Towards Full-Body Haptic Feedback: The Design and Deployment of a Spatialized Vibrotactile Feedback System

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ABSTRACT

This paper presents work we have done on the design and implementation of an untethered system to deliver haptic cues for use in immersive virtual environments through a body-worn garment. Our system can control a large number of body-worn vibration units, each with individually controllable vibration intensity. Several design iterations have helped us to refine the system and improve such aspects as robustness, ease of donning and doffing, weight, power consumption, cable management, and support for many different types of feedback units, such as pager motors, solenoids, and muffin fans. In addition, experience integrating the system into an advanced virtual reality system has helped define some of the design constraints for creating wearable solutions, and to further refine our implementation.

Categories and Subject Descriptors: H.5.2 [User Interfaces]: Haptic I/O; H.1.2 [User/Machine Systems]: Human factors; I.3.6 [Methodology and Techniques]: Interaction techniques.

General Terms: Human Factors.

Keywords: Virtual reality, haptic feedback, full-body, CQB.

1. INTRODUCTION

In this paper, we present work we are doing on designing and implementing a system for delivering vibrotactile stimuli to the whole body for use in applications in both real and virtual worlds. The problem we are addressing is how to accomplish this in a way that minimizes cumber, yet still provides sufficient coverage of the body to impart collision information to the wearer in order to improve the overall realism of the experience. We use a two-pronged approach to this work. We have gone through several design-implement-evaluate-refine cycles within our lab. In addition, employing a user-centric approach, we have built and deployed several prototypes that have been integrated into the existing virtual reality systems of outside labs to gain better insights into several design aspects. This has brought us to a design that can be rapidly reconfigured using components that can be tailored to specific applications.

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2. BACKGROUND

A number of research groups have been exploring the use of multiple tactors (vibration units) in body-worn contexts [10, 11, 3, 2, 4, 14]. Over the past few years, we have been refining the hardware control system necessary for the support of a large number of output devices [7, 15]. In addition, we have constructed several systems for testing the use of vibration in various settings [17, 8, 9]. Haptic cues have successfully been used to draw the user's attention to an area of interest [12], to improve spatial awareness [10, 16, 1], and to deliver collision information when interacting with virtual objects [6]. It is this last area that is the focus of this paper.

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) [6]. Current technology limits our ability to provide as rich a virtual 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.

2.1. Types of Contact

There are a number of ways that we interact physically with objects in the real world. Intuitively, it seems we would like to provide cues in the virtual environment that vary in similar ways. We identify at least two types of contact: *impulse* and *continuous*. Impulse contact refers to ballistic interaction, such as knocking on a door or bumping into someone. Continuous contact is a more-common occurrence, and refers to situations where we maintain contact over a period of time. This type can be further broken down into the sub-classes of sliding and pushing or pulling.

Sliding. Sliding one object over another, such as our hand along the edge of a table, involves computing forces for satisfying penetration constraints, as well as for resultant friction, which influence our perception of the contact. As this subtype is primarily tactile in nature, surface texture will also have an effect on the experience.

Pushing/Pulling. Pushing or pulling on objects results in changes in forces that are a product of the exerted force, the weight of the object, deformability, and/or object movement constraints. In addition, these properties might change over the lifetime of the contact. This subtype is primarily kinesthetic in nature.

2.2. Providing the Feedback

Common approaches to providing haptic feedback typically use force-reflecting devices or exoskeletons. These devices can provide very effective feedback, but their use is limited by their expense and cumber. Our current approach positions tactors at different points on the body and controls their vibration intensity from a simulation computer using a wireless connection. Our use of vibrotactile feedback is built on previous work, and represents an evolutionary step towards the ultimate goal of providing a high-fidelity experience to users of VEs.

Kume *et al.* [5] introduced vibrotactile stimulation on the sole of the foot, and developed a slipper-like interface. They put two tactors on each sole and made use of phantom sensations elicited by these tactors. They measured the characteristics of the phantom sensation psychophysically, and found that the location, movement, and rotation of objects could be perceived.

Yano *et al.* [19] developed a suit-type vibrotactile display with 12 tactors attached to the forehead (1), palms (2), elbows (2), knees (2), thighs (2), abdomen (1), and back (one on the left side and one on the right). They examined the effectiveness of using this vibrotactile display for tasks that required the user to walk around a virtual corridor visually presented in a CAVE-like display. They showed that presentation of tactile cues was effective for imparting collision stimuli to the user's body when colliding with walls.

3. TACTAVEST HARDWARE SETUP

To support the delivery of vibrotactile cues, we have designed the TactaBoard system [7]. This system incorporates the control of 16 vibrotactile devices into a single interface, and multiple boards can be controlled from a single host computer, providing a scalable solution. We assembled the TactaBoard into a 15.2cm × 10.1cm × 5.1cm (6" × 4" × 2") box, two rechargeable batteries, and wireless communication, to form a TactaBox. Power for this application is provided by two rechargeable NiMH batteries, each with a capacity of 1800mAh, 6V at 500mA. The system runs completely from battery power, and uses a Bluetooth wireless serial bridge connection (Free2Move AB, model F2M02, free2move.se) to provide control from the host computer running the simulation software.

The pager-motor-type tactors, ruggedized in house, have an operating voltage range of 2.5-3.8V at 40mA. They have a frequency of 142Hz at 3.0V, and have a vibration quantity of 0.85G. We designed the shape of the tactor casing to be a disk with a cone on top that tapers to a near-point on the side that contacts the body. Several researchers have reported that maintaining good contact of the tactor with the body is a major problem in similar systems [10, 14], and this shape was chosen to mitigate this problem. The tactors are mounted using hook-and-loop fastener on the inside of the garment, allowing the tactor locations to be precisely adjusted. Light-weight cable carries the power signal to the tactors, and connects to the TactaBox using friction lock connectors inside the box.

The TactaBoard understands a set of simple commands to perform actions on behalf of the user, such as setting an output to a specified level (*i.e.*, "set motor 1 to level 150"), querying current levels, and pausing/unpausing an output. Any output command can be broadcasted to all outputs, allowing for the motors to be controlled in unison. Each output can hold any value between 0 and 255, inclusive. The level corresponds to a linear ramping of the duty cycle of a Pulse-Width Modulation (PWM) signal fed from the TactaBoard through the output connector. Each output holds the current level until receiving a new level, so only changes need to be sent to the TactaBoard.

4. GARMENT DESIGN

One of the major issues to be dealt with in designing garments is the variation in size of potential wearers. Because tactor location is so important for most applications, the garment needs to keep each tactor fairly tight against the body, even during vigorous movement. In addition, the garment needs to fit different-sized users. These two, seemingly opposing requirements are addressed by making the garment out of five individual pieces of stretch neoprene (**Figure 1**): two identical, yoke-shaped pieces for the upper torso, two thin straps for the elbows, and a belt for the lower-torso/waist area. Hook-and-loop fastener is used to secure the pieces in place, and during the donning procedure, each piece can be adjusted to correctly fit the user.

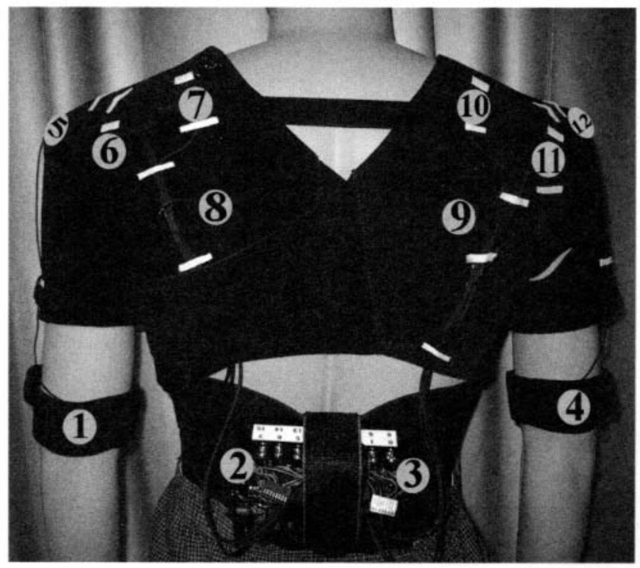

Figure 1: TactaVest (back) with Tactor Locations Marked (locations on the front of the vest are roughly equal to locations 2, 3, 8 & 9, but on the front)

Each of the yokes is anchored around the upper-arm, and fastened to its mate across the chest and back. A range of users can be accommodated using this approach, as the halves can be moved closer together or further apart depending on the user's girth. The elbow straps and belt can be adjusted in a similar fashion. Finally, two pairs of yokes, one large and one small, were fabricated, allowing coverage of a fairly large segment of our target population (in this case, U.S. Marines). In order to reduce the amount the garment restricts the movement of the user, care was taken to minimize the amount of material used in the overall garment. The use of five distinct pieces of material also helps in this regard. The garment's neoprene material helps reduce the vibration propagation and localize the vibrations.

4.1. Tactor Placement

Some previous work on vest design uses a regularly-spaced layout pattern for placing the tactors [10, 11, 3, 2, 4, 18], reflecting the fact that their target application is information display, as opposed to virtual contact. Similar to Yano *et al.* [19], we choose to mount the tactors at locations on the body with a high probability of contacting virtual objects. In addition, our application environment has users wearing a military tactical protective vest (a modern version of a flak jacket) during the simulation, so care was taken to choose locations that would not be adversely affected by this and other gear worn during a typical session. The 16 tactors we are currently using are positioned on the elbows (numbers 1 & 4 in **Figure 1**), on the end of the shoulders (5 & 12), across the shoulder-blades (6, 7, 10 & 11), along either side of the spine (2, 3, 8 & 9), and the front-side of the torso (not shown). Multiple tactors can be triggered together, and at varying vibration levels, to accommodate different contact scenarios.

4.2. Donning and Doffing

The donning process for the TactaVest requires assistance from another person, and can be donned and correctly adjusted in about three minutes. We store the garment on a mannequin to help keep the shape of the garment, and also to ease the donning/doffing procedure. All of the electronics, wiring, and tactors can be removed when the garment needs to be cleaned.

5. SYSTEM INTEGRATION

The TactaVest system has been successfully integrated into the high-fidelity VE system of the Immersive Simulation Section (ISS) at the U.S. Naval Research Laboratory (NRL). This group performs basic and applied research in novel human computer interaction techniques, and has done extensive work on locomotion controls for immersive virtual environments. A significant achievement has been Gaiter [13], a technique that allows moving through a virtual space by walking in place in the real world.

5.1. Close-Quarters Battle Simulation System

For the Office of Naval Research's VIRTE program, the group is part of a team working to create a fully immersive simulator for training small-unit tactics, techniques, and procedures for close-quarters battle (CQB). This task involves small groups of Marines operating in urban areas, frequently inside of buildings. To perform CQB in the real world requires the Marine to constantly go through a team-coordinated cycle of carefully looking, moving, and potentially shooting. The interiors of buildings may be dark and without power, may be filled with smoke, and may be rubble or debris strewn. The environment may have a high, disorienting level of sound, or, conversely, may be near silent and require stealth on the part of the Marines. Both intentional and unintended contact with structures and objects in the environment are common. This is the physically and mentally demanding task that we want to simulate as accurately as possible.

The ISS has the facilities for fully immersive, HMD-based virtual reality (**Figure 2**). Currently, nVisor SX head mounted displays by NVIS, Inc. are used, providing the immersed user with stereo 1280 x 1024 images and a 60 degree diagonal field of view. Either of two optical motion tracking systems are used, a passive optical system by Vicon Motion Systems, Inc. and an active optical system from PhaseSpace. The user's head, torso, waist, forearms, lower legs, and typically a weapon prop, are tracked. Rendering and other processing are done using commercially available PC workstations.

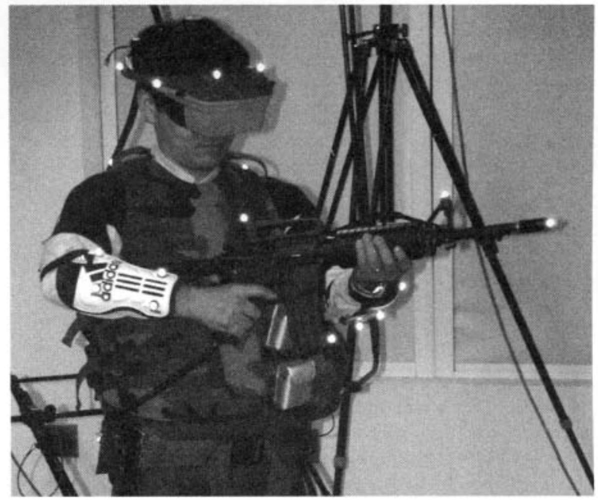

Figure 2: VIRTE Immersive VR System.

The current software base is named ManSIM, developed for the VIRTE program by Lockheed Martin Simulation, Training and Support. ManSIM is built on top of the Gamebryo 3D graphics toolkit and engine from Numerical Design Limited. A spatialized audio system, named SoundScape3D, was developed for VIRTE by VRSonic, Inc. Vibrotactile feedback is provided by the TactaVest. A custom centering harness was developed by Roger Kaufman's group in the Department of Mechanical and Aerospace Engineering at The George Washington University. Immersed users wear a military protective vest, providing a rigid surface well suited for mounting optical markers to track the user's torso. The vest also has pockets that are used to hold the batteries, TactaBox, and custom electronics to wirelessly transmit the weapon-prop trigger pulls to the host computer. The only tether remaining in this system is the video cable delivering the graphics to the HMD. All other features are delivered using wireless approaches.

When trying to simulate CQB in a VE, contact with the virtual environment may occur for a number of reasons: the user may be looking in one direction while moving in another, the limited field of view of the HMD may make collision with objects more likely, due to low light or limited visibility (*e.g.*, smoke-filled) situations, and the user may decide to collide on purpose (*e.g.*, to push on a door to open it, or to lean on a wall). The goal is to make the system handle and display these collisions realistically, in order to improve the user's awareness of the current situation. The main constraint on the system is that cues must be delivered with a minimum of added latency, cumber, and inertia. This last point has proven elusive in most previous haptic approaches, such as those employing force-reflecting devices.

5.2. VE System Evolution

Each new iteration of the ISS VE system attempted to provide better support for CQB tasks. In particular, users found it difficult to maintain an adequate sense of where their body was in relation to the environment, and hence often bumped into, or became hung up on, immovable objects. Better enforcement of penetration constraints, spatialized audio cues, and an avatar representation of the user seemed to improved the situational awareness of the user, somewhat, but it was still not uncommon for users to get "stuck" on objects like doorframes.

To illustrate how users can unintentionally collide and/or get stuck, the left image in **Figure 3** shows the first-person view of a common scenario: a user is attempting to enter a building through a doorway. From his view, limited by the field of view of the HMD, he should be able to enter without a problem, because there are no visible obstacles. As shown in the over-the-shoulder view on the right, however, the user's shoulder is actually colliding with the doorframe, arresting his movement into the building. Avoiding this situation typically requires the user to attend very closely, or to be coached from outside, both of which are undesirable, and interfere with task performance.

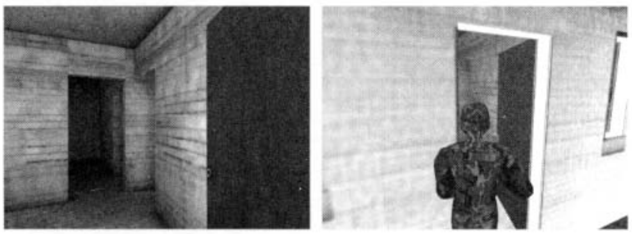

Figure 3: First-person and over-the-shoulder views of a user stuck on a door frame.

The ISS has integrated the TactaVest into the current system in order to address the contact problems. There are a number of requirements that a haptic system needs to meet to work well with this application, including free placement of the tactors, modest addition of weight and bulk, and wireless communication. For this application, it is very important for the garment, tactors, wiring, TactaBox, and batteries to not interfere with the user's freedom of movement, including the ability to raise and aim a weapon. Apart from the tight fit of the garment restricting somewhat the movement of the user, the design of the TactaVest system has been found to be sound for this application.

When the TactaVest is used within the system, the user's torso is modeled as a rectangular box for collision detection purposes. This box is equally sub-divided into eight smaller boxes, covering the upper and lower regions of the front and back of the torso for both the left right sides. The program maintains an internal mapping of where the tactors are geometrically on the user, and activates or deactivates them based on collisions with the environment.

6. CONCLUSIONS AND FUTURE WORK

The next logical step in the development of our system is to attempt to measure the impact that the introduction of haptic cues into this system has on such aspects as user performance, presence, and training transfer. We are also looking to improve the system in several key ways. The TactaBoard allows us to vary the intensity of the vibration, in addition to simply turning the tactors on and off. We would like to explore the different ways in which this variation can be used to enhance the user experience. Training aids could be added to the simulation to provide real-time feedback for critical things such as exposure to uncleared areas.

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