Lindeman, R.W., Templeman, J.N., Sibert, J.L., Cutler, J.R. (2002). Handling of Virtual Contact in Immersive Virtual Environments: Beyond Visuals, *Virtual Reality*, 6(3), 2002, pp. 130-139.

HANDLING OF VIRTUAL CONTACT IN IMMERSIVE VIRTUAL ENVIRONMENTS: BEYOND VISUALS

Robert W. Lindeman[1], James N. Templeman[2], John L. Sibert[1] and Justin R. Cutler[1]

[1]Dept. of Computer Science
The George Washington University
801 22nd St., NW
Washington, DC 20052 USA
{gogo | sibert | jrcutler}@gwu.edu

[2]CODE 5513
Naval Research Laboratory
4555 Overlook Ave, SW
Washington, DC 20375 USA
templeman@itd.nrl.navy.mil

ABSTRACT

This paper addresses the issue of improving the perception of contact that users make with purely virtual objects in virtual environments. Because these objects have no physical component, the user's perceptual understanding of the material properties of the object, and of the nature of the contact, is hindered, often limited solely to visual feedback. Many techniques for providing haptic feedback to compensate for the lack of touch in virtual environments have been proposed. These systems have increased our understanding of the nature of how humans perceive contact. However, providing effective, general-purpose haptic feedback solutions has proven elusive.

We propose a more-holistic approach, incorporating feedback to several modalities in concert. This paper describes a prototype system we have developed for delivering vibrotactile feedback to the user. The system provides a low-cost, distributed, portable solution for incorporating vibrotactile feedback into various types of systems. We discuss different parameters that can be manipulated in order to provide different sensations, propose ways in which this feedback can be combined with feedback of other modalities to create a better understanding of virtual contact, and describe possible applications.

KEY WORDS: haptic feedback; multimodal interaction; vibrotactile feedback

1. INTRODUCTION

Virtual contact research addresses the problem of what feedback to provide when the user comes into contact with a purely virtual object within a virtual environment (VE). Current technology limits our ability to provide as rich an environment as we experience in the real world. Therefore, it is of interest to us to help define the subset of feedback for these environments that will maintain or improve human performance, and to find ways of effectively presenting the stimuli, thereby allowing the higher-level cognitive systems to construct a reality that, though of a lower fidelity, still produces an equivalent experience.

As humans, we interact with our environment using multiple feedback channels, all coordinated to help us make sense of the world around us. The limited multimodal feedback in current VE systems, however, hinders users from fully understanding the nature of contacts between the user and objects in these environments. It has been found that because real-world contact combines feedback spanning multiple channels (*e.g.*, tactile and visual), providing feedback to multiple channels in VEs can improve user performance [1,2]. Grasping virtual controls, opening virtual doors, and using a probe to explore a volumetric data set can all be made more effective by providing additional, multimodal feedback. In essence, we are addressing the need for supporting effective user actions in environments with reduced sensory feedback, because the only feedback the user receives is that which we provide.

Current approaches to providing haptic feedback, described in more detail below, typically use force-reflecting devices, such as the PHANToM, or exoskeletons. These devices can provide very effective feedback, but their use is limited by their expense and cumber. Our current focus in this area is on developing a mobile, extensible system for delivering vibrotactile feedback to multiple parts of the body using a single device controller. The vibrotactile elements (*tactors*) are positioned at different points on the body, and controlled from a proximal control unit. Multiple units can be linked together and controlled either from a handheld computer carried on the person, or from a remote host using a wireless connection. Our use of vibrotactile feedback is built on previous work in the use of passive props, and represents an evolutionary step towards the ultimate goal of providing a high-fidelity experience to users of VR.

2. PREVIOUS WORK

Next we review previous work on providing feedback to the different sensory channels, with particular focus on the haptic channel.

2.1 The Sensory Channels

Although it is the visual sense that has received the most attention from VE researchers, some work has been done on feeding the other senses. After visuals, the auditory sense has received the most attention [3,4,5]. The proprioceptive sense has also received some attention [6]. The senses of smell and taste have received less attention, possibly because of the difficulty and intrusiveness involved in delivering a wide range of stimuli [7]. The area of haptics has received increasing attention from VE researchers over the past decade.

A common finding of researchers in these different sensing modalities is that it is not enough to address only one of the senses; that to give a deeper feeling of immersion, multiple senses need to be stimulated simultaneously, and in a coordinated fashion. Furthermore, providing more than one type of stimulus allows researchers to achieve acceptable results using lower "resolution" displays [8]. This becomes important for low-cost applications, like game consoles or aids for the hearing impaired [9], or in applications with potential transmission delays, such as on-line conferencing or gaming. For example, it is possible that relatively simple haptic feedback when combined with high-quality visual images, which have become very inexpensive to produce, could create a similar sense of contact produced by more-expensive haptic displays alone. Further work is needed to quantify this.

2.2 The Human Haptic System

Describing the physical elements and cognitive processes involved in how we perceive and process the sense of touch has proven to be a difficult task [10]. Loomis and Lederman [11] define two main *tactual modes* by the amount of control the user has over the exploration of the touched surface. We choose here to follow the categorization used in much of the perception literature [11,12]. Broadly, the human haptic system can be broken down into two major subsystems. The ***tactile*** subsystem refers to the sense of contact with an object, and receives information mediated by the response of mechanoreceptors in the skin within and around the contact area. Experiments have been performed defining the characteristics and thresholds of the different mechanoreceptors [8,1]. The ***kinesthetic/proprioceptive*** subsystem (referred to as the kinesthetic system here) allows the nervous system to monitor the position and motion of limbs, along with the associated forces, and to receive information from sensory receptors in the skin around the joints, joint capsules, tendons, and muscles, as well as from motor-command signals [8]. The tactile and kinesthetic systems play roles of varying influence depending on the task we are performing. If we arrange their influence as axes on a graph, we can define a space for plotting tasks we perform in VEs as shown in **Figure 1**.

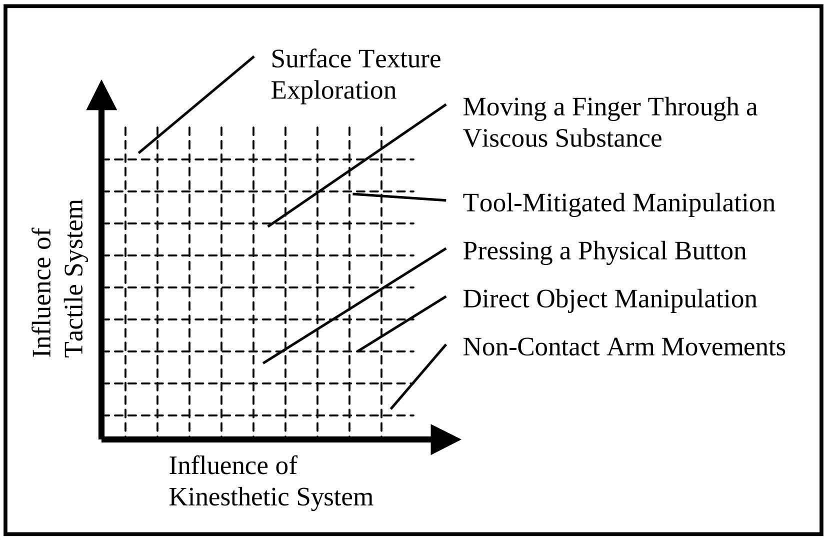

Figure 1: Influence of Tactile System vs. Influence of Kinesthetic System

It is clear that obtaining an accurate understanding of the haptic system requires more than simply studying the tactile and kinesthetic systems in isolation. Gibson formulates this notion by stating that to "lump one set of receptive systems together as *touch* and another as *kinesthesis*, then, is to obscure the function of the systems in combination" [10, p.484]. He goes on to argue that sensing is different if we are passively being touched, *e.g.*, a probe is poked into the finger pad, versus actively touching, *e.g.*, exploring the probe with the finger pad. Taking this notion into account could have a major influence on how we design interfaces that incorporate the haptic sense.

Another view is taken by Srinivasan [8] who uses the terms *exploration* and *manipulation* to describe a framework for studying biomedical, sensory, motor, and cognitive subsystems. The process of exploration is mainly concerned with extracting attributes of objects, and is therefore a tactile-dominated task. Manipulation is mainly concerned with modifying the environment, and is therefore dominated by kinesthetic feedback. Indeed, both subsystems play a role in almost every type of interaction; it is the strength of their influence that varies.

In terms of producing haptic feedback, passive approaches use properties inherent in physical props to convey stimuli [13,2]. These systems do not require any computer control to provide a stimulus, and can provide high-fidelity, inexpensive (both computationally and monetarily) feedback. An example of this would be to register a physical railing with the representation of a railing in a VE, allowing the user to feel the real railing when reaching for the virtual one [14]. Props can be instrumented with sensors to make them into input devices [13]. Because these objects are passive, however, the range of feedback any given object can provide is limited in both type and strength. Therefore, a more flexible approach to stimulating the haptic sense is through the use of active-haptic feedback [15]. These approaches typically deliver stimuli using some sort of force-reflecting device, such as an arm-linkage employing sensors and actuators [16,17], force-feedback gloves [18], or master manipulators [19].

Much of the empirical work into determining how we sense touch has focused on the hands, and, in particular, on the finger pad of the index finger [20]. Some approaches combine tactile and kinesthetic stimulation into a single system. Howe [17] describes a teleoperation system for supporting a precision pinch grasp, using a two-fingered linkage. Wellman and Howe [21] augmented this device by attaching inverted speakers, controlled by output from a PC sound card, to each of the master finger brackets, thereby adding a vibratory component to the feedback system. Kontarinis *et al.* [22] describe the addition of arrays of shape memory alloy (SMA) wire actuators to this system for providing feedback directly to the finger pad. Howe *et al.* [23] describe methods for improving the responsiveness of SMA actuators by producing faster heating response using feed-forward derivative compensation, faster cooling response using pneumatic cooling jets, and reduced hysteresis through the use of position-sensing LEDs.

Some researchers have conducted studies using SMA arrays [24,20]. In addition to SMA, other materials can also be used for tactile stimulation (see [25] for a comparison of material properties). Some researchers have focused on our ability to discern combinations of sinusoidal waveforms at differing frequencies [9,26,24]. Others have looked at our ability to discern patterns in the presence of temporal masking of pattern elements [20]. In teleoperation experiments, researchers have looked at how vibratory feedback can be used to regulate the amount of pressure applied at the slave side [27].

Some researchers have begun to explore the use of vibrating motors, similar to those used in pagers and cell phones, as a means of providing inexpensive haptic feedback [28,29,30]. Hughes and Forrest [12] instrumented a standard desktop mouse with vibration elements and discuss its application to multivariate map exploration. We propose combining low-cost vibrotactile (VT) feedback units with feedback through other channels to relay contact or other information to the user. In the absence of actual, physical walls, tactors mounted on the user (*e.g.,* on the arm) could be triggered to simulate physical contact between the arm and a virtual wall. It is hoped that this integration of VT feedback into a VE system would thereby improve a user's sense of contact made with objects in the VE.

Commercial products have also emerged, both in the home-entertainment and research areas. Simple vibrotactile attachments for game console controllers have been commercially available for some time now. Sony, Nintendo, and Microsoft all produce devices utilizing eccentric motors to add vibration to the gaming experience. Consumer-grade force-feedback joysticks from Microsoft and Logitech, and commercial-grade force-feedback joysticks from Immersion Corporation [31] use actuators to control the resistance/force delivered to the handle of the controller. Virtual Technologies, Inc., produces a glove instrumented with six VT units, five on the fingers and one on the palm. This is a representative, rather than exhaustive, list of commercial force-feedback offerings, and underscores the attention currently being paid to the use of VT feedback by industry.

2.3 Research Questions

We see several important steps within VT feedback research where more work is required, and posit them as fertile areas of short- to medium-term research. These include:

1. Methodical studies of the parameter sensitivity of VT feedback, across devices, users, applications, *etc.*,
2. A framework for combining VT with other feedback modalities, and
3. Exploration of application areas (tasks) where this holistic feedback could be effective.

Currently, we are concentrating our efforts on designing a testbed for comparing different types and amounts of multimodal feedback. This will allow us to address some of these issues.

3. CURRENT PROTOTYPE

We have built a prototype VT feedback system using a proprietary control circuit (**Figure 2**) and commercial, off-the-shelf tactors. The TactaBoard is based on a Microchip PIC 16F873-20 microcontroller. It is clocked at 20 MHz, supports 2 kilobytes of program memory (used to store the program and default values), 128 bytes of EEPROM (non-volatile memory used to store configuration values for the board), and 192 bytes of RAM. Support circuitry includes a Maxim MAX233CPP serial interface chip, and one transistor per tactor for switching the tactor supply voltage.

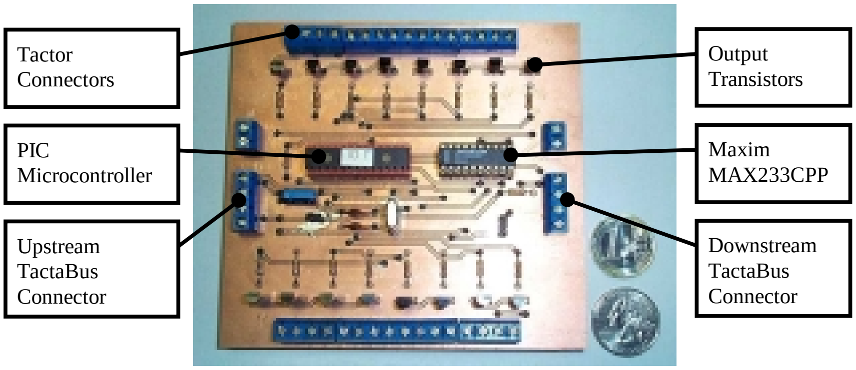

Figure 2: TactaBoard Prototype

Each TactaBoard is a self-contained unit for controlling 16 tactors, and communicates with the host computer using an RS-232 serial connection. Additional TactaBoards can be connected to the first board using a proprietary TactaBus connection. Each TactaBoard has connectors for the tactors, power, and the TactaBus cables. The high-level layout of a system with multiple TactaBoards is shown in **Figure 3**.

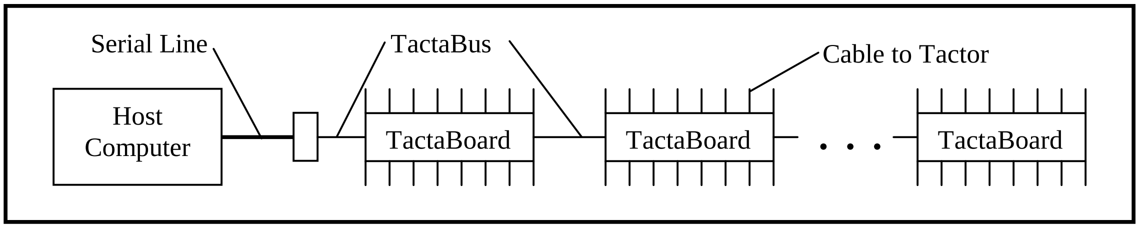

Figure 3: Multiple TactaBoards

The tactors we are using are the vibration motors found in most cell phones or pagers. They use an eccentric mass attached to the shaft of a DC motor to provide vibration. Varying the voltage changes the spin rate, thereby changing the vibration. By placing the tactors at strategic locations on the body, and triggering them appropriately, we can provide a sense of contact.

3.1 Design Goals

VR has not lived up to its initial hype, and we feel one reason for this is the lack of adequate feedback to allow users to perform precise tasks effectively. Providing better support for object manipulation should improve this situation. The TactaBoard system has been designed with certain characteristics in mind. These include:

Energy Efficiency: Pulse-Width Modulation (PWM) allows for less power to be consumed, compared to constantly feeding analog signals to the tactors.

Flexibility: Different types of tactors can be controlled using a single system. In addition, each board can either receive its power from the TactaBus, or external power can be provided through the on-board power connector. Also, each TactaBoard can operate at a different update frequency.

Scalability: Each TactaBoard can support up to 16 tactors, and up to 255 TactaBoards can be connected on a single TactaBus.

Mobility: The system can use a wireless modem, connected directly to the TactaBoard, to communicate with a host. Alternatively, combined with a handheld computer, the system can run completely autonomously.

Distributability:	Each TactaBoard refreshes its 16 tactors independently of the other TactaBoards, thereby increasing the overall update capacity of the system.
Compactness:	Each TactaBoard is about the size of a handheld computer (*i.e.*, PDA).
Expense:	We have used mainstream electronic components for our design, reducing the cost of the parts.
Simplicity:	A minimum number of components has been incorporated into the design, thereby reducing the complexity of assembly.
Updateability:	The firmware on each TactaBoard can be updated using an in-socket updating process.

In addition to VE applications, these characteristics make this system well suited for a variety of other application areas described later.

3.2 Pulse-Width Modulation

A main concept used by the TactaBoard is Pulse-Width Modulation (PWM) [32]. This is similar in nature to the way commercial "dimmer switches" work. The idea is to vary the amount of *time* voltage is sent to a device, rather than varying the *level* of voltage that is sent. This means that PWM devices can be installed into existing electrical systems without the need for varying the power being supplied to the system. As an example, **Figure 4** shows a comparison of how to reduce an output voltage from 50% of to 25% by decreasing the input voltage (a) and by decreasing the duty cycle of a PWM signal (b). As an example, if a light bulb requires 9 volts in order to achieve maximum illumination, we can achieve half of the illumination by reducing the input voltage to 4.5 volts, or by sending the 9 volt input to the bulb 50% of the time at some frequency. Maintaining a sufficient frequency eliminates the apparent flicker of the bulb.

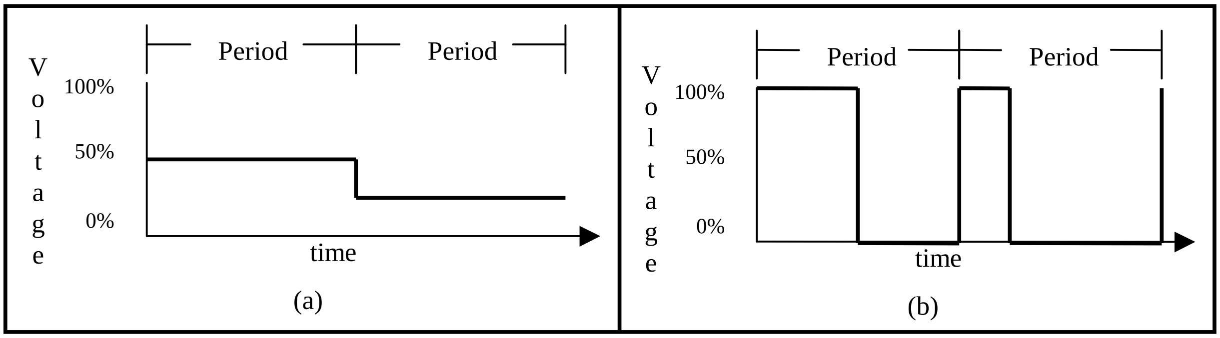

Figure 4: Varying the Output: The resulting output produced by halving the input voltage (a) can be achieved by halving the ON time (duty cycle) within a pulse period (b).

Proprietary firmware we have written, running on each TactaBoard, performs the generation of a separate PWM signal for each tactor connected to the TactaBoard. This firmware updates the PWM signal for each tactor while handling requests from the host computer as they arrive on the TactaBus. A signal frequency ranging from 0.3 Hz to 316 Hz can be generated. The period can vary from 3.16 milliseconds to 3.3 seconds, and the switching resolution (*i.e.*, the resolution of the duty cycle) can be computed as the period divided by 256, which results in a range from 12.4 microseconds to 13 milliseconds. The required update rate described in studies found in the literature, 10-250 Hz [1,11], is within the range supported by the TactaBoard. The frequencies in the literature are reported primarily for the finger pad. Studies will have to be done to measure sensitivity at other body locations.

3.3 Software API

The low-level protocol uses standard serial output and a byte stream for commands. On top of this, we have developed an Application Programming Interface (API) for programs on the host computer to control the devices using the TactaBoard system. We have developed APIs for C/C++ and Tcl/Tk, with Java support currently under development. Extending support to additional languages or other hosts, such as handheld computers, is straightforward.

Using a connection-oriented approach, the API allows the application to control the output level of each individual tactor by passing a board-ID, tactor-ID, and target level. Each of these parameters is one byte in size. Passing a value of 255 for the board-ID broadcasts the command to all boards for the tactor specified by tactor-ID, and passing a value of 255 as the tactor-ID broadcasts the command to all tactors on the board specified by board-ID. **Figure 5** shows a code example for generating a sine wave for a single tactor.

```
// sinetest.cpp
// Test of TactaBoard API
// Set Output 0 on Board 0 to
//   the output of the sine function.

#include <stdio.h>
#include <math.h>
#include "tactaboard.h"

const unsigned char BOARD_ID  = 0;
const unsigned char OUTPUT_ID = 0;

int main( int argc, char* argv[] )  {
  TactaBoard tb;   // Instance of a TactaBoard object.
  double x = 4.71; // Make first value start at 0.
  unsigned char v; // Value to set the output to.

  tb.open( "COM1" );   // Open the serial port.

  for( int i = 0; i < 1000; i++ )  {
    // Value: 0 <= v <= 255
    v = ( 1.0 + sin(x) ) * 127.5;

    // Set output 0 on board 0 to v.
    tb.SetOutputValue( BOARD_ID, OUTPUT_ID, v );
    x = x + 0.1;
  }
  return( 0 );
}
```

Figure 5: Sample code for generating values using a sine wave.

3.4 Device Types

A range of tactors can be controlled using the TactaBoard. We are currently using two different form factors, one cylindrical and one disk shaped. The cylindrical tactor (**Figure 6**) is 6 mm (1/4") in diameter x 14 mm (9/16") long, weighs 2 grams, and provides up to 4000 RPM on 1.5 VDC. The disk-shaped tactor (**Figure 7**) is 14 mm (9/16") in diameter x 3 mm (1/8") thick (slightly smaller than a US dime), and operates on 1.5 VDC (no RPM rating was given). These tactors are lightweight, draw low to moderate current, and are inexpensive (about US$3), because they are mass produced for many types of larger devices, such as cell phones.

Figure 6: Cylindrical Tactor **Figure 7: Disk-Shaped Tactor**

These tactors have the advantage of being low in cost, but precisely controlling the stimulus is problematic. Ideally, one would like to have independent control over the frequency and amplitude of the tactor. Because we only have control over the voltage being applied, it is mechanically impossible to decouple the frequency and amplitude of the stimulus. Other devices, such as those used in tactile aids for the hearing impaired, like the Tactaid from Audiological Engineering Corporation, support independent control of both frequency and amplitude, but cost approximately US$40. These devices can also be driven by the TactaBoard with some additional electronics to translate a PWM signal to frequency and amplitude control. Each of these values could be attached to a different output on the TactaBoard, so that only eight such devices could be attached to a single board.

It is important to note that the system can act as an intelligent voltage regulator that is independent of the actual voltage being regulated. The current prototype supports any output device requiring 6 volts or less. This allows, for example, one TactaBoard to control devices requiring 1.5 volts, and another to control devices requiring 6 volts, on a single TactaBus. This allows a single, unified interface to be used, even if the output devices vary. For example, to simulate feedback for someone kicking in a door, one could use a fairly substantial solenoid attached to the boots of the user, while devices providing finer stimulus control are used on the hands. Devices requiring higher voltages can be supported using additional switching hardware.

4. VARYING VT FEEDBACK

There are a number of parameters that can be manipulated to provide different types of VT feedback. These can be divided into parameters that affect each tactor individually, and those that affect a group of tactors.

Parameters for Individual Tactors:

1. ***Frequency***: Modulation can be used to vary the frequency of the feedback [24,9].
2. ***Amplitude***: Modulation can be used to vary the intensity of the feedback [9].
3. ***Temporal Delay***: By varying the time-delay of a stimulus, we can aid the identification of spatial patterns [28,20,9].
4. ***Pulse***: Pulses can be output in differing patterns in order to convey information.

Parameters for Groups of Tactors:

1. ***Waveform***: Applying different waveforms to define the stimulus across the array will allow more-complex stimulation to be displayed. These waveforms can be viewed as tactile "images," and their propagation can be viewed as "moving images."
2. ***Tactor Placement***: It is well known that the concentration and sensitivity (*i.e.*, type) of haptic receptors in the human body vary with location. Feedback will need to vary with the location on the body being stimulated. However, people are aware of the gross spatial location of tactors on different parts of the body, such as the difference between stimulating the shoulder versus the leg.
3. ***Interpolation Method***: By varying the vibration of adjacent tactors over space and time, a relatively-sparse area of the skin can be fooled into believing that the tactor resolution is higher than it actually is [29].

Some work has been done to compare how a user's performance or perception of data varies when:

1. visual and VT channels are fed from the same data [33],
2. visual and VT channels are fed from different, but complementary data [12],

3. visual and VT channels are fed from different, but conflicting data [12], and
4. visual-only feedback versus visual+VT feedback are provided [34,33].

Our prototype will allow us to rapidly configure, deploy, and experiment with a wide range of form factors. As most of the previous research in the use of VT feedback has focused on the hand, the effectiveness of applying VT feedback to other parts of the body is still an open area of inquiry. Rupert [29] has developed a VT vest for aiding pilots in determining the down vector during flying maneuvers. Ertan *et al.* [35] developed a VT vest for aiding in navigation tasks, to add quality of life to the blind. Tan *et al.* [36] have embedded tactors in a three-by-three array configuration into an office chair, as an additional feedback channel for traditional user interfaces, or as an aid for drivers to give some indication of surrounding traffic. In subsequent work [37], they describe experiments conducted to tease out the differences between VT feedback on Earth and in reduced gravity. They found that the stimulus presented to the user was not effected by a change in gravity, and concluded that differences in performance on tasks involving VT feedback must therefore be due to the increased cognitive load encountered in reduced gravity. Campbell *et al.* [33] looked at multimodal systems for path-tracing tasks. They compared visual-only, visual+matched-tactile, and visual+unmatched-tactile feedback conditions, and found that tactile feedback can help if it is matched with visual feedback.

Most of the literature we have found, which reports on using computer-controlled VT feedback, describes systems that use the tactors in a digital manner (*i.e.*, they turn the tactors on or off) to provide a stimulus. The TactaBoard system allows for the VT feedback presented to the user to be varied in a pseudo-continuous manner, with a maximum of 256 levels of vibration. This allows us to add an additional parameter to the use of VT feedback.

This, combined with the ability to deploy a large number of tactors, allows us to expand the space of possible applications.

5. APPLICATIONS FOR VT FEEDBACK

A system with the characteristics of the TactaBoard could be applied to many different areas. Arrays of VT feedback devices could be placed on parts of the body (for instance, on the forearms), and users could be fed collision information as their arms intersect virtual objects. This "virtual bumping" into the environment might aid users in maneuvering. Physical props could be outfitted with VT devices to provide feedback for when the prop contacts virtual objects. For instance, a rifle prop could be outfitted to give the user a sense of bumping the barrel into something, or resting it on a support. In addition to virtual contact, many other applications suggest themselves.

5.1 Data Perceptualization

Hughes and Forrest [12] talk about *data perceptualization* as the extension of the notion of data visualization to cover all the senses, as well as the associated cognitive processing. They note that a large percentage of the literature on data visualization deals with presenting data from a single sensory channel. They posit that if we could use multiple channels to provide feedback, we might be able to support the understanding of a larger number of variables.

As a data perceptualization technique, we are experimenting with the use of a single tactor, mounted on a stylus, for exploring a volume data set. As the user moves the stylus through the data set, the vibration fed back through the stylus is proportional to the value of a particular variable in the data. It will be interesting to compare this inexpensive device with similar techniques which use force-reflecting devices, such as the PHANToM.

5.2 Spatial Awareness

Rupert [29] has developed a system using a vest with tactors sewn into it. This system allows pilots to better judge the down-vector when performing aerial maneuvers that alter the pilot's vestibular system in such a way as to cause possibly-fatal errors in judgment. A similar system could be used by scuba divers to orient them as to the up-vector.

Systems have been used for decades in devices that substitute VT feedback for sounds in the real environment for use by the hearing impaired. These systems are typically limited to a few (usually two) tactors for feedback. With the TactaBoard system, a large number of tactors could be attached to different parts of the body to increase the fidelity of the feedback possible for the hearing impaired, improving their quality of life.

The automobile industry could embed tactors in the driver's seat or steering wheel as a feedback system for alerting or notifying drivers of certain situations. For example, a monitoring system could be used to measure how close a car is to the line markers on the road, and alert the driver using vibrotactile feedback when the car nears the line.

5.3 Navigation Aid

GPS systems used today in many vehicles could be coupled with a TactaBoard system in a route-following application to alert drivers when it is time to make a turn. If the tactors are spaced at different locations in the driver's seat, spatial information can be used as well.

In firefighting scenarios, a firefighter with a GPS transponder could be guided through a smoke-filled building in order to search for victims (*e.g.*, find the bedrooms). This could be done autonomously, or using a human guide. Because these environments are often very loud, verbal communication is not always an option, so VT feedback could provide the same information using a nonverbal channel.

5.4 Nonverbal Communication

Some of our research is driven by the application of VT feedback for allowing members of a special forces team to communicate nonverbally. Tactors placed on the team members can be controlled using standard hand signals interpreted using pattern recognition, passed to team members wirelessly, and displayed using VT feedback. Special forces also often communicate with each other through physical contact. One member might kick the back of the shoe of another member manning a position in front of them to move the person along (*e.g.*, off of a door). They touch shoulders when lining up in a stack prior to entering a room. They maintain contact while moving, so as to track the other's position while covering different fields of fire. We could use VT techniques, coupled with location sensing, to feed similar proximity information to members of a team, so that they can use tactile cues to communicate at a distance, or through walls.

5.5 Computer Interface Support

A stylus form factor could be used in a virtual modeling system, such as in molding virtual clay. The VT feedback could be varied as a function of how hard the user is pushing on the surface, taking into account surface compliance, and therefore possibly improving the user's overall sense of the surface being molded. Studies into human VT perception using this point-contact approach could be compared with similar studies done using other commercial active-haptic feedback devices [38].

Snibbe *et al.* [39] discuss the use of instrumented, special-purpose interface devices for controlling the flow of digital visual and auditory media in editing and searching tasks. The authors draw on their backgrounds as audio/video engineers to apply their insights into the physical feedback that make non-digital interfaces (*e.g.*, editing machines) easy and precise to use, and how these qualities have been lost in the move to mouse-based control interfaces.

This innovative paper underscores the need to include domain-specific knowledge into interface design.

Traditional computer interface devices can be augmented to provide additional information about mouse [34] or TrackPoint [33] movement. Telemanipulation systems using this type of feedback can allow users to get a better understanding of the remote environment [16,19].

The virtual contact work reported here is partially driven by a desire by the United States Marines to use VT feedback in dismounted infantry simulations to improve the user's sense of collision with purely virtual objects. Soldiers training for a mission can use this feedback to improve the realism of their training environments. The tactors can be placed in garments worn by soldiers, or in physical props (*e.g.*, weapons) carried by them, depending on the situation.

6. CONCLUSIONS

We have designed a prototype system for integrating VT feedback with visual and auditory feedback in VEs. This system is flexible enough for us to test different combinations of feedback, and measure the impact of these combinations on the ability of users to understand the nature of contact with purely virtual objects. After further research and testing, we believe vibrotactile feedback will have a significant impact on improving the user experience in virtual environments.

Furthermore, we have provided a starting point for framing the ways of combining feedback to multiple sensory channels for virtual contact studies. In order to take advantage of the bandwidth that humans typically use in the real world when interacting with objects, research in this direction will allow VE system designers to provide a richer, more-expressive environment to support effective interaction.

ACKNOWLEDGEMENTS

The authors would like to thank the reviewers for their insightful comments which have greatly improved this paper. Funding for this work was provided by the Office of Naval Research under Grant No. N000140110107, and by DARPA under Grant No. N66001-98-x-6905.

REFERENCES

1. Kontarinis D, Howe R. Tactile display of vibratory information in teleoperation and virtual environments. Presence: Teleoperators and Virtual Environments 1995; 4(4); 387-402.
2. Lindeman R, Sibert J, Hahn J. Towards usable VR: An empirical study of user interfaces for immersive virtual environments. In: Proc. of ACM CHI '99 1999; 64-71.
3. Wenzel E. Localization in virtual acoustic displays. Presence: Teleoperators and Virtual Environments 1992; 1(1); 80-107.
4. Takala T, Hahn J. Sound Rendering. In: Proc. of ACM SIGGRAPH '92 1992; 211-220.
5. Foner L. Artificial synesthesia via sonification: a wearable augmented sensory system. Mobile Networks and Applications 1999; 4(1); 75-81.
6. Mine M, Brooks F, Séquin C. Moving objects in space: Exploiting proprioception in virtual-environment interaction. In: Proc. of ACM SIGGRAPH '97 1997; 19-26.
7. Hoffman H, Hollander A, Schroder K, Rousseau S, Furness T. Physically touching and tasting virtual objects enhances the realism of virtual environments. Virtual Reality: Research, Development, and Application 1998; 3; 226-234.
8. Srinivasan M. Haptic Interfaces, Virtual Reality: Scientific and Technical Challenges. In: Report to the Committee on Virtual Reality Research and Development, National Research Council, Durlach N, Mavor A eds. Washington: National Academy Press. 1994; 161-187.
9. Tan H, Durlach N, Reed C, Rabinowitz W. Information transmission with a multi-finger tactual display. Perception & Psychophysics 1999; 61(6); 993-1008.
10. Gibson J. Observations on Active Touch. Psychological Review 1962; 69(6); 477-491.
11. Loomis J, Lederman S. Tactual Perception. In: Handbook of Perception and Human Performance: Vol. 2: Cognitive Processes and Performance. Boff K, Kaufman L, Thomas J eds. New York: John Wiley and Sons. 1986; Ch. 31.
12. Hughes R, Forrest A. Perceptualisation Using a Tactile Mouse. In: Proc. Visualization '96 1996; 181-186.
13. Hinckley K, Pausch R, Goble J, Kassell N. Passive real-world interface props for neurosurgical visualization. In: Proc. of ACM CHI '94 1994; 452-458.
14. Hodges L, Rothbaum B, Kooper R, Opdyke D, Meyer T, North M, de Graaff J, Williford J. Virtual environments for treating the fear of heights. IEEE Computer 1995; 28(7); 27-34.
15. Salisbury K, Brock D, Massie T, Swarup N, Zilles C. Haptic rendering: programming touch interaction with virtual objects. In: Proc. of the 1995 Symp. on Interactive 3D Graphics 1995; 123-130.

16. Brooks F, Ouh-Young M, Batter J, Kilpatrick P. Project GROPE - Haptic displays for scientific visualization. In: Proc. of ACM SIGGRAPH '90 1990; 177-185.
17. Howe R. A force-reflecting teleoperated hand system for the study of tactile sensing in precision manipulation. In: Proc. of the 1992 IEEE Int’l. Conf. on Robotics and Autom. 1992; vol. 2; 1321-1326.
18. Burdea G, Zhuang J, Roskos E, Silver D, Langrana N. A portable dexterous master with force feedback. Presence: Teleoperators and Virtual Environments 1992; 1(1); 18-28.
19. Iwata H. Artificial reality with force-feedback: Development of desktop virtual space with compact master manipulator. Computer Graphics 1990; 24(4); 165-170.
20. Craig J. Vibrotactile pattern isolation/integration. Perception & Psychophysics 1998; 60(5); 888-899.
21. Wellman P, Howe R. Towards realistic vibrotactile display in virtual environments. In: Proceeding of the ASME Dynamics Sys. and Control Division, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Sys., Alberts T. ed. 1995; DSC-Vol. 57-2; 713-718.
22. Kontarinis D, Son J, Peine W, Howe R. A tactile shape sensing and display system for teleoperated manipulation. In: Proc. of the Int’l. Conf. on Robotics and Autom. 1995; 641-646.
23. Howe R, Kontarinis D, Peine W. Shape memory alloy actuator controller design for tactile displays. In: Proc. of the 34th IEEE Conf. on Decision and Control 1995; vol. 4; 3540-3544.
24. Bensmaïa S, Hollins M. Complex tactile waveform discrimination. J. of the Acoustical Soc. of America 2000; 108(3); 1236-1245.
25. Fletcher R. Force transduction materials for human-technology interfaces. IBM Sys. J. 1996; 35(3&4); 630-638.
26. Choi S, Tan H. A parameter space for perceptually stable haptic texture rendering. In: Proc. of the Fifth PHANToM Users Groups Workshop, Aspen, CO, October 2000.
27. Amanat I, Riviere C, Thakor N. Teleoperation of a dexterous robotic hand using vibrotactile feedback. In: Proc. of 16th Annual Int’l. Conf. of the IEEE Eng. in Med. and Bio. Soc. 1994; 1059-1060.
28. Massimino M, Sheridan T. Sensory substitution for force feedback in teleoperation. Presence: Teleoperators and Virtual Environments 1993; 2(4); 344-352.
29. Rupert A. An instrumentation solution for reducing spatial disorientation mishaps. IEEE Eng. in Med. and Bio. 2000; March/April; 71-80.
30. Cheng L-T, Kazman R, Robinson J. Vibrotactile feedback in delicate virtual reality operations. In: Proc. of the Fourth ACM Int’l. Conf. on Multimedia 1996; 243-251.
31. Okamura A, Dennerlein J, Howe R. Vibration feedback models for virtual environments. In: Proc. of the IEEE Int’l. Conf. on Robotics and Autom. 1998; 674-679.
32. Barr M. Pulse Width Modulation. Embedded Systems Programming, Sep. 2001; 103-104.
33. Campbell C, Zhai S, May K, Maglio P. What You Feel Must Be What You See: Adding Tactile Feedback to the Trackpoint. In: Proc. of INTERACT'99: 7th IFIP Conference on Human Computer Interaction 1999; 383-390.
34. Akamatsu M, MacKenzie I. Movement Characteristics Using a Mouse with Tactile and Force Feedback. Int'l J. of Human-Computer Studies 1996; 45; 483-493.
35. Ertan S, Lee C, Willets A, Tan H, Pentland A. A wearable haptic navigation guidance system. In: Digest of the Second Int'l Symp. on Wearable Computers, Oct. 19-20, Pittsburgh, PA 1998; 164-165.

36. Tan H, Lu I, Pentland A. The chair as a novel haptic user interface. In: Proc. of the Workshop on Perceptual User Interfaces, Oct. 19-21, Banff, Alberta, Canada 1997; 56-57.
37. Traylor R, Tan H. Development of a wearable haptic display for situation awareness in altered-gravity environment: Some initial findings. In: Proc. of the Int'l Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Orlando, FL, 2002; 159-164
38. Yamashita J, Lindeman R, Fukui Y, Morikawa O, Sato S. On determining the haptic smoothness of force-shaded surfaces. In: Conference Abstracts and Applications, SIGGRAPH 2000; 240.
39. Snibbe S, MacLean K. Haptic Techniques for Media Control. CHI Letters (Proc. UIST 2001) 2001; 3(2); 199-208.