ABSTRACT
Navigation and obstacle avoidance, especially regarding head-level objects, are of major concern to visually impaired people. This paper describes the advances on the design of an augmented white cane, STIC (Sensory and Tactile Improved Cane), making use of an ultrasonic distance sensor for head-level and a laser-based distance sensor for ground-level obstacle detection. The distance information is encoded via vibrotactile actuators. Additionally, a novel approach to retain obstacle information with the help of haptic Afterimages is presented. Finally, the discriminability of distances based on the vibrotactile feedback was measured via a psychometric study. Objects shifting by more than 13.58 cm yield a 90% detection accuracy.

KEYWORDS
visually impaired, obstacle detection, portable device, white cane, smart cane, psychometric study, tactile feedback

1 INTRODUCTION
Determining the position of obstacles is a challenging task in the daily life of the visually impaired. According to Manduchi and Kurniawan, “Head-level and fall accidents represent a non-negligible risk associated with walking without sight.” [9]. They report that head-level accidents leading to medical consequences are often compensated by a lower walking speed. A white cane is the de-facto tool for visually impaired persons (VIPs) to navigate and avoid crashes [9]. Nevertheless, it lacks the ability to detect objects above floor level. Therefore so-called smart canes make use of ultrasonic or infrared sensors which obtain distance and position of obstacles [8]. Auditory or vibrotactile feedback patterns are needed to encode and deliver relevant information to the user in a comprehensible way. This work introduces the Sensory and Tactile Improved Cane (STIC), another smart cane design and a novel approach to maintain obstacle information in an actuator array via haptic Afterimages. A psychometric study is conducted evaluating the discernability of an object’s longitudinal motion relative to the participant based on the vibrotactile feedback.

2 RELATED WORK
Results from recent studies suggest that VIPs experience improved perception throughout other senses such as hearing and the sense of touch [4, 6]. White canes make use of the haptic sense but typically lack in detecting objects above floor-level. Therefore attempts have been made to augment white canes with additional sensors for detecting obstacles e.g. hanging signs, low door frames, etc. (see UltraCane[2], WeWALK[1], GuideCane [12]). Wang et al. implemented HALO, an attachable device for white canes consisting of an ultrasonic sensor and a vibrating motor. It responds to low-hanging obstacles by providing vibrotactile feedback [15]. Additionally, navigating along predefined paths has been realized by tactile and auditive feedback via a smart cane [10]. The NavBelt, an obstacle-avoidance system, consisting of 8 ultrasonic sensors to scan the environment, provides binaural audio feedback. Its downside is the aggravation of putting it on [11].
STIC Layout
The current STIC prototype (Figure 1) mimics a typical white cane and consists of a wooden stick with a plastic ball attached to the lower end and a 3D printed plastic ergonomic handle attached to the upper end. Furthermore, two sensors - an infrared sensor and an ultrasonic sensor - are part of the cane. The infrared sensor aims to detect obstacles at ground-level and is placed near the stick’s bottom end and aligned horizontally. The ultrasonic sensor is located at the height of the user’s knee and points orthogonally from the stick in a diagonally upwards direction, detecting objects placed in front of the user’s head. The STIC’s electronics are wrapped in a case, placed near the handle on its lower side to minimize the force needed to balance and sweep the cane.

Figure 1: The design of the STIC. The image shows the placement of the sensors, the Arduino board, and the handle.

All in all, the STIC is 151cm long and weighs 477 grams. The wooden sticks diameter is 1.5cm and the ballpoint diameter is 5cm. The container for the Arduino board is formed in length 17cm, width 8.5cm and height 3cm.

Handle Layout
The two-point discriminability on the palm amounts to about (~9mm) to (~10mm) with similar numbers having been found for point localization distances. Also, pressure sensitivity evoked by vibrotactile stimuli is reported to be at a maximum between 220Hz and 300Hz [16]. The frequency for vibrotactile stimuli was set to 240Hz and the handle layout was designed to leave at minimum 11mm space between the five used piezo actuators.

Feedback Function
Based on the sensor capabilities, we defined the detection range to be 20cm to 300cm. A function maps the sensor’s measured distance to a frequency of the actuator activations.

\[ f(x) = a_{\text{max}} \times \left( \frac{a_{\text{min}}}{a_{\text{max}}} \right)^{\frac{x-d_{\text{min}}}{d_{\text{max}}-d_{\text{min}}}} \]  

\[ \frac{f(x_1)}{f(x_1-a)} = \frac{f(x_2)}{f(x_2-a)} \]  

This exponential decay function maps the minimum distance to the maximum activation frequency and vice versa (Equation 1), for the maximum and minimum activation frequency \( a_{\text{max}}, a_{\text{min}} \) as well as the maximum and minimum distances \( d_{\text{max}}, d_{\text{min}} \). Based on tests with the STIC and software limitations, the activation frequencies minimum and maximum were set to 1Hz and 7Hz. The previous function was chosen because it satisfies the “same offset — same ratio” property (Equation 2), which is essential since the perceived differences of activation frequencies correspond exponentially with the measured distances.

Afterimage Technology
This section aims to introduce a novel technology which is referred to as Afterimage Technology. Typical smart canes [1, 2, 12] are excellent approaches for obstacle detection, but they are limited to obstacle information directly in front of a cane user. When the cane is turned away, the information is lost. Afterimage Technology adds some obstacle memory to the feedback encoded by three additional actuators placed on the handle’s bottom side (see Figure 2: west, north and east), which form a 1-D haptic display.

On detection, an obstacle’s distance is recorded and remains in memory for a specified lifetime. Since the goal of the cane is to detect knee-level up to head-level obstacles, the data from the ultrasonic sensor is used for the Afterimages. If the ultrasonic sensor detects an object and the cane is rotated around the user’s z-axis, the Afterimage wanders precisely in the opposite direction given the same angle. Hence the actuator that now points at the obstacle, is activated the most. The information about the cane’s orientation is accessed via an IMU placed on the Arduino board and is updated continuously. For determining the strength at which an Afterimage actuator shall vibrate, the amplitude is manipulated according to the match between actuator placement and amount of shifting, as well as the time since the Afterimage was recorded. The activation frequency stays the same for all actuators for one Afterimage over its lifetime and is determined.
by the recorded distance of the detected object as described in the Feedback Function section. To determine the match between the angle in which an Afterimage was recorded and the angle a given actuator is assigned to, a Gauss-like function is used given by the following equation:

\[
A_{T, \sigma, \phi}(x) = T \ast \exp\left(-0.5 \ast \left(\frac{1}{\sigma \ast (\phi - x)}\right)^2\right), \quad (3)
\]

where \(A \in [0, 1]\) is the feedback amplitude, \(T = 1 - \frac{T_{\text{lifet ime}}}{T_{\text{stored}}}\) is the lifetime dependent falloff factor, \(\sigma\) is the spread of the Gauss-like curve (in this example \(\sigma = \frac{90}{N_{\text{act}}}\) with \(N_{\text{act}}\) the number of actuators used) and \(\phi\) the offset relative to the canes global rotation. Figure 3(left) shows the Gauss-like function directly after the initialization of an Afterimage i.e., an object detected by the ultrasonic sensor. The following rotation around 45 to the right results in the corresponding Gauss-like function shifting along its x-axis by \(-45\) and diminishing by the elapsed time since initialization, as seen in Figure 3(right). In this case, the west actuator (allocated to \(-60\)) will provide feedback by about 40% of the maximum amplitude and the north actuator by about 10%. When the Afterimages lifetime is over the device will be ready to receive the distance of the next detected obstacle which generates a new Afterimage.

4 PSYCHOMETRIC STUDY

A study was conducted to calculate the psychometric function, which depends on the vibrotactile feedback. Feedback was given by one single vibrating actuator which was related to the detection of head-level obstacles. The psychometric function determines the minimum change in stimulus intensity that is perceptible by a person. Regarding a smart cane, the function shows the perceptible distance change in the depth relative to the user that can be detected with a certain probability. The goal was to calculate the minimum distance shift that is necessary to be at least 90% sure whether the object moves towards or away from the sensor.

Equipment and Software

The embedded code is executed on an Arduino-compatible microcontroller\(^1\) based on an ARM Cortex M0 processor, clocked at 48 MHz at 3.3V, and featuring Bluetooth Low Energy. Two sensors support distance estimation. First, a high-performance optical distance measurement sensor\(^2\), based on an edge-emitting, 905nm (1.3 watts), single-stripe laser transmitter with a 0-40m range and an accuracy of +/- 2.5cm. Second, an ultrasonic distance-sensor\(^3\) with a calibrated beam pattern with a resolution of 1 inch, a 20Hz reading rate, and a range starting from 6 inches to 254 inches. In order to provide vibrotactile feedback, the unit contains five haptic drivers\(^4\) controlling piezo discs with a 9mm diameter. The piezo haptic driver integrates a 105-V boost switch, an amplifier, and supports overdriving and active-breaking. The tactile signals can be parameterized by frequency and amplitude simultaneously, as well as envelopes and the beginning/end of the signal.

For the current prototype, the Unity3D game engine running on an external PC is used to compute the feedback using the feedback function described above. The sensors are connected to the microcontroller, which reads their data and calculates distances. These distances are transmitted to Unity3D via Bluetooth. After computing the tactile feedback based on the measured distances, signal are sent back to the microcontroller, which then controls the piezo actuators.

Design

For measuring the discriminability of the feedback function, an experimental room was set up, in which the total distance

---

that is covered by the distance sensor was marked on the floor. Four reference points from near to far (55, 125, 195 and 265 centimeters) were determined to cover the whole spectrum of possible object distances. A box was placed on the respective reference point and shifted by 5, 10, 15, 20, 25 or 30 centimeters closer to the participant (negative shift) or further afar (positive shift). After each shift, the participant had to decide whether the box was shifted further away or closer in depth. The participant was blindfolded and received white noise over noise-canceling headphones. The only cue presented was feedback given by one actuator on the handle, and every participant was instructed to place the thumb of their dominant hand on the actuator. Before shifting the box another time, it was placed back on the reference point to offer participants the opportunity to memorize the vibrational pattern once again. Per reference point, each shift ranging from 5 until 30 centimeters was presented two times as well as in both the negative and positive direction. The closest possible obstacle distance was 25cm, and the farthest possible was 295cm. The order was always the same, starting from the closest reference point up to the last reference point. After 24 decisions, the reference point was changed, and the participant could have a short break if preferred. A total of 96 decisions have been recorded per participant.

Results
Each participant experienced 48 positive and 48 negative shiftings. Data from 6 (4 male, 2 female; age: 23-36, M = 26.33, SD = 4.93) participants were collected for a total of 288 negative as well as the same amount of positive shiftings. A paired T-Test comparing the two shifting directions positive (M = 0.91, SD = 0.08) and negative (M = 0.93, SD = 0.08) presented no significant difference, t(5) = -1.22, p > 0.05.

Since there were no significant differences according to the previous test, the Pearson correlation was computed regarding the absolute value of the shift and the probability of correct answers (M = 0.92, SD = 0.08). The result indicates a strong correlation (Pearson’s r(4)= 0.91, p < 0.05). In total, 96 trials were completed by every participant (24 per reference point). The mean number of wrong answers was 7.33 (SD = 2.92) across all participants. The best and worst performing participants had an error rate of about 4% and about 12% respectively. Figure 5 (left) shows the error rates across all reference points. There were 144 conducted trials for each reference point. Mean probability of false decisions across all reference points is given with 7.64% meaning 11.00 (SD = 3.74) wrong decisions. Figure 5 (right) shows the error rate across all distance differences from the object to the point of reference. Each distance of the object to a reference point had 48 corresponding trials. The mean of the number of errors across all distance differences was 3.67 (SD = 3.59). A non-parametric Friedman test yielded no significant difference regarding the different reference points concerning the error rate, \( \chi^2(3) = 5.95, p > 0.1 \). In order to determine the psychometric function, a model was used which predicted the values between the discrete shifting steps of 5cm. Also, a shift lower than 5cm has not been assessed and the probability is expected to reach 50% for an infinite small shift close to 0cm. The data has been extended with the respective values for the 0cm shift. This procedure resulted in a probabilistic distribution which allowed to compute the threshold at which at least 90% of forced choices were expected to be correct. The threshold for negative shifts is given at 12.34cm, 95% CI [10.15cm, 15.88cm]. Whereas the threshold for positive shifts is given at 14.56cm, 95% CI [12.22cm, 17.48cm]. Since there is no difference assumed between negative and positive shifting, the psychometric function for absolute shifts was calculated, with a threshold at 13.58cm, 95% CI [11.64cm, 15.56cm]. Using the same model for absolute shifts, the 80% threshold for the minimum necessary distance shift decreases to 8.24cm, 95% CI [6.70cm, 10.09cm].
Taking into account the model that was calculated for the absolute shifting, the psychometric function describes the relationship between the difference in obstacle distances and the probability to decide correctly whether the obstacle was moved closer or further apart. Given a minimum distance shift of 12.33 cm, the participants could determine the direction of shifts with a probability of 90% on a whole spectrum ranging from 20 cm to 300 cm. Most notable is the higher error rate for the first reference point in comparison to the other ones as seen in Figure 5 and the counter-intuitive distribution of errors in the negative distance differences, i.e., when the object was moved closer to the sensor. Although not significant, the hypothesis is formulated that one reason for this was the limitations of the hardware and software implementation at the time of the study. Empirical testing and feedback from most participants suggested an issue with the feedback in which the activation frequency was more irregular when an object is placed in the front, closer to the sensor. The effect was only notable in the range of the first reference point, hence the higher corresponding error rate. Furthermore, the effect also slightly biased negative distance differences towards a higher error rate, which partly explains the observed distribution of error rates seen in Figure 5. Another possible reason for the higher error rate while conducting trials concerning the first reference point is the order of reference points for each participant.

5 DISCUSSION

According to a pilot study, the use of stronger actuators is vital to avoid a masking of the tactile feedback by the motion of the ballpoint over rough ground. Another related topic is the use of STIC in cold weather. If the user decides to wear gloves, the sensitivity to the actuator activations diminishes severely.

So far, STIC uses a constant frequency for its vibrotactile feedback; this bears the risk of an adaption effect [13]. In this case, the user’s subjective magnitude could decrease, which could lead to a weakened perception of possible dangers. However, such an adaption effect is avoidable by switching between different frequencies.

Due to limitations of the layout for most sensitive locations for vibrotactile feedback on the human hand and the number of actuators the prototype should use, it was not possible to design a handle which accommodates to the usual way a VIP holds a white cane. However, STIC’s ergonomic designed handle creates a haptic affordance and is comfortable to hold. Whether users of traditional white canes prefer conventional handles over STIC’s one, has not been determined yet.

6 CONCLUSION AND FUTURE WORK

This article presented the design and implementation of STIC - an enhanced white cane. Making use of an ultrasonic distance sensor and tactile actuators, STIC aims to help visually impaired people to avoid obstacles by encoding the distance of detected objects as an activation frequency of the tactile actuators. In the course of a study, participants were asked to discriminate whether a presented obstacle was moved closer or further apart. The results indicate a high rate of correct answers (90%). Additionally, Afterimages – a theoretical novel approach to improve obstacle avoidance – was presented. Further research will include an obstacle course study to test the Afterimage Technology and obstacle avoidance capability. Additional optimizations are ongoing, related to handle ergonomics, weight reduction, quality improvement of the vibrotactile feedback as well as testing novel actuators (e.g., audio-based haptic actuators/reactors) and wearable time-of-flight (ToF) distance sensors.

REFERENCES


