ABSTRACT
The traditional white cane has been an effective primary device that enables the visually impaired to stay mobile and independent. However, this mobility aid does have limitations, as it cannot warn the user of head-level obstacles, drop offs, and obstructions over a meter away. There are some electronic mobility aids available that target these limitations, but they are either expensive or limit the use of the hand. The sensory substitution glove we designed is a cost-effective, gesture-aware device meant to be used in conjunction with the white cane. Ultrasound and infrared sensors are utilized to detect drop-offs (i.e. stairwells, ditches) and head-level objects that may be potential hazards to the user. Through gesture-mediated modulation, the user can switch to different modules to change the functionality of the device. The modules can determine whether the device has a wide or narrow sensing angle and also determine whether the device is looking for a drop-off or a head-height object. The sensor outputs are processed and then mapped nonlinearly to tactile vibration frequencies at the user's index finger. Our device allows the user to retain his innate ability to actively sense, which is the capability to redirect focus to areas of interest. With the device implemented on the backside of a glove, the user's hand is free to perform other tasks. Through experimentation, it was found that the device could successfully transmit environmental information to the user and help with identifying potential hazards.

BACKGROUND
In 2011, it was estimated that over 10% of Americans (21 million adults) have trouble seeing even with corrective lenses[1] and 4.8 million of the visually impaired use white (long) canes.[2] The white cane is the most prominent and widely used mobility aid for the visually impaired.[3] However, there some important limitations of the white cane that can leave the user prone to injury. They are ineffective at detecting head-height objects, which leaves the user at risk to head injuries.[3] Additionally, they are limited to a short range, which gives users little time to react to their surroundings and increases the risk of tripping or falling.

An important feature for a visual impairment aid device is head-height obstacle detection, as head injuries are a major and recurrent problem for the blind. At the University of Santa Cruz, 300 legally blind and completely blind individuals, who are considered expert users of white canes and/or guide dogs, were asked about their head-related trauma accidents. It was found that 98% of those interviewed indicated they experienced one or more head-related injuries. Furthermore, 23% of those injuries needed medical attention of which some needed stitches or dental treatment.[4] We believe that most of these injuries could have been avoided by using a supplementary device to detect obstructions at head-level. Not only do these accidents cause physical harm, but 26% of the head-related injuries resulted in the person's loss of confidence as an independent traveler.[1]

Another critical element for visual impairment aid devices is the ability to detect sudden changes in elevation, as falling is one of the largest threats and fears of the visually impaired. A study done at the University of Santa Cruz found that roughly 90% of all participants experienced a type of fall once or more a month.[4] About 36% of these falls resulted in medical attention and many of these victims needed stitches, orthopedic surgery, or rehabilitation.[4] Another study shows that elderly people with visual impairments have a fall per person year ratio of 1.65 and over 20% of falls result in medical attention.[5]

<u>Pre-existing Technology</u>
Presently, there are many electronic devices available to aid the visually impaired and prevent injuries. Numerous products use ultrasound emitters and detectors. The Mini Guide, first introduced in 2001 [6], is a handheld device that uses ultrasonic echolocation to detect objects up to 8 meters away. It vibrates at a higher frequency when objects are closer to the device. Limitations to the Mini Guide include poor detection of drop offs, which could result in a fall, and requirement of one hand, eliminating that hand's functionality. Currently, a highly promising available device is the UltraCane.[7] This device is used like a white cane, but is additionally equipped with two ultrasound beams that are able to detect both ranged and head-height obstacles. The UltraCane is useful because it builds off a pre-existing primary aid – the white cane – keeping one hand free. Through anecdotal observation however, subjects may have difficulty simultaneously integrating vibrations from the ultrasound sensors with the ordinary tactile feedback of the cane into a coherent percept of the environment. Secondly, from a review of a user [8], the rotation of the hand to scan walls was found to be cumbersome and physically taxing. Despite the technological advancements to address these issues, there has been little adoption of new electronic mobility aids by the visually impaired and blind communities. The abandonment rate for these electronic assistive devices is estimated to be about 75%.[10] Therefore, we propose our device which addresses the shortcomings of the other products in the market.

Continuation of Previous Device

This design continues upon the work first established by a previous vibrotactile sensory substitution device developed in The Ritt Lab at Boston University.[11] Guirguis et. al created a mobility aid using light intensity for environmental obstacle data collection. For their final prototype, a device was created that used three optical sensors, which only worked under certain lighting conditions, to acquire raw ambient light and filtered light. Two algorithms were created, each for the different modes of operation – navigation and color detection. The ADXL335 accelerometer was intended to detect the position and movement of the hand to switch between the two modes but was not fully implemented. Each algorithm was created using the filtered and ambient data to later affect the tactile signal sent to the user. The group used a TI MSP430 microprocessor for the computation of the device but was unable to be reprogrammed within the device. The group also used a small 3.6V battery to power the whole device, but the battery was soldered into the circuit, which prevented convenient replacement.

DESIGN AND INNOVATION

Our device continues the work done by Guirguis et. al. in the Ritt Lab. We modified their design to not only detect objects, but accurately identify head-level objects and drop-offs. Our primary objectives in designing the mobility aid are as follows:

Aim 1: Develop a gesture-aware sensory substitution device to be used along with a primary mobility aid.

- **Aim 1.1:** Develop software for a microprocessor to take information gleaned from active optical and ultrasonic systems and to send a vibrotactile response to the user.
- **Aim 1.2:** Design a vibrotactile actuator system that utilizes known information of the human hand's somatosensory system to optimize perceptual sensitivity for the user.
- **Aim 1.3:** Design a system that utilizes active-sensing and gesture-modulation implemented as a wearable glove.

Aim 2: Develop a communication protocol for users to detect objects and drop offs at least 2 meters ahead.

Aim 3: Develop a communication protocol for users to detect head level objects at least 1 meter ahead.

Device Specifications

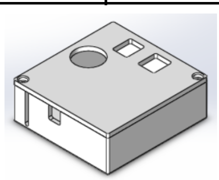


Figure 1a

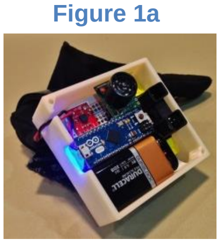


Figure 1b

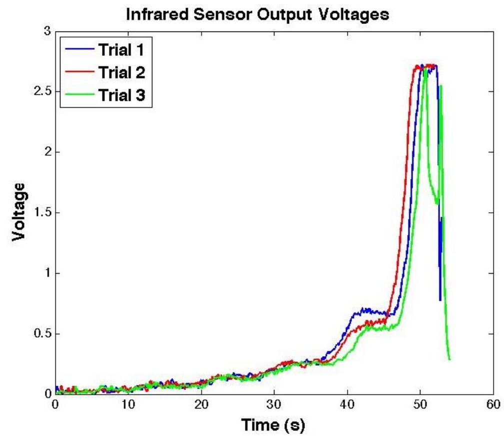
Figure 1c

Figure 1a: SolidWorks Assembly model of casing designed for hand mounted device. **Figure 1b:** Our final prototype design for the sensory substitution mobility aid. The device is show with the top off and mounted on a black glove. Inside, there is an Arduino microprocessor, ultrasound and infrared sensors, an accelerometer, and a 9V battery. **Figure 1c:** Our final prototype design on a user

We have created a more intuitive and accurate sensory substitution device by incorporating active sensing (Figure 1). Active sensing is the ability to change the region of observation upon demand, similar to how normal eyesight functions. The visual system relies on changing the region of focus rapidly to analyze and construct a detailed observation of the surroundings.[12] This device incorporates active sensing by allowing the user to employ hand motions to change the area under inspection based on hand orientation. We have integrated the device into a glove so the hand is free and the user can use a cane or perform other tasks with the mobility aid still on, unlike the Mini Guide.

Another innovative design specification is the detection of head-height obstacles. Users can scan in front of themselves to see if there are oncoming head-level obstacles. By directing the back of the hand towards the area near the head while keeping the hand down by the waist, one can determine if there is object at head-height. An ultrasonic sensor in conjunction with the device will emit, receive, and output a response to the user every 20ms (50Hz). This speed allows the user to move the device at a natural 0.5 Hz oscillating pace from his side and to his front. The range of the sensor allows the user to keep their hand at their side as they walk. This allows the user to use the device in a very comfortable and natural state.

Our device is also designed specifically to warn the user of sharp changes in elevation such as steps, ditches, and holes. The user will be notified via vibration to the index finger if the device tracks a change in depth. This allows the user to avoid drop-offs and obstructions, navigate past them, or observe them without making physical contact. A common limitation in using ultrasound as a detection method is poor detection of sharp changes in elevation. The reflected ultrasound signal returning from the ground back to the device is weak because the ground far ahead is almost parallel to the propagation of the sound wave. Therefore, when there is a change in elevation, the contrast between the returning signal from the ground and the immediate lack of returning signal from the drop-off is very small. Our device relies on infrared sensors to detect drop offs. Despite the infrared sensor also emitting and measuring a reflected signal, the amount of return signal is much greater than that of ultrasound. The infrared sensor has a very small breadth of detection allowing for very accurate depth information, which is ideal for localizing the distance to a drop off. Our use of an infrared sensor is our approach to the problem of detecting drop offs.



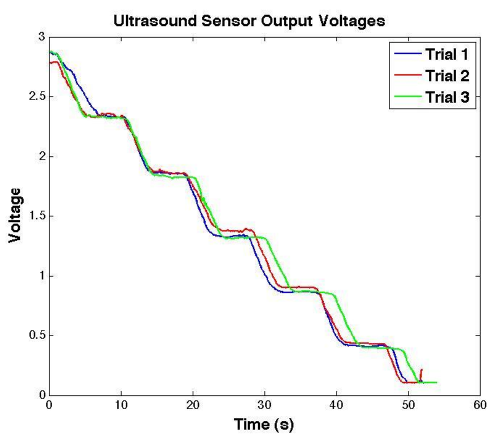


Figure 2: The infrared (top) and ultrasound (bottom) sensor output voltage data are plotted against time. Starting from 5 meters away from a wall, the sensor is moved 1 meter towards the wall every 5 seconds and is then still for 5 seconds.

A simple test was conducted to determine the relationship between the output voltages from the sensors and the distance to the object. The user carrying the sensor would approach a wall in intervals of ten seconds. The subject would proceed one meter in five seconds, then stay stationary for another five seconds before continuing. The IR and ultrasound sensor data can be found in the upper plot and lower plots in Figure 2. The voltage-to-distance mapping equations were found for both sensors.

$$d_{ult} = 2.04v + 0.1$$

$$d_{ir} = 506.4 - 512.6v + 382.3v^2 - 129v^3 + 16.3v^4$$

As can be seen, the IR sensor voltage to distance mapping is nonlinear and is approximated with a fourth order polynomial. The sampled output voltages from the sensors were mapped to distances and then the information was processed to present the user with vibration response.

Lastly and most importantly, our device utilizes the information from an accelerometer to detect the orientation and motion of the hand. Based on this information, the Arduino can use different methods of detection and actuation. This results in a device that is more responsive to the users' objectives. A total of three models were created with two models utilizing the accelerometer information. The first model directly reads the voltage from the sensor, converts the data to a distance, and maps the distance to a frequency the user can feel. The second model, called the Threat Warning Model 1, detects the amount of motion the device is experiencing by finding the variance of the accelerometer data within a 500ms window. Using this information, the device can decide whether the user is moving the device back-and-forth to obtain general information of the area or if the user's hand is steady in order to observe specific details in the surrounding environment. When the accelerometer reads that the user is greatly moving the device, the ultrasonic sensor is used because it has a wide angle of detection. This allows for quick detection of head-height objects and upcoming objects on the ground. However, when the user wants to observe an obstruction after being warned of its presence, they will slowly direct the device in the area of the object. In this instance, the device will begin to implement the infrared sensor because it will provide the user with an accurate description of the edges of the obstruction. The third model called the Threat Warning Model 2 uses the accelerometer to measure the pitch angle of the device. This will provide information as to whether the device is directed towards the ground or above the user. With this information, the microcontroller is set to use the infrared sensor when the device is directed towards the ground. The microcontroller will then read the input voltage from the infrared sensor and map it to a distance. It will compare the distance reading with a normal, flat ground reading for the corresponding pitch angle. The normal flat ground reading is given by the following equation:

$$\textbf{Equation 1}: \quad D = \frac{d_i}{\cos(\theta)}$$

D is the distance from the sensor to the ground and theta is the angle normal to the ground. The numerator value of d_i was set to 0.75 because the approximate distance from the ground to the user's hand resting at their side is roughly 0.75 meters. If the distance reading from the infrared sensor was above a given tolerance, then a warning would be given to the user. The tolerance was set similarly to the formula from Equation 1 but with a d_i of 1 meter. When the user directs the device slightly forward and upward, the ultrasonic sensor is activated. Objects that are well above the user's head are not of interest and would not provide useful information to the user. Therefore, Equation 1 was used to create a threshold distance for varying angles with a d_i of 1 meter. If the recorded distance measurement from the ultrasound was found to be greater than the distance threshold, then no warning is given to the user. Table 1 shows a list of each model and their descriptions.

Table 1: This table shows a list of the three device models, describing which sensors are used, the use of the accelerometer, and a brief summary of the description.

Model	Sensors Used	Accelerometer	Description
Direct Ultrasound Or Infrared Range Detection	Ultrasound or Infrared	No use	Either Ultrasound or Infrared is programmed to be used. Simple voltage to frequency mapping is utilized.
Threat Warning Model 1	Ultrasound and Infrared	Measures the amount of hand movement	During a general scan of the environment, a fast sweeping motion is used, cueing the ultrasound to be used. To localize objects, the movement of the hand is greatly reduced, cueing the infrared sensor.
Threat Warning Model 2	Ultrasound and Infrared	Determines pitch angle of the device	Depending on the pitch angle of device the sensor will switch from ultrasound (-30 to 90 degrees) to infrared (-30 to -90 degrees). When directed downwards, the microcontroller will compare the distance readings to normal flat ground distance measurements to detect drop-offs.

Actuation System

We created a communication system that would reduce the amount of environmental information lost to the user. In order to do this we began with the Weber-Fechner Law of Perception:

$$\textbf{Equation 2}: \quad change\ in\ perception = k\frac{change\ in\ frequency}{\text{applied frequency}}$$

The magnitude of change in perception should decrease as the applied frequency increases.[13] Through experimentation, the optimal distance frequency mapping was found. This was done by testing various frequency jumps: specifically, 1, 5, 10, 20, 50, and 100 Hz intervals from applied frequencies of 0 to 200Hz. The subject wore headphones, was blindfolded, and placed their finger on the small speaker within the mounting glove. Then two different frequencies were emitted in succession. The subject then indicated if they perceived a change and whether the change was an increase or decrease in frequency. Figure 3 (left) shows the results of the 5Hz perception test. The results of the other frequency jumps were analyzed and the applied frequencies that exceeded 80% correct were extracted: in the 5Hz test, that meant the applied frequencies up to 15Hz were considered successful. Those frequency sets were compiled and used to create the Frequency vs. Frequency Change graph shown in Figure 3 (center). With this graph, we were able to solve for the k constant, which is the slope.

However, the relationship we want to obtain is the device's frequency output as a function of distance. To obtain this, we integrate the Weber-Fechner Law (Equation 2), solve for the applied frequency, and substitute Perception for Inverse Distance, which works because we want a lower percept for a larger distance.

$$\textbf{Equation 3}: \quad \boldsymbol{Applied\ Frequency = ke^{Perception} = ke^{-Distance}}$$

As we already know the constant k, we were able to solve for the exponential equation $\mathbf{y = 631e^{-2.08x}}$, which is utilized in our microprocessor to determine the vibrational output response for the user. Figure 3 (right) shows the graph of this relationship.

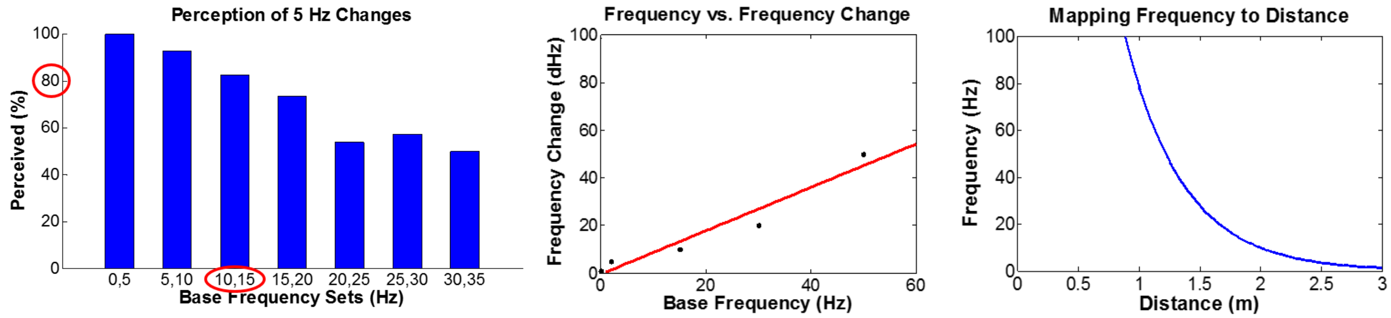


Figure 3: The left graph shows the 5Hz perception test over various applied frequencies. 15Hz was the maximum applied frequency where the subject could feel the change in perception at least 80% of the time. The center graph shows the other frequency changes for the 80% perception test. The slope of this relationship solves for the k constant in equation 2. The right graph displays the exponential equation $y = 631e^{-2.08x}$ and shows the frequencies the device will output depending on the distance from the threat.

<u>Device Testing</u>

We conducted informal testing to see the accuracy and precision of the Direct Ultrasound/Infrared Range Detector Model and the Threat Warning Model 2 of our device in identifying objects of various sizes. Shown in Figure 4, the objects were placed at 1m, 2m, and 3m away from the subject, who stood at the vertex of the testing area. From there, small, medium, and large objects were individually placed within a range of 1, 2 or 3 meters for the ground level objects. For head height objects, distances of 0.5, 1 and 1.5 meters were used. The subject was blindfolded and wore noise cancelling headphones as they searched for threats and located the object based on the device's vibratory feedback. The second experiment for both models involved the identification of drop-offs. Finally, Model 1 was not exclusively tested as its results were expected to be similar to that of Model 0 since the use of the sensors is identical but with the additional ability to select a specific sensor.

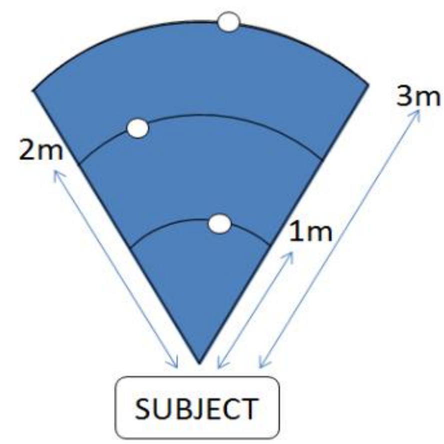


Figure 4: This diagram shows the setup of the experimental trials to detect obstacles with the different models.

RESULTS

The accuracy and precision of the Direct Ultrasound/Infrared Range Detector Model and the Threat Warning Model 2 were observed through identification of head and ground level objects of various sizes and distances (Figures 5-7**).** The error bars factor in the identification of surrounding objects within the detection radius. Therefore, it is predicted the results would be greater in open spaces and worse is cluttered environments.

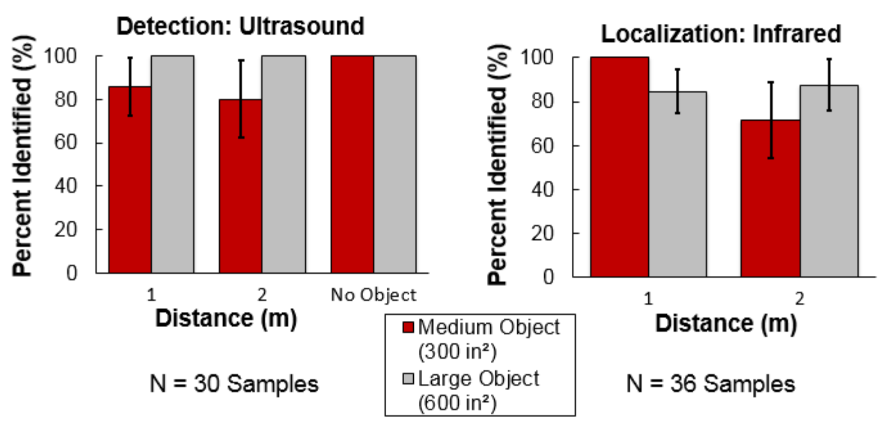


Figure 5: Ground-Level Object detection for medium, and large objects over various distances. The left shows the Direct Ultrasound with 30 samples while the right shows the Direct Infrared with 36 samples.

For the experiment in Figure 5, the device used the ultrasound sensor to detect ground-level obstacles and the infrared sensor to locate them. There was almost a 100% correct detection of the large objects at all distances. For medium objects, the majority were detected across 1 and 2 meters but were almost never identified at 3 meters. It was expected that the objects would become more difficult to detect at longer distances and harder to localize. This is most likely due to the fact that the changes in distance measurements from the object the adjacent ground are very small.

The head-level object results (Figure 6) again show that the medium and large objects were successful identified. At 1.5 m, small obstacles could not be identified. Notably, obstacles at 1.5 m ahead are not imminent collisions, especially when they can be detected as the user approaches these objects. Moreover, the Threat Warning 2 Model could be used effectively indoors to detect head-level obstacles. Even with ceilings, the Model was created to ignore objects above the users head based on the pitch angle of the device.

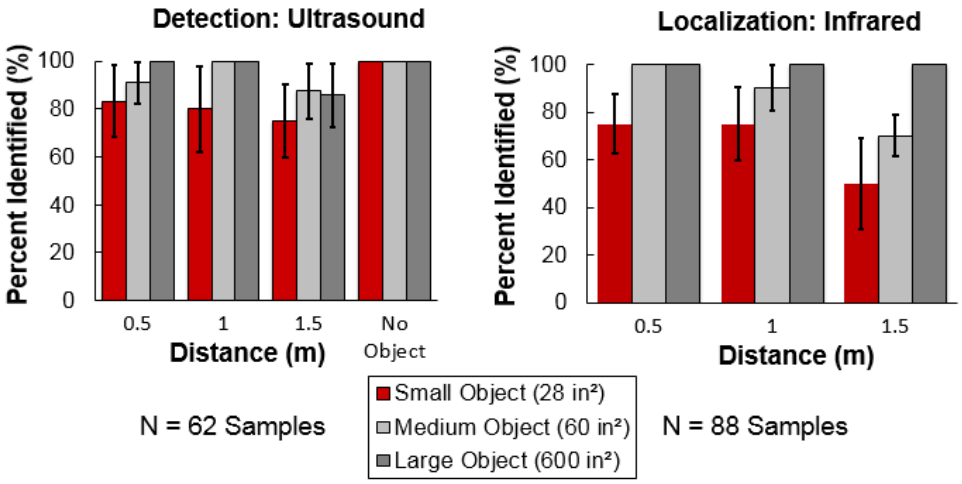


Figure 6: Head-Level Object Detection for small, medium, and large objects over various distances. The left shows the Direct Ultrasound with 62 samples while the right shows the Direct Infrared with 88 samples.

The ability of the Direct/Fixed IR Detection Model to detect a downward staircase was examined. The subject was randomly placed various distances from the drop off then the subject indicated if a drop off was present and approximately how far. The results of the study are shown in Figure 8. It was concluded that the increase in distance from the device as the user tilts the device more parallel, masks the change in distance in the presence of a drop off. This resulted in correct identification of about 50%, which is the result of random guessing in Bernoulli's equation.

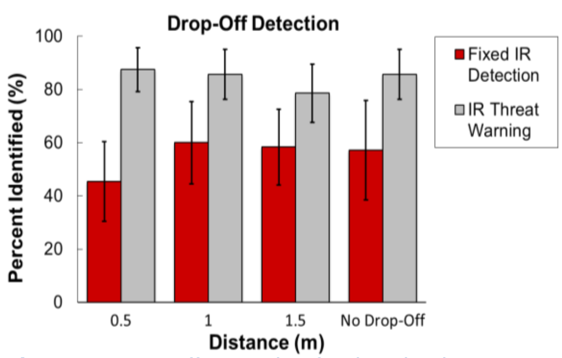


Figure 7: Drop-off Detection for the Fixed IR Detection and IR Threat Warning models. Each model has its own respective error. The subject was also placed in front of no drop-off and asked to identify that as well. 40 samples were taken for Model 0. 58 samples were taken for Model 2.

The ability of The IR Threat Warning Model 2 to detect drop offs was also measured. The change in pitch angle was designed for drop-offs specifically. The measured distance from the IR sensor at a specific pitch angle is compared to the expected distance at the same pitch angle. When there is a large discrepancy between the two measurements, a warning is given to the user. When the device was used properly, the accuracy of the model was just below 100%. Error arose when the device was off center or the device was angled too high. At a large enough angle, the sensor switches to ultrasound, giving a reading for obstacles. Sometimes, this reading was mistaken for a drop-off. Through active learning, the user was able to determine which angle emitted IR and which was ultrasound. The user's quickly adapted and learned how to use the device; however, slight modifications to the industrial design of the device can quickly remove the associated issues.

The sensory substitution glove has shown promising results in its ability to detect and locate threats while the user is static. The next step is to see how well the device performs in a more formal testing situation, where the user is mobile. After obtaining those results, we would expect further modification and reprogramming of the device to better detect and locate threats. In the future, feedback about our device from white cane users is necessary for improvement. We envision that the sensory substitution glove will one day be widely adopted by the visually-impaired.

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