Vibro-Haptic White Cane With Enhanced Vibro Sensitivity

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Abstract— **The traditional white cane allows blind persons to understand the environment by tapping the white cane against the objects. It has limited capabilities in detecting objects far from the person. Available electronic blind navigation systems require wearable devices that would cause discomfort to the blind person. This paper proposes a low cost but yet a rugged vibro-haptic white cane to be used as a navigational aid for the blind community. The proposed system allows a blind person to understand distant environment with haptic sensations without any additional wearable devices. The frequency of vibration utilized as the sensation of distance. Proposed device was tested with blind middle school students. The proposed controller was modified accordingly to create a linear distance perception.**

Keywords— Haptics; Navigation with ETA; Obstacle detection; Vibrotactile; Visually impaired care; White cane

I. INTRODUCTION

World Health Organization (WHO) estimated that there are around 253 million visually impaired people in the world. 36 million of blind population is completely blind, and other 217 million suffers from low vision [1]. According to the total population estimates, five people in every 1000 is estimated to be completely blind, and low vision amounts to 3 people in every 100 [2]. According to the WHO, 81% of the visually impaired people are 50 years and older [1]. A high percentage of world blind population lives in African and Asian regions where the per capita income levels are significantly low. The population of visually impaired people requires additional needs for their socio-economic well-being. Enhanced healthcare and supportive infrastructure development are essential for the well-being of the blind community. The affordability of these services and support devices are also important because a high percentage of these people live in a region of Africa and Asia where most countries have low-income levels.

Navigation in a changing environment is considered to be one of the most challenging tasks for a blind person. Different techniques of navigational aid developed over the years to aid the visually impaired community. In 1930, the white cane was distributed around the world. The white cane used as one of the important tools to provide independent mobility to the blinds [3]. The white cane provides a haptic and acoustic sensation about the world to the blind cane holder. The cane holder uses these clues to understand the space and objects around the person. The blind person effectively uses the cane as an extended arm. Animals such as dogs are also trained to guide visually impaired people in navigation [4].

Adequate information about the surrounding and the travel path provide comfortable navigation through the unfamiliar spaces. "Electronic Travel Aids" (ETAs) transform environmental information which is usually captured through camera vision, into a form which is understood by the visually impaired person and preventing him walking into obstacles [5]. ETAs include image processing techniques [5], [6], [7] haptic feedback systems [8], [9], neurological feedback systems [10], [11] and acoustic-based navigation systems [12], [13]. The modern blind mobility systems commonly use complex electronics to provide navigational information to the blind user.

ETA systems proposed in [5] and [7] uses wearable haptic systems. These systems work using battery power. The blind user should carry the battery and equipment weight. If the battery is exhausted or if the controller fails, then the blind user is left with no option to navigate in the middle of the journey. ETAs use combination of sensors such as accelerometers, image-based depth sensors, etc. Sensor fusion technology employs a significant computational cost, which would require more power which in turn introduce additional carry on weight. Reliability of complex ETA systems are not normally discussed, in the literature. But it is very important to consider the reliability and ease of use of these systems from the perspective of a blind person.

The current technologies aim to provide vibrotactile and/or audible feedback as a navigation aid to the user [9], [14], [15]. Audible navigational instructions are provided through a speaker or a headphone. Speaker instruction is noisy to others, and headphone instruction blocks the attention from the surrounding sounds. In haptic based navigation systems, the designer should consider the skin responses of different parts of the body for the haptic sensation. Adam et al. [9] propose a wearable belt around the waist and the vibration around the waist could cause a tickling sensation. Selvi et al. [8] presented a haptic based navigation aid which requires the operator to wear sensors/actuators around the neck, waist, and knees which is inconvenient.

ETA devices are becoming versatile with many features like 3D sensing with tactile displays. Unfortunately, such devices have not penetrated to the vast low income blind population as the WHO statistics estimations suggest that 90% of visually impaired people are in the low income category and most of them live in developing countries [1]. For example, "The UltraCane is a commercially available primary electronic mobility aid for blind or visually impaired which costs around USD 880 which is not affordable to low income African and Asian population [16]. Therefore, the blind population still commonly uses the white cane. The white cane has been a robust solution for all the dynamic conditions faced by the blind person since it detects the object collision at the cane's length and allows other people to identify the blind person with the symbolic "white cane" [17].

The tactile based application designs require an understanding of human tactile sensations. Brooks [18] presents four types of tactile sensations sensed by the human hand namely compressive stress, skin motion stimulus, skin stretch, and vibration. The bandwidth of tactile sensation differs as for the four motion types. The skin can sense the mechanical vibrations up to 10,000 Hz but frequency differentiation capability decline for frequencies above 320 Hz [18]. The human hand is capable of sensing vibrations within 50-400 Hz [18] which is higher bandwidth than the other three forms of tactile sensing mechanisms. The skin vibration has been selected as the haptic feedback considering the human tactile sensation [19]. A novel low cost and versatile, white cane based navigational system with vibrotactile sensation is proposed in this paper.

The proposed system uses ultrasonic sensors, built on top of a white cane. Therefore, it could be used as a conventional white cane in an unlikely event of a controller failure or a power failure. The sonar sensors are fired in three directions to acquire object distances within a $150\ cm$ arc. The sonar sensors provide available free space and object information to the controller. The controller then converts this information into tactile sensation using micro vibrators. Initially, the PWM duty ratio is calculated based on the distance to the object. When the distance is nearer, the system sends a higher PWM duty (i.e. higher average voltage).

The human haptic perception was tested in this research to improve the navigation system performance. Vibration perceived by the user as a measure of the object distance is given special attention in this study. This paper proposes a novel vibration perception linearization method which is validated with results. The effort on linearizing the human haptic perception mitigates the errors in distance prediction. The novel frequency based linearization of human distance perception has been tested and developed in the paper using the distance prediction readings of the students. This proposed method provides a superior solution for the blind community using a white cane based tactile system. Table 1 shows the design parameters of the proposed system.

TABLE 1 DESIGN PARAMETERS

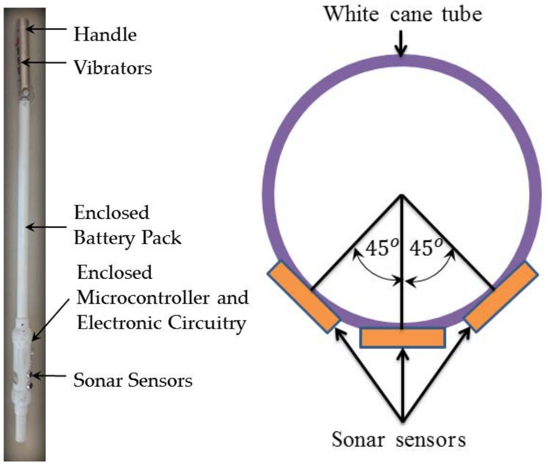
Detail	Value
Stick length	80 cm
Stick diameter	4 cm
Handle length	17.5 cm
Handle diameter	3 cm
Finger touch area length	2.5 cm
Finger touch area width	1.8 cm
Weight	760 g
Charging voltage	12 VDC
Battery charging capacity	13600 mAh
Stick object detection length	6 -150 cm
Stick object detection angle	-75° to + 75°

Section II describes the hardware implementation and methodology used in the research. Section III explains the results gathered using the proposed stick with the details of carried out tests. The paper is concluded in section IV.

II. HARDWARE IMPLEMENTATION

The implemented white cane is shown in Fig. 1(a). The system uses three sonar sensor arrays and three vibrator motors for tactile sensation. The sensors are placed in an arc around the cane to avoid cross-talk and sensors sense an object within a range of $150\ cm, 150°$ arc. An ARM cortex M3 microcontroller is used as controller. The sonar sensors are capable of sensing up to $2.5\ m$ distance objects but a small arc is selected to enhance controller speed. The microcontroller is clocks at $75\ MHz$ frequency. The system is powered by an AAA battery pack. The battery system can be recharged using a commonly available $12\ V$ charger. The tactile sensation is provided to the human using three micro vibrator motors with low power consumption. The motors are mounted in the walking stick handle. Batteries are placed along the walking stick tube. The system senses the environment to detect obstacles. Sonar sensors were selected over infra-red sensors as it could be used in indoor as well as outdoors. Sensors were placed such that there is no overlapping of the sensory area. If individual sonar fields are overlapped, it leads to errors in the obstacle detection whereas if there are gaps in between individual sonar fields, obstacles may not be detected. After an initial measurement, three sonar sensors were mounted vertically $45°$ apart as shown in Fig. 1(b).

According to the design, each sonar sensor is assigned a separate vibrator motor. A Pico Vibe Eccentric Rotating Motor (ERM) was selected to provide vibrations considering its miniature size and ability to control frequency and amplitude using Pulse Width Modulation (PWM) without complex drive techniques. The technique of PWM based voltage control is used to transform the sensed distance signal into a vibro-haptic signal. The PWM duty ratio determines the voltage applied to the vibrator motor. The vibration intensity is used to convey the information about the distance to the obstacle. Three vibrator motors are placed in separate rubber enclosures as shown in



(a) (b)

Fig. 1. (a). Haptic walking stick (b). Sensor arrangement on walking stick.

Fig.2. The three vibrators provide sensations about objects in front of right, left and front sensors. The rubber enclosures prevent vibration transmission into the handle and provide comfortable gripping of the stick. The left, right and front object sensations are separately sent to the three fingers through vibrators.

The controller triggers the individual sonar sensor separately and measures the time taken for the echo signal to arrive at the sensor. The sensor distance sensations were separately tested to test the accuracy and linearity of the sensors. The sensor was found to be adequately linear around the interested distances. The controller measures the distance to the nearest object using the sonar echo signal. The controller measures the time taken for the echo signal and provides the distance to the nearest object within the 150 cm arc. The controller then uses the sensed distance to calculate the motor vibration. The PWM duty is initially commanded as a function of the distance to the obstacle as in (1). The simplified control logic is shown in Fig. 3.

$$PWM\ duty = Start\ duty + \left(\frac{total\ distance - object\ distance}{total\ distance}\right) \times (full\ duty - start\ duty) \qquad (1)$$

The vibrators were tested for their PWM output to measure the vibrator frequency response for given PWM duty ratios as shown in Fig. 4. The vibrator frequencies were measured using an acoustic sensor. The effect of PWM frequency variation was indifferent within the range. Vibrating frequency vs. PWM duty shows some nonlinearity as shown in Fig. 4. PWM duty ratio determines the voltage supplied to the vibrating motors. Therefore, as for the Fig. 4, it is found the direct PWM duty controlling as a measure of distance can be further improved by linearizing the voltage vs. distance variations for the vibration motor.

The human perceived distance for different levels of PWM voltages was taken as a benchmark to linearize the distance vs. PWM relationship. A fourth order polynomial function was used to linearize the Frequency vs. perceived distance of humans as in (2). The polynomial order was selected considering the least square based error of the trained function. And the least square error based polynomial curve fitting was selected considering the available amount of train data. Based on the information gathered from the Fig. 4, PWM duty is proposed to be commanded such that the vibration frequency to be linear. The proposed control block diagram is shown in Fig. 5 using the calculated distance vs. PWM curve.

$$PWMduty = \sum_{i=1}^{4} b_i\,(object\ distance)^i + c \qquad (2)$$

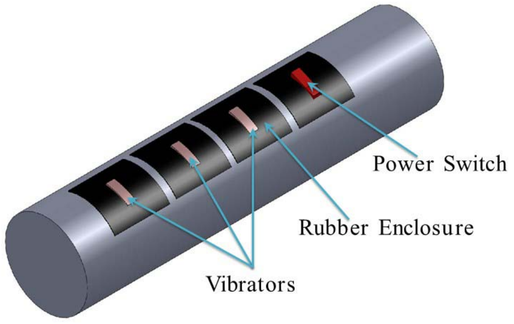


Fig. 2. Vibrator placement in handle.

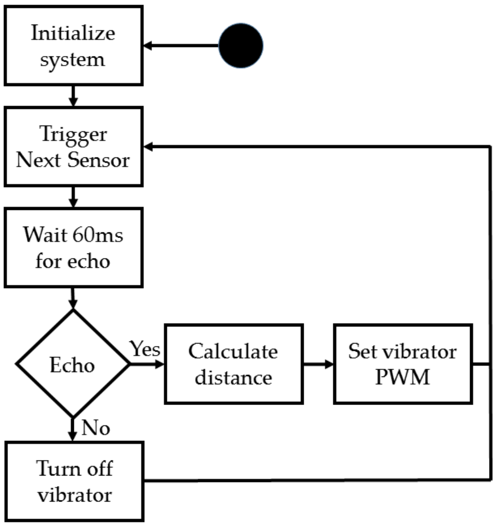


Fig. 3. PWM based controller.

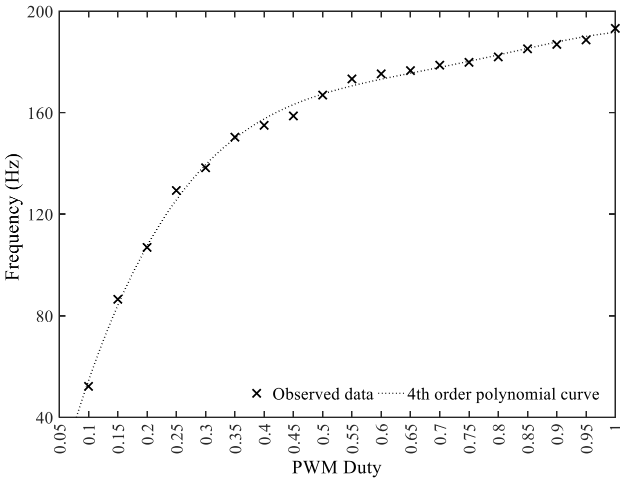


Fig. 4. Vibration frequency vs PWM duty.

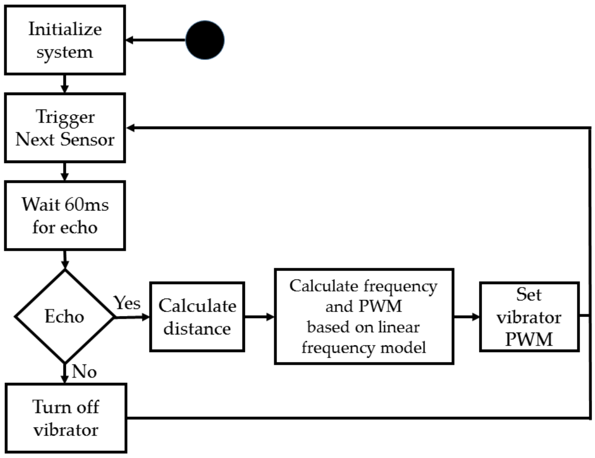


Fig. 5. Frequency based controller.

III. RESULTS

The proposed system's usability has been tested for different scenarios. The system calibration tests results are also included in the results. Walking stick tests were carried out in a laboratory environment to detect the usage and object identification capability of the system. A series of field tests were carried out using Rathmalana Blind School students, Sri Lanka. Students used for these tests were completely blind, and they are normally using a traditional white cane for navigation.

A. Gap Identification Test

A laboratory floor was arranged as shown in Fig. 6 using a classroom with obstacles spaced at different distances. 15 students were requested to navigate through the test arena to assess the device's ability to detect the narrow gaps. The distance between objects was varied from 80 cm to 30 cm. The students were asked to identify the gaps using tactile sensation of the haptic based cane. The students' gap identification capability is shown in Fig. 7. The results suggest that they were able to identify the objects and gaps with the tactile sensation. The gap identification capability is reduced when objects are closer than 40 cm. Gaps less than 40 cm are not adequate for a blind person to freely move. Therefore, the proposed haptic stick is capable of identifying the practical gaps. In subsequent trails, the results become more accurate.

B. Object Identification Capability at Different Heights of the Stick Test

Objects with different heights were placed in the laboratory and students were asked to identify the objects with the walking stick. The results of the test are shown in Fig. 8 for different heights. The 15 students' identification capability suggests that the system was able to identify objects within 10 cm to 50 cm. There is a small reduction in object identification capability in 10 cm height suggesting that the effects of holding angle differences of haptic stick.

C. Object Identification Capability with Usage Test

Ten obstacles were placed in a random order, and the students were asked to walk along a path and move through the randomly placed obstacles without collision. The students' object identification capability of the white cane was 70%. Then the students were allowed to use a haptic cane for few more attempts. The initial object identification capability rose from 73% to 90% with a 10-minute usage. The results of the test are shown in Fig. 9. The test results suggest that the students' object identification capability improves with the usage of the walking stick. The results also suggest that the students were able to understand the usage of the system very quickly and their navigational speed has increased rapidly with the confidence they gain in using the device.

The system was tested to measure the perceived distance to calibrate the system. Providing direct PWM output using the inverse of the distance could be improved by using frequency based control of the vibrators. The controller is then checked for different distance vs. vibration mechanisms to measure the humans' perceived distance between different levels of vibrations.

D. PWM vs. Vibration Frequency Measurement Test

Vibration frequency was measured using an acoustic sensor. The controller was programmed to provide different PWM duty

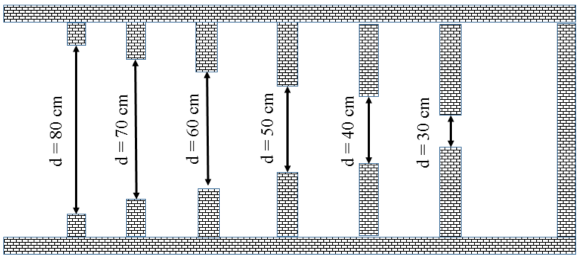


Fig. 6. Gap identification test arena.

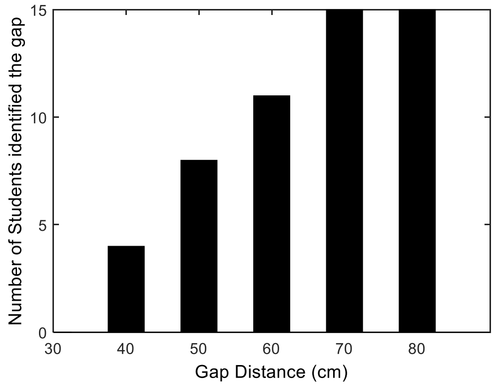


Fig. 7. Gap identification capability of the students.

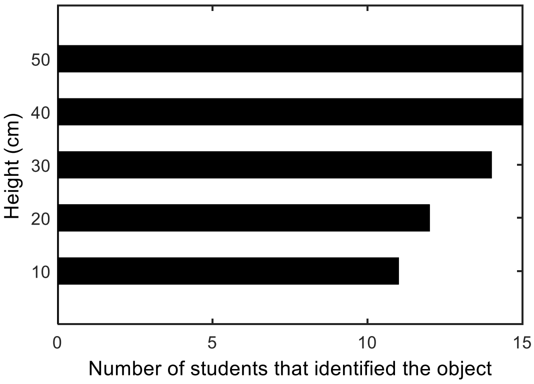


Fig. 8. Object identification capability of students at different heights.

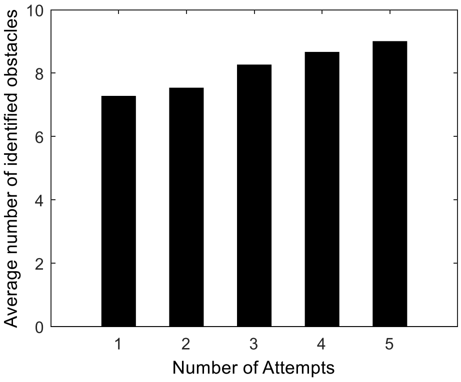


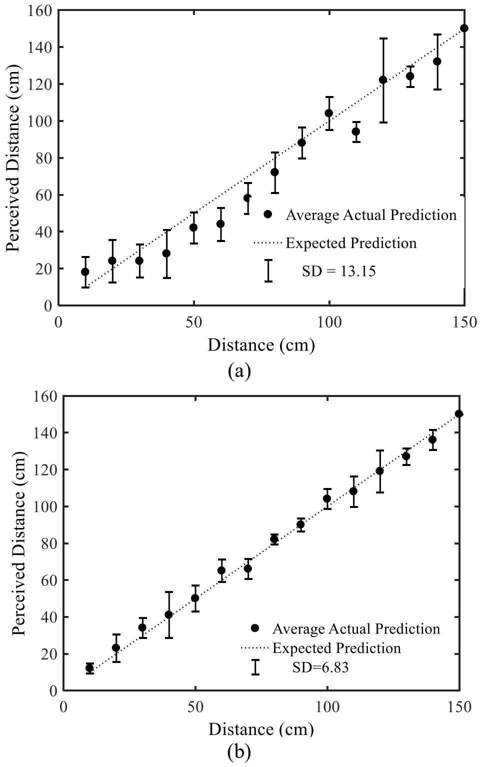
Fig. 9. Learnability of the haptic stick, the object identification capability in different attempts.

to the middle vibrator, and the acoustic vibration was captured and analyzed using sound analyzing software to measure the vibration frequency for different PWM duty levels. The vibrator frequency vs. PWM duty relationship was shown in Fig. 4. The system frequency and distance relationship are obtained by fitting a fourth order polynomial curve within the interested region.

E. Human Perceived Distance Test

The system was tested to measure the obstacle distance prediction ability. A wooden object was moved in front of the walking stick while a stationary person was experiencing the vibration. First, the object was moved to different predefined distances and the distance information was verbally provided to the person. The person was allowed to feel the vibration intensity at those distances. Afterward, the object was moved to random positions and predictions were recorded. The Fig. 10, 11, 12, and 13, show the predicted distance vs. actual distance for four sample students. Direct PWM based control results are shown in graph (a) and the linearized frequency based results in graph (b). Each 10 cm point was tested for five times randomly to measure the average prediction accuracy and error bars denote the variation. The results show the students were able to predict the distances more accurately in the linear frequency variation method than in the direct PWM based control.

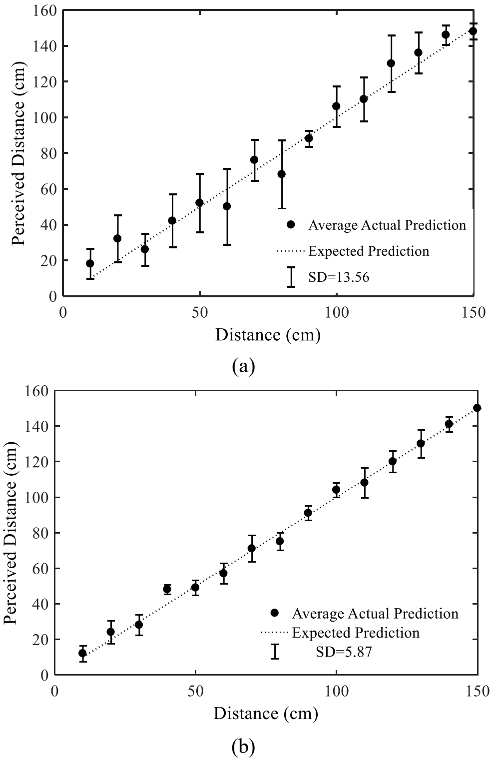
Fig. 14 compares the two methods for 15 students. Standard deviation is significantly low in the proposed method. The direct PWM based control method has a prediction error (standard deviation) around 13 cm and the linearized frequency based control strategy has reduced standard deviation to 6 cm. The results show a considerable improvement in human distance prediction capabilities with the new linearized frequency based design.



(a)

(b)

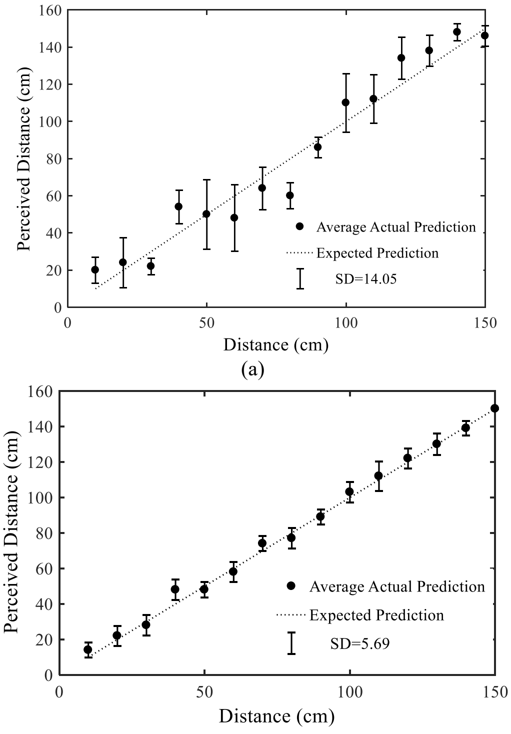
Fig. 10. Perceived distance vs actual distance of person 1 (a) PWM based control (b) frequency based control.



(a)

(b)

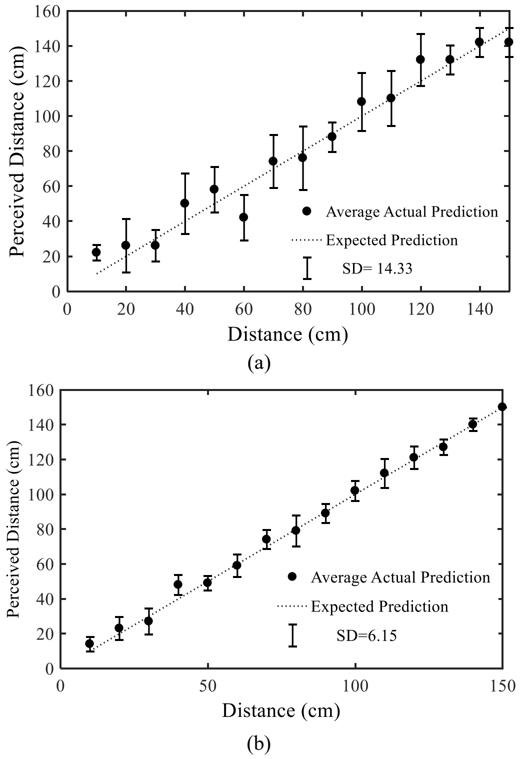
Fig. 11. Perceived distance vs actual distance of person 2 (a) PWM based control (b) frequency based control.



(a)

(b)

Fig. 12. Perceived distance vs actual distance of person 3 (a) PWM based control (b) frequency based control



(a)

(b)

Fig. 13. Perceived distance vs actual distance of person 4 (a) PWM based control (b) frequency based control.

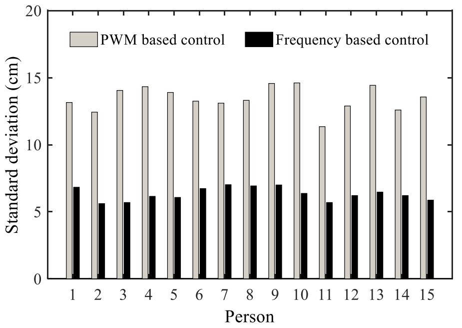


Fig. 14. Comparison of standard deviations of PWM based control and frequency based control.

IV. CONCLUSIONS

The developed haptic based white cane provides mobility information to a blind user using tactile sensations. The linearized frequency based vibrotactile motion has improved the linear distance perception of the white cane user. The tactile sensation is created by a skin vibration with an amplitude less than $0.05\ mm$. Skin vibration is not harmful to the operator as the acceleration is very small and it is not persistent on a single finger when navigating. The proposed haptic based stick provides inexpensive mobility support for blind people specially in poor communities as it could be manufactured at a value less than USD 50. Proposed walking stick has low energy consumption which allows long distance mobility with lesser carry on weight. The improved linearized frequency based haptic sensation provides enhanced distance identification capabilities. The proposed system performance provides evidence for the usability and reliability of the system providing a robust solution for the blind people at an affordable cost. One of the field tests carried out with the proposed haptic based walking stick is available online in [20].

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