensitivity of the modules to sunlight. "Go straight" audio message was produced all the way as there was no obstacles colliding the user's path. In order to not annoy the user with same message every time, a timer is setup.

Scenario 4: this scenario was conducted outdoor to evaluate the proposed collision 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 to avoid detected static and dynamic obstacles and safely proceed along his path. The user was able to avoid the existing obstacles by following the provided instructions.

Scenario 5 &6: both scenarios were conducted indoor at the University of Bridgeport. The purpose of scenario 5&6 is to evaluate the performance of the collision avoidance approach with different heights of existing obstacles. The user was able smoothly to pass the obstacles and move on along his path.

Scenario 7,8&9: more scenarios were conducted outdoor with different settings to ensure the efficiency of the proposed algorithm. We had more outdoor experiments because the user would be more familiar with indoor environments especially if he/she is in his/her property. However, outdoor environment has more sudden appear obstacles and unexpected type of obstacles. Therefore, these scenarios were conducted to ensure efficiency of the proposed algorithm with different type of obstacles such as: trees, stop signs, animals, cars, and buildings.

Table 5.2 illustrates the type of modules were used in the abovementioned experiments, the environment settings, and the results of each scenario based on the user's feedback. Table 5.3 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.

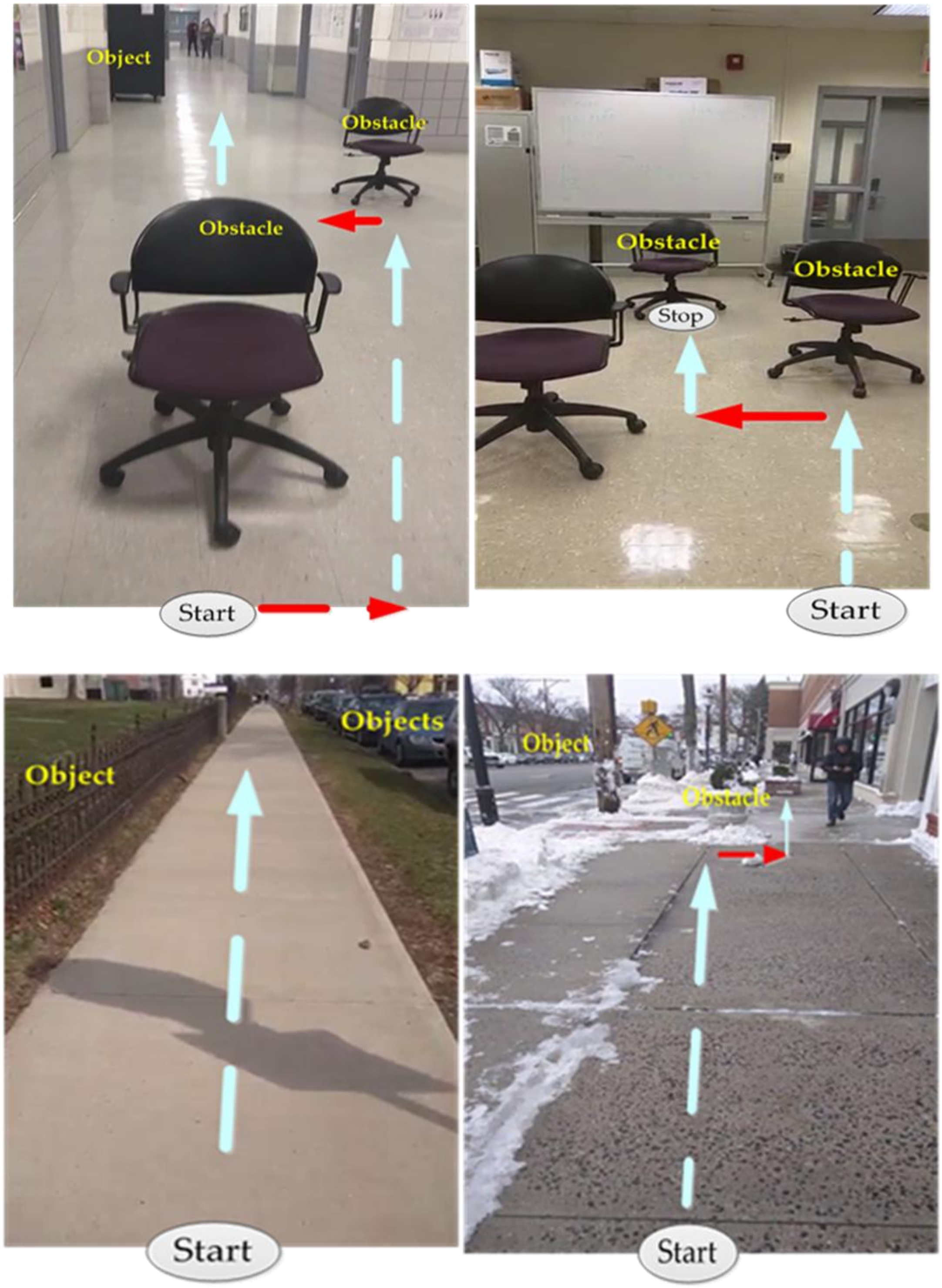


Figure 5. 11: A snapshots of the real-time experiments for indoor/outdoor navigation using simple to a complex path setup

TABLE 5. 2: OVERVIEW OF THE RESULTS OF THE NINE SCENARIOS

Scenario	Type of Experiment/Type of Module	Experimental Platform	Results
1	Indoor using two camera modules, a Wi-Fi module, a music module. PIR module, Gyro, and compass. 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 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	Indoor using two camera modules, a Wi-Fi module, a music module. PIR module, Gyro, and compass. All were 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	Outdoor using two camera modules, a Wi-Fi module, a music module. PIR module, Gyro, and compass. All were 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	Indoor using two camera modules, a Wi-Fi module, a music module. PIR module, Gyro, and compass. 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.
5 & 6	Indoor using two camera modules, a Wi-Fi module, a music module. PIR module, Gyro, and compass. All were connected with a FEZ spider main board.	A complex setting indoor invironment ,whereas, close static abstacles are exist with different hights.	The system was allowed to detect and give institutions information to avoid all obstacles with different heights in front of the VI person. The user was able to follow the instructions that were provided.
7,8 &9	Outdoor using two camera modules, a Wi-Fi module, a music module. PIR module, Gyro, and compass. All were connected with a FEZ spider main board.	Very complex outdoor setting environments where different types of obstacles were exist.	The proposed aproach provided precise audio messages to avoid front abstacles with resoanable time frames.

TABLE 5. 3: TIME TABLE FOR EVACUATING THE PROPOSED COLLISION AVOIDANCE APPROACH WHILE PERFORMING A REAL-TIME SCENARIO

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, 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.

CHAPTER 6: EXPERMINTAL RESULTS, EVALUATION AND COMPARISION

The focus of this chapter is to present, analyze and evaluate the experimental results of our proposed collision avoidance algorithm, The framework provides an efficient and economically accessible device that assists VI people in navigating indoor and outdoor and detecting dynamic and static objects. An in-depth comparison between the performances of the various algorithms is carried in this chapter to assess the strengths and weaknesses of each approach.

6.1 Results and Analysis

Extensive real-time experiments were conducted to determine the achievement level of the proposed collision avoidance algorithm (obstacle avoidance) and whether it can provide the best performance in term of avoiding the static and dynamic obstacles by evaluating a number of real time experiments that were done indoor and outdoor. Different environmental settings were accommodated as well as the size, position and type of the obstacle. We are examining the performance and accuracy of the adopted sequence of the techniques we used to have an efficient detection algorithm. In order to have an accurate evaluation for our proposed collision avoidance algorithm, we needed to make sure that each obstacle is detected in order to issue the correct audio message. In other words, the performance of the detection algorithm can affect the collision avoidance algorithm's performance even if the collision avoidance algorithm is robust. Furthermore, Table 6.1 illustrates the results of examining the designed system for a video dataset of 30 videos. Each video has an average of 700 frames. The total number of samples in this dataset is 21,000 frame. This dataset contains different type, size and height of obstacles as well as it contains indoor and outdoor scenarios. The outdoor scenarios were very complex environment setting.

TABLE 6.1: THE STATIC AND DYNAMIC DETECTION ALGORITHM PERFORMANCE RESULTS

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%	100.00%	98.36%
		Average: 96.72%		
		Best: 100%		

The detection rate in the proposed framework was computed using the following formula:

$$Accuracy = \frac{TP + TN}{TP + FP + TN + FN} * 100 \qquad (1)$$

where TP, TN, FP, and FN are the number of true positive, true negative, false positive, and false negative detected objects and obstacles, respectively.

Accordingly, we present the accuracy based on the results of 30 the videos given in Table 6.1. We employed the static/dynamic objects detection algorithm on a sequence of videos, which considered a challenge for other systems. An average accuracy of 98.36% was achieved with a higher number of videos and a higher number of objects per frame. Since we cannot call each single object in the frame as an obstacle, therefore, we classified the type of the objects to two classes: class 1 is the objects that exist in the frame, but they do not intercept the user's path; we call it "Objects". Class 2 is the objects that in front of the user and they may collide with; we call it "Obstacles".

ORB does a great job in detecting the dynamic and static obstacles in front of the user even if the rotation exists; that leads to accuracy 100%. However, ORB performs less when the size of the objects gets too large in the frame. In other words, ORB starts to mismatch the objects between two frames when the objects approached the camera too close. Accordingly, the worst accuracy for detecting class 2 (objects type) was 85.71%, the average was 96.72% and the best performance was 100%.

Table 6.2 illustrates the experimental results of number of real-time scenarios that were conducted indoor and outdoor to evaluate the proposed collision avoidance algorithm (obstacle avoidance). For each scenario, Table 6.1 illustrates average number of frames, average number of obstacles, average number of detected obstacles, average number of avoided obstacles, obstacle detection rate, and collision avoidance rate. The resolution of GHI camera was 320×240 at 20 fps. The frames are sent to the remote server for an image processing and the responses are received in turn. An accuracy of 96.53% as detection rate and 100% as collision avoidance rate were obtained for the nine real-time scenarios with a small number of objects. Although ORB fails in detecting the too large sized obstacles in the frame, our proposed collision avoidance algorithm was able to provide the accurate navigational instructions to avoid the detected obstacles. Hence, the proposed collision avoidance algorithm was able to avoid 100% the detected obstacles. Thus, as long as the obstacle is detected, our proposed algorithm will able to provide the precise navigational information in order to avoid that obstacle. For example in scenario#5, we have 10 obstacles in the view, 9 only were detected by ORB. However, 9 obstacles were avoided by user based on the navigational message that user followed.

However, higher detection rate was obtained in Table 6.1 because we were using larger dataset with higher number of obstacles. This finding indicates that our algorithm adequately performs for crowded environments based on a large dataset. In order to navigate the blind user freely, it is important to the proposed systems to be able to accommodate and have full information about the obstacles' parameters such as: size, position, and distance. The systems was able to get the size and distance of the obstacle using the x-y coordinates system. We were able to get the size of each obstacle by measuring the lower corner of (x_{min1}, y_{min}) & (x_{min2}, y_{min}). The position of the obstacle was detected by the distance between the obstacle and threshold $\frac{1}{3}h$.

TABLE 6.2: ACCURACY AND EXPERIMENTAL RESULTS OF REAL-TIME SCENARIOS TO EVALUATE THE PROPOSED COLLISION AVOID ALGORITHM

Scenario	Average Number of Frames	Average Number of Objects	Average Number of Obstacles	Average Number of Detected Objects	Average Number of Detected Obstacles	Average Number of Avoided Obstacles per Video	Objects Detection Rate	Obstacles Detection Rate	Obstacles Avoidance Rate
scenario 1	288	36	20	32	20	20	88.89%	100%	100%
scenario 2	237	15	15	15	15	15	100.00%	100%	100%
scenario 3	862	50	15	44	15	15	88.00%	100%	100%
scenario 4	590	35	17	35	17	17	100.00%	100%	100%
scenario 5	300	32	10	31	9	9	96.88%	90%	100%
scenario 6	250	14	8	13	8	8	92.86%	100%	100%
scenario 7	410	39	18	39	18	18	100.00%	100%	100%
scenario 8	630	44	7	44	7	7	100.00%	100%	100%
scenario 9	280	20	11	18	10	10	90.00%	91%	100%
Detection Rate 96.53% Collision Avoidance Rate 100%									

Furthermore, the proposed collision avoidance approach was tested for their capabilities. In this experimental study, the folded blind user was tested to examine the proposed approach based on the obstacle characteristics. The main purpose was to determine whether the subject can detect and avoid the obstacles easily. The collected information was based on the obstacle's characteristics while the user was using the system. The results was collected manually. Table 6.3 demonstrates the rate of the detection and avoidance for the obstacles based on: object position to the threshold line, size of obstacle and distance between the user and obstacle within the scanning area (explained in chapter 5).

TABLE 6. 3: TEST RESULTS OF THE PROPOSED COLLISION AVOIDANCE APPROACH IN TERM OF THE CHARACTERISTICS OF OBSTACLES

Characteristics	Average Detection Rate	Average Collision Avoidance Rate
Position of the obstacles (top, bottom)	100%	100%
Position of the obstacle (left, right)	100%	100%
Distance	85%	85%
Size	97%	97%

The tested results that are presented in Tables 6.3 are the average percentage of the results that were obtained from the real-time scenarios. These results were collected based on all obstacles that existed in overall view even the ones are not detected. Therefore, we can find that 85% of the obstacles were detected and avoided by applying our proposed algorithm in term of distance parameter, whereas 15% were missed because they are very close to user in term of the camera view. Furthermore, the size of obstacle can affect the performance of the system if the obstacle is too large in which the camera cannot get most of the obstacle's corners. A 97% of the obstacles were detected in term of the size. Those 97% of the detected obstacles were avoided by applying the proposed collision avoidance approach. ORB is a detection algorithm that detects the corners' of objects. However, in most of the tested cases, the large sizes obstacles were not fully appeared in the camera view that makes it is hard to be detected. On the other hand, it is noticeable that all obstacles that in top, bottom, left and right were 100% detected and avoided.

In addition, Figure 6.1 represents a real-time outdoor scenario. Snapshots of some frames at different times were taken to show different outputs. Figure 6.2 shows a real-time indoor scenario that we recorded while the user employed the system. The figures illustrate 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 that were given through a headset within a reasonable time according to the user's report. The user mentioned that the device was light and easy to use, and the instructions were clear. User did not have any previous knowledge of the surrounding environment. This video was retaken and fed to the system directly after the experiment was done. It is just for demonstration purpose.

		
No obstacle within the range (go straight)	No change	Obstacle <3 m (move right)
		
Slight right then straight	Go straight	Move right

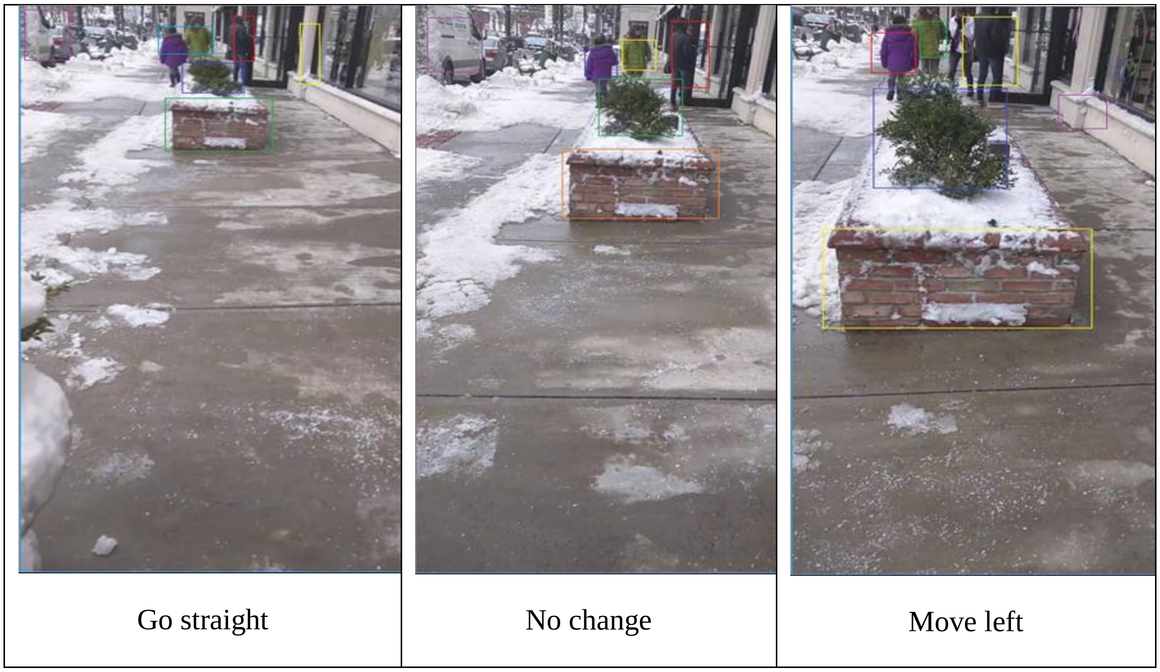


Figure 6.1: The proposed system applied to an outdoor real-time scenario

Figure 6.2: The proposed system applied to an indoor real-time scenario

Furthermore, in order to demonstrate the fuzzy rules which we implemented using C sharp programming language for the proposed approach. Before the implementation step, we used MATLAB in order to examine the proposed approach and the feedback that to be given to the user based on the fuzzy rules. Figure 6.3 illustrates one of the fuzzy rules examples using rules viewer. This figure demonstrates the case where the obstacle is in the left and middle sides; in addition, the obstacle is near (ObsRange = 201cm < threshold (300cm)) and the user is in the middle. Therefore, the given feedback was "Move Right " (Feedback value = 252).

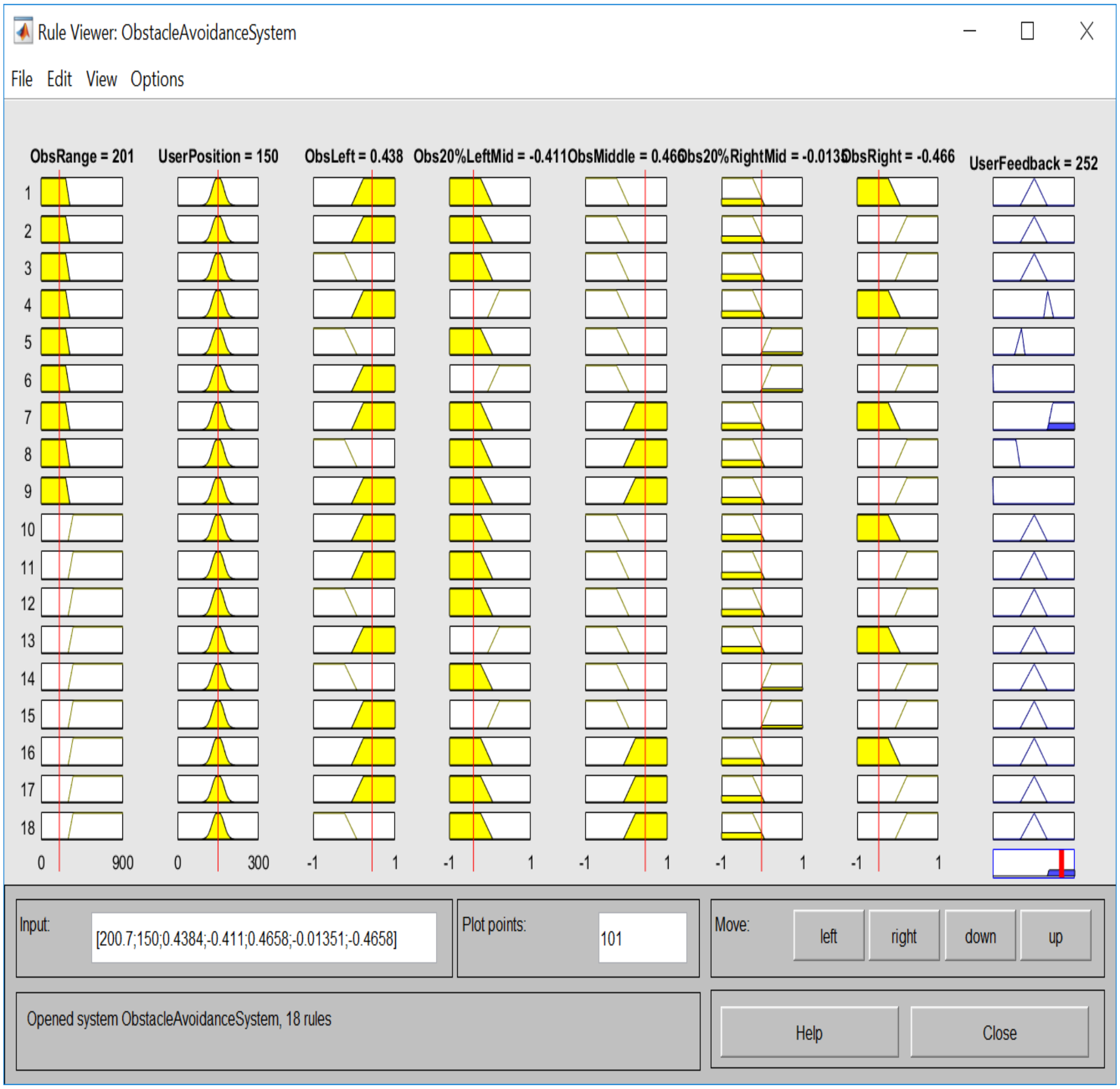


Figure 6. 3: An example of the Collision Avoidance approach at MATLAB's rules viewer.

As a result, Figure 6.4 illustrates the surface viewer that displays the boundary of the differences and combination of obstacle's range, obstacle's positions 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.

As shown in this figure, the user will go straight (purple color) as long as the obstacle is far (value > 300cm). The feedback will be various {SlightLeftStraight, GoStraight, SlightRightStraight, MoveLeft, MoveRight, and Stop} as the obstacle is within the first three meters ahead the user (threshold = 300cm) as termed as near.

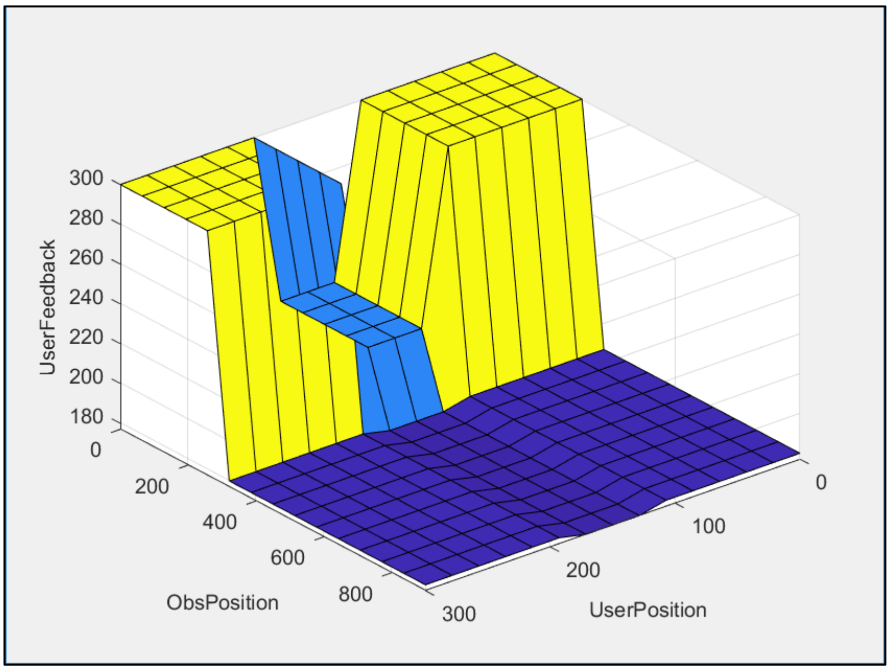


Figure 6. 4: The Surface Viewer that examines the output surface of an FIS for obstacle’s position and user’s position using fuzzy logic toolbox

6.2 The Evaluation of the Collision Avoidance Algorithm Performance

A collision avoidance or collision avoidance algorithm for visually impaired people should be reliable, and cost as little computational time as possible, require a short travel distance for a free path, and be economically accessible. Moreover, the main contribution of such an algorithm is to provide a fast response to ensure safe mobility for the user in crowded and complex environments with low economic and time costs.

Figure 6.5 demonstrates the performance of the collision avoidance system. The figure is a representation of nine scenarios to which the proposed system was applied. The first column (light blue) represents the average number of objects in each scenario; the orange column represents the average number of detected objects; the gray column is for the average number of front obstacles that the user may collide with; whereas, the average number of detected front obstacles is represented in the yellow column; and the dark blue column illustrates the average number of avoided obstacles that been detected.

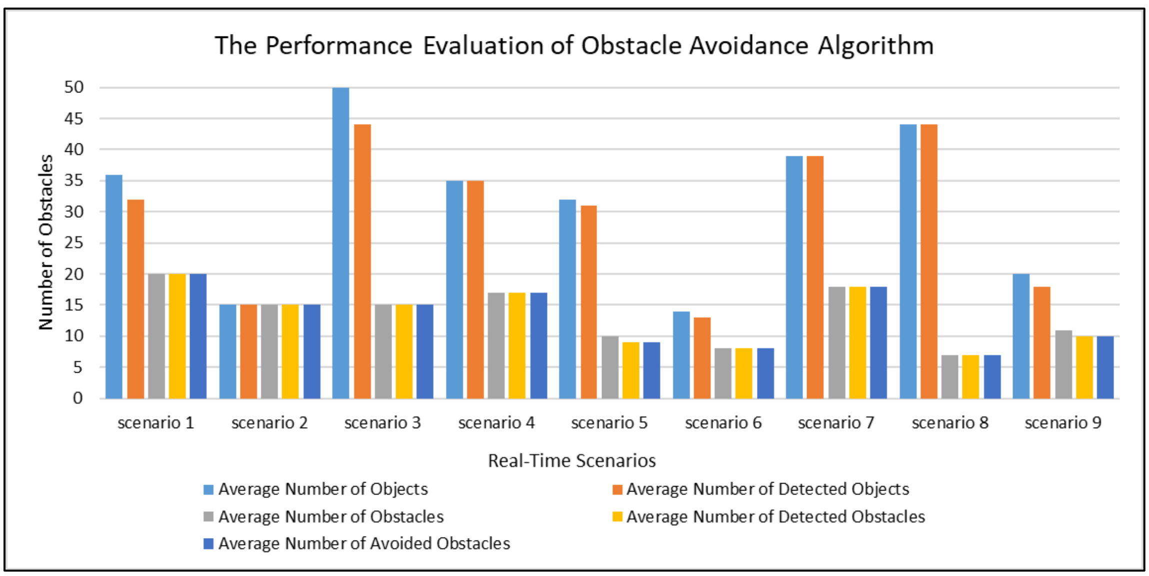


Figure 6.5: Performance evaluation of the collision avoidance system

For example, in scenario #1 we have 36 objects in that scenario as an average, however, 32 objects were detected; Out of this number we have 20 front obstacles which were all detected and avoided. The reason behind this mismatch in the detection, as was explained in chapter four, is the large size of some objects inside the frame. The results that presented by the dark blue column (representation of the collision avoidance approach's performance) indicates that the collision avoidance approach is 100% accurate in providing a free path to the user as long as the obstacle is detected.

Figure 6.6 illustrates the performance of the proposed collision avoidance approach that been applied on the detected obstacles. The figure represents the percentage of avoiding the obstacles that been detected for one of the tested scenarios that contains around 500 frames. The blue line represents the percentage of the detected obstacles and the orange line represents the percentage of avoided obstacles using the proposed approach. Both lines are overlapping each other, which indicates that the proposed collision avoidance algorithm is capable to avoid 100% detected obstacles. In general, the system has capability more than 90% in detecting and avoiding the obstacles that are in front of the user.

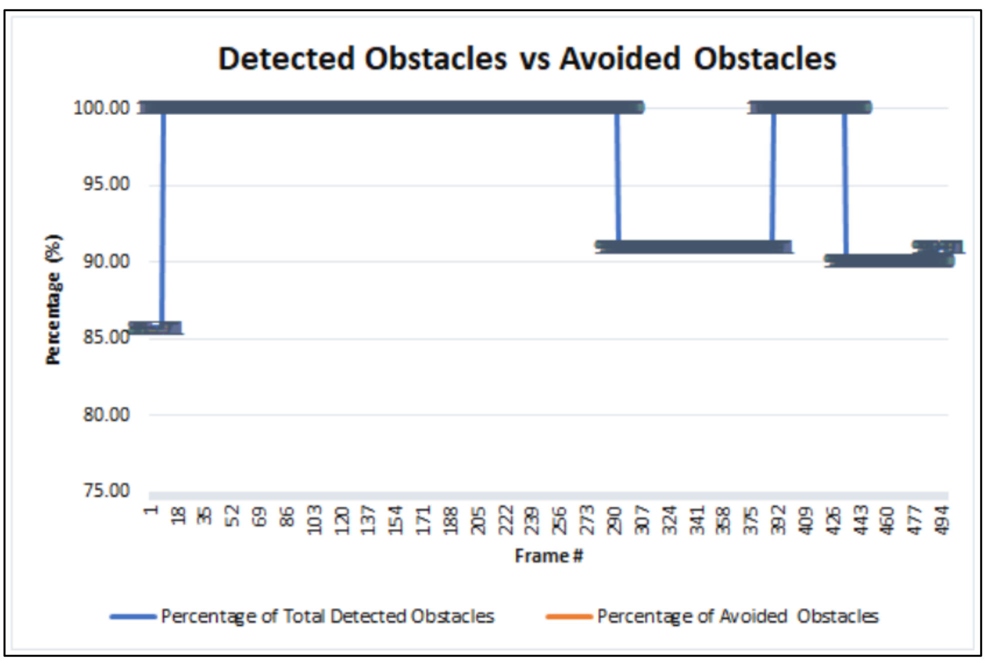


Figure 6. 6: Detected obstacles Vs avoided obstacles to evaluate the performance of the proposed approach

6.3 Algorithm Complexity Analysis

In computer science, the time complexity of any algorithm is measured based on the number of the operations that been performed and the number of inputs. In addition, there are three cases for the time complexity: best case, average case and worst case. Whereas, worst case is expressed by the big O notation. In this case, the result will be only the highest order of the polynomial functions [111, 112]. For instance:

Example	Cost	Times
i = 1;	C1	1
sum = 0;	C2	1
while (i <= n) {	C3	n+1
sum = sum + i;	C4	n
i = i + 1;	C5	n
}		

The total cost of abovementioned example is T(n) = c1 + c2 + c3 * (n + 1) + c4 * n + c5 * n. Therefore, the required time of this algorithm is proportional to n.

Our algorithm depends on the number of obstacles need to be avoided within the research area (scanning level) and the number of frames been processed per scenario. Consequently, in order to analyze our algorithm, we have grouped the average number of obstacles per frame. Since each detected object needs to be executed by the proposed algorithm, we have one-dimensional loops. The loop rotates up to the number of obstacles within the scanning level. The first part is for locating the obstacle and to measure each obstacles based on the x-y coordinating system. The second part is to provide the appropriate warning message to avoid the obstacle that in the middle area of the scanning level.

6.3.1 Time Complexity of Collision Avoidance Algorithm in Worst-Case

The worst case would be the maximum number of operations of the algorithm that have been executed for all the objects in term of for loop. Table 6.4 represents the calculation of time complexity for each statement in the worst-case. According to the Table 6.4 , the running time of the proposed algorithm is T(n) = 3 + 23n. Discarding the constant terms, we can conclude that the time complexity of our proposed algorithm is proportionally linear O(n).

To determine the complete computational time of the whole system, we added the time complexity of the detection algorithm and the time complexity of the collision avoidance algorithm. Most collision avoidance algorithms are applied after SIFT or SURF algorithms for object detection. Our collision avoidance approach is applied after the ORB algorithm for object detection, which requires less memory and computational time than other systems [93]. According to [113 and 114], the time complexity of the ORB algorithm is almost half of the time complexity of the SIFT and SURF algorithms.

TABLE 6. 4: TIME COMPLEXITY ANALYSIS OF THE PROPOSED COLLISION AVOIDANCE ALGORITHM

No of Statement	Statement	Running Time	Time Complexity
1.	rows ← firstFrame. Rows / 3	T(n) = 1	O(1)
2.	Xcorner1← 2 *firstFrame.cols / 5	T(n) = 1	O(1)
3.	Xcorner2 ← 3 * firstFrame.cols / 5	T(n) = 1	O(1)
4.	For (Objectsi) : NoObjects	T(n) = n	O(n)
5.	x ← objectsi.x	T(n) = n	O(n)
6.	y ← objectsi.y	T(n) = n	O(n)
7.	ymin ← y + objectsi.height	T(n) = 2n	O(n)
8.	xmax ← objectsi.x + objectsi.width;	T(n) = 2n	O(n)
9.	If (ymin >= rows && x >= Xcorner1 && xmax <= Xcorner2) Middle ← true	T(n) = n	O(n)
10.	Else if (ymin >= rows && xmax >= Xcorner2 && x<=Xcorner2) twentypercenttoright=Xcorner2-twenty	T(n) = 2n	O(n)
11.	If(x>=twentypercenttoright) MiddleRight← true	T(n) = n	O(n)
12.	Else if (ymin >= rows && xmax >= Xcorner1 && x<= Xcorner1) twentypercenttoleftt=Columnfourth+twenty	T(n) = 2n	O(n)
13.	If(xmax<=twentypercenttoleftt) MiddleLeft← true	T(n) = n	O(n)
14.	Else if (ymin >= rows && (xmax <= Xcorner1 && x<= Xcorner1)) Left ← true	T(n) = n	O(n)
15.	Else if (ymin >= rows && (x >= Xcorner1 && xmax>= Xcorner1)) Right← true	T(n) = n	O(n)
16.	If (Middle || MiddleLeft || MiddleRight)	T(n) = n	O(n)
17.	If (Middle || (MiddleRight && MiddleLeft))	T(n) = n	O(n)
18.	IF(!LEFT) Output: “move left "	T(n) = n	O(n)
19.	Else if (! Right) Output: "move right "	T(n) = n	O(n)
20.	Else Output: ”Stop”	T(n) = n	O(n)
21.	Else If(MiddleLeft && !MiddleRight) Output: ”slight right then straight”	T(n) = n	O(n)
22.	Else Output: ”slight left then straight”	T(n) = n	O(n)
23.	End For		

Hence, the time complexity of the overall system including the detection algorithm is $O(n^2)$ since two nested loops are needed to iterate into each frames. Although all the detection algorithms are quadratic, however, ORB is proportionally increased. We conclude that our overall system provides a faster and reliable collision avoidance system compared to traditional systems, and the fast collision avoidance system in this field is $O(nlogn)$ without the complexity of the detection algorithm system.

6.3.2 Time Analysis

The processing time is dependent on the resolution of the camera, and a higher resolution consumes a larger amount of time. Therefore, we chose a GHI camera module with a reasonable resolution to save time.

Table 6.5 represents the time required to process each frame depends on the number of objects. In addition, this table describes the actual time taken to detect obstacles, avoid obstacles and trigger the appropriate feedback in milliseconds. However, Figure 6.7 demonstrates the time required to run the detection/avoidance algorithm, establish the HTTP request and play the audio feedback. Thus, the complete processing time increases proportionally to the number of detected objects.

The cost of the time function was recoded for one of the real time scenarios over all the frames. There was around 35 objects in this scenario. The required processing time for one frame is 309.33ms. The serial camera used has a resolution of 320×240 at of 20 fps. In addition, the scenarios were done with remote server: Windows 7, core i7. Therefore, most of the consuming time is due to establishing HTTP and playing the audio message through the headphone. Using faster machine, the processing time can be reduced.

TABLE 6. 5: DEMONSTRATES THE TIME REQUIRED TO RUN THE DETECTION/AVOIDANCE ALGORITHM

Scenario	Average Number of Objects	Average Number of Obstacles	Average Number of Detected Objects	Average Number of Detected and avoided Obstacles	Processing Time for Detection and Avoidance Approaches
scenario 1	36	20	32	20	17.5 ms
scenario 2	15	15	15	15	18 ms
scenario 3	50	15	44	15	45 ms
scenario 4	35	17	35	17	26.66 ms
scenario 5	32	10	31	9	20 ms
scenario 6	14	8	13	8	16 ms
scenario 7	39	18	39	18	27 ms
scenario 8	44	7	44	7	32 ms
scenario 9	20	11	18	10	17 ms

Thus, our system is capable of processing more than three frames within a second, indicating that the proposed system is a real-time system that was effectively designed for pedestrians.

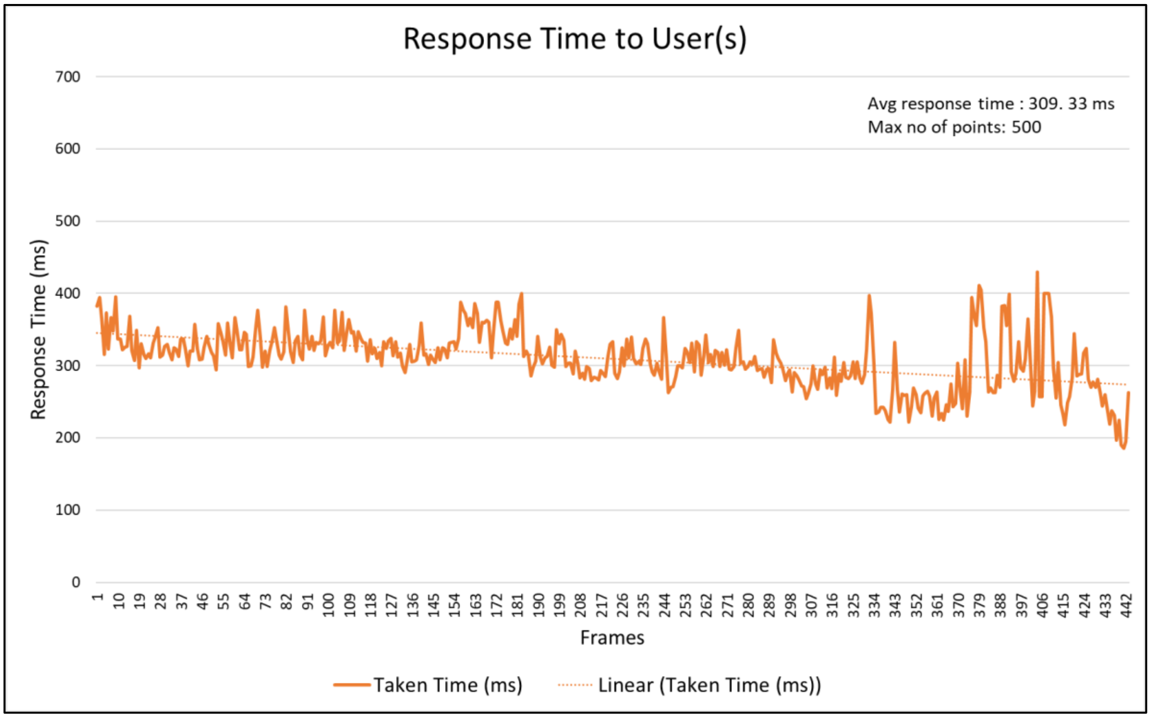


Figure 6. 7: The cost of the proposed collision avoidance approach as a time function

6.4 Comparison

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 6.6 presents a comparison of previous systems that were reviewed in section 3 and the proposed system; this comparison is based on the user's needs and the engineers' perspectives.

Table 6.6 focuses on the performance of the systems. The parameters in Table 6.6 were chosen based on our in-depth study [20]. 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 types of detected objects, the range of the detection, and the total accuracy of the system. Other parameters can be added to Table 6.6, and some of the listed parameters can be combined as requirements of both users and engineers.

However, the types of sensors and techniques that we discussed in chapter 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 [64]. The limited scope of radio frequency technology makes it less preferable in this field because the installation of tags is required in surrounding areas [65]. In addition, systems based on the Kinect sensor have a small detection range because the accuracy of the Kinect sensor decreases when the distance between the object and the camera increases [66, 67]. Changes in environmental parameters can have a significant effect on the performance of ultrasonic sensors [68]. Thus, ultrasonic sensors have a small detection range.

As shown in Table 6.6, some 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 requirements (Table 6.6). For instance, [22] does not provide indoor 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 sensor limitations and unpredictable behaviors due to the 'influence of the environment on these systems, which is usually unpredictable. Hence, systems that are based on computer vision technology can also have limitations.

Furthermore, we have surveyed numerous published articles, including articles that present the rules of O&M [115] for visually impaired people. All the published work agreed on one point: the guidance of the visually impaired requires precise instructions and accurate positioning, and systems must be economically accessible [115]. We have designed a system that integrates sensor-based and computer vision systems. The sequence of algorithms used (computer vision based) provides us with an efficient multi-object detection system. As we can locate the user's position and the coordinates of obstacles, the accurate positioning condition is applied.

Based on this study, O&M, the instructions, and the benchmark Table 6.6, we suggest that the proposed system stands outperforms other systems due to its features and the ability to satisfy the requirements of both the user and engineers. Notably, the proposed system provides high accuracy using both sensor-based technology and computer vision technology.

TABLE 6. 6: COMPARISON BETWEEN THE PROPOSED SYSTEM AND EXISTING SYSTEMS BASED ON THE USER'S NEEDS.

	System	User's Perspective					Engineer's Perspective			
		Cost	Weight	Real Time	Performance		Object Classification		Detection Range	Accuracy
					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	-
	[31]	-	-	✓	✓	-	✓	✓	0.8 m – 4 m	-
	[33]	-	-	-	-	✓	✓	✓	Short	-
	[34]	-	-	✓	✓	✓	✓	-	50 m – 60 m	-
	[35]	Low	Light	✓	✓	-	✓	✓	0.5 m–8 m	99% ± for object detection
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 (user position
	[49]	-	-	✓	✓	-	✓	-	1.5 m–4.0 m	-

	[50]	Low	-	✓	✓	✓	✓	-	Up to 10 m	High Accuracy
	[52]	Low	-	✓	✓	-	✓	-	> 3 m	95%
	[54]	Low	750 gram	✓	✓	✓	✓	✓	2 < R ≤ 5 m	-
	Proposed System	**$ 242.41**	**180 gram**	✓	✓	✓	✓	✓	**0 m < R <= 9 m**	**96.53%± 2 Detection rate , 98.36% for the data set ; 100% Obstacle Avoidance rate**

CHAPTER 7: CONCLUSION AND FUSTURE WORK

7.1 Conclusion

Collision avoidance topic has been a research focus in the wireless sensors and artificial intelligence field. In this dissertation, we presented a hardware and software implementation that provides a framework for a wearable device that can assist VI people. This device supports the user's mobility by detecting and avoiding any emerging obstacle on his/her path. 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-based and sensor-based technologies. This integration allows us to measure the obstacle's position and the user's position in order to provide the VI user a free path. In order to get accurate and precise information, we have used a fuzzy logic controller. Multiple membership functions for inputs and outputs were developed.

At the hardware level, the proposed system includes modules such as GPS, camera, compass, gyroscope, music, microphone, Wi-Fi, and a FEZ spider microcontroller.

The proposed measurement method enables us to 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 96.53%±2 for the static and dynamic detection system is achieved based on the proposed sequence of well-known algorithms. Our proposed collision 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 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 2.1, 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 it is easy to use and does not require previous knowledge (speech recognition and audio feedback for navigational instructions).

Wearable: based on our previous study and review [20], we made the proposed system to 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.

7.2 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. Thus, the average detection rate of the accuracy is 96.53%±2. The results presented in this dissertation show a significate improvement in the performance of the object detection and avoidance field. However, the above-mentioned issue related to the size of the objects in the frame, makes distinguishing between the foreground and the background difficult. Therefore, ultrasonic sensors can be an efficient solution for these type of objects. The ultrasonic module is a reliable source of obstacle detection that can measure distance between the user and object. Therefore, additional ultrasonic sensors will increase the accuracy. Further enhancements that can be considered in the future include:

- conduct an intensive study on the effect of the environmental parameters (e.g: light, rain, and speed of moving obstacles),
- design an App that analyzes the location of the user and allows the user to contact his/her relatives in any emergency, and
- add vibration motors to the framework in order to make it accessible to for people who are visually and hearing impaired.

REFERENCES

[1] World Health Organization, Visual Impairment and Blindness, Available online: http://www.who.int/mediacentre/factsheets/fs282/en/ (Accessed on June 2017).

[2] National Federation of the Blind, Available online: http://www.nfb.org/ (Accessed on January 2016).

[3] American Foundation for the Blind, Available online: http://www.afb.org/ (Accessed on January 2016).

[4] Velázquez, Ramiro. "Wearable assistive devices for the blind," In: Lay-Ekuakille A., Mukhopadhyay S.C. (eds) Wearable and autonomous biomedical devices and systems for smart environment, Lecture Notes in Electrical Engineering, Springer, Berlin, Heidelberg, vol.75, 2010, pp. 331-349.

[5] Marion Hersh, and Michael Johnson, eds. Assistive technology for visually impaired and blind people, Springer Science & Business Media, May 2010.

[6] Tiponut, Virgil, Daniel Ianchis, Mihai Bash, and Zoltan Haraszy. "Work directions and new results in electronic travel aids for blind and visually impaired people," In Proceedings of the 14th WSEAS international conference on Systems: part of the 14th WSEAS CSCC multiconference-Volume I, World Scientific and Engineering Academy and Society (WSEAS), 2010, pp. 347-352.

[7] Virgil Tiponut, Sorin Popescu, Ivan Bogdanov, and Catalin Caleanu, "Obstacles detection system for visually impaired guidance," WSEAS International

Conference, Proceedings. Mathematics and Computers in Science and Engineering, No. 12. WSEAS, 2008.

[8] Marion Hersh, “The Design and Evaluation of Assistive Technology Products and Devices Part 1: Design,” International Encyclopedia of Rehabilitation, CIRRIE: Buffal6+o, NY, USA, 2010.

[9] Hyun Kim, Sung Han, Jaehyun Park, and Joohwan Park "The interaction experiences of visually impaired people with assistive technology: A case study of smartphones," International Journal of Industrial Ergonomics 55, 2016, pp. 22-33.

[10] Dimitrios Dakopoulos, and Nikolaos Bourbakis "Wearable obstacle avoidance electronic travel aids for blind: a survey," IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews) 40.1, 2010, pp. 25-35.

[11] Laurent Renier, and Anne De Volder, "Vision substitution and depth perception: early blind subjects experience visual perspective through their ears," Disability and Rehabilitation: Assistive Technology 5.3, 2010, pp.175-183.

[12] Ruxandra Tapu, Bogdan Mocanu, and Ermina Tapu. "A survey on wearable devices used to assist the visual impaired user navigation in outdoor environments," Electronics and Telecommunications (ISETC), 2014 11th International Symposium on, IEEE, 2014, pp: 1-4.

[13] William Wiener, Richard Welsh, and Bruce Blasch. Foundations of orientation and mobility, Vol. 1, American Foundation for the Blind, 2010.

[14] Jin Liu, Jingbo Liu, Luqiang Xu, and Weidong Jin "Electronic travel aids for the blind based on sensory substitution," Computer Science and Education (ICCSE), 2010 5th International Conference on, IEEE, Hefei, China, 2010, pp. 1328-1331.

[15] Jaime Sánchez, and Miguel Elías, "Guidelines for designing mobility and orientation software for blind children," IFIP Conference on Human-Computer Interaction, Springer, 2007, pp. 375-388.

[16] René Farcy, Roger Leroux, Alain Jucha, Roland Damaschini, Colette Grégoire, and Aziz Zogaghi "Electronic travel aids and electronic orientation aids for blind people: Technical, rehabilitation and everyday life points of view," Conference & Workshop on Assistive Technologies for People with Vision & Hearing Impairments Technology for Inclusion, Vol. 12, 2006.

[17] Slim Kammoun, Marc Macé, Bernard Oriola, and Christophe Jouffrais, "Toward a better guidance in wearable electronic orientation aids," IFIP Conference on Human-Computer Interaction, Springer, Berlin, Heidelberg, 2011.

[18] Douglas Baldwin, "Wayfinding technology: A road map to the future," Journal of Visual Impairment and Blindness 97.10, 2003, pp. 612-620.

[19] Chirayu Shah, Mourad Bouzit, Meriam Youssef, and Leslie Vasquez. "Evaluation of RU-netra-tactile feedback navigation system for the visually impaired," Virtual Rehabilitation, 2006 International Workshop on, IEEE, 2006, pp. 72-77.

[20] Wafa Elmannai and Khaled Elleithy,"Sensor-based assistive devices for visually-impaired people: current status, challenges, and future directions," Sensors 17.3, 2017, p. 565.

[21] Mohd Wahab, Amirul Talib, Herdawatie Kadir, Johari, Ahmad Noraziah, Roslina Sidek, and Ariffin Mutalib., “Smart cane: Assistive cane for visually-impaired people,” IJCSI International Journal of Computer Science Issues, Vol. 8, Issue 4, No 2, 2011.

[22] Sachin Bharambe , Rohan Thakker, Harsharanga Patil, and Kishor Bhurchandi, “Substitute Eyes for Blind with Navigator Using Android,” In Proceedings of the India Educators Conference (TIIEC), Bangalore, India, 2013, pp. 38–43.

[23] Stanislav Vítek, Miloš Klíma, Libor Husník, and Daniel Spirk, "New possibilities for blind people navigation," 2011 International Conference on Applied Electronics (AE), Pilsen, Czech, 2011, pp. 1–4.

[24] Yiting Yi, and Lunfu Dong, "A design of blind-guide crutch based on multi-sensors,"12th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD), IEEE, Zhangjiajie, China, 2015.

[25] A. García, R. Fonseca, and A. Durán, "Electronic long cane for locomotion improving on visual impaired people. A case study," In 2011 Pan American Health Care Exchanges (PAHCE), Rio de Janeiro, Brazil, 2011.

[26] Krishna Kumar, Biswajeet Champaty, K. Uvanesh, Ripunjay Chachan, Kunal Pal, and Arfat Anis, “Development of an ultrasonic cane as a navigation aid for the blind people,” The 2014 International Conference on Control, Instrumentation, Communication and Computational Technologies (ICCICCT), Kanyakumari District, India, 2014.

[27] Benjamin, Jr JM, “The laser cane,” Bulletin of prosthetics research, 1973, pp.443-450.

[28] Aymaz, Şeyma, and Tuğrul Çavdar, “Ultrasonic Assistive Headset for visually-impaired people,” 39th International Conference on Telecommunications and Signal Processing (TSP), IEEE, Vienna, Austria, 2016.

[29] Larisa Dunai, Beatriz Defez Garcia, Ismael Lengua, and Guillermo Peris-Fajarnés, "3D CMOS sensor based acoustic object detection and navigation system for blind people," 38th Annual Conference on IEEE Industrial Electronics Society (IECON 2012), Montreal, QC, Canada, 2012.

[30] Jizhong Xiao, Kevin Ramdath, Manor Losilevish, Dharmdeo Sigh, and Anastasis Tsakas, "A Low Cost Outdoor Assistive Navigation System for Blind People," 8th IEEE Conference on Industrial Electronics and Applications (ICIEA), Melbourne, Australia, 2013, pp. 828–833.

[31] B. Prudhvi, and Rishab Bagani., "Silicon eyes: GPS-GSM based navigation assistant for visually-impaired using capacitive touch braille keypad and smart SMS facility," The 2013 World Congress on Computer and Information Technology (WCCIT), Sousse, Tunisia, 2013.

[32] Muhamad Saputra, , and Paulus Santosa, "Obstacle Avoidance for Visually-impaired Using Auto-Adaptive Thresholding on Kinect's Depth Image," The IEEE 14th International Conference on Scalable Computing and Communications and Its Associated Workshops (UTC-ATC-ScalCom), Bali, Indonesia, 2014.

[33] Firas Jassim, and Fawzi Altaani, "Hybridization of Otsu Method and Median Filter for Color Image Segmentation," Int. J. Soft Comput. Eng, 2013, pp. 69–74.

[34] Oliveira, João Fradinho, "The path force feedback belt," 2013 8th International Conference on Information Technology in Asia (CITA), Kuching, Malaysia, 2013.

[35] Martinez-Sala, Alejandro Santos, Fernando Losilla, Juan Carlos Sánchez-Aarnoutse, and Joan García-Haro, "Design, Implementation and Evaluation of an

Indoor Navigation System for Visually-impaired People," Sensors, 15, 2015, pp. 32168–32187.

[36] Lukas Everding, Lennart Walger, Viviane Ghaderi, and Jörg Conradt, "A mobility device for the blind with improved vertical resolution using dynamic vision sensors," The 2016 IEEE 18th International Conference on e-Health Networking, Applications and Services (Healthcom), Munich, Germany, 2016.

[37] Viviane Ghaderi, Marcello Mulas, Vinicius Felisberto Santos Pereira, Lukas Everding, David Weikersdorfer, and Jörg Conradt, "A wearable mobility device for the blind using retinainspired dynamic vision sensors," In Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE, IEEE, 2015, pp. 3371-3374.

[38] Elias Mueggler, Christian Forster, Nathan Baumli, Guillermo Gallego, and Davide Scaramuzza, "Lifetime estimation of events from Dynamic Vision Sensors," 2015 IEEE International Conference on Robotics and Automation (ICRA), Seattle, WA, USA, 2015.

[39] N. Owano, Dynamic Vision Sensor Tech Works Like Human Retina, Available, http://phys.org/news/2013–08-dynamic-vision-sensor-tech-human.html, (Accessed on August 13, 2016).

[40] Thanh Nguyen, Thi Nguyen, Thi Le, Thi Tran, Nicolas Vuillerme, and Tan Vuong, "A wearable assistive device for the blind using tongue-placed electrotactile display: Design and verification," The 2013 International Conference on Control, Automation and Information Sciences (ICCAIS), Nha Trang, Vietnam, 2013.

[41] Thanh Nguyen, Thi Le, Thi Tran, Nicolas Vuillerme, and Tan Vuong, "Antenna Design for Tongue electrotactile assistive device for the blind and visually-impaired," 7th European Conference on Antennas and Propagation (EuCAP), Gothenburg, Sweden, 2013, pp. 1183–1186.

[42] Clemens Icheln, Joonas Krogerus, and Pertti Vainikainen, "Use of balun chokes in small-antenna radiation measurements," IEEE Trans, Instrum, Meas, 2004, pp. 498–506.

[43] Mohammad Saaid, Ismarani Ismail, and Mohd Noor, "Radio frequency identification walking stick (RFIWS): A device for the blind," 5th International Colloquium on Signal Processing & Its Applications, Kuala Lumpur, Malaysia, 2009.

[44] Mark Harrison, Duncan McFarlane, Ajith Parlikad, and Chien Wong. "Information management in the product lifecycle-the role of networked RFID," 2nd IEEE International Conference on Industrial Informatics (INDIN'04), Berlin, Germany, 2004.

[45] Daniel Ahlmark, Håkan Fredriksson, and Kalevi Hyyppä., "Obstacle Avoidance Using Haptics and a Laser Rangefinder," The 2013 IEEE Workshop on Advanced Robotics and its Social Impacts (ARSO), Tokyo, Japan, 2013.

[46] SenseGrapics AB, Open Source Haptics—H3D.org, http://www.h3dapi.org/ (accessed on 18 June 2013).

[47] Greg Olmschenk, Christopher Yang, Zhigang Zhu, Hanghang Tong, and William H. Seiple., "Mobile crowd assisted navigation for the visually-impaired," In Ubiquitous Intelligence and Computing and 2015 IEEE 12th Intl Conf on

Autonomic and Trusted Computing and 2015 IEEE 15th Intl Conf on Scalable Computing and Communications and Its Associated Workshops (UIC-ATC-ScalCom), 2015 IEEE 12th Intl Conf on, IEEE, 2015, pp. 324-327.

[48] Christopher White, David Bernstein, and Alain L. Kornhauser, "Some map matching algorithms for personal navigation assistants," Transportation research part c: emerging technologies, 8(1), 2000, pp.91-108.

[49] Adrien Brilhault, Slim Kammoun, Olivier Gutierrez, Philippe Truillet, and Christophe Jouffrais, "Fusion of artificial vision and GPS to improve blind pedestrian positioning," 4th IFIP International Conference on New Technologies, Mobility and Security (NTMS), Paris, France, 2011, pp. 1–5.

[50] Arnaud Delorme, and Simon Thorpe, "SpikeNET: An event-driven simulation package for modelling large networks of spiking neurons," Network: Computation in Neural Systems, 14, no. 4, 2003, pp. 613–627.

[51] Jack Loomis, Reginald Golledge, Roberta Klatzky, Jon Speigle, and Jerome Tietz., "Personal guidance system for the visually-impaired," In Proceedings of the First Annual ACM Conference on Assistive Technologies, Marina Del Rey, CA, USA, 1994.

[52] Adán Landa-Hernández, and Eduardo Bayro-Corrochano, "Cognitive guidance system for the blind," World Automation Congress (WAC), Puerto Vallarta, Mexico, 2012.

[53] Ruxandra Tapu, Bogdan Mocanu, and Titus Zaharia, "A computer vision system that ensure the autonomous navigation of blind people," The IEEE E-Health and Bioengineering Conference (EHB), Iasi, Romania, 2013.

[54] Ruxandra Tapu, B. Mocanu, and Titus Zaharia, "Real time static/dynamic obstacle detection for visually impaired persons," The 2014 IEEE International Conference on Consumer Electronics (ICCE), Las Vegas, NV, USA, 2014.

[55] Aitor Aladren, Gonzalo López-Nicolás, Luis Puig, and Josechu Guerrero, "Navigation assistance for the visually impaired using RGB-D sensor with range expansion," IEEE Syst. J., 10, 2016, pp. 922–932.

[56] Nahum Kiryati, Yuval Eldar, and Alfred Bruckstein, “A probabilistic Hough Transform,” Pattern Recogn, 24, 1991, pp.303–316.

[57] Bogdan Mocanu, Ruxandra Tapu, and Titus Zaharia, "When ultrasonic sensors and computer vision join forces for efficient obstacle detection and recognition," Sensors, 16, 2016, p. 1807.

[58] Adisorn Sirikham, Werapon Chiracharit, and Kosin Chamnongthai, "Banknote and coin speaker device for blind people," Advanced Communication Technology, 2009 ICACT. 11th International Conference on, Vol. 3. IEEE, 2009, pp. 2137–2140.

[59] Larisa Dunai, Mónica Pérez, Guillermo Peris-Fajarnés, and Ismael Lengua, "Euro banknote recognition system for blind people," Sensors, 17, 2017, pp. 184.

[60] Roy Shilkrot, Jochen Huber, Connie Liu, Pattie Maes, and Suranga Chandima Nanayakkara, "FingerReader: a wearable device to support text reading on the go," In CHI'14 Extended Abstracts on Human Factors in Computing Systems, ACM, 2014, pp. 2359-2364.

[61] Suranga Nanayakkara, Roy Shilkrot, Kian Yeo, and Pattie Maes, "EyeRing: a finger-worn input device for seamless interactions with our surroundings," In

Proceedings of the 4th Augmented Human International Conference, ACM, 2013, pp. 13-20.

[62] Alan Black, and Kevin Lenzo, "Flite: a small fast run-time synthesis engine," 4th ISCA Tutorial and Research Workshop (ITRW) on Speech Synthesis, Perthshire, Scotland, 2001.

[63] Ray Smith, "An overview of the Tesseract OCR engine," Document Analysis and Recognition, ICDAR 2007, Ninth International Conference on, Vol. 2, IEEE, Paraná, Brazil, 2007, pp. 629–633.

[64] Photonics, H. Characteristics and use of Infrared Detectors, https://www.hamamatsu.com/resources/pdf/ssd/infrared_kird9001e.pdf, Solid State Division, (Retrieved 12 February 2004).

[65] Luke McCathie, "The advantages and disadvantages of barcodes and radio frequency identification in supply chain management," University of Wollongong: Wollongong, NSW, Australia, 2004.

[66] Michael Andersen, Thomas Jensen, Pavel Lisouski, Anders Mortensen, Mikkel Hansen, Torben Gregersen, and Peter Ahrendt, "Kinect depth sensor evaluation for computer vision applications," Technical Report Electronics and Computer Engineering, Vol 1, No (6), 2012.

[67] Laurindo Neto, Felipe Grijalva, Vanessa Maike, Luiz Martini, Dinei Florencio, Maria Baranauskas, Anderson Rocha, and Siome Goldenstein, "A kinect-based wearable face recognition system to aid visually impaired users," IEEE Transactions on Human-Machine Systems 47(1), 2017, pp. 52–64.

[68] AIRMAR, Tech. Overview for Applying Ultrasonic Technology (AirducerTM Catalog). www.airmar.com; 2011, (Accessed on June 2016).

[69] Marco Pieralisi, Valerio Petrini, Valentina Mattia, Giovanni Manfredi, Alfredo Leo, Lorenzo Scalise, Paola Russo, and Graziano Cerri, "Design and realization of an electromagnetic guiding system for blind running athletes," Sensors 2015, 15, pp.16466–16483.

[70] Marco Pieralisi, Valentina Mattia, Valerio Petrini, Alfredo Leo, Giovanni Manfredi, Paola Russo, Lorenzo Scalise, and Graziano Cerri, "An Electromagnetic Sensor for the Autonomous Running of Visually-impaired and Blind Athletes (Part I: The Fixed Infrastructure)," Sensors, 17, 2017, p. 364.

[71] Florian Dramas, Simon Thorpe, and Christophe Jouffrais, "Artificial vision for the blind: a bio-inspired algorithm for objects and obstacles detection," International Journal of Image and Graphics, 10(04), 2010, pp. 531-544.

[72] Roman Vlasov, Karl-Ingo Friese, and Franz-Erich Wolter, "Haptic rendering of volume data with collision determination guarantee using ray casting and implicit surface representation," In Cyberworlds (CW), 2012 International Conference on, IEEE, 2012, pp. 91-98.

[73] Nikolaos Bourbakis, Robert Keefer, Dimitrios Dakopoulos, and Anna Esposito, "A multimodal interaction scheme between a blind user and the tyflos assistive prototype," In Tools with Artificial Intelligence, ICTAI'08, 20th IEEE International Conference on, Vol. 2, 2008, pp. 487-494.

[74] David Calder, “Travel aids for the blind-The digital ecosystem solution,” In Industrial Informatics, INDIN 2009, 7th IEEE International Conference on, IEEE, 2009, pp. 149-154.

[75] Pawel Strumillo, “Electronic interfaces aiding the visually impaired in environmental access, mobility and navigation,” In Human System Interactions (HSI), 2010 3rd Conference on, IEEE, 2010, pp. 17-24.

[76] Slim Kammoun, Florian Dramas, Bernard Oriolaand, and Christophe Jouffrais. “Route selection algorithm for Blind pedestrian,” In Control Automation and Systems (ICCAS), 2010 International Conference on, 2010, pp. 2223-2228.

[77] Kris Koiner, Haytham Elmiligi, and Fayez Gebali, “GPS Waypoint Application,” In Broadband, Wireless Computing, Communication and Applications (BWCCA), 2012 Seventh International Conference on, 2012, pp. 397-401.

[78] Manh Le, Son Phung, and Abdesselam Bouzerdoum, “Pedestrian lane detection for assistive navigation of blind people,” In Pattern Recognition (ICPR), 2012 21st International Conference on, 2012, pp. 2594-2597.

[79] Christophe Jacquet, Yacine Bellik, and Yolaine Bourda, “Electronic Locomotion Aids for the Blind: Towards More Assistive Systems,” In Intelligent Paradigms for Assistive and Preventive Healthcare. vol. 19, N. Ichalkaranje, A. Ichalkaranje, and L. C. Jain, Eds., ed: Springer Berlin Heidelberg, 2006, pp. 133-163.

[80] Chucai Yi, and Yingli Tian, “Assistive text reading from complex background for blind persons,” Camera-Based Document Analysis and Recognition, 2012, pp. 15-28.

[81] Amiya Tripathy, Avanish Pathak, Amruta Rodrigues, and Charu Chaudhari. "VIMPY — A Yapper for the visually impaired," In Information and Communication Technologies (WICT), 2012 World Congress on, IEEE, 2012, pp. 167-172.

[82] Rémi Parlouar, Florian Dramas, Marc Macé, and Christophe Jouffrais, "Assistive device for the blind based on object recognition: an application to identify currency bills," Presented at the Proceedings of the 11th international ACM SIGACCESS conference on Computers and accessibility, Pittsburgh, Pennsylvania, USA, 2009.

[83] John Black, and David Hayden, "The Note-Taker: An assistive technology that allows students who are legally blind to take notes in the classroom," In Computer Vision and Pattern Recognition Workshops (CVPRW), 2010 IEEE Computer Society Conference on, IEEE, 2010, pp. 1-8.

[84] David Hayden, Liqing Zhou, Michael Astrauskas, and John Black Jr, "Note-taker 2.0: the next step toward enabling students who are legally blind to take notes in class," Presented at the Proceedings of the 12th international ACM SIGACCESS conference on Computers and accessibility, Orlando, Florida, USA, 2010.

[85] Pelin Angin, Bharat Bhargava, and Sumi Helal, "A Mobile-Cloud Collaborative Traffic Lights Detector for Blind Navigation," In Mobile Data Management (MDM), 2010 Eleventh International Conference on, 2010, pp. 396-401.

[86] Vladimir Kulyukin, and Aliasgar Kutiyanawala, "From ShopTalk to ShopMobile: vision-based barcode scanning with mobile phones for independent blind grocery shopping," In Proceedings of the 2010 Rehabilitation Engineering and Assistive

Technology Society of North America Conference (RESNA 2010), Las Vegas, NV, 2010.

[87] Boris Schauerte, Manel Martinez, Angela Constantinescu, and Rainer Stiefelhagen, "An assistive vision system for the blind that helps find lost things," Computers Helping People with Special Needs, 2012, pp. 566-572.

[88] Florian Dramas, Bernard Oriola, Brian Katz, Simon Thorpe, and Christophe Jouffrais, "Designing an assistive device for the blind based on object localization and augmented auditory reality," Presented at the Proceedings of the 10th international ACM SIGACCESS conference on Computers and accessibility, Halifax, Nova Scotia, Canada, 2008.

[89] Chucai C Yi, Roberto Flores, Ricardo Chincha, and YingLi Tian, "Finding objects for assisting blind people," Network Modeling Analysis in Health Informatics and Bioinformatics, 2013, pp. 1-9.

[90] Roberto Manduchi, "Mobile vision as assistive technology for the blind: an experimental study," Computers Helping People with Special Needs, 2012, pp. 9-16.

[91] Wafa Elmannai and Khaled Elleithy, "A Highly Accurate and Reliable Data Fusion Framework for Guiding the Visually Impaired," Vol (6), IEEE Access 2018, pp. 33029 - 33054.

[92] G.H.I Electronics, Catalog | .NET Gadgeteer - GHI Electronics. Available:http://www.ghielectronics.com/catalog/category/265/, 2016.

[93] Ethan Rublee, Vincent Rabaud, Kurt Konolige, and Gary Bradski, "ORB: An efficient alternative to SIFT or SURF," In Computer Vision (ICCV), 2011 IEEE international conference on, IEEE, 2011, pp. 2564-2571.

[94] Edward Rosten, and Tom Drummond, "Machine learning for high speed corner detection," In European Conference on Computer Vision, volume 1, 2006, pp.430-44.

[95] Michael Calonder, Vincent Lepetit, Christoph Strecha, and Pascal Fua, "BRIEF: Binary Robust Independent Elementary Features," In Proc. of the Europ, Conf, on Computer Vision (ECCV), 2010.

[96] Paul Rosin, "Measuring corner properties," Computer Vision and Image Understanding, 73(2), 1999, pp.291 – 307.

[97] Liang Zhang, Peiyi Shen, Guangming Zhu, Wei Wei, and Houbing Song, "A Fast Robot Identification and Mapping Algorithm Based on Kinect Sensor," Sensors, 15(8), 2015, pp.19937-19967.

[98] Lei Yu, Zhixn Yu, and Yan Gong, "An Improved ORB Algorithm of Extracting and Matching Features," International Journal of Signal Processing, Image Processing and Pattern Recognition, 8(5), 2015, pp.117-126.

[99] Vinay A., Avani Rao, Vinay Shekhar, Akshay Kumar, KN Balasubramanya Murthy, and S. Natarajan, "Feature Extraction using ORB-RANSAC for Face Recognition," Procedia Computer Science, 70, 2015, pp.174-184.

[100] George Klir, , and Bo Yuan, "Fuzzy sets, fuzzy logic, and fuzzy systems," selected papers by Lotfi A. Zadeh, NJ: World Scientific Publishing Co., Inc, 1996.

[101] Pedro Albertos, Antonio Sala, and Manuel Olivares. "Fuzzy Logic Controllers. Methodology. Advantages and Drawbacks," Dept. de Ing. de Sistemas y Automatica, Universidad Politecnica de Valencia, 1998.

[102] Wafa Elmannai, and Khaled Elleithy, "A novel obstacle avoidance system for guiding the visually impaired through the use of fuzzy control logic," In Consumer Communications & Networking Conference (CCNC), 2018 15th IEEE Annual, IEEE, 2018, pp. 1-9.

[103] Microsoft. (May 5, 2016), Home - Gadgeteer. Available: http://www.netmf.com/gadgeteer/

[104] http://ghielectronics.com/catalog/product/297 (Accessed on 1/26/2016)

[105] http://ghielectronics.com/catalog/product/283(Accessed on 1/26/2016)

[106] http://ghielectronics.com/catalog/product/323 (Accessed on 1/26/2016)

[107] http://ghielectronics.com/catalog/product/325 (Accessed on 1/26/2016)

[108] http://ghielectronics.com/catalog/product/331(Accessed on 1/26/2016)

[109] http://ghielectronics.com/catalog/product/317 (Accessed on 1/26/2016)

[110] http://ghielectronics.com/catalog/product/357 (Accessed on 1/26/2016)

[111] Allen, Weiss Mark. Data Structures and Algorithm Analysis in C++, Pearson Education, India, 2007.

[112] https://www.sitepoint.com/time-complexity-algorithms/ (Accessed on 12/10/2017)

[113] Antonio Canclini, Matteo Cesana, Alessandro Redondi, Marco Tagliasacchi, João Ascenso, and R. Cilla. "Evaluation of low-complexity visual feature detectors and descriptors," Digital Signal Processing (DSP), 2013 18th International Conference on, IEEE, 2013.

[114] Lian Yang, and Zhangping Lu, "A new scheme for keypoint detection and description," Mathematical Problems in Engineering, 2015.

[115] Michele Williams, Amy Hurst, and Shaun Kane, "Pray before you step out: describing personal and situational blind navigation behaviors," ASSETS '13: In Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility, ACM, 2013, p. 28.