Perceiving the Unseen for Enhanced Tool Use

Body Schema Extension via a Vibrotactile Feedback Sensing System

HCI 585X Project Report

April 21, 2011

Prepared by: Corey Gwin

Prepared for: Alexander Stoytchev

Iowa State University: Human Computer Interaction Engineering Online Learning cgwin@iastate.edu

Table of Contents

Project Overview

The following report reviews the research, design, implementation, testing, and results of a vibrotactile feedback sensing system (VFSS). The aim of a VFSS is to enhance an agent's perception of body schema in tool use where the agent's own senses are occluded by use of the tool itself. The VFSS reviewed in this report accomplishes this enhancement by transferring information about the three-dimensional nature of the environment at the distal regions of the tool the agent is operating into vibrotactile feedback. This transfer affords the agent an alternative and improved way of perceiving and utilizing the tool in the environment that it would otherwise be incapable of perceiving. The project draws heavily from the research of Alva Noë and Kevin O'Regan in the field of action in perception and saliency and attention. It also draws from previous research and work done on the tactile vision substitution systems (TVSS) created by Paul Bach-y-Rita and the minimal TVSS developed by Jon Bird.

Introduction & Background

Our brain's ability to perceive is limited by the body's ability to sense information from its physical interactions with the world. We can only move what our muscles move, see what our eyes see, hear what our ears hear, or touch what our skin touches. Nevertheless, thanks to the plasticity of the human brain and continual technologic advancements, we have come to employ a plethora of tools that enhance our physical capabilities and augment our limited sensory abilities. Ranging from simple objects, like hammers that increase our strength, to extremely complex and advanced machines, like the massive United States Air Force C-17 cargo jet, that can enhance our navigation, speed, maneuverability, or power. There are, however, limitations to our tool use and these limitations limit our performance, abilities, and level of perception with them.

Often instead, we utilize robots to perform tasks where the human cannot achieve the same level of precision, consistency, speed or strength. Robots, though, also have their own limitations. Unlike humans, robots lack an innate intrinsic motivation to understand their environment and adapt to the frequently occurring changes in it. A new field of robotics, developmental robotics, is attempting to design intelligent machines that learn and develop with a "brain" that understands the world just as humans develop their brain from childhood to adulthood. As a result, the nature, capability, and limitations of the brain have become the focus of roboticists hoping to design machines that will help further evolve human capability. By studying the limitations of the brain, roboticists can design intelligent machines that complement the human incapability. It is important to understand the malleability of the human brain. From the brain, we can understand where perception of self begins and ends.

Through this understanding, we can begin to remove our perceptual limitations and better employ tools in our world.

In the last few decades, neurophysiological, psychological and neuropsychological research has shown the amazing plasticity of the brain to incorporate objects into one's body schema[1] through sensorimotor experiences (i.e. tool use). Maravita et al. (2004) showed, by monitoring the somatosensory and visual receptive fields (sRF & vRF) in Japanese macaques' brains, that after extended tool use, changes in the sRF and vRF indicated "inclusion of tools in the 'Body Schema' as if the effector (e.g. the hand) were elongated to the tip of the tool" [1]. In other words, the tool was not simply an object; it was a controllable feedback providing extension of the brain's body.

In his book Phantoms in the Brain, Ramachandran (1999) shows how our own body "is a phantom, one that your brain has temporarily constructed purely for convenience." Through several demonstrations, he illustrates how "the mechanisms of perception are mainly involved in extracting statistical correlations from the world to create a model that is temporarily useful." In a simple experiment where a subject observes taps on the fake prop hand while simultaneously being tapped on their own occluded from view hand, the subject concludes, in a matter of seconds, that the fake hand is of their own body [2]. We realize from this experiment that our perception of self is not just the physical body we often feel we are constrained to, but rather a malleable and extendable representation formed by correlations of the types feedback we receive from the world.

David Clark illustrates numerous examples of modern day technologies taking advantage of the brains ability to learn new types and channels of input: Australian cyber-artist Stelarc can voluntarily control a mechanical third hand and doctors have enabled quadriplegic patients to move computer cursors through their brain activity [3]. Clark finds that due the capacity of the human brain to learn new modes of controlling action, we experience a fluid, transparent mesh between our will and motion. This fluid experience is what allows the experienced car driver, athlete, and video gamer to operate without ever contemplating the necessary actions required for using the throttle, swinging the baseball bat, or navigating the virtual world with an Xbox controller. He concludes that what we consider as "self" is really a matter of what we can continually and reliably control for our desired outcomes.

Problem

Simple tools are easy to perceive: when I hit the nail with the hammer I feel the strike, I hear the collision, and I see the nail go into the wood. However, with complex and advanced

---

[1] One's body schema is a "multicomponential, action-oriented construction" of self-perception "that besides proprioception, other sensory modalities (typically somatosensory and vision) are crucial to its construction" [1].

machines, our perception is still limited to the confines of our bodies while often much of the physical interaction with the world is occurring elsewhere. We are only able to perceive as far as the tool provides sensory information to us. For example, a military helicopter pilot may be able to feel the G-forces of a maneuver and the feedback from the joystick, hear the increases in the engine's RPM and audible warning alerts, or see their orientation from the horizon and the optical flow outside the cockpit, but without periodically checking the many gauges around them and listening and communicating with air traffic control and other operators, the pilot may become quickly overwhelmed an unable to operate the helicopter [4] (Figure 1). The leading cause of recent military helicopter mishaps has been due to brownouts[2]. The loss of spatial awareness and reliance on gauges in this rapid and crucial phase of flight causes many pilots to lose control of the air vehicle and crash. Because the pilot lacks the ability to see where they are, they have no easy way of knowing where to go.

Figure 1. The many visual cues required to fly a UH-60 Black Hawk helicopter. Source: defenseindustrydaily.com.

Of course we have developed robots that eliminate these perceptual complications for us. The United States Navy's MQ-8B Fire Scout Vertical Takeoff Unmanned Aerial Vehicle (VTUAV) is an autonomous helicopter that can takeoff, land, and fly entire missions on its own. While this "unmanned" system and others like it have their advantages over humans, they are still prone to their own perceptual limitations as allowed, designed or, many times, unforeseen by their designers. For example, Fire Scout does not have the ability to sense, avoid, or track objects and targets on its own. While machines may be able to perform and detect in greater capacity than humans, their ability to know what to do with what information they can detect is limited. For now, it seems only animals have the ability to intelligently use information they perceive to influence and understand their world (i.e. learn). By continuing to study how humans perceive, perhaps we can design more intelligent machines that learn do the same.

The main function of visual perception is to keep the agent in touch with the environment in guiding their action. Close examination reveals that an agent's perception requires action. Visual perception specifically is the "activity of exploring the environment in ways mediated by mastery knowledge of the relevant sensorimotor contingencies" [5]. In other words, we only

---

[2] A brownout is a dense cloud of swirling sand and dust that blinds helicopter pilots as they attempt to land.

[3] If the human eye were a digital camera, its full angle of vision captures spatial detail with a resolution of 576 megapixels (this is just with just one eye) [23]. Compare this resolution to the PrimeSensor's measly 640 by 480

see that with which we physically turn our attention to and, importantly, then recognize or understand. We cannot simply glance at a panoramic photograph of a cityscape, for example, and then instantly recall and report all the exact details of the entire scene. You may not be able to recall how many buildings were in the scene or even what color the frame that held the cityscape photograph was. To do so would likely require you to actively explore the entire scene and gain all the necessary information that you can understand about it. Visual perception requires that we physically align our bodies, move our heads and eyes and focus our attention on a particular region of interest. As a result, we only experience the aspects of the world with which we attend to – this fact leads to phenomenon like "change-blindness" and "inattentional blindness" [6] [7]. Research has shown that the most salient and greatest attractors of attention are obviously those stimuli that standout from their neighbors in space and time. There is a certain "wow-factor" that draws your attention to perceive specific details in the environment and those details what allow you to draw information necessary for interacting with it [8]. Herein lies a significant problem for human tool use: with the growing complexity and size of tools, the perceptual reliance on eyesight to keep tabs on the world outside our tools limits our capability with them.

As humans, we have come up with creative ways of extending our perceptual awareness to the world outside of our tools primarily by use of various visual and audible cues. We use mirrors, gauges, blinking lights, or high pitched tones, but even still, these types of visual and audible cues are not sufficient. Due to automobile blind spots, 50 children are backed over by vehicles each week. Between 2004 and 2008, motor vehicle blind spots caused 41.6% of all children auto deaths. A majority of these accidents occur while the car is coming out of a driveway or parking space [9]. The major factor in these accidents is the driver's inability to perceive or turn their attention to what is occurring outside of their vehicle because their vision is occluded (even when the vehicles have mirrors). To respond to this problem, automakers have begun to install wide-angled cameras in automobile rear ends that provide drivers a view of the occluded area behind the vehicle as it reverses. While certainly better than mirrors, these camera systems still require the driver take notice of dangers. It also requires that they utilize the side mirrors in tandem since the camera can only show exactly where it is looking. In addition, the cameras do not alert the driver's attention if an out of view object is approaching. To alleviate the object detection problem, automakers also include audible alerts that alert the driver as the vehicle approaches objects out of the driver's view. Some systems alter the pitch or frequency of the tone accordingly as the proximity to the object changes [10]. While the audible cue is capable of alerting the driver and providing useful information, it is still incapable of providing the exact location or identification of the object. Such a system would require a 3D audio system that would at least allow the driver to perceive the location of the object.

This vision problem can especially become magnified at high speeds when the driver does not have time to keep tabs on the location of objects outside of their visual and perceptive field. A Formula 1 driver, for example, must maintain awareness of other vehicles around them while vigorously navigating and frequently communicating with team members. The race driver does not have time to constantly check their mirrors or cameras or listen for audible alerts since the navigation of the course is taxing their attention. The driver cannot afford to hesitate at the risk of a slower lap time but if they can't detect danger in their blind spot, they may be risking their own and other's safety. Perhaps an easier way for the driver to perceive other vehicles would be if he could simply *feel* their presence around him.

Solution

I have created and tested a vibrotactile feedback sensing system (VFSS) that attempts to extend the nervous system of the operating user to the surrounding outer surfaces of the tool they are actively using for enhanced tool use perception and performance. For the purposes of this project, that tool is an automobile. Recall from earlier that if a system can sense what the user cannot sense and is a result of the agent's actions and control, then that system can enhance the agent's perception and become an extension of the agent's body schema. Due to the availability and cost of hardware, the VFSS described in this project consists of a single sensing sensor that detects the three dimensional nature of the occluded environment and then relays that information with a vibrotactile array.

Visual stimuli require that they come into your field of view to draw your attention to it and then be perceived; tactile stimuli are similar in that they require your attention for perception, but in the case of the VFSS, since the vibrotactile feedback is in direct contact with the nervous system, salient information about the environment becomes a direct result of active tool use. In this regard, the "field of view" of the nervous system can be considered considerably different from that of the eyes. It's important to note, as reinforced in [8], that neural responses greatly weaken with repeated experience to initially novel stimuli. In this way, it is important to ensure that all attention grabbing sensory stimuli, such as the vibrotactile feedback, be particularly salient. Visual stimuli require an agent to actively explore a specific region of interest to perceive it, a tactile stimulus only requires that the user feel it, acknowledge the location of its presence and then interpret its meaning. For example, we do not have to continually see the chair or ground under us to know that it is there; we just feel that it is there. With vision, we must make a greater physical effort to perceive. The tactile stimulus is also different from an audible stimulus since it is possible to detect the shape, form, and even identity of objects by touch alone and very difficult to do so by sound alone. Perhaps you have played the game of trying to identify objects in a bag by touching them while blindfolded – this task would be nearly impossible to do by simply listening to them (especially if they are inanimate and soundless).

Of course haptic feedback in a sensing system will only be as good as the system's sensors' abilities are to provide relevant feedback to the tactile array; however, it is not important that the sensors have a particularly high resolution. As [11] mentions, because the brain extracts information from patterns of stimulation, a poor resolution sensory substitution system can provide the information necessary for perception. Instead, what is more important is that a VFSS operator learn to recognize the sensorimotor contingencies (i.e. the vibrotactile patterns of stimulation) from interacting with the environment with the tool. This is developed through experience with the VFSS. Using the expansive human nervous system as an input surface for feedback can provide a new opportunity for enhanced perception in tool use. Using haptic feedback to extend the nervous system to the surfaces and capabilities of tools allows the agent to not only see, but to simultaneously feel the world in new ways.

Target Users

Several uses for such a haptic system can come to mind: truck drivers who physically feel the presence of vehicles entering their occluded blind spots, helicopter pilots who feel the ground approach beneath them as they land in swirling clouds of dust, or security agents who can feel the presence of intruders while focusing their visual attention with a camera elsewhere.

The system proposed in this project will focus primarily on enhancing an automobile driver's ability to perceive visually occluded objects during activities such as reversing, parking and lane changing. The VFSS would be appropriate for all automobile drivers but especially for drivers with vehicles that have large visual occlusion (e.g. SUV, semi-trucks, etc.). The VFSS will also be ideal for operators whose visual and audible attentive awareness are already heavily utilized in their tool use. Race car drivers, aviators, exoskeletons, and astronauts are all examples.

Previous Work

Most haptic feedback systems up to today have primarily been designed for telerobotics, virtual reality immersion or vision replacement systems for the blind [12].

Bach-y-Rita was one of the pioneering researchers in using tactile feedback to perceive the world through his tactile vision *substitution* systems. The first TVSS was a stationary chair with four hundred solenoid stimulators that vibrated according to the stimuli detected by a television camera the subject could manipulate. Through this first TVSS, Bach-y-Rita reported that blind subjects are able to develop visual concepts of perspective, shadows, and shape distortion simply through the tactile feedback of the chair. Much later, he successfully created a high resolution TVSS by providing electrotactile stimulation to a user's tongue, a particularly sensitive input surface on the human body. As the name implies, these systems were focused primarily as being a sensory substitution for the loss of vision for blind subjects [13]. They found that skilled users of the TVSS were able to track, identify objects and respond accordingly as they manipulated objects in the world. Skilled users with the TVSS also reported the sensation of altogether not even noticing the tactile nature of the sensor, simply just saw.

Inspired by Bach-y-Rita's pioneering work, Bird et al. created similar sensors on a much smaller scale. They call their TVSS a minimal TVSS. Their research found that a simple 5 by 4 array of vibrotactile sensors were ideal for proficient perception and object tracking, but even a two by three array was sufficient for a simple ball tracking tasks. The minimal TVSS was worn as a belt, bracelet, and vest and could be felt through clothing by simply attaching them Velcro [14]. Recently, Bird et al. have begun exploring the uses of vibrotactile systems as guides for human behavior. In a similar manner to what i wish to achieve, the minimal TVSS can provide guidance for learning in activities such as learning to play a violin or the drums (Figure 2) [15].


Figure 2. Vibrotactile feedback used to train novice violin players. Photo by Jon Bird.

In other work, at the University of Minnesota's Center for Transportation Studies, the HumanFIRST program is employing the tools and methods of psychology and human factors engineering to improve driver performance and cognitive functions. In one relevant study, the HumanFIRST researchers studied a variable resistance feedback accelerator pedal that varied with how closely the driver's vehicle followed a lead vehicle. Interestingly, they found that drivers responded much more quickly to a sudden slowdown by lead vehicle with the haptic feedback, but took longer to transition to the brake, suggesting that the driver performs a visual double-take to insure the lead vehicle is actually slowing down since they are not used to the system. The overall reaction time, however, was significantly better with haptic feedback than without it. In a follow-on study with the same system, drivers followed a lead vehicle as a primary task but also manipulated a touch screen display as a secondary task as many times as they could within a two minute period. This secondary task was considered a relatively more perceptually demanding task than simply adjusting the stereo. Researchers found that the haptic feedback improved driver's ability to perform both of the primary and secondary tasks, suggesting that drivers took advantage of the "newly freed resources" from the haptic system [16].

Current Systems in the Consumer Market

As mentioned, all tools provide the user some form of feedback, but for a majority of the advanced systems on the consumer market, visual perception appears to be primary designed feedback source. Current haptic feedback is weak or nonexistent for many advanced consumer market systems. This may primarily be because it is hard to implement a system that can reliably touch the user. Perhaps cell phones are the only wide users of haptic feedback. We've become very familiar with cell phones using vibration to discretely alert their users. Newer smartphones and video game controllers are using haptic feedback in much more realistic ways to enhance the perception of their virtual games and applications (e.g. feeling the virtual guitar vibrate when strummed or table shake when the pinball hits a bumper [17]).

For vehicle sensing, the car company Infiniti is perhaps the leading industry innovator for smart car sensing technologies but all but one of their systems do not utilize haptic feedback (and it is a rather indirect braking that provides the feedback). By utilizing various radars, ultrasonic detectors, wide angled cameras, blinking lights, and audible tones, Infiniti offers their customers a wide array of smart sensing systems for their vehicles. These systems include an intelligent brake assist that helps warn against potential collisions by automatically applying the brakes, a blind spot intervention system that monitors and detects other vehicles in the driver's blind spot area with blinking lights and tones, and a parking aid gives the driver the ability to see a virtual 360° view of the parking environment [18]. While the above are all very helpful perception systems, but none of them providing haptic feedback for the freeing of perceptual resources.

Qualifications

I am a first year graduate student in the Human-Computer Interaction program via Engineering Online Learning at Iowa State University. I received my BS in Mechanical Engineering from the California Polytechnic State University, San Luis Obispo in 2009 focusing primarily in mechatronics. Among a myriad of other projects at Cal Poly, I designed, programmed and built an autonomous heliostat that tracked the sun's position across the sky and reflected its energy at specific target for solar-thermal power.

Currently, I am employed by Northrop Grumman Aerospace Systems at the Tactical Unmanned Systems division in San Diego, California. There I work as a payload and weapon systems integration engineer for the MQ-8B Fire Scout program, providing state-of-the-art reconnaissance, surveillance, and target acquisition solutions. Though my degree was in mechanical engineering, all of my professional experience, including work at the Edwards Air Force Base Flight Test Center, has primarily been electrical and software engineering based. In addition to systems design, I've designed several engineering visualization and simulation software tools. One tool visualizes Join Direct Attack Munition (JDAM) Launch Acceptability Range (LAR) telemetry data for the B-1B test program, another simulates B-52H weapons employment hardware procedures for test engineer training, and another quickly displays and calculates and presents intuitive displays of mass properties data for various weapons configurations on the F-35 Joint Strike Fighter program.

With a strong love for technology and learning, I strive to apply my technical ingenuity and passion for innovation, advancing the capabilities and ensuring the safety of the human race. I hope to integrate new computer and sensor technologies into our human experience that allow us to further interact with the world in better ways that we previously could not. My aim is to move technology away from one's fingertips and instead into one's natural existence where the smarts are not in a device, but instead in us.

System Design Overview

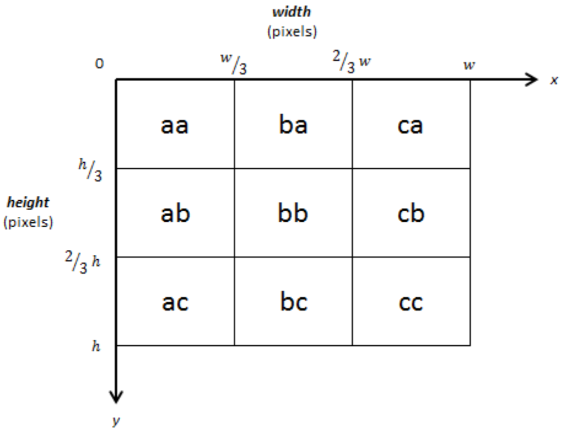


Figure 3. The VFSS 3 by 3 depth and vibrotactile grid coordinate system. The PrimeSensor depth image has a resolution of 640 by 480 (width and height).

The implementation schedule necessary to complete this project can be found in the appendix. The VFSS consists of a 3D vision sensor, a vibrotactile array, and a laptop computer for image processing and vibrotactile array control. An Arduino Duemilanove microcontroller with an ATmega328 processor receives commands from the laptop computer via USB. The programmed Arduino uses its digital I/O and PWM pins to control a Texas Instruments (TI) TLC5940 16-Channel LED integrated circuit which in turn controls the pulse width modulated (PWM) signals of vibration motors in an array (i.e. the Arduino varies the intensity of the vibration by the motors via the TI TLC5940). In this first VFSS, the vibration motors are arranged in a 3 by 3 array and attached to a vest the driver wears under their clothes. The array was tested in two layouts to enhance the user's sensitivity in the perception.

The 3D vision system employed for this project is the Microsoft Kinect with the PrimeSense PrimeSensor technology. The Kinect is affixed at the rear of the automobile for sensing the environment in the driver's blind spot. The laptop processes the imagery by determining the depth of objects behind the automobile and trigger specific vibrotactile intensities to clue the driver in on the depth of the environment. The 3 by 3 grid of the Kinect's field of view correlates to the 3 by 3 grid of the vibrotactile array controlled by the Arduino. Each box in the grid measures the average depth value of all the pixels in each box and then uses that average value to relay the appropriate vibrotactile intensity to the TLC5940. Figure 3 shows the 3 by 3 depth and vibrotactile grid. Note that the Kinect provides a 640 by 480 pixel capture, width and height respectively. Gleaning from Bird et al.'s research, I suspected that satisfactory object perception will be capable from the resolution of depth detection[3] in the 3 by 3 array.

Preconditions

In building my own prototype I required that the system only be used in controlled environments. These environmental details included ensuring there is little or no sunlight during testing to minimize the amount infrared (IR) interference on the PrimeSensor outdoors, no adverse weather, and properly functioning hardware. These conditions ensure the reliability of the hardware, safety of the testers and produce consistent data and reliable results.

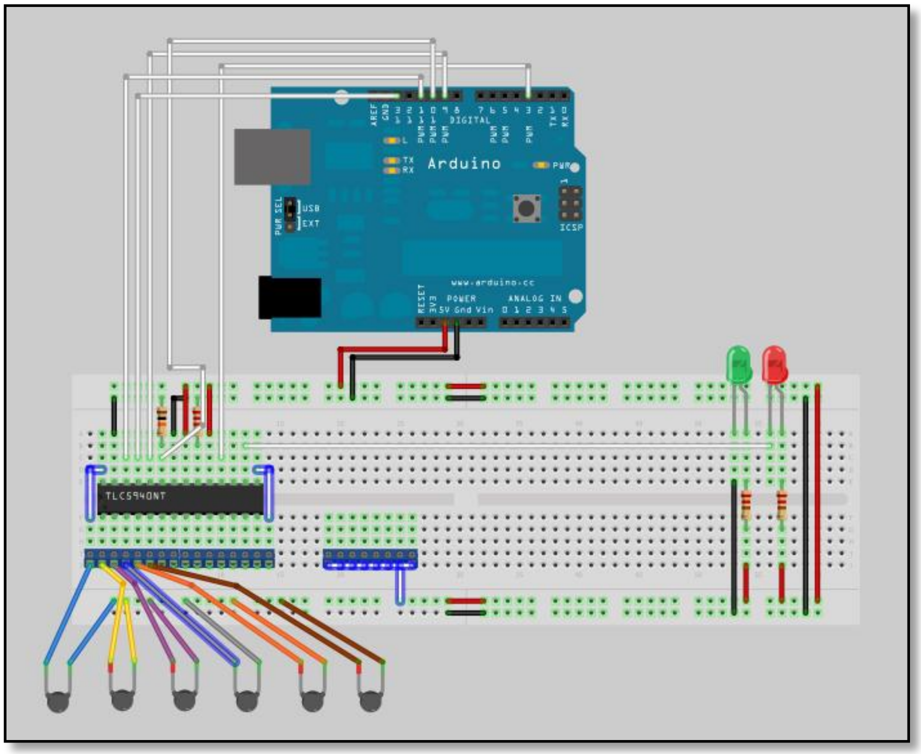


Figure 4. Breadboard schematic of the vibrotactile feedback sensing system (VFSS).

Hardware

Figure 4 shows the breadboard schematic of the vibrotactile array electronics that were constructed and evaluated in this project. Figure 5 is photo of the VFSS electronics constructed using the breadboard schematic from above.

---

[3] If the human eye were a digital camera, its full angle of vision captures spatial detail with a resolution of 576 megapixels (this is just with just one eye) [23]. Compare this resolution to the PrimeSensor's measly 640 by 480 depth image at only 0.3 megapixels. Even if we could scrounge up 576,000,000 vibration motors, I'm not sure we would have enough real estate one's body to relay the amount of detail through touch that the eye can effortlessly detect. Even though we do not perceive all of this detail, it is captured by the eye nonetheless and there for us to detect (with brightness, depth, and color and all). One may begin to wonder what the sensing "resolution" of the one's own skin is.

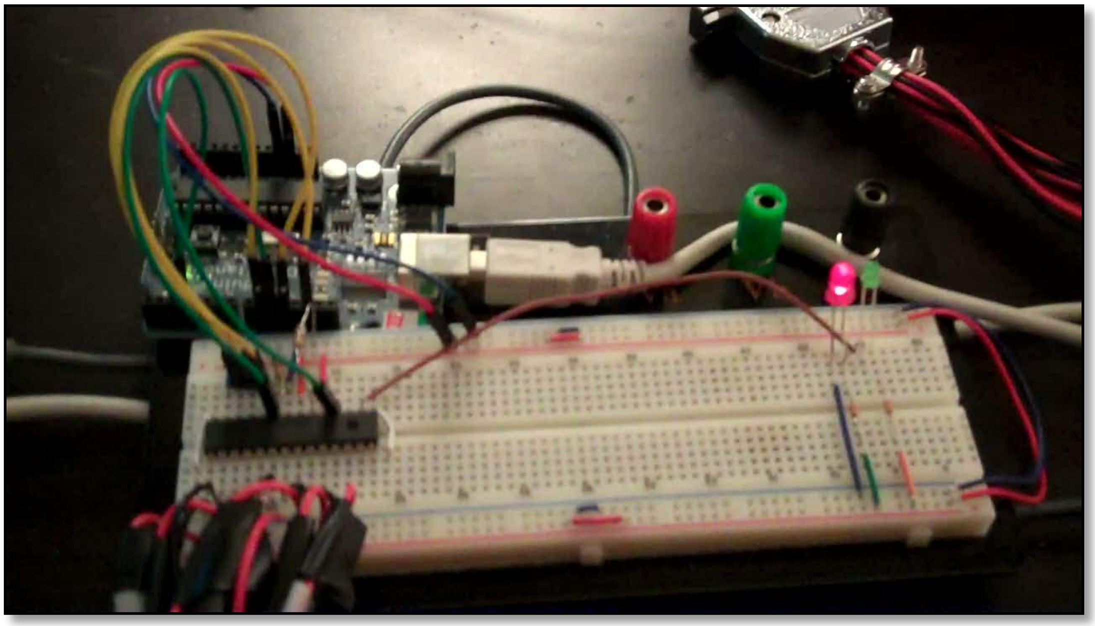


Figure 5. VFSS electronics as constructed and tested in this report – the nine TLC5940 channels are terminated on a DB25.

The following hardware and their quantities were required for the VFSS:

- Microsoft Kinect with PrimeSense PrimeSensor x 1
- Arduino Duemilanove microcontroller board (ATmega328) x 1
- Texas Instruments 16-Channel LED Driver (TLC5940NT) x 1
- LilyPad Vibe Board x 8
- Laptop computer (Intel i3 with 4 GB memory and an ATI HD5740 with 512 MB onboard)
- 2000 Ford Focus ZX3 x 1
- 12 V cigarette lighter AC power inverter
- ½” x 4’ PVC x 2
- Zip ties
- Felt
- Adhesive backed Velcro strips

Table 1. Microsoft Kinect Technical Specifications [19].

Horizontal Field of View (HFOV) (°)	Vertical Field of View (VFOV) (°)	Dead Zone of Depth Detection (m)	Field of View Range of Depth Detection (m)	Data Stream Resolution (-)
57	43	0 - 1.2	1.2 – 3.5	640x480 32-bit color @ 30 frames/sec

The Microsoft Kinect technical specifications can be found in Table 1. The Kinect optical subsystem, the PrimeSense PrimeSensor, consists of three components: a depth projector (high powered IR LED), a depth sensor (CMOS IR image sensor), and an RGB sensor (CMOS color image sensor). By scattering a specific pattern of coded, near-infrared, structured light into the environment, the PrimeSensor is capable of capturing a depth image based on the returns of the IR light within its field of view. It then creates a topographical view of the scene by correlating the depth pixels with each pixel of the simultaneous color image. Unfortunately, due to the PrimeSensor's use of IR light, VFSS can only be operated inside, in the shade, or during the evening when ambient IR light from the sun or other IR emitting sources will not interfere. The Kinect also has a motor subsystem capable of a few degrees of vertical tilt and an audio subsystem pinpoint noise canceling audio capture, but these features will be disabled for the VFSS.

Figure 6 shows a sketch of the Microsoft Kinect mounted on my 2000 Ford Focus ZX3. The green circle indicates the start of the PrimeSensor's depth detection; everything prior to this area is considered a dead zone and results in no depth detection and vibration. The red circle indicates the furthest depth detected by the sensor. The Kinect is fixed in position on the vehicle by use of PVC pipe, zip ties, and tape. The vehicle's cargo rack provides a good location to tie the assembly down to the roof of the vehicle as shown in Figure 7. The Kinect cables are routed through the passenger door and taped in place allowing the passenger door to be open and closed as necessary. Power for the Kinect is provided from a12 V cigarette lighter via a 150 watt AC power inverter. The rest of the VFSS electronics are positioned in the center console and the laptop placed on the passenger seat.

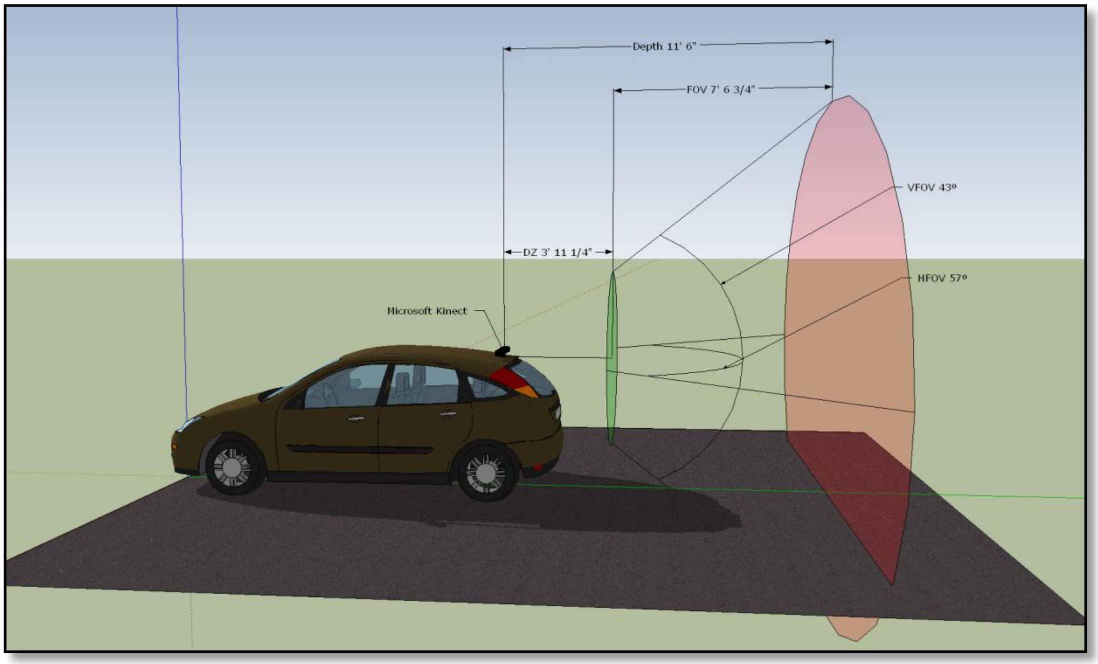


Figure 6. Microsoft Kinect mounted on my 2000 Ford Focus ZX3 and the corresponding Field of View (FOV) dimensions.

Figure 7. Microsoft Kinect as mounted on my 2000 Ford Focus for testing of the VFSS.

For the vibrotactile array, the LilyPad vibe boards from sparkfun.com came prefabricated, each with a 10 mm shaftless motor, resistor, and snub diode on perf boards. Small adhesive backed Velcro strips were applied on the vibe boards to help fix them to the felt they were mounted on. The shaftless motor vibration varies in frequency from 75-200 Hz and the amplitude 0.2-.85 g at a start voltage of 1 V to full power at 5V. Each of the nine vibe boards were soldered and then terminated on a DB25 to aid in disconnecting the vibrotactile array that the operator may wear from the rest of the VFSS electronics.

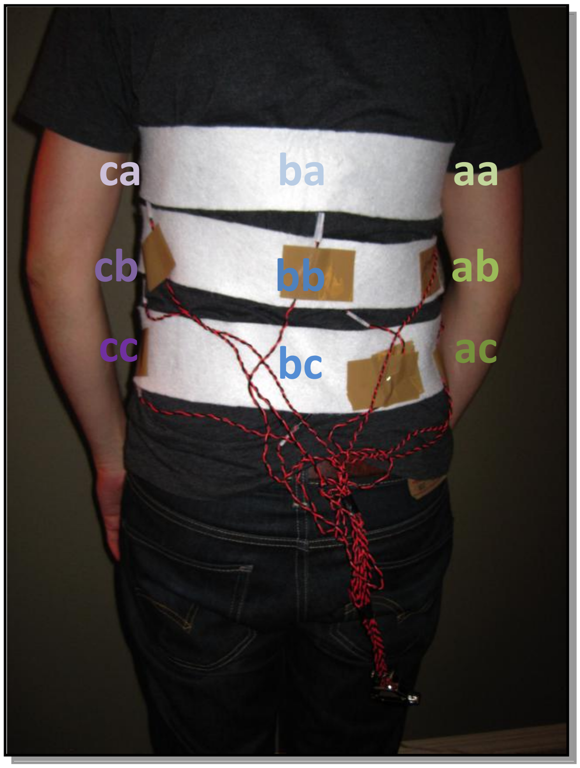
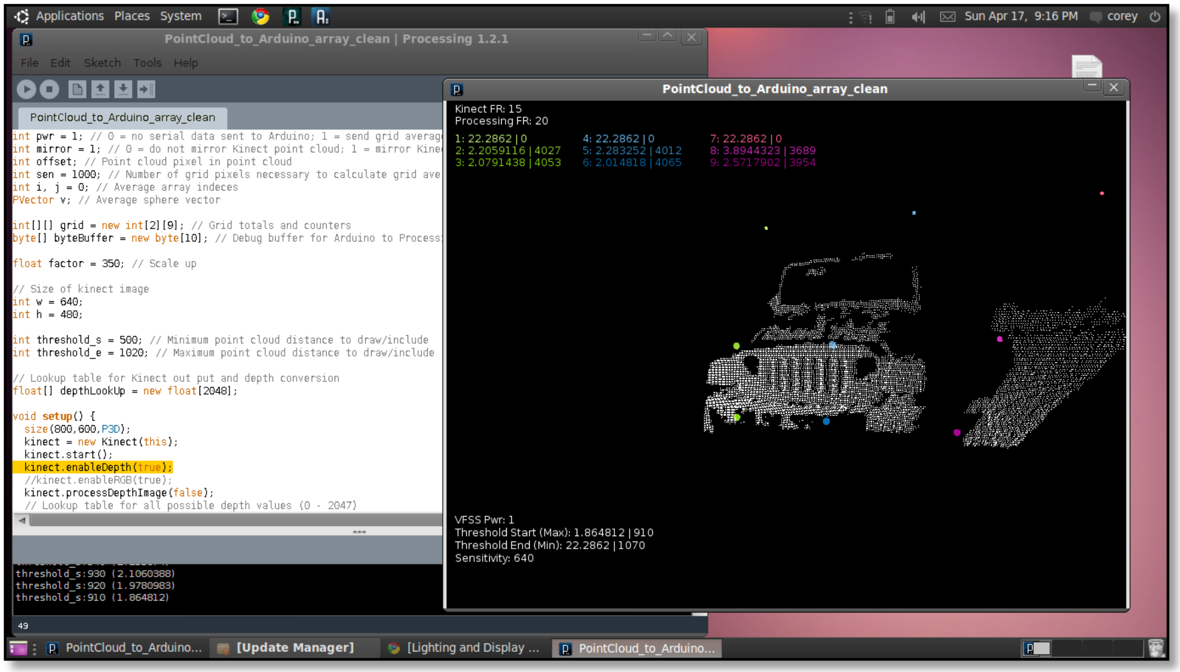


Figure 8. Final vibrotactile array configuration as worn by VFSS operator with location of array grids.

The first vibrotactile array had the vibe boards arranged in a 7.5” x 5“ equally spaced grid that approximately kept the same 4:3 picture ratio of height and width of the 640 x 480 Kinect point cloud image capture. This first grid was fixed to a piece of felt that had been glued to a cardboard backing with the idea that the backing would be left in place on the driver’s seat and not require the operator to wear the vibrotactile array. After initial testing, it was decided that the cardboard’s rigidity transmitted too much vibration from neighboring motors causing a cloudy and misinterpreted impression of the environment captured by the Kinect. In addition, the relatively small spacing of the motors felt inadequate in conveying captured environmental depth information for the untrained VFSS user. Alternatively, for the final configuration of the vibrotactile array, the vibe boards are fixed to individual rows of felt, which lower the transmission of neighboring motors (Figure 8). This requires the VFSS user to wear the vibrotactile array, but allows for much better transmission vibration energy to the nervous system and for detection of vibrational intensity changes. In addition, the final array does not keep the same 4:3 picture ratio of the image capture but instead exaggerates the capture such that the grids span across the VFSS user's entire back, both from the left and right side of the body and upper and lower back. This exaggeration seems to aid in perception.



```
int pwr = 1; // 0 = no serial data sent to Arduino; 1 = send grid averag
int mirror = 1; // 0 = do not mirror Kinect point cloud; 1 = mirror Kine
int offset; // Point cloud pixel in point cloud
int sen = 1000; // Number of grid pixels necessary to calculate grid ave
int i, j = 0; // Average array indeces
PVector v; // Average sphere vector

int[][] grid = new int[2][9]; // Grid totals and counters
byte[] byteBuffer = new byte[10]; // Debug buffer for Arduino to Process

float factor = 350; // Scale up

// Size of kinect image
int w = 640;
int h = 480;

int threshold_s = 500; // Minimum point cloud distance to draw/include
int threshold_e = 1020; // Maximum point cloud distance to draw/include

// Lookup table for Kinect out put and depth conversion
float[] depthLookUp = new float[2048];

void setup() {
  size(800,600,P3D);
  kinect = new Kinect(this);
  kinect.start();
  kinect.enableDepth(true);
  //kinect.enableRGB(true);
  kinect.processDepthImage(false);
  // Lookup table for all possible depth values (0 - 2047)
```

```
threshold_s:930 (2.1060388)
threshold_s:920 (1.9780983)
threshold_s:910 (1.864812)
```

```
Kinect FR: 15
Processing FR: 20

1: 22.2862 | 0             4: 22.2862 | 0           7: 22.2862 | 0
2: 2.2059116 | 4027        5: 2.283252 | 4012       8: 3.8944323 | 3689
3: 2.0791438 | 4053        6: 2.014818 | 4065       9: 2.5717902 | 3954

VFSS Pwr: 1
Threshold Start (Max): 1.864812 | 910
Threshold End (Min): 22.2862 | 1070
Sensitivity: 640
```

Figure 9. Screenshot of my Laptop running the VFSS image processing and point cloud capture Kinect Processing code.

Software

The Processing and Arduino code used by the VFSS can be downloaded at http://www.thenureality.com. Figure 9 is a desktop screen shot of the VFSS software running on my laptop during operation. The VFSS uses the libfreenect drivers and libraries to communicate with the Kinect from the laptop computer running the Linux based operating system Ubuntu 10.10. The image processing software is written in Processing[4] with the use of Daniel Shiffman's OpenKinect[5] library for Processing. His Kinect point cloud Processing example

---

[4] Processing is an open source java based programming language and environment for people who want to create images, animations, and interactions. Initially developed to serve as a software sketchbook and to teach fundamentals of computer programming within a visual context, Processing also has evolved into a tool for generating finished professional work. Today, there are tens of thousands of students, artists, designers, researchers, and hobbyists who use Processing for learning, prototyping, and production. http://processing.org/

[5] OpenKinect is an open community of people interested in making use of the amazing Xbox Kinect hardware with PCs and other devices. They are working on free, open source libraries that will enable the Kinect to be used with Windows, Linux, and Mac. http://openkinect.org/wiki/Main_Page

sketch served as a starting point for the VFSS's point cloud algorithm (http://www.shiffman.net/p5/kinect/). Since Shiffman's OpenKinect Processing library was originally compiled for the Mac OSX operating system using the Java Native Interface (JNI) wrappers to call the C++ based libfreenect Kinect libraries, the JNI wrappers for the OpenKinect Processing library had to be recompiled under Ubuntu – this process proved to be considerably difficult due to my unfamiliarity with it.

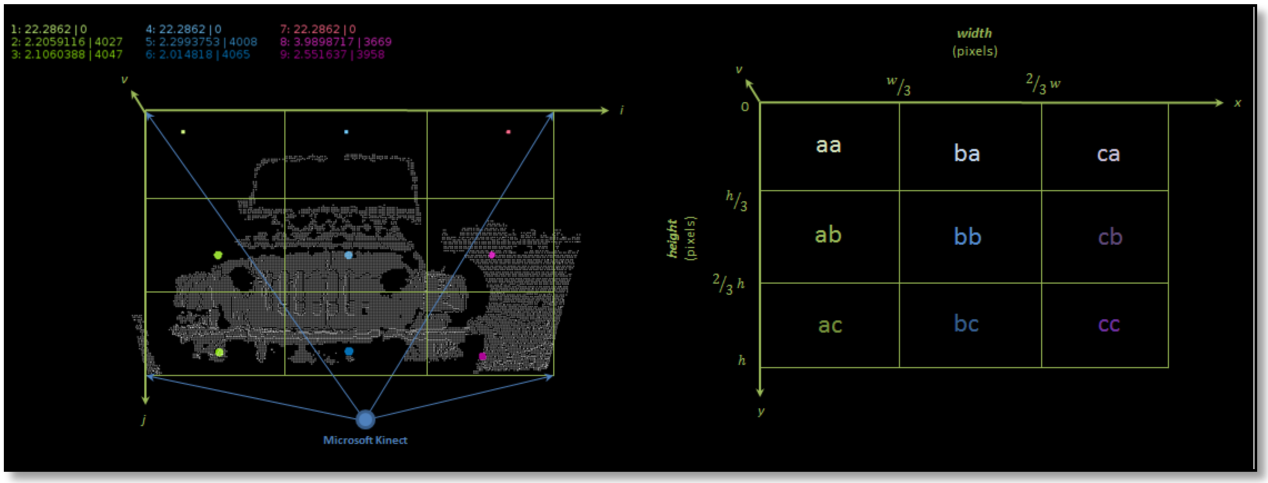
Box 1. Calibrated conversion of Kinect raw depth value (0-2048) to meters.

```
float RawDepthToMeters(int depthValue)
{
    if (depthValue < 2047)
    {
        return float(1.0 / (double(depthValue) * -0.0030711016 + 3.3309495161));
    }
    return 0.0f;
}
```

Figure 10 shows a depth image point cloud captured from the PrimeSensor with VFSS grid coordinate system overlayed. Raw sensor values returned by the Kinect's depth sensor are not directly proportional to physical depth; sensor values scale with the inverse of the depth. Other individuals have done relatively accurate studies to determine the necessary coefficients resulting in high accuracy depth detection. Using the appropriate formula from [20] and shown in Box 1, I am able to map these raw PrimeSensor depth values (*i*, *j*, *v*) into physical depths, where *i* and *j* are the horizontal and vertical locations of the depth value, respectively, and *v* is the raw depth value mapped to physical depth. The depth value, *v*, varies between 0 and 2048.

After receiving, counting, and storing the value and count of each raw depth point cloud pixel in each grid in an array, the Processing algorithm then calculates the average depth point cloud pixels within each grid of the Kinect's field of view. These average values for each of the grids are used to determine the intensity with which the corresponding vibration motor will vibrate. If no pixels are detected, then no vibration occurs. The number of pixels required before a value is sent, known as the sensitivity, can be selected as part of calibration. This method of averaging depth for each grid was thought to be satisfactory for perception of objects in the rear of vehicle. The assumption is that from the Kinect's mounted perspective, there would be no fore or background objects within the its field of view that would significantly offset the averaging depth of the perceived objects (i.e. no outliers).

However, as part of development, the ability to change the minimum and maximum depths that the VFSS uses to map the motor intensities was added. This allows the operator to change the depth range that the Processing algorithm will display and utilize to calculate depth averages. This was found to be necessary for calibrating the VFSS depth detection because for certain situations, the Kinect would detect significant regions of the road behind a close object which would throw off the depth averaging. Ideally this depth range would update accordingly on the rate at which vehicle is traveling. For example, at low speeds the driver will need more sensitivity to objects closer to the vehicle and at high speeds they will need better sensitivity to objects further away.



```
1: 22.2862 | 0          4: 22.2862 | 0          7: 22.2862 | 0
2: 2.2059116 | 4027     5: 2.2993753 | 4008     8: 3.9898717 | 3669
3: 2.1060388 | 4047     6: 2.014818 | 4065      9: 2.551637 | 3958
```

Figure 10 Point cloud capture in Processing from the Microsoft Kinect with Kinect depth and array coordinate systems. The shown average value format is "[Depth (meters)] | [PWM Intensity (0-4095)]".

Processing is also used to communicate to and control the Arduino running a simple custom firmware that utilizes the TI TLC5940 library for Arduino. Firmware code utilizing the TLC5940 library is uploaded to the ATmega328 for control of nine of the TLC5940's channels. Each of the TLC5940's channels has an individually adjustable 4096-step grayscale PWM brightness control that corresponds to the intensity that the motor will vibrate. Once the depths of the environment within the grid have been determined by the Processing algorithm, the value is sent to the Arduino via the USB serial interface and the corresponding vibration motors are controlled by the Arduino TLC5940 code. A simple sync byte alerts the Arduino of an incoming change in gird values message and is then read and utilized to update the motor vibration intensities accordingly.

Test, Evaluation, and Results

The VFSS was subjected to three different tests to evaluate the utility of the human nervous system as an alternative means to perceive the world in advanced tool use. The proposed fourth test, blind spot detection, was determined to be too dangerous given the limited sensing capabilities of the Kinect in the outdoor environment. The three tests were also concurrently evaluated with two already implemented visual cues, mirrors and a rear facing camera. The rear facing camera will be the RGB camera in the mounted Kinect. Two other individuals and I were each given an hour getting accustomed with the VFSS by driving around and performing

Test 1. This first test evaluated the VFSS's sensitivity to detection and object localization. The second test, similar to the first, requires the operator to perform an action (driving in reverse) to initiate the sensory input. To test both the detection and localization and utility, the driver will be required to reverse through a course, aiming to hit as many objects of various sizes as possible and attempting to finish in the best possible time. The third test evaluates the VFSS's ability to aid complex tool use perception (parallel parking).

Figure 11. Early developmental testing of the VFSS where an operator attempts to maintain localization of a moving individual.

Initial Developmental Testing and Results

The VFSS was constantly evaluated during the development to verify and compare the findings of Paul Bach-y-Rita's and Jon Bird's research and work with their TVSS.

Early on, just as described in their findings, VFSS operators realized that it was not enough to leave the sensor stationary in the environment and then interpret the vibrotactile feedback it captured. Instead, it was necessary for the operator to actively control and manipulate the Kinect in order to explore the environment and understand the meaning of the vibrotactile feedback. In this indoor environment with direct control of the VFSS as a TVSS, blindfolded and operators were capable of orienting themselves in an unfamiliar room, navigating around unknown obstacles, and locating another moving individual (as shown in Figure 11). From the indoor test experience, there was concern that indirect control and manipulation of the sensor once removed via the vehicle's steering wheel would not be sufficient for control of the sensor. There was also concern that the outdoor environment would prove difficult for the Kinect sensor designed for closer, indoor, and stationary use.

Initial vehicle testing of the VFSS revealed that control of the vehicle and therefore Kinect was sufficient for interpreting the vibrotactile feedback it generated. While the average depth algorithm for object detection proved somewhat unreliable for the indoor testing due to background depth saturation (i.e. walls), the outdoor testing over open road provided more reliable and accurate vibrotactile feedback. Unfortunately, currently with this algorithm, it is necessary to point the Kinect upwards to avoid capturing too much of the road which alters the accuracy of the depth capture. One possible resolution would be to develop an algorithm that eliminates common background pixels (i.e. the road).

Test 1: Object Detection and Localization

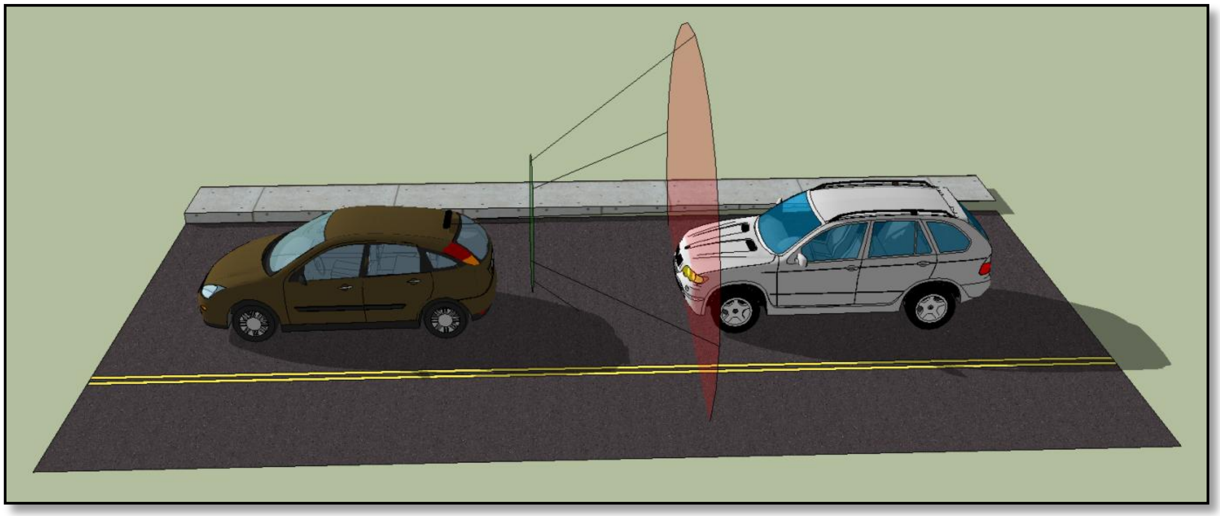


Figure 12. Test 1 object detection and localization example.

Setup: Mount the VFSS sensor facing directly backwards on the rear end of the vehicle.

Test: While the vehicle remains stationary, during a one minute period, the driver should attempt to detect and localize a moving person in the rear at three different heights (standing, crouching, and sitting) and distances every 10 seconds, moving at random locations, but remaining stationary at least three times, for the following sensory cases three times each:

- Case A: Using mirrors alone
- Case B: Using a rear facing camera alone
- Case C: Using the VFSS alone
- Case D: Using the VFSS, mirrors, and rear facing camera

Results: Results from three runs of Test 1 by three separate VFSS operators is shown in Table 2. Each of the operators had about 30 minutes of experience with the VFSS. The results are ranked by the driver's ability to successfully detect objects and, separately, successfully continually locate the object while in the field of view. A successful localization did not imply a successful detection since there was a possibility that VFSS operator could be guessing. The rankings were determined by evaluating the correctness of stated heights and locations at the 10 second intervals.

Table 2. Test 1 Test Result Rankings.

Rank	Detect Change	Continually Locate
1	Case D	Case D
2	Case B	Case C
3	Case A	Case B
4	Case C	Case A

The results from Table 2 indicate that use of visual and tactile feedback from the environment provides the strongest perception of object detection and localization of objects about the environment around the vehicle. The VFSS tactile feedback provides better localization than mirrors but is not capable of detecting changes as well as the mirrors. The mirrors were the least capable of continually localizing while the VFSS was the least capable of detecting change.

Test 2: Object Perception in the Action of Reversing

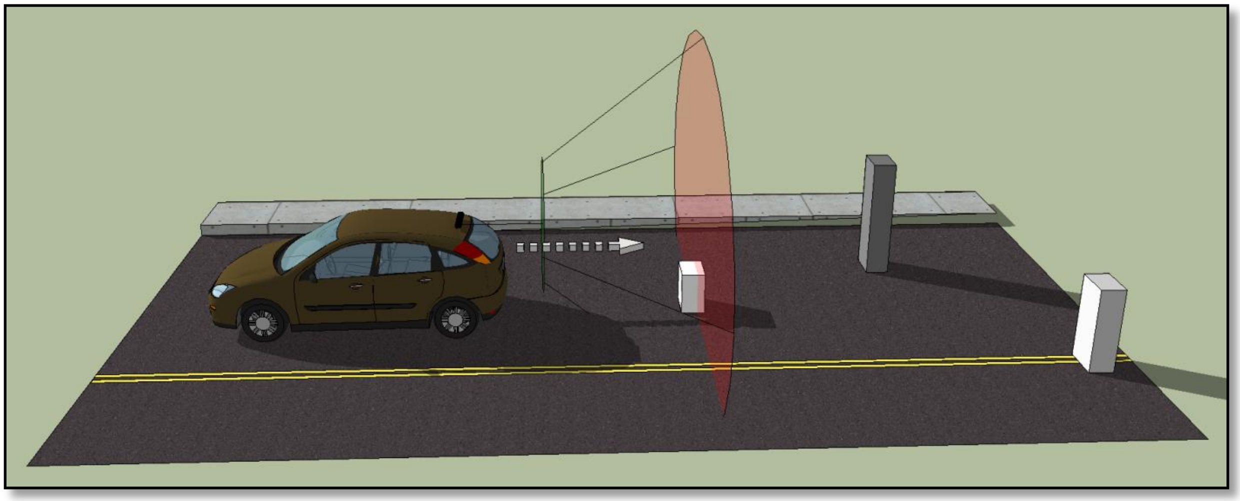


Figure 13. Test 2 object perception through the action of reversing a course.

Setup: Mount the VFSS sensor facing directly backwards on the rear end of the vehicle. Setup a 160 ft course with by randomly place objects of three different heights (2 ft, 4 ft, and 6 ft) about 8 ft apart.

Test: The driver should maneuver the vehicle in reverse, attempting to run over all objects in the course for the following sensory cases:

- Case A: Using mirrors alone
- Case B: Using a rear facing camera alone
- Case C: Using the VFSS alone
- Case D: Using the VFSS, mirrors, and rear facing camera

Evaluate: Results in Table 3 are ranked by the driver's ability to successfully detect objects and come into contact with them.

Table 3. Test 2 Result Rankings.

Rank	Course Success	Average Time
1	Case D	26.4 s
2	Case A	31.5 s
3	Case C	1:04.8 s
4	Case B	1:15.1 s

The ability to use both visual and tactile stimuli proved useful in providing the greatest perception of object detection and localization in tool use.

Test 3: Complex Tool Use Perception (Parallel Parking)

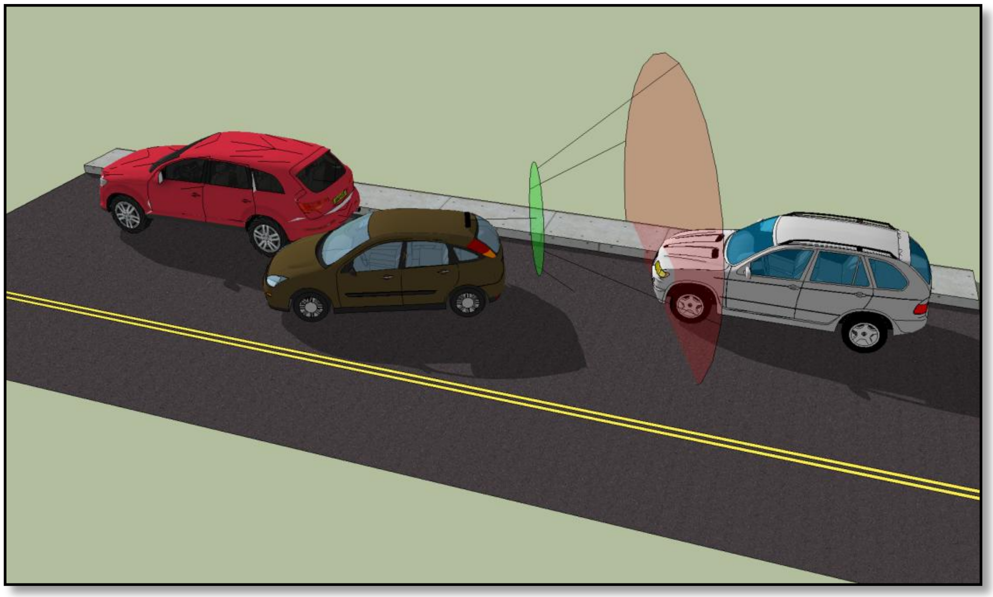


Figure 14. Test 3 complex tool use perception (parallel parking).

Setup: Mount the VFSS sensor facing directly backwards on the rear end of the vehicle. Place two cars far enough apart to allow for the test vehicle to park via a parallel parking maneuver. The driver should be unfamiliar with the vehicles parallel parking characteristics.

Test: Staring from along the side of the front vehicle, attempt to park the driver should attempt to park their vehicle using a parallel parking maneuver as quickly as possible for the following sensory cases three times each:

- Case A: Using mirrors alone
- Case B: Using a rear facing camera alone
- Case C: Using the VFSS alone
- Case D: Using both the VFSS, mirrors, and rear facing camera

Results: Results in Table 4 are ranked according to the driver's time required to park. None of the cases ended with the operators striking the curb or vehicle.

Table 4. Test 3 Result Rankings.

Rank	Case	Average Time
1	Case D	11.8 s
2	Case A	12.9 s
3	Case B	18.6 s
4	Case C	20.2 s

Interestingly, again, combination of both visual and tactile feedback provided the best perception of environment around the employed tool; however, the tactile feedback alone was demonstrated to be the worse form of feedback for perception.

Test 4: Bind Spot Object Perception

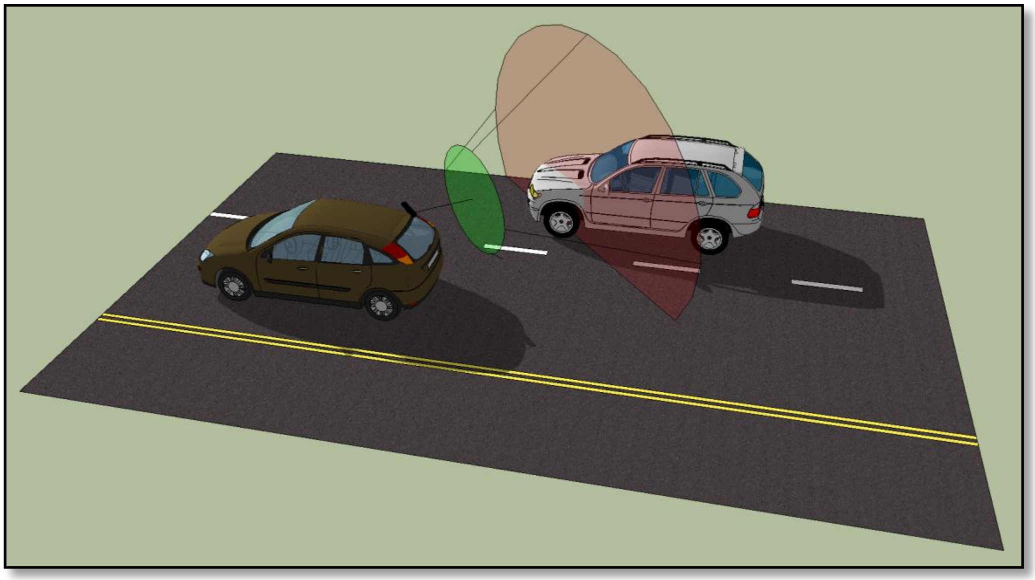


Figure 15. Test 4 blind spot object perception.

Setup: Perform this test in an empty parking lot with space and at low rates of speed. Mount the VFSS sensor on the vehicle facing backwards and slightly angled towards the passenger side (Figure 15). Place 3 cones roughly 20 ft apart. A second vehicle will tail the vehicle and attempt to pass through the blind spot and random.

Test: At low speed, the driver should attempt weave from one side of the starting cone to the other of the middle, around the end cone, and back again for following cases three times each:

- Case A: Using mirrors alone
- Case B: Using a rear facing camera alone
- Case C: Using the VFSS alone
- Case D: Using both the VFSS and rear facing camera

Results: For Test 4, a test point would have been considered successful if the driver did not weave around the cone due to detection of another object in its blind spot.

It was decided to not perform Test 4 due to the limited detection capabilities of the Kinect at longer range and high speed. The Kinect tended to aid the VFSS operator better in close detection, which in the case of higher speeds, could possibly prove dangerous.

Discussion & Conclusion

Tests 1, 2 and 3 demonstrate that a combination of haptic and visual feedback provides the best perception of the environment in active occluded tool use. Specifically from the test results in Test 1 and 2, it is worth noting that the haptic feedback with visual verification appears to improve the detection and localization of occluded objects verse visual acquisition through mirrors alone. The tactile feedback appears to reinforce and supplement the visual perception.

Similarly to the previously discussed University of Minnesota's HumanFIRST program haptic feedback research, I have found that there is a tendency of the VFSS operators to attempt to visually verify the haptic feedback from the region that the VFSS alerts the operator to – a sort of double take or reassurance – but overall it improves perception and reaction. Perhaps with possibly more exposure and experience with the VFSS designed in this project, operators may have come to trust the haptic feedback and interpret its meanings more reliably and naturally. However, as mentioned earlier, there is concern that by becoming familiar with the VFSS, the operator would begin to lose attention or "wow-factor" associated with the tactile feedback. An improved algorithm for alerting the VFSS operator may need to be considered.

Ernst and Bulthoff state, in [21], that perception is a multisensory experience. Sensory modalities generally cooperate or complement one another. According to Ernst and Bulthoff, "no single sensory signal can provide reliable information about the three-dimensional structure of the environment in all circumstances." Given the opportunity to glean information from the environment, the brain will select the single best solution from all the sensory possibilities. With the VFSS tested in this project, it is true that the VFSS did not attempt to replace vision entirely. Given the opportunity in Case D, operators were able to enhance or provide additional information from either the visual or tactile feedback. With the feedback otherwise unavailable, as in the other test cases, perception and tool use performance appears degraded in comparison. However, I suppose it is important to note, that all whether it be tactile or visual, both are capable of aiding in perception for tool use.

I believe the rear facing camera may have ranked higher in the tests if it had been a camera with a wide angled lens. My previous experience driving a vehicle with a rear facing wide angled camera for reversing has proven to me its utility. For a better comparison, it would be wise to retest the test cases with a wide angle lensed camera.

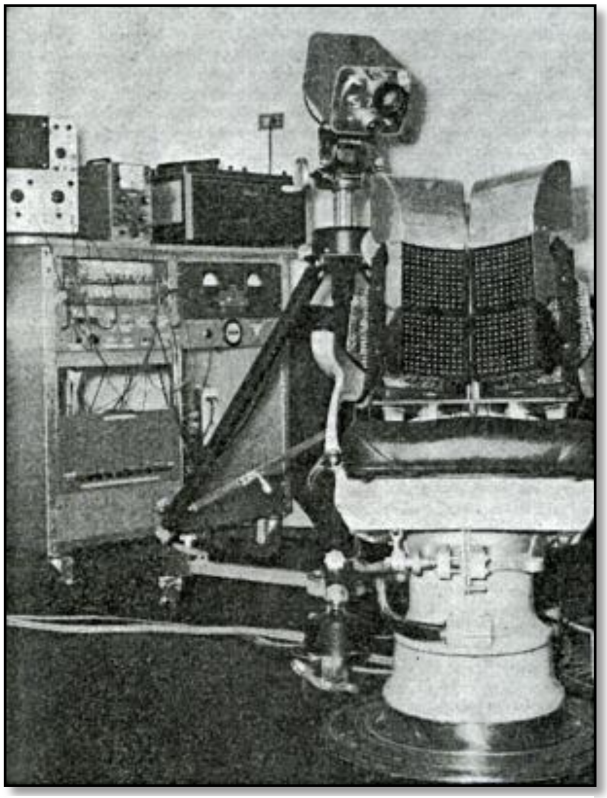


Figure 16. Bach-y-Rita's first tactile vision substitution system with four hundrend solenoid stimulators (1969). Source: Nature, VOL 221.

It is also likely that perception in tool use with the VFSS could be improved if more vibration motors and corresponding Kinect grids were added. Bach-y-Rita suggests in [13] that for face recognition and hand-eye coordination, “a few hundred points of stimulation” are necessary. As shown in Figure 16, the first TVSS had 400 tactile stimuli and the recent electrotactile TVSS has 144 stimuli. Considering only nine stimuli were providing feedback in this VFSS, one can conclude that the VFSS may not be providing perception detail to its best capacity. The VFSS in this project was generally only capable of detecting relatively large objects and the general region with which they were located (i.e. on the right, on the left, down low or tall). More motors would allow for more accuracy but I suspect there is a limit to the number of vibration motors the human body can comprehend before the feedback becomes saturated. Although Bird had indicated in [14] that simple five by two array was sufficient, the accuracy and reliability from the test results in this report show that there is a room for improvement, particularly for use with a vehicle moving at high speeds.

Admittedly, one major weakness of the VFSS developed in this project was that the Kinect’s requires noiseless reception of its IR emissions for depth detection. This limitation restricts the time of day that the VFSS in this project could be utilized. In addition, often even at night, ambient light from other vehicle head lamps or street lights would saturate Kinect’s IR image sensor, severely degrading perception of the world.

In addition, as seen in Figure 10, capture of the ground behind any objects in the sensor’s field of view skews the depth data towards the further depth. This provides unreliable perception on the location of objects. One possible solution would be to shrink the size of the grids, allowing for smaller object detection and providing those averages to larger array of corresponding motors. Another solution would be to better calibrate, null out, or ignore the consistent depth of the ground data upon installation and initialization. This limitation of the VFSS algorithm severely limited its capabilities at high speed driving perception.

I also believe the VFSS built in this project suffered from poor transmission of vibration to the user's skin. The back, while sensitive, does have regions that are not as sensitive as other regions of the back. Specifically, the region surrounding one's spine does not appear to detect vibration as well as the sides of the body. Other possible array locations could have been the stomach, neck or hand and these locations were not investigated due to time constraints. Also, given the size of the vibration motors, I do not believe the hand or neck would have been a useful location. Others, including Bach-y-Rita and Jon Bird, have shown that the stomach, neck, hand, fingertips, and even tongue are all excellent locations for tactile vision substitution.

I believe a better and much simpler approach and design would have been to use ultrasonic range detectors around the vehicle. While not as capable of capturing with the same resolution or detail as the Kinect, the ultrasonic rangefinders would be capable of operating in almost any environment and provide reliable depth data of any object, distant or far in a relatively smaller field of view. Such a configuration would not require an array of vibrotactile feedback motors, but instead a belt that would relay information about the environment from the full 360° around the vehicle.

Future Work

The VFSS designed and tested in this project is only an initial prototype. As mentioned, future VFSS and TVSS works should seek to utilize better sensing algorithms or sensor technologies and corresponding haptic feedback arrays. They should also better investigate regions of the body that provide better transmission of feedback to the nervous system. In the future, the entire area surrounding the tool may be capable of providing feedback to clue the operator in on information from locations they do not currently perceive.

A significantly more improved vision system than the one currently proposed for this VFSS should be investigated. The PrimeSensor cannot operate in outdoors during day time due to infrared interference and it's depth of detection may not be ideal for tool use situations. Also, research should investigate the ability for the user to manipulate the sensing control from their own movements in the tool or by movements of the tool.

Research should also investigate the relaying of other information from the tool use different from or in addition to external environmental information. Perhaps a VFSS could provide status of the tools health or activity in a sort of proprioception extension of the user's body schema extension with the tool. For example, the RPM of the helicopter's motor could be conveyed via the tightening of a bracelet worn around the wrist or the wear of the tires on a race car could be conveyed via vibration on the four fingers. This simple seems relatively simple to implement but does not appear to be a widely used means of tool use information.

An example of a future VFSS as installed on a formula 1 race is shown in Figure 17. Cars are also not the only application. Aircraft and telerobotics can benefit from a VFSS by providing additional information from a distant environment to the operators' skin and not relying entirely on visual cues. Any tool that taxes the operator's perceptual abilities may benefit from a vibrotactile feedback system.

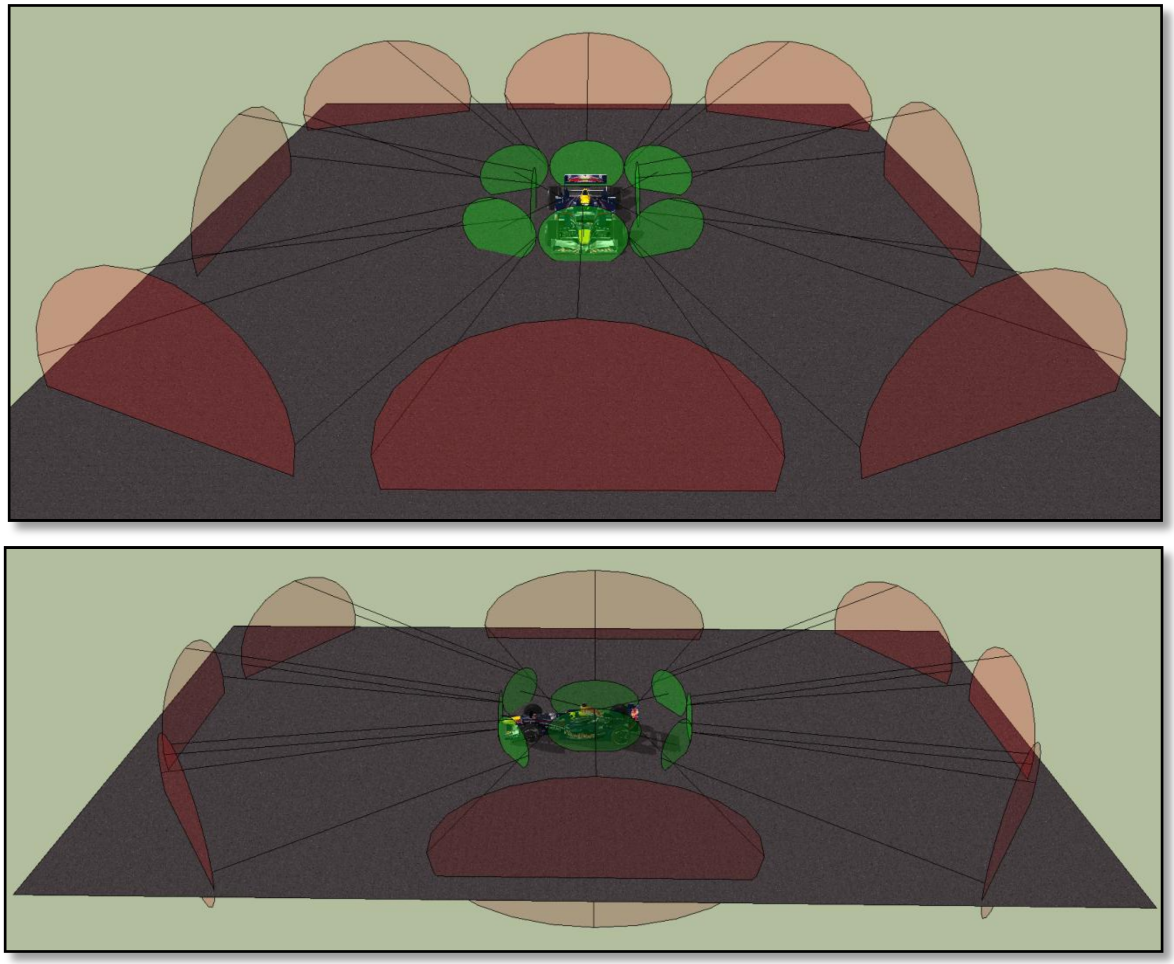


Figure 17. Future multi-sensing VFSS as installed on a formula 1 race car with enhanced sensing system.

One possible configuration that future VFSS could consist of is an entire suit, much like the G-suits worn by aviators and astronauts. With such a suit, operators could learn to attain significantly more information from the environment in all directions, constantly, and simultaneously surrounding their tool use. Such a suit would provide information that is easily accessible to the wearer and does not require active search, only attention.

Conclusion

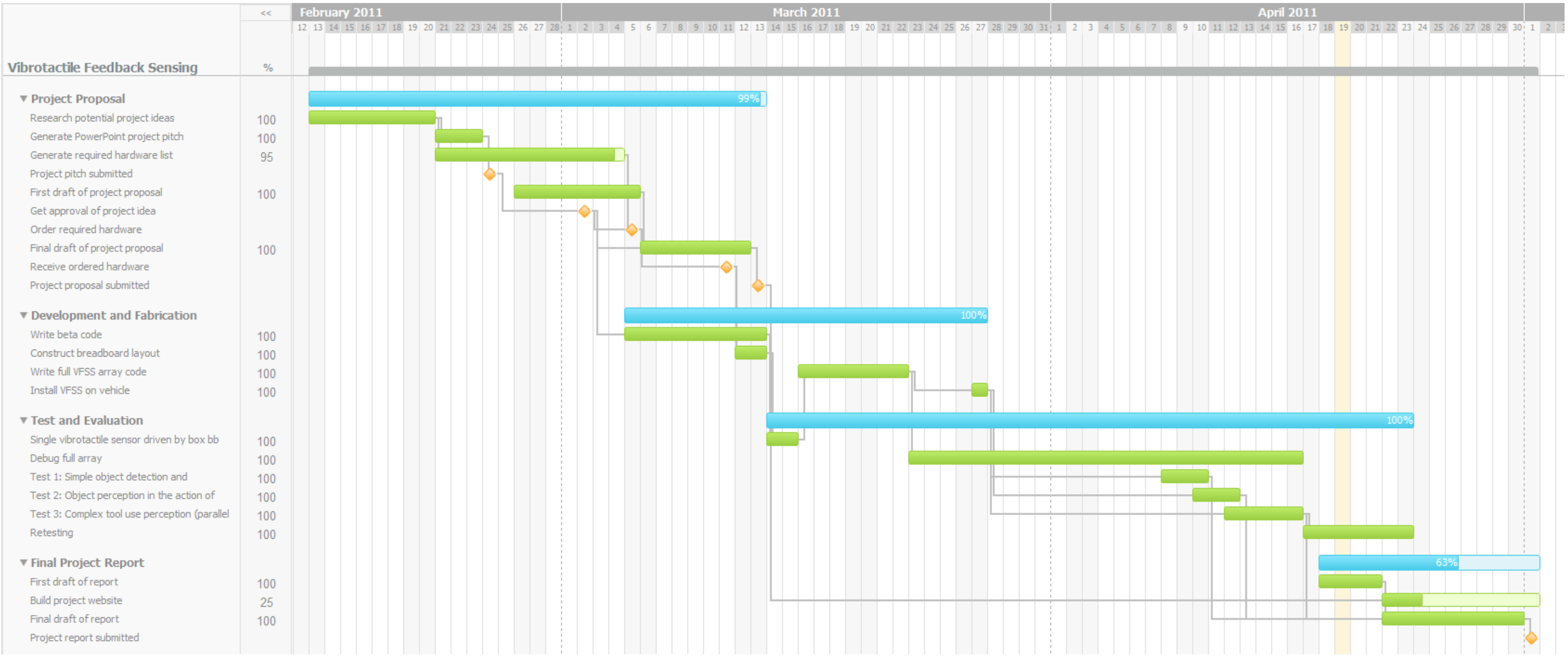
The aim of this project was to enable users of the VFSS to extend their perception via the nervous system to the outer surfaces of the very tool they are actively using. Results from testing of the VFSS showed that perception through extension of the body schema was achieved and that tool use can be accomplished with vibrotactile feedback. Importantly, the results showed that the active use of tactile feedback in combination with visual feedback provide a strong perception of the environment surrounding the operated tool that can exceed that of visual feedback alone.

The fabrication of the initial VFSS reported here requires very little material and uses readily available open source hardware. By making use of open source software and drivers, the VFSS was capable of being design, constructed, debugged, and utilized within a month's time. Further development should be pursued, but this report serves as a good starting point for future VFSS.

The VFSS developed in this project has allowed for further study of human attention and perception. It also further revealed the brain's plasticity both in tool use and in perception. The VFSS has proven a sensible venture into utilizing the human nervous system as an alternative means to perceive the world in advanced tool use.

I hope that the findings reported here will aid in the continued pursuit of better understanding action in perception. By better understanding how we see the world through touch and systems like the VFSS, we can reveal new and other efficient ways of interacting with our world.

Implementation Schedule



Vibrotactile Feedback Sensing	%
Project Proposal	
Research potential project ideas	100
Generate PowerPoint project pitch	100
Generate required hardware list	95
Project pitch submitted	
First draft of project proposal	100
Get approval of project idea	
Order required hardware	
Final draft of project proposal	100
Receive ordered hardware	
Project proposal submitted	
Development and Fabrication	
Write beta code	100
Construct breadboard layout	100
Write full VFSS array code	100
Install VFSS on vehicle	100
Test and Evaluation	
Single vibrotactile sensor driven by box bb	100
Debug full array	100
Test 1: Simple object detection and	100
Test 2: Object perception in the action of	100
Test 3: Complex tool use perception (parallel	100
Retesting	100
Final Project Report	
First draft of report	100
Build project website	25
Final draft of report	100
Project report submitted	

References

[1] Angelo Maravita and Atsushi Iriki, "Tools for the body (schema)," *TRENDS in Cognitive Sciences*, pp. 79-86, 2004.

[2] V.S. Ramachandran, *Phantoms in the Brain: Probing the Mysteries of the Human Mind*.: Harper Perennial, 1999.

[3] Andy Clark, *Natural-Born Cyborgs: Minds, Technologies, and the FUture of Human Intelligence*.: Oxford University Press, 2003.

[4] Lt. Col. Steve Colby. (2005, March) Aviation Today. [Online]. http://www.aviationtoday.com/rw/training/specialty/1418.html

[5] J. Kevin O'Regan and Alva Noë, "A sensorimotor account of vision and visual consciousness," *Behavioral and Brain Sciences*, pp. 939-1031, 2001.

[6] Jr. Raymond W.Gibbs, *Embodiment and Cognitive Science*, 1st ed.: Cambridge University Press, 2005.

[7] J. Kevin O'Regan, & James J. Clark Ronald A. Rensink, "To See or Not To See: The Need for Attention to Perceive Changes in Scenes," *Psychological Science*, vol. VIII, no. 5, pp. 368-373, September 1997.

[8] Pierre Baldi Laurent Itti, "Bayesian surprise attracts human attention," *Vision Research*, vol. 49, pp. 1295-1306, September 2009.

[9] Tatiana Morales. (2002, October) CBS News. [Online]. http://www.cbsnews.com/stories/2002/10/22/earlyshow/living/parenting/main526462.shtml

[10] (2006) JDPower.com. [Online]. http://www.jdpower.com/autos/articles/Reverse-Parking-Assist-Systems/

[11] Paul Bach-y-Rita and Stephen W. Kercel, "Sensory substitution and the human-machine interface," *TRENDS in Cognitive Sciences*, vol. VII, no. 12, pp. 541-546, December 2003.

[12] Robert J. Stone, Haptic Feedback: A Potted History, From Telepresence to Virtual Reality.

[13] Paul Bach-y-Rita and Stephen W. Kercel, "Sensory substitution and the human-machine interface," *TRENDS in Cognitive Sciences*, pp. 541-546, 2003.

[14] Jon Bird, Paul Marshall, and Yvonne Rogers, Low-Fi Skin Vision: A Case Study in Rapid Prototyping a, 2009.

[15] Jon Bird, Janet van der Linden, and Erwin Schoonderwaldt, Towards a Real-Time System for Teaching Novices Correct Violin Bowing Technique, 2009.

[16] Mike Manser. (2007) ITS Institute. [Online]. http://www.its.umn.edu/Publications/Sensor/2007/03/HapticFeedback.html

[17] Immersion Corporation. (2011) MOTIV. [Online]. http://www.immersion.com/index.html

[18] (2011) Infiniti Technology. [Online]. http://www.infinitiusa.com/technology/#/blind-spot-intervention/

[19] Luke Plunkett. (2010, June) Kotaku. [Online]. http://kotaku.com/#!5576002/here-are-kinects-technical-specs

[20] Nicolas Burrus. (2010) Kinect Calibration. [Online]. http://nicolas.burrus.name/index.php/Research/KinectCalibration

[21] Marc O. Ernst and Heinrich H. Bulthoff, "Merging the senses into a robust percept," *TRENDS in Cognitive Science*, vol. VIII, no. 4, pp. 162-169, April 2004.

[22] (2011) Kids and Cars. [Online]. http://www.kidsandcars.org/back-overs.html

[23] Roger N. Clark. (2009, November) ClarkVision.com. [Online]. http://www.clarkvision.com/imagedetail/eye-resolution.html