Wearable Vibration Device to Assist with Ambulation for the Visually Impaired

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Abstract. People with visual impairment have increased difficulty in performing activities of daily living, such as walking without bumping into obstacles. Many assistive technologies are used to help with ambulation as one walks forward, such as a white walking cane or a service dog. These have proven to be of tremendous help, but the cane may miss suspended objects not touching the ground, and service dogs are not available to all who need them. Further assistive technologies continue to be developed and tested. In nature, those without visual acuity tend to obtain much information from their environment through the other senses, such as hearing or tactile touch. This study is exploring the mapping of obstacle detection to tactile vibration motors on the skin. Ultrasonic sensors were used to detect obstacles in the forward direction where the user would be walking, and calculate the distance. The distance was mapped to a vibration pattern, with the pattern being more intense for closer obstacles. A prototype was developed and had several tests run. Obstacle detection and distance were useful up to 3 m. The functional field of view was 10° to 30° from centerline, but became more narrow as the distance increased and for harder to detect obstacles. The distance was mapped to 3 different vibration patterns, and human subjects were able to distinguish the patterns in a consistent manner. The prototype shows promise, but more testing and development would be required toward widespread application.

Keywords: ultrasound · proximity sensor · arduino · microcontroller · tactile · haptic · vibration · wearable electronics

1 Introduction

The World Health Organization (WHO) reported in 2013 that an estimated 285 million people live with some form of visual impairment: 39 million were reported to be blind and 246 million had low vision [1]. Visual impairments contribute to challenges in activities of daily living (ADL), such as difficulty with navigation and mobilization. This difficulty increases risk of injury due to collision with undetected obstacles in their environment. For example, 88% of blind or visually impaired individuals reported at least one injury as a result of their condition, and 23% report the need for serious medical attention as a result of the injury [2].

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Standard techniques that are currently used for assisting visually impaired include the white cane and seeing-eye service dogs. Many individuals use the standard white cane to manually scan their surroundings in order to detect and avoid hazardous obstacles, especially low-lying obstacles near the ground. While the standard white cane is a low cost and widely used device, issues remain, such as the cane getting stuck in cracks or potholes and the inability to assist with the detection of hanging obstacles. Some people utilize a guide dog that was specifically trained to assist blind or visually impaired people. A guide dog may not be accessible to some due to the high cost and low availability [3].

Assistive technologies have been developed to provide support for blind or visually impaired individuals with certain tasks [3]. Assistive technologies for the visually impaired can be separated into three categories: vision enhancement (when a camera input is processed and then the results are visually displayed), vision replacement (which includes displaying information directly to the visual cortex of the brain or through an ocular nerve), or vision substitution (which constitutes non-visual display, such as tactile vibration or auditory). Vision enhancement has two disadvantages of not being able to assist individuals who are blind, and may distract the remaining visual capacity for those who are low vision. The vision replacement may be a robust solution in the future, but needs much more development. Visual substitution can build on techniques to map informational signals onto tactile vibrations that can be felt on the skin.

Mapping onto tactile vibrations has been reported for music [4], touch screens [5], virtual reality [6], and spatial tasks [7]. Several assistive technologies and systems have been reported. Audio Bracelet for Blind Interaction is an advanced vision substitution technology consisting of an auditory bracelet that uses auditory modality to convey spatial information of the user's surroundings [8]. Intelligent white canes have been developed that use color sensors, vibrations, and audio signals to alert the user during ambulation [9]. Although these are promising technologies, none have yet been able to fully support the needs of a blind or visually impaired individuals. Many users have found the auditory alerts to be distracting in a busy environment, and a bracelet worn on the wrist may not accurately pick up objects due to the constant mobility of the arms when walking.

There is still a need for the development of assistive technology that would assist the blind and visually impaired with ambulation, especially if it is more affordable and simpler to use [10]. Such a device should inform the user of surrounding obstacles that could be hazardous. A device with these capabilities might allow blind and visually impaired individuals to walk through their surroundings with a higher level of confidence, comfort, and safety. The purpose of this project was to develop and test prototype modules for a wearable, hands-free vision assistive technology system to help with navigation for blind or visually impaired individuals during ambulation.

2 Materials and Methods

2.1 Overview

The full system has three functional modules, each consisting of an ultrasonic sensor, microcontroller (MCU) and vibration motor. Figure 1 shows the block diagram of one functional module.

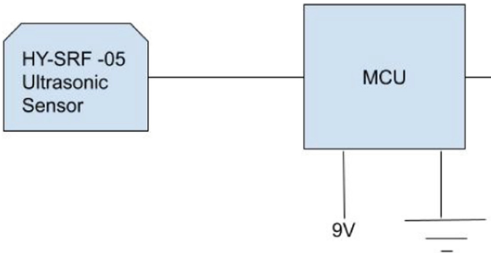

Fig. 1. Block diagram of the primary functional unit of the prototype. The ultrasonic sensor maps a spatial area, the microcontroller (MCU) converts the spatial information into a distance measurement, and then sends control signals to a vibration motor that provides haptic feedback to the user by vibrating on skin.

The primary functional unit for the prototype system had three modules as shown in Fig. 1: an ultrasonic sensor for obstacle detection, a MCU to map spatial information to vibration patterns, and a tactile vibrator. The full system of the prototype had three of these functional units of sensor-MCU-vibrator. Ultrasonic sensors were used for obstacle detection. Each ultrasonic sensor was connected to a microcontroller and the microcontroller drove a tactile vibration motor. The physical layout of the prototype is shown in Fig. 2. A control algorithm was developed for the MCU, within which the MCU received the time measurement of the reflected signal recorded by the ultrasonic sensor. The time measurement was converted to a distance value. The algorithm then determined a control pattern for output voltage pulses to be sent to a vibration motor, where the pattern of pulses was related to the distance. The system operated continuously while the device was powered on. A flow chart for the system is shown in Fig. 3.

2.2 Electrical

The ultrasonic sensor chosen for the prototype was the HY-SRF-05 Ultrasonic Sensor (CYD, Hong Kong, China). The sensor transmitted a 40 kHz ultrasonic pulse through the air, and any obstacles in its path would reflect the signal back to the receiver. The time was recorded from the echo of the wave as it reflected from an obstacle back to the receiver. The ultrasonic sensor module was chosen to use in the prototype due to low cost, availability and reliability. The full system of the prototype contained three functional units. Each functional unit consisted of an ultrasonic sensor, microcontroller, and vibration motor. The functional units were positioned so that their ultrasonic sensors pointed in the right, center, and left directions respectively to span the user's field of vision in the forward direction when walking forward.

The MCU module for the prototype was an Arduino Nano (Arduino, Monza, Italy, https://arduino.cc), which has an ATmega 328 8-bit microcontroller by Atmel (Microchip Technology, Westborough, MA). The Arduino integrated development environment (IDE) was used for code development and testing. The vibration motor selected for the prototype was the Tatoko DC Coreless Motor (Tatoko) due to its suitable size and vibration pattern. Each Arduino Nano was connected to an ultrasonic sensor and a Tatoko vibration motor (Fig. 1). The vibration motors were rated for 1.5−3 V and vibrated at

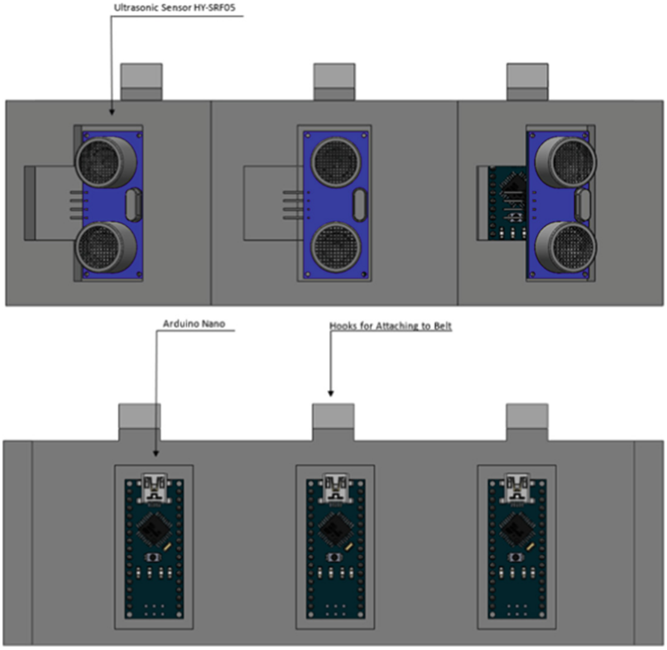

Fig. 2. The top diagram shows the front view of the model for the enclosure with the three ultrasonic sensors facing forward in the direction the user would be walking. The bottom diagram shows the inside view of the model with the MCU placed behind the corresponding ultrasonic sensor.

8000–16000 RPM. The Arduino output a voltage pulse pattern to the vibration motor which was related to the distance of an obstacle based on the readings from the ultrasonic sensor. The Arduino Nano was powered by a 9V battery. Power to the module could be turned on and off via a switch located on the battery enclosure.

2.3 Mechanical

Using Solidworks (Dassault Systems, Waltham, MA, USA), an enclosure was designed to mount the three functional units of an ultrasonic sensor, microcontroller and haptic vibrator. The ultrasonic sensor was mounted to the front of the enclosure which would face forward in the direction the user would be walking. A small cutout was provided to route the wires through the enclosure to connect the sensor with the MCU. The MCU was mounted inside the enclosure adjacent to its corresponding sensor. 3D models of the physical layout can be seen in Fig. 2.

The enclosure was mounted via hooks to an adjustable belt to be worn around the waist. The vibration motors were attached to the inside of the belt aligned with the corresponding ultrasonic sensor. Attaching the vibration motor inside the belt allowed for the user to feel the haptic vibrations on their skin.

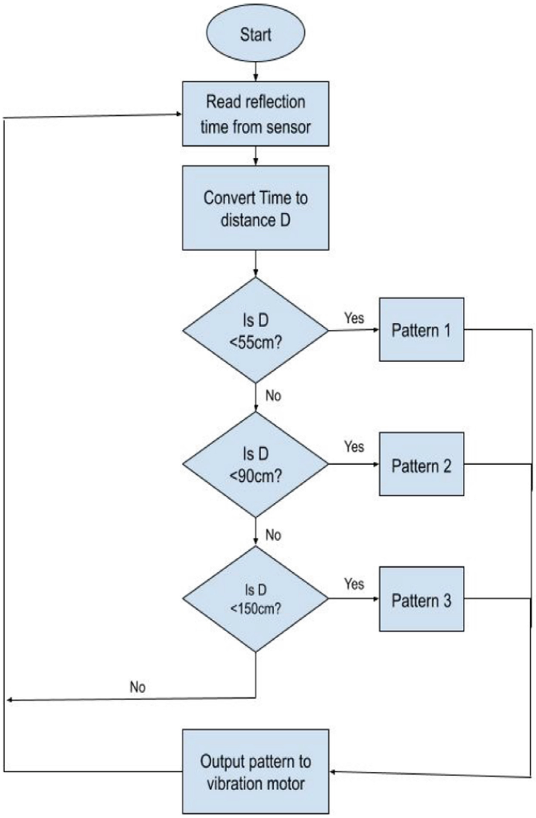

Fig. 3. Example of a flow chart of the algorithm in the MCU to read ultrasonic sensor for distance to the obstacle, and map that distance to a vibration pattern for tactile feedback.

2.4 Software

In order for the system to be able to process the information received from each ultrasonic sensor and convert into an output voltage pattern for the corresponding vibration motor, an algorithm was written and programmed in the Arduino version of C. A part of the algorithm is shown in Fig. 3 as a flow chart. The software read the voltage from the ultrasonic sensor on the analog to digital converter (ADC). The voltage corresponded to the time of the ultrasonic transmission and reflection. The read value for the time duration was converted to a distance. This distance would be from the sensor to the object that reflected the ultrasonic wave. At any moment of time, a sensor would only return one value for the primary object that reflected back the ultrasonic signal. So, the distance would be calculated for this object. The software mapped the distance to a pulse pattern for the vibration motor. Three patterns were generated with pulse width modulated (PWM) output voltage. Pattern 1 had intervals of 0.5 s, pattern 2 had intervals of 1.0 s, and pattern 3 had intervals of 3.0 s (Fig. 4). The voltage pulse pattern was then output to the vibration motor.

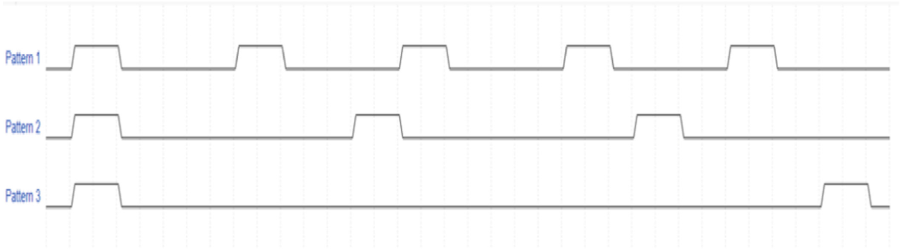

Fig. 4. Waveform to control the vibration motors. The positive pulse induces a burst of vibrations that last 0.2 s. The interval between pulses is different for the three patterns. The interval for Pattern 1 was 0.5 s, Pattern 2 was 1.0 s, and Pattern 3 was 3.0 s.

2.5 Prototype Development

A prototype was developed with three functional units of the ultrasonic sensor, MCU, and vibration motor placed in the enclosure and belt. The belt would go around the waist as they walked forward. The electronics were powered by batteries that were placed into the system with an on/off switch.

The ultrasonic sensors were mounted with screws to face forward. The ultrasonic sensors were oriented vertically because the vertical position allowed for better obstacle detection by seeming to limit interference compared with horizontal placement. The wires from the ultrasonic sensors were routed through openings in the enclosure and connected to the MCU. The MCU were mounted inside the enclosure using Velcro straps. The power cabling between the battery pack, MCU and vibration motors were routed through holes in the top cover of the enclosure. The enclosure was attached to the belt using hooks, which helped to maintain the enclosure and ultrasonic sensors in a more straight and forward direction.

The belt strap could be adjusted to be able to fit many different body types. A photograph of the final prototype being worn can be seen in Fig. 5 and a top view of the prototype can be seen in Fig. 6.

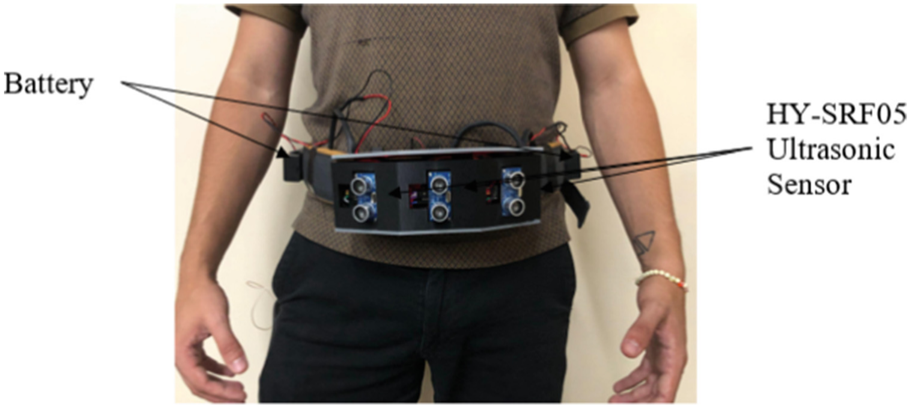

Fig. 5. Prototype being worn. This demonstrates the ultrasonic sensors being positioned to respond to obstacles in the user's forward field of view.

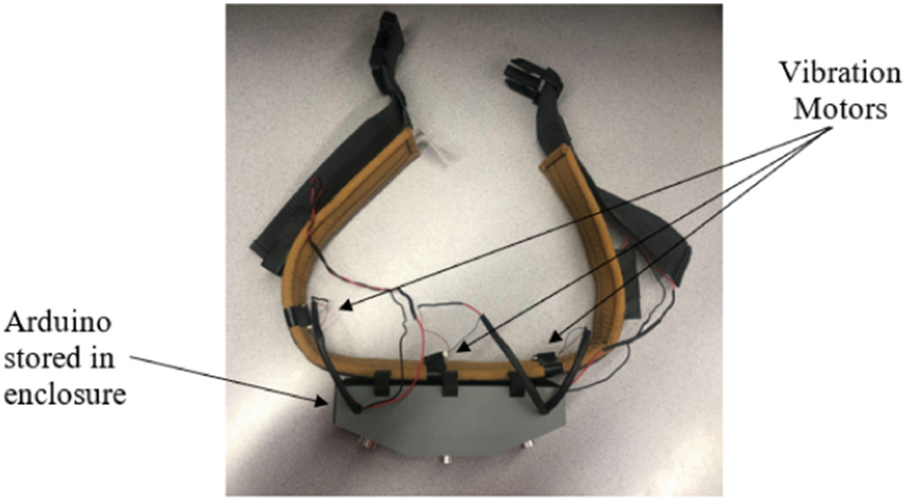

Fig. 6. Top view of prototype showing enclosure and vibration motors attached to the belt. An enclosure where electronics lay being covered is also shown.

3 Testing and Results

Several tests were conducted to assess the function of one functional unit, consisting of the ultrasonic sensor, MCU and vibration motor.

3.1 Object Detection Testing for Variability

A test was done to assess the performance of the sensing module for a static object. The ultrasonic sensor was placed so that the transmitter and receiver were in line with where the object was placed at different distances from the sensor. The object was a 1.8 m high metal pole with a 3.8 cm diameter. The sensor output a voltage value that corresponded to the time of transmission and reflection. The prototype functional unit was set up on a stand at the mid pole height. The obstacle was placed at distances of 0.6 m, 1.5 m and 3 m to the pole. Based on pre-measured tape marks marked on the floor in front of the pole. The sensor was set at each distance marker and the test was run. Then the sensor was moved to the next distance marker and test repeated. At each distance a screenshot was taken of the plot, and the distance values were reported as central value ± variation. After some initial testing of the ultrasonic sensor and conversion to distance, the overall pattern was that closer objects would be well detected and result in a steadier value for distance, having little variation, but farther objects would be less well detected and result in a less steady distance value, having more variation. At placement distance of 0.6 m, the measured distance was 0.61 m with no variability in distance value. At the longer distances of 1.5 m and 3.0 m, the measured distance had more variability of 0.3 m. Table 1 shows results from this testing of distances.

Table 1. Distance readings for placement of the prototype functional unit at specified distances to a metal pole (1.8 m high, 3.8 cm diameter). Distance reported as central value ± variation.

Placed Distance (m)	Measured Distance (m)
0.6	0.61 ± 0.00
1.5	1.50 ± 0.03
3.0	3.05 ± 0.03

3.2 Obstacle Detection for Range and Field of View

Another set of trials was performed to observe how well the ultrasonic sensor detects obstacles at the boundary of its field of view. The primary objective of the sensor system was to detect obstacles in front of a walking user. The ultrasonic sensors have a field of view where it can detect obstacles. If an obstacle was outside this field of view, it may not be detected. This boundary was important to assess how wide the coverage was in front of a walking user. Obstacles of different shape and material were used to determine whether those factors affect detection. Two obstacles used for this test as follows: 1) a 1.8 m high metal coat pole with a 3.8 cm diameter, and 2) a plastic, 1.2 m tall cylindrical fan enclosed in a plastic case with a 19 cm diameter. The prototype functional unit was placed about 1.2 m above the floor to simulate the height as if worn by a user. The obstacles were placed in front of the sensor at a particular distance and angle from the center line. A protractor was used to measure the angles from the center line that was straight out from the sensor. Angles were marked with tape on the floor at 0° (straight out from the sensor), 10°, 20° and 30°. The obstacles were moved to these points, and the distance readings were made.

Based on the resulting plots of distance over time, a classification was made for each trial of “Clear” or “Not Clear”. The classification of Clear indicated the object was detected on the plot, with a persistent center line and modest variation. The classification of Not Clear indicated the object was not detected on the plot, lacking a persistent center line and having much variation. Figure 7 shows the classification of the obstacles at different distances and angles.

Figure 7 is a visualization of the results. The boxes display the distance of the object from the sensor and the angle, with 0° being straight ahead in the direction a user would walk. The color of each box indicates which objects (wider fan or narrower pole) were clearly detected. At 0.6 m, both object types were clearly detected from 0° to 20°, but at 30° only the wider fan was clearly detected. Maybe the wider object provided more surface area to reflect the ultrasonic signal. At 1.5 m both object types were clearly detected, but only for 0° to 10°. In contrast, for 20° to 30° only the wider fan was detected. At 2.4 m only the wider fan was clearly detected, and only for the angles of 0° to 20°. These results are summarized in Table 2.

3.3 Mapping of Distance and Vibrations

The MCU was programmed to detect the distance to an object, and map that distance to one of four vibration patterns as shown in Table 3. The duration of a single burst of

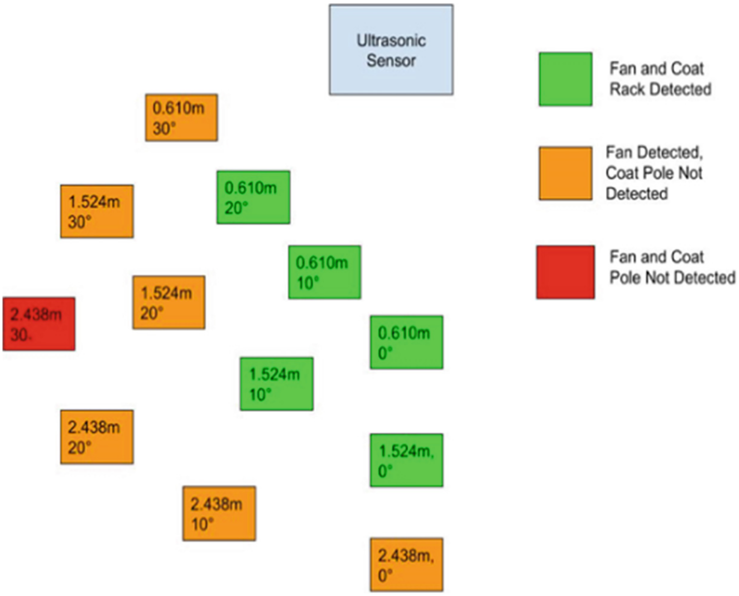

Fig. 7. Location of Obstacle Detection, the green box locations mark places where both the pole (narrow diameter) and fan (wide diameter) were consistently detected, the yellow box locations mark places where the pole was not consistently detected, but the fan still was, and the red box marks a spot where neither the pole nor the fan was consistently detected. (Color figure online)

Table 2. Results of object parameters and whether clearly detected by the prototype functional module utilizing the ultrasonic sensor. The objects were either Wide (19 m, diameter plastic cylindrical fan) or Narrow (1.8 cm, diameter metal pole).

Distance (m)	Angle (degree)	Clearly Detected
0.6	0°, 10°, 20° 30°	Wide or Narrow Wide
1.5	0°, 10° 20°, 30°	Wide or Narrow Wide
2.4	0°, 10°, 20° 30°	Wide Neither

vibration was 0.2 s. Then there would be a delay before the next burst of vibration would begin. This delay was the burst interval, which had values of 0.5 s, 1.0 s, and 3.0 s. Figure 4 shows the waveform of control signal to the vibration motor. When the voltage was high, the motor would vibrate.

The software on the MCU mapped the distance to a pattern of vibration that the user would feel. A distance of 3.0 m or more would not result in any pattern, being too far away to warn the user yet. A distance of less then 3.0 m would result in a vibration pattern. The smaller the distance the more frequent the vibration bursts. Each burst was

0.2 s, and the interval between bursts would vary from 3.0 s for farther objects and 0.5 s for closer objects. Table 3 shows the mapping of distance to vibration pattern.

Table 3. Mapping by the software running on the MCU for distance to vibration pattern. Each burst lasted 0.2 s. Distances beyond 3.0 m resulted in no vibration pattern.

Distance (d) to Detected Object (m)	Interval between Bursts (s)	Description
$d < 0.25$	0.5	Intense pattern (danger)
$0.25 \leq d < 0.50$	1.0	Moderate pattern (adjust path)
$0.50 \leq d < 3.0$	3.0	Warning (object ahead)
$d > 3.0$	none	Fine (continue walking forward)

A trial was set up to observe this mapping of distance to vibration pattern. The functional module of the prototype having the sensor, MCU and vibration motor was placed on a stationary stand. An obstacle (metal pole, 1.8 cm diameter) to be detected was placed straight in front of the sensor at the specified distance. The distance between the sensor and object progressively increased from 26 cm, and each increase in distance was 13 cm until about 3 m. Following obstacle placement, two observations were made and recorded: which vibration pattern was being performed by the vibration motor, and what voltage did the control signal have that was sent to the motor. Figure 8 shows the result of distance to vibration pattern sent to the vibration motors. The vibration pattern was indicated in the plot as the interval between the bursts of vibrations.

The observed generated vibration patterns (Fig. 8) closely followed what the software on the MCU was intending to map for each tested distance (Table 3). Exceptions were observed at the longer distance near 3.0 m. The measurement at 2.9 m did not have the correct interval of 3.0 s, instead no value as plotted as a 0. Possibly, the prototype failed to detect the obstacle at this longer distance and so did not map to an interval value. Moreover, when a vibration pattern was generated, the voltage value for each of the pulses to control the vibration motors had a stable value, and did not decline through the tested range.

3.4 Discrimination of Vibration Pattern

Once an object was detected by one of the ultrasonic modules, the corresponding haptic motor vibrated. The pattern of the vibration indicated the distance to the object. There were three different patterns to indicate a close, medium or far distance. Testing was done to ensure that the user could differentiate the three states of vibration. If the user could not tell the difference between the vibration pattern, then the prototype would be of limited use. The purpose of the vibration pattern was to communicate to the user that there is an obstacle ahead and about how far away it is. To test this, 10 volunteer subjects

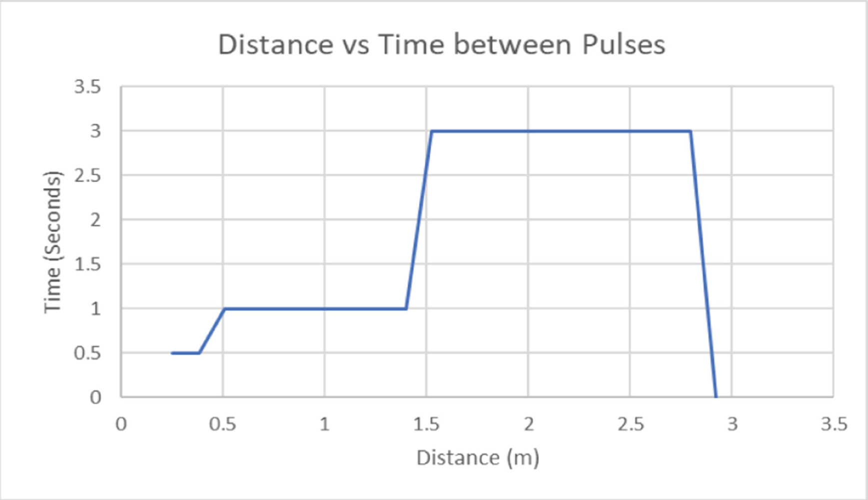

Fig. 8. Mapping of distance from the obstacle to the vibration pattern as indicated by the interval between the bursts of vibrations. The x-axis shows the distance between obstacle and the prototype functional module having the ultrasonic sensor. The y-axis shows the interval in seconds between the bursts of vibration. The interval was smaller as the distance decreased to indicate a higher level of urgency for the user to adjust their walking pattern to not bump into the obstacle. The voltage of the control signal sent to the vibration motors was consistent and did not decline over the tested intervals.

were recruited to assess whether they could distinguish between any two consecutive vibration patterns.

The subjects in this study were able-bodied, with no known sensory perception deficits. The ages of these volunteers ranged from 19 to 55, with 3 identifying as female and 7 as male. These pairs of vibration patterns were ordered randomly between the volunteers. The patterns of vibrations were labeled as Pattern 1, Pattern 2, and Pattern 3 as shown in Fig. 4. For the test, the prototype functional module having the vibration motors was placed adjacent to the abdomen over the volunteers' clothing. For each trial, the volunteers were alerted that a two-vibration pattern sequence was about to occur. Then, after both patterns were completed, the volunteer was asked whether the two patterns were the same or different. Each volunteer underwent 3 sets, with 6 trials per set. Each trial did the following pattern pairs in random order: 1–1, 1–2, 1–3, 1–1, 2–2, and 3–3. Thus, each subject had $3 \times 6 = 18$ trials, with the total numbers of trials for all 10 volunteers was $18 \times 10 = 180$ trials.

The subjects were correct for most of the trials on whether the two consecutive patterns were the same or different. Only 3 subjects had an error, and each had exactly 1 error out of their 18 trials. So, there were a total of 3 errors for 180 trials. Thus, the percent error was 1.7%. Overall, the subjects were able to distinguish between the 3 patterns generated by the vibration motors.

4 Discussion and Future Directions

The prototype of the system showed promise as a potential assistive technology for visual impairment being able to detect obstacles and provide haptic feedback to the user. Obstacles up to 1.5 m meter in front of the ultrasonic sensor module were consistently detected. The three vibration patterns could be distinguished by the users.

Considering the results for the obstacle detection for the application of a visually impaired user walking forward at a moderate pace, the obstacle detection would be helpful, but improvements would be desired. The more challenging narrow object (1.8 cm diameter metal pole) was clearly detected at 0.6 m and 1.5 m, but not consistently at 2.4 m. A warning range of 1.5 m would allow the user to stop or change direction, but a warning at an even greater distance (2.4 m) would allow more time to plan a more natural adjustment in walking speed or direction. Further testing would help clarify how consistent and potentially helpful the prototype system would be to a visually impaired person while walking.

The next step of development would be a system test of the whole prototype system being worn during ambulation through obstacles. Additionally, improving the vibration patterns and placement to provide improved feedback to the user. This would include adding more patterns to differentiate more obstacle distances.

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