

# **Considerations for the Development of Non-Visual Interfaces for Driving Applications**

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## **ABSTRACT**

While haptics, tactile displays, and other topics relating to non-visual user interfaces have been the subject of a variety of research initiatives, little has been done specifically related to those for blind driving. Many technologies have been developed for the purpose of assisting and improving the safety of sighted drivers, but to enable a true driving experience without any sense of sight has been an essentially overlooked area of study. Since 2005, the Robotics & Mechanisms Laboratory at Virginia Tech has assumed the task of developing non-visual interfaces for driving through the Blind Driver Challenge®, a project funded by the National Federation of the Blind. The objective here is not to develop a vehicle that will autonomously mobilize blind people, but to develop a vehicle that a blind person can actively and independently operate based on information communicated by non-visual interfaces.

This thesis proposes some generalized considerations for the development of non-visual interfaces for driving, using the instructional interfaces developed for the Blind Driver Challenge® as a case study. A model is suggested for the function of blind driving as an open-loop control system, wherein the human is an input/output device. Further, a discussion is presented on the relationship between the bandwidth of information communicated to the driver, the amount of human decision-making involved in blind driving, and the cultivation of driver independence. The considerations proposed here are intended to apply generally to the process of non-visual interface development for driving, enabling efficient concept generation and evaluation.

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## List of Abbreviations

BDC	-	Blind Driver Challenge®
DG	-	DriveGrip
HCI	-	Human-Computer Interface
KTD	-	Kinesthetic Tactile Display
NFB	-	National Federation of the Blind
NVI	-	Non-Visual Interface
RoMeLa	-	Robotics & Mechanisms Laboratory
SS	-	SpeedStrip
VT	-	Virginia Tech

# Chapter 1: Introduction

By introducing the Blind Driver Challenge® to American universities in 2004, the National Federation of the Blind (NFB) took the first step in achieving the goal of a full-size street-legal vehicle that can be independently driven by a blind person. Since accepting the challenge in 2005, Virginia Tech’s Robotics & Mechanisms Laboratory has successfully developed such a research vehicle platform, as well as what are called *non-visual interfaces* (NVI’s): devices that can be used to obtain real-time information about an environment without sense of vision.

The work presented in this thesis is intended to summarize and analyze the efforts that have gone into developing these non-visual user interfaces. An approach to the development of non-visual interfaces for blind driving is proposed, using the NVI’s produced in the Blind Driver Challenge® as a case study. Some recommendations are offered for future NVI research and development as well as the forthcoming Blinder Driver Challenge® efforts.

## 1.1 Motivation

The following is a description of the motives behind the National Federation of the Blind, the Blind Driver Challenge®, and the research presented in this thesis.

### 1.1.1 Motivation of the National Federation of the Blind

In 1940, Jacobus tenBroek founded the National Federation of the Blind in order to target “the advancement of vocational opportunities for the blind and removal of legal and social barriers preventing their full acceptance as normal members of society” [1]. Today, the NFB comprises a population of over 50,000 people in every U.S. state [2] and maintains similar objectives. The NFB’s current mission statement is as follows:

The mission of the National Federation of the Blind is to achieve widespread emotional acceptance and intellectual understanding that the real problem of blindness is not the loss of eyesight but the misconceptions and lack of information which exist. We do this by bringing blind people together to share successes, to support each other in times of failure, and to create imaginative solutions[3].

Aside from providing education and many different modes of support for the blind, the NFB has in recent years focused on educating the *public* on the capabilities of the blind. By striving to demonstrate to the public the capabilities and independence of the blind, the NFB hopes to open up more opportunities for the blind as “normal individuals who can compete on terms of equality” [4].

### **1.1.2 Motivation of the Blind Driver Challenge®**

In order to effectively convey this message of blind independence to the public, the NFB wanted to enable the blind to accomplish something that previously would have seemed impossible. The ability of a blind person to independently drive a car fit that motive well. The car is symbolic of freedom, power, status, and mobility. Accomplishing the difficult task of creating a car that a blind person can drive would “serve to organize and measure the best of energies and skills” [5]. Certainly, the world would take notice of the capabilities of a successful blind driver.

Thus, in 2004, the National Federation of the Blind introduced the Blind Driver Challenge® (BDC). The motivation is evident in NFB’s defined goals for this initiative [6]:

1. To establish a path of technological advancement for nonvisual access technology, and close the gap between access technology and general technology.
2. To increase awareness among the university scientific community about the “real problems” facing the blind by providing expertise from the perspective of the blind within the context of a difficult engineering challenge.
3. To demonstrate that vision is not a requirement for success and that the application of innovative nonvisual solutions to difficult problems can create new opportunities for hundreds of thousands of people—blind and sighted.
4. To change the public perceptions about the blind by creating opportunities for the public to view blind people as individuals with capacity, ambition, and a drive for greater independence.

From these objectives, it is clear that the NFB is not simply motivated to create a physical vehicle that a blind person can drive. They are interested in utilizing the challenge as a manner of expressing the capabilities of the blind to the public. They are interested in the spinoff technologies that can stem from the challenge, with the thought that additional research institutions will take notice of the value in investing in such technologies.

Dennis Hong offers some thoughts on the values of the Blind Driver Challenge® initiative relating to non-visual user interfaces, sensing, and autonomous vehicle research [7]:

The nonvisual user interfaces we develop can be used for applications other than for driving – in everyday home appliances, in office settings, in educational settings. The possibilities of spinoff technologies are endless. Also we would like to show the world the true capability of the blind through this project. I want to inspire other scientists and engineers to develop new technology to help the blind.

The sensors we use for the blind driver challenge vehicle are almost identical to the ones we use for autonomous vehicles, and we have used for this project many of the technologies we have developed for our autonomous cars for the 2007 DARPA Urban Challenge. But the similarity ends there.

The focus of autonomous vehicle research is on developing intelligent vehicles, or artificial intelligence for cars in some sense, while the focus of the blind driver challenge vehicle is developing methods to convey a vast amount of information to the driver through nonvisual means, fast enough and accurately enough for safe driving.

### **1.1.3 Motivation of the Research Presented in this Thesis**

The motivation behind this thesis is to document a portion of RoMeLa's efforts on the Blind Driver Challenge®. Since successful demonstration of the current Blind Drive Vehicle in January, 2011, BDC has received an extraordinary amount of publicity through news stories, magazine articles, and the like. The NFB is showing significant success in terms of attending to the public view of the blind, thus fulfilling the latter two goals of the Blind Driver Challenge® as outlined in the previous section. Thus, the research documented here is to fulfill the former two goals of BDC.

This thesis is motivated by the goal of demonstrating the technological advancement for non-visual access technology, and acting as a medium for the topic of non-visual user interface development to take some of its first steps into the research community. It is meant to serve as a piece for further research to be built upon, therefore alerting the research community of the significance of the engineering challenges facing the blind.

## **1.2 Objectives**

Aside from detailed documentation of the user interface aspect of the Blind Driver Challenge®, this thesis offers essentially two contributions to the area of interface development and the Blind Driver Challenge® initiative.

The primary contribution of this thesis is to offer an organized set of considerations for the development of non-visual interface. Based on the research and development completed through the Blind Driver Challenge® (BDC), an organized approach has been improved upon, utilized, and now documented in detail. As more research institutions continue to investigate these non-visual interfaces, whether specifically related to blind driving as part of NFB's Blind Driver Challenge® or for other tasks such as those related to education or communications, such a set of guidelines to organize the development of these devices will be critical. This includes considerations for the entire design process, from concept generation to hardware selection and testing. This also includes thoughts on how to characterize non-visual interfaces, relating to how much information is being communicated and how much decision-making is being completed by the human driver. These thoughts are applied to the development and performance of the current NVI's used in the Blind Driver Challenge®.

The secondary contribution of this thesis is to organize considerations on the future of the BDC project as well as non-visual interfaces for the blind in general. It is crucial to document these

findings, as the Blind Driver Challenge® has now created a successful research vehicle platform capable of integration with any non-visual interface, thus rendering the NFB's research domain more accessible. This means that with the BDC vehicle and the current NVI's, the NFB has a unique foundation with which to develop additional tools for the blind. This thesis will include considerations for improvements on the current set of non-visual interfaces as well as thoughts on future testing of these interfaces.

### **1.3 Research Approach**

As discussed in the body of this thesis, several iterations of non-visual interfaces were employed in the Blind Drive Challenge® project over the past few years, by several evolving teams in RoMeLa at Virginia Tech. Brainstorming, feedback from blind users, and testing with blind users were all critical pieces of the design process.

The primary contribution of this thesis – Considerations for the Development of Non-Visual Interfaces for Driving – was developed based on the design process cycle for the most current set of NVI's (DriveGrip and SpeedStrip, as well as the Kinesthetic Tactile Display), specifically during this cycle, Fall 2010 through Spring 2011. Notes, observations, research and evaluation were conducted during this design process, alongside relevant literature review concerning previous work in developing non-visual interfaces.

Informal testing with blind users, as well as iteration of parameters based on qualitative feedback from blind users, were the main method of refinement in integrating DriveGrip and SpeedStrip into the current blind driver vehicle platform, the TORC ByWire XGV™. Later on, these interfaces would be used in a blind driver simulator for the general blind population; data was collected from the simulator in order to collect data pertaining to the interfaces' performance and sufficiency. The recommendations for further blind driver research and implementation stem from these results and observations.

### **1.4 Summary of Chapters**

Chapter 2 presents a review of literature, including descriptions of key terminology related to human sensation and perception. Here will also be a review of previous related work outside of Virginia Tech and the Blind Driver Challenge®. This includes the history and examples of non-visual interfaces both related and unrelated to driving, as well as definition and discussion of haptic interfaces and tactile displays.

Chapter 3 presents an overview of the history of the Blind Driver Challenge® as a project funded by the National Federation of the Blind. The Blind Driver Challenge® has been a joint effort

between the Virginia Tech's Robotics & Mechanisms Laboratory and the National Federation of the Blind since 2005. This chapter will look more in depth at the NFB's motivation behind the project and summarize the development of the project and the work completed prior to the fall of 2010.

Chapter 4 presents the principal contribution of this thesis, *Considerations for the Development of Non-Visual Interfaces for Driving*. This discusses a proposed set of guidelines to consider from the lowest level of generating non-visual interface concepts to a more specific means of characterizing different types of interfaces. This involves an approach to the human as an input/output device for the purposes of modeling blind driving process.

Chapter 5 illustrates how the Robotics & Mechanisms Laboratory at Virginia Tech utilized such an approach to develop the current interfaces. This will include a focus on both *instructional* non-visual interfaces such as DriveGrip and SpeedStrip, as well as *informational* non-visual interfaces, such as the Kinesthetic Tactile Display. The chapter will present a history on the development of these interfaces developed through BDC and descriptions of the interfaces used in the current platform. Considerations for hardware selection and usability are discussed. The completed testing and analysis will also be presented here.

Chapter 6 presents recommendations for future work related to the Blind Driver Challenge®. This chapter suggests some ideas for improvements for the instructional interfaces, DriveGrip and SpeedStrip, as well as the next steps to take in the development of the Kinesthetic Tactile Display. This involves identification of design challenges that will materialize and some ideas for improved quantitative assessment of the non-visual interfaces.

## Chapter 2: Literature Review

As outlined previously, this chapter will contain a discussion on related work done outside of Virginia Tech's Blind Driver Challenge® efforts. It is necessary to include a description of key terminology relating to haptics and human-computer interfaces, before exploring what types of non-visual interfaces, visual driving interfaces, and finally, non-visual interfaces for driving, have already been considered.

### 2.1 Human Sensation and Perception

In the more fundamental stages of the development of any human-computer interfaces, it is necessary to take into consideration all possible modes of human sensation and perception, as will be discussed in Chapter 4. By defining human sensing from a scientific perspective, it will become easier to create and evaluate different types of human-computer interfaces. The sense of vision is omitted not discussed.

#### 2.1.1 Sensation, Perception, and Recognition

*Sensation* is the conscious or unconscious awareness of external or internal stimuli. Sensation is accomplished in the human body through the peripheral nervous system. The peripheral nervous system includes the *sensory receptors*, which are located at the ends of the peripheral nerves, and *sensory and motor neurons*, which transmit information from these various sensory receptors to and from the central nervous system [8]. Of interest here are the sensory receptors, which can be classified by their stimulus type:

- *Mechanoreceptors*, which respond changes in pressure, including vibrations, and stretch (related to touch and sound)
- *Thermoreceptors*, which respond to changes in temperature
- *Photoreceptors*, which respond to light energy (all located in the retina of the eye; related to sight)
- *Chemoreceptors*, which respond to changes in chemical concentrations (related to taste and smell)
- *Nocioreceptors*, which respond to extreme and harmful stimuli by producing the sensation of pain (tied in with all above sensory receptors, related to all senses) [9]

It is worth noting that each of these sensory receptors, except for the nocioreceptors, become less responsive after continuous stimuli. In other words, after continuous stimulation of any particular receptor, it will have undergone *sensory adaptation* and it will become less effective to utilize that receptor to convey information to the human.



*Perception* is the process of consciously interpreting the different types of stimuli. While the act of *sensation* has to do with the actual reception of the different types of stimuli, the act of perception is necessary for the human for the human to distinguish the significance of the stimuli.

In order for the perception process to occur, it is necessary for the human to have prior *knowledge* of the possible stimuli that he may sense, as well as prior *experience* of interpreting the particular sensation and linking it to that knowledge. These concepts become particularly crucial when considering distinct types of information to convey to the human through the same sensory receptor. This ability to use experience and knowledge to perceive a sensation is called *recognition* [10].

### **2.1.2 Somatic Senses**

Those senses falling in the category of touch, or *tactition*, are more formally known as the *somatic senses*. A large portion of non-visual interfaces make use of the somatic senses due to their accessibility. All other senses fall under the title of *special senses*.

The somatic senses can be grouped into three categories. The *proprioceptive senses*, which detect changes in muscles, tendons, and body position, and the *visceroceptive senses*, which detect changes in the internal organs of the human body, both make use of the stretch receptors as well as the nociceptors for pain. The third category, *exteroceptive senses*, detect changes at the body's surface, including touch, pressure, temperature, and pain. These are the senses that will be the most relevant in the application of non-visual user interfaces.

Touch and pressure are sensed using two types of mechanoreceptors. The *Meissner's Corpuscles* are those mechanoreceptors which detect light touch. They are abundant in the hairless portions of skin, such as the lips, fingertips, palms, soles, nipples, and external genitalia. The *Pacinian Corpuscles* are those mechanoreceptors which detect heavy pressure. They are abundant in deep subcutaneous tissues of the hands, feet, penis, clitoris, urethra, and breasts.

Temperature is sensed using two types of thermoreceptors. *Cold receptors* are sensitive to temperatures between 10°C (50°F) and 20°C (68°F), while *heat receptors* are sensitive to temps between 25°C (77°F) and 45°C (113°F). For temperatures below 10°C, nociceptors are triggered, producing a painful freezing sensation; likewise, a painful burning sensation is felt at temperatures above 45°C. Thermoreceptors undergo rapid sensory adaptation, which means that stimulating the human using temperature becomes ineffective relatively quickly.

Pain is sensed through free nerve endings, which are the nociceptors that are widely dispersed throughout the body. They cover the entirety of the skin as well as the internal tissues, except the nervous tissue of the brain, and are stimulated by extreme sensations of many types, such as pressure and temperature. There are two pain nerve pathways.

*Acute pain* occurs rapidly, within 0.1 sec, and is a sharp, fast pain that will result from stimuli such as a paper cut, needle prick, or contact with a hot stove. It is conducted on myelinated fibers, or those neurons which are electrically insulated by a material called myelin [11]. These are located less on the deep tissues like muscles and ligaments and more on the skin of the body. Acute pain ceases when stimulus is removed.

*Chronic pain* is experienced slowly can increase in intensity over long periods of time, up to seconds or minutes. It is a dull, aching, burning, throbbing pain as a result of physical injury [12]. It is conducted on unmyelinated fibers and thus can occur anywhere on the body, and may continue after stimulus is removed [9].

*Sensory Homunculus* and *Motor Homunculus* are models of the human body that visualize the connection between different body parts and areas in brain hemispheres [13]. *Motor Homunculus* is a model which depicts the body parts proportionally based on the amount of brainpower utilized to control them, or the area of the cortex of the brain concerned with their movement [14]. For instance, the hands and facial features on *Motor Homunculus* are much larger, thus requiring a greater quantity of motor signals from the brain [15]. *Sensory Homunculus* is similar, but depicts the body parts in proportion to the area of the cortex of the brain concerned with their sensory perception. Once again, the hands and face are depicted much larger, although not as drastically. This helps to demonstrate which areas of the body would be most receptive to somatic stimuli.



**Figure 1.** *Sensory Homunculus.* The Natural History Museum, London. <http://piclib.nhm.ac.uk/searchresults.asp?image=041490> (accessed 10 November 2011) Used with permission from The Natural History Museum, London.



Figure 2. *Motor Homunculus*. The Natural History Museum, London. <http://piclib.nhm.ac.uk/popuppreview.asp?image=041489> (accessed 10 November 2011) Used with permission from The Natural History Museum, London.

### 2.1.3 Sense of Audition and Sound Localization

While the somatic senses are those related to tactile stimuli, the rest of the senses can be grouped under the title of *special senses*. These include gustation, olfaction, equilibrium, vision, and audition.

*Audition* is the human sense of sound. In the inner ear, there are 16000 mechanoreceptors located on the basilar membrane that essentially detect vibrations from sound waves. The outer ear collects the sound waves and directs them toward the *tympanic membrane*, or eardrum, which is located in middle ear and amplifies and concentrates the sound waves, directing them to the inner ear. Humans can hear frequencies between about 16Hz and 20kHz [16].

A valuable feature of audition is that humans can determine the location of a sound source three-dimensionally. In order to accomplish this, the brain takes advantage of small differences in timing, frequency, amplitude, and timbre of the detected sounds waves between the two ears, called *interaural cues* [17].

*Interaural time differences* occur when a sound wave from the side reached the right ear at a different time than the left ear. At low frequencies (below 800Hz) for an average human head size of 21.5cm, the two ears are less than half a wavelength apart, and thus the auditory system can detect phase delays between the two ears. At higher frequencies, a group delay can be more easily detected, wherein the time delay of the amplitude envelopes between the two ears. It is possible for humans to detect interaural time differences of 10 microseconds or less [18].

*Interaural level differences* are also prevalent at the higher frequencies (above 1600Hz) wherein the two ears are more than a full wavelength apart from each other. The human will experience a difference in the amplitude of the sound waves, and when combined with the group delay, the auditory system can detect the lateral direction of the sound source at these frequencies.

In the middle-range frequencies, between 800Hz and 1600Hz, the human will most likely have to combine information from both interaural time differences and interaural level differences, known as the *duplex theory* [19]. The human can localize a sound source to within 1° error ahead or behind them and within 15° to the left or right [20].

To determine the distance of a particular audible cue, there are several indications which the human uses to its advantage. Higher frequency sounds are more damped by the air than low frequencies, so a distant sound source appears muffled, due to a higher prevalence of its higher frequencies. Distant sound sources are also perceived with less intensity than closer sound sources; thus, the receiver can more easily estimate the proximity of a sound with which it is familiar.

Humans are also capable of consciously distinguishing between desired sound sources and noise. This is known as the “cocktail effect”, and is the result of recognition of critical frequency bands in the environment [21].

#### **2.1.4 Other Special Senses: Gustation, Olfaction, and Equilibrium**

*Gustation* (taste) and *olfaction* (smell) are detected using chemoreceptors in the upper nasal cavity and in the taste buds of the tongue, respectively. Both undergo rapid sensory adaptation. Gustation is a bit more intriguing, as four different taste sensations are detected based on the location on the tongue: sweet on the tip of tongue, sour on the lateral tongue, salt on the perimeter of tongue, and bitter on the posterior tongue.

The sense of *equilibrium* is detected using mechanoreceptors in the inner ear called *hair cells*. These function similar to the receptors which are used to process sound waves. The human is capable of using *static equilibrium* to sense the position of the head and maintain posture while motionless as well as *dynamic equilibrium* to prevent loss of balance during rapid head or body movement.

## **2.2 Human-Computer Interfaces, Haptic Devices, and Tactile Displays**

Non-visual interfaces, as developed and utilized in the Blind Driver Challenge® are a subset of *human-computer interfaces (HCI's)*. Human-computer interfaces are any tools which the human uses to interact and communicate with a computer [22]. In recent years, much of the emphasis in human-computer interaction has been related specifically to *graphical user interfaces*, with the advancement of mobile electronic devices and increased use of computers. However, the usability of a device that interfaces a computer is also a significant topic in human-computer-interaction. *Human factors* is the study of the human capacity to utilize and comprehend information using the given interfaces, and how these concepts are applied to BDC's non-visual interfaces are the focus of this document. Considerable research and development has been

conducted on the usability of common interfaces such as keyboards, mice, and smartphones, but such work relating to non-visual interfaces for driving has been thus far untouched.

### 2.2.1 Haptic Devices and Tactile Displays

Human-computer interfaces play an important role in *haptic devices*. While differing in definition depending on the source, *haptics* can be defined as any feedback technology relating to the sense of touch in all its forms, including *cutaneous*, *kinesthetic*, and *vestibular sensations*, typically coupled with *force feedback devices* [23].

*Cutaneous* sensations are simply those perceived by the exteroceptive somatic senses, such as touch, pressure, vibration, indentation, temperature, and pain on the skin's surface. Some sources will distinguish *tactile* sensations as a subset of the cutaneous, including only those senses from mechanoreceptors: touch, pressure, vibration, and indentation. *Kinesthetic* sensations are those related to the proprioceptive changes in muscles, tendons, joints, and body position, utilizing the stretch and pain receptors as previously discussed. *Vestibular* sensations are those related to the sense of equilibrium, including balance, head position, and acceleration. *Force feedback devices* are used to mechanically produce information and present it to the human through one or more of these senses [24].

Haptically-enabled devices enable information flow from the machine to the user as well as vice versa. In *active* devices, the history of the information flowing from the human to the interface is considered, creating a complete control loop, whereas *passive* devices do not take into account the human's previous actions. An active haptic device is required to simulate the exploration of a synthetic environment or the dynamics of a steering wheel on a car such as the blind driver vehicle [25]. In complex environments such as these, an accurate haptic presentation may be accomplished without providing a complete physical representation, due to the limitations of human perception. To this matter, considerable research has been done to determine how to simplify complex information and convey this information to the user in a more efficient manner [26]. For instance, the overall geometric shape of an object can be more easily detected using low frequency, high amplitude signals, whereas surface textures should be represented using high frequency, low amplitude signals [27].

*Tactile displays* are those haptic interfaces which tap only into the cutaneous sensations. A tactile display that includes vibrotactile elements or something similar is required to perceive surface texture [28]. *Tactile imaging* is the process by which a tactile display displays geometric shapes such as a picture or a two-dimensional environment. Here, low-frequency mechanical stimuli may be used to create a touchable raised representation of the image [29]. Tactile displays are also naturally in the category of *direct contact interfaces*, wherein the user interacts with a task utilizing part of the body, notably the hand. Other haptic interfaces may utilize a probe, such as a stylus, to explore an environment; these are known as *remote contact interfaces* [27].

### 2.2.2 Previous Work in Non-Visual Interfaces

In 2007, Vidal-Verdu and Hafez completed a survey of graphical tactile displays for visually-impaired people [30]. In 2010, Paneels and Roberts completed a review of designs for haptic data visualization [31]. This section will emphasize some of the most significant methods and devices for displaying information non-visually.

Aside from audible tools such as text readers, blind people mostly access information somatically, through Braille. Braille is a digital form of writing wherein each Braille cell consists of six dot positions, arranged in two columns of three. Different combinations of the dots are raised in each character, denoting a particular letter, number, contraction, or symbol allowing representation of traditional written alphabet and punctuation [32]. Braille printers are used to print Braille paper, but these machines are bulky and expensive, and can only print 25 lines of 43 characters on the standard 11" by 11.5" page [33, 34]. Braille printers are also used to create two-dimensional graphics such as maps, graphs, and charts, simply using the raised dots to represent shapes and text side by side [35]. In addition to the bulkiness and fragility of paper Braille, there is a need to display dynamic information through dots, such as internet and computer information or changing visual representations. Therefore, much research has gone into the development of refreshable tactile screens, which essentially replace the pixels of a typical screen with *taxels*, or some form of raised stimulation unit similar to a Braille dot [30]. The primary issue with creating a two-dimensional tactile interface like this one is cost.

Some have researched the possibility of using thermal stimulation for a tactile display, given the skin's quick recognition of differences in temperature [36]. Yamamoto determined that the resolution offered by this concept is not adequate enough to apply to the recognition of text or graphics.

Electrotactile stimulations have also been considered, such as those providing information through tingle, itch, vibration, buzz, touch, pressure, pinch, sharp, and burning pain. There exists a small dynamic range of the intensity of current that is both noticeable by touch and below the pain threshold, thus making it difficult to use current intensity to represent different reliefs [37]. However, simple binary actuation is possible, as well as modifying pulse width or frequency. Kaczmarek tested the effectiveness of pattern recognition using the fingers on a 7x7 array of electrodes versus an array of raised dots of the same physical dimensions. He observed a 78.5% recognition rate of common shapes using the electrode vs. 97.2% using the raised dots, although mean response time was four to six times faster with the raised dots [38]. Further work by Kaczmarek suggests that the human undergoes greater sensory adaptation with electrotactile stimuli [39].

Since the 1970s, piezoelectric and electromagnetic have been utilized to create taxel-interface devices, though typically only for a single line of Braille display, up to eighty Braille cells long [40, 41]. Vidal-Verdu calculates that, with a cost of roughly \$35 per cell, it would cost hundreds

of thousands of dollars for a sizeable display of reasonable resolution [30]. A company called Index Braille Accessibility [42] is developing such a product for costs on the order of ten thousand dollars.

Other types of mechanical stimulation that have been explored include electrorheological and magnetorheological fluids, shape memory alloys, pneumatic pumps, and electrostatic forces. One instance even used pressure from ultrasound radiation to create a display. For truly dynamic refreshable displays, the most functional displays have used piezoelectric actuation.

### **2.2.3 Previous Work in Visual and Non-Visual Interfaces for Driving**

Some instances of visual interfaces for driving have been developed for driving under low-visibility conditions. These are helpful to consider because with the non-visual interfaces developed for BDC, the same types of information may be considered relevant. Lim et al designed a Heads Up Display that overlays the outlines of lane in a small rectangular screen on the windshield, using GPS to detect vehicle position and then communicating the lane information visually to the driver [43, 44]. A similar interface was designed by Steinfeld and Tan specifically for snowplow drivers [45]. As opposed to an overlay, this was a console on the dashboard that displays a graphic of the lane curvature up to 50 feet ahead, as well as the predicted trajectory of the vehicle based on current steering angle [46]. For the same application, Ravani added instructional visual and audio cues in order to quickly alert the driver of errors and therefore adhere to the display [47]. This included a beeping tone when an alert was necessary, and large arrows on the display screen guided the driver in the correct direction.

An early non-visual interface for driving developed by Fenton utilized a joystick both for conveying information to the driver as well as operation of the vehicle [48]. The joystick has two degrees of freedom – left and right as well as acceleration and deceleration – although the tactile aid is used solely to improve the driver’s headway following behind a leading vehicle. A “finger” is actuated linearly, protruding through the front and back of the joystick to tell the driver to slow down or speed up; it is meant as a supplement to driving visually. It was found through experiment that the use of the tactile display improved performance for headways of 30 to 60 feet for speeds up to 40 mph [49].

A vibrotactile interface designed by van Erp and van Veen uses four vibrating elements positioned down each thigh of the driver. The four vibrating motors on the right thigh vibrate to cue a right turn, those on the left thigh for a left turn, and all eight to cue a straight desired trajectory. This interface is to be used as an addition to the visual driving experience; its objective is to improve the driver’s performance while decreasing the workload on the driver, thus freeing up the driver to pay attention to additional modes of communication. In a series of driving simulation experiments, van Erp concluded that the intuitiveness of an in-vehicle navigation system is very critical. Additionally, he identified the potential for tactile devices such as this one to enhance the indication of time-critical events such as collision avoidance.

Another interface called the Vibrotactile Glove was designed for use in a semi-autonomous wheelchair, specifically for wheelchair-bound persons with severe visual impairment [50]. The interface consists of a 3-by-3 array of vibrating disk motors on the back of a glove, which the user wears on the same hand they use to operate the joystick for the wheelchair. The Vibrotactile Glove provides the user with warnings as well as direction guidance and spatial representation of obstacles detected by its close-proximity sensor array. The warning message sends long pulses to all nine vibrotactors, and occurs when an obstacle is approaching two-meter proximity. When an obstacle comes within that two-meter range, direction is provided by alternating pulse patterns between the center vibrotactor and one of the outer eight vibrotactors, depending on the location of the obstacle. Lastly, the proximity of the obstacle is represented by varying lengths and numbers of pulse patterns. Far-range obstacles are denoted by single short pulses, mid-range obstacles are denoted by three short pulses, and close-range obstacles are denoted by single long pulses.

#### **2.2.4 Considerations for the Development of Non-Visual Interfaces**

In 1993, Fricke and Baehring proposed a design for a tactile graphical I/O tablet for blind users, presenting a list of ideal properties for a taxel-based interface. The focus of this analysis is on the physical measurables of such an interface, including dot size and resolution as well as screen size [51].

Vidal-Verdu's 2007 survey of graphical tactile displays for visually-impaired people presents some points on the ideal tactile display relating to the sense of tactition. Here, the sensitivity of the mechanoreceptors in the human hand is evaluated in relation to the resolution and force applied by a raised-dot screen. Vidal-Verdu also examines the effective frequencies of vibrotactile actuators and sensory adaptation. They evaluate the effectiveness of devices by considering the refreshing time, the resolution, bandwidth, force, and stroke of the taxels, and the size of the screen [30].



## Chapter 3: History of Non-Visual Interfaces and the Blind Driver Challenge®

Since accepting the Blind Driver Challenge® in 2005, RoMeLa researched, developed, and implemented several interfaces before creating the final interfaces in 2010 to 2011. These include different types of tactile and audio devices and were used in operation of two different small-scale vehicle platforms, an electric dune buggy and a golf cart.

### 3.1 Acceptance of the Blind Driver Challenge® and Preliminary Brainstorming (2005-2006)

After accepting the Challenge in 2005, the initial Blind Driver team at Virginia Tech was not focused primarily on the design of non-visual interfaces as the primary objective. Instead, the efforts were put toward the development of a vehicle platform. This included work on sensor evaluation, waypoint navigation, obstacle avoidance, steering, and braking that would lay the groundwork for the eventual Blind Driver Challenge® vehicle used today [52].

The team did complete some initial brainstorming of ideas for non-visual interfaces for driving. Some of the types of information they wanted to display to the driver include traffic information, emergency alerts, weather, vehicle speed, upcoming stops and turns, and objects in the road.

One idea was to use two-speaker cross-talk cancellation, which would take advantage of a small surround sound system in the car. Items such as traffic information, emergency alerts, weather, and vehicle speed could be announced using this setup.

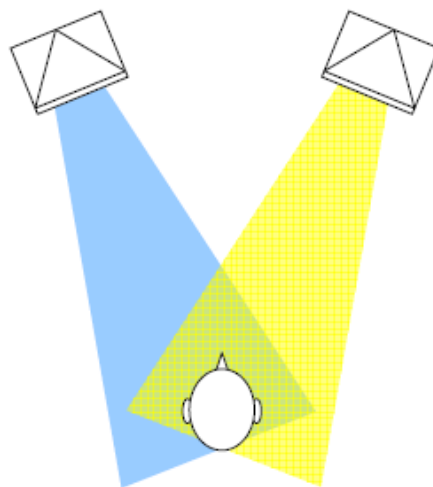


Figure 3. Concept of cross-talk cancellation

The team also proposed a control knob that included movement in yaw, pitch and roll as well as a series of buttons on top of the knob. The goal of this interface was to enable operation of many controls such as air temperature or radio with one simple device, eliminating the need for a blind driver to locate many different controls in the console.

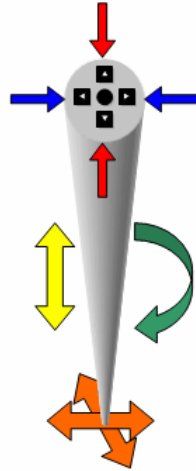


Figure 4. Concept of Control Knob with ranges of motion shown

To display information through text, the team looked into a refreshable Braille display [53]. This would be a device with which blind users are already very familiar; however, the price on a display like this is quite steep.

The final idea devised by this year's team was a wearable tactile vest that would contain vibrating motors and send stop and turn signals to the driver. By increasing the number of motor used and using vibrations of different frequencies, an array of different signals could be achieved. The Blind Driver team would revisit this idea in later years.

### 3.2 Development of Tactile Seat and Audio System (2007)

The following year, the Blind Driver team focused more on the design and fabrication of NVI's, namely a Tactile System and an Audio System. As well, they programmed an off-the-shelf joystick for human input to a simulated driving environment. Meanwhile, the efforts for creating an autonomous vehicle platform diverged to another project, Virginia Tech's entry for the DARPA Urban Challenge [54]; thus, the Blind Driver team set up a software architecture in LabVIEW to navigate a driver through a simulated environment. Lastly, the team tested the interfaces using simulated path data from a separately developed autonomous vehicle platform [55].

The Tactile System is a device used to convey speed information to the user, and is designed to optimize ease of use, comfort, and cost. In consisted of a massage chair containing fourteen

vibrating motors arranged in four modes extending down the leg and four modes extending up the back of the chair. The motors are wired to accept voltages of 9V or 15V, one at a time, resulting in variable intensities of vibrations. The Tactile System calculates the error between the *actual* speed of the vehicle and the *desired* speed of the vehicle; then, the appropriate mode on the legs or back of the seat is stimulated. The device utilizes parts of the body that are already in contact with the vehicle, yet not engaged in operation of the vehicle, like the hands and feet. It is very simple – a binary system of modes on or off is implemented – and cheap to fabricate. Additionally, it is not bulky or burdensome, allowing the user to enter or exit the vehicle without hassle.

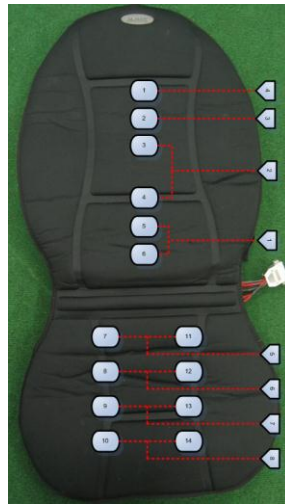


Figure 5. *The Tactile System, a seat with fourteen vibrotactile elements*

The Audio System is also a very simple interface, consisting only of pair of headphones, thus minimizing hardware and relying on all of the work to be done in software. Using the built-in libraries in the LabVIEW software, easily configurable audio cues are possible. For example, patterns such as constant tones, beeping tones, and changes in frequency or volume can all be programmed. The first configuration the team implemented was called “center zero”, where a constant tone in the left ear cues the driver to steer more toward the left, and a constant tone in the right ear cues the driver to steer more toward the right. Just as in the Tactile System, the error between the desired and actual steering angles is calculated in software, generating a constant tone with amplitude proportional to the magnitude of the error. When the steering angle error is small enough, within a defined deadband, there is no tone generated, hence the name “center zero”.

For user input, the team programmed a Saitek Cyborg Evo Force joystick as opposed to the more conventional steering wheel and pedals. While the steering wheel and pedals may be more familiar to the traditional driver, the team decided at this point that since blind people had never driver in the past, this factor does not apply. The joystick setup was kept simple, just as the user interfaces; adjustment in the y-direction would be used for acceleration and deceleration, and

adjustment in the x-direction would be used for steering left and right. Additionally, a trigger button on the joystick would be used as an emergency stop, causing abrupt deceleration when engaged.

Preliminary testing was completed for a blind driver simulation consisting of the tactile vest, headphones, and joystick. While simulated data from the actual autonomous vehicle, Odin, was not available, motion profile data from a typical Odin run was collected and implemented. Using LabVIEW, the team created a test sequence that took the user through a series of motion profiles, using error calculations to convey speed and steering information through the user interfaces and accepting joystick data from the user at a rate of 3Hz. Each of ten sighted participants with an average of six years of driving completed one experimental run with just the audio cues, one with just the tactile cues, and then a third with both cues. This was not a closed loop, meaning that the error in human input was not accounted for in the dynamics of the vehicle on the road.

The results revealed a 64% increase in curvature error in the full audio-tactile experiments compared to those with just audio cues, as well as a 52% increase in speed error in the full experiments compared to those with just tactile cues. Thus, the team determined that an increased mental load on the driver negatively affects his performance. Users did prefer receiving acceleration cues progressing down the legs of the Tactile System, while receiving deceleration cues up the back, as this configuration is more intuitive. Most users also claimed that the traditional steering wheel and pedals would be much more intuitive, even considering they were sighted and had previous driving experience. Lastly, users offered that these types of interfaces had high potential for use in other applications such as increased situational awareness for sighted drivers, new driver education, pilots flying in instrument conditions, surgical operations, mining, biking, military Special Forces operations, deep sea exploration, operation of construction equipment, adaptive automobile cruise control, obstacle proximity for remote robotics applications, and video game [56].

### **3.3 Development of Tactile Vest, Click Wheel and AirPix (2008-2009)**

In 2008 to 2009, the BDC team recognized the fact that the previous designs had “reduced the intelligent individual in the driver’s seat to a mere actuator”, and thus shifted the focus to include more active decision-making for the driver. This initiative was more in line with the NFB’s ultimate goals for the BDC project. The second major focus this year was on the acquisition and development a new vehicle platform, separate from the Urban Challenge team’s Odin. This was motivated by the notion that the blind driving system should be modular and thus adaptable to many different vehicles in order to maximize accessibility. Thus, the team developed an electric dune buggy platform as well as three new NVI’s: a Tactile Vest for speed signals, a Click Wheel for turning signals, and finally, a new type of dynamic tactile display called AirPix [57].



**Figure 6.** *The new vehicle platform, an electric dune buggy*

The Tactile Vest is an interface very similar to the tactile seat system, utilizing progressive vibrating elements in order to instruct the driver speed signals. The primary issue with the previous interface was now that it is being integrated into an actual vehicle, there is interference with the environment that comes into play: the vibrations of the dune buggy were interfering with the vibration signals in the tactile seat, thus reducing their effectiveness. The team designed the Tactile Vest, which drapes around the user's neck with two strips down the front of the torso. Cues to accelerate progress down the right side of the torso with increasing magnitude, while cues to decelerate progress similarly down the left side. This arrangement is meant to naturally mimic the gas pedal on the right side and the brake pedal on the left side.



**Figure 7.** *The Tactile Vest*

The Click Wheel's original motivation was to provide the user with a quantitative means of knowing exactly how far he has turned the steering wheel, since users relying on audio signals alone had interpreted the signals too subjectively. The Click Wheel is simply an addition to the

normal steering wheel that contains minor notches every 5° and major notches every 45°, with a physical flapper that emit an audible click each time a notch is passed over. Now the audio cues can be altered to provide the driver with commands to steer a specific number of clicks left or right, and the user can objectively follow this command.



**Figure 8.** *Click Wheel mounted on the steering column of the dune buggy*

By the end of the year, the team was able to implement and test the full blind driver vehicle, including the Click Wheel, the Tactile Vest, and the dune buggy outfitted with laser range finders. Reaction time for the Click Wheel was measured to be 1.5 to 2.5 seconds, while reaction time for the Tactile Vest was measured between 0.1 and 0.5 seconds. The full system was tested on a closed course, wherein three blind drivers were able to navigate without error.

While the Tactile Vest and the Click Wheel were fabricated and tested on the dune buggy vehicle platform, the team began research and development on a new type of non-visual interface called AirPix. AirPix utilizes compressed air to provide a pixelated, refreshable tactile representation of the two-dimensional environment. This is different than the more instructive interfaces that have been previously implemented; this is an environmental observation system that informs the user what is in the surroundings and up ahead, enabling them to make decisions while navigating the vehicle. Choosing to represent the pixels using compressed air has a few distinct advantages. Since there are no moving parts on the surface of the interface, as opposed to using something with raised pins, for example, it is safer and more robust. The pressure of the individual air pixels is easily adjustable, and the display can be refreshed with adequate frequency. The first prototype was designed and built this year, consisting of fifteen pixels represented by 1/64” holes. This would serve as a proof of concept for the AirPix interface.

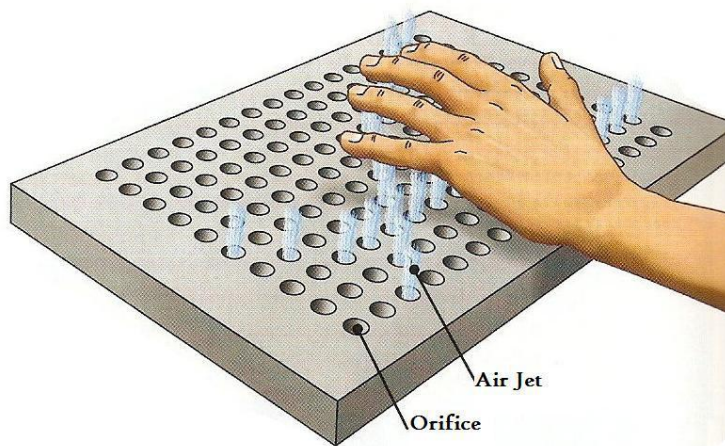


Figure 9. *The concept of AirPix*



Figure 10. *Initial prototype for the AirPix interface*

The 2008-2009 team recommended that AirPix become a primary focus of the Blind Driver Challenge® going forward, recognizing the need to efficiently increase the bandwidth of data transfer. Receiving a greater bandwidth of data would enable the driver to drive with more independence, as he could now make more decisions instead of relying on strictly instructional cues such as the ones provided through the audio cues or tactile vest. Lastly, the team suggested that as these interfaces improve in quality and reliability, additional applications, such as low-vision or elderly drivers, might be considered.

### **3.4 Development of DriveGrip, Foot-Oriented Speed Control Interfaces, and AirPix (2009-2010)**

In 2009 to 2010, the team introduced a new concept for steering information, a set of gloves called DriveGrip that contains vibrating motors in each finger, as well as some new ideas for speed control. They also continued development of AirPix, the refreshable two-dimensional

compressed-air display. Due to the dune buggy's transmission failures, a green golf cart was acquired as the new vehicle platform. This new platform still used a traditional steering wheel and gas and brake pedals as human inputs to the system. However, the team also began investigation of a full-size street-legal vehicle that would be utilized the following year [58].



**Figure 11.** *The golf cart is the newest vehicle platform in 2008-2009*

### **3.4.1 DriveGrip**

Because of the unreliability of the Click Wheel setup, the team reconsidered options for conveying steering information to the driver. The result was DriveGrip, a pair of gloves that contains a vibrating motor on each finger. Several types of gloves and different vibration motors and mount locations were tested, as well as different strategies and combinations of the motors being stimulated.

Comfort was a significant factor in the development of DriveGrip, so the team considered different types of athletic gloves. Closed-finger baseball gloves were utilized for first couple iterations, but after obtaining feedback from the NFB, it was declared essential that the user keeps all fingertips open as a mode of sensing the environment. Subsequently, the team tried other variations with the fingers of the baseball gloves cut off. The final model was a pair of Harbinger weightlifting gloves, which are made without fingers, so they have a natural, comfortable fit while keeping the fingertips free for the driver to utilize for other sensory modes. Additionally, since no part of the Harbinger gloves needs to be cut away, the sturdiness of the gloves is kept intact, making it easier to solidly mount the necessary wiring for the motors.





*Figure 12. The final design concept for the DriveGrip interface, with vibrotactile motors on knuckles as shown*

The selection of motors and where they were mounted on the DriveGrip gloves was also an iterative process for the team. Two different types of bulky 3-volt motors were utilized before discovering small, flat, lily pad motors that were roughly 1cm in diameter, which the team eventually used in the final iteration of DriveGrip. Minimizing the weight and the size of the hardware on the gloves is essential in ensuring excellent comfort and maneuverability. Lastly, the location of the four motors on each hand was considered. After initially placing the motors below the base knuckles, consultation with the NFB revealed that closer proximity to the fingertips was ideal, as long as the fingertips remain exposed, as discussed previously. Thus, the final DriveGrip design positioned the motors on the base segment of each finger [59].

### **3.4.2 Foot-Oriented Speed Control Interfaces**

The 2009-2010 team sought to improve upon the Tactile Vest for a few reasons. First, it was difficult for the user to distinguish between the acceleration cues along the right side of the torso and the deceleration cues on the left side. To this end, a remodeled Tactile Vest was designed, wherein the deceleration cues remained on the torso, conveniently positioned by the seatbelt, and the acceleration cues were now located on the right thigh, attached to the driver by a belt and strap. However, as with the previous iteration of the Tactile Vest, this did not effectively communicate gradual changes in acceleration to the driver.



**Figure 13.** *Speed control interfaces: integration into the seatbelt, and two interfaces attached to the driver's thigh*

In addition to exploring alternative locations for the speed control interfaces, the team also considered different sensory inputs. This led to efforts in foot-oriented interfaces, which initially used pressure stimulations in order to markedly distinguish between the vibration stimulation of the DriveGrip. The two-footed speed control interface required the user to slip both feet into straps on the two pedals: the right foot on the accelerator and the left foot on the brake pedal. To notify the driver to apply a higher load to a pedal, a strap on the toe of each foot would tighten, giving pressure to the toe of that foot. Similarly, a strap near the ankle would tighten in order to notify the driver to ease off the pedal of the respective foot. This method was designed to be simple and intuitive, inputting signals only to the feet of the driver. However, after discussing with the NFB, it was made clear that receiving signals via pressure from the straps was not a comfortable or safe option. Additionally, requiring the driver to employ the brake pedals with the left foot is not the conventional method for driving, thus the driver does not receive the genuine driving experience.

The team developed other iterations of foot-oriented interfaces, now returning to vibration stimulations and using only the right foot for the pedals. The final design uses a shoe and a calf strap on each leg, all equipped with the same pancake-shaped motors as DriveGrip. Vibrations in the calf straps indicate to the driver that he needs to switch pedals. Then, vibrations in the toe of the shoe would notify the driver to increase pressure on that pedal, while vibrations in the heel of the shoe would notify the driver to ease off that pedal. While this system remains simple and intuitive, it fails to address the need to communicate gradual changes in acceleration. It must also be noted that comfort and ease of use are concerns.

### **3.4.3 AirPix**

Expanding on the work completed the previous year, the BDC team continued development on AirPix, a refreshable tactile mapping interface that conveys a two-dimensional representation of the world model. Based on experience with the proof of concept model, the team created a final

prototype consisting of a 4.9”×2.8” grid of 1/8”-diameter orifices on a 3/8”-thick clear acrylic plate. The orifices are arranged 0.35” apart in a 15 × 9 rectangle, and thus provide a resolution of about 10 orifices per square inch when all orifices are activated. Two small alignment pegs are located above and below the center of the grid to assist the user in constantly identifying their location in the grid. After testing, an air pressure of 20psi for each nozzle was deemed ideal. This is based on a series of eight criteria for designing the first full-scale prototype [58].

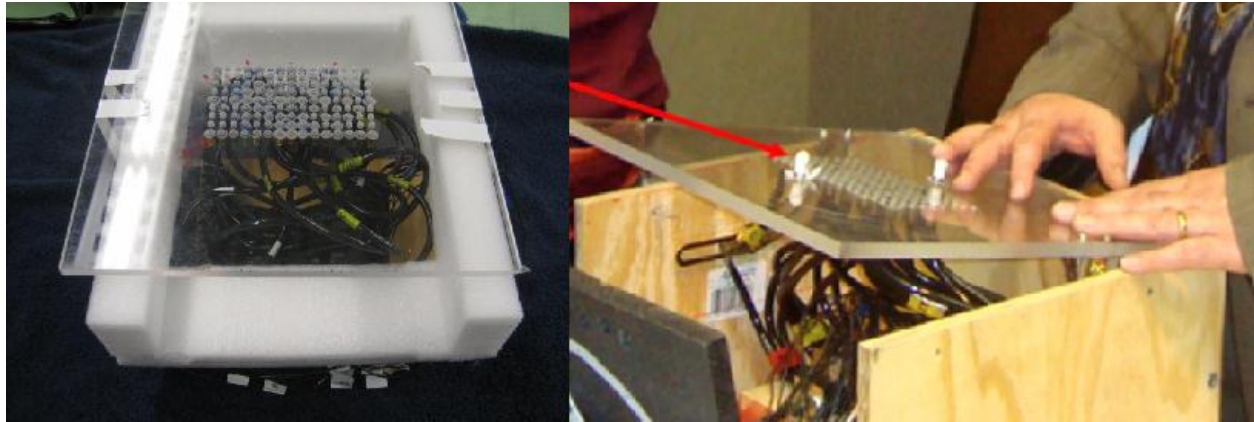


Figure 14. AirPix interface in testing frame and shown with alignment pegs as a blind user tests the concept

Table 1. Metrics for compressed air-powered refreshable tactile mapping interface

Characteristic	Direction of Improvement	Units	Ideal level	Least Acceptable Level
Sound Level (from AirPix plate while in use)	↓	Decibels (dB)	25	75
Air Pressure in contact with user’s skin	↓	Psi	10	30
Refresh Rate	↑	Hz	80	20
Resolution	↑	# orifices per in <sup>2</sup>	1.5	0.3
Total # of Orifices	↑	# orifices	40	8
Price (system without compressor or computer)	↓	Dollars	<\$2000	\$5000
Level of distraction	↓	# mistakes made in mental exercise while using device: # mistakes made in mental exercise without using device	<5%	25%
Effectiveness	↑	(1-% error) between desired route and actual route	>90	70

While testing with the NFB, the team created a rubric for measuring user-related variables for the AirPix device. The team tested the display mode, wherein it was found that positive space (activated orifices) would represent objects of interest in the display, as opposed to positive space representing the surrounding environment. Next, pulsating streams of air was found to be less effective and desirable than constant streams of air. A reaction test was conducted to ensure that the user can quickly distinguish between on and off states of the device. Finally, a user recognition test was completed, splitting the grid into 3×3 squares, and requiring the user to choose the correct stimulated region using a typical keyboard number pad.

**Table 2. User-related variables to measure for the AirPix device**

Variable	Description
Reaction Time	Time required for user to detect that an air flow has been activated/deactivated
Recognition Time	Time required for user to identify a characteristic of the air flow (such as shape displayed, location of air flow on plate, etc.)
Sensitivity	Smallest distance between two points of indentation that the user can distinguish (on hand, various parts of each fingers, etc.)
Hand height	Height of pads of main sensor area of hand above plate
Preferred height	Height above plate at which user prefers to have hand by end of testing session
Range of Motion	Horizontal and vertical range of user's comfortable scanning (or scrubbing) once familiar with device

After some informal testing of the new interface, the team did not get a chance to achieve its end goal, to integrate the system with both the DriveGrip and speed control interfaces.

## **Chapter 4: Considerations for the Development of Non-Visual Interfaces for Driving Applications**

The experience gained through the development of interfaces by the Blind Driver Challenge® teams between 2005 and 2010 as well as related projects and investigations conducted by outside research institutions suggest some modes of thinking, techniques, and criteria for developing non-visual interfaces for the purpose of driving. Here is an approach to organizing these considerations into a design process, including the model of the human as an input/output device, investigation into signal communication through all modes of human sensing and anatomy, and concept generation for non-visual interfaces specifically for driving.

These considerations can be used to evaluate the final non-visual interface designs completed in 2010 to 2011. These NVI's will be used as case studies in Chapter 5.

### **4.1 Human as an Input/Output Device**

A strategy is to break down the problem as simply as possible. The human needs to receive an amount of information, process that information, and then execute a number of actions based on what they have processed. A blind human, in an environment where they are receiving some cues or signals and then driving a car based on what they perceive, can be likened to an open-loop control system. The human is essentially an *input/output device*.

#### **4.1.1 Blind Driving as an Open-Loop Control System**

For the purpose of the development of the non-visual interfaces, it is important to keep in mind a simplified, open-loop model of the blind driver system. However, it should be noted that the performances of each individual human as the plant in this model of an open-loop control system will be different. As well, you could model blind driving as a *closed-loop* control system, wherein the performance of the individual driver (the output) is taken into account when creating the non-visual signals (the input) that the driver receives. This closed-loop concept is researched in depth using driver modeling in a RoMeLa Internal Report titled “Driver Assistance Algorithms and Interfaces for the Blind Driver Challenge®” [60].

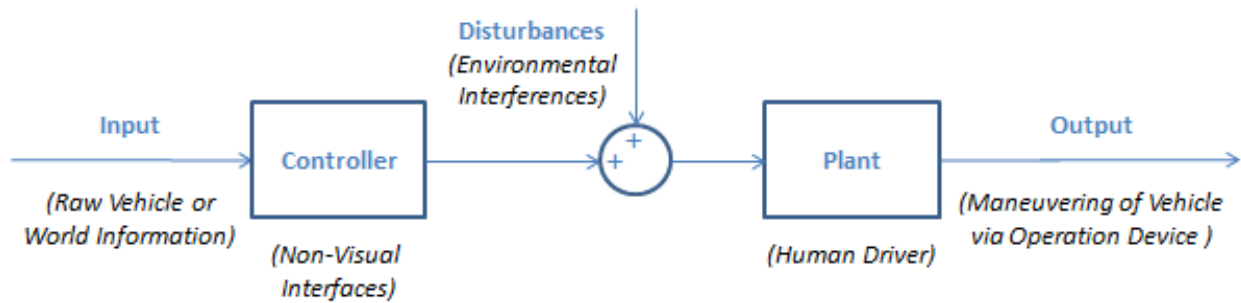


Figure 15. The blind driver system can be modeled as an open-loop control system

The components of the classic model of an open-loop control system include the *input*, the *controller*, *disturbances*, the *plant*, and the *output*. If the blind driver system is to be equated to an open-loop system, these components must be defined. The plant is the most intuitive element with which to begin. The plant is represented by the human driver, whom in this case is constrained by his lack of vision. The plant's purpose in the loop is to create an output, which is represented here by the vehicle operation. This output can take many forms, such as a joystick, a throttle, a steering wheel, or acceleration and brake pedals; as it goes, the output could be represented by multiple elements.

In order to generate this output, the plant receives a signal containing three elements. A constant stream of input is first fed into the controller, which creates a signal to pass to the plant. However, this signal coming from the controller may be altered by one or more disturbances to the system before it is received by the plant. In the blind driver system, the initial input is some sort of raw information about the world or the vehicle. For instance, the inputs might be the steering wheel error as well as the vehicle speed error. The input is not necessarily relevant to the design process, as will be discussed later. The controller is represented by the non-visual interfaces, which receive the information from the input signal and generate a non-visual stimulation that can be transmitted to the human driver (the plant). This controller can be any physical haptic device such as a Braille display or vibrating vest. Finally, before the signals (or non-visual stimulation in this case) created by the NVI are passed on to the human driver, they may be distorted by a disturbance signal. This could be any environmental interference such as the vibration of the blind driver vehicle platform muffling the vibration signals produced by the NVI's.

The main design choices to be made in this model are the non-visual interfaces (the controller) and the operation device (the output of the system). The remaining components of the system will place certain constraints on these designs. Thus, it will be important to first consider how complex a role the human driver will play in the loop.

#### 4.1.2 Extent of Human Involvement in the Operation of Blind Driver Vehicle

The information that will be passed to and from the blind driver can vary in form and in quantity. The true design challenge is maximizing this quantity of information that a human can handle as input while effectively controlling an output. In the specific case of the Blind Driver Challenge®, a higher quantity of information flow is desired, as this allows the driver greater independence in the driving experience. It follows that this inclination has a direct impact on the *form* or *mode* of the information that is communicated to the driver; this matter is discussed in detail in Section 4.1.3.

A generalized blind driver vehicle model may be assumed, wherein the vehicle senses the environment and subsequently passes some amount of information to driver, who in turn operates the vehicle. The basic principles of robotics can be boiled down to the model of: *sense, plan, and act*. In the blind driver scenario, the *sensing* phase is to be completed by the vehicle; the precise methods for doing so are beyond the scope of this thesis, but some form of world model resulting from the sensing phase may be assumed.

The opportunity for progress comes in during the *acting* and *planning* phases. Here, some portion of planning is to be executed by the vehicle's computer, and some portion by the human. The goal is to enhance the portion of the planning that is executed by the human, which would bring about a higher degree of driver independence. For the acting phase, it is assumed that the human driver completes most, if not 100%, of the operation of the vehicle; however, the means by which this is accomplished is unlimited.

While considering the possible range of the amount of planning that is executed by the human, consider first the base case, wherein all planning is done by the computer. As discussed previously, it is a possibility to simply place a blind passenger in a fully autonomous vehicle, such as Odin, where, in addition to the planning, the acting phase is actually executed by the computer as well. This represents the lowest end of the spectrum of human involvement in the blind driving process, and once again, this type of model is strictly not what the NFB is aiming to achieve.

On the opposite end of this spectrum would be some ideal device that allows a blind driver to have complete sense of vision, as a sighted person would have. In this hypothetical setting, the vehicle would sense the environment and then provide visual feedback to the driver, including navigation of the driver's field of view without moving the head. The frame rate necessary to sufficiently deliver such an experience is currently unknown, although it has been suggested that 30 frames per second or 60 frames per second may be enough [61]. Here, all planning is accomplished by the human. It is worth noting here that many features on modern street-legal cars include desired computer decision-making, such as cruise control, and therefore the ideal device may not necessarily include 100% human decision. This device represents the positive end of the spectrum of human involvement, and is theoretical, perhaps an unrealistic venture to

consider at this time. Another option at this end of the spectrum would be a hypothetical interface directly to the brain, something that could send simulated electrical signals through the central nervous system similar to a prosthetic body part. Here, if vision signals could be successfully transferred directly through some device to a blind person's brain, the disability of blindness is basically eliminated. An additional function of the device would be necessary to gain active feedback from the driver to determine in what direction they are looking with their eyes.

The non-visual interfaces that have been developed in BDC lie between these two ends of the spectrum. These NVI's combine some amount of computer decision and human decision in order to create an element of independence for the blind driver. For instance, based on the world model produced by the sensing phase, an interface may provide the driver with knowledge of certain components populating the environment, and then allow the human to decide how to maneuver the vehicle based on this information. The interfaces may be categorized by many different measures, but as far as the current work that has been completed, one way to do so is by *instructional interfaces* and *informational interfaces*.

*Instructional interfaces*, such as the DriveGrip interface, minimize the quantity of information communicated to the driver, while allowing the human to still operate the vehicle independently. Here the computer intends to complete the bulk of the planning. In the case of DriveGrip, the computer decides the required trajectory of the vehicle, and commands the desired steering angle in order to accomplish it. There is a small window for the human in the decision-making process – he can choose not to follow the instructions he receives – but the role of the human in the planning process is minimal.

*Informational interfaces*, such as AirPix, attempt to maximize the quantity of information it provides to the driver, requiring the human to make more active decisions and create his own plan for maneuvering the vehicle. These provide more of a raw depiction of the world model, for example, the position of the vehicle in the lane of the road or the locations of upcoming obstacles. The human receives more information from the NVI, and because of this, he can make more independent decisions.



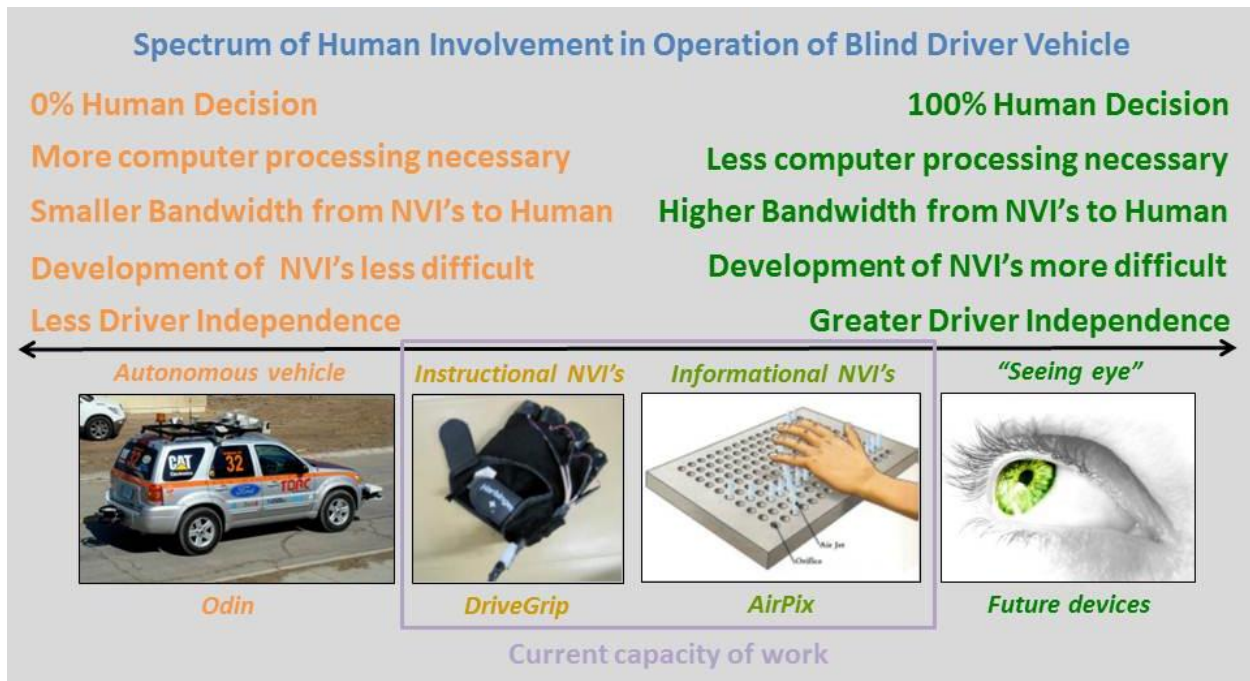


Figure 16. Spectrum of human involvement in operation of blind driver vehicle. TORC Robotics. <http://www.torcrobotics.com/darpa-urban-challenge> (accessed 17 December 2011) Used with permission from TORC Robotics.

Figure 16 outlines the amount human involvement in the types of non-visual interfaces previously discussed. It serves to demonstrate that research in this area must shift away from simple instructional NVI's in order to accomplish the goal of greater blind driver independence. As well, increasing the quantity of information that can be effectively communicated to the driver is essential in the advancement of blind driver research. Thus, while less computer processing is necessary, the difficulty in the development of non-visual interfaces increases; the complexity of the NVI's themselves must increase even though less actual computation is required.

## 4.2 Input to the Human: Non-Visual Interfaces

It is useful to break down the types of desired instructional and informational cues into the simplest conceivable sets of variables. By doing this, it is possible to quantitatively define how much information the driver is to receive from the non-visual interfaces at once. Once the desired information is split into a set of known variables, it becomes easier to develop the physical device that will produce these signals. This involves an examination of all the different human senses and locations on the body, as well as consideration of the signal performance within the particular environment inside the blind driver vehicle.

It is an essential prerequisite to have an understanding of the nature of the available vehicle or world information. For instance, there is a huge difference in capability between receiving

specific processed data about obstacle location and size as opposed to just raw two-dimensional profile information about the environment. If more processed, quantifiable data is available, this enables more options for instructional cues. On the other hand, cruder data may be less quantifiable, making the information more difficult to communicate non-visually and forcing the driver to play a larger role in the decision-making process. Thus, it is not necessarily detrimental to be working with crude data provided to the non-visual interfaces, but it certainly limits what types of non-visual interfaces can be developed, whether they are more instructional or more informational.

It would also be preferable to have a selection for the output device to the vehicle before considering options for the NVI's. There are more limited options for the interface that will be used to operate the vehicle and with a solid idea of what modes of human operation may be dedicated to output, it will be easier to coordinate which modes will function well for receiving input signals at the same time. While the selection process for the output interface is not a major focus of this thesis, it is discussed in some detail in Section 4.3.

After establishing the desired form of the information to be conveyed through the non-visual interfaces, the medium may be considered. This involves an investigation into the different human senses and human anatomy that may be exploited. Along with these, any environmental interference that may influence the effectiveness of the NVI's must be taken into account.

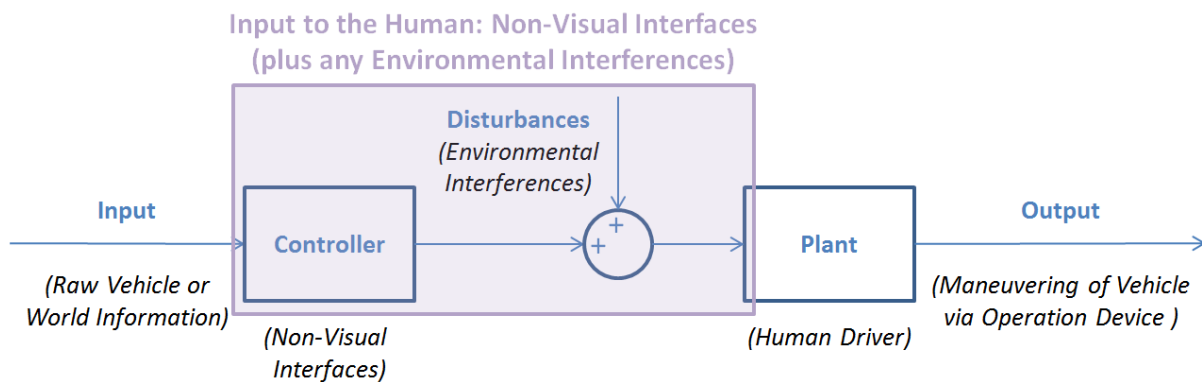


Figure 17. The information passed from the non-visual interfaces to the human driver is discussed in this section

#### 4.2.1 Instructional Cues Produced by the Non-Visual Interfaces

It has been established that more information to the blind driver enables him to make more decisions on his own, therefore yielding a greater sense of independence for the driver. This quantity of information may take on many different forms.

First, the information may be broken down into a set of different variables. For instance, speed cues plus steering wheel orientation cues will complete a set of useable information for the driver. A distinct set could be lane data plus obstacle data. Thus, the most fundamental way to

begin developing a non-visual interface is to consider the different sets of variables that could conceivably be used to communicate a complete model to the blind driver. This would entail providing sufficient information for the driver to make decisions and then knowledgeably operate the vehicle. It is worth noting that as in some cases, such as with the AirPix interface, this may entail simply providing enough relatively raw data that the driver can do the work of making his own decisions.

This set of variables may be communicated in a number of different ways. To represent known measurable quantities such as the steering wheel angle error, varying levels of detail may be used. If, say, the measurable quantity is to range anywhere from -1 to 1, the minimum requirement would be to provide the *direction* of the error. With this simplest of signals, the driver would only be notified to correct to either the left or to the right (Figure 18). Thus, it may be possible to convey steering information with only a single bit of information; this may or may not be sufficient for accurate operation of the vehicle.

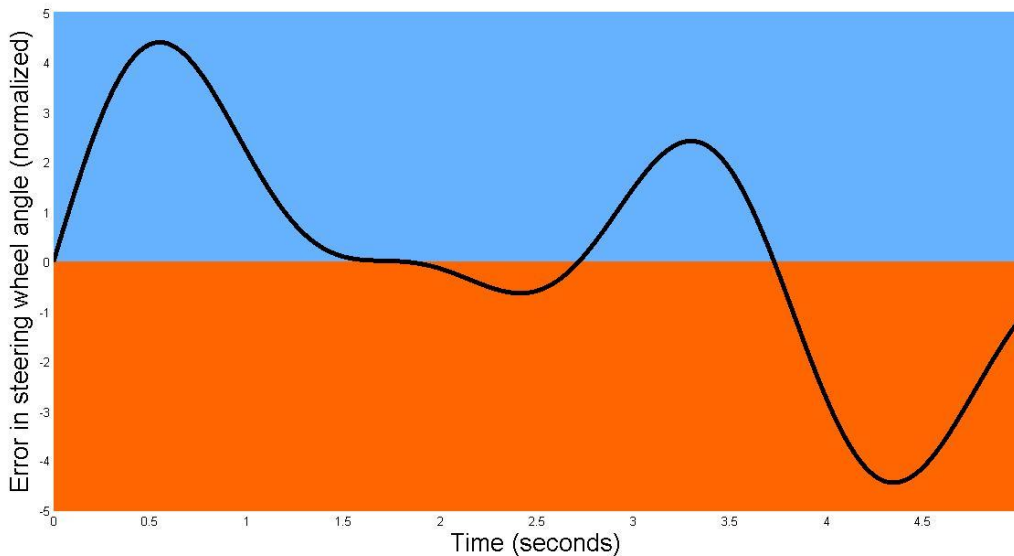
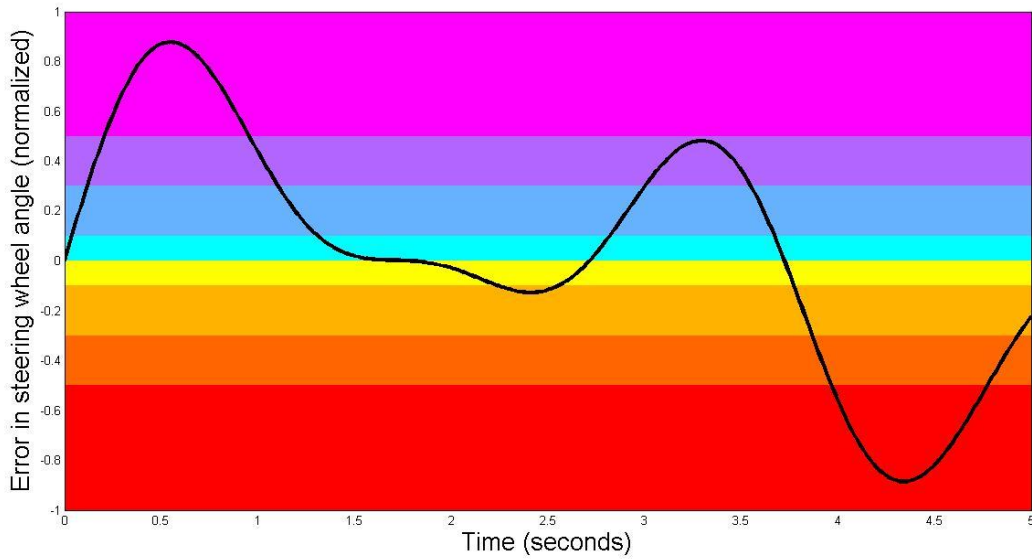


Figure 18. Directional representation of steering wheel angle error sample data

It may be desired to provide the *magnitude* of this error in addition to direction; this will require increased information flow to the user. There are two ways to represent the magnitude value: *binary (digital)* or *analog*. In the *binary* or *digital representation*, the magnitude is converted into a number of levels based on the range in which it falls. For instance, the sample binary representation of the signal in Figure 19 splits the signal into eight discrete quantization levels. Each level in which the magnitude may be contained would correspond to a separate stimulation to the driver by means of the non-visual interfaces. Thus, in this example, the steering information is communicated digitally, using eight bits of information. This strategy may of course be extended or limited to any number of finite bits, keeping in mind that the purpose of

discretizing an analog signal is to filter the packets of information passed to the driver, making them clearer and simpler for the human to process.



**Figure 19.** *Binary (digital) representation of steering wheel angle error sample data*

If it is insufficient to discretize the signal, due to unsatisfactory performance, the nature of the vehicle information received, or otherwise, the next option is to convey the signal using analog display (Figure 20). This becomes less trivial than simply creating eight separate stimulation signals for the user interface; a device that can vary in intensity, frequency, location, or another mode will be necessary. In addition, it may become difficult to distinguish between different values in magnitude; unlike the binary representation, a well-defined reference will need to be established.

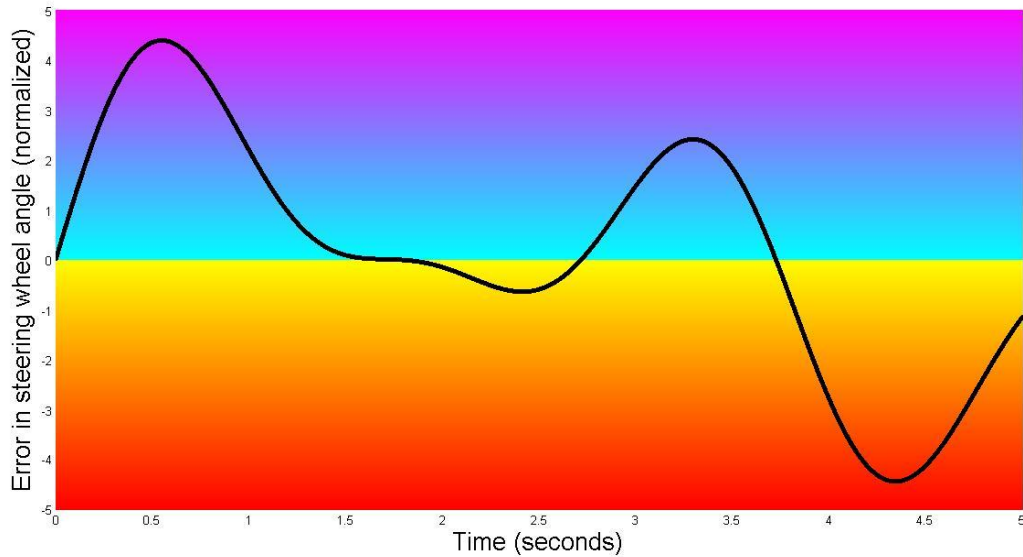


Figure 20. Analog magnitude representation of steering wheel angle error sample data

More complex, *informational* signals to the driver may be discretized as well. For instance, a two-dimensional environment may be divided into a finite number of features of interest, such as obstacles and lane position. With identifiable feature type, shape, size, and location, it is possible to display these features with simple directional or magnitude signals to the driver, as previously outlined. Uchiyama’s Vibrotactile Glove, using a 3-by-3 array of vibrating motors on the back of the hand, is a good example of this method [50]. Here, the location of the nearest impending obstacle is communicated simply by direction, and the stimulation is only induced when that obstacle is within a certain range. This generalizes the overall two-dimensional environment to a two-bit informational input to the human driver.

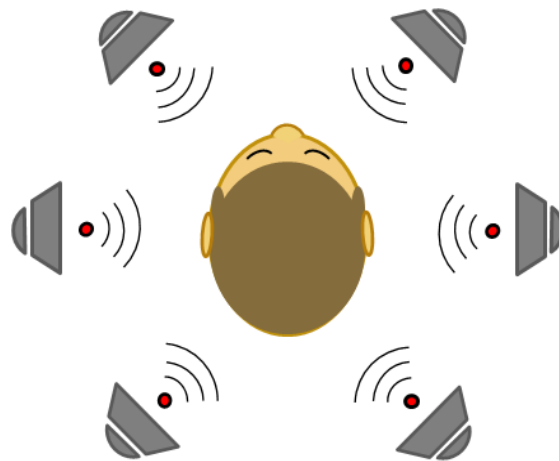
#### 4.2.2 Informational Cues Provided by the Non-Visual Interfaces and Passive vs. Active Interfaces

Rather than simplifying the signals to bits of data as instructions to the blind driver, it may be advantageous to provide an immeasurable set of information to the driver, allowing them to engage more of the overall picture and act in a more functional capacity in the decision-making process. Here, instead of the computer processing the raw data and determining the desired action for the driver to take, the computer reiterates the raw data as efficiently as possible to the driver. The driver then makes the decisions based on received knowledge of the environment surrounding the vehicle. As established previously, this may be preferred because it offers a greater sense of independence for the blind driver.

Cues that are conveyed as more *informational* may be done so using either *active* or *passive* techniques. An active technique would be one in which the user dynamically explores an environment, wherein the user has the ability to choose which features in the environment to

survey more closely at any given time. Thus, active information transfer requires some sort of feedback from the user to the non-visual interface. For example, the AirPix interface provides a two-dimensional representation of the environment with a consistent field of view (see Figure 9). However, since the driver uses his hand to explore this environment, he has the opportunity to pay attention to certain details while ignoring others. If there are particular features on the left side of the field of view, the driver can actively choose to ignore the right side momentarily while he concentrates on processing what is happening on the left side.

*Passive* information transfer to the blind driver would include any signal that is not dependent on feedback from the driver. Here, the driver receives consistent types and quantities of signals without the ability to focus in on a particular feature. For example, a surround-sound audio setup might provide the positions of other motorists to the side and in front of the blind driver vehicle on a highway. Much like a true driving experience, the driver may not be able to dynamically focus on particular features of these signals. Thus, the interface provides a consistent form or information without human feedback, and would be considered a passive informational cue, and would be considered a passive informational cue.



**Figure 21.** A surround-sound setup may be classified as a passive technique if there is no human feedback to alter the signal provided by the user interface

The exemplary active platform concept, which was actually developed in 2010 to 2011, is a touchpad interface, wherein the user dynamically explores the two-dimensional field of view with one or more fingers. The interface detects the areas of explorations by the user, and provides information pertaining to those specific areas. With a setup like this one, several advantages can be exploited. This adds a dimension of freedom to the user experience, allowing minimization of the number of actuators necessary. For instance, with the touchpad, it is conceivable that only five sources of stimulation may be needed in order to correspond to the maximum number of fingers the blind user is using to explore the environment. With this

reduction in computing cost, a greater tactile resolution is now permitted. Thus, adding active feedback from the user to the interface adds more capabilities for the device.



Figure 22. A touchpad interface platform is an example that may be used to provide truly active feedback to the blind driver

Both AirPix and the surround-sound interface could be altered to become either active or passive. AirPix could be limited to passive information transfer if the ability to dynamically explore the field of view is removed. This could be accomplished by positioning the non-visual interface on a stationary sensory location, such as the leg or torso, or even rigidly attaching it to the front or back of the hand. As long as the driver is able to receive the full field of view, the AirPix is currently a passive non-visual interface.

Likewise, the surround-sound interface may be set up to actively deliver information to the driver. By adding in the capability to concentrate on a particular feature, similar to the original AirPix strategy, the driver can dynamically explore the environment. For example, voice commands or a physical toggle switch could be used to choose increase the volume of a passing car on one particular side of the vehicle.

#### **4.2.3 Considerations for the Human and Environment for Communication of Non-Visual Driving Information Flow**

Apart from determining *what* information will be communicated to the blind driver, another crucial step in the development of non-visual interfaces is *how* that information will be communicated. The goal of a non-visual interface is to provide information to the driver by exploiting one or more of the human senses. Here, it is important to consider the receptiveness of the human body to particular stimuli as well as the sensory adaptation tendencies related to particular senses and anatomy. As well, using a particular sense as a medium for information flow may be disruptive to the unrelated routine actions or the overall comfort of the driver. What follows is an approach to investigating the human senses, the applicable parts of the human anatomy, and the effectiveness of utilizing these in the environment and circumstances

associated with a particular blind driver vehicle. Table 3 outlines the most fundamental considerations for information flow through the human senses and anatomy. Some of these pertain specifically to the actual sensation to the human body, while others pertain more to interactions with all the other things that are going on during the blind driving process.

Table 3. Considerations for the human and environment for communication of non-visual driving information flow

<b>Considerations for the human senses and anatomy as media for information flow</b>	<b>Consideration of disturbances and disruptions to the sensory modes</b>
<ul style="list-style-type: none"> <li>• Investigation of all human senses and anatomy</li> <li>• Receptiveness of the human body to stimuli for that part of the anatomy</li> <li>• Sensory adaptation of stimuli</li> </ul>	<ul style="list-style-type: none"> <li>• Comfort of the driver</li> <li>• Coordination with the operation of output interfaces</li> <li>• Unrelated routine driver actions</li> <li>• Interferences in the vehicle environment</li> </ul>

Aside from vision, human capabilities include tactition, audition and sound localization, gustation, olfaction, and equilibrium. While the sense of taste and sense of smell seem far less practical than the others, it is good exercise to consider these as well. *Sensory adaptation* is extremely important to keep in mind; gustation and olfaction both undergo quite speedy sensory adaptation, which means that any stimulation that utilizes these senses will be perceived with far less intensity after a fairly minimal amount of use. As well, these two senses are restricted to the face, particularly the nose and mouth, which inhibits the driver’s routine actions such as breathing, speaking, and even detection of mechanical car problems through smell. Thus, gustation and olfaction are not ideal media through which information may flow to the driver.

It should be noted that despite while there are downsides to utilizing gustation and olfaction, there are potential advantages to be gained as well. Gustation consists of four separate sensations all on different regions of the tongue: sweet on the tip of tongue, sour on the lateral tongue, salt on the perimeter of tongue, and bitter on the posterior tongue. That so many distinct stimuli may be sensed in clearly discrete but proximate regions could potentially be a great advantage. In addition, consider that taste and smell use chemoreceptors to detect stimuli. It is conceivable that a small non-disruptive device could be coordinated to interface directly to the receptors to provide signal to the driver.

The sense of equilibrium, or proprioception, includes two functions. *Static* equilibrium is used to sense the position of the head and maintain posture while motionless, and *dynamic* equilibrium to prevent loss of balance during rapid head or body movement. In these cases, the body detects acceleration using the head as a reference point; thus, as in a normal driving setting, the driver is actively using his sense of equilibrium to gain feedback on his maneuvering of the vehicle. It is valuable to leave this capability undeterred. In addition, any non-visual interface signal that may introduce movement of the driver’s head or entire body will severely interrupt his ability to operate the vehicle.



The sense of proprioception may be helpful if isolated to a particular area of the body. Haptic devices such as the Sensable PHANTOM-OMNI® make use of force feedback on the user's hand, so that the user may "touch and manipulate" virtual objects and environments [62]. Here, a blind driver could employ his sense of equilibrium to explore edges of obstacles, lanes, or other features in a three-dimensional or two-dimensional virtual environment.

The most valuable human senses to utilize for non-visual communication are the sense of audition and the sense of tactition. Many of the tools that blind persons use on a daily basis incorporate one or both of these, such as Braille for reading and phones and other electronic devices that read abbreviated version of text. These two senses can certainly be utilized concurrently for non-visual interface cues; however, since blind people constantly rely on audition and tactition for other routine actions, including those while driving, it will be important to leave some modes of sensation as open as possible. The next two sections focus on the considerations for information flow using these two classifications of sensation

#### **4.2.4 Considerations for Audition as a Medium**

Drivers use the sense of sound to accomplish many things simultaneous with driving, and this applies to blind drivers just the same. For this reason, usage of the auditory sensory mode may be considered disruptive. From the outside environment, it is important to be audibly aware of emergency sirens, crosswalk signals, and other motorists. Aboard the vehicle, it is ideal to have the ability to converse with passengers, listen to the radio, and pay attention to notifications from the vehicle, such as maintenance warnings or mechanical issues that are not automatically undetected by the vehicle. In addition to these activities, blind people are heavily reliant on voice readers for checking messages on the mobile devices. It is conceivable to devise a way for the driver to toggle audio cues on and off when they become unnecessary, like at a stoplight or once the car is parked, so that he may tend to other audition tasks undeterred. However, for most of these tasks, competing with the constant transmission of audio driving cues from non-visual interfaces would be inconvenient.

Not only can audio cues disrupt other necessary activities during the driving experience, but the vehicle and outside environment can interfere with the effectiveness of the NVI's cues as well. Outside noise, including traffic signals, emergency sirens, other motorists, and weather such as heavy rain or winds may obstruct the cues. Aboard the vehicle there may exist interferences including the passengers as well as the engine, temperature control, and other normal vehicle operations. Thus, conflicts go both ways: the NVI's would be surely disrupted by the environment, and the driver's responsibilities aside from driving would be hindered by the NVI's. It is also worth considering that the usage of an audio interface would not be limited by any choice for an output interface to the vehicle.

For completeness, it is necessary to investigate if different audio communication methods used can be modified to compromise these conflicts. The sense of sound is confined to a small area of

the human body, much the same as gustation or olfaction. Thus, the design goal is to try to permit some sounds to reach the receptors in the ears, while disallowing others. There is not a well-defined boundary between what is acceptable and unacceptable to block out from environment, since some external sounds are necessary for the driver to receive, but those same sounds may be disruptive to the NVI's instructions at the same time. For example, providing all driving commands through a pair of headphones would be advantageous for avoiding environmental interference. However, pertinent external actions such as conversation and recognition of activity outside the vehicle are then hindered; plus, wearing headphones while driving a vehicle on public roads is illegal. On the other hand, a non-visual interface that is not as invasive, such as a surround-sound speaker system built into the vehicle, allows the driver to still admit the necessary outside sounds, but some of these are now permitted to interfere with the cues from the speaker system.

The other factor that goes along with the invasiveness of a non-visual interface is the comfort of the driver while using the blind driver vehicle. A requirement such as wearing a set of headphones may cause distraction to driver if they have to constantly deal with discomfort of the interface. It may also be frustrating for the user to settle into any interfaces that take an extended effort to attach to their body upon entering the driver's seat

Since there are so many different modes of audition that are necessary during the driving experience, it is improbable that any compromise between direct sensation (headphones) and indirect sensation (surround-sound system) would be ideal. However, it may be possible to find a workable mode that filters out some unwanted noise and permits some desired environmental sounds and the NVI cues: by virtue of the "cocktail effect", humans are able to recognize critical frequency bands in the environment, distinguishing between a sound source and noise. So, even with an imperfect NVI setup, the driver can overcome the interference issues to some degree by selective hearing.

There are significant advantages to using audio to communicate information to the human driver. Unlike many of the other senses, audition does not experience sensory adaptation, so audio cues do not decrease in effectiveness over time. Due to level differences between the two ears, humans can localize sounds very well in three dimensions, within 1° error ahead or behind them or within 15° to the left or right. This may give the NVI's the ability to provide analog cues to the driver, as discussed previously.

Advantages may also be gained from the abundance of different sounds that can be created. Frequency (pitch) and amplitude (loudness) can be varied for any given tone. Tones may be played on and off at a particular oscillation rate which may be varied. Tones may be combined in any number of ways involving various frequencies, amplitudes, or oscillation rates to create unique sound cues for the driver. As well, easily recognizable sounds such as a car horn or a human voice cue can be used to get an instinctive response from the driver. Thus, audition can be a quite versatile stimulation to activate in a non-visual interface.

A more applicable role for audio signals may be in the form of on-command cues for the driver. Here, the driver would have a finite list of information about the vehicle or the environment that he may query at any given time, perhaps using a separate controller from the vehicle's output devices, such as a handheld series of buttons or even the driver's own voice. The driver can receive immediate audio feedback through a speaker system. As well, since the driver has control over querying the NVI's in this case, he can choose to receive the cues at appropriate times, when there will be less chance of coincidence with other actions. The possible queries that the driver might desire include dynamic vehicle information such as speed, steering wheel angle, location, or compass orientation; vehicle diagnostics such as gas level, oil level, or amount of air in the tires; or other dashboard information such as radio statistics or information regarding the sensor systems on board. Supplemental driving cues may be practical as well, such as the ability to query the vehicle's lateral position in the lane while using other interfaces as the primary means of information flow. Thus, while it may be difficult to take advantage of the helpfulness of audio signals effectively on a constant input basis, querying for them as on-command cues may be a more useable option.

#### **4.2.5 Considerations for Tactition as a Medium**

Tactition is the most applicable sense of all due its versatility. The exteroceptive somatic receptors are located on almost the entire surface of human body, although some locations are more receptive than others. These somatic receptors detect several different stimulations, including touch, pressure, temperature, and pain.

The nociceptors are those that sense pain and actually exist throughout the body as well as the surface. There are two categories of pain. Chronic pain is a more long-term, throbbing type of sensation that is felt even after the stimulus. This time of sensation is difficult to control, so it is impractical to apply using a non-visual interface. On the other hand, acute pain occurs rapidly, within 0.1 sec, and is a sharp, fast pain that does not subsist after stimulation is ended. Acute pain is sensed predominantly on the external parts of the human body, and many types of acute pain sensations, such as those similar to a needle prick or electric shock, do not undergo any sensory adaptation. While there are clearly some advantages to utilizing pain as a stimulus in non-visual interfaces, it must seriously be weighed against the amounts of discomfort and lasting damage to the human body which may accompany it.

For temperature detection, each individual person has two separate temperature ranges that trigger distinct heat and cold receptors, which could provide very applicable to sense binary cues from an NVI. However, these sensations undergo rapid sensory adaptation, so they become ineffective after a short amount of time. As well, outside the extremities of the short ranges – above the 10°C (50°F) to 20°C (68°F) warm range and below to 25°C (77°F) to 45°C (113°F) cold range – the pain receptors are triggered. With small limits in which to work to avoid pain sensations, and slow sensory response to changes in temperature, the only application of temperature stimulation may be the usage of up to two quick binary cues: warm and cold.

In consideration of environmental interference with temperature cues, there are a few other stimulations with which it may be confused. The temperature control inside the vehicle may have vents nearby the driver's body, and desensitize the driver to the manufactured NVI temperature cues. Other noise such as wind coming through the window may desensitize as well. To the positive end, temperature, like all somatic senses, can be detected on almost the entire human body. Thus, even if restricted to two simple binary cues, temperature stimulation might be useful as a supplement to additional primary interfaces due to the flexible location of its applicability.

The sense of touch includes all sensations relating to light touch, pressure, vibration, and indentation. Light touch and pressure are similar in concept but differ in a few ways. Light touch is the most sensitive of all of these, detected using mechanoreceptors that are prevalent in the hairless portions of the skin, such as the lips, fingertips, palms, soles, nipples, and external genitalia. Thus, these body parts are excellent for feeling the texture on solid objects such as Braille or a touchpad. Higher amounts of pressure and indentation are received well in the next most sensitive tier of anatomical parts including the tissues just a bit deeper in the skin of the hands, feet, breasts, and other genitalia. This is because the stretch receptors are stimulated in greater magnitude, although not so much that the pain receptors become excited. The illustration of the Sensory Homunculus (Figure 1) again illustrates the relative sensitivity of these particular body parts. With the stimulations that involve indentation and pressure, excellent responsiveness is also observed, with lesser sensory adaptations complementing greater indentations. Stimulations that may match up well in these areas may include those produced by blood pressure cuffs or moveable pieces that are larger than the standard Braille dots. For all of these that include indentation, discomfort and fatigue are issues that must be considered.

Vibration is a sensation that involves no indentation of the skin, and is therefore susceptible to more rapid sensory adaptation. However, since it is unobtrusive on the skin, there exists a trade-off in the form of less discomfort to the user than some of the previous touch sensations. While sensory adaptation is observed more rapidly with vibration, there exists a high degree of initial responsiveness from the sensory receptors.

Similar to audition, variables such as frequency and amplitude on touch stimulation can increase the amount of different signals that can be communicated. These concepts apply well directly to vibration, where the frequency and intensity can be altered easily and rapidly with different amperages and voltages to vibration motors. The oscillation rate of sharp indentations can be varied in addition to frequency and amplitude. Different arrangements on these modes can create patterns that are natural cues to the driver. For instance, high intensity on/off vibrations could be used to indicate a dangerous obstacle is in close proximity.

Table 4. A comparison of stimulus variables between the touch senses and audition

Stimulus variable	Touch senses	Audition
Frequency	Change in vibration frequency	Change in pitch of sound
Amplitude	Intensity of vibration	Volume level of sound
Oscillation rate	On/off stepping patterns of applied pressure, indentation, or vibration	On/off stepping patterns of tones
Patterns	Combination of above three	Combination of above three
Location	Stimuli located over entire body; sensory receptors in direct contact with stimuli at the site of sensation	Stimuli located throughout environment; sensory receptors in one location at the ears
Recognition	Simple shapes and primitives	Human voice, car horn, etc.
Environmental interference	Vibration of vehicle, reading Braille messages, vehicle ventilation	Outside environment, vehicle noise, conversation, radio; mostly unavoidable due to indirect sensation
Interference with output interface(s)	Hands, arms, and feet are common modes of operation, thus limiting touch options for input to human	Ears are not characteristically used as a mode of operation, so no limitations for audio inputs to human

Also similar to audition, the touch sensation can take advantage of changes in location of signals. However, in this case there is a difference in location of the actual sensory receptors being stimulated, rather than that the same receptors simply perceive the signals to be in a different location. This attribute is especially valuable in the usage of binary signals, wherein sensory receptors are very responsive to stimulation of separate body parts using touch.

Representing simple shapes and primitives that are easily recognizable by the user is also a strategy that can be employed using the sense of touch. Once again, this matches an advantage familiar in the audition mode of sensation, as this is similar to the recognition of human vocal cues and other known sound signals. Shape recognition would be most applicable in an informational type of interface, where the driver is less expectant up front about the possible options for NVI output. Knowledge of a pre-defined subset of quickly recognizable forms will help to reduce the uncertainty in an otherwise unknown environment.

With all these possibilities for various signals and locations of sensation, environmental interferences must be considered. It is fundamentally much easier to work around environmental interferences with the touch senses due to the fact that the locations of the sensory receptors are more widespread than those of the auditory senses. With receptors located over nearly the entire outside of the human body, localized disturbances may be avoided. However, consider that environmental interferences may be extremely detrimental to specific types of touch stimulations. For example, if the vehicle induces enough constant vibration felt through part of the vehicle, there is a low possibility that using vibrations for NVI signals will be successful.

However, just as with the auditory sense, it is important not to have an interface that is disruptive to other routine activities while driving. The driver typically needs access to his hands with

ample range of motion to not only maneuver the steering wheel, but also the seatbelt, window, center console, and dashboard buttons. Blind people in particular also are accustomed the using the fingertips for processing data due to their familiarity with reading Braille. The driver needs full range of motion to move his right foot between the gas and brake pedals. Lastly, while a sighted driver typically needs a significant range of motion for his neck and head to check for cars to the left, right and rear of the vehicle, a blind driver would not necessarily need this luxury. This is not to imply that the ability to move his neck is not important to the driver.

Comfort may also be reconciled with many types of touch interfaces, especially when considering usage of parts on the entire human anatomy for reception of the driving signals. Generally, an NVI that distracts the driver from putting full focus on the driving cues is not desired. Full range of motion to complete all normal driving tasks should not be restricted by cables, rigidity of the NVI's or otherwise. This presents a challenge in the development of NVI's which may try to take advantage of touch sensation at odd locations of the human anatomy.

### 4.3 Output from the Human: Operation of Vehicle

The remaining phase in the open-loop model of the blind driver process is the final output from the driver. After receiving the driving signals from the non-visual interfaces, the human driver must do some planning and complete the operation of the vehicle accordingly. There are different devices that may be in place to accomplish this. While the output device is not a main focus of this document, it is relevant to the development of the non-visual interfaces.

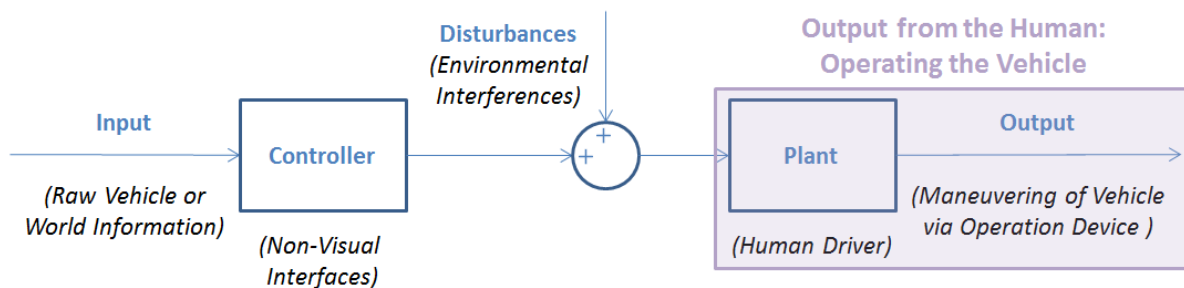


Figure 23. The information passed from the human driver to the vehicle is discussed in this section

As discussed previously, it is ideal to select on an output device prior to development of the NVI's. This is because there are not as many available options for the output device. As well, in many cases the amount of attention needed to operate the vehicle may limit the modes of information flow from the non-visual interfaces. For example, operation of the vehicle using a steering wheel restricts the capacity of using the hands as a mode for NVI signals. Thus, the

selection of the output interface can play a significant role in the development of the NVI's for blind driving.

The output device certainly will be actively operated, even though this may not necessarily be the case with the non-visual interfaces. This means that some amount of attention to the output interface is necessary at all times. However, in many situations there are times when less attention is necessary; for instance, a normal sighted driver does not necessarily always need both hands on the steering wheel or on the clutch for a manual car. Having access to one free hand 90% of the time will certainly help in the development of the non-visual interfaces. Thus, it is beneficial to recognize that the number of modes available for NVI usage may vary during the driving process.

The somatic senses are the sense almost exclusively utilized in the operation of the vehicle, so the emphasis falls on the considerations for development of the non-visual interfaces relating to the touch sense. As discussed previously, operation of the output devices in the vehicle will not limit the ability to utilize audition for the NVI's.

Since the positions of the hands and feet in the vehicle are common restrictions placed by the output interfaces, it can be convenient to plan the input interfaces accordingly. It is an option to design a touch-based NVI such that the stimulations can be produced for separate parts of the anatomy than are used for vehicle operation. For example, dedicating the torso or head areas for NVI's could keep the inputs separate from the outputs, thus avoiding the issue of the potentially moving hands and feet.

The other possibility is to design the NVI's so that the locations of the stimulations can interplay with the output devices. This involves some flexibility in the hands and feet if they are constantly in motion in order to operate the vehicle. One advantage of overloading one or two areas of the body with the burden of handling both input and output signals is to improve the intuitiveness of the process; passively receiving signals to one specific area and then translating that to an action in that same area can be easy to process naturally for the driver. Any way the driver can naturally associate a driving action, such as steering, with a specific area of the body increases the effectiveness of the non-visual interface. Thus, selection of the output interfaces prior to the development of the NVI's is crucial to the coordination of the locations of the NVI stimulations with the active body parts related to the output interfaces.

The driver will have to control a small set of variables within the dynamics of the vehicle, typically its speed plus either rotational velocity or steering angle. Common output devices include: the steering wheel plus gas and brake pedals, as are used in all street-legal vehicles; a single joystick or pair of joysticks, common for treaded military vehicles; and the throttle, as used for all dynamics in aircraft. All of these devices simplify the driving duties to just a couple variables to make operation as intuitive as possible for the driver. This is the same reasoning for

breaking down instructional cues to binary representations is a good strategy for the non-visual interfaces.

Motivation of the design problem is also a point to consider for the output interface for a blind driver vehicle. If the ultimate goal is to create a vehicle that will be street-legal, the traditional setup of the steering wheel and gas and brake pedals should be strongly considered. Aside from this, the primary focus of the driver's efforts should be with the non-visual interfaces. Any output device that requires complicated operation will take away from the amount of information that a non-visual interface could potentially convey to the driver.



## Chapter 5: Development of Non-Visual Interfaces for the Blind Driver Challenge® (2010-2011)

The 2010 to 2011 Blind Driver Challenge® team developed and finalized a set of *instructional* interfaces called DriveGrip (DG) and SpeedStrip (SS), and continued work on *informational* driving cues through a new device called the Kinesthetic Tactile Display (KTD) [63]. This chapter focuses on how these interfaces measure up with the set of considerations for the development of non-visual interfaces proposed in Chapter 4. The hardware selection processes as well as the completed testing and analysis for these interfaces are also examined.

### 5.1 Motivation and the TORC ByWire XGV™ Vehicle Platform

The principal motivation of this year's team was to complete a fully functional blind driver system on a street-legal vehicle. The new platform for this vehicle is the TORC ByWire XGV™, for which the DriveGrip and SpeedStrip interfaces were developed. This vehicle creates a world model of the environment surrounded a prescribed course using an inertial navigation system, laser scanner sensors for obstacle detection, and cameras for active road detection. On-board computation yields various forms of information that are available to pass along to the blind driver using the non-visual interfaces [54].



Figure 24. TORC ByWire XGV™, the vehicle platform for the Blind Driver Challenge®. TORC Robotics. <http://www.torcrobotics.com/products/bywirexgv> (accessed 2 January 2012) Used with permission from TORC Robotics.

While the team finished work on DG and SS and integration into the blind driver vehicle, they separately developed the Kinesthetic Tactile Display as a more informational interface. The KTD is a means of exploring a two-dimensional environment similar to the setup for AirPix, but

this one uses a touchpad instead of pixelated airflow. The KTD is currently still being tested for feasibility in a standalone, non-driving setup.

As discussed previously, it is an important first step to be conscious of the types of vehicle or world information that are available for the vehicle prior to consideration of the interfaces. Since the variation of the ByWire XGV™ platform used in the Blind Driver Challenge® is based on an autonomous vehicle platform, the entire process of sensing the environment and path-planning is computed on board. Thus, the entire spectrum of information is available, from raw sensor data all the way to the commands that set the outputs of the steering wheel, gas pedal, and brake pedal.

In the cases of DriveGrip, SpeedStrip, and the Kinesthetic Tactile Display, some of the intermediary types of information are utilized. On board the ByWire XGV™, a world model is constructed from the raw sensor data. The KTD uses the information from this world model: the locations of static and dynamic obstacles, and the position of a lane relative to the vehicle. It is evident that the KTD is a very *informational* interface, as just a small amount of decision-making has been done by the computer at this point.

From this information, an ideal vehicle trajectory through the lane is calculated. This consists of the next ten desired vehicle locations and orientations in 0.1-second intervals. From these intervals, steering angle and velocity goals are proposed. These goals are the data that are passed to the human through the DriveGrip and SpeedStrip interfaces. This is the point in the ByWire XGV™ process immediately before converting to actual steering wheel, gas pedal, and brake pedal commands, so this certainly makes DG and SS more *instructional* interfaces.

The 2010-2011 Blind Driver team was tasked with providing a complete set of non-visual interfaces that would be useable for a January 29, 2011 demonstration at Daytona International Speedway. This involved the design of the interfaces, integration with the new blind driver vehicle platform, and adequate testing. Although this did limit the scope of the team's research for this year, the efforts were successful. A blind member of the NFB team demonstrated this final platform by driving a 1.5-mile course at Daytona International Speedway using the new DriveGrip and SpeedStrip interfaces.

## **5.2 Development of Instructional Non-Visual Interfaces: DriveGrip and SpeedStrip**

The DriveGrip and SpeedStrip interfaces are similar in concept to the instructional interfaces previously designed by Blind Driver teams at Virginia Tech. Since the team has seen the design process of DriveGrip and SpeedStrip through to finished products useable in a blind driver vehicle, this section is an excellent case study to demonstrate the considerations for the

development of NVI's (outlined in Chapter 4). This includes concept generation, hardware selection, and testing.

The team chose to go with the most basic instructional interfaces for the DriveGrip and SpeedStrip in order to meet the January 2011 deadline for demonstration of the full blind driver vehicle. The amount of information communicated to the driver is minimal, with the majority of the decision-making made by the computer. This involves two eight-bit cues, one for steering wheel information and one for speed information. Together, these two cues, DriveGrip and SpeedStrip, create a complete set of informational non-visual interfaces for blind driving.

### 5.2.1 Concept of DriveGrip

The DriveGrip interface consists of a pair of gloves that has four small vibration motors on each hand, one on the base segment of each forefinger. While using the DG for blind driving, at any given time exactly one of these eight motors will be actuated. This communicates the direction and magnitude of the error in steering wheel angle compared to what is desired by the computer. For direction, the driver is to correct the steering wheel angle *toward* the direction of the vibration. Thus, a cue detected on the right hand is instructing the driver to steer more to the right than the current angle. For magnitude, the driver is to correct the angle a greater amount the further down the hand he feels the sensation. Thus, a cue detected on the pinky, as opposed to the index finger, is instructing the driver to correct the angle a greater amount. The overall idea, as the cues move across the driver's hands, is to try to balance the vibration between the two index fingers, wherein the error in steering wheel angle is minimized.



Figure 25. The DriveGrip interface is a pair of gloves with a vibration motor positioned on the base segment of each forefinger

The error in steering wheel angle is determined by comparing the current steering angle to the optimum trajectory to follow in order to complete a route, as calculated by the computer. The size of this error is discretized to one of eight quantization levels, including four levels to

command a correction to the left, and four levels to command a correction to the right. Much like in the binary representation of data illustrated in Figure 19, exactly one of the eight quantization levels will be actuated at a time, based on the one that corresponds to the steering wheel angle error.

$$\Delta\theta = \text{Current Steering Angle} - \text{Desired Steering Angle} \quad (5.1)$$

The value of  $\Delta\theta$  is discretized to one of eight quantization levels, each complementing one of the four forefingers on either hand. For instance,  $\Delta\theta = -5^\circ$  yields a stimulation to the index finger on the right hand. To the driver, this is instructing a small correction of the steering wheel to the right, or clockwise. The span of each of the eight ranges is illustrated in Figure 26. These values were determined experimentally; this is outlined in Section 5.1.4.

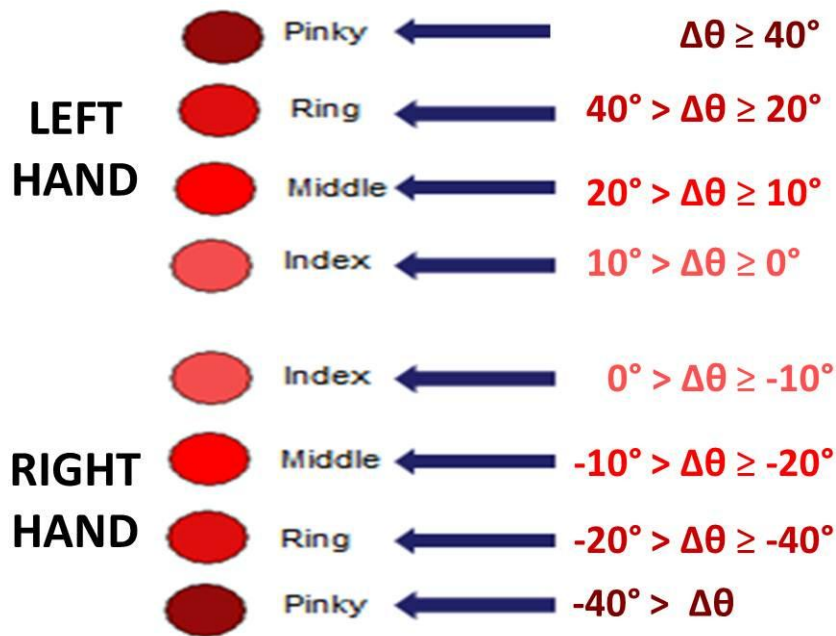


Figure 26. Breakdown of DriveGrip interface

The DriveGrip interface consists of two weightlifting gloves with one-centimeter diameter disc-shaped “lily pad” vibration motors located just above the base knuckle of each forefinger. The weightlifting gloves allow for flexibility in the hands and keep the fingertips open an additional sensory mode for activities unrelated to the DriveGrip interface. The lily pad motors’ flat shape and small size limit the bulkiness on the user’s hands. Currently, the DriveGrip gloves are attached to a headrest mount behind the driver’s shoulders using ethernet cables. With the slack in the cables hanging below the arms of the driver, this reduces the hassle for the driver while using DriveGrip.



*Figure 27. The headrest mount behind the driver's shoulders connects the DriveGrip's ethernet cables and allows the SpeedStrip interface to strap in rigidly to the seat*

### **5.2.2 Concept of SpeedStrip**

SpeedStrip is similar in concept to the DriveGrip interface. SS again uses two groupings of four vibration cues to convey vehicle speed information to the driver. Each of these stimulations is actually a pair of vibration motors inside a seat cushion, with four pairs of motors lined down the thighs of the seat and four up the back of the seat. These are used to communicate the direction and magnitude of the error in vehicle speed compared to what is desired by the computer. For direction, vibrations on the thighs of the seat instruct the driver to accelerate from the current speed, while vibrations on the back of the seat instruct the driver to decelerate. For magnitude, the driver is to correct a greater amount the further from the tailbone he feels the sensation. Thus, a cue detected on the lower thigh (near the knee), as opposed to the upper thigh, is instructing the driver to accelerate a greater amount. Likewise, a cue detected on the upper back, as opposed to the lower back, is instructing the driver to decelerate a greater amount. The overall idea, as the cues move up and down the back of the driver's body, is to try to balance the vibration right around the tailbone, wherein the error in steering wheel angle is minimized.



**Figure 28.** *The SpeedStrip interface is a seat cushion with vibration motors positioned up the back and down the thighs*

The error in vehicle speed is determined by comparing the current speed to the optimum trajectory to follow in order to complete a route, as calculated by the computer. The size of this error is discretized to one of eight quantization levels, including four levels to command amounts of acceleration, and four levels to command amounts of deceleration. One of the eight quantization levels will be actuated at a time, based on the one that corresponds to the steering wheel angle error.

$$\Delta v = \textit{Current Speed} - \textit{Desired Speed} \quad (5.2)$$

There is a slight difference in discretization strategy for the SpeedStrip compared to DriveGrip. For SpeedStrip, the value of  $\Delta v$  is technically discretized to one of *nine* quantization levels: four for positive values, four for negative values, and one for error close to zero. For an error of less than 0.5m/s, there is a deadband where the value of the error is simply rounded to zero, thus yielding no vibration cue. Outside of this deadband, the quantization levels function similar to those in DriveGrip; for instance,  $\Delta v = -3.0\text{m/s}$  yields a stimulation to lower thigh of the driver, instructing a significant acceleration of the vehicle is necessary. The span of each of the eight ranges is illustrated in Figure 29. These values, as well as the capability to include a deadband, were determined experimentally; this is outlined in Section 5.1.4.

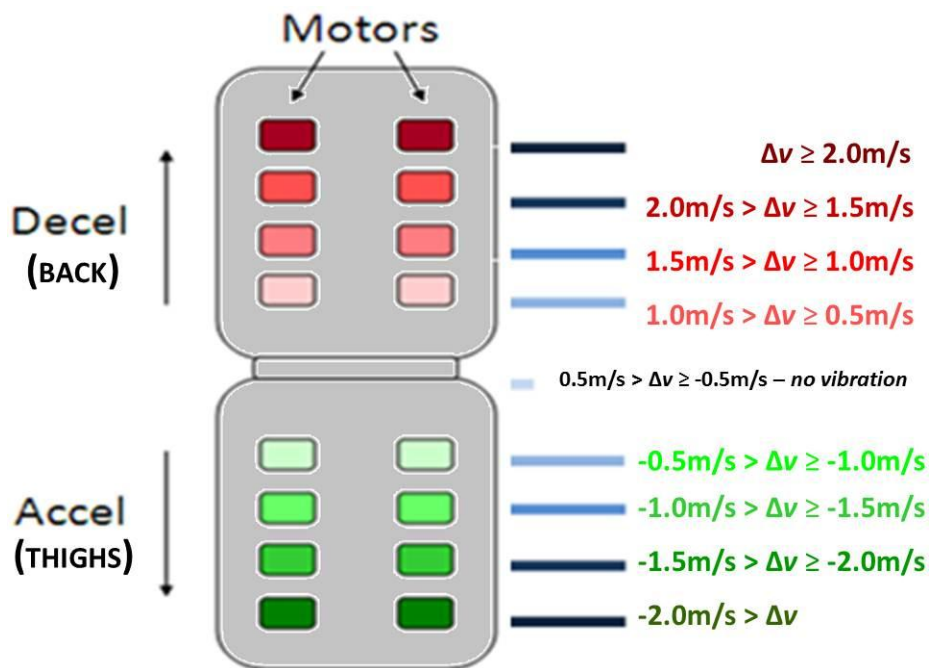


Figure 29. Breakdown of SpeedStrip interface

The SpeedStrip interface consists of a pair of store-bought vibrating seat cushions from which the vibration motors have been extracted and then rearranged inside the cushions as eight pairs, four in the back and four in thighs. More intense sensations are necessary for the back and thighs of the human body than the fingers. Thus, the motors are much invasive, each mounted inside 2”x2” plastic pods. These positioned in the fabric of the cushion, which simply rests on the original seat of the blind driver vehicle. The cushion is secured to the same headrest mount as the DriveGrip’s ethernet cables, utilizing Velcro straps at the top of the back of the cushion to rigidly attach to the seat.

### 5.2.3 Considerations for the Development of DriveGrip and SpeedStrip

The process of developing these two interfaces reflects the approach outlined in Chapter 4. With the goal of achieving blind driver independence, purely instructional interfaces were acceptable at this time, even if the amount of decision-making completed by the human driver is small. Early concept generation was completed with all possibilities of human senses and anatomy in mind, although the team’s prior experience with non-visual interfaces helped to move through the process relatively quickly. A great deal of the design process involved weighing the receptiveness of different body parts to different stimuli with how disruptive to the driving experience it would be to actually apply it.

There was little opportunity to engage some of the more atypical human senses. For example, while an interface that taps into the gustatory or olfactory sense is conceivable, it would require a vast amount of research on the biological and biochemical scale. Similarly, a device that taps

directly into the electrical signals transmitted through the human driver's central nervous system could have some potential, but not under these circumstances.

After factoring in all the advantages for leaving the auditory channel open, audio devices were rejected for this set of interfaces. One of the objectives of the project is to make this similar to a true street-legal experience, and audition is necessary to detect cues in the outside environment. Since this is a research platform, taking away some of the ability to hear and communicate with the team during the many testing phases could become cumbersome. As well, constant sound cues could become irritating for the driver and for passengers, even aside from interference with the necessary tasks unrelated to driving.

Many additional options were considered for application of the audition sense in supplementary roles in the future. If other senses were employed for the primary interfaces, audition could be used to receive on-command communications such as traffic information and vehicle diagnostics. The team determined that this would be a more practical use of the auditory channel, since the driver can prompt for cues at his discretion, perhaps using voice commands or by toggling through menus using the buttons on the steering wheel. These ideas would certainly be for consideration further down the road as features to enhance the driving experience once the main interfaces are perfected

Thus, the team decided to relegate their options to the somatic senses. Here, there are many points for consideration. There are many different forms of stimulation that could be involved with different parts of the human anatomy. Different locations on the human anatomy vary in receptiveness and partiality to sensory adaptation. How well the stimulation would integrate into the overall driving setup must be considered: interference with the environment and unrelated human actions, the comfort of the driver, and coordination with the output device are all important. After all of these, the design alternatives of the hardware selection must not be overlooked.

The move from the dune buggy and golf cart to the full-size ByWire XGV™ platform meant a few things for the Blind Driver team. The output devices – steering wheel and gas and brake pedals – were definitive, at least for this first set of instructional interfaces. The vibrations and loud noise that hampered NVI signals in the dune buggy were no longer issues. The position of the driver, along with the seatbelt, was now well defined.

Heavy emphasis was placed on how the interfaces would integrate into the overall setup. The Blind Driver team had already attempted non-visual interfaces involving the foot, leg, back, chest, and hands, so some ideas on the incorporation of interfaces with certain body parts was acknowledged. The seamlessness of the user getting into and out of the driver's seat was a deemed significant. For example, the foot-oriented and calf interfaces called for an undesirable amount of effort and infrastructure just to settle into the interfaces. The Tactile Vest could be utilized along with the now more standardized version of the seatbelt, but integrating it with this



retracting seatbelt would require some fitting and adjustment of the position of the seatbelt in order to fit smoothly for each individual driver. Even the final DriveGrip product requires some rearrangement and adjustment with putting the gloves on the hands and placing the ethernet cables beneath the arms.

The SpeedStrip interface is excellent with regard to driver comfort and usability. Since the interface simply lies on the seat, the driver can get into and out of the car without worrying about placing the SpeedStrip. The SpeedStrip straps rigidly to the headrest mount at the top of the back in an attempt to remain in place. This interface actually takes advantage of perhaps the only areas of touch sensation on the human body that would not require any special adjustments compared to normal entrance to the car: the back and thighs. To engage any other part of the human body with some device would require an unnatural effort from the driver when getting in the driver's seat of the vehicle.

While the DriveGrip interface does require some extra effort to place on the hands at the start of the blind driver experience, there are many motives for using the hands as a sensory input. Recall that the Blind Driver team created an initial prototype of DriveGrip in 2009-2010. Positive feedback was received from blind testers at the National Federation of the Blind in response to the intuitive nature of this prototype, in translating signals directly through the hands to the steering wheel. As well, along with features on the face, the hands are the most receptive part of the human anatomy to the sense of touch (see Figure 1). Thus, if a way to comfortably utilize the hands for communication with the blind driver interface, one of the best modes of human sensation could be exploited.

One important factor in the development of DriveGrip was that receiving cues on the hands is satisfactory only if the fingertips are kept as open mode of communication. Several iterations of DriveGrip were considered, including different types of gloves (e.g., baseball batting gloves, football receiver gloves) before the Harbinger weightlifting gloves were chosen. These were made for the purpose of fitting snugly while keeping the fingers open; since they did not need to be altered or hemmed, they fit comfortably as blind driver gloves.

The selection and mounting of the motors was the next consideration. In fact, the great match found for the gloves is quite trivial if the motors cannot be mounted without causing burden or discomfort to the user. Fortunately, the 5V lilypad vibration motors were available, featuring a small one-centimeter diameter and low cost. Mounting them just above the base knuckle of the gloves using hot glue is a simple, robust method, but harnessing the wires is an issue.

Wires from the four motors need to unite with an ethernet connector, which links with an ethernet cable to a box on the headrest mount. These ethernet connectors are located at the base of the metacarpal corresponding to the pinky finger of each hand. There are two main issues with directing the wires to the connector. First, since the wires are along the back of the hand, there needs to be enough slack to clench the hand in a fist without introducing tension in the

wires. Second, the wires need to be protected because a blind user feeling around with his hands could easily get his fingers caught in the thin, light wires without being aware of the conflict. These issues are avoided by: adding an appropriate amount of hot glue, routing the wires from each finger along the knuckles and bundling them as one from the pinky knuckle down to the ethernet connector, and adding a small piece of fabric over the ethernet connector.

In order to route the ethernet cable as efficiently as possible from the hands to the headrest mount, the team established that this ethernet connector should be at the base of the metacarpal corresponding to the pinky finger. This allows the ethernet cables to hang below the driver's forearms with the slack in the cables reaching up the headrest mount behind the driver's shoulders.

Taking a look at the overall picture for the DriveGrip and SpeedStrip interfaces, coordination with the output devices is seamless and intuitive. As discussed previously, vibratory cues through DriveGrip provide an intuitive way of quickly and directly transmitting instructions to an output through the steering wheel. According to blind drivers who have used this interface, the easiest way to think about processing the signals is to try to balance the vibration signal between the two index fingers. This concept fittingly illustrates the concept of *instructional* interfaces, wherein the human driver has very little role in decision-making, instead adhering to directions from the non-visual interfaces. Additional actions related and unrelated to driving are also undisrupted by the setup of the DriveGrip; access to the gear shift knob, center console, seatbelt, and the rest of the driver's body is unrestrained by the DriveGrip gloves and ethernet cables.

There is an element of intuitiveness in converting SpeedStrip instructions to the outputs for the gas and brake pedals as well. Since all other inputs and outputs are restricted to the hands, it is easy for the driver to associate the lower body cues with producing an output through the feet. As suggested by one of the blind driver from the National Federation of the Blind, arranging the acceleration cues in an increasing fashion down the thighs can be linked to stepping forward with the body, while placing the deceleration and stopping cues up the back of the driver can be likened to someone grabbing the driver's shoulder from behind to request them to stop. Thus, one way to think about processing the inputs from the SpeedStrip is to try to lean toward or away from the location of the signals on the thighs or back. As discussed previously, SpeedStrip does not disrupt any other actions the driver may need to make, as the seat is essentially unchanged compared to a normal driver seat.

One concern with SpeedStrip may be that the thighs and back are not as receptive to touch sensations as the hands on the human body. Taking this into account, larger 12V motors are used in the SpeedStrip than the 5V motors in DriveGrip. These SpeedStrip motors are bastardized from an actual vibrating massage chair, so their original intention is to provide sensation to the thighs and back.

It can be argued that the DriveGrip cues are more crucial than the SpeedStrip cues, because steering incorrectly can quickly bring the vehicle off course. In fact, many drivers can detect that they are going relatively slowly, and when first learning to use the interfaces, they choose to ignore the SpeedStrip commands, instead favoring an emphasis on steering while advancing at a relatively slow speed.

Hardware selection for these instructional interfaces was made simple due to the simple nature of the stimulations produced. The lilypad motors for DriveGrip are commercially available at a low cost, and have had 100% reliability thus far. The gloves are robust, made for activities much more strenuous than driving. The vibrating massage chair that comprises the SpeedStrip interface is also cheap and has been reliable thus far. Other than these few common items, the only additional hardware is the moderate amount of simple wiring. Here, the only issue is ensuring enough slack in the wiring for interface flexibility, as discussed previously in the case of DriveGrip. Thus, the availability, cost, feasibility, and reliability of the hardware needed for these instructional interfaces are satisfactory.

#### **5.2.4 Testing and Analysis of DriveGrip and SpeedStrip**

Most of the initial testing of the final DG and SS interfaces was informal, including proof of concept and identification of appropriate quantization levels. A more formal testing procedure was completed at the NFB National Convention in July, 2011, with data collected from 300 blind volunteers who drove a test course on the Blind Driver simulator. The most valuable observations here came in the form of qualitative results rather than quantitative results. Fine-tuning of these interfaces is ongoing, as researched continues in a separate project on adaptive path planning algorithms for real-time blind driver assistance.

The early, informal stages of testing DriveGrip and SpeedStrip involved verifying the basic functionality of the entire setup. The first step was to make sure the vibration stimulations could be well-detected through the gloves and seat. Adjacent signals on each interface need to be clearly distinguishable when in the exact blind driver environment.

Next, the different configurations of each interface needed to be tested and a final one selected. For example, DriveGrip could also be set up where the driver is to steer *away* from the vibration on the fingers, instead of *toward* the vibration, which was the eventual selection. Many members of the team pointed out that steering away from the vibration makes sense intuitively, as this concept resembles balancing between the rumble strips on the outside of the lanes on a highway. After qualitatively testing this concept, the team decided that while this configuration may be initially more intuitive, after enough experience is gained to learn both configurations of DriveGrip, steering *toward* the vibration is the easier way of following.

Similar options were considered for the SpeedStrip configuration. For example, since the motors were arranged in pairs inside the seat cushion, it is possible to restrict acceleration cues to just the right thigh, and move the deceleration cues to the left thigh. This idea may be intuitive

because the gas pedal is on the right side, while the brake pedal is located on the left side. However, this concept was rejected for a few reasons. The traditional method of driving is to switch the right foot back and forth between the pedals, so it would not work as a direct translation like the DriveGrip signals do on the two hands. Plus, a deceleration cue does not necessarily indicate for the driver to use the brake, so there would be some inconsistencies in the regard. Lastly, since the thighs are not the most sensitive receptors on the body, it may be tough to distinguish the sides as quickly and seamlessly. This configuration and others were considered before settling on the final selection for the SpeedStrip interface.

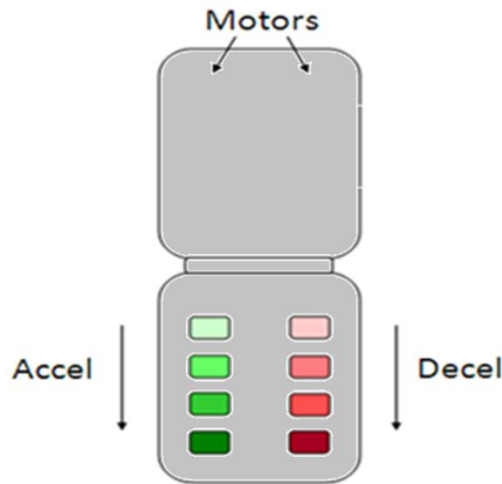


Figure 30. An example of an alternative configuration for SpeedStrip considered by the Blind Driver team in the early stages of testing

Once the concept was proven valid and the configurations were decided, the next step was to determine the quantization levels for the steering wheel angle error and the vehicle speed error. In order to do this, the team used TORC's Blind Driver simulator, which simulated the vehicle driving a route through a fabricated environment. The tester would receive DriveGrip and SpeedStrip cues just as in a real car, and output to a standalone steering wheel and pair of pedals, a setup commonly used for racing video games.

Initially, DriveGrip was isolated as the sole interface used in the scenario. This allowed the focus to remain on the performance of the driver with regards to steering wheel angle independent of vehicle speed. At first, a qualitative examination of the performance could reveal inadequacies in the quantization levels in the steering wheel angle. For example, if the driver was trying to correct too frequently, thus oscillating out of the lane at a fairly quick rate, the quantization levels were too close to zero; in other words, with the quantization levels close to zero, the ring and pinky fingers would be stimulated too often for errors that were relatively small. The driver, following these cues, would therefore attempt to correct too far and too often. This could be correlated to an *underdamped* system. On the other hand, if the driver was trying to correct too infrequently, thus oscillating out of the lane at a slower rate, the quantization levels were too large in magnitude. With the quantization levels too high, he driver would not be

correcting enough because the stimulations for rather large errors would be providing cues too close to the center. This could be correlated to an *overdamped* system. As this qualitative process was completed as well for the SpeedStrip, rough estimates of the appropriate quantization levels could be found.

To fine-tune these values, plots were created in the software to display the desired value versus the actual value. Steering wheel angle and vehicle speed were both still monitored independently. Here, the team could observe either significant overshoot or significant overdamped behavior of the human driver across all quantization levels. Through trial and error, effective quantization levels were determined independently for the steering wheel angle error and the vehicle speed error on the blind driver simulator.

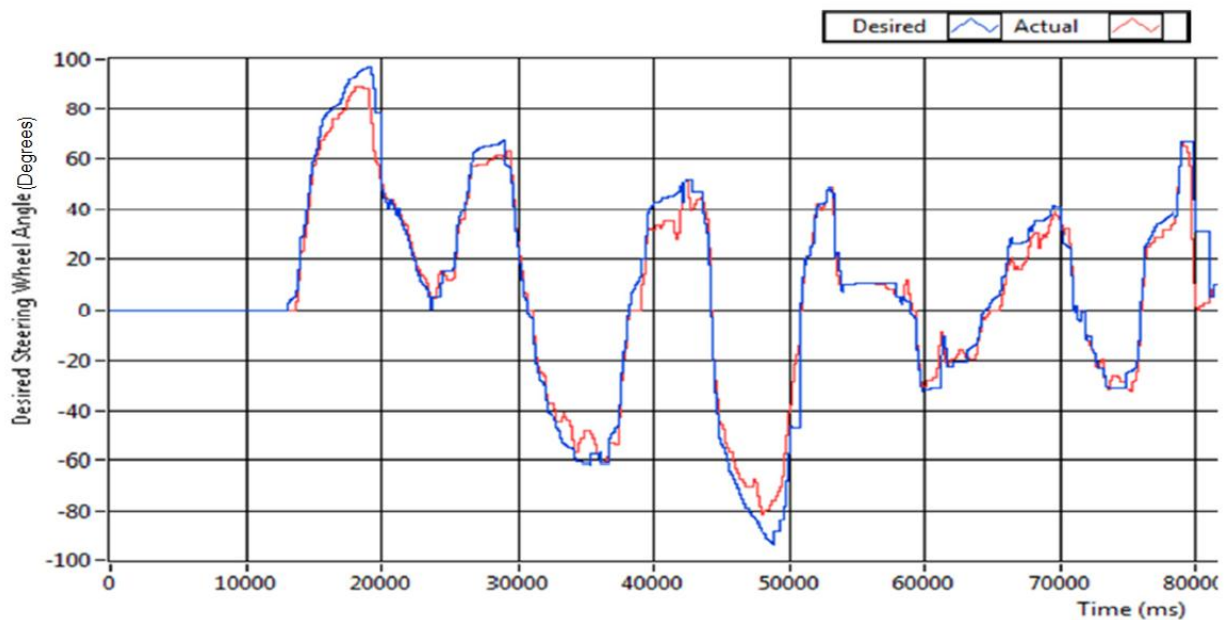


Figure 31. Sample of desired and actual steering wheel angle data for a blind driver using the DriveGrip interface for steering cues

The next step was to combine the two interfaces and operate them on the full-size blind driver vehicle platform to complete the driving experience. Further tweaking was done using the quantitative type of trial and error above, utilizing feedback and recorded data from blind drivers at the National Federation of the Blind.

During this phase of the testing, blind test drivers first recognized that the DriveGrip cues were more critical to adhere to than the SpeedStrip cues. Thus, the team introduced the deadband error between  $-0.5\text{m/s}$  and  $0.5\text{m/s}$ , which intentionally produced zero stimulation to the driver through SpeedStrip. This allows the driver to devote less attention to speed cues while he is successfully driving at constant commanded speed. The same could not be done for the DriveGrip cues, as the steering wheel angle is a more critical variable in the blind driving model. In other words, allowing for less speedy correction of the steering cues would have much more

adverse effects than if the speed cues were neglected temporarily. After blind driving practice was conducted over multiple days, the final quantization levels were chosen for the steering wheel angle error and vehicle speed error. These were the values given in Sections 5.2.1 and 5.2.2 and the ones used in the demonstration of the blind driver vehicle at Daytona International Speedway in January 2011.

Following the demonstration, efforts have been made to further analyze and improve the instructional interfaces. In July 2011, the Blind Driver team opened the simulator equipped with DriveGrip and SpeedStrip to 300 blind test drivers in order to collect data for analysis. This was called the NFB Blind Driver Test Track and took place at the NFB National Convention in Orlando, Florida.



*Figure 32. A blind participant tests the DriveGrip and SpeedStrip interfaces on the NFB Blind Driver Test Track in July 2011. National Federation of the Blind. <http://www.nfb.org/images/nfb/Publications/bm/bm11/bm1108/bm110802.htm> (accessed 6 January 2012) Used with permission from the National Federation of the Blind.*

While no data were valid enough to produce quantitative results (see Section 6.1.2), some qualitative results were noted. Since time was limited to ten minutes per subject, an overwhelming majority of the subjects failed to learn the interfaces well enough to effectively navigate the simulated blind driver vehicle through the environment. Based on the general performance of the subjects, the team estimated that one to two hours of simulation time would be necessary for the majority of blind drivers to learn well enough to produce usable data.

One factor with which most drivers most had an issue was their inability to get the feedback from the simulator that you would naturally receive in an actual moving vehicle. Typically, although most blind drivers have difficulty recognizing small accelerations at very low speeds (less than ten miles per hour), large accelerations in the actual moving blind driver vehicle can be detected very effectively. In the simulator testing in July, many subjects with little to no driving experience were having difficulty controlling the gas pedal. Blind Drivers were not quickly detecting significant accelerations of the simulated vehicle. Thus, in the learning process on the blind driver simulator required tremendous attention to the details of both the DriveGrip and

SpeedStrip interfaces, which was difficult for the overwhelming majority of the subjects to master in a short amount of time.

Continuing efforts to improve the effectiveness of DG and SS are being rendered by Paul D'Angio in the Robotics & Mechanisms Laboratory. D'Angio is investigating adaptive algorithms that take driver responsiveness to the non-visual interface cues into account, adjusting NVI inputs to the human driver accordingly. This effectively closes the control loop for the human blind driver model, as the output from the human becomes a factor in what the NVI's produce as instructional driving cues. For details, see the RoMeLa Internal Report titled "Driver Assistance Algorithms and Interfaces for the Blind Driver Challenge®" [60].

### **5.3 Development of Informational Non-Visual Interfaces: The Kinesthetic Tactile Display**

As a separate initiative, the Blind Driver team also completed some work on a more *informational* non-visual interface called the Kinesthetic Tactile Display. This was to improve upon the previous work on the AirPix device, and several ideas were considered for the new interface, including a three-dimensional audio setup, force feedback devices, and different options for a touchpad, which was the platform eventually chosen for the KTD. Two prototypes of the kinesthetic tactile display have been produced, with the most recent prototype a current work in progress.

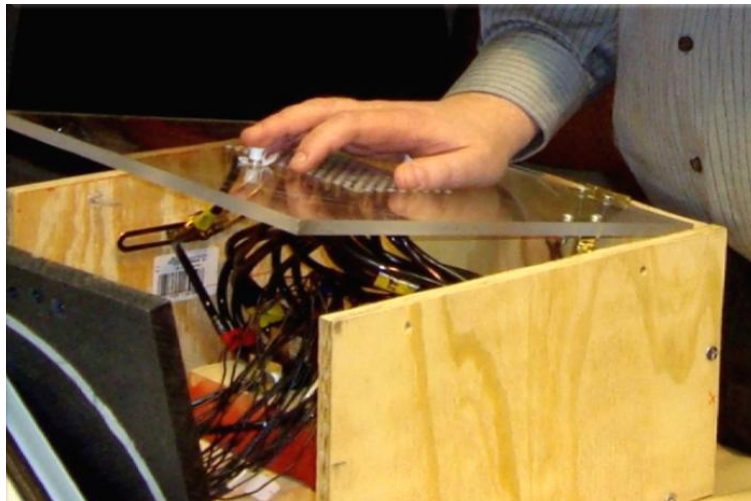
This section will examine the 2010-2011 Blind Driver team's considerations for the development of informational NVI's. Descriptions and analysis of the final product, the KTD, are provided. Since this is a work in progress, many recommendations are offered for the future development, testing, and application of the KTD; these will be discussed separately in Chapter 6.

The Blind Driver team wanted to develop an interface that was similar in function to the AirPix device, but with improved usability. Defined design specifications required the new device to convey static obstacle location, dynamic obstacle location, and lane location to the driver. These items are included in the next level of information available through the ByWire XGV™ platform after the instructional DriveGrip and SpeedStrip cues discussed previously.

#### **5.3.1 Identification of Problems with AirPix Device**

While AirPix was an excellent first step in proof of concept of an informational non-visual interface, it demonstrated several flaws that would make it impractical as a final product for driving. The current setup could support the specifications mentioned above, but the number of drawbacks to using the AirPix device outweighed the perceived functionality. These include: bulkiness and cost of the equipment necessary for operation, noise, and limited resolution.

AirPix is powered by an air compressor which distributes air pressure to each of the 135 orifices on the surface of the interface through solenoid valves [58]. Each individual orifice requires its own dedicated solenoid valve, polyurethane tubing, and nozzle, which connects the tubing to its location on the grid etched into an acrylic plate. All this equipment is extremely bulky and its size would be increased with every additional dimension of resolution added. An entire seat would have to be dedicated to the blind driver vehicle to support the 15x9 grid used in the final AirPix prototype.



*Figure 33. An early test of the AirPix interface with only 20 orifices hooked up shows how bulky the device would be if a higher resolution was attempted*

The fairly intense buzzing noise created by the pumping of the air compressor would be burdensome on the environment inside the blind drive vehicle as well. With a given auditory interference in the environment, supplementary interfaces using audition could not easily be utilized, and unrelated actions such as those discussed in Section 4.2.5 would certainly be affected.

Cost must also be taken into account. Around \$600 was spent on the parts listed above, not including the solenoids, which were donated to the 2009-2010 Blind Driver team. This may be considered relatively cheap, but consider that with any improved resolution, the total quantity of solenoid valves, polyurethane tubing, and nozzles increases with each additional orifice. A larger air compressor or more expensive manufacturing costs for the grid on the acrylic plate might also be necessary.

Formal testing of the AirPix interface revealed that simple graphics could be displayed and magnitude and direction easily detected by the user. However, for more complex graphics, such as a two-dimensional representation of the road including static obstacle location, dynamic obstacle location, and lane location, a greater amount of precision would be necessary. Fricke and Baehring, in their investigation into the design of a tactile graphic I/O tablet, determined some properties for a nearly ideal tablet. Although this applies to surfaces using taxels, the



recommended resolution of 30 dots per inch demonstrate the amount of detail a human user can recognize with the fingers [51]. This resolution turns out to equal  $1.4 \text{ dots/mm}^2$ , which is comparable to Vidal-Verdu's suggested  $1 \text{ dot/mm}^2$  to  $2 \text{ dots/mm}^2$  for virtual screens and dynamic displays. Vidal-Verdu goes further to suggest a 1 to 2N force is necessary for detection of non-vibrotactile displays, while forces as small as 1mN would suffice for stimuli that include vibration [30].

Bulkiness, cost, and noise all considered, each would increase with the desired improvement in the resolution of the interface. Thus, the team decided to investigate methods of providing informational driving signals other than pressurized air. However, some of the positive aspects of the AirPix device were noted, such as the robustness of the device, the lack of moving parts, and the incorporation of the entire hand's involvement in sensing the two-dimensional environment.

### **5.3.2 Concept Generation for Informational Non-Visual Interfaces**

For the development of a completely new informational non-visual interface, the team began again with basic brainstorming, thus considering all types of sensation and human anatomy once more. Force feedback devices and refreshable Braille displays were investigated. Three-dimensional audio cues were also reconsidered as a viable option for research as well.

Force feedback devices such as the Sensable PHANTOM-OMNI® and the Novint Falcon have been popular in the virtual reality field of research over the past decade. These consist of a stylus at the end of a multiple degree-of-freedom robotic arm, with joints that can be actuated to produce forces in three dimensions. Thus, the driver could explore around a three-dimensional environment using the stylus, receiving force feedback when encountering objects of interest such as the lanes or obstacles.

Implementing an intuitive feedback device like this would enable the human to truly be responsible for the decision-making in the driver experience. It is possible to create additional stimulations different between the different objects of interest, or program the device to provide different magnitudes or directions of force. However, this idea was considered as a potential future endeavor, since implementation would be difficult to design, program, and fine-tune. As well, cost was an issue for this device.

A refreshable, two-dimensional Braille display was another option the team investigated. Since blind people typically can read graphs and plots that are created on Braille paper through dots, a refreshable display using taxels, or raised pixels, could be a familiar and intuitive way to communicate a dynamic two-dimensional environment. Many displays using piezoelectric and electromagnetic actuation are already on the market, although only to the extent of one of two lines of Braille writing. As determined as recent as 2007 by Vidal-Verdu, a display using piezoelectric or electromagnetic methods would cost roughly \$35 per cell, thus costing hundreds of thousands of dollars for a sizeable display of reasonable resolution. A couple companies who

have such displays in development were contacted, but none had one yet available, and the pricing was confirmed to be as high as predicted. Thus, the refreshable Braille display was considered for possible future investigation along with force feedback devices.

A three-dimensional audio system was reconsidered for a number of reasons. The human's ability to localize to sounds provides a straightforward way of communicating the direction of objects of interest. As outlined in Table 4, sounds of different pitch and volume, oscillating tones, and other patterns could be exploited to distinguish between different types of cues and distances of the cues. Surround sound was perhaps already built into the ByWire XGV™ vehicle platform, could be incorporated into the vehicle without being invasive.



**Figure 34.** *Representation of a possible implementation of the three-dimensional sound system*

Audio cues for the proximity of other vehicles on the highway were one idea that was explored. For example, a pinging noise that changes in frequency dependent on the margin or clearance to the car directly in front of the blind driver could be useful. However, as ideas like this began to form, it was clear that the more appropriate function for audio cues would be as on-command information or supplementary cues, rather than information describing the raw environment as a whole. As well, constant three-dimensional audio cues would certainly interfere with the driver's actions related and unrelated to the driving responsibilities. Nonetheless, the team strongly considered further investigation of audio cues due to potential applications of this concept involved with user interfaces outside of blind driving. Audible signals could play a role as a supplementary type of cue to assist or enhance the main informational interface.

### **5.3.3 Considerations for the Development of the Kinesthetic Tactile Display**

The option chosen to be investigated further in 2011 was the concept of a “Kinesthetic Tactile Display”, some form of touchscreen display through which the driver can explore the two-dimensional environment. The overall concept would be similar to that of the AirPix device, wherein a non-invasive flat surface was the main platform for sensation, with stimulations

corresponding to environmental features on the surface being employed based on the driver's finger locations. Some of the design issues included the selection of the touchpad platform, the method for distinguishing between the different types of features in the environment, the types and locations of the stimulations, and how the device would coordinate with the operation of the vehicle.

The stimulation type and location was the first design problem. Based on early brainstorming along with members of the National Federation of the Blind, it was declared essential that any touch cues be rendered at the location of examination – in this case, whichever fingertip encounters a particular feature in the environment. This was not an issue with the AirPix device, as airstream cues were available at all locations in the field of view. The team investigated any touchpad devices that may produce vibration, shock, pressure or another somatic sensation on the surface of the pad.

One option that was ideal for this application was ViviTouch™, a product made by Artificial Muscle, Inc. that was unreleased as of spring of 2011. This add-on to a mobile device is a thin layer that covers the screen, using electroactive polymer technology to detect touch on the screen and produce localized vibration sensation [64]. The concept of this product is ideal for the KTD, but a couple issues prevented the team from utilizing it. It was unavailable at the time of concept generation, and now it is available for small screens such as those on smartphones. This is certainly a device to keep for future consideration.

Another option was to create physical lane markers that overlay on top of the touchpad. It is possible to set up the environment like this because a lane is almost always given when navigating a route on the blind driver vehicle. On this note, there would have to be some alternative signal that could be given when the vehicle could not find a workable lane to follow. One advantage to this concept is that many of the typical modes of touch sensation, such as vibrotactile cues, could be reserved as a completely different type of cue for obstacles. A pair of flexible members would be positioned vertically over the surface and actuated to create trajectories for right turns and left turns. A static reference point, similar to the one conceived for the AirPix interface, would be necessary to give the driver a sense of position relative to the lane.



**Figure 35.** *The concept of lane markers, shown with the static vehicle reference and signaling a right-hand curve*

This idea was not pursued for a few reasons. First, the requirement of moving parts makes this device bulkier, less safe, and less reliable. Second, having physical lanes makes it difficult to update quickly changing lane locations with ease; delays in information cues were possible due to mechanical actuation, unless expensive linear actuators were utilized. Lastly, any lack of versatility in the lane markers would make it difficult to display any possible configuration of the lane locations.

The remaining option was to choose one of many commercially available typical touchpads and strategically position separate vibration cues as stimulations. It is not a requirement for the touchpad to also produce a display on-screen, as some options such as the iPad™ and some small monitors included. The size of the active touch area is important; an area too small will make it tough to create satisfactory resolution. One of the toughest issues to overcome was actually software integration, as the ease of obtaining raw touch data varied by platform. Lastly, multi-touch capability is an important feature to investigate in a product search.

With a workable touchpad as the platform, the next design problem is how to create intuitive vibrotactile cues. As discussed previously, rendering the cues at the site of the environment examination is a priority. For this setup, this site would be at the fingertips, which presents a conflict in that keeping those open as modes of communication for other purposes is a greater priority. Positioning the small lilypad motors on each fingertip with a small stylus piece on the underside of each motor is a possibility that was considered. This would allow the vibration to be felt directly between the fingertip and the point of contact with the environment. Ultimately, this idea was scratched because of the value in keeping the fingertips available for additional purposes.

Other considerations pertaining to the signal creation include differentiation between the types of features in the environment. Static obstacle location, dynamic obstacle location, and lane location should be considered for separate cues. As well, since vibration cues cannot be

positioned at the ideal location of the fingertips, other options must be considered. Wiring coming from any actuators or vibrating elements need to be harnesses for driver comfort and usability.

A final design consideration is how the device will coordinate with the operation of vehicle and other actions within the environment of the vehicle. With one hand likely dedicated to the KTD the majority of the time, the design must ensure that the remainder of vehicle operation can be handled. The positioning of the interface within the vehicle must be determined. There is nominally enough space in the center console to fit a sizeable interface even with the gear shift knob, but a device with a lot of wiring or a large base, like the final AirPix product, would be difficult to contain. Any additional or supplementary cues need to be considered as well, such as audio signals or a version of instructional cues meant for assistive purposes to the KTD.

### **5.3.4 First Generation Prototype of the Kinesthetic Tactile Display**

The initial prototype featured a Bamboo Pen and Touch™ (Pen and Touch) display platform coupled with a glove similar to DriveGrip with the locations of vibrating lilypad motors strategically relocated. This iteration could truly be classified as a quick and rough proof of concept. The device was tested as a standalone interface and simple shape recognition was successful. Static lane and dynamic obstacle scenarios were investigated as well.



*Figure 36. An early prototype of the Kinesthetic Tactile Display*

A baseball glove was utilized to mount three lilypad vibration motors on the backs of the thumb, middle, and pinky fingers. Stimulation of these motors would represent detection of the left side of the lane, an obstacle, and the right side of the lane, respectively. With a glove that originally had complete fingers, the vibration motors could be positioned as close to the fingertip as possible while still arranging for the fingertips to remain open.

The active area of this Pen and Touch device is 4.9" x 3.4" with a satisfactory resolution of 2540 dots per inch. One issue here was that the absolute positioning of the finger in the active area was not possible on this device unless the stylus was used. This brought about a tedious start-up procedure. As well, this platform did not have a multi-touch feature.

These shortcomings did not impede a valid proof of concept for this device. Before moving toward actual blind driving tasks, identification of simple solid and unfilled shapes in the virtual environment was tested using the KTD. This was done using just one vibration motor, as the user was pursuing just one potential target at a time. Test subjects found that this identification was accurate, but it took a long time to discern that level of detail.

Next, two static vertical lane edges along with a dynamic circular obstacle were placed in the virtual environment. The circular obstacle was programmed to move vertically, similar to an approaching obstacle in a real driving setting. Test subjects were to scan the environment in search of any obstacles between the lane edges, using thumb and pinky cues to ensure that they were in fact examining the area contained within the road. These tests were successful in that the concept of using the fingertips to explore a touchpad interface was proven to be a viable method of non-visually communicating information to a human. However, it was clear that the size of the active area was too small: test subjects could not quickly trace the clear pathways between the circular obstacle and the lane edges.

The team identified a potential for exploiting the intuitiveness of visualizing a two-dimensional environment using a touchpad interface. Questions still remain on whether perception using the KTD will be quick enough to be practical for a dynamic application such as driving a vehicle. A few known flaws involved with the Pen and Touch platform could be improved upon as well.

### **5.3.5 Second Generation Prototype of the Kinesthetic Tactile Display**

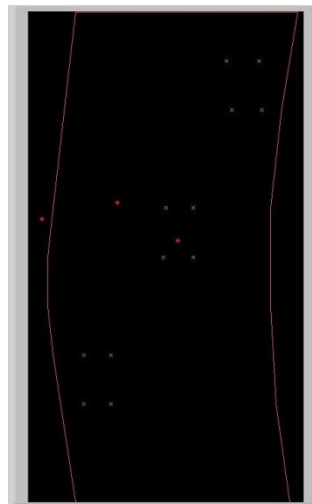
In order to alleviate some of the flaws in the Pen and Touch, the next prototype involved an upgrade to the Bamboo Create™. Here, the active area is increased to 9" x 5", so a more effective resolution may be experienced by the driver. Multi-touch capability is built into this model, so the driver can truly use his feeling hand to its full potential and observe an entire field of view at once. Lastly, absolute positioning of the point(s) of interest is possible without the use of a stylus, which makes for a seamless start-up procedure in the software.



**Figure 37.** *The second generation prototype for the Kinesthetic Tactile Display demonstrating multi-touch exploration of the two-dimensional environment*

A major focus of this prototype was to arrange the software framework to be integrated directly with the TORC software in the blind driver simulator. This required formats for receiving bundles of lane location information, dynamic obstacle information, and static obstacle information to be created. Thus, a varying quantity of geometric shapes could be positioned in the rectangular field of view. The locations of the fingers exploring the two-dimensional plane could then be compared to the regions occupied by those geometric shapes and determine if there is any encounter with an obstacle or lane edge.

Advancement on the stimulation scheme for this device has been a priority up to this point, as it is a recent development at the time of this documentation. Recommendations for future implementation on this front will be discussed in Section 6.2.



**Figure 38.** *The graphical representation of the two-dimensional environment shows the lanes edges, obstacle locations, and points of coincidence of the user's investigative fingers*

## **Chapter 6: Recommendations for Further Research and Implementation in Non-Visual Interfaces for Driving**

While DriveGrip and SpeedStrip have been demonstrated as a finished operational product, areas of future research will focus on functionality, aesthetics, and user comfort. Thoughts on blind driving tests in order to acquire a more quantitative characterization of these interfaces will also be presented in this chapter. An outline for the next steps in the development of the Kinesthetic Tactile Display is also proposed, including testing and alternative design solutions. The Robotics & Mechanisms Laboratory at Virginia Tech is already planning on implementing many of these recommendations in spring of 2012.

### **6.1 Recommendations for DriveGrip and SpeedStrip**

Aside from Paul D'Angio's scheduled efforts on the development of adaptive path-planning algorithms for blind driving, tweaks in the design relating to hardware and functionality are also being considered. For hardware, wireless DriveGrip gloves and integrated SpeedStrip motors are two simple concepts that might be investigated. On the functionality side, more invasive cues for commanding full stops as well as sharp 90° turns are in the works. In addition to these changes, some simple test procedures could be implemented in order to realize more quantitative characterization of the DriveGrip and SpeedStrip interfaces

#### **6.1.1 Improvements on DriveGrip and SpeedStrip**

Perhaps the most glaring fault of the DriveGrip interface discussed in Section 5.2.3 was the pair of ethernet cables necessary to connect the gloves to a power source, which cause inconvenience for the driver when putting the gloves on as well as limitations on comfort and range of motion. Changing this to a wireless setup could potentially alleviate these issues. This would require a small wireless antenna in each glove that will receive the signals from a separate transmitter somewhere else in the blind driver vehicle. The motors and antenna would now require battery power incorporated into the gloves. Thus, there may be some disadvantages if the gloves became too heavy or bulky. Other potential issues include the frequency and inconvenience of having to swap batteries as well as the possibility of the wireless signals failing to retain consistent connection. These design tradeoffs may or may not render the development of wireless DriveGrip gloves a worthwhile endeavor

The other potential improvement involving hardware is to more cleanly integrate the SpeedStrip motors into the seat of the blind driver vehicle. The current setup has the shell of a store-bought massage cushion simply resting on the seat, hooked in only by two Velcro straps to the headrest



at the top of the cushion. The cushion often gets scrunched down in the crack of the seat, and because of this, it requires readjustment and focused attention nearly every time the driver gets in the vehicle. Away to eliminate this would be to more rigidly fasten the sixteen vibration motors to the seat of the vehicle. A tight-fitting seat cover, which is commonly purchased for the purpose of protecting the seat from damage or wear, could serve to better integrate the motors with the seat. One potential item to be aware of is that enough padding on the seat cover should be present in order to protect the motors from damage by the weight of the driver. Padding here also would help to preserve the comfort of the driver.

A couple of adjustments have also been proposed to improve the functionality of the current DriveGrip and SpeedStrip setup with drastically changing the overall scheme. One of these is something that has actually already been added to the SpeedStrip: a “full back stop”, wherein the entire back vibrates any time the computer is instructing the driver to come to a complete stop. This feature was in response to frequent overshoot when the driver is obeying deceleration cues. With vibration signals rolling up the back, the driver is often unsure of the urgency of the deceleration, and therefore most likely plays it safe by quickly halting to a complete stop. With the “full back stop” implementation, the driver now does not have to worry whether they must quickly achieve zero speed, because the entire back of the SpeedStrip interface would have produced sensation if this was so. As stated, this feature has already been incorporated into the system; qualitative validation must be completed in order to verify the intuitiveness of the concept.

On a similar mark, blind drivers at the National Federation of the Blind requested a special case be made to warn the driver of a 90° turn in the road. This was noted when in a particular driving setting, the driver was following instructions to turn from one street onto another, and the 90° turn required extreme focus to maneuver. What follows is that during this particular testing, significant corrections in steering wheel angle on straightaways were misconstrued as the beginning of 90°, thus causing a similar element of panic to that of the deceleration cues discussed above. Thus, the blind drivers have recently requested investigation into a feature analogous to the “full back stop”. Perhaps a “full hand turn” feature could be implemented, wherein all four motors on the right hand vibrate to cue a full 90° right hand turn. However, this might not work just as simply as the “full back stop”; the driver cannot just crank the wheel all the way to the right to execute the turn. Something like a temporary (around one second) full hand stimulation could be utilized, followed by continuing the normal DriveGrip signals to help execute the turn.

Aside from these recommendations, as the DriveGrip and SpeedStrip interfaces become more finalized, supplementary cues might be added to the full blind driving experience. These may include the ability to prompt the vehicle for: vehicle dynamics such as speed, steering wheel angle, location, or compass orientation; vehicle diagnostics such as gas level, oil level, or amount of air in the tires; or other dashboard information such as radio statistics or information regarding the sensor systems on board. To accomplish this, an interface could be set up for the driver to

prompt the computer using voice commands or a switch toggle switch. Here the application of audio cues could be utilized most effectively, on an occasional on-command basis.

### **6.1.2 Further testing of DriveGrip and SpeedStrip**

To quantify the effectiveness of the instructional non-visual interfaces, some simple tests might be implemented. For characterizing DriveGrip, turns of varying curvature and total angle rotation could be standardized to a test procedure to see if there are any breaking points where blind drivers begin to have trouble with sharper turns. For SpeedStrip, accuracy of following zero speed commands might be helpful. Beginning from varying constant start speeds, zero speed may be signaled and the results analyzed to see when overshoot occurs. This concept might be applied to other simple speed tests involving stepping up and down from different speeds. Simple procedures like this might be helpful for determining inadequacies in the DriveGrip and SpeedStrip setup.

One last related thought is that once the *informational* interfaces become operational, *instructional* interfaces might be used as supplementary cues. To incorporate the current instructional interfaces this way, the DriveGrip concept might be moved to another area of the body, such as the sides of the legs, in order to completely free the driver's hands for use of the KTD or other informational device.

In collaboration with the National Federation of the Blind, the idea of creating a "Blind Driving School" has been discussed. The team could produce around a dozen sets of interfaces and blind driver simulation stations and instruct a class of blind subjects on how to operate the simulated blind driver vehicle. While this could be of benefit the NFB and the participants in learning and spreading the technology, the team could format it so that data and feedback could be effectively collected. A more formal test procedure including the assessments discussed previously should be created, such that a proven method for qualitative data collection is used. As observed in the testing completed in July, 2011, test subjects must have at least one to two hours experience using the interfaces before consistent data may be obtained. As well, the inadequacies of the simulation station must be considered, such as the lack of realistic feedback from the vehicle motion. If these obstacles can be managed, hosting a Blind Driving School would certainly be a testing platform to consider for the future.

## **6.2 Recommendations for Informational Non-Visual Interfaces**

On informational NVI's, the Kinesthetic Tactile Display is currently just past proof of concept, and next needs to be implemented in a more full capacity. This will include the development of an intuitive stimulation technique, and implementing with the device in conjunction with the blind driver simulator. There is certainly much to be observed about the feasibility of the KTD

when tested in a driving scenario. Aside from progress on the basic concept of the KTD, a few ideas for enhancing the interface will be proposed.

### **6.2.1 Further Development of the Kinesthetic Tactile Display**

As the KTD is currently set up to represent lane locations and dynamic and static obstacle locations, the next step is to accept this information real-time in the simulated driving experience. This will begin to address the concerns that a user may not be able to process oncoming environmental information quickly enough to make the appropriate driving decisions. Additionally, there will be further considerations for the communication of the signals to the driver.

It will be important to begin slowly in simulator testing; limiting the maximum vehicle speed (to as slow as 10mph) to begin with would be helpful. When the interface becomes tuned enough to increase vehicle speed, the ability of the driver to look further ahead in the environment will certainly be critical. If it is possible to alter the field of view so that the driver may look a greater distance ahead, it will be necessary to consider a way for the driver to keep perspective on the scale of the field of view. For example, as the vehicle accelerates, if the field of view is expandable to keep a consistent amount of projected *time* in the field of view, then the driver may lose perspective on the distance aspect. By the same notion, particular attention to the blind driver's aptitude in processing the curvature of oncoming turns in the road will be of interest. This may also be an issue for distance laterally, as the apparent width of the lane will become a more complex variable.

In preliminary testing with the blind driver simulator, implementing obstacles of varying dimensions as well as drivable gaps of varying widths would be helpful. There will be concerns about how well a blind driver can determine relative distances in a real-time environment, and some initial qualitative testing with different sized obstacles and gaps would give some indication on this. An alignment peg such as the one used on AirPix (see Figure 14) may provide some benefit in this regard.

For the current Kinesthetic Tactile Display setup, an effective method for communicating the signals to the driver is still in question. As mentioned previously, and recently introduced as a capability in the latest generation prototype of the KTD, multi-touch is a critical feature. A simple threefold vibration glove such as in Figure 36 provided indications on the left and right lane edge as well as a single indicator for obstacles; with multi-touch, this will be insufficient. Multi-touch will require individual stimulations for obstacle detection by each of up to five fingers, as well as distinct stimulations for lane detection. Later on, separate indicators will also be needed to distinguish dynamic obstacles from static obstacles. The current glove with lilypad vibration motors may be expanded to have a motor for each of the five fingers, covering the bases for static obstacle cues. Dynamic obstacles cues might be accomplished by increasing the intensity or frequency of the vibrations. Distinct cues for lane location will still need to be

addressed. Additional variations on vibration intensity, frequency, or oscillating pattern combination are options to consider here, or even pressure or one of the other touch sensations. This might also be a good application for audio cues.

### **6.2.2 Additional Design Solutions for Informational Non-Visual Interfaces**

In addition to future considerations for the current KTD prototype, some types of supplementary cues may be valuable. For example, consider the ability to prompt for information on particular obstacles. Obstacle proximity could be verified perhaps by tapping on its location on the touchpad. With advancements in the computer vision capabilities of the blind driver vehicle, characterization of obstacles – human, animal, traffic sign, etc. – might also be a feature that is cued on command.

Once the KTD or another informational non-visual interface is successfully established, combination with instructional interfaces may be an advantage. As described earlier, variations on the DriveGrip concept could be implemented in order to free the use of the driver's hands. In this case, instructional cues may be used primarily to verify the information obtained through the KTD or other information interface. Prompts for on-command vehicle information would also apply for usage in conjunction with the informational interfaces.

Lastly, as the development of informational non-visual interfaces are difficult and present many design challenges, alternatives for the interface platform should be continually reconsidered. Most notably, the ViviTouch<sup>TM</sup> vibrating touch interface and the various graphical refreshable Braille displays should be focused on as they become more commercially available and therefore viable as options blind driver interfaces. With a device like ViviTouch<sup>TM</sup>, stimulation can be provided at the location of exploration, thus eliminating the non-ideal circumstances of creating a detached stimulation to effectively correlate to the virtual objects of interest. This may also be accomplished if a refreshable Braille display or something that can similarly change physical shape becomes available. If such a device can provide a large enough surface area and resolution to effective at a reasonable cost, this would also be a type of instrument with which blind people are familiar. Thus, some of the alternatives initially considered for informational non-visual interface development may still be feasible with technological advancement.

## Chapter 7: Conclusions and Significance of Contribution

The goal of this thesis was to offer a set of guidelines for the development of non-visual interfaces, using the Blind Driver Challenge® project as a case study. Relevant literature has been cited, a background of the Blind Driver Challenge® has been provided, and finally, a generalized approach to designing non-visual interfaces for driving has been proposed. DriveGrip and SpeedStrip, the pair of instructional non-visual interfaces used in the Blind Driver Challenge®, have been considered a completed project and have been established as successful in several public blind driving demonstrations. Therefore, for the purposes of this thesis, the development of these interfaces has proven to be an excellent case study to follow for the considerations of the development of non-visual interfaces for driving. The development of an informational interface called the Kinesthetic Tactile Display has also been documented, and recommendations for further development on all non-visual interfaces have been proposed.

The function of blind driving has been modeled as an open-loop control system, wherein the human driver represents the plant, receiving inputs from the nonvisual interfaces and maneuvering the blind driver vehicle as the output of the system. Viewing the human as an input/output device, conclusions can be drawn using the amount of human involvement in the operation of a blind driver vehicle. Two classes of non-visual interface are defined: *instructional* interfaces, which provide minimal amount information to the driver, requiring less human decision and therefore generating less driver independence; and *informational* interfaces, which provide a greater amount of information to the driver, therefore requiring the human to make more decisions and cultivating a greater impression of independence.

As a result of the formal development of some of these interfaces for the Blind Driver Challenge® project, a set of considerations for the development of non-visual interfaces for blind driving has been formulated. A major element of this is the model of human senses and anatomy as media for information flow in the blind driving experience. Here, seven general guidelines have been proposed regarding the receptiveness and sensitivity of parts of the anatomy of the human driver and the implications of using that part of the human anatomy to receive non-visual interfaces cues. This includes thoughts on the interaction between the human and the environment and output interface(s). Thus, it has been shown that a formal method for evaluation of design concepts for non-visual interfaces is achievable.

Further, some discernible similarities and differences between the touch senses and the sense of audition have also been exposed. For instance, stimuli for both senses can vary in frequency, amplitude, and oscillation rate, and many combinations of distinct patterns can be formed from these three. Recognizable stimuli readily exist for both senses and therefore may be exploited for quickly communicating information through these sensory modes. At the same time, both endure common environmental interferences, although acknowledgment of their presence can

help to efficiently evaluate the expected proficiency of a particular sensory mode. A major difference between touch and audition is the location of stimuli compared to the sensory receptors for each. For touch, the sensory receptors are found over the entire external of the human body and stimuli must be located in direct physical contact with the sensory receptor; however, for audition, the sensory receptors are found in just one part of the body (in the ears) but stimuli may be located all throughout the environment. This trend has at least one direct consequence in that the hands and feet are common modes for operation (such as for output interfaces), thus limiting the opportunities to use the sense of touch for input interfaces. This limitation does not apply to audition.

Finally, some recommendations can now be made for the further development of the particular non-visual interfaces used in the Blind Driver Challenge®. These include thoughts on the aesthetic appeal and comfort, critical issues for testing, and suggestions for improvements and supplementary functionalities of the interfaces. Since the Kinesthetic Tactile Display, an informational non-visual interface, is currently still in the earlier stages of development, recommendations for approaching the next steps in its design process are also included.

Aside from thorough documentation of the development of the non-visual interfaces specifically for the Blind Driver Challenge, this thesis intends to organize some generalizations on the considerations necessary for the design process for non-visual interfaces for blind driving. Approaching a human function such as blind driving by modeling the human as an input/output device can be a valuable exercise, permitting the development of the input and output methods to be broken down in a simpler manner. In this way, all possible methods of communicating information between a computer and a human may be objectively considered and easily evaluated. It is conjectured that this process may be applied to other instances of human-computer interaction, with blind driving acting as a specific case study in this thesis.

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Ryan Colby <rscolby@gmail.com>

---

RE: Image Order/Price

1 message

---

Juliet McConnell <j.mcconnell@nhm.ac.uk>

Wed, Dec 7, 2011 at 7:51 AM

To: Ryan Colby <rscolby@vt.edu>

Dear Ryan,

Thank you for your image order/price query.

We are very happy for you to use the image Sensory homunculus (041490) in your Masters Thesis.

Please credit the image 'Copyright Natural History Museum, London.

If you have any further questions please do not hesitate to get in touch.

With kind regards,

Juliet

Juliet McConnell

Image Sales Executive

NHM Image Resources (Photography/Picture Library/ Wildlife Photographer of the Year)

The Natural History Museum, Cromwell Road, London, SW7 5BD

Tel. 0207 942 5376

Fax. 0207 942 5443

Web: <http://piclib.nhm.ac.uk/>

-----Original Message-----

From: Ryan Colby [mailto:rscolby@vt.edu]

Sent: 01 December 2011 04:16

To: NHMPL

Subject: Image Order/Price

A user has ordered or priced an image.

Client ID: 20028401

Client IP: 157.140.2.10

Email: rscolby@vt.edu

First name: Ryan

Surname: Colby

Company/org.: VT

VAT Number:

Phone: 5402311000

Fax:

Address: Virginia Tech

Address:

Address:

Town: Blacksburg

Post code: 24061

Country: USA

Nature of Business: Academic/Research

Image ID: 041490

Content: Using the image for Masters Thesis, with proper citation of course. Thank you.



Ryan Colby <rscolby@gmail.com>

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RE: Image Order/Price

1 message

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Juliet McConnell <j.mcconnell@nhm.ac.uk>

Fri, Nov 18, 2011 at 7:40 AM

To: Ryan Colby <rscolby@vt.edu>

Dear Ryan,

Thank you for telling us your intention to use this image in your MA thesis. We are quite happy for you to use the image providing it is credited 'Copyright Natural History Museum, London'.

If you have any further queries, please do not hesitate to get in touch.

With kind regards,

Juliet

Juliet McConnell

Image Sales Executive

NHM Image Resources (Photography/Picture Library/ Wildlife Photographer of the Year)

The Natural History Museum, Cromwell Road, London, SW7 5BD

Tel. 0207 942 5376

Fax. 0207 942 5443

Web: <http://piclib.nhm.ac.uk/>

-----Original Message-----

From: Ryan Colby [mailto:rscolby@vt.edu]

Sent: 10 November 2011 23:58

To: NHMPL

Subject: Image Order/Price

A user has ordered or priced an image.

Client ID: 20028401

Client IP: 157.140.2.10

Email: rscolby@vt.edu

First name: Ryan

Surname: Colby

Company/org.: VT

VAT Number:

Phone: 5402311000

Fax:

Address: Virginia Tech

Address:

Address:

Town: Blacksburg

Post code: 24061

Country: USA

Nature of Business: Academic/Research

Image ID: 041489

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Ryan Colby <rscolby@gmail.com>

---

Image use for Masters Thesis

2 messages

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Ryan Colby <rscolby@gmail.com>

Sat, Dec 17, 2011 at 11:54 PM

To: David Cutter <cutter@torcrobotics.com>

Hi David,

It's Ryan from the Blind Driver Challenge team at RoMeLa, hope everything is going well at TORC.

I'm writing my Masters thesis and was hoping to use a photo of Odin in a graphic that explains the spectrum of human involvement in blind driving (Odin being an example of a vehicle that uses zero human decision). The image I would like to use is on your website here: [http://www.torcrobotics.com/files/duc\\_photo\\_003.jpg](http://www.torcrobotics.com/files/duc_photo_003.jpg)

In order to do so, I would need a simple email stating I may "use with permission". I thought you might be able to help me here, or else direct me to the person that would be most appropriate?

Thank you!

--

**Ryan S. Colby**

M.S. Candidate, Robotics & Mechanisms Laboratory

Mechanical Engineering

Virginia Tech, Blacksburg, VA 24061-0238

rscolby@vt.edu | [www.romela.org](http://www.romela.org) | (585)269-9592

---

David Cutter <cutter@torcrobotics.com>

Mon, Dec 19, 2011 at 9:13 AM

To: Ryan Colby <rscolby@gmail.com>

Hi Ryan,

Yes, you may use with permission. If possible or appropriate, a “Photo courtesy of TORC Robotics” would be awesome. Good luck finishing up your thesis!

David

**From:** Ryan Colby [mailto:rscolby@gmail.com]

**Sent:** Saturday, December 17, 2011 11:54 PM

**To:** David Cutter

**Subject:** Image use for Masters Thesis

[Quoted text hidden]

---



Ryan Colby <rscolby@gmail.com>

---

## One more image use for Masters Thesis

2 messages

---

Ryan Colby <rscolby@gmail.com>

Tue, Jan 3, 2012 at 1:23 AM

To: David Cutter <cutter@torcrobotics.com>

Hi David,

Thanks for your quick response to my previous request. I have one more I'd like to use, Image 19 at <http://www.torcrobotics.com/products/bywirexgv>, the black XGV(TM) with the red TORC logo on the passenger door. Can you send me an email for this one to officially grant permission?

Thanks again, and Happy New Year!

--

Ryan S. Colby

M.S. Candidate, Robotics & Mechanisms Laboratory  
Mechanical Engineering  
Virginia Tech, Blacksburg, VA 24061-0238

rscolby@vt.edu | [www.romela.org](http://www.romela.org) | (585)269-9592

---

David Cutter <cutter@torcrobotics.com>

Tue, Jan 3, 2012 at 9:08 AM

To: Ryan Colby <rscolby@gmail.com>

Hi Ryan,

Yes, you have permission to use that photo. If possible and appropriate, we would appreciate a "courtesy of TORC Robotics" statement.

Thanks, and good luck!

**From:** Ryan Colby [mailto:rscolby@gmail.com]  
**Sent:** Tuesday, January 03, 2012 1:24 AM  
**To:** David Cutter  
**Subject:** One more image use for Masters Thesis

[Quoted text hidden]

---



Ryan Colby <rscolby@gmail.com>

---

## Request image use for Masters Thesis

2 messages

---

**Ryan Colby** <rscolby@gmail.com>

**Sat, Jan 7, 2012 at 5:20 AM**

To: "Lewis, Anil" <ALewis@nfb.org>, "Riccobono, Mark" <MRiccobono@nfb.org>

Anil or Mark,

I would like to request permission to use a photo of a blind person using the blind driver simulator in Orlando in July 2011. This photo is the sixth image down in the article at the URL:

<http://www.nfb.org/images/nfb/Publications/bm/bm11/bm1108/bm110802.htm>

I realized that I didn't have any good photo from the simulator, and it would be nice to include one. I just need an email from someone at NFB that says I have permission to use it for my thesis, with proper reference of course.

Thanks!

--

**Ryan S. Colby**

M.S. Candidate, Robotics & Mechanisms Laboratory  
Mechanical Engineering  
Virginia Tech, Blacksburg, VA 24061-0238

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**Riccobono, Mark** <MRiccobono@nfb.org>

**Sat, Jan 7, 2012 at 10:33 AM**

To: Ryan Colby <rscolby@gmail.com>

Cc: "Lewis, Anil" <ALewis@nfb.org>

Ryan,

You are approved to use this photo assuming you give appropriate credit: Courtesy of the National Federation of the Blind - [www.nfb.org](http://www.nfb.org)

Sent from my iPhone with built in nonvisual access and connectivity to an external Braille display. Who says accessibility is hard to do?

[Quoted text hidden]

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## Appendix B: IRB Approval



**Office of Research Compliance**  
Institutional Review Board  
2000 Kraft Drive, Suite 2000 (0497)  
Blacksburg, Virginia 24060  
540/231-4606 Fax 540/231-0959  
e-mail [irb@vt.edu](mailto:irb@vt.edu)  
Website: [www.irb.vt.edu](http://www.irb.vt.edu)

### MEMORANDUM

**DATE:** June 29, 2011

**TO:** Dennis W. Hong, Ryan Colby, Paul D'Angio

**FROM:** Virginia Tech Institutional Review Board (FWA00000572, expires May 31, 2014)

**PROTOCOL TITLE:** Blind Driver Test Track

**IRB NUMBER:** 11-593

Effective June 29, 2011, the Virginia Tech IRB Chair, Dr. David M. Moore, approved the new protocol for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at <http://www.irb.vt.edu/pages/responsibilities.htm> (please review before the commencement of your research).

### PROTOCOL INFORMATION:

Approved as: **Expedited, under 45 CFR 46.110 category(ies) 7**

Protocol Approval Date: **6/29/2011**

Protocol Expiration Date: **6/28/2012**

Continuing Review Due Date\*: **6/14/2012**

\*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

### FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals / work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

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Date*	OSP Number	Sponsor	Grant Comparison Conducted?

\*Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this IRB protocol is to cover any other grant proposals, please contact the IRB office ([irbadmin@vt.edu](mailto:irbadmin@vt.edu)) immediately.

cc: File