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Peer-reviewed paper

Designing and testing wearable range-vibrotactile devices

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Abstract

Purpose – *The purpose of this paper is to demonstrate how commercially-off-the-shelf sensors and stimulators, such as infrared rangers and vibrators, can be retrofitted as a useful assistive technology in real and virtual environments.*
Design/methodology/approach – *The paper describes how a wearable range-vibrotactile device is designed and tested in the real-world setting, as well as thorough evaluations in a virtual environment for complicated navigation tasks and neuroscience studies.*
Findings – *In the real-world setting, a person with normal vision who has to navigate their way around a room with their eyes closed will quickly rely on their arms and hands to explore the room. The authors' device allows a person to "feel" their environment without touching it. Due to inherent difficulties in testing human subjects when navigating a real environment, a virtual environment affords us an opportunity to scientifically and extensively test the prototype before deploying the device in the real-world.*
Research limitations/implications – *This project serves as a starting-point for further research in benchmarking assistive technology for the visually impaired and to eventually develop a man-machine sensorimotor model that will improve current state-of-the-art technology, as well as a better understanding of neural coding in the human brain.*
Social implications – *Based on 2012 World Health Organization, there are 39 million blind people. This project will have a direct impact on this community.*
Originality/value – *The paper demonstrates a low cost design of assistive technology that has been tested and evaluated in real and virtual environments, as well as integration of sensor designs and neuroscience.*

Keywords *Blind people, Assistive technologies, Sensors, Visually impaired, Virtual reality, Wearable, Vibrotactile, Infrared range sensor, Multimodal*

Paper type *Research paper*

Introduction

According to the 2012 World Health Organization, there are more than 285 million visually impaired people, 39 million of whom are blind (www.who.int/mediacentre/factsheets/fs282/en/). Research into alternative perception will greatly benefit this community, especially with important and seemingly simple daily tasks, such as that of navigating an environment. With this in mind, this paper describes the design and test of a wearable range-vibrotactile field (Palmer *et al.*, 2012) that will allow a visually impaired person to "feel" his/her surroundings. Unlike current electronic travel aid technologies, we strive to not overload a user's senses (Dakopoulos and Bourbakis, 2010; Working Group on Mobility Aids for the Visually Impaired and Blind, Committee on Vision, 1986). Furthermore, we wish to develop a sensorimotor model to more fundamentally aid in the developments of alternative perception for the blind and non-visual sensors for robots, which could be cheaper and easier than using conventional computer vision algorithms.

We propose to use virtual reality techniques (Khoo *et al.*, 2012) to determine what kinds of sensors (or combination of sensors) are better suited as "input" devices, along with how to display such information to the user ("output" devices) before the sensors and display devices

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have been integrated or even designed. Implementing these sensors and display devices in a virtual environment not only reduces the cost and time in development, but also provides an opportunity to examine how the human brain responds to and processes this information in a well-controlled environment that minimizes head movements to allow for more precise measurements of brain activity.

This paper describes an overview of using virtual reality to test our design ideas in a realistic manner for both optimizing the sensor designs/selection and better understanding of the human brain. Details on the construction of the device are provided, along with some preliminary results in both real and virtual settings.

State of the art

Many efforts have been made to develop a navigational aid for the blind. Most recently, Argus II from Second Sight (www.2-sight.com), a retinal prosthesis, consists of a camera mounted on some eyewear that communicates with an implanted receiver and a 6 × 10 electrode-studded array that is secured to the retina. Due to its low-resolution signal (60 pixels), very little information is being conveyed from the camera to the retina and into the brain. According to one of our collaborating consultants who have been using this prosthesis, the device would be more useful if it could provide higher contrast, color perception, and depth information.

Unlike the invasive retina implant, Brainport from Wicab (http://vision.wicab.com/technology/) is a tongue-based device that conveys the brightness contrast of a scene in front of the user through a 20 × 20 electrode array pressed against the tongue. A camera is mounted on some eyewear that captures a grayscale image and converts it into voltages across electrodes on the user's tongue. Some advantages are that it is hands-free and no surgery is needed. However, some disadvantages are that the device has to be in the mouth, which makes it awkward and difficult to speak, and the resolution of the device and ability to discriminate information on the tongue is very limited.

Depth (perception) is important for spatial navigation; many devices have been developed to utilize this information. Gonzalez-Mora *et al.* (2006) used a camera to create a depth map, which was then translated into a series of sounds that conveyed the scene in front of the user. While such a technique can convey substantial amounts of information, it has a high learning curve for appreciating variations in pitch and frequency, and it can easily overload a user's hearing. Another device uses sonar sensors that are mounted on the user's chest to convey spatial information via vibrators that are also on the chest (Cardin *et al.*, 2007). Also, with the advent of Microsoft Kinect, researchers and programmers alike have used it in a non-gaming fashion, notably a research group from University of Toronto has developed a similar depth-conveying device with the Microsoft Kinect mounted on a helmet and depth information transmitted via a set of vibrators surrounding the head (Mann *et al.*, 2011).

Haptic vibrational feedback has become quite a popular technique to help people perform tasks that need spatial acuity. Lindeman *et al.* (2006) developed a rugged vibrotactile suit to aid soldiers performing combat-related tasks. Furthermore, vibrators have been paired with optical tracking systems (Lieberman and Breazeal, 2007) and inertial measurement units (Lee *et al.*, 2011) to help people in physical therapy and mobility rehabilitation.

Obtaining ground truth of human performance in real world navigation tasks can be very challenging. Torres-Gil *et al.* (2010) developed a virtual reality simulator that tracks the user's head orientation and position in a room. Instead of presenting the visual view of the scene to the user, an auditory representation of it is transduced.

Multimodal sensing in a virtual environment

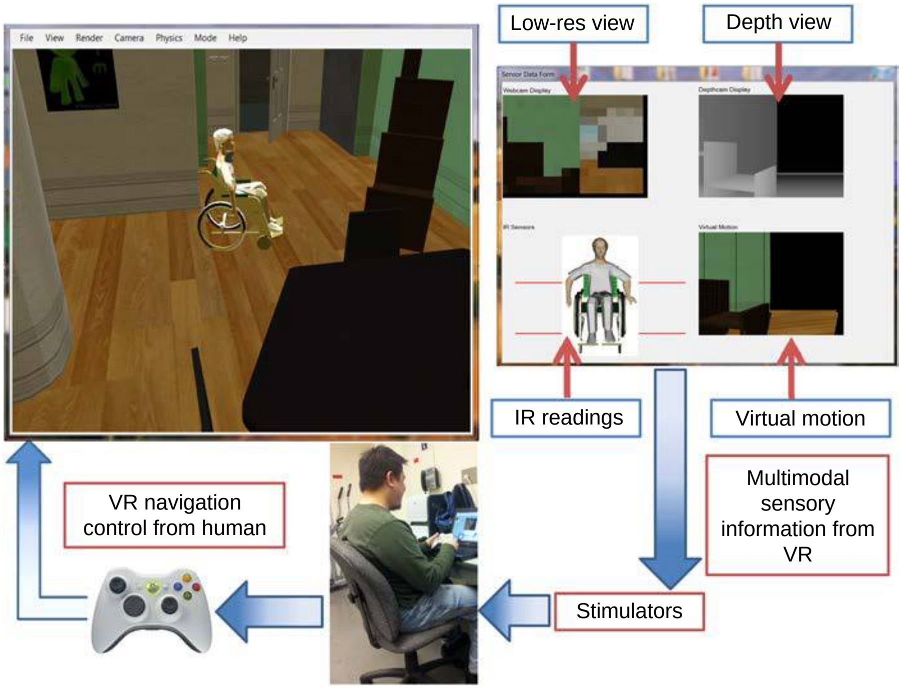
We initially used Microsoft Robotics Developer Studio (www.microsoft.com/robotics/) to simulate multimodal sensors such as infrared (IR), sonar, and Microsoft Kinect. Microsoft Robotics Developer Studio is particularly useful for exporting our algorithms to real sensors since those sensors and the algorithms used in the virtual environment map to corresponding real sensors. We also want to study various non-classical interfaces or “display” methods that are effective to the user. Effectiveness will be measured by recording a test subject’s performance in addition to their visual and multisensory brain activity (Beauchamp *et al.*, 2008; Mathewson *et al.*, 2009) and motor responses (Prilutsky *et al.*, 2005), which is made feasible with a virtual environment. The preliminary setup is as shown in Figure 1.

In the setup, we have the user sit on a chair in front of a computer to simulate the avatar sitting in a wheelchair; navigating in a wheelchair provides a smooth motion and does not necessarily mean that the user is mobility impaired. The user can control the avatar via an Xbox controller. Of course, the user cannot see the virtual environment while navigating, instead they will be presented with a set (or subset) of information that can be transduced into non-visual stimulation. As displayed on the top right corner of Figure 1, the multimodal sensing modalities include a simulated low-resolution image, a depth view, a simulated motion map, and IR sensors. In particular, this paper focusses on “displaying” the IR readings to the user via a wearable range-vibrotactile field. Multimodal sensory information from Figure 1 can also be transduced to various stimulators, such as motion information to a Brainport tongue stimulation device, depth, and/or low-resolution views to a haptic device, etc., all of which are worn by the user.

Simulated low-resolution images will be fed into the Brainport device for testing. The depth view is obtained from a virtual Microsoft Kinect. The depth view is used to derive the simulated motion map by computing the disparity value for each pixel, since we already know the intrinsic and extrinsic parameters of Microsoft Kinect. The depth view can also be used to test out obstacle detection algorithm that can provide feedback to a blind user either by speech or a vibrotactile belt (Khan *et al.*, 2012). The motion map is finally generated by shifting all of the pixel locations to the left and right by its disparity. The depth and virtual motion information could be translated into auditory or vibrotacitle feedback to the user.

We are not only trying to determine what kind of sensors are suitable for surrounding awareness, but also what kind of stimulators are suitable as a novel “display” method to convey sensor information to visually impaired users for navigation.

Figure 1 Sensing and navigating a virtual environment



Source: Khoo *et al.* (2012)

Sensors

Some other sensors that can be simulated include stereo cameras, laser range finders, sonar sensors, etc. Stereo cameras can be used as a comparison to Microsoft Kinect, studying the difference in depth of field and computational complexity. Similarly, laser and sonar sensors can be used as a comparison to IR sensors, studying the difference in range, and field of view (Khoo *et al.*, 2012). As we have discussed above, these sensors can be simulated in the virtual environment.

Stimulators

There are many other types of stimulators beside vibrators and Brainport-like stimulators. Since braille is a traditional communication method for the visually impaired, we can use it to indicate range (Amemiya *et al.*, 2004). Mimicking a bat's echolocation ability, we can convert distance information into stereophonics (Bourbakis, 2008; Torres-Gil *et al.*, 2010). Lastly, haptic feedback (Amemiya *et al.*, 2004), which is similar in concept to vibration, can also be used. The simulated sensory information will be fed into real stimulators worn by the user.

Designs of range-vibrotactile devices

While many of the commercially-off-the-shelf sensors can be used in our test, we have designed a highly cost-effective sensory-actuator package: the IR-range-vibrotactile field system. The range-vibrotactile field system consists of very cheap (~$10 a pair) IR ranger-vibrotactile pairs that are worn on the whole body. A "display" of range information will be transduced via vibration on different parts of the body to allow the user to feel the range perpendicular to the surface of that part. Imagine feeling a whole body "range field" that will cause vibration on part(s) of the body which is near an obstacle; vibration intensifies as the wearer gets closer to the obstacle (Palmer *et al.*, 2012).

We have developed several prototypes based on this idea: hand sensor-display pairs for reaching tasks (Plate 1), arm and leg sensor sets for obstacle detection, and a foot sensor set for stair detection.

We designed these prototypes with the following design objectives in mind:

1. modular interchangeable parts;

Plate 1 Early prototype for the arm sensor-vibrotactile set; two sets on two arms, each having three pairs of sensors

Source: Palmer *et al.* (2012)

2. comfortable and effective clothing for wearing sensor/vibrator pairs;
3. circuitry for testing and controlling using Arduino; and
4. software for testing vibratory sensitivity of different body parts.

User testing, as shown in Plate 2, demonstrated that the small device was easy to use and was liked because it is light and provides direct information without much interpretation or learning. The user was able to navigate into a room without using her retinal prosthesis. However, it was difficult for her to detect dynamic obstacles.

By sewing or otherwise attaching the sensor/vibrator pairs onto clothes, we hope to minimize potential interference to the senses that could be used for other tasks. However, it is unknown whether constant vibration will desensitize the user over time so further investigations are necessary. Modularity will allow us to use different kinds of sensors and stimulators and to study the optimal placement of them, as well as the number of range-vibrotactile pairs needed to minimize discomfort and noise while maximizing spatial information.

We plan to test the prototype in four different experiments:

1. vibrators will be activated one at a time in order to find the threshold of sensitivity for different vibrators on different body parts;

Plate 2 One of our consultants, a visually impaired person, testing one set of sensor-vibrotactile pairs

Source: Palmer *et al*. (2012)

2. all or a subset of the vibrators will be activated at the same time as a result of the user navigating in a virtual environment, such that the vibrators are virtually connected to the simulated IRs in the virtual environment;
3. corresponding vibrators are activated as the user navigates in a real environment; and
4. brain activity in response to the vibrators will be recorded as subjects navigate a virtual environment.

Preliminary results of experiments 1 and 2 will be discussed in the Experimental Results section. We have yet to conduct experiments 3 and 4 because we want to complete further testing in the lab to ensure the optimal design in these experiments. In addition, the lab setting gives us a controlled environment to refine our prototype and programming, if needed, and to more precisely measure brain function.

Evaluating range-vibrotactile sensors in a virtual environment

Design

For a rapid evaluation of the range-vibrotactile device in a virtual environment, we used Unity3D (http://unity3d.com/). Unity3D is a mature, free, and simple to use game engine. We chose Unity3D over Microsoft Robotics Developer Studio mainly for its straight-forward interface:

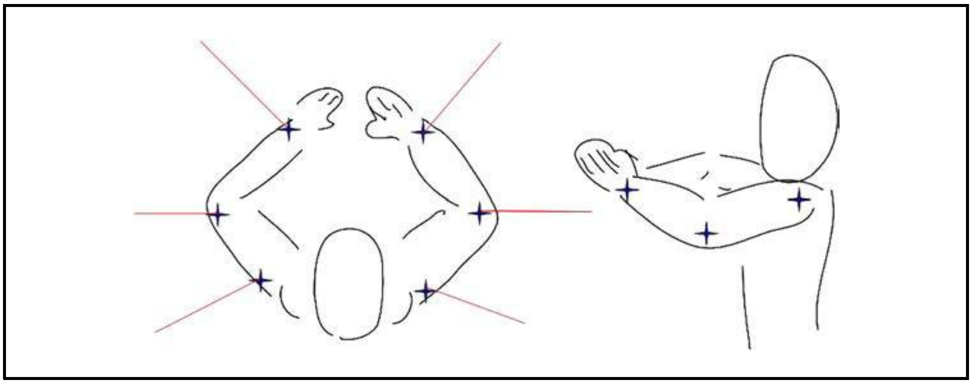
- Objects can be added to the scene by dragging and dropping; 3D models can be made using the free software Blender (www.blender.org/).
- Scripts, which define how objects behave, can be written in a few different programming languages. We use Python and Javascript.
- Collaboration with Unity3D is hassle free; simply transfer modified files to collaborators.

We have simulated the vibrotactile shirt as shown in Plate 1 in a configuration illustrated in Figure 2 in Unity3D to test the thresholds for sensing vibrations and the user's ability to complete a navigation course (designed as a game – Chicken Finder). Roughly, the sensors on each arm are placed on the subject's wrist, elbow, and upper arm (or shoulder, depending on the subject size). Note that this is only a preliminary experiment and that we aim to test the concept of a full-body wearable range-vibrotactile field to aid visually impaired people in navigation. Toward that end, more sensors that cover the critical parts of a human body for navigation will be tested in subsequent experiments to determine the optimal number and locations of these sensor-actuator pairs. Unity 3D allows us to run over 60 vibrator outputs simultaneously, making our subsequent experiments with full-body wearable sensors feasible.

The game is set up as follows:

- user has to find the source of the sound of a baby chick chirping without any visual information;

Figure 2 Placement of sensors in Unity3D



- the computer screen is faced away from them; and
- they have to navigate the virtual environment and avoid obstacles based on the varying intensity of sounds and vibrations.

Plates 3 and 4 show the two levels that we have created. The first level (Plate 3) is based on an actual floor on our campus. A lot of people found this virtual level to be quite difficult and most were unable to complete the task of reaching the white sphere (starting point is the white cylinder in the map); the location of the source of the chirping sound is at the white sphere object. Therefore, a second easier level was created for people to get familiar with the vibrotactile shirt. The easy level contains stationary people that should be avoided while trying to reach the white sphere at the end of the hallway. Most people reached the goal on the second level, but on an average of five minutes time span, compared to one minute of navigation while looking at the screen.

Configuration

Since Unity3D does not have a sensor package, we have to simulate the behavior that we desire by exploiting Unity's raycast function. The raycast function is used to measure the distance from one point to game objects in a given direction, which in turn will activate the corresponding vibrator on the vibrotactile shirt with varying intensity. In terms of location, the sensors are configured as shown in Figure 2, as if a person is walking with their arm raised in front of them, elbows bent. The sensors are mounted on their wrists, elbows, and shoulders at 30, 90, 100 degree angles, respectively.

The script that controls the avatar also writes data to a text file every frame. It records the player's position and orientation in the virtual world as well as a flag that marks if the user was bumping into an object (bumping into objects will also generate a sound in the virtual world). The game engine updates the sensors output at 60-70 Hz. Bumping is recorded because it allows us to evaluate how well the subject performed and where the subject bumped into something.

Plate 3 Aerial view of the first level

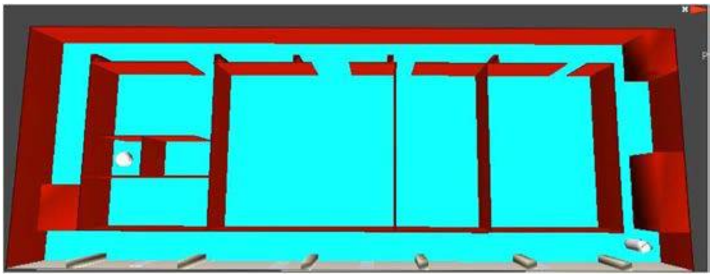
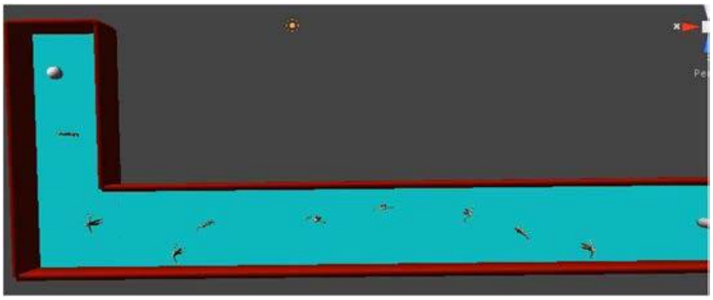


Plate 4 Aerial view of the second level



We also configured Unity3D to take screenshots and make sounds, such as when the user is walking, bumping into something, or reaches a goal. Screenshots are taken by subjects clicking a button on a joystick, and subjects were advised to take a screenshot whenever they were stuck somewhere in the virtual environment. Screenshots are also useful for debriefing subjects on the experiment because it allows the experimenter to inform the subjects about where they got stuck or where they were confused.

In addition, we connected a modified mouse to Unity3D. A regular mouse does not give you any feedback, visual, or physical, when you rotate. Thus you have no idea how many degrees you have turned in the virtual environment. To remedy this, we built a steering device by cutting a roller ball mouse in half to expose one of the rollers. We then attached a knob to the roller, which the subject can use to steer. This fix ensures the subjects that when they rotate the knob 90 degrees, the virtual avatar also rotates 90 degrees.

Experimental results

In total, 24 subjects (range of 18-24 years) gave written informed consent and took part in the experiments for monetary compensation or for partial fulfilment of a course requirement. Six subjects completed the vibrotactile sensitivity experiment whereas 18 subjects completed the virtual navigation experiments. This study was approved by the Institutional Review Board of the City University of New York.

Sensitivity experiments

In one experiment, we tested sensitivities of various parts on the body where we thought placing the range-based vibrotactile pairs would be useful. In particular, we tested the elbows, shoulders, and wrists, as shown in Plate 5a. This allows the subject to perceive a “force field” around their arms. The next stage of this experiment will be to test other parts of the body, including the legs, waist, chest, back, etc.

Plate 5b shows how the vibrators are connected to the Arduino microcontroller and controlled. The microcontroller will output a pulsed width modulation signal which will take advantage of the inductive nature of the vibrators in order to average the pulses into a corresponding equivalent voltage applied to the vibrator.

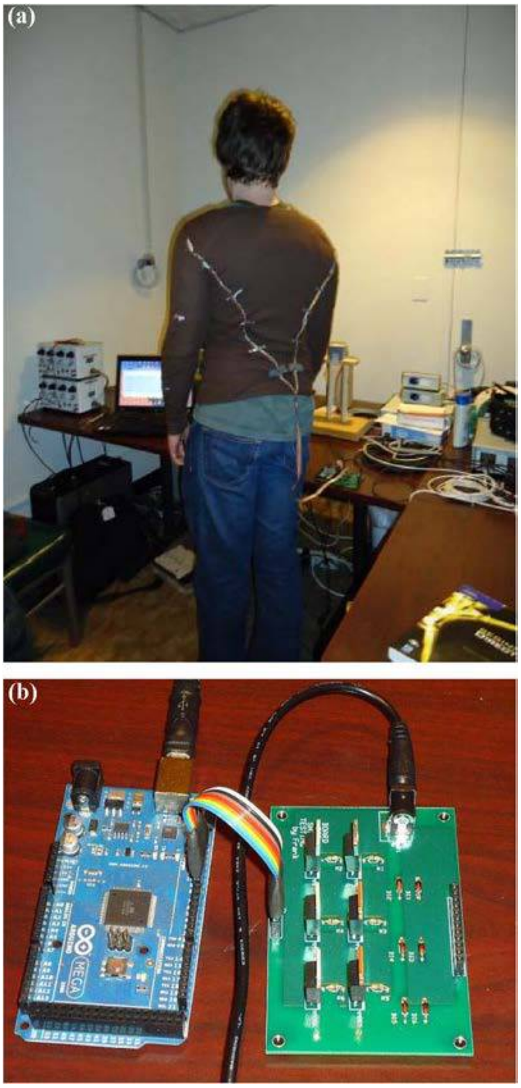
We have tested our prototype shirt with six vibrators using an algorithm based on the PEST approach (Lieberman and Pentland, 1982) for finding the thresholds for different parts of the body of a user. Figure 3 shows the operator interface. The PEST algorithm presents the user with sensations of more and more similar intensity of vibration, until the user indicates that they feel the same. The PEST algorithm operates in a manner similar to binary search.

It usually took about 45 minutes to discern the range of detectable intensity differences for all six locations we were testing. Further work will be needed to improve the speed with which the algorithm converges to finding a given difference threshold. In some cases, especially those subjects with inconsistent responses, the algorithm was unable to detect a difference threshold and the program was halted before it had reached its conclusion. However, the difference thresholds that had been found up to that point were saved and recorded. We hope that we can cut the time down to a minute or two for each location, thus we could perform full body vibration sensitivity evaluation in a reasonable amount of time, for example, within an hour for 100 locations.

Figure 4 shows the experimental results of the discerning thresholds with six human subjects. The average interval distance and the average number of difference thresholds for each location along the arms are shown in Table I. From this experiment, we have the following observations:

1. Similarity and differences among locations. We have found that, on average, the sensitivity of various locations of human arms is very similar. In our experiments, human arms can discern about three to four levels of vibration whose voltage is from 0 to 5 volt. However, we found a tendency for the left arms are more sensitive to vibration than the right arms, although this difference was not statistically reliable. This asymmetry might be due to the sensor setup, the real discerning power of humans, or a combination of both. More experiments with larger numbers of subjects are needed for verifying this difference.

Plate 5 Testing vibrotactile shirt



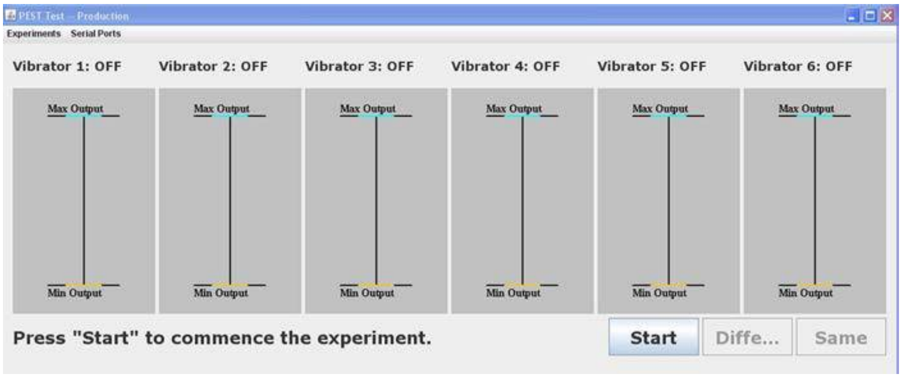
Note: (a) Subject wearing the shirt (b) Arduino controller
Source: Palmer *et al*. (2012)

2. Similarity and differences among human subjects. We have found that the number of difference thresholds of the six participants vary from three to six. However on average, the number is about four.

The small number of participants does not produce statistically significant experimental differences in the number of difference thresholds on the different body parts. However, this is an important first step and at least shows that we could provide the users via their skin with three to four different vibration intensities. Adding no vibration for safe range, this could be sufficient to tell a user the range is far/safe, medium, medium to close, close, and very close, so the user can respond accordingly.

Once we have completed enough experiments finding difference thresholds for each user, we will switch our attention to the second set of experiments in testing the design using virtual reality, followed by connecting sensors to the vibrators and testing the device in a real environment, as well as in a virtual environment while recording brain activity (the third and fourth

Figure 3 User interface for the PEST approach

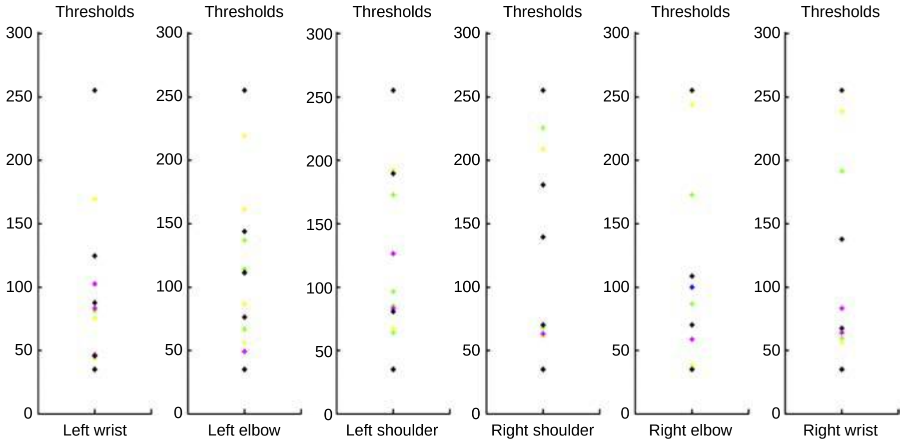


Vibrator 1: OFF Vibrator 2: OFF Vibrator 3: OFF Vibrator 4: OFF Vibrator 5: OFF Vibrator 6: OFF

Press "Start" to commence the experiment.

Source: Palmer *et al*. (2012)

Figure 4 Vibrotactile difference thresholds of six locations for six human subjects



Note: The vertical axes are the voltage of vibration strengths quantized from 0 to 255
Source: Palmer *et al*. (2012)

Table I Descriptive statistics of vibrotactile thresholds on six arm locations (length of intervals as quantized on a 0-255 scale)

	Left wrist	*Left elbow*	*Left shoulder*	*Right shoulder*	*Right elbow*	*Right wrist*
Average Interval Length	77.6	77.6	82.5	94.3	94.3	94.23
Average Number of Thresholds	3.8	3.8	3. 7	3.3	3.3	3.3

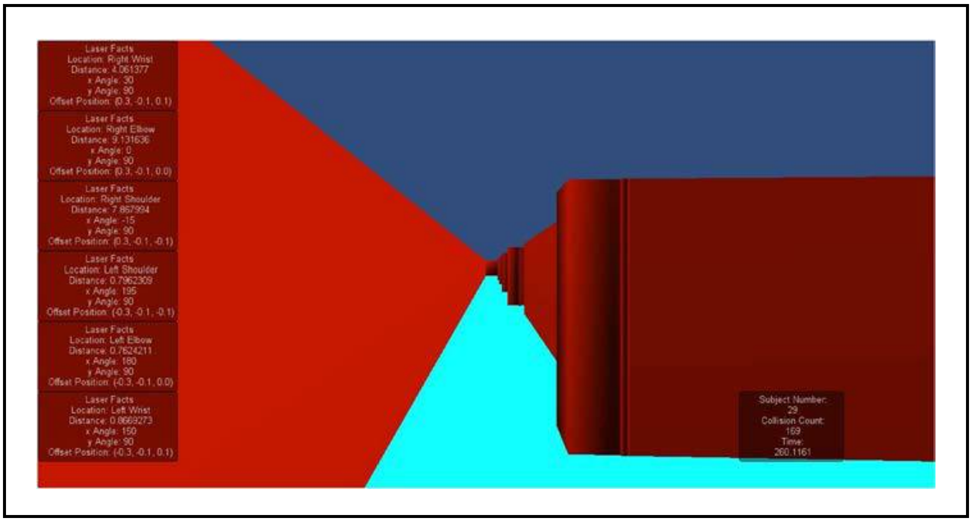
Source: Palmer *et al.* (2012)

set of experiments). All the while, we will continue testing different kinds of vibrators and sensors to find the optimal combination of each.

Virtual environment navigation experiments

Plate 6 shows the virtual environment (of Plate 3) in first-person view. Note that this screen is not seen by the subject while the experiment is running. The experimenter, however, can see all of

Plate 6 Screenshot and view of the screen (not seen by subject)



Laser Facts
Location: Right Wrist
Distance: 4.061377
x Angle: 30
y Angle: 90
Offset Position: (0.3, -0.1, 0.1)

Laser Facts
Location: Right Elbow
Distance: 9.131636
x Angle: 0
y Angle: 90
Offset Position: (0.3, -0.1, 0.0)

Laser Facts
Location: Right Shoulder
Distance: 7.857994
x Angle: -15
y Angle: 90
Offset Position: (0.3, -0.1, -0.1)

Laser Facts
Location: Left Shoulder
Distance: 0.7962309
x Angle: 195
y Angle: 90
Offset Position: (-0.3, -0.1, -0.1)

Laser Facts
Location: Left Elbow
Distance: 0.7624211
x Angle: 180
y Angle: 90
Offset Position: (-0.3, -0.1, 0.0)

Laser Facts
Location: Left Wrist
Distance: 0.8669273
x Angle: 150
y Angle: 90
Offset Position: (-0.3, -0.1, 0.1)

Subject Number:
29
Collision Count:
169
Time:
260.1161

the information on the screen, such as distance information for each sensor, time, and the number of times the subject bumped into something.

Because data are sampled and recorded on every frame, this experiment generated a large amount of data. One-way of visualizing the result is to plot the subject's trajectory through the hallway, as shown in Figures 5 and 6. The plot also shows where the subject has bumped into something, as indicated by a black cross in the figure. For illustration purposes, we superimposed a single trial of a subject onto all trials for both cases of easy and complex hallway.

Most subjects were able to find the goal object in the easier hallway (Plate 4). There were 18 subjects that tried the hallway and ten were able to find the goal. Table II shows the time to completion and the number of bumps for subjects who experimented in the easy hallway.

Figure 5 Trajectory plots of subjects in easy hallway

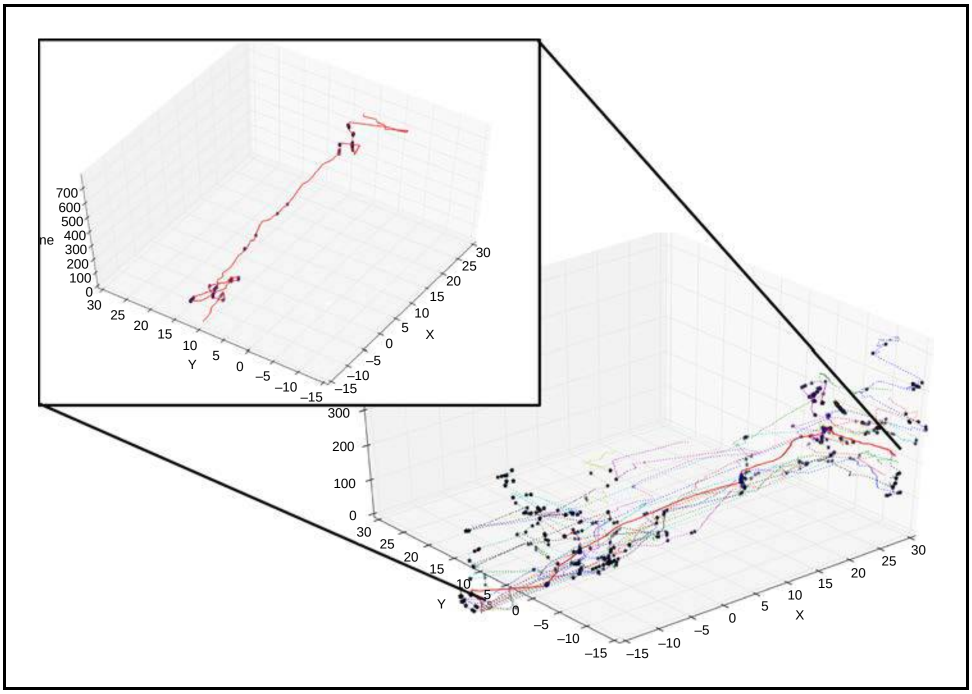


Figure 6 Trajectory plots of subjects in complex hallway

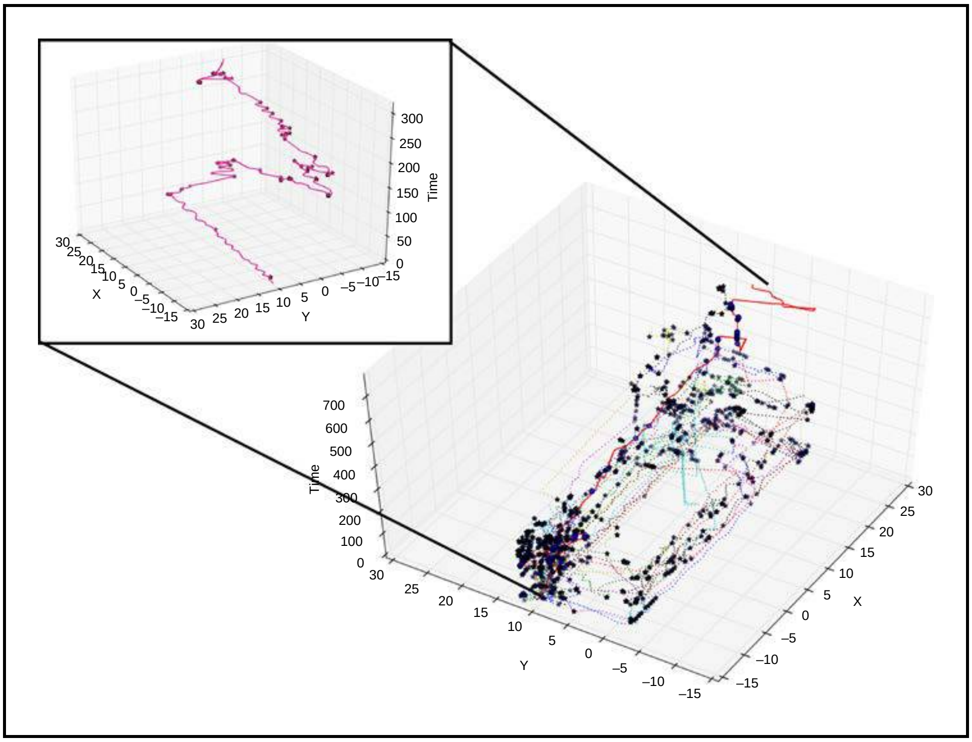


Table II Chicken finder data: time and bumping for easy hallway scenario

	Time (s)	*Bumping*	*Result*
S1	257.02	13	Failed
S2	246.12	18	Failed
S3	252.54	12	Failed
S4	339.16	26	Failed
S5	316.76	5	Failed
S6	286.54	17	Succeeded
S7	266.70	32	Failed
S8	145.34	21	Succeeded
S9	185.62	16	Succeeded
S10	150.56	4	Succeeded
S11	292.30	26	Succeeded
S12	325.18	65	Failed
S13	210.34	20	Succeeded
S14	305.74	6	Failed
S15	230.38	15	Succeeded
S16	527.36	17	Succeeded
S17	389.52	9	Succeeded
S18	383.08	28	Succeeded

The average time is 280.10 seconds and the average bumping is 17.3 for those who succeeded. And for those who failed, the average time is 288.65 seconds and the average bumping is 22.1. We speculate that the similar numbers is due to individual learning curve, and while some people are tenacious in finding the goal, others gave up easily.

Only three subjects out of 18 were able to find the goal object in the more complex hallway shown in Plate 3, and Table III shows the time and number of bumps of subjects who experimented in this scenario. The average time is 120.25 seconds and the average bumping is

Table III Chicken finder data: time and bumping for complex hallway scenario

	Time (s)	*Bumping*	*Result*
S1	58.32	13	Succeeded
S2	102.12	6	Succeeded
S3	200.30	19	Succeeded
S4	351.02	17	Failed
S5	412.08	3	Failed
S6	373.3	22	Failed
S7	602.32	27	Failed
S8	325.40	25	Failed
S9	241.86	60	Failed
S10	272.74	48	Failed
S11	311.78	34	Failed
S12	316.66	31	Failed
S13	472.40	60	Failed
S14	311.54	108	Failed
S15	315.04	66	Failed
S16	307.32	42	Failed
S17	306.22	36	Failed
S18	385.32	62	Failed

12.7 for those who succeeded. And for those who failed, the average time is 353.67 seconds and the average bumping is 42.7. One would assume that the complex hallway will take more time to reach the goal; however, our average time to goal is 120.25 seconds, much less than the easy hallway. This could be contributed by subjects who had participated in the easy hallway experiment previously and were familiar with it to navigate with relative ease.

Note that some subjects participated in the easy hallway and not in the complex hallway, and vice versa.

More people succeeded in the easy hallway than in the complex one for several reasons. In the easy hallway, the goal is just down a hall and around one corner, while the complex hallway requires users to navigate through rooms to find the goal. While the vibrotactile array is informative about objects and wall nearby, the environment feedback could be confusing the users. For example, in the complex hallway, when the goal was very near, the goal could have actually been in another room while outside of it in the hallway. Openings such as doors, are hard to detect, thus reaching the goal is also difficult.

Conclusion

This paper describes the design ideas and the virtual environment techniques for testing the concept of multimodal sensors to aid visually impaired people in navigation. In particular, a wearable range-vibrotactile field was designed and tested. This essentially allows individual to “see” with their body, a novel form of spatial navigation.

Furthermore, the range-vibrotactile device was designed using a highly cost-effective sensory-actuator package. Because the device was demonstrated positively on a visually impaired person, we plan to systematically test the prototype on a larger sample size. The same design was also virtually designed and tested in Unity3D. Note that other configurations of sensors and actuators will be designed and tested in Unity3D as well. A separate experiment, using the PEST algorithm, was also done to determine the sensitivity threshold for different parts of the body of a user. Although there were a small number of participants in that preliminary experiment, it was an important first step to know that users can distinguish around four vibration intensities. This result directly led into the virtual reality navigation experiment. Using the thresholds found, we quantized the distance information from the virtual reality environment and activated the actuators at one of the four intensities. Lastly, the virtual reality navigation results showed the effectiveness of our device; ten out of 18 subjects were successful in reaching the goal in the easy hallway scenario, and three out of 18 succeeded in the complex hallway scenario.

The important first step of this concept is achieved by determining the absolute and difference thresholds of perception on different parts of the body as the foundation of locations and discriminative levels of the vibrotactile stimulation.

The second step that we have started is to evaluate this concept virtually. We were able to simulate the prototype in the virtual environment and configured it in such a way to mimic a real world setting. Some of the valuable insights about designing assistive technology that we gained are:

- it is difficult to navigate in a virtual environment without any feedback from the navigation device; thus we created a steering device that provides users with information regarding the extent of their turns;
- the vibrotactile device works for stationary obstacle avoidance, but it becomes a challenge when obstacles become dynamic; and
- virtual reality gave us a positive outlook on real world testing; however, virtual testing is no substitute for real world testing.

The last step that we plan to do is to conduct psychophysical and neuroscientific testing using a virtual environment and bringing the experiment to a real world setting. Toward this end, we plan to recruit more subjects to test out our virtual environment system while at the same time obtaining measures of brain activity. The goal of this research is to understand how well a subject learns a new technology and how effective a sensor stimulator is. Since brain activity cannot be reliably measured while the subject is walking in a real world setting, we plan to first test subjects in a virtual environment and will then export any refinements we make in the virtual environment to the real design to compare performance in the two different settings. In this plan, multiple experiments of various sensor combinations and placements will be performed, and various groups of subjects (sighted but blindfolded, low-vision, totally blind) will be tested.

The ultimate goal of this project is to provide a research platform for the development of assistive technologies for the visually impaired. Specifically, we want to determine which interface method (i.e. what type of information and how to present it) is the most efficient, reliable, and robust based on our experimental testing. The key idea here is to test how visual and non-visual stimulation can enhance vision through understanding the underlying neural mechanisms and enhancing the effects of non-visual stimulation on navigation and other daily functions.

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