Divyawear- A Wearable Haptic Cueing System for the Visually Impaired Indian People

Keyur D. Joshi, Nakshatra Maheshwari, Harsh Patel, Priyam A. Parikh
School of Engineering and Applied Science, Ahmedabad University, Ahmedabad, India
Institute of Design, Nirma University, Ahmedabad, India

ABSTRACT

This research investigates the conception and assessment of an innovative smart vest engineered to augment the mobility and autonomy of individuals with visual impairments. Recognizing the inherent limitations of conventional aids like canes and guide dogs, which often impede navigation in intricate environments, this study proposes a smart vest integrating advanced technologies, including 3-D cameras, LiDAR, and vibration motors. The system aims to furnish real-time environmental perception and directional guidance through haptic feedback, thereby mitigating the constraints associated with existing assistive devices. The paper details the design and development of two prototypes, DW-1 and DW-2, emphasizing the technical implementation of object detection algorithms (YOLOv8), distance measurement methodologies, and predefined vibration patterns for conveying environmental cues. Rigorous empirical evaluation across diverse navigational scenarios, encompassing linear trajectories, turns, and obstacle avoidance, demonstrated the efficacy of both prototypes in facilitating user navigation, with the DW-2 variant exhibiting superior performance attributed to its enhanced sensor suite. A comprehensive review of the extant literature contextualizes the advancements in assistive technologies and delineates the specific research lacunae addressed by this investigation. The findings of this study underscore the significant potential of intelligent wearable systems to enhance the quality of life for visually impaired individuals, thereby highlighting the imperative for continued scholarly inquiry and the refinement of such technological interventions.

Keywords

Visually impaired Indians, smart jacket, machine learning, YOLO algorithm, wearable technologies

1. INTRODUCTION

The World Health Organization (WHO), classifies visual impairment into five categories, spanning from mild vision loss to total blindness or no light perception. As per their report [1], at least 2.2 billion people in the world are victims of visual impairment. According to International agency for the prevention of blindness (IAPB), 270 million people in India are suffering from some type of vision loss in 2020 [2]. Therefore, at least 12% of the people out of all the visual impaired people from the world are Indians. India has large community suffering from the vision related problems. A report from National Program for Control of Blindness and Vision Impairment (NPCBVI) undertook two age groups: the first consists of an age range from 0 to 49 years, and the second consists of an age range from 50 or more years under consideration for their survey. The survey was carried out to provide evidence about the present status of blindness and visual impairment in India. The report further classified eight levels of vision impairment for the second age group. In this age group, the percentage of people with all eight visual impairment categories was found to be 54.99 % after examining 85,135 individual people from 31 districts with a response rate of 91.5% in the survey [3]. Vision loss can affect people of all ages; however, most people with vision impairment and blindness are over the age of 50 years [4]. Targets were set for two major eye care treatments: 1) effective cataract surgery coverage (eCSC), and 2) effective refractive error coverage (eREC) to be achieved by 2030 during the seventy-third World Health Assembly in 2020 [5]. This was due to the huge unmet need for eye care.

Assistive technology involves the practical application of knowledge and expertise in the development and utilization of assistive products, encompassing both devices and supportive services. An assistive product refers to any external item, such as devices, equipment, tools, or software, designed or commonly accessible, with the primary aim of enhancing an individual's functioning and autonomy, thus contributing to their overall well-being. Additionally, assistive products serve to forestall impairments and mitigate the onset of secondary health issues. WHO's definition of assistive product refers to the improvement of an individual's functioning and independence to promote their well-being; while ISO definition refers to support for body functions and activities [6]. Accessibility, affordability, adaptability, availability, acceptability, and quality are principles of assistive technology access [7]. The Rapid Assistive Technology Assessment (rATA) by WHO is a population-based survey to measure need, demand, supply, and barriers to accessing assistive technology. In twenty-nine rATA surveys, they have selected five functional domains: cognition, communication, hearing, seeing, and self-care. The survey participants reported at least some difficulties with the listed functional domains. Seeing was the functional domain where the majority of the participants reported having some difficulties. At the global level, more than 2.5 billion people need at least one assistive product. By 2050, it is estimated that more than 3.5 billion people will need assistive technology due to several reasons including the aging global population and the rise in noncommunicable diseases [7]. Moreover, the report suggests that many countries have people who need assistive technology but do not have access to it.

Individuals with visual impairments face a multitude of obstacles, frequently necessitating assistance from others especially in unknown areas exploration. This reliance can evoke feelings of vulnerability, especially in unfamiliar environments. Traditional mobility aids such as canes and guide dogs offer limited support and may not adequately address the complex navigation needs of visually impaired individuals. Smart vests have the potential to address these limitations by leveraging advanced sensor technologies, tactile feedback mechanisms, and integration with navigation systems to provide real-time environmental information and guidance.

There has been some work in this direction. As will be shown in the next section, little research has been done on preparing torso-based vests for aid in India. Smart vests represent a promising solution to enhance mobility and independence by providing real-time environmental feedback and navigation assistance. By researching smart vests, the objective was to improve quality of life and promote greater independence for individuals with visual impairments. This work was aimed at exploring the effectiveness and usability of smart vests as assistive devices for visually impaired individuals, with a focus on improving the processes of navigation, obstacle detection, and spatial awareness. The concept of torso-based vests is not new. It has roots in research from the year 1998 [8]. For navigator assistance without the involvement of another human with normal vision, the amount of information that can be received without the visual system is less than that of the visual system.

A preliminary meeting with representatives of the Blind People's Association (BPA), Ahmedabad, India suggested the researchers have prepared smart shoes and smart sticks to help the needy, however, the cost of such wearables is much higher for them to take advantage of. Therefore, one of the central ideas behind this research was to look for a cost-effective solution that would be feasible for the common man. This work was set out to address information transformation from the environment to the user through attentional and directional cues such as various patterns of vibrations. A multi-model interface would be designed to combine the inputs from sensors. A camera in the torso-based system would sense the environment and provide output to the user to assist the user's movement. This output can be indicative of the type of obstacles in front of the user if that is the case. The Light Detection and Ranging instrument (LiDAR) would work toward maintaining a safe distance from the obstacles. Multiple actuators would work in sync with each other providing output patterns discernable by the user. The vibratory motors fixed at predesigned locations on a vest would provide output in a pre-defined pattern for cueing. The work carried out revolved around the idea of promoting well-being and supporting navigator activities for visually impaired people.

2. RELATED WORKS

2.1 Historical Perspective

More than two decades ago, Ertan et al (1998) proposed haptic navigation guidance system where they have used infrared transceivers to detect current position and haptic display for the directional feedback to the user [8]. There has been increased interest in haptic-based research afterwards. Tan et al (2003) worked on attentional and directional cueing. They realized after a set of experiments that the correct haptic cue lead to reduced reaction time for the user action whereas wrong haptic cue lead to increased reaction time [9]. Nakamura and Jones (2003) proposed an actuator for tactile vest based on shape memory alloys [10]. Lindeman et al (2004) researched on haptic feedback for virtual reality considering two types of touch: sliding and pushing/pulling. They worked towards full body haptic feedback for the user in virtual reality [11]. Jones et al (2004) used vibration motors and shape memory alloys as tactile inputs to the torso-based vest. They discussed in the paper what can be said as the ideal sensors for the said purpose and recommended stretchable fabric for the vest material [12].

The next decade after [12], went through active research in the domain of skin stretch feedback device, haptic interface for psychotherapeutic treatment, haptic hug to enhance social interactivity, haptic vest, ultrasonic sensors for object detection and enriching story listening experience with the help of vest providing haptic feedbacks [13-21]. Garcia-Valle et al (2016) controlled vibration motors with Lilypad Arduino and pulse width modulation signals after attaching the motors with the wearable vest. The output of their project was good in which the experimental subjects followed the same path as the original designated path for the test [22]. In the next year, same authors have implemented collision and temperature simulation for the user wearing the vest to interact in virtual environment. Choi (2017) presented comparison of range-based sensors and concluded that it is important to sense data by using multiple types of active sensors because passive sensors provide unreliable data [23]. Pacchierotti et al (2017) provide a thorough review of haptic systems. They summarized that wearable haptics have a strong role in cutaneous haptics that brings out the current technologies to wider commercial market in near future [24]. A nice survey of literature is found in Sorgini et al (2017) who reviewed papers related with the haptic sensory substitution for deaf, blind and deaf-blind individuals. They concluded that the aim for future researches would be the improvement of the haptic assistive technologies for sensory disabled population [25]. Further, they wrote that portability, ease of handling, intuitiveness and low invasiveness are the key features for the development of such assistive systems. Ahlmark (2016) explored the virtual white cane and LaserNavigator options as haptic navigation aids for the visually impaired [26].

Durrant-white and Bailey (2006) suggested that implementation of an introductory version of simultaneous localization and mapping known as SLAM was possible using the combination of depth camera and tracking sensor [43]. Although SLAM is aimed to be used by a mobile robot, a vest can be understood as a smart device that is capable of locating itself in the map prepared by it. This could generate a valuable understanding of the unknown environment where a user has to spend most of the time. In other words, the visually impaired user already has a preliminary understanding of the environment, similarly, the vest could also have some understanding about the environment.

2.2 Summary of Reviewed Literature

Upon review of the literature, it was concluded that despite India constituting a significant amount of the world's vision-impaired population, little research has been carried out on assistive systems providing haptic cueing from the multimodal interface. While considerable research exists on utilizing sensors for obstacle detection, no known efforts have combined this technology with vision sensors for assisting purposes. The scholarly literature lacks significant contributions concerning haptic vests designed to offer assistance to visually impaired individuals. Additionally, a gap is evident in the available literature regarding cueing patterns tailored to the specific needs of Indian users.

2.3 Rationale of Divyawear-Smart Vest

Majority of haptic products are used in virtual reality to provide user the feelings that mimic realistic behavior. For example, Woojer ltd, USA Inc. uses a patented technology of oscillated frame actuators the use of which would provide an optimal combination of tactile sensation, size, and weight. Vest -3 is one product from Woojer ltd [39], that can be used for at-home gaming, movies, VR, and music by using the Haptic feedback originating from six independently operating oscillators placed strategically within the vest. Teslasuit, a product from VR Electronics, UK, is a full-body haptic motion capture suit. It uses probabilistic models from sensor data to detect exercise errors in real-time providing immediate haptic feedback to correct movements [40]. With nine haptic feedback devices across the entire body, Holosuit enables people to experience, capture, and replay real, virtual, and augmented experiences [41]. Merkel Haptic Systems, a research and development company that develops haptics-enabled virtual reality technologies for healthcare simulation [42]. This company deals with healthcare simulations using virtual reality systems and haptic feedback technology in India. Unfortunately, in India, such products do not exist partly due to the lower population segment of gaming. Moreover, the use of such devices for gaming is not a necessity because it is considered a luxury in the context of the Indian region. However, for visually challenged people, such devices would help in increasing their confidence levels.

3. METHODOLOGY

The work started with the design of the vest. Figure 1 shows pencil sketch for the very basic prototype of the system showing just the array of the vibration motors fixed on front, back, left and right side of torso-based vest. The sketch shows array of vibratory actuators only as the correct position of the remaining sensor was not decided at that stage. Moreover, the sketch assumed an array of 5x12 dimensions on both front and back sides. The front side of the vest must collect the information from environment so as to assess the current situation. The work comprised preparing prototypes for testing out the performance and applicability for the intended use. The earlier prototypes had inputs in the form of ultrasonic sensors, and output in the form of vibration actuators. In this work, inputs were LIDAR sensor, 3-D camera; and outputs were vibration motors accordingly. Two prototypes DW-1 and DW-2 in this paper where the front side was reserved to accommodate input sensors. Only the backside was used to place the vibration sensors.

The patterns on which the vibration actuators vibrate can be generated thoughtfully and by turning some actuators on/off at a predetermined frequency. Some of the patterns can be suited for cueing the wearer about certain situations. After identifying the cueing patterns, the vest can call predefined patterns at an appropriate time when required. The result should be useful as haptic feedback to the system wearer. It was hypothesized that the combination of the input sensors could provide information to help the user. Incorporating such inputs and outputs in/onto a wearable torso-based vest would mean that the user has both hands free without any restriction as to the movements. This is an advantage over the guiding cane type of assisting device, where one hand will be used to hold the cane. In a meeting with a visually impaired person, there was a suggestion that providing a choice to the user on which type, color, and size of the vest one can wear would be a positive sign. Another suggestion was that the vest has to be user-friendly, lightweight, and flexible.

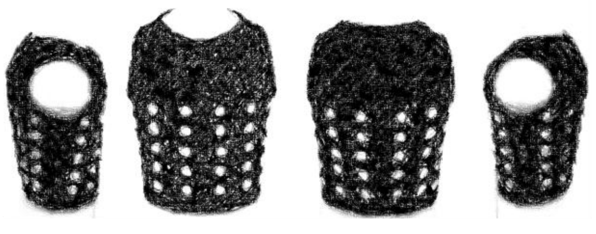

Fig 1: Pencil sketch of the four views (left, front, back, and right) for a wearable vest with white dots representing vibratory motors

3.1 Haptic Vest Fabric Material

Material selection is crucial for wearable technology design due to its significant impact on user comfort. Integrating electronics into smart garments can affect wearability. This research aims to minimize the electronics and maximize the wearability. Wearable devices utilize various natural and synthetic textiles, but achieving all desired properties like lightweightness, breathability, strength, stretch, water resistance, softness, and affordability in one material is unlikely. Therefore, the selection process prioritizes materials with the most beneficial attributes. A thorough comparison of fabric types [45-47] was conducted, considering subjective factors like comfort through a generalized framework. For example, cotton, silk, chiffon, polyester, and spandex are lightweight. A point-based system was used to rank fabrics for the vest, with cotton being identified as the most suitable for initial prototypes, as shown in Table 1. Later, a cotton-spandex blend was found to offer improved comfort and was chosen for DW-1 and DW-2.

While searching for the actual fabric for the prototype, Ankur textiles which is a division of Arvind Ltd understood the need of the project and provided fabric for the prototypes. If a fabric is given without tag that has listed the composition materials in percentage, it is not easy to identify the constituting materials in percentage. Moreover, the electrical resistance of the material needed to be known as the vest contained electronic parts to serve the purpose.

A very basic version of the prototype- the vest was prepared using a t-shirt comprising of 100% cotton fabric [48]. In next prototype, the lizzy bizzy fabric material, also known as PV fabric was used. This material had composition of 67% cotton and 33% polyester fabric type. The addition of the polyester increased the strength, a slight reduction in comfortability was noticed as the vest was less breathable [49]. The fabric of the next prototypes (DW-1 and DW-2) contained different percentages of cotton and spandex mixtures Table 2 provides fabric compositions and electrical resistance. For blend analysis and finding the value of electric resistance of a given

Table 1: Eleven fabric types and their comparison

#	Fabric type	Strong, durable	Lightweight	Affordable	Soft -smooth	Comfortable	Water resistant	Cruel to animals	Breathable	Rank
1	Cotton	✓	✓	✓	✓	✓	x	x	✓	1
2	Silk	✓	✓	x	✓	✓	x	✓	x	4
3	Linen	✓	✓	x	x	✓	x	x	✓	3
4	Denim	✓	x	x	✓	✓	x	x	✓	7
5	Satin	✓	x	x	✓	✓	✓	x	x	9
6	Chiffon	x	✓	x	✓	✓	x	x	✓	6
7	Velvet	x	x	x	✓	✓	x	✓	x	8
8	Leather	x	x	x	x	x	x	✓	x	11
9	Wool	x	x	x	✓	x	x	✓	✓	10
10	Polyester	✓	✓	✓	x	x	x	x	x	5
11	Spandex	✓	✓	x	✓	✓	x	x	✓	2

Table 2: Vest fabric properties for prototypes

Details	Blend Analysis Material Composition			Electric Resistance (MΩ)	Weight of prototype (Kg)
	Cotton (%)	Spandex (%)	Polyester (%)		
DW-1	98.1	1.9	0	77 & 77	1.22
DW-2	98.5	1.5	0	117 & 723	1.47

fabric, the samples were given to Ahmedabad Textiles Industries Research Association (ATIRA) lab for testing purposes. The material composition values shown in Table 2 are the result of the test method specified by standard IS 3416, on a dry basis. The resistance values listed Table 2 were determined using the testing protocol outlined in the standard EN 1149-1. This procedure involves placing the sample on an insulating base plate, applying a group of electrodes to the sample, and then subjecting it to a continuous current to measure its surface resistance. The two values specified for electric resistance in the table for Pv3, Pv4, and Pv5 refer to the outer layer (first value) and the inner layer (second value) on which the electronic components were stitched. The weight of both the prototypes was more from the user perspective, included battery, camera, vibration motors vest fabric with one inner layer, Jetson Nano, connecting wires for circuit, and LIDAR. This could be further optimized.

3.2 Development of DW-1 and DW-2

3.2.1 Need of Vision Sensor

The primary advantage of incorporating cameras into smart vests is the ability to capture high-resolution visual data in real-time. This visual information can be used for a variety of purposes, including object detection, and identification. For example, vest without vision sensor would only provide information that there is an obstacle on the way, whereas the vision sensor would provide information on the type of the obstacle. This additional information could be useful for the wearer. Cameras are capable of capturing a wide range of visual information, from simple shapes and colors to complex scenes and actions. This flexibility allows smart vests with vision sensors to be used in diverse applications, such as deciding if left/right/front movement would be possible without collision, and some hints on types of obstacles if present through haptic feedback on unexplored areas. Furthermore, a 3-D camera provide distance between user and obstacle which will be essential factor in deciding if the user's movement will be collision free. By processing the input data from camera, smart vests can extract valuable insights and provide personalized feedback to users. For instance, user can select one of the patterns available in the list (discussed in next subsection) for emergency situations where a collision is imminent. Table 3 shows the component list for the two prototypes.

3.2.2 DW-1 Prototype

Figure 2 shows the DW-1 prototype. The core components of DW1 include a 3D camera from Intel (D435i), vibration motor clusters, Nvidia Jetson nano, and power supply with the necessary connecting wires. Nvidia Jetson nano was selected for object detection and identification along with the help of the camera. A 20,000 mAh power bank was used to supply power to all electronic components. This was kept in a pocket, on the front side of the prototype.

Table 3: Component list of the two prototypes

#	Details of major components	Qty in DW-1	Qty in DW-2
1	Cam-1: Intel D435i camera	1	0
2	Cam-2: Intel D455 camera	0	1
3	DC vibration motor modules	20	30
4	TF-Mini-S LIDAR module	0	1
5	Inner layer from pure cotton	0	1
6	Jetson nano module with its carrier board	1	1
7	Fan & heat sink for Jetson nano module carrier board	1	1
8	Battery: Power bank 20K mAh	1	1

The core of the object detection and identification system was Yolo v8, that identified the objects through the camera. To enhance performance and reduce latency, the Python code was optimized with TensorRT. This optimization process minimized inference time, addressing the challenge of real-time object detection. Initially, the system was tested with a limited set of objects to reduce the load on the Jetson Nano's GPU. This approach helped in optimizing the code and conserving energy. The vest was designed with an average size to accommodate a wide range of users. Velcro straps were included to allow for adjustable sizing, ensuring a proper fit for various body types. The camera was mounted vertically rather than horizontally. This orientation was chosen as an experiment to check for a better view. This DW-1 was tested by multiple users and the results are discussed in next section

3.2.3 DW-2 Prototype

Figure 3 shows the DW-2 prototype. The transition from DW1 to DW2 introduced significant improvements in several key areas. The core components of DW2 include a 3D camera from Intel (D455), a LIDAR, more vibration motor clusters, Nvidia Jetson nano, and power supply with the necessary connecting wires. The D455 camera offered a wider field of view as compared with D435i, providing a more comprehensive environment scan. In this prototype, the camera was repositioned horizontally within the vest, situated below the LIDAR. The horizontal orientation was selected because it provided better view compared with the vertical orientation. The LIDAR was used as a necessary redundancy, for help in situations when the camera malfunctions.

The object detection and identification technique remain the same as with the DW-1. There were two improvements in user experience: 1) fabric and comfort: The fabric used in DW2 is thinner than that in DW1. This reduction in thickness enhances haptic feedback, allowing users to experience more precise sensations and 2) size and adjustability: The size of DW2 has been slightly increased to accommodate a wider range of users while maintaining adjustability through Velcro strips. The length of the strips was increased for a proper fitting. The Velcro strips engage from back to front, easier for the user to wear the prototype. This change ensures that the device fits comfortably and securely on various body types.

Fig 2: DW-1 prototype; front-back-left-right side views of user 1 (a-d) and user 2 (e-h) wearing DW-1, internal layer of the vest showing vibration motors, connecting wires, and Jetson Nano (i)

Fig 3: DW-2 prototype; front-back-left-right side views of user 1 (a-d) and user 2 (e-h) wearing DW-2, internal layer of the vest showing vibration motors, connecting wires, and Jetson Nano (i)

3.3 Vibration Patterns

The vibration patterns were designed in a way that is easy to understand and not very surprising to the user. The user can quickly feel the different vibration patterns if the patterns are simple enough. There should not be too many patterns that can confuse the user

3.3.1 Vibration Patterns amongst Prototypes:

The vibration pattern in prototype DW-1 has been meticulously designed to ensure that users can effortlessly identify the vibration at different positions. Each cluster, comprising four strategically connected vibration motors, delivers a distinct and precise vibration sensation, enhancing the overall user experience. In DW-1, there are a total of five clusters, amounting to 20 vibration motors. This configuration was hypothesized to provide comprehensive and nuanced feedback. The clusters were arranged in a "+" formation for optimal coverage and effectiveness. One cluster is positioned at the top, three are centrally located, and one is at the bottom. This thoughtful arrangement ensures that the vibrations are distributed evenly and can be distinctly felt across the designated areas. The placement strategy not only enhances the functionality but also demonstrates the commitment to providing an intuitive and responsive user interface.

As shown in Figure 4, six vibration patterns were designed for six detected classes of the obstacle in front of the user. The six classes were: person, laptop/TV, chair, table, bottle, and bench. According to the different nearest objects present in front of the user, we had assigned different patterns that can work as a cue.to the user. The dark color of the cluster means that the vibration motors in the cluster are on. In another words, the cluster is excited. In the first vibration pattern, the leftmost cluster excited; and in the second pattern (Fig. 4a), the right-most cluster excited (Fig. 4b). For the third pattern, the uppermost, bottom and the middle cluster excited simultaneously, making a vertical line pattern (Fig 4c). The fourth pattern, where the 3 clusters present at the middle excited, making it a horizontal pattern (Fig. 4d). The fifth pattern where the uppermost cluster excited (Fig 4e), and in the sixth pattern all the clusters excited simultaneously (Fig 4f). The sixth pattern kept as an alert to the user about possible collision in near future.

The patterns in DW-2 were uniquely designed to offer users an enhanced and differentiated tactile experience. Specific vibration motors were meticulously assigned to distinct clusters to achieve this. DW-2 features a total of seven clusters, each configured to provide a unique vibration pattern. Three of these clusters were arranged with four vibration motors each, forming a "+" sign. This arrangement ensured that vibrations are felt uniformly and distinctly at the points where the motors are positioned. Two additional clusters, also with four vibration motors each, are configured in a horizontal line, delivering a consistent and linear vibration pattern. This horizontal arrangement is particularly effective for applications requiring a broader distribution of vibrations across a single axis. Furthermore, DW-2 includes two clusters with five vibration motors each. These clusters are designed to create more complex patterns: one forms a clockwise tilted 'T,' while the

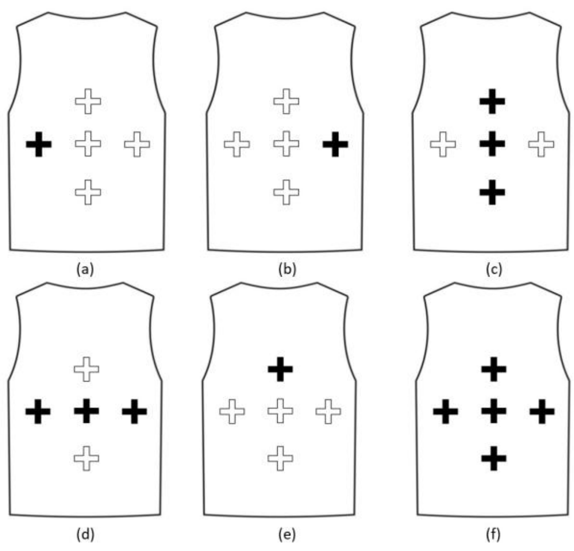

Fig. 4: Six vibration patterns for DW-1 (a-f)

other forms an anti-clockwise tilted 'T.' This innovative configuration provides a sophisticated and varied tactile response, enhancing the overall user interaction with the device. The diverse patterns and strategic placement of the vibration motors in DW-2 were hypothesized to provide a better user experience.

Figure 5 shows six vibration patterns. The first pattern was assigned to the clusters on the right side of the device. This included one cluster configured in a "+" sign pattern and another cluster arranged in a clockwise tilted 'T' formation. This strategic placement ensured that the right-side vibrations were easily identifiable and distinct (Fig. 5a). The second pattern was designated for the clusters on the left side. It comprised of one cluster with a "+" sign pattern and another cluster with an anti-clockwise tilted 'T' formation. This arrangement provided a balanced and symmetrical tactile experience, complementing the right-side pattern (Fig 5b). The third pattern focused on the clusters located in the middle of the device, forming a vertical line. This vertical alignment ensured a consistent and linear vibration sensation, ideal for applications requiring central feedback (Fig. 5c).

The fourth pattern is assigned to the topmost clusters and an additional cluster in the middle. This combination creates a dynamic vibration experience, integrating the upper and central parts of the device for a cohesive tactile response (Fig. 5d). The fifth pattern is designated for all the clusters at the bottom of the device. This configuration ensures that the lower part of the device delivers a concentrated and uniform vibration sensation, enhancing the overall user interaction (Fig. 5e). Finally, the sixth pattern included all the clusters, causing the entire device to vibrate simultaneously (Fig. 5f). This comprehensive approach ensured a robust and immersive tactile experience, fully engaging the user with the device's feedback system. Each pattern has been thoughtfully designed and strategically assigned to specific clusters to provide a rich and varied tactile experience the RealSense pipeline.

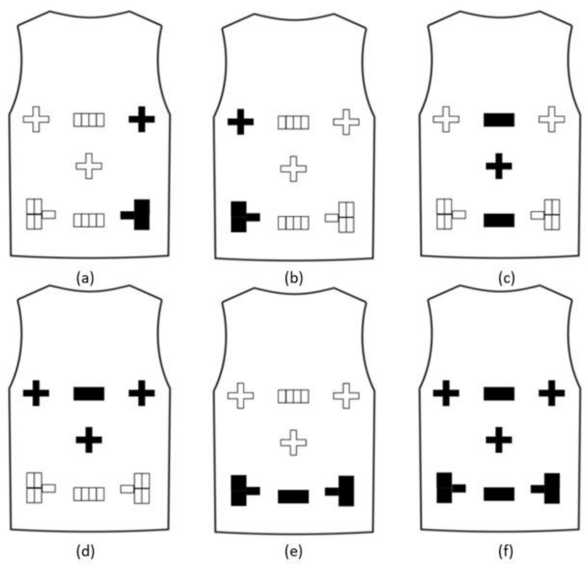

Fig. 5: Six vibration patterns for DW-2 (a-f)

3.4 Code Summary

Figure 6 shows the flowchart of the process followed by DW-2 prototype. For DW-1 prototype, the flowchart remains the

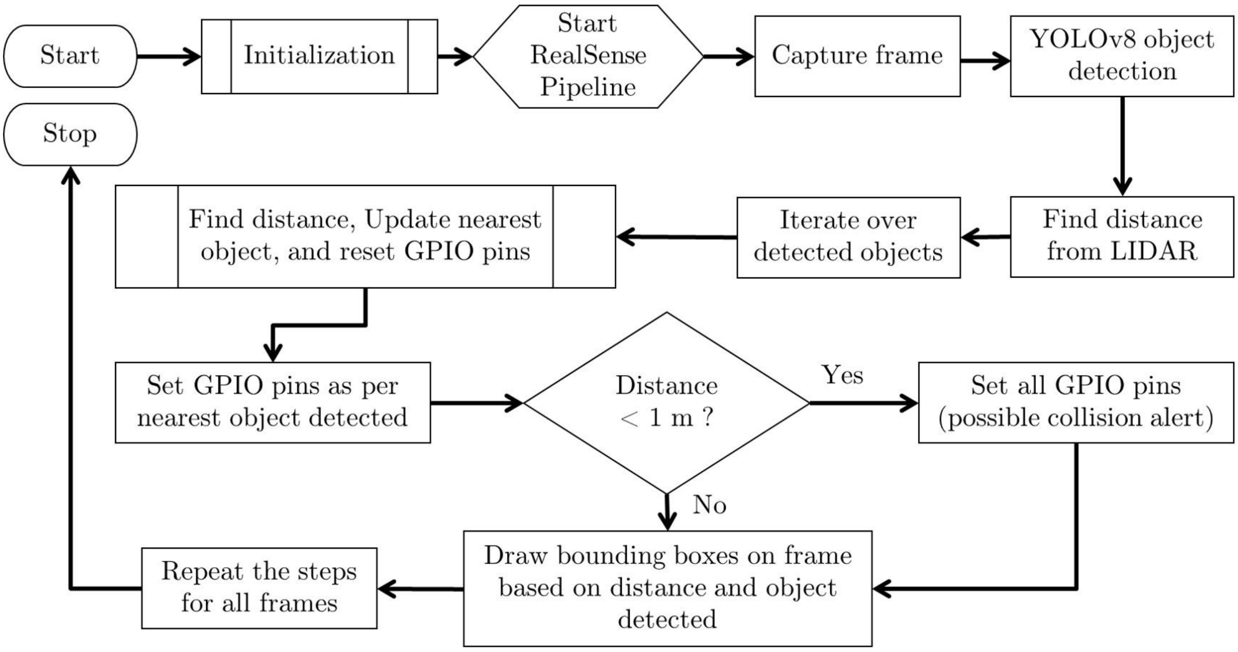

Fig. 6: Flowchart of the process for DW-2 prototype

same; however, LIDAR was not incorporated with it. For the DW-1 prototype, following is the outline of the code. First, import the necessary libraries for computer vision, numerical operations, RealSense camera, YOLO model, GPIO control, serial communication, and time management. Then, load the YOLOv8 model for object detection. Define GPIO output pins and group them into specific sets for different control logic, and define lists of stationary and semi-stationary objects for classification purposes. Set up GPIO pins for output and initialize them to a LOW state, and define the camera matrix and distortion coefficients for camera calibration. Set the object size at the reference distance. Initialize video capture for the camera, start the RealSense pipeline, and configure it to capture depth and color streams. Initialize the depth scale for the RealSense camera to measure distance. Enter an infinite loop to continuously read frames from the camera. Get frame dimensions, perform object detection on the current frame using the YOLO model, and get frames from the RealSense pipeline. Check if depth and color frames are available; if not, continue to the next iteration. Initialize variables to store the nearest object's label and its minimum distance. Iterate over detected objects, get the bounding box coordinates and object label, calculate the distance of the detected object using the depth frame, and update the nearest object and its distance if the current object is closer.

After that, reset all GPIO pins to a LOW state, and set specific GPIO pins to HIGH based on the nearest object detected. Draw the object label and its distance on the frame, draw the bounding box around the detected object with a color indicating its distance, and print the nearest object's label and its distance. Display the frame with detected objects and distance information. Exit the loop if the user presses the 'q' key, and release the video capture and destroy all OpenCV windows when exiting the loop.

For DW-2 following is the code outline. First, import the necessary libraries for computer vision, numerical operations, RealSense camera, YOLO model, GPIO control, serial communication, and time management. Then, load the YOLOv8 model for object detection. Define GPIO output pins and group them into specific sets for different control logic, and define lists of stationary and semi-stationary objects for classification purposes. Initialize a serial connection to communicate with the LiDAR sensor, set up GPIO pins for output, and initialize them to a LOW state. Define the camera matrix and distortion coefficients for camera calibration, and set the object size at the reference distance. Next, initialize video capture for the camera, start the RealSense pipeline, and configure it to capture depth and color streams. Initialize the depth scale for the RealSense camera to measure distance. Enter an infinite loop to continuously read frames from the camera, get frame dimensions, perform object detection on the current frame using the YOLO model, and get frames from the RealSense pipeline.

Check if depth and color frames are available; if not, continue to the next iteration. Initialize variables to store the nearest object's label and its minimum distance. Iterate over detected objects, get the bounding box coordinates and object label, calculate the distance of the detected object using the depth frame, and calculate the distance using data from the LiDAR sensor. Update the nearest object and its distance if the current object is closer. Reset all GPIO pins to a LOW state, and set specific GPIO pins to HIGH based on the nearest object detected. If the LiDAR distance is less than 15 units (0.5 meters), set all GPIO pins to HIGH. Draw the object label and its distance on the frame, draw the bounding box around the detected object with a color indicating its distance, and print the nearest object's label and its distance. Display the frame with detected objects and distance information. Finally, exit the loop if the user presses the 'q' key, and release the video capture and destroy all OpenCV windows when exiting the loop.

3.5 Prototype Testing

To evaluate the performance of the DW1 and DW2 prototypes, three distinct types of test tracks were developed; each designed to simulate various conditions and progressively challenge the prototypes. These test tracks are shown in Fig.7 (design) and Fig.8 (actual). The first track was straight, without any turns. The second track involved one mandatory turn while the third track had two possible turns, near the end of the track.

Test Track Type A is a straightforward straight-line track designed to assess the basic detection capabilities and control performance of the prototypes. Level I: The track was a simple straight path with a wall at the end. The objective was to determine whether a prototype can detect the wall from a safe distance. Level II: Stationary obstacles, including a table, chair, and a human, are introduced along the path. This level evaluated how well the prototypes can detect and navigate around these obstacles to reach the end of the track. Level III: A semi-stationary human, who intermittently moves, was introduced in along halfway of the track. This setup tested the prototypes' ability to adapt to moving obstacles while maintaining accurate detection and control.

Test Track Type B features an L-shaped track with a sharp right turn to examine the prototypes' capability to handle directional changes and navigate through a more complex path. Level I: The track is empty except for the turn itself. The goal is to see if a prototype can detect the wall and navigate. Level II: Stationary obstacles, including a table, chair, and a human, were placed along the track and near the turn. This level assessed the prototypes' performance in detecting and avoiding these obstacles while making the turn. Level III: Semi-stationary humans who move intermittently were introduced, to increase complexity and test the prototypes' ability to handle dynamic conditions.

Test Track Type C represented the complex scenario, featuring a T-shaped track with two possible turns. Level I: The track is a T-shape with no obstacles, focusing on basic navigation through the turns. Level II: Stationary obstacles, including a table, chair, and a human, were introduced. This setup evaluated the prototypes' ability to detect obstacles, choose the correct route, and navigate effectively. Level III: The track included humans and other moving obstacles, and hence created a highly dynamic environment. This level tested the prototype’s advanced detection capabilities, and responsiveness.

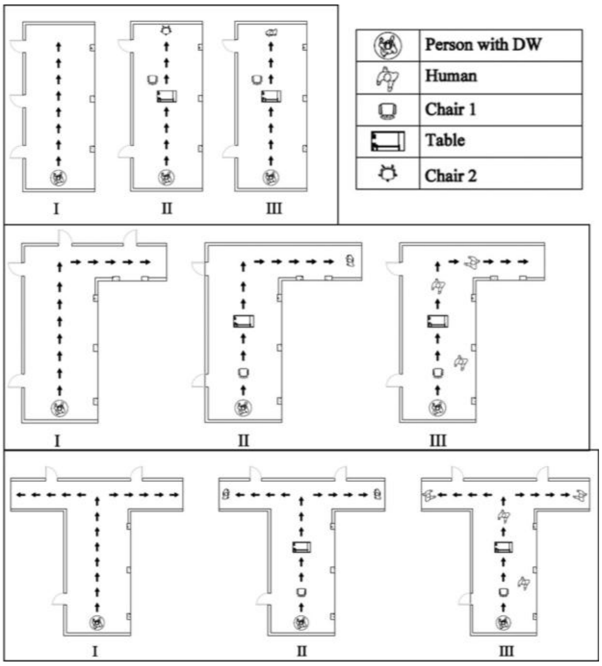

Fig.7: I (top), inverted L (middle) and T (bottom) shaped testing tracks design, the three Roman numerals show increased level of difficulty (I, II, and III) in terms of the objects encountered

Fig. 8: Actual test tracks Type A, B, and C to evaluate the performance of prototypes

Each test track evaluated the latency in providing the cues to the wearer of the prototype which in turn reflected in the feedback of the prototype’s usage. The feedbacks are discussed in the next section.

Fig. 9 shows real-time testing of the prototype DW2. Three cases are shown: 1) a human is on the way of the wearer, while a rectangular table is on the left side of the wearer, 2) A chair containing books is on the way of the wearer, and 3) a human and a chair is on the way of the wearer, while a round table is on the right side, and a rectangular table is on the left side of the wearer’s path. While Fig. 9 shows how a person looks when he is wearing the prototype, Fig. 10 shows how a camera perceives the environment. The images shown in Fig. 10 shows small white dots. These dots are a pattern projected by the camera's infrared (IR) component. To remove the dots, the IR emitter must be turned off. However, to get accurate depth measurements, the IR emitter must be on.

Fig. 9: Testing of DW2: A human in front of the wearer (left), a chair containing book in front of the wearer (middle), and human and chair in front of the wearer (right)

(a) (b)

(c)

Fig. 10: Camera view from DW2: (a) object identification with confidence value, (b) depth estimation in meters, and (c) a case where all the objects were at a depth of more than 2 m.

In a test to measure the accuracy of the depth, it was found that the specified accuracy is the actual accuracy. That is, less than 2% at 4 m depth. For instance, 2.12 m was the depth value from the physical measurement, and the estimation from the camera was 2.11 m.

Figure 10 (a) shows object identified with confidence value ranging from 0 to 1; along with the color coding. The closest objects are shown in red bounding box (depth up to 1 m), the objects from the depth range of 1 m to 2 m are shown in yellow bounding box, and the objects at a depth beyond 2 m are shown in green bounding box. The numbers on the right indicate the confidence. For example, the far sitting person was identified with confidence of 0.54, while the near sitting person was identified with a confidence of 0.88. The two laptops were identified with 0.80 and 0.34 confidence scores. Figure 10 (b) shows the identified objects with the depth value in meters. The person with red colored bounding box was at 0.73 m depth that was less than 1 m. That showed that the color code was working as expected. Here, the algorithm mistakenly identifies the small portion of the visible rectangular table as 'sink' at the depth of 1.17 m, mainly due to the similar appearance. Fig. 10 (c) shows the case where the detected objects were at a distance more than 2 m.

4. RESULTS AND DISCUSSION

The object detection system was evaluated across three test tracks: A, B, and C using the two developed prototypes. Each track presented varying levels of difficulty, impacting the performance of the detection system. The performance of the detection system was assessed by measuring how effectively it detected objects on each track. The results are presented in terms of the number of objects introduced on the tracks and how well the system detected and provided cues to the wearer.

Table 4 shows the sample response by one person who tested both the prototypes. The system underwent an update from DW1 to DW2, leading to significant changes in its capabilities. For instance, while DW1 was able to detect a certain number of stationary and semi-stationary objects, DW2 showed enhanced performance with more accurate detection of these objects. This is evident from Table 4. The user provided better response to DW2, than DW1. The transition from DW1 to DW2 brought notable improvements in the object detection system's performance. The updated version was more effective in sending the cues to the user for assist, reflecting significant advancements in the system's capabilities.

Upon completion of the testing phases for DW1 and DW2, a comprehensive analysis was conducted based on feedback collected from five normal vision users. The analysis of the multiple responses is presented in Table 5, and Table 6. Table 5 shows a sample user response for overall response to comfortability in terms of wearability, perceived vibratory feedback, and cueing pattern identification. The output criteria for DW1 and DW2 were assessed on a scale of Poor, Fair, and Good. The results were recorded and compared in Table 6. The poor performance was assigned value of -1, the fair performance assigned a value of 0, and a good performance assigned a value of +1.

Table 4: Sample response by a user who tested both the prototypes

Details: Type A test track (Select one categorical property for each point below)	**DW-1**			**DW-2**		
	Poor	**Fair**	**Good**	**Poor**	**Fair**	**Good**
1. Point of Interest 1 = Wall			✓			✓
2. Point of Interest 1 = Table		✓			✓	
3. Point of Interest 1 = Chair 1		✓			✓	
4. Point of Interest 1 = Chair 2		✓				✓
5. Point of Interest 1 = Human		✓				✓

Details: Type B test track (Select one categorical property for each point below)	**DW-1**			**DW-2**		
	Poor	**Fair**	**Good**	**Poor**	**Fair**	**Good**
1. Point of Interest 1 = Wall			✓			✓
2. Point of Interest 1 = Chair 1			✓			✓
3. Point of Interest 1 = Table 1		✓				✓
4. Point of Interest 1 = Human 1			✓		✓	
5. Point of Interest 1 = Table 2		✓				✓
6. Point of Interest 1 = Human		✓			✓	

Details: Type C test track (Select one categorical property for each point below)	**DW-1**			**DW-2**		
	Poor	**Fair**	**Good**	**Poor**	**Fair**	**Good**
1. Point of Interest 1 = Wall		✓				✓
2. Point of Interest 2 = Chair 1		✓				✓
3. Point of Interest 3 = Table			✓		✓	
4. Point of Interest 4 = Human 1			✓		✓	
5. Point of Interest 5 = Human 2		✓			✓	
6. Point of Interest 6 = Human 3			✓			✓
7. Point of Interest 7 = Human 4		✓			✓	

Table 5: Sample user feedback on comfortability of the prototype

Details (Select one categorical property for each point below)	DW-1			DW-2		
	Poor	Fair	Good	Poor	Fair	Good
1. Easiness of wearing the product			✓			✓
2. Vibration feedback of the motor			✓			✓
3. Pattern 1 Vibration identification			✓			✓
4. Pattern 2 Vibration identification		✓				✓
5. Pattern 3 Vibration identification		✓				✓
6. Pattern 4 Vibration identification		✓				✓
7. Pattern 5 Vibration identification	✓				✓	

Table 6: Sample user feedback on comfortability of the prototype

Test Analysis	DW-1						DW-2					
	U1	U2	U3	U4	U5	Mean	U1	U2	U3	U4	U5	Mean
Basic	0.29	0.43	0.57	0.43	0.43	0.43±0.01	0.86	0.57	0.86	0.86	0.86	0.80±0.13
Type A	0.20	0.00	0.00	0.60	0.40	0.24±0.26	0.60	0.80	0.60	0.60	0.80	0.68±0.11
Type B	0.50	0.17	0.17	0.67	0.67	0.44±0.25	0.66	0.33	0.33	0.67	0.67	0.53±0.18
Type C	0.43	0.14	0.14	0.43	0.57	0.34±0.19	0.43	0.57	0.57	0.71	0.71	0.60±0.11
Overall	0.35	0.18	0.22	0.53	0.51	0.36±0.16	0.64	0.57	0.59	0.71	0.76	0.65±0.08

For instance, a score of -1 means 1) The vest is highly ineffective, uncomfortable, or unreliable; and 2) Users are very dissatisfied, with numerous complaints and issues. A score of 0 means 1) The vest is adequate but unremarkable, meeting minimum standards; and 2) Users have a neutral experience, with the vest performing sufficiently but not impressively. A score of +1 means 1) The vest is highly effective, comfortable, and reliable; and 2) Users are very satisfied, with positive feedback and few if any issues.

The scoring of results was calculated based on stochastic analysis, reflecting how individuals perceived DW-1 and DW-2 across different test tracks and varying levels of difficulty. Considering feedback response of the five individuals: U1 to U5, the mean values were obtained in Table 6 with the observed variation. The analysis highlighted that DW-2 performed better overall compared to DW-1. This was evident from the calculated mean values, which took into account user tolerance and feedback on the devices' friendliness and functionality.

Figure 11 shows a visualization of the scoring table by the users and their mean, highlighting that both prototypes were considered as good, however DW-2 is better than DW-1. Here, the scale is categorical with distinct values of -1 for "Poor," 0 for "Fair," and 1 for "Good," interpreting values like 0.36 and 0.65 can be a bit more nuanced. These values need to be mapped to the closest categorical rating. Here’s how this can be interpreted: 1) DW-1 scored 0.36: This value suggests that that the vest performs well and users are generally satisfied, but there may be areas where it doesn't excel completely or could use some improvement. Users likely find the vest to be beneficial and functional, with performance meeting some of their needs. However, some might have reservations or suggestions for improvement. 2) DW-2 scored 0.65: This value suggests that the vest is viewed as effective and reliable, meeting user expectations in many areas. It shows that users are generally satisfied with its performance. Users find the vest to be highly functional, comfortable, and reliable, with minimal complaints. The vest likely excels in several key aspects, providing a good level of satisfaction.

The bar chart in Figure 11 reflected that while DW-1 received mixed feedback, DW-2 consistently performed better, with higher user satisfaction in terms of environmental computation and overall user friendliness. Moreover, while the updates made in DW-2 were beneficial, there is potential for further enhancements to make DW-2 stand out even more in the open market. Overall, the testing confirms that DW-2 offers improved performance and user experience compared to its

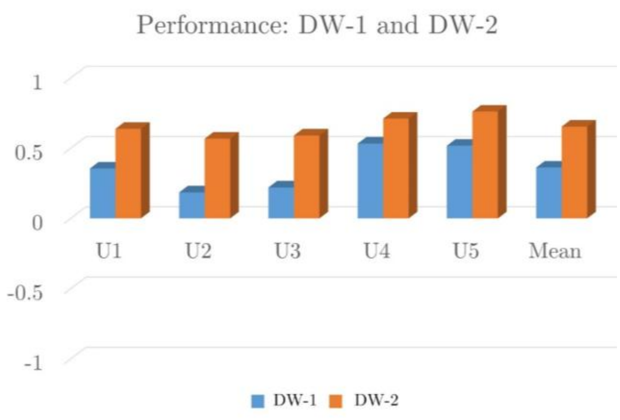

Fig. 11: Comparison of performance by prototypes, showing that DW-2 was better than DW-1

predecessor, though additional updates could further optimize its market competitiveness.

5. CONCLUSIONS AND FUTURE WORK

In this study, two smart vest prototypes, DW-1 and DW-2, were developed using a range of advanced components, including vibration motors for haptic feedback, 3-D cameras for spatial recognition, a Jetson Nano board for real-time processing, and LIDAR technology for precise distance measurement. These elements were carefully selected to create a responsive system capable of detecting and alerting users to obstacles in their environment. The prototypes underwent testing with participants who had normal vision, serving as a control group to evaluate the baseline effectiveness of the devices. The experimental results indicated that both DW-1 and DW-2 successfully assisted users in navigating their surroundings. However, DW-2 was found to outperform DW-1.

Future work will focus on the further refinement of the DW-2 prototype, with particular attention to reducing costs, weight, and the complexity of wiring. In addition to these improvements, feedback from visually impaired users will be integral to optimizing the design. A potential enhancement involves replacing the physical wiring with a conductive layer embedded within the fabric, which could significantly reduce the overall weight of the vest while maintaining its functionality. This innovation would not only reduce the physical bulk of the device but also enhance its flexibility and comfort. Additionally, future iterations may explore the integration of wireless communication modules to further reduce the complexity of the system. This evolution of the prototype aimed to make the device more practical and accessible for widespread use in India amongst the visually impaired community. The ultimate goal was to develop a commercially viable product that is both affordable and accessible, paving the way for widespread adoption and greater independence for those who are visually impaired.

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