Sensing the environment through SpiderSense

Victor Mateevitsi[1], Brad Haggadone[2], Jason Leigh[1], Brian Kunzer[3], Robert V. Kenyon[1]
[1]Electronic Visualization Laboratory, Department of Computer Science
[2]Department of Communication
[3]Neural Engineering Vision Laboratory, Department of Bioengineering
University of Illinois at Chicago
{vmatee2, bhagga2, spiff, bkunze1, kenyon}@uic.edu

ABSTRACT

Recent scientific advances allow the use of technology to expand the number of forms of energy that can be perceived by humans. Smart sensors can detect hazards that human sensors are unable to perceive, for example radiation. This fusing of technology to human's forms of perception enables exciting new ways of perceiving the world around us. In this paper we describe the design of SpiderSense, a wearable device that projects the wearer's near environment on the skin and allows for directional awareness of objects around him. The millions of sensory receptors that cover the skin presents opportunities for conveying alerts and messages. We discuss the challenges and considerations of designing similar wearable devices.

Categories and Subject Descriptors

H.5.1 [**Multimedia Information Systems**]: Multimedia Information Systems—*Artificial, augmented, and virtual realities*; H.5.2 [**User Interfaces**]: Haptic I/O

General Terms

Algorithms, Design, Experimentation

Keywords

Environment Perception, Human Augmentics, SpiderSense, Tactile Displays, Wearable Computing

1. INTRODUCTION

Humans have always had the ambition to radically change the world around them and recently our opportunity to do so has increased due to rapidly evolving technology. Feeling, tasting, smelling, seeing, hearing and communicating with the world is limited by our body's sensors and our interpretation of their signals. Radiation for example, is invisible, does not have any taste or odor, emits no sound and cannot be detected by our sensors, yet should be avoided since it is extremely deadly.

In the Comic Book world, the heroes and their villains have senses and powers that enable them to feel some of those invisible threats. Daredevil for example, while blind, possesses an echolocation system that allows him to "feel" the environment instead of seeing it. Spiderman on the other hand can feel imminent dangers with a tingling sensation at the base of his skull, a power known as SpiderSense. Even though he was never trained in martial arts, SpiderSense allows him to "feel" incoming attacks, lasers, and blasts, enabling him to react before they cause him harm.

While the latest advancements in bioengineering and genetics are promising, we are far from engineering such biologic sensory systems. Electronic sensors on the other hand are capable of detecting environmental factors that humans cannot. Geiger counters for example can sense and measure radiation; infrared sensors can do the same for infrared light; ultrasonic microphones can detect frequencies that are outside the audible range of human hearing. To communicate such information to the user, these devices primarily use a display screen (this screen can either be an embedded screen, or a remote screen, like a smart-phone's display) and visualize the information using graphics, charts or quantitative methods.

Our body is covered with skin that contains millions of sensory receptors. The density of the receptors varies on different parts of our body, with the fingertips having the most receptors per square centimeter [2, 6, 18]. Visually handicapped individuals have relied on these receptors as one of the primary channels for information capture, such as when reading Braille texts or navigating a space with a cane.

In this paper we examine the scenario in which the multiple sites all over the body, rather than just the hands, is fitted with transducers to transform information about the environment into a tactile sensations.

2. RELATED WORK

Advances in bioengineering, technology miniaturization and computing are paving the ground to technologies referred as Human Augmentics (HA) for expanding the capabilities, and characteristics of humans [7]. These technologies aim to improve the quality of life by monitoring the user or environment using smart sensors, then intervening at an appropriate time to inform or persuade him to change behavior.

One example of a HA technology is a tactile display. Gemperle et al [3], defines a tactile display as a device that presents information to the wearer by stimulating the sen-

AH'13, March 07 - 08 2013, Stuttgart, Germany

sors on the skin. One type of a tactile display is a tactile vest. These vests have tactors (vibrators) sewn inside the fabric at various locations and communicate information to the wearer through vibro-tactile stimulation.

"ActiveBelt" is a wearable device that conveys directional information through eight vibrators that are positioned at equal distances along the length of a belt [15]. The wearer selects a destination and the belt, like a compass, vibrates in the direction that the user needs to travel. Distance to the target destination is conveyed through changes in vibration frequency. In the user study, even though subjects failed to recognize changes in pulse intervals when walking, they succeeded in navigating to the target location. Van Veen and Van Erp [17] also showed that a vibro-tactile stimulus on the torso generates a percept of external direction, an effect which is called the "tap on the shoulder" principle [16]. Multimodal motion guidance systems using different feedback modalities are discussed in Schönauer et al [13] and Miaw et al [9]. Cassinelli et al [1] demonstrated that a vibrotactile headband on untrained users causes head movement in response to an unseen object approaching from behind.

3. SPIDERSENSE

The brain learns from a young age how to combine multiple sensory stimuli to create an awareness of the surrounding environment in order to accomplish various goals such as protecting the body from harm [10]. The perception of pain for example is helpful in identifying the location of a bodily injury so that the individual can take appropriate action. Yet each sense has its limitations or blindspots; therefore it is impossible to be fully aware of all aspects of ones surrounding environment all the time.

Drawing inspiration from Spiderman's SpiderSense, our HA wearable tactile display utilizes the skin's pressure receptors to communicate an awareness of the surrounding environment by conveying information about the wearer's distance from surrounding objects. While previous tactile vests communicate directional information, SpiderSense creates an actual feeling of the environment by conveying distance information from objects by applying pressure on the skin. SpiderSense consists of a series of Sensor Modules that are positioned on the body of the user (Figure 1). The Sensor Modules scan the environment using ultrasound to alert the user of objects that are closer than 60 feet. Worn at strategic points over the body (see 7.1), the user can potentially gain a sense of all the obstacles that surround him.

4. APPLICATIONS

One can envision two categories of broad applications of SpiderSense: compensating for a dysfunctional or missing sense (i.e. visually or hearing impaired); or supplementing the existing senses (spatial awarness in a spacesuit or seeing behind one's head).

4.1 Compensating for a dysfunctional or missing sense

Individuals with dysfunctional or missing senses may not perceive important cues from their surroundings. For example a person with a hearing disability or poor vision may not be able to perceive an oncoming car while crossing a street. Research suggests that tactile displays are beneficial to visually impaired people, by being able to detect and avoid obstacles as they walk [14].

Figure 1: SpiderSense on a blindfolded user

SpiderSense steps in as an aid to supplement those senses. The pressure stimuli from the sensors could possibly allow them to navigate faster and safer, while avoiding obstacles.

4.2 Supplementing existing senses

SpiderSense could provide another gateway for information; if the user can learn how to use it to supplement their natural perception of the environment. There are three senarios that can benefit from the use of SpiderSense.

1. One of the wearer's senses has already identified an object and SpiderSense helps localize the direction of the object. Pedestrians for example when walking use their vision to locate obstacles and avoid them. By using SpiderSense they could benefit by "feeling" on their body how far away, qualitatively, an obstacle is. This is especially useful if, at some point, the object is hidden from the wearer as they approach.
2. Sometimes senses are overwhelmed with information and SpiderSense may be used to ease the load on one sense by displaying this information through another sense. Firemen for example, when working in a hazardous environment have limited visibility because of smoke and need to be constantly aware of their surroundings to avoid falling debris for example. By using SpiderSense they get spatial information of the room from these Sensor Modules, therefore potentially allowing them to concentrate their vision on the fire hazards.
3. There is an incoming obstacle or threat that is not being detected by any of the other senses (e.g. an intruder approaching from behind).

Scaled-down versions of SpiderSense could augment the wearer as well. Imagine positioning two Sensor Modules on a pair of slippers of an elderly person with vision disabilities. His vision would be supplemented with feedback from the slippers, keeping him safe from obstacles that could potentially harm him. Bicyclists could have one sensor on each forearm facing outwards and two sensors on their back therefore being aware of passing or incoming traffic.

Furthermore, the sensor itself could be completely separated from the feedback mechanism but communicate via a wireless connection. For example, for racing car drivers, a set of sensors can be mounted to the exterior of the car enabling the driver to sense other surrounding drivers when competing for tight turns allowing full attention of their vision to the task of driving.

5. SPIDERSENSE DESIGN

The prototype wearable system (Figure 2) consists of Sensor Modules that scan the environment providing pressure to the skin and are connected to and controlled through a Controller Box. The Controller Box contains the power source, the electronics and the logic of the system. The Sensor Modules are connected to the Controller Box through 10-pin ribbon cables but one can imagine this being replaced in the future by a wireless Bluetooth connection.

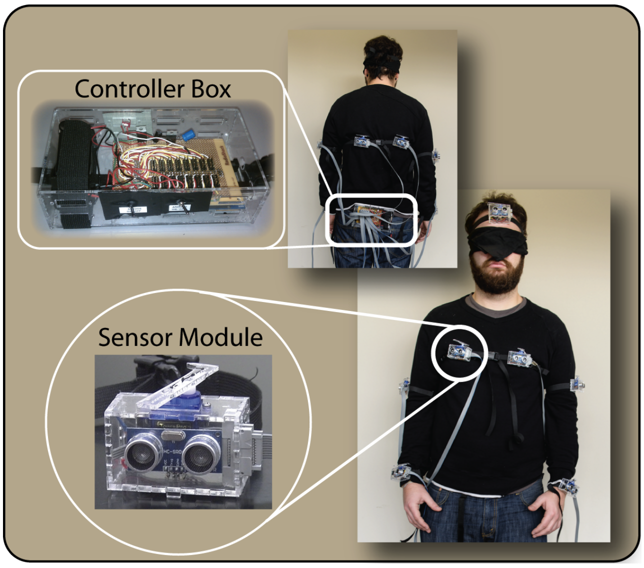

Figure 2: Positioning of Sensor Modules and Controller Box

5.1 Sensor Module

The Sensor Module (Figure 3) is the device that scans the room for objects and provides pressure feedback to the wearer. Thirteen Sensor Modules were constructed to enable us to experiment with a variety of placements on an individual's body. Each Sensor Module houses an ultrasonic distance sensor, a rotary servomotor and a 10-pin connector port. The distance sensor detects the closest object to the wearer inside its field of "view"; and the arm of the servomotor rotates to provide pressure information to the wearer in accordance to distance - the shorter the distance, the stronger the pressure. To measure distance we use the HC-SR04 Ultrasound Sensor that has a 15° "view" angle and 200 inch range. To create pressure we use the T-Pro Mini Servo SG-90 9G that has a stall torque of 16.7oz/in and rotation speed of 0.12sec/60degrees as the servo motor.

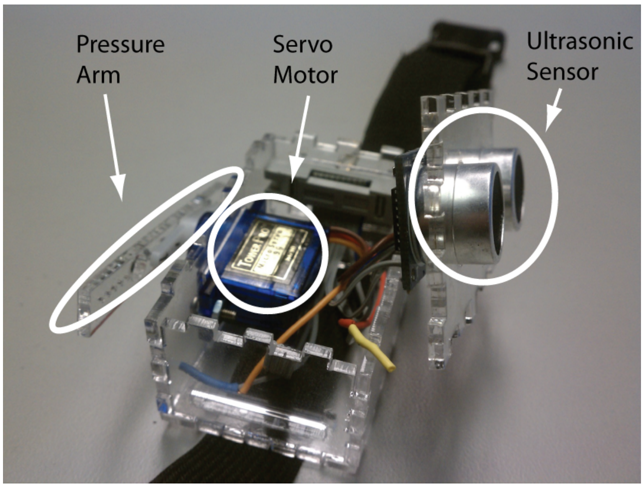

Figure 3: The Sensor Module

5.2 Controller Box

The Controller Box (Figure 4) houses the logic of the hardware which primarily consists of an Arduino Mega microcontroller. The Controller Box controls and synchronizes the Sensor Modules to avoid sonar interference and calculates the rotation angle for the Sensor Module arm.

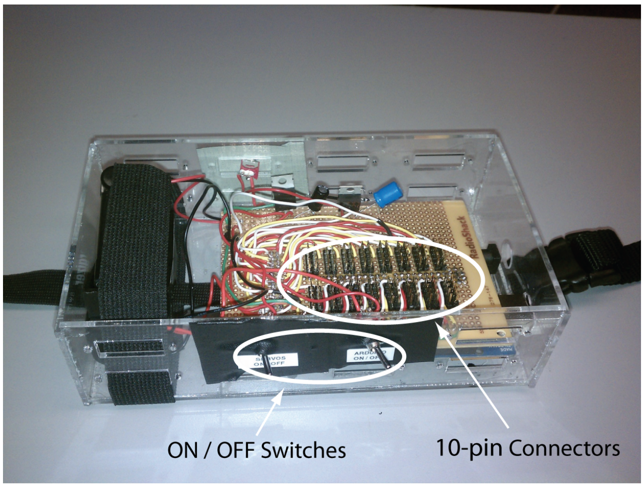

Figure 4: The Controller Box

6. CONTROLLER ALGORITHM

The software architecture of the system is shown in Figure 5. The Sensor Module initially emits a pulse and listens for a reflection. After the reflected wave has been received (i.e. there is an obstacle in the range of the SensorModule) or the Module timed out without any response (i.e. no obstacle in range) the Sensor Module sends the reading to the

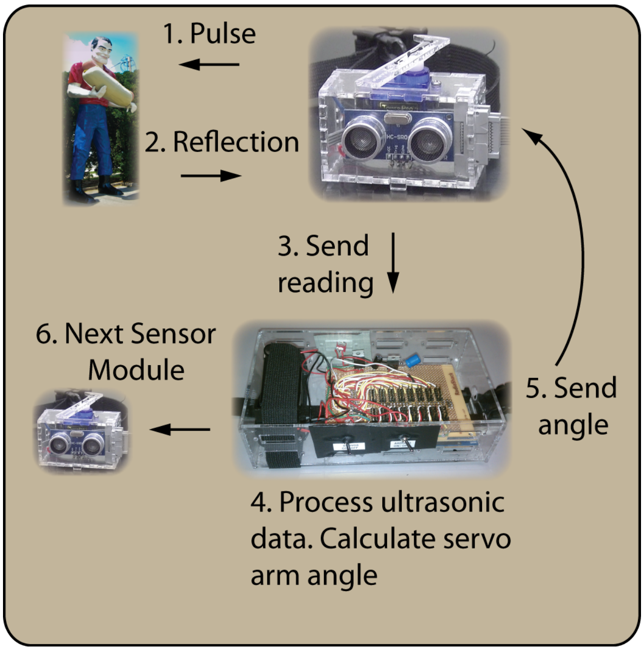

Figure 5: Architecture of SpiderSense

Controller Box. The Controller Box converts that reading into a rotation angle and commands the Sensor Module to rotate accordingly. After the rotation has finished the next Servo Module of the vest will initiate the same process.

6.1 Environment Scanning

Operating akin to radar, the ultrasonic sensors are transceivers that generate and emit a pulse of high frequency waves and then listen for the signal's rebound from an object. The HC-SR04 sensor emits a 12μs pulse of 40 kHz sound wave. An internal clock records the elapsed time from the end of the transmission to receiving the reflected wave (reflection). Ultrasonic waves travel at the speed of sound (1126ft/s) allowing us to convert the time between transmission and reception to distance information:

$$d = t * c \tag{1}$$

where d is the distance in inches, t is the time in microseconds and c is the speed of sound ($0.01351\text{in}/\mu$s in dry air at 68° F). If the wave does not encounter any object no reflection is received. Therefore when listening for a response, the amount of time that the sensor awaits an answer needs to be specified, else it may forever wait for a reflection. The HC-SR04 has a maximum range of 200 inches, thus substituting d with 200 inches in the above equation yields the maximum timeout threshold t of a Sensor Module to be: 14803μs.

6.2 Distance to pressure transformation

The measured distance d needs to be converted to an angle for the servomotor to rotate the arm. The initial position of the servo arm is parallel to the body surface. When an object is very close the servo arm will apply the maximum pressure, hence a maximum allowable rotation must be defined. For our implementation we found that a rotation of 50 degrees or more is somewhat painful to the user. However, conversion of the reflection distance d to the servo arm rotation a can be mapped in a variety of ways. This system allows both linear and logarithmic mapping of the distance information to the pressure applied to the skin. For SpiderSense, we used linear mapping:

$$a_{linear} = a_{min} + \frac{d - d_{min}}{d_{max} - d_{min}} * (a_{max} - a_{min}) \tag{2}$$

where a_{min} is the minimum and a_{max} is the maximum allowed angle for the arm, d_{min} is the minimum and d_{max} is the maximum ranging distance that can be computed and d is the measured distance from the previous step. For SpiderSense, $a_{min} = 0$, $a_{max} = 50$, $d_{min} = 6$, $d_{max} = 60$.

6.3 Concurrent use of ultrasonic sensors

Concurrent use of ultrasonic sensors can result in interference between the audio signals. For example if two Sensor Modules operate concurrently, one Sensor Module could pick up the other one's reflected pulse, falsely interpreting it as its own. To minimize this problem, the sensors are commanded to initiate sensing in round-robin fashion. In the worst case scenario when there is no object in the range of the sensor, the controller will timeout after:

$$t_{timeout} = \frac{d_{max} - d_{min}}{c} \tag{3}$$

If there are n Sensor Modules, and there is no object in the ranging distance dmax of all the Sensor Modules, then all of them will timeout. In this case, the worst case scenario for one full cycle of the system is:

$$t_{timeout} = n * \frac{d_{max} - d_{min}}{c} \tag{4}$$

For the system we developed, $n = 13$ and d_{max} - $d_{min} = 54$, therefore one full cycle can take up to 51.96ms.

Another consideration is that since the ultrasonic sensors are actually microphones that operate in the ultrasonic range, they are extremely sensitive and can pick up noise from other sources. More specifically, the servos when moving can also create noise that the ultrasonic sensors pick up as false positives. To solve this problem, the operation of the Sensor Modules is halted until the servomotor rotates to its final position. The delay induced here for one servomotor is:

$$t_{delay} = (a_{dest} - a_{curr}) * t_{speed} \tag{5}$$

Where a_{dest} is the angle that the servomotor needs to rotate to, a_{curr} is the position where the servomotor is currently and t_{speed} is the time in milliseconds for the servo to turn by one degree.

To sum up, the total time for a system with n sensors to cycle once through all the sensors, is:

$$t_{total} = n * t_{emit} + \sum_{i=1}^{n} tm_i + \sum_{i=1}^{n} td_i \tag{6}$$

Where t_{emit} is the duration of one sensor to emit the initial signal (12μs for the HC-SR04 sensor), tm_i is the timeout for sensor i and td_i is the delay for sensor i. Therefore if all the Sensor Modules do not detect any object and do not need to rotate, the total time is 52.11ms; if the user is suddenly surrounded by objects that are touching him, the total time is 1300.15ms.

7. TACTILE PERCEPTION

7.1 Positioning

Weber's [19, 21, 20] and Weinstein's [22] research on pressure sensitivity thresholds for different regions of the body have yielded a complete acuity map of the human skin. Using their findings we can compute the minimum distance needed between two sensors in order to be perceived as two discrete points. For example, the calf has a two-point discrimination threshold of 47mm; this means that any two points that touch the calf in a radius of 47mm or less will be perceived as the same point by the subject. The sensor placement in SpiderSense is such that the sensors are sufficiently apart to be perceived as separate locations, but the acuity map needs to be consulted for higher resolution configurations. Figure 6 shows the chosen positions for sensor placement.

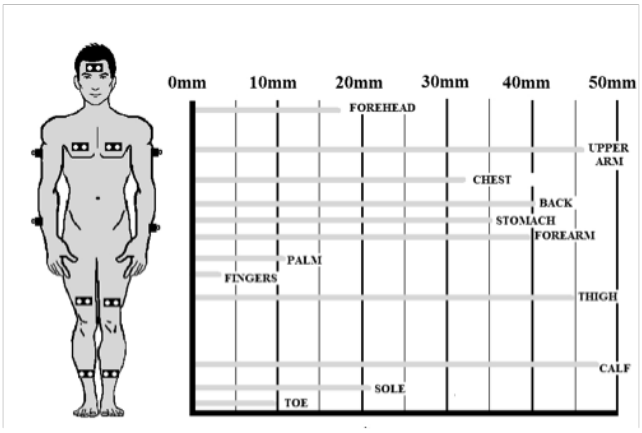

Figure 6: Two point discrimination threshold.

7.2 Reaction Times

Reaction time (RT) is defined as the time between the onset of a stimulus and the motor response for that stimulus. [4]. Studies have shown that reaction time for touch is 155ms [11]. Age does affect reaction time with decreasing RT from infancy to the late 20s, slightly increasing until the 50s and 60s and faster increasing in the 70s [23, 5, 8, 12].

Consequently the total delay from the moment an object appears in the sensing distance of a sensor, to the motor reaction time is:

$$t_{RT} = t_{emit} + t_{timeout} + t_{delay} + RT \qquad (7)$$

8. PRELIMINARY EXPERIMENTS

Four preliminary experiments were performed on two subjects to quickly assess the prototype: a hallway navigation trial; outside walkway pedestrian recognition; navigation inside a library (a confined space); and static surrounding threat detection. In all the experiments the subjects were blindfolded.

8.1 Hallway Navigation

The experiment took place inside a building in a hallway of 80 inches width and 50 feet length (Figure 7). The subject was instructed to walk down the hallway blindfolded without touching or bumping into the walls. No obstacles were present. The subject was initially seated on a chair and spun several times to disorient him. Eight trials were performed. The subject was able to successfully turn to identify the hallway's orientation and then navigated down the hallway. He also successfully "felt" using SpiderSense the end of the hallway, stopped and turned away and continued walking on a second perpendicular hallway. Furthermore, as the subject became accustomed to the new sensory input and learned to utilize the new information gateway, his walking speed increased. With the increase in the walking speed, accidental bumps into the wall also occurred more frequently. Subjects noted that with constantly applied pressure from SpiderSense it became difficult to gauge distance except when there was a large change in distance. Despite this difficulty, they were still able to identify the walls and avoid them. Subjects also noted a constant "twitching" sensation from the armature. This tends to occur inside buildings when the user is surrounded by objects at a distance less than the maximum sensing distance (d_{max}). Due to the sensitivity of the sensors, a small change in distance from an object could result in a change in pressure that is perceived as a repetitive twitch sensation.

Figure 7: Hallway Navigation Experiment.

8.2 Outside walkway pedestrian recognition

The second experiment took place on a 26 foot wide walkway (Figure 8) on the university campus during the busiest time of the day. The subject after looking and memorizing the surrounding area was instructed to walk straight while blindfolded and speak aloud whenever he felt an obstacle. The subject successfully sensed all the pedestrians that walked within a distance less than dmax from him. Not unsurprisingly, as the subjects were in an open space they reported that sensations of oncoming individuals were much more apparent.

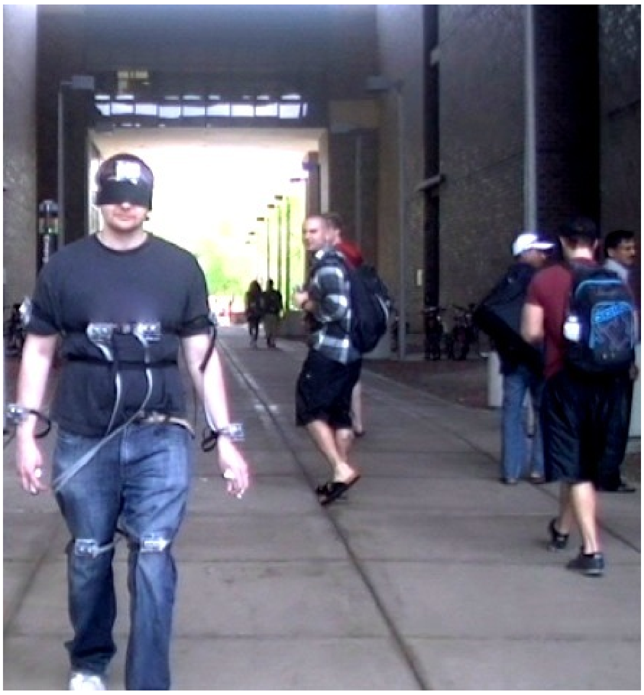

Figure 8: Outside walkway pedestrian recognition.

8.3 Navigation inside a library

Figure 9: Library Experiment.

The third experiment took place inside the university library (Figure 9) and was intended to determine how well subjects could navigate cramped environments. Figure 10 shows the library top-down organization, starting positioning and path of the subject for one of the experiments. The subject was given verbal instructions describing the route he had to follow (e.g.: On the third opening go left, then straight down the corridor and on the first opening go right and then straight again). We performed ten trials and all of them were unsuccessful. The subject was unable to find the openings and constantly bumped into the bookshelves. The subject said that he was constantly feeling pressure on his forearms without a significant change that would have allowed him to gauge his distance from the bookshelves. Another problem was that when there was an empty space in a bookshelf, the sensors would stop applying pressure hence the subject would falsely perceive that as an opening.

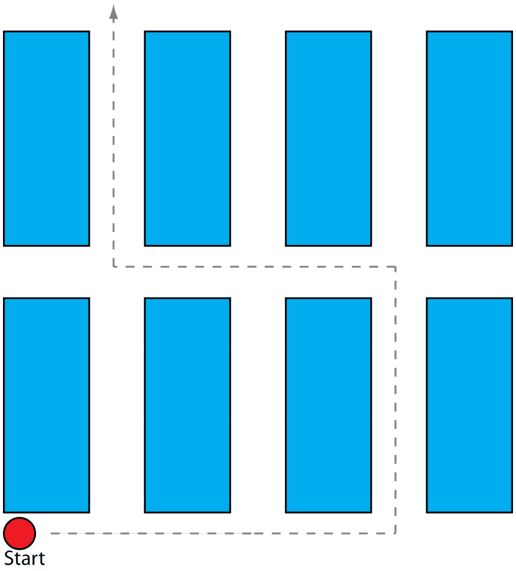

Figure 10: Starting position of the user and one of the paths he followed. The blue boxes show the shelves positioning.

8.4 Static surrounding threat detection

Figure 11: The wearer sensing one of the experimenters approaching from behind and throwing a cardboard shuriken.

In this last experiment the subjects were asked to stand still in an open space, while the experimenters approached him from random directions (Figure 11). The subject was asked to throw a cardboard shuriken to the direction of the approaching experimenter. In all the trials the subject successfully recognized when somebody was approaching and from which direction, and was able to hit the experimenter with the shuriken. Furthermore, when somebody was inside the sensing distance and was walking around the subject, the subject could localize and describe the direction of the movement.

9. DISCUSSION AND FUTURE WORK

The preliminary experiments showed that the tactile display works well in outdoor environments where the number of obstacles is low. However this is more challenging indoors when the sensor modules overwhelm the user with tactile feedback.

We described how to calculate the maximum delay that occurs when using ultrasonic distance sensors to build a tactile display. While we identified a positioning for the Sensor Modules that we believe is representative for 360o coverage, other configurations need to be evaluated as well. Psychophysical studies show that tactile distance is overestimated on areas with high mechanoreceptor density (as opposed to low) [20] hence a more elaborate algorithm needs to take this into consideration when providing tactile feedback. Furthermore, we experimented only with a linear mapping between sensor distance and tactile pressure, therefore other mappings need to be investigated. It is conceivable that different environments will require different distance to pressure mappings.

Also to be determined is whether an individual, through long-term use of the sensors, can learn to adapt to them and begin to recognize signature patterns such as the feeling on both their arms whenever they walk through a door; and whether sequences of signature patterns can be remembered and therefore used to form a tactile map of the environment.

Lastly it would be interesting to solicit the feedback of individuals who are visually handicapped to compare how well their current technologies (physical or ultrasound cane) compares to SpiderSense.

10. REFERENCES

[1] A. Cassinelli, C. Reynolds, and M. Ishikawa. Augmenting spatial awareness with haptic radar. In *Wearable Computers, 2006 10th IEEE International Symposium on*, pages 61–64. IEEE, 2006.

[2] J. C. Craig and K. B. Lyle. A comparison of tactile spatial sensitivity on the palm and fingerpad. *Attention, Perception, & Psychophysics*, 63(2):337–347, 2001.

[3] F. Gemperle, N. Ota, and D. Siewiorek. Design of a wearable tactile display. In *Wearable Computers, 2001. Proceedings. Fifth International Symposium on*, pages 5–12. IEEE, 2001.

[4] P. Jaskowski. Simple reaction time and perception of temporal order: Dissociations and hypotheses. *Perceptual and motor skills*, 82(3):707–730, 1996.

[5] S. Jevas and J. H. Yan. The effect of aging on cognitive function: a preliminary quantitative review. *Research Quarterly for Exercise and Sport*, 72:49, 2001.

[6] K. O. Johnson and J. R. Phillips. Tactile spatial resolution. i. two-point discrimination, gap detection, grating resolution, and letter recognition. *Journal of Neurophysiology*, 46(6):1177–1192, 1981.

[7] R. V. Kenyon and J. Leigh. Human augmentics: Augmenting human evolution. In *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE*, pages 6758–6761. IEEE, 2011.

[8] C. W. Luchies, J. Schiffman, L. G. Richards, M. R. Thompson, D. Bazuin, and A. J. DeYoung. Effects of age, step direction, and reaction condition on the ability to step quickly. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, 57(4):M246–M249, 2002.

[9] D. R. Miaw and R. Raskar. Second skin: Motion capture with actuated feedback for motor learning. In *Proceedings of the 27th international conference extended abstracts on Human factors in computing systems*, pages 4537–4542. ACM, 2009.

[10] G. Mowbray and J. Gebhard. Man's senses as informational channels. Technical report, DTIC Document, 1958.

[11] E. S. Robinson. Work of the integrated organism. 1934.

[12] S. A. Rose, J. F. Feldman, J. J. Jankowski, and D. M. Caro. A longitudinal study of visual expectation and reaction time in the first year of life. *Child Development*, 73(1):47–61, 2002.

[13] C. Schönauer, K. Fukushi, A. Olwal, H. Kaufmann, and R. Raskar. Multimodal motion guidance: techniques for adaptive and dynamic feedback. In *Proceedings of the 14th ACM international conference on Multimodal interaction*, pages 133–140. ACM, 2012.

[14] B.-S. Shin and C.-S. Lim. Obstacle detection and avoidance system for visually impaired people. *Haptic and Audio Interaction Design*, pages 78–85, 2007.

[15] K. Tsukada and M. Yasumura. Activebelt: Belt-type wearable tactile display for directional navigation. *UbiComp 2004: Ubiquitous Computing*, pages 384–399, 2004.

[16] J. B. van Erp and H. Van Veen. A multipurpose tactile vest for astronauts in the international space station. In *Proceedings of eurohaptics*, pages 405–408. Dublin, Ireland: ACM, Press, 2003.

[17] H. Van Veen and J. B. Van Erp. Providing directional information with tactile torso displays. In *Proceedings of EuroHaptics*, pages 471–474, 2003.

[18] R. T. Verrillo. A duplex mechanism of mechanoreception. *The skin senses*, pages 139–156, 1968.

[19] E. Weber. De tactu. *Koehler, Leipzig*, 1834.

[20] E. Weber. The sense of touch (he ross, trans.). *Academic, London (Original work published 1834)*, 1978.

[21] E. H. Weber. Der tastsinn und das gemeingefühl [1846], hg. v. *Ewald Hering, Leipzig*, 1905.

[22] S. Weinstein. Intensive and extensive aspects of tactile sensitivity as a function of body part, sex and laterality. In *the First Int'l symp. on the Skin Senses, 1968*, 1968.

[23] A. Welford. Motor performance. *Handbook of the psychology of aging*, 2:450–95, 1977.