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VIBROTACTILE FEEDBACK FOR HANDLING VIRTUAL CONTACT IN IMMERSIVE VIRTUAL ENVIRONMENTS

Robert W. Lindeman[1] and James N. Templeman[2]

[1]Dept. of Computer Science, The George Washington University, 801 22nd St., NW, Washington, DC 20052 USA
[2]CODE 5513, Naval Research Laboratory, 4555 Overlook Ave, SW, Washington, DC 20375 USA

ABSTRACT

This paper addresses the issue of improving a user's perception of contacts they make with 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 designed and implemented. These systems have increased our understanding of the nature of how humans perceive contact. However, providing effective, general-purpose haptic feedback solutions has proven illusive.

We propose a more-holistic approach, incorporating feedback to several modalities in concert. We describe a low-cost, prototype system we have developed for delivering vibrotactile feedback to the user, discuss different parameters that can be manipulated in order to provide different sensations, and propose ways in which this simple feedback can be combined with feedback to other modalities to create a better understanding of virtual contact.

1. INTRODUCTION

Virtual contact research addresses the problem of what feedback to provide when the user comes into contact with a purely virtual object (PVO) within a virtual environment (VE). We define virtual reality as fooling the senses into believing they are experiencing something they are not actually experiencing. In the visual domain, for instance, this means creating the scenery and viewpoint changes that induce the user into believing that what they are seeing is "real," or at least predictable.

As humans, we interact with our environment using multiple feedback channels, all coordinated to help us make sense of the world around us. The lack of 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 (Kontarinis and Howe, 1995; Lindeman *et al.*, 1999). 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 given a sensorially-deprived environment, because the only feedback the user receives is that which we provide.

2. PREVIOUS WORK

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

2.1 The Sensory Channels

For the most part, it is the visual sense that has received the most attention from VE researchers. Some work has been done on fooling the other senses. After visuals, the auditory sense has received the most attention (Wenzel, 1992). The area of haptics has received increasing attention from VE researchers over the past decade. The proprioceptive sense has also received some attention (Mine *et al.*, 1997). The senses of smell and taste have received less attention, because of their inherently intrusive nature (Hoffman *et al.*, 1998).

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. Furthermore, providing more than one type of stimuli allows researchers to achieve adequate results using lower "resolution" displays (Srinivasan, 1994). This becomes important for low-cost applications, like game consoles or aids for the hearing impaired (Tan *et al.*, 1999). For example, relatively-simple haptic feedback could be combined with high-quality visual images, which have become very inexpensive to produce, in order to create a similar sense of contact produced by more-expensive haptic displays.

2.2 The Human Haptic System

Though much work has been done in the study of the human haptic system, there is still no unequivocal evidence showing exactly how haptic input is transformed from external stimuli into internal understanding. Broadly, the human haptic system can be broken down into two major subsystems. The ***tactile*** system, referring to the sense of contact with an object, receives information mediated by the response of mechanoreceptors in the skin within and around the contact area. Experiments have been performed into defining the characteristics and thresholds of the different mechanoreceptors (Srinivasan, 1994; Kontarinis and Howe, 1995). The ***kinesthetic*** system (also called the *proprioceptive* system), referring to the position and motion of limbs along with the associated forces, receives information from sensory receptors in the skin around the joints, joint capsules, tendons, and muscles, as well as from motor-command signals (Srinivasan, 1994). 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.

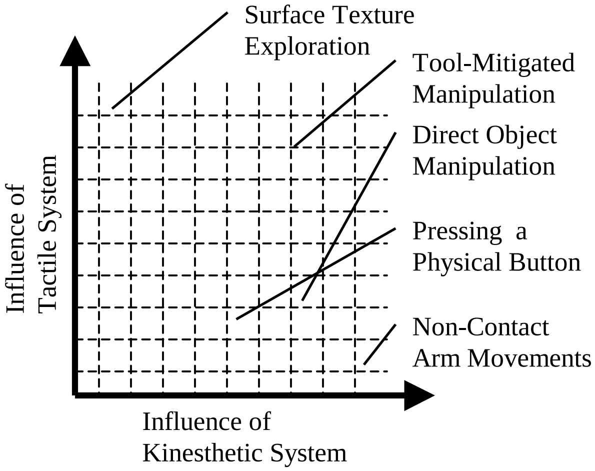

Figure 1: Influence of Tactile System vs. Influence of Kinesthetic System

Srinivasan (1994) 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 (Hinckley *et al.*, 1994; Lindeman *et al.*, 1999). 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 (Hodges *et al.*, 1995). 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 common approach to stimulating the haptic sense is through the use of active-haptic feedback (Salisbury *et al.*, 1995). These approaches typically deliver stimuli using some sort of force-reflecting device, such as an arm-linkage employing sensors and actuators (Brooks *et al.*, 1990; Howe, 1992), force-feedback gloves (Burdea *et al.*, 1992), or master manipulators (Iwata, 1990).

Much of the empirical work into determining how we sense touch has focused on the hands, and, in particular, on the finger pad (Craig, 1998). Some approaches combine tactile and kinesthetic stimulation into a single system. Howe (1992) describes a teleoperation system for supporting a precision pinch grasp, using a two-fingered linkage. Wellman and Howe (1995) 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.* (1995) describe the addition of arrays of shape memory allow (SMA) wire actuators to this system for providing feedback directly to the finger pad. Howe *et al.* (1995) 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 (Bensmaïa and Hollins, 2000; Craig, 1998). In addition to SMA, other materials can also be used for tactile stimulation (see Fletcher, 1996, for a comparison of material properties). Some researchers have focused on our ability to discern combinations of sinusoidal wave forms at differing frequencies (Tan *et al.*, 1999; Bensmaïa and Hollins, 2000). Others have looked at our ability to discern patterns in the presence of temporal masking of pattern elements (Craig, 1998). In teleoperation experiments, researchers have looked at how vibratory feedback can be used to regulate the amount of pressure applied at the slave side (Amanat *et al.*, 1994).

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 (Massimino and Sheridan, 1993; Rupert, 2000; Cheng *et al.*, 1996). We propose combining these low-cost vibrotactile (VT) feedback units with feedback through other channels to relay contact information to the user. In the absence of actual, physical walls, tactors mounted on the extremities of a user (*e.g.*, on the arm) could be triggered to simulate 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. Nintendo, Sega, and Sony 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 (Okamura *et al.*, 1998), use actuators to control the resistance/force delivered to handle controllers. 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.

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

We are currently addressing these issues in our research.

3.1 Current Prototype

We have built a prototype VT feedback system using commercial, off-the-shelf tactors, and a proprietary control circuit. A simple protocol is used to send commands from a host computer to a microcontroller unit (MCU) via a standard serial connection (Figure 2). The MCU interprets the commands from the host, and through control circuitry, is able to set the vibration level of any tactor to one of 32 levels.

A high-level Application Programming Interface (API) allows the application to control the vibration level of each tactor individually. The tactors are inexpensive DC pager motors, each with an eccentric weight, and a maximum of 1,000 revolutions per second. By integrating this type of system into a traditional VE system, we can experiment with ways of combining visual, audio, and haptic feedback to produce effective contact feedback.

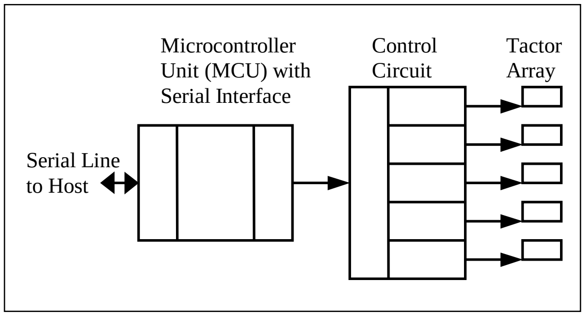

Figure 2: Prototype vibrotactile feedback system.

3.2 Varying VT Feedback

There are a number of parameters that can be manipulated to provide varying VT feedback. These can be divided into parameters which 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 (Bensmaïa and Hollins, 2000; Tan *et al.*, 1999).
2. ***Amplitude***: Modulation can be used to vary the intensity of the feedback (Tan *et al.*, 1999).
3. ***Temporal Delay***: By varying the time-delay of a stimulus, we can aid the identification of spatial patterns (Massimino and Sheridan, 1993; Craig, 1998; Tan *et al.*, 1999).

Parameters for Groups of Tactors:

1. ***Waveform***: Applying different waveforms to the propagation of a 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.
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 (Rupert, 2000).

Our prototype allows us to rapidly configure, deploy, and experiment with a wide range of form factors. We are currently focusing on stylus, hand-controller, and glove form factors. Physical props could be outfitted with VT devices to provide additional feedback. 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. As a test environment, 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. Experiments could be done to compare how the user's perception of the data set varies when 1) the visual and VT channels are fed from the same variable, 2) the visual and VT channels are fed from different, but complementary variables, 3) the visual and VT channels are fed from different, but conflicting variables, 4) other senses are stimulated in addition to using the visual and VT channels.

4. CONCLUSION

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.

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