Design of a Wearable Tactile Display

Francine Gemperle, Nathan Ota and Dan Siewiorek
Carnegie Mellon University
Pittsburgh, PA 15213 USA
gemperle@cmu.edu, nota@andrew.cmu.edu, dps@cs.cmu.edu
http://www.wearablegroup.org

Abstract
Tactile displays are a viable way for people to interact with wearable computers. Human tactile perception is robust. A variety of shrinking tactile stimulator (tactor) technologies are available. Tactile displays are uniquely appropriate for wearable applications because of their close proximity to our 20 square feet of touch receptors: our skin. Tactile displays can solve issues of intrusive computers and multiple demands on user visual and audio attention. They are discreet and seamlessly integrate with most human activity. Tactile displays will neither conflict with nor replace audio and visual display but rather support information on these other displays and fill in the gaps where necessary. This paper presents our work in optimizing the design of a tactile display and discusses some of the issues and opportunities surrounding tactile displays for wearable computers. Additionally, we hope to inspire more work in this area.

INTRODUCTION

The Wearable Group at Carnegie Mellon has been designing and testing wearable computers for industrial and military maintenance applications for 10 years. These applications find our users in warehouses, aircraft hangars in cockpits and vehicles in rain or bright sun. Diverse and extreme situations such as these open the user to uncontrollable variables such as lighting, ambient noise, weather and a plethora of distractions. As a result the interaction and interface with wearable and mobile computers continues to be a major area of research, development, and innovation [1,2,].

Issues of user interaction in a wearable context are often successfully addressed with multiple modalities for input and output [3,4]. Typically these interaction modalities are various combinations of audio and visual for both input and output. Often the design of interaction with wearable computers is driven by a need for users to have their hands free [5]. Our experience prompted the question, what about when a user must be eyes free or ears free? In addition to situations where users are deaf, blind or both, environmental factors might prohibit audio or visual input and output. At certain times, making noise or diverting the eyes to a computer display might be socially inappropriate or physically unsafe. The use of touch as an additional modality is one opportunity to address these issues. Some good work has already been done in considering the use of tactile displays for wearable and mobile computers [6,7,8]. Additionally, researchers in the Navy have been working with tactile displays to convey information to pilots for over 10 years [9] There is also considerable reference material from tactile work for Virtual Reality (Haptics) and (Sensory Assistive) Devices for Deaf-Blind people. (See below)

We define a tactile display as a device which presents information to the wearer by stimulating the perceptual nerves of the skin. A familiar model for this is the 'silent' function on most pagers and cellular phones. In this model, one signal is presented through vibration. Our hypothesis is that with multiple addressable tactile stimulators (or tactors) spread across an area of the body we will be able to convey more complex and coordinated information.

Haptics and Sensory Assistance vs. Tactile Information Display

Our work is in the area of Tactile Information Display. This work is different from the work of both the Haptics community and work in sensory assistance for the deaf blind communities.

Haptics usually describes any computer peripheral that adds the tactile sense to a Virtual Reality or Tele-operations application. These devices provide a force feedback or vibration based on cues from a visual interface. For example, a haptic device would be a desktop mouse that provides some force feedback creating the sensation of an 'edge' when the mouse is rolled over the edge of a window [10]. Tactile stimulation takes its cues directly from the visual interface.

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Similarly, Sensory Assistive devices aim to aid the deaf or blind in their ability to perceive the world around them. Here tactile stimulation is used to translate visual or audio information. A sensory assistive device takes visual images and creates a texture map display [11] whereby there is direct correlation from the image to the texture map.

Both Haptics devices and Sensory Assistive devices are concerned primarily with a direct translation of real or computerized visual or audio information into tactile stimulation. Whereas, a tactile information display is neither direct nor a translation – it will present coordinated tactile information – not directly based on visual or audio information. Tactile information displays employ a different channel for communication between humans and computers.

Currently pagers and cell phones employ a tactile display of notification. This 'vibrate mode' does not take cues from a previously computerized interface experience. It takes cues from real life. Information design and learning have occurred [12]; this allows a user to understand that when this device vibrates, it is someone trying to get their attention. The metaphor here is that vibrations in your pocket can be akin to someone shaking your shoulder to get attention. This vibration is the tactile display of tactile information. The differentiation between Virtual Reality Haptics and a vibrating pager, is a subtle but important one.

We foresee a need for more exploration and experimentation in the area of tactile information design. This will give us a better understanding of the difference between the different kinds of information that can be presented through touch and how that information can be presented. Ultimately so that we can design effective tactile displays. In this paper we present a tactile display design and discuss the application framework for using these displays for tactile information design experimentation.

TACTILE DISPLAY DESIGN

Our initial efforts in tactile display design included research into temperature, electric stimulation, compressed air, and vibro-tactile means for stimulating the skin. Other research will not be discussed in this paper. Vibro-tactile methods were found to be the most promising because of their small size, and weight, low mechanical and electrical requirements. Vibro-tactile motors are also best suited to meet our Tactile display requirements (see table 1).

Table 1. Wearable Tactile Display requirements:

Light weight
Silent
Tiny, very tiny
Low power
Tactors can be felt through clothing
Tactors must be held tight on the body
Physically discreet
Support experiments in tactile information design, i.e. flexible!

In addition to tactor selection, our early efforts have helped to identify other requirements: 1) tactors must be held tight to the body, 2) general locations for tactors, and 3) details that help create a flexible vest design that will support multiple experiments. These initial designs are customized for wayfinding or navigation applications.
Directions on how to get from here to there are presented as tactile information, steering the user through speed distance and turns. Navigation using a tactile display has a simple information set to begin experimentation. Forward, Backward, Left and Right in addition to information about speeding up, slowing down is a great starting point for our research.

Figure 1. Early Tactile vest designed during the '99-'00 academic year.

Figure 1 depicts our first tactile display vest design. Tactors are contained inside hemispheres on the harness. These tactors are modified piezo buzzers from Radio Shack and are wired (down the back) to a belt-worn infrared receiver. A customized remote control has buttons to turn each tactor on and off. The piezo buzzer is rated at 12 volts DC and 15 milli-amps operational specifications. In addition, the buzzer was rated at a sound level of 75 decibels and buzzer tone of 300 to 500 Hertz. Buzzer dimensions are .59 x .59 x .98 inches. This design was loud, bulky and consumed too much power. For these reasons, it was not a reasonable tactile display. We do like the overall harness styling. It is comfortable (for someone with a 32" chest), easy to get on and off, and the design highlights the embedded technology.

The tactile display design in this paper represents an optimization and application of all that we learned in our initial efforts. For this newer design we were able to locate and customize a tactor that is smaller, silent, and uses less power. A wireless infrared kit allowed us to create a testable vest that did not require any programming. Additionally, we created a vest design that can be customized for testing purposes.

Tactors

Tactors used for the tactile display contain a modified miniature vibrating electric motor. The vibrating motor is characterized by an off-center weight located at the end of the shaft. As the shaft rotates, the off-center weight creates a centrifugal force that is transmitted through the entire motor as a vibration.

These Motors are from Alcom [13]. They were originally intended for a Nokia 3210 cell phone. We found three simple problems with this motor. The motors are designed for a specific application where tabs are required, and they are soldered directly on the circuit board of a cell phone. For our purposes the tabs are inconveniently placed at an angle from the motor. As such, these motors are difficult to connect to a power source. A simple solder connection to extension wires is difficult and imprecise. Additionally, the motors are easily obstructed. The rotating weight on the shaft is stopped with minimal resistance from fingers or fabric. The motors can also become tangled in threads from clothing. While experimenting with the motors, a thin wool fiber from a sweater wound around the spinning shaft, causing the motor to seize. Thus, a custom housing for the tactor module was designed to address these problems.

The Alcom vibrating motor is the heart of the tactor module. One housing shell covers the motors. The shell allows us to both stabilize the wire leads and shield the moving parts from any interference. The motor is secured inside of a 0.25-inch hollow aluminum rod with epoxy. The motor leads are exposed outside of the housing. This tactor module is a .3 by .7 inch cylinder. Figure 2 shows the module components.

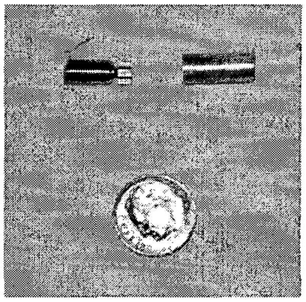

Figure 2: Tactor Module Components

After securing the shell on the motor, wire leads are soldered to the motor lead tabs. The wire leads are used to connect each of the six tactors to the infrared receiver circuit board discussed in the next section.

This tactor design meets the criteria established in Table 1. It is small lightweight, physically discreet and virtually inaudible. At a distance of 1cm the motors rate at 55dB. Despite its small size, our initial tests indicate that this tactor can be felt through one layer of clothing.

Wireless Communications system

An inexpensive off-the-shelf infrared kit serves as the wireless communication system. This kit contains an IR Receiver and Remote Control. The minimal operating voltage of the receiver is eight volts. The output from the receiver to the tactor is equal to the supply voltage of the receiver circuit. Thus, six voltage dividers are included to reduce the voltage to the required motor voltage. Lastly, wires are soldered to the supply voltage leads of the circuit.

The remote controller has six momentary and two toggle buttons. Two "AA" batteries supply power to the transmitter. The range of the remote is several feet. This will allow us to do testing in the lab and around campus with minimal bulk or weight for the subject and no tether or wires to other computers.

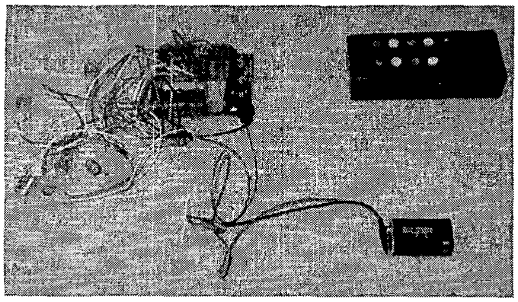

Figure 3: Completed System without harness. On the left are the tactors in a jumble of wires connected to the IR unit. On the upper right is the remote controller and the lower right is a 9Volt battery.

Power Supply

The power supply is divided into two sections: tactor power supply and wireless communication system power supply. Both power supplies will be dictated by the estimated power consumption of the two subsections. At this time, a conservative estimate has been derived from a simple assumption: the vest will be in operation for twenty hours a day. In addition, the required voltage of the vibrating motors is known to be 1.3 volts DC. Thus, the milli-amp hours can be determined for a single motor using simple calculations. Several different assumptions were also made to constrain the "on" time for the tactor. The results are shown in Table 2 below.

Motor On	Motor Off	Milli-amp Hours
continuous	none	1300
5 seconds	1 second	1083
1 second	1 second	650

Table 2: MilliampHour Consumption for Various Signal Schemes

As shown in the estimates, the power required is small enough for several small batteries. We considered the option of coupling a watch battery with each tactor. This idea was rejected because watch batteries would have to be sealed with epoxy to the tactors to prevent the wire connections from jiggling loose – this then would make it impossible to replace the batteries. A better solution is to design toward a single power grid for entire body – i.e. power the display tactors and wireless communications from the same source.

The power source is a common nine-volt battery. A standard nine-volt battery adapter is soldered to the leads of the receiver. The battery provides power to the receiver as well as the tactors, since they are powered directly from the receiver output. While on, the receiver draws thirty milli amps. Assuming the worst-case scenario in which the receiver is continuously on, a standard nine-volt battery will power the system for four to five hours.

Harness Design

The harness for the tactile display is designed to house the technology pictured in fig 3. It takes into account our criteria established in Table 1. It holds tactor modules close to the skin, it is tight to the torso and can be configured for future experiments. Additionally the vest design reflects our Design for Wearability [14] work presented at the Second ISWC in Pittsburgh, 1998.

The harness design was based on the need for the vest to be easily and comfortably put on and taken off by the user. A familiar waistcoat or vest shape, it is made from heavy weight Lycra. On the inside are taut pockets for tactor modules. These are made from a lightweight mesh material to allow optimal contact with the skin. Tactor pockets allow us to move the tactors around the torso to identify prime locations. On the back of the vest is a pocket, which houses the Ir. circuitry and the battery. A hole is cut in the Lycra and a stabilizer 'bulls eye' is attached and connected to support the IR receiver.

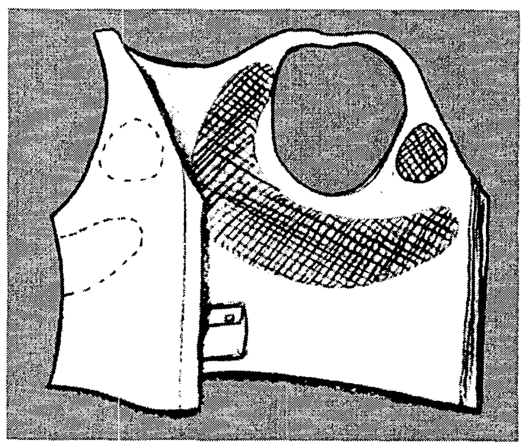

Figure 4 is a sketch of the harness design. This design will be produced for testing during the summer 2001.

The Wearable Tactile display described here will be used to experiment with the presentation of navigational information through the skin. The systems will be evaluated to determine optimal locations on the body, optimal operating frequency for the motor, and optimal signal modulation for navigational instructions. Use of an infrared remote control will allow testing of specific timing of vibrations both in and out of the lab. These tests will help us gain a much better understanding of how we can use variations in frequency, amplitude and sequencing to communicate. Work in this area has already begun. Hong Tan's study of the *sensory saltation phenomenon* [15] has generated valuable information about the numbers of tactors it takes for a person to perceive a directional signal.

Tactile Information Design

As mentioned, our preliminary experimental application will be navigation. Navigation is relevant for many types of travel, walking, cycling or operating vehicles. For the sake of simplicity we will begin our experiments with walking moving on to motorcycle and automobile operation in the future.

In the initial signal scheme for the tactile display walking navigation application, information will have four forms of instructions: linear direction, speed, rotation, and acceleration. These four instructions will be sufficient for normal walking. Signaling a single tactor will indicate linear direction. Rotation will be indicated by a series of signals across several tactors. The result will be a sense of pressure across the body, as opposed to a single spot for linear directional information. Velocity and acceleration are similar in the methods of signaling. Velocity may be indicated by three different methods. First, the frequency of the signals can increase to indicate an increase in velocity or vice versa. Likewise, the amplitude could be modulated. In such a scheme, a stronger vibration would indicate an increased velocity. Lastly, the signal duration could be used to indicate a different velocity. While the spacing between the signals would remain constant, shorter signal duration could indicate a faster velocity. The acceleration of the user can also be instructed in similar fashion to the velocity. An increased rate of change in frequency could represent that greater acceleration is needed. Likewise, an increased rate of change in the signal amplitude could indicate a larger acceleration.

Anne Murray's work greatly informed this signaling plan [16]. Ms Murray tested the quality of a hand based haptic device. Using speakers as a tactor she experimented with varying frequency and amplitude. Results indicated that alone, neither frequency or amplitude provided enough contrast for subjects to differentiate. However, when signal varied by amplitude and frequency at the same time – the quality of perception of the instructions increased. While the fingertips have a different kind of skin than the torso, we are interested to see if this applies. Our testing will experiment with variations in frequency and amplitude variations as well as signal locations and sequencing of signals as in the sensory saltation phenomenon.

There is a real need for better understanding of the arena of tactile information design. Like visual or audio information design designers will soon rely on physical space, segments of time sequencing and other sets of tactile elements with which to communicate discreet information to mobile users.

Applications

There are numerous applications for tactile interfaces on wearable computers. We chose a simple navigation application to conduct user tests with the display described above. Navigation requires a set of tactile messages: forward, back, left, right, speed up, and slow down, that can be applied to many familiar navigation scenarios. All kinds of people navigate in all kinds of contexts – from a campus visitor to a hiker in the wilderness. Figure 5 depicts an Industrial Design Student project. It is a concept for a wearable tactile display. This wearable (called Kahru) would allow a hiker to enjoy unfamiliar territory without a guide or frequent stops to check a compass and topographical map. Embedded tactors would simply nudge the hiker in the right direction – guaranteeing a return to the car by sundown.

Figure 5. *Kahru Tactile Outdoor Navigator* by Chris Kurtz while a student at Carnegie Mellon.

This application is a simple and viable one for consumer marketplace. Multiple navigation situations require people to be eyes and ears free. For example walking as tourist, driving a rental car in a new city, travelling on motorcycle or bicycle.

Beyond navigation applications, tactile displays will be an essential component of rich interaction scenarios. These will rely on a robust infrastructure and a more complex tactile messaging model. The Aura project at Carnegie Mellon is working to create such a scenario [17]. The Aura model of a pervasive computing environment is utilizing a campus wide wireless network and creating behind the scenes server applications to meet the goal of distraction free computing and an invisible 'halo' (or aura) of computing and information services, accessible regardless of user location.

The Sprout conceptual earpiece in Figure 6 is designed to create a link between the behind the scenes work of the Aura project and the person. It couples tactile notification with a simple speaker and microphone earpiece for audio interfacing. Sprout would be the only wearable interaction device necessary in a pervasive computing environment. It would provide the user interface to any and all computers. An array of 5 micro tactors would provide various notifications to the user in a very discreet way.

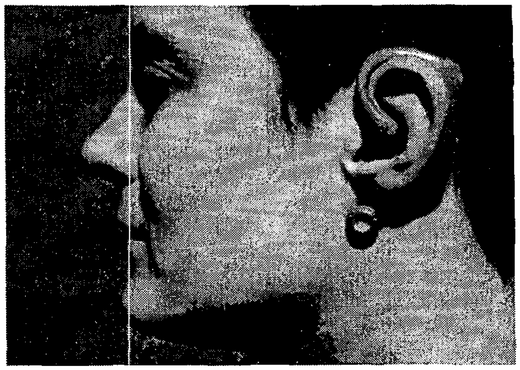

Figure 6. *Sprout*, A conceptual wearable interface to a pervasive computing environment.

In Figure 7 below we show the other side of Sprout. Taking advantage of the skin area behind the ear, the array of 5 rings on the left is a tactile display.

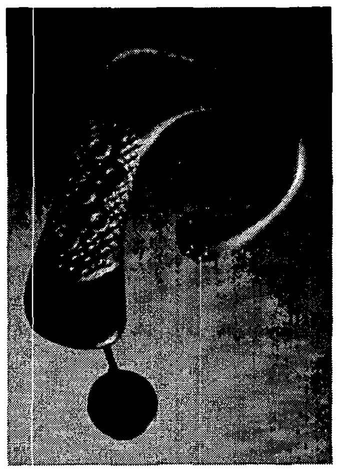

Figure 7. Sprout Tactile Display area.

The complexity of information we can present with tactile stimulation is directly related to the elements of touch that can be varied. The first is simple vibration, as in a pager. Variations in vibration in either frequency or amplitude could be correlated with kinds of information. Notification of a phone call, an email, an urgent email, or an incoming file could be differentiated by variations in the vibration. This could also extend to notification beyond messaging. It could be used to notify you of anything that you want to keep track of. For example, the score of a basketball game, the progression of an impending event, your status on an online auction or even the status of your body and mind. *BodyMedia* makes a body monitoring wearable [18]. Imagine your wearable reminding you to "take 5" and get some fresh air on a really stressful day.

In addition to variation in frequency and amplitude we can vary physical space. This could be used to discern who or what is creating the notification vibration. An assistant, a colleague, a stranger or a family member would all have access to different locations in the physical space of the tactile display.

A third area for a tactile display is a two-way personal communicator. This would require a tactile input that would closely integrate with the output. Buttons and tactors would exist on either side of the same wearable piece. This concept is not a new one and has long been considered a solution for intimate communication between two people across a distance.

CONCLUSION

Our silent data point consideration of tactile displays is an inclusive design project, that is not *only* for the sensory impaired or the sensory enabled user. Touch is a powerful sense. It enables far more understanding and interaction with the world than the eye alone. Touch supports the experience and understanding that accompany hearing and sight.

In the past 2 years we have optimized the design of a tactile harness style wearable display
This design meets all of our criteria established for a tactile display-testing unit. In addition we have begun to create taxonomy for tactile information design and applications for the use of a tactile display. We will continue to explore navigation as an application. Our next steps include further testing and experimentation in transmitting information to users through their skin

Our third generation design of the tactile display will be a USB device that will be plugged into the wearable computer research platform known as Spot [19]. Running Linux, this computer will allow us to program more complex sequences of vibrations for testing and connect vibration sequencing to spatial information. This spatial information will be transmitted from an internal GPS, from localization on the campus Wave LAN network and from simple text based navigational information, allowing us to test the usability of the tactile display when used alone or in conjunction with a head-worn display and audio information.

Initial testing of the vest on students in our lab suggests that this is a compelling and viable way for people to interact with wearable computers.

Though touch will never replace hearing or vision as our primary sense for navigating the world, touch displays will go a long way to make interactions with computers more closely match our interactions with humans and products in the real world. Touch will also allow us to end the noise pollution created by unnecessary audio signals from mobile and wearable devices, it will minimize the distraction levels associated with mobile and wearable computing applications and it will nourish our innate human need for tactile stimulation. Our lives are multi-sensory and our interactions vary from the bold to the subtle. It is time that our interactions with computers reflect this.

For further reading on the human sense of touch, the following texts have been very helpful to us:

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[19] Carnegie Mellon University Wearable Group http://www.wearablegroup.org