CANE: A Wearable Computer-Assisted Navigation Engine for the Visually Impaired

Seth Polsley
Sketch Recognition Lab
Texas A&M University
spolsley@tamu.edu

Vijay Rajanna
Sketch Recognition Lab
Texas A&M University
vijay.drajanna@gmail.com

Larry Powell
Sketch Recognition Lab
Texas A&M University
larry.powell@tamu.edu

Kodi Tapie
Sketch Recognition Lab
Texas A&M University
kstapie@tamu.edu

Tracy Hammond
Sketch Recognition Lab
Texas A&M University
hammond@tamu.edu

ABSTRACT

Navigating unfamiliar environments can be difficult for the visually impaired, so many assistive technologies have been developed to augment these users' spatial awareness. Existing technologies are limited in their adoption because of various reasons like size, cost, and reduction of situational awareness. In this paper, we present **CANE**: "Computer Assisted Navigation Engine," a low cost, wearable, and haptic-assisted navigation system for the visually impaired. CANE is a "smart belt," providing feedback through vibration units lining the inside of the belt so that it does not interfere with the user's other senses. CANE was evaluated by both visually impaired and sighted users who simulated visual impairment using blindfolds, and the feedback shows that it improved their spatial awareness allowing the users to successfully navigate the course without any additional aids. CANE as a comprehensive navigation assistant has high potential for wide adoption because it is inexpensive, reliable, convenient, and compact.

Author Keywords

Visually impaired; Wearable; Haptic assisted; Navigation system; Ultrasonic sensors; Non-intrusive; Ubiquitous; Internet of Things

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation: User Interfaces—*Haptics I/O*

IUI 2016 Workshop: A joint Workshop on Smart Connected and Wearable Things, March 10th, 2016, Sonoma, CA, USA

urn:nbn:de:tuda-tuprints-54208

INTRODUCTION

Most people rely heavily on their sight when navigating unfamiliar environments. While vision is an important sense in many daily tasks, it becomes crucial to the capability to explore and wander new places freely. Even with other senses to help cope with the loss of sight, the visually impaired can still be limited in their ability to explore new environments. Studies have shown that only about one quarter of working age blind individuals are employed [20] and nearly every blind individual can struggle with day-to-day tasks at some point. It is important for the visually impaired to be able to explore in order to be immersed in ordinary life, but it is easy to imagine how difficult wandering new places can be. "My biggest fear is being alone in a huge parking lot with nothing around me and no sounds," says one blind man from our user study about exploring outside. Because of a combination of healthcare costs, concerns over quality of life, and the fact that the number of visually impaired individuals increases yearly [11], there is a strong motivation to help solve the problems faced by these individuals.

Researchers have spent years trying to find better ways to accommodate the visually impaired to ensure that they can enjoy the same opportunities and capabilities as normal-sighted individuals; independent mobility is one such valuable capability. There are several traditional solutions outlined by Strumillo [15] that have long been available, but these methods have their limitations. Guide dogs have been used for many years as a means of helping the visually impaired, but in addition to needing care like any other dog, their training is time consuming and expensive. A human caregiver can help alleviate many issues faced by the visually impaired, but this solution inherently limits independence. White canes are a common alternative that allow their users to reclaim some independence, but despite the low cost and efficiency in detecting obstacles, there are still restrictions on how much canes can detect, especially at levels above the waist. Unsurprisingly, researchers have turned to technology in recent years as a possible means of navigation for the visually impaired that is inexpensive, convenient, and reliable.

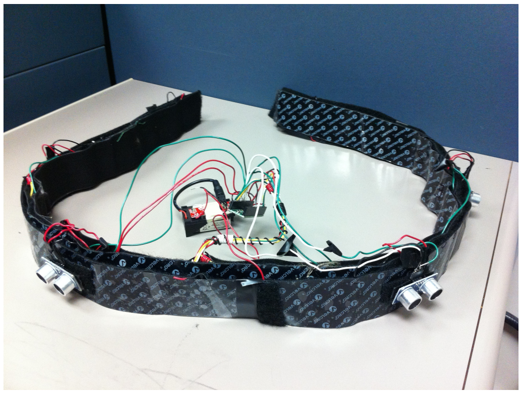
a 

Figure 1: The complete CANE system with the sensors on the outside edge and the vibration units hidden inside.

This work introduces the Computer-Assisted Navigation Engine (CANE) for assisting visually impaired individuals in the form of a wearable “smart belt.” As with any such system, CANE is intended to promote increased mobility and independence, but it was built around several design principles that provide advantages over other blind navigation technologies. First and foremost is the advantage of it being a wearable device that can interact with other mobile devices over wireless communication. CANE uses on-board ultrasonic sensors and vibration motors to give users vibrotactile-based directions in an indoor environment, and the system can be further extended to integrate with the Internet of Things (IoT) for enhanced navigational support. The built-in sensors can detect the proximity of objects to the user, as well as their location within the sensor’s field of view. This information is used to provide real-time vibrotactile feedback for guiding the user. Because the sensors are spread around the front, CANE reduces the need for sweeping motions, such as those made with physical canes or many other sensor-equipped feedback systems. Furthermore, not only is it designed to be lightweight and inexpensive, the fact that it can be worn as a normal belt makes it less conspicuous than larger, more complex systems. This is also aided by its simple design that excludes headsets, helmets, or other highly noticeable components. Because the visually impaired rely strongly on their other senses, such as sound, CANE does not use any audio feedback or cover their face, which could be distracting. By using the sense of touch, CANE behaves much more like traditional navigational tools like physical canes or guide dogs. A pictorial depiction of CANE is shown in Figure 1. In order to understand the robustness and potential impact of CANE, it was tested on normal-sighted users first and then on visually impaired users. The sighted users were asked to navigate blindfolded in an unfamiliar environment while being assisted by CANE. During post-study interviews a majority of these users shared that, although they were apprehensive at the beginning of the study, they adapted quickly to using CANE. Further, CANE was tested by two visually impaired individuals. Experiences shared following testing with both the normal-sighted and visually impaired users showed that the feedback from CANE was reliable and intuitive, although additional sensors may be beneficial. In particular, users liked CANE’s affordability, wearability as a belt, and small form factor.

The remaining sections are organized as follows. First, we will discuss the related works in the area of assistive technologies for the visually impaired and how they differ from CANE. After the discussion of related works we describe the system design and implementation. The experimental design section then explains the procedures followed during the user studies. We subsequently present the results of our user studies and discuss the key findings. Finally, we conclude with a brief discussion of the areas of improvement for CANE, and the future of low cost, wearable, inconspicuous, assistive technology for the visually impaired.

PRIOR WORK

Many visual impairment navigation technologies have been developed that combine wearables with sensors, global positioning, and some means of feedback for guiding users. Unfortunately, a technological solution has yet to gain widespread adoption, which is perhaps due to issues with many current solutions.

Cost and size are significant barriers for some technologies. Willis and Helal proposed a grid of RFID chips be created to pair with their wearable system for navigation, but the RFID chips must be installed everywhere the system is intended to be used [20]. This carries a large upfront cost and necessary infrastructure before users would begin to benefit in unfamiliar terrain. Ran et al., proposed Drishti, a system combining ultrasound and GPS for both indoor and outdoor navigation [11]. While an ultrasound-based wearable is less expensive than requiring an external grid, Drishti weighs around 8 pounds and includes a waist strap and headset for voice control and audio feedback, making it very noticeable. Some visually impaired users may be hesitant to wear such a device due to its size and weight; they may also feel more comfortable with smaller devices that are less conspicuous. It has been shown that blindness can carry with it physical and mental health implications, and it can have an impact on an individual’s self-esteem [17]. Related to the size of a navigation system is the number of components. Dakopoulos and Bourbakis presented four major findings in his survey of visually impaired navigation and obstacle detection systems, and one of them is that the system should be hands-free [5]. He argues that users will always feel more comfortable if they have the option to hold a traditional cane alongside the system. Tools like Borenstein’s second iteration of the Navbelt included a cane as part of the navigation system, restricting the user’s choice [14]. The limitations of these works reflect that guidance systems should aim to be subtle, small, and lightweight.

The feedback system is also very important to consider when looking at these technologies. Two of Dakopoulos’ and Bourbakis’ other findings both relate to the feedback system—it should be simple and not obstruct hearing [5]. Simplicity is an important concept in every human-computer interaction system. Keeping the ears free is a less obvious requirement, and many existing systems ignore this design recommendation. However, research has shown that the blind come to rely more heavily on their hearing than normal-sighted individuals, with parts of their visual cortex even being re-purposed for auditory processing [16]. Given the importance of sound in their interactions with the environment, a navigation system that provides auditory feedback may actually be an impediment. One of the earliest ultrasonic-based navigation systems, Navbelt from the University of Michigan, required the user to wear a set of headphones to receive the feedback from the sensors [13]. The successor system also could only provide feedback via headphones [14]. NOPPA, developed by Ari and Sami, is a mobile guidance system that pairs obstacle detection and GPS to direct users [18]; unfortunately, its only means of interfacing is done through a speaker and microphone. Even Drishti included a headset [11].

Some systems have been built that use haptic feedback rather than audio. Haptics is a promising approach that solves both of Dakopoulos' and Bourbakis' concerns about the interface. First, the user's hearing is unimpeded, and hence his or her situational awareness remains fully intact. Second, touch can be a very intuitive means of communication, as seen in the widespread usage of touch-enabled devices today. Colwell, et al., created a haptic device for exploring virtual worlds and three-dimensional objects through touch, rather than navigating real-world environments [2]. Similarly, Lahav, et al., used haptics to help blind users build mental maps of new environments, but the technology does not provide real-time feedback to new environments [8]. Many other works have examined the usage of haptics as a means of increasing mobility for the visually impaired and encouraging the development of mental maps, but much of this work focuses around virtual environments [3, 7, 12]. One of the earliest wearable haptic devices was developed by Ertan, et al. They created a vest that provided a physical map of the environment through a vibrotactile array on the user's back [6]. Unfortunately, this system required ceiling-mounted infrared transceivers to track the user's location and a stored map of the environment in the vest's memory. A similar work was developed by Dakopoulous, et al., in [4] where they used a similar vibrotactile array but received the environment's mapping from a camera-based system. The algorithm was reliable, but users had difficulty interpreting their location relative to obstacles. Researchers at the University of Toronto built a head-mounted vibrotactile system that uses a Kinect to interpret the user's surroundings [9]. While the collision avoidance capabilities are promising, a headset-based solution interferes with hearing and is conspicuous. HALO (Haptic Alerts for Low-hanging Obstacles), an incremental work, integrates ultrasonic sensors and vibrators with a traditional white cane to warn of overhead obstacles [19]. There exist commercial products that perform a similar function, like the SmartCane™ [1]. One of the most similar systems to CANE is the wearable vest developed by Cardin, et al. Like CANE, it features four ultrasonic sensors and eight vibrotactile motors for feedback, but they are placed on the chest, limiting obstacle detection strictly to the horizontal plane at chest level [1]. Another wearable vest using haptic feedback was constructed by Prasad, et al., that also used chest-level sensors for obstacle detection and paired with GPS to provide directions [10].

Unsurprisingly, there has been a lot of research using ultrasonic sensors and audio or haptic feedback as they apply to navigation solutions for the visually impaired. Most haptic-equipped navigation systems have been developed only in recent years, but none of these have been able to present a low-cost, standalone solution that is also inconspicuous and non-restrictive on the user's situational awareness. While it cannot address each concern as well as every system, CANE is designed to provide a balance of all of these aspects, making it a powerful option.

SYSTEM ARCHITECTURE

CANE is a "smart belt" – a wearable, multi-agent, haptics-based assisted navigation system for the visually impaired. CANE uses state of the art technologies like *sonar sensors*, *vibrotactile motors*, and a microcontroller to create a robust, intelligent system that enhances spatial awareness of the visually impaired. One important aspect of CANE that bears mention is its low-cost. The whole system was built at a cost of \$59 comprising of four main electronic components: a) Vibrotactile motors: \$16, b) Ultrasonic sensors: \$8, c) Teensy microcontroller: \$30, and d) Wires and solder: \$5. The system consists of three modules working together: 1) an input array of four ultrasonic sensors, 2) a feedback array of eight vibrotactile motor, and 3) a central control system. The outer module is an array of ultrasonic sensors. These sensors face outward from the front of the belt and are constantly receiving feedback from the environment. This feedback includes information like which sensor is active, for direction purposes, and the distance to an obstacle. The input from the sensor array is used to drive the inner module, the vibration units. There are a total of eight equidistant vibration units lining the inner layer of the belt. Vibrators are activated based on the information provided by the outer sensors, and their intensity level changes according to the proximity of the obstacle. The most important module is the central control system that connects the input to the output, which is implemented on a Teensy++ 2.0 board running software which parses the data provided by the sensor array. It uses the distance measure from a given sensor to activate the associated vibrotactile motors with an appropriate intensity. This module handles most of the system logic and may be extended for communication with other devices for enhanced navigation modes through IoT. A pictorial depiction of the working model is shown in Figure 2.

SYSTEM IMPLEMENTATION

Input Layer of Ultrasonic Sensors

A total of four HC-SR04 ultrasonic sensors[2] are included on CANE to detect obstacles. In early iterations, one pair of sensors was placed outward on the front while the other pair was placed on the back of the belt. Following initial testing, later implementations of CANE moved the sensors more frontward, since the back sensors served little purpose in their

[1]smartcane.saksham.org/overview/

[2]micropik.com/PDF/HCSR04.pdf

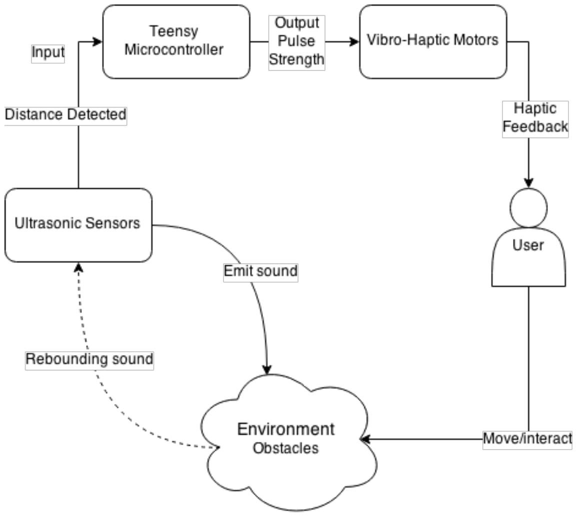


Figure 2: The working model for CANE

original location. For each pair, the sensors are intended to angle away from the center at approximately a 30-45 degree angle on each side. The sensors connect to the belt using velcro in specific regions on the surface of the belt. One consequence of this design is that the sensors' angles will vary based on an individual's waist size. The HC-SR04 sensors activate localized vibrotactile motors on the inside of the belt. These sensors provide a distance measure from their echo port, which the software uses to determine the intensity of the haptic feedback. A braided wiring harness connects the sensors to the inner layer of the belt in order to reduce clutter.

Feedback Layer of Vibrotactile Motors

The feedback layer is an array of eight LilyPad Vibe Boards[3]. Input from a single sonar sensor controls the activation and deactivation of two vibration motors. The vibration motors are arranged on the inward surface of CANE that makes contact with the wearer's body. Locations of the vibration motors correspond to the locations of the sonar sensors; this arrangement provides an accurate estimate of the direction and orientation of the obstacle.

Central Control System

The central control system is implemented using a Teensy++ 2.0 microcontroller; it establishes a common platform for all the components to interact. Unlike the ultrasonic sensors and the vibration units, the microcontroller is not embedded inside the belt. Current iterations of CANE place the Teensy++ 2.0 on top of the center of the belt, allowing easy access to the system's power and pin reconfigurability. The microcontroller constantly receives trigger input signals from all four ultrasonic sensors, which it then maps to specific vibrators. There are a total of three intensity levels, that are dynamically calculated based on the distance of the obstacle from the wearer. Based on values determined empirically, the vibration motors only become active when an obstacle is within 80 cm, which corresponds to the lowest level of vibration intensity. After the mid-range level, which begins at 65 cm, the motors will provide maximum vibration for obstacles within 50 cm. A pictorial depiction of the system implementation is shown in Figure 3.

[3] sparkfun.com/products/11008

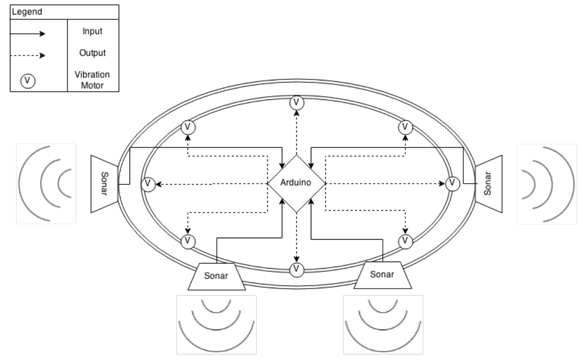


Figure 3: A diagram view of CANE's implementation

EXPERIMENT DESIGN

CANE's evaluation had two goals to explore: 1) test the validity of the proposed design principles and 2) cultivate a deeper understanding of the traits necessary for an assistive technology to address blind navigation. Hence, the system evaluation was divided into two phases. First, a pool of sighted participants tested the system and provided their feedback. This study was conducted under laboratory settings that simulated real-world scenarios in a controlled environment. A group of 25 university students participated in the study; that total includes 22 males and 3 females aged between 18 to 25. One of these participants was legally blind. Users were tasked with navigating a single lap around a square hallway while blindfolded. Each side of the hallway was approximately 10 meters in length. After walking straight down a short walkway, users had to make a right turn into the hallway, navigate obstacles, and make appropriate left turns to traverse the path in a counter-clockwise fashion. Before testing began, users were instructed about the navigation task, but no information was provided regarding functionality of the system. In doing so, we aimed to gauge the learning curve and users' spatial awareness based on the intensity and relative positioning of haptic feedback. Using the *think-aloud* strategy, we constantly sought users' feedback as they navigated the hallway. Upon completion of the task, each user was briefed on the design principles and the system's functionality. During the second phase, the system was tested by one completely blind participant, a male aged 60. He had lost his sight in an accident at 31 years of age. The blind participant tested the system at his residence and validated the feedback provided by the normal-sighted participants. He was also able to provide more key insights by evaluating the system from a blind user's perspective, as well as providing an experience-based comparison to some of the other navigation technologies he had used.

RESULTS AND DISCUSSION

Sighted User Testing

While having sighted users wear a blindfold is not an accurate simulation in every regard, the purpose of this first round of testing was primarily to find flaws and identify issues that could be fixed in the subsequent versions of CANE. Hence, these tests were conducted over several iterations of the device. A significant amount of feedback was received as the tests included 25 users with distinct statures and physiological conditions. Users quickly learned to interpret the vibrotactile feedback and navigated confidently, while successfully moving away from obstacles. The short learning curve supports our reasoning that the vibrotactile approach is intuitive. We also found that since CANE is worn around the waist, the varying heights of the users limit its ability to detect objects at knee height. An attempt was made to address this issue by pointing the sensors at a partial downward angle. However, a downward orientation raises two issues: 1) limited range of sensors, and 2) a larger activation distance when compared to the outward orientation. We believe that including sensors with varying levels of sensitivity could alleviate this problem.

Some users had a related concern regarding the placement of the vibration units. As the sensors were placed equidistantly inside the belt, some users with larger waists found the placement sparse. This issue was countered with minor adjustments of vibrator positions, but more vibrators could be added to reduce the likelihood of large gaps. As we expected, most users were able to navigate the complete course using CANE; further, they approved of its wearability and small form factor. It was unsurprising that sighted users, being blindfolded, moved slowly while they completely relied on CANE. An interesting revelation is that, despite their ability to avoid obstacles, they still preferred walking along one side of the hallway as they used the wall as their reference and stayed just close enough to receive constant feedback. Another useful result from these studies showed that sensors on the back side of the belt added no value, and in the later versions, these sensors were moved frontward. However, when sensors are placed directly on the side of the belt, they can meet interference from users' arms, implying that they could be moved further frontward.

Blind User Testing

A user who is blind evaluated CANE by using it as a navigational aid in a familiar environment. This test also included an interview component, both before and after using CANE. The initial discussion centered around existing navigational tools for the visually impaired, in terms of their availability, usability, and limitations. The user has both a guide dog and a cane, which constitute his primary means of navigation. He had formerly used two ultrasonic devices, both of which were similar in design to the SmartCane^{TM}, but one placed the sensor lower on the shaft while the other replaced the shaft with a longer-range, downward-pointing sensor. Both had to be used like a normal cane, requiring a constant sweeping pattern, so the additional cost of the ultrasonic sensors did not add value to the user. However, he did appreciate their ability to detect curbs and stairway edges like a typical cane. "Gravity never fails!" is the motto he repeated several times, and it is one of the first lessons taught when learning to navigate blind. Confidently being able to detect drops in the floor was his foremost concern, more so than detecting obstacles.

Following a brief initial interview, we asked the user to test CANE by walking around his home, a well-known environment, only by using the feedback provided by the belt. This test was run at his home primarily to ensure his safety, and it allowed him to validate CANE's feedback with his own spatial knowledge of the environment. He seemed very comfortable with the existing design and wearability of CANE, but he found the waist-level feedback to be too high on the body under some circumstances. For instance, downward pointing sensors would give more assurance about the ground, and one additional complication was the level at which he held his hands. When walking without his guide dog or cane, he would hold his arms in front of him to give early detection of obstacles. Unfortunately, this could lead to false positives for the presence of an obstacle. The angle of approach could also be a concern; because the sensors are angled to detect side obstacles, they can miss certain objects like corners.

An interesting behavior emerged during testing in which the user performed slight sweeping motions of the upper body. The intended goal of the sensor placement was to remove the sweeping pattern of canes, but the user still rotated his body to build a small mental map of the objects around him. He said this was important because it gave a better sense of his environment in a manner which he controlled. This leads to a larger discussion on the importance of the sweeping motion to a visually impaired user. CANE can reduce this need by providing more sensors, but sweeping may always be a component of the navigation process for the visually impaired.

A small closing discussion followed the test. The user mentioned that his main concern using CANE was that the range of the sensors seemed too limiting. "You would not want to move very fast," he commented. This limitation appeared during the first round of user testing as well, suggesting that it is not just tied to the user's comfort walking without sight. Longer-range sensors will be important in providing earlier warnings of obstacles so that the wearer can move around more confidently. The user liked the varying levels of intensity that CANE provides, and this intensity scaling model fits with distinguishing between farther and nearer objects. Finally, he noted that CANE could help build user assurance by giving a constant pulsing feedback to signify it is still operational, similar to how cane users tap walls every few steps to ensure safety. This validates the earlier finding that sighted users stayed close enough to a wall to receive constant feedback as they moved. Overall, CANE was well-received by the test users. We found that providing more sensors with longer range and adjustable orientations would make it more applicable to many real-world environments. The user results did indicate that CANE has an excellent form factor, is very lightweight, and gives useful feedback to supplement spatial awareness.

(a) (b)

Figure 4: Images from the visually impaired user study showing a user wearing CANE from the (a) front and (b) side.

FUTURE WORK

There are many improvements to be made in CANE. First, as validated in testing, it will be important to redesign the sensor layout on the belt. The current layout can miss corners and obstacles depending on the angle and height relative to the person. By adding more sensors and making the locations or angles more adjustable, users will be able to move better in greatly varied environments. Also, the distance of the sensors can be limiting to the user's speed; using longer-range ultrasonic sensors may allow the user to move more quickly by providing more timely feedback. Second, while it is flexible and wearable, to make the belt easier to use, the system would benefit from stitching the wiring into the lining. Once the sensor configuration is finalized, the microcontroller can also be placed inside the belt and the battery compartment moved to a more convenient place. We also hope to build a smartphone application to pair with the microcontroller to make it easier to configure and extend with other navigational modes over the Internet. Finally, more studies will be conducted with visually impaired users so that CANE can be designed to suit more people's needs. In order to evaluate CANE's performance in varying environments, these studies will be run with different scenarios and obstacle types, including new measures like timing.

CONCLUSION

Navigating unfamiliar environments without sight can be difficult. While many tools and technologies exist that try to address this issue, many of them are restricted by issues like expense, size, or usability. In this work we have presented CANE: "Computer Assisted Navigation Engine," a low-cost, wearable, non-intrusive, and haptic-assisted navigation system for the visually impaired. CANE is a "smart belt" that is fitted with an array of four ultrasonic sensors on its surface to identify obstacles, their relative locations, and an approximate estimate of the distance to the user. This localized knowledge of the environment is delivered to the user through eight vibrotactile motors along the inside surface of the belt. The locations of the sensors and vibrators align so that the haptic feedback naturally augments the user's spatial awareness. The system was evaluated in two phases, first by a pool of 25 sighted participants simulating blindness and second by a blind participant. Both studies yielded many interesting findings that will be used to direct future development. Among these is that users value constant feedback to assure them the system is working and that they are on the right path. Additionally, greater user control in placement, range, and direction of the sensors would help CANE appeal to more users in many environments. CANE was found to be a useful system that could aid in navigation for the visually impaired both inexpensively and inconspicuously. It balances a combination of many factors that other such projects have failed to consider. When paired with the current IoT trends toward smaller, faster, and wearable devices, these results show that technological tools may soon replace more traditional solutions and make navigating the world much easier for the visually impaired.

ACKNOWLEDGEMENTS

We acknowledge Matt Harper, Grant Hendley, and Jeff Harrison for their initial work on CANE. We are very grateful to Dr. Nancy Leslie for her guidance during the course of this work. Additionally, Cassandra Odoula and David Turner were instrumental in this project. We also thank the members of the Sketch Recognition Lab, the IAP members, and the Computer Science and Engineering Department at Texas A&M University for their feedback and support.

REFERENCES

1. Cardin, S., Thalmann, D., and Vexo, F. A wearable system for mobility improvement of visually impaired people. *The Visual Computer 23*, 2 (2007), 109–118.

2. Colwell, C., Petrie, H., Kornbrot, D., Hardwick, A., and Furner, S. Haptic virtual reality for blind computer users. In *Proceedings of the third international ACM conference on Assistive technologies*, ACM (1998), 92–99.

3. Crossan, A., and Brewster, S. Two-handed navigation in a haptic virtual environment. In *CHI'06 Extended Abstracts on Human Factors in Computing Systems*, ACM (2006), 676–681.

4. Dakopoulos, D., Boddhu, S., and Bourbakis, N. A 2d vibration array as an assistive device for visually impaired. In *Bioinformatics and Bioengineering, 2007. BIBE 2007. Proceedings of the 7th IEEE International Conference on*, IEEE (2007), 930–937.

5. Dakopoulos, D., and Bourbakis, N. Wearable obstacle avoidance electronic travel aids for blind: a survey. *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on 40*, 1 (2010), 25–35.

6. Ertan, S., Lee, C., Willets, A., Tan, H., and Pentland, A. A wearable haptic navigation guidance system. In *Wearable Computers, 1998. Digest of Papers. Second International Symposium on*, IEEE (1998), 164–165.

7. Lahav, O., and Mioduser, D. A blind person's cognitive mapping of new spaces using a haptic virtual environment. *Journal of Research in Special Educational Needs 3*, 3 (2003), 172–177.

8. Lahav, O., and Mioduser, D. Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind. *International Journal of Human-Computer Studies 66*, 1 (2008), 23–35.

9. Mann, S., Huang, J., Janzen, R., Lo, R., Rampersad, V., Chen, A., and Doha, T. Blind navigation with a wearable range camera and vibrotactile helmet. In *Proceedings of the 19th ACM international conference on Multimedia*, ACM (2011), 1325–1328.

10. Prasad, M., Taele, P., Olubeko, A., and Hammond, T. Haptigo: A navigational 'tap on the shoulder'. In *Haptics Symposium (HAPTICS), 2014 IEEE* (Feb 2014), 339–345.

11. Ran, L., Helal, S., and Moore, S. Drishti: an integrated indoor/outdoor blind navigation system and service. In *Pervasive Computing and Communications, 2004. PerCom 2004. Proceedings of the Second IEEE Annual Conference on*, IEEE (2004), 23–30.

12. Sánchez, J., and Tadres, A. Audio and haptic based virtual environments for orientation and mobility in people who are blind. In *Proceedings of the 12th international ACM SIGACCESS conference on Computers and accessibility*, ACM (2010), 237–238.

13. Shoval, S., Borenstein, J., and Koren, Y. Auditory guidance with the navbelt-a computerized travel aid for the blind. *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on 28*, 3 (1998), 459–467.

14. Shoval, S., Ulrich, I., and Borenstein, J. Navbelt and the guide-cane [obstacle-avoidance systems for the blind and visually impaired]. *Robotics & Automation Magazine, IEEE 10*, 1 (2003), 9–20.

15. Strumillo, P. Electronic interfaces aiding the visually impaired in environmental access, mobility and navigation. In *Human System Interactions (HSI), 2010 3rd Conference on* (May 2010), 17–24.

16. Théoret, H., Merabet, L., and Pascual-Leone, A. Behavioral and neuroplastic changes in the blind: evidence for functionally relevant cross-modal interactions. *Journal of Physiology-Paris 98*, 1 (2004), 221–233.

17. Tuttle, D. W., and Tuttle, N. R. *Self-esteem and adjusting with blindness: The process of responding to life's demands*. Charles C Thomas Publisher, 2004.

18. Virtanen, A. Navigation and guidance system for the blind. *Proceedings of Interactive Future and Man 1* (2003).

19. Wang, Y., and Kuchenbecker, K. J. Halo: Haptic alerts for low-hanging obstacles in white cane navigation. In *Haptics Symposium (HAPTICS), 2012 IEEE*, IEEE (2012), 527–532.

20. Willis, S., and Helal, S. Rfid information grid for blind navigation and wayfinding. In *ISWC*, vol. 5 (2005), 34–37.