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Vibration Feedback Models for Virtual Environments

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Abstract

Vibrations can significantly enhance touch perception for virtual environment applications with minimal design complexity and cost. In order to create realistic vibrotactile feedback, we collected vibrations, forces, and velocities during various tasks executed with a stylus: tapping on materials, stroking textures, and puncturing membranes. Empirical models were fit to these waveforms and a library of model parameters was compiled. These models simulated tasks involving simultaneous display of forces and vibrations on a high-bandwidth force-feedback joystick. Vibration feedback adds little complexity to virtual environment algorithms. Human subjects interacting with the system showed improved execution and perception when performing surface feature discrimination tasks.

1 Introduction

High-frequency vibrations are an essential part of many manipulation tasks. Unfortunately, many current human interfaces for virtual environments do not provide vibrotactile feedback. Recent research has shown that vibrotactile feedback adds to touch perception without significantly increasing system complexity or cost [1, 3, 4, 6, 8, 12]. In telemanipulation, it has been shown vibration feedback improves performance of master-slave teleoperated tasks [1, 2]. The benefits of vibration feedback systems include easy addition to existing haptic displays often without additional hardware. Vibration feedback augments force-feedback, making simulations of high frequency contact, texture, and phenomena like puncture, more realistic. It can also compensate when force-feedback is limited by saturation limits of interface actuators. Applications include surgical training, critical-procedure training of astronauts for space missions, and commercial computer interface devices for Computer Aided Design (CAD) and entertainment.

In this work, we first develop a library of vibration signal parameters by collecting and modeling data obtained during task execution. Vibrations selected from this library can be played back through a haptic interface interacting with a virtual environment. Second, we demonstrate the performance enhancements of vibrotactile feedback for virtual environments using an existing commercial joystick product. In the discussion, we address issues in using vibration feedback to develop realistic feel of surface interactions in virtual environments.

2 Vibration Data Collection and Identification

An instrumented stylus was used to collect acceleration, force, and position (velocity) data during execution of several tasks. Mounted on the stylus, an aluminum shaft attached to a 3-D digitizing arm, the Immersion MicroScribe-3DX, was an accelerometer (Kistler 8616A500 ±500 g). The MicroScribe provided position and velocity data. For most experiments, a force sensor (strain gauge load cell) mounted under a Delrin table acting as a base measured the force applied by the stylus on the materials (Figure 1). Data were collected through an A/D board on a PC at 25 kHz.

We characterized the vibrations resulting from three tasks: tapping on various materials, stroking the stylus tip across different textures, and puncturing membranes. Analysis of the vibration waveforms gathered yielded parametric, empirical models describing the various tasks. The model forms and parameters described were assembled into a vibration waveform library. The following sections describe data acquisition and analysis for each task.

2.1 Tapping

Tapping on an object's surface and feeling the resulting vibrations allows humans to detect the stiffness of an object. Earlier work has shown that by recreating different vibration waveforms on a vibration display, subjects can differentiate between virtual materials by tapping [12]. We extended this work in vibration sensing with a wider array of materials, and by using the Immersion Impulse Engine to simultaneously display both force and vibration. Figure 1 shows the experimental setup for tapping.

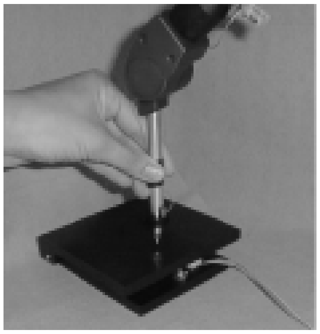

Figure 1. Tapping experiment

The empirical model selected (from Wellman and Howe [12]) for the tapping waveforms was an exponentially decaying sinusoid whose parameters depended upon the material. The approximation is given by

$$Q(t) = A(v)e^{-Bt}\sin(\omega \cdot t) \quad (1)$$

where $Q(t)$ is the vibration produced by the contact, measured by the accelerometer, $A(v)$ is attack amplitude, a function of the attack velocity, v, for a given material, B is a decay constant picked to match the apparent decay envelope of a the waveform, and ω is the frequency of the attack portion of the wave (in radians/sec). The attack amplitude, which is measured from the maximum acceleration during the first cycle of $Q(t)$, varied linearly with the attack velocity for each material (Figure 2). This linearity was described by a line fitted to the data, $A(v)$. A total of 16 materials were tested, and Table 1 lists the parameters for vertical taps on a subset of these materials. Figure 3 shows measured and modeled vibrations for a typical case, wood.

Attack frequency generally increased with increasing stiffness. However, parameterization did not yield a good enough fit (r^2 = 0.61) to use stiffness as a predictor. The

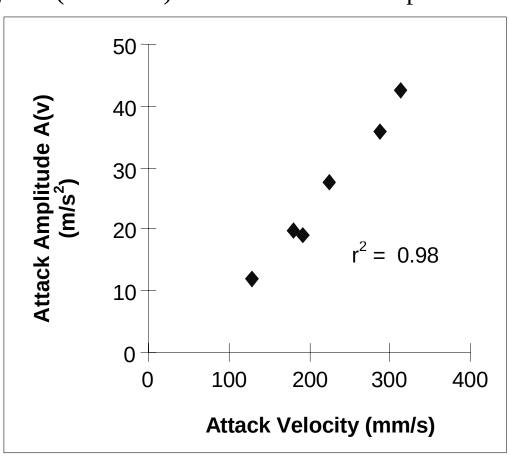

Figure 2. Attack velocity and amplitude for rubber, exhibiting linearity

Table 1. Modulus of elasticity and tapping model parameters for selected materials

Material	Modulus (10^{-6} psi)	Slope (s^{-1})	Frequency (Hz)	1/B (ms)
Wood	0.14	309	67	6.48
Acrylic	0.4	389	128	2.13
Delrin	0.45	509	93	4.12
Aluminum	10	681	1471	0.47
Glass	7	750	1721	0.56
Cast iron	26	1334	1668	0.4
Steel	29	1692	1682	0.32

vibrations resulting from tapping are likely due to several parameters in addition to modulus of elasticity, such as hardness, object geometry, and material density. This makes it difficult to predict the frequency based on modulus of elasticity alone; thus the vibration waveform library should be expanded to include materials for which only a thorough testing and analysis have been performed.

2.2 Textures

Stroking textures with our fingertips results in vibrations that indicate the relative surface roughness of a material [8]. We examined two different types of textures. The first were general textures, such as sandpaper. The second was patterned texture, where a series of grooves/ridges or dimples/bumps were arranged in an orderly fashion on a surface. Texture vibration data were collected by holding the stylus at an approximately 60-degree angle to the surface and stroking the tip across the surface. The accelerometer was mounted perpendicular to the stylus, parallel to the direction of the input vibrations.

Sandpaper samples of varying grit (60, 100, 400, and 600) were tested. The vibration signals from these textures had a broad range of frequency components (Figure 4). However, there were characteristic frequencies that depended on the roughness of the material. The

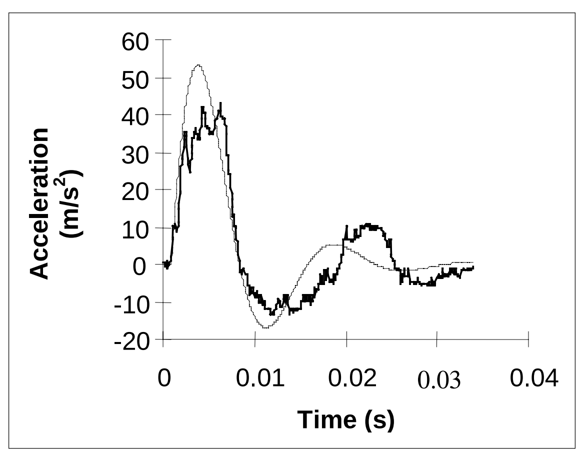

Figure 3. Actual and modeled vibrations for wood at 164 mm/sec

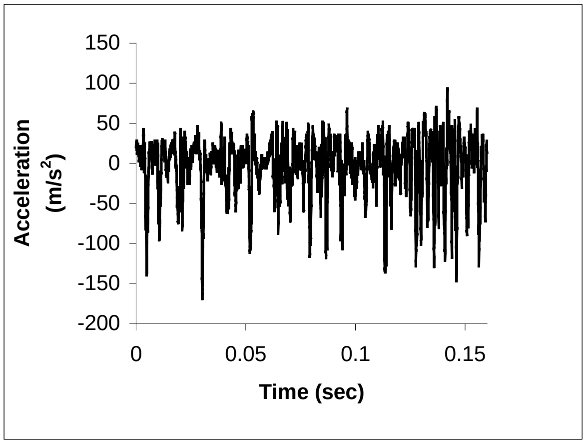

Figure 4. Vibration data for 100 grit sandpaper at 0.1 m/s and 0.64 N

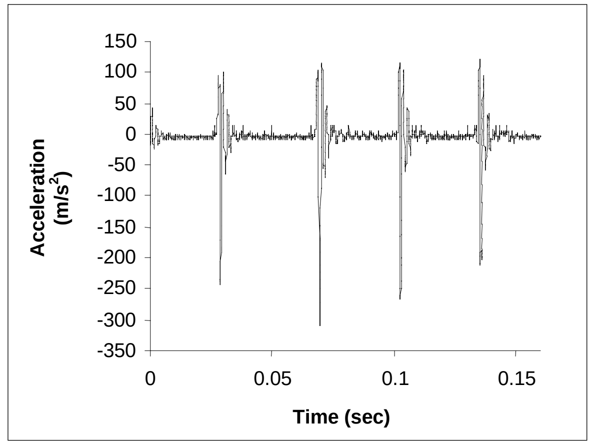

Figure 5. Patterned texture with 0.03” grooves at 0.06 m/s and 2.3 N

parameters chosen to describe the different grits were the mean and maximum power frequency from a power spectral analysis and the root mean square (rms) value of the vibration signal. The analysis indicated that the frequency parameters, while varying, did not depend upon the velocity of the stylus across the sandpaper. The amplitude of the waveforms did, however, depend on both the applied force and the velocity as described by Equation 2 below.

Dragging over patterned textures resulted in a series of vibrations that individually look like horizontal taps (Figure 5). The frequency of the individual vibrations (exponentially decaying sinusoid) is therefore dependent on the material, velocity and force. The frequency with which the small vibrations repeat themselves is related to the spacing of the pattern and the velocity of the stroking.

For patterned textures, the attack amplitude was related to force and velocity by

$$A(v,F) = Av + BF \qquad (2)$$

Where A and B are parameters determined by least squares methods, v is the velocity of the stylus, and F is the force applied by the tip. As an example of pattern texture parameters, a texture with groove spacing of 2 mm and groove width of 0.5 mm was found to have $A = 1.2 \times 10^3\ sec^{-1}$ and B = 63.4 $m/s^2/N$ with a correlation of 0.81.

2.3 Puncture

For medical training applications, the tactile task of puncture, used in procedures such as biopsies, is very important. We performed puncture experiments on cellophane tape stretched across a hollow cylinder resting on the force table. The configuration is similar to that shown in Figure 1, with the membrane below the stylus. In puncture data collection, the objective was not only to observe the vibration waveforms, but also to measure the appropriate timing for combined force and vibration. Figure 6 shows acceleration and force data during quasi-static puncture of cellophane tape. The puncture data was repeatable and easy to parameterize. As shown in Figure 6, the force breaks away close to the time that vibration occurs. The model for puncture vibration is a decaying sinusoid

$$Q(t) = Ae^{-Bt}\sin(\omega \cdot t) \qquad (3)$$

This is similar to the tapping model; however, the amplitude does not depend on attack velocity. For the membrane used in our experiments, A was 38 m/sec^2, B was 330 sec^{-1}, and ω was 1260 radians/sec.

3 Combined Force and Vibrotactile Display

The addition of vibrotactile information to virtual environments involved three primary tasks: selection of an appropriate vibration display that could be used simultaneously to display forces, creation of algorithms

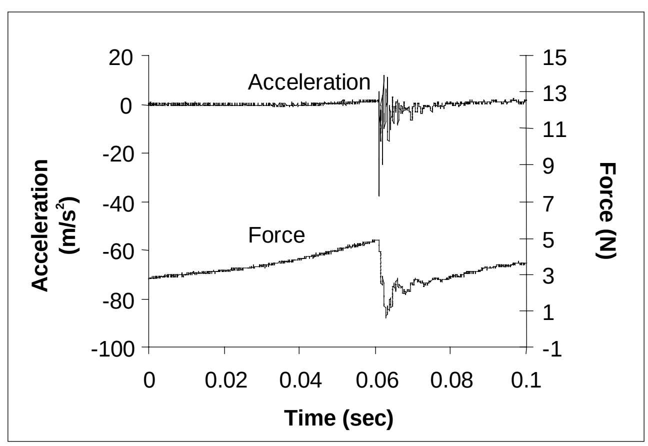

Figure 6. Data for puncture of cellophane tape

for using the vibration waveform library, and testing the effectiveness of vibration feedback in task execution.

3.1 Haptic Device Selection

One paradigm for combined vibration and force display uses two separate actuators, one for force and the other for vibration. Initially, we explored adding vibration information to Immersion's Impulse Engine force-feedback joystick using a separate device. However, we decided to follow a new paradigm that uses the high bandwidth of the force display. The cable-driven Impulse Engine has sufficient bandwidth to display high-frequency vibrations, so as a single device it can be used to simultaneously display forces and vibrotactile information. To verify this, the frequency response of the device was recorded with different grasp stiffnesses (since the user's grasp changes the dynamics of the system). The frequency response (up to 1.6 kHz) was shown to be adequate for many vibrations because it can accurately display vibrations in the area of peak sensitivity for humans.

3.2 Vibration Algorithms

Algorithms for vibration and force feedback were easily created using the existing framework of software (the SDK, or Software Development Kit) commercially available for the Impulse Engine. Vibration waveforms, parameterized by the waveform library, can be superimposed on force signals. Although the vibration data collected was acceleration, vibrations are commanded to the joystick as forces. The actual acceleration depends also on the stiffness of the grasp and the joystick mass.

Tapping: The display of vibrations for tapping uses the velocity of the approach orthogonal to a virtual wall when contact occurs and the vibration parameters for the material of the wall. At contact, the combination of two different algorithms creates simultaneous force and vibration feedback. The force feedback consists of a force applied proportional to penetration distance, a virtual wall modeled as a stiffness. A vibration waveform, calculated from the vibration waveform library for the particular material and contact velocity, is superimposed onto the force signal sent to the actuator motors. Five decay time constants after contact, the vibration is eliminated and only force-feedback remains.

Textures: Vibration feedback for general textures is dependent on the force orthogonal to the surface, and vibrations for patterned textures are dependent on both the velocity and the force along the surface. For general textures, such as sandpaper, the vibration algorithms have not yet been implemented. For patterned textures, the algorithm superimposes vibrations representing texture and forces representing the stiffness of the surface. At certain positions along the surface, reflecting the desired spacing of the pattern, a vibration is displayed as the operational point of the joystick passes. This vibration is applied in the direction of the motion, parallel to the surface. The waveform shape was calculated similar to that for tapping, with the amplitude depending on both velocity and force against the surface.

Puncture: For puncture, forces and vibrations are applied in the direction orthogonal to the puncture membrane. Since the membrane to be punctured acts as a spring, force feedback is applied first. Upon contact with the membrane, the force is ramped up using the stiffness law described earlier. When the deflection passes the maximum strain of the membrane, puncture occurs. The force is immediately removed and a vibration waveform for puncture is played.

4 System Evaluation and Results

A series of experiments with 8 human subjects (7 male, 1 female, mean age = 27 years) evaluated the enhancements of the vibration feedback for virtual environments. Half the subjects were novice force-feedback users. For the tapping and texture experiments, subjects were asked to compare and identify objects based on the haptic properties of the virtual environment. For the puncture experiment, subjects were presented with different combinations of force and vibration feedback and were asked to puncture a virtual membrane with the minimum possible penetration distance after puncture. To prevent interference from noise caused by the motors, subjects wore headphones playing audio white noise. Users were shown visual displays of the virtual objects and stylus, but no visual differences between materials, textures or other characteristics were displayed.

Subjects were also presented with qualitative questions regarding the performance of the system. These qualitative results are important because a display algorithm that is more realistic or provides more comfort to the user should reduce operator fatigue.

4.1 Tapping

For the tapping task, we hypothesize that vibrations aid discrimination of material properties. To acquaint and instruct subjects with the tapping task, subjects first tapped with a real stylus on various materials. Afterwards, they were presented with a series of virtual environments consisting of two virtual surfaces each. The algorithm for the haptic display presented vibrations corresponding to different materials but with the same virtual stiffness for both materials. Thus, subjects had to use the vibration information alone to compare stiffness. Different combinations of 7 possible materials were presented and subjects could choose "material 1 stiffer", "material 2

Table 2. Tapping experiment results. Number shown is percent of correct responses for comparison of two materials.

Material		1	2	3	4	5	6	7
Wood	1	75 / 40	40	60	80	80	100	100
Acrylic	2	50	87.5 / 40	40	100	100	100	80
Delrin	3	50	50	75 / 80	80	60	80	80
Aluminum	4	75	75	87.5	75 / 60	60	60	60
Glass	5	75	62.5	62.5	25	62.5 / 100	20	0
Iron	6	62.5	75	62.5	25	25	37.5 / 60	60
Steel	7	87.5	87.5	75.0	25	37.5	25	50 / 60

Vibrations only

Force and vibrations

stiffer", or "material 1 and material 2 have the same stiffness".

The order of presentation was random and 28 pairs were presented once each. The subjects tested selected the correct ranking with median 64.3% (1st quartile 50.9%, 3rd quartile 68.8%). The median is almost twice the rate of chance (33%). Correct discrimination decreased with the decrease in difference of parameters between the two surfaces, especially for the higher stiffnesses materials where the vibrations were of very high frequency. Poor discrimination often occurred when two identical materials were perceived as not identical or that two dissimilar materials were perceived as the same. In very few cases were two different materials improperly ordered. Experienced force-feedback users performed better on average than novice users.

In addition to combined force and vibration feedback, the use of vibration feedback alone has specific application in ungrounded haptic devices[10]. Again, subjects were asked to tap on two "surfaces" which displayed only vibrations upon contact. In this experiment, subjects selected the correct ranking with median 67.9% (1st quartile 64.3%, 3rd quartile 75.0%). A subset of 5 subjects was used in this experiment. Table 2 shows the percent of correct responses for each pair of materials from both the tapping experiments. Therefore, when force-feedback is not available vibrations alone help discriminate between material properties.

4.2 Texture

We hypothesized that vibrations assist in the discrimination of different textures. To verify this, we compared the vibration display against other methods of texture display. One method applies small damping (force is proportional to in the opposite direction of the velocity), and another calculates and displays forces describing the local geometry of the texture (i.e. varying the location of the virtual wall in the grooves).

For each type of feedback, subjects ordered the two textured surfaces presented in order of frequency of pattern, which represented a series of grooves. A higher frequency corresponds to the pattern with the grooves closer together. Median values for success were 80% (1st quartile 80%, 3rd quartile 80%) with the local geometry algorithm, 90% (1st quartile 80%, 3rd quartile 90%) with the damping algorithm, and 90% (1st quartile 80%, 3rd quartile 100%) with the vibration feedback. Table 3 shows the experimental results for texture discrimination.

4.3 Puncture

Again we hypothesize that vibrations assist puncture tasks by reducing the distance that one travels after puncture occurs (over travel). Subjects performed puncture tasks with and without vibration and the amount of penetration past the membrane was measured. Penetration distance was on average slightly less when vibration feedback was used, but not significantly so. The average penetration distance with vibrations was 0.161 mm (std. dev. 1.04 mm) less than without vibrations.

5 Discussion & Conclusions

The algorithms developed and experimental results indicate that the feedback of vibrations in virtual environments is a practical method to enhance haptic interfaces. Because force feedback systems are often designed for low frequency force and have instabilities associated with the discrete nature and nonlinear properties of the virtual wall stiffness, open loop display of vibrations provides a low cost and simple technology to increase system performance. While true realism in haptic rendering is still down the road, the addition of vibrations

Table 3. Percent of correct responses for texture discrimination tasks.

Groove spacing		Geometry				Damping				Vibrations			
		1	2	3	4	1	2	3	4	1	2	3	4
1.6 mm	1	50				100				87.5			
2.4 mm	2	100	62.5			100	87.5			100	87.5		
4.8 mm	3	100	75	100		100	75	87.5		100	100	75	
6.4 mm	4	100	87.5	37.5	87.5	100	100	37.5	87.5	100	100	62.5	87.5

provides a large step in that direction.

In the collection and analysis of data, we found that parameterization of real-world data yields efficient implementation algorithms. The open-loop nature of the empirical models obtained from this data is straightforward and simple to implement. In vibration display, we have discovered that vibrotactile feedback can be used with conventional force-feedback devices, given a high bandwidth.

The results from the tapping and texture display are promising. For tapping, the percentage of correct responses is much higher when considering a subset of lower stiffness materials. Our results for tapping have lower percentages of correct responses than those in [12] for their experiments in both actual and virtual stiffness discrimination. This may be attributed to the larger number of materials presented and greater number of high stiffness materials used in this study. Additionally, the ability of vibration feedback to enhance the apparent stiffness of a surface without increasing the stiffness of a virtual wall can make a haptic device with limited torque output represent a larger variety of virtual environments.

Beyond the quantitative results, which show that the vibration algorithms perform, the qualitative observations indicate that vibrations provide a more realistic or crisper feel to all three tasks. Subjects reported that the tapping task generally felt more realistic with vibrations. Some subjects noted that the “activeness” of the surface during vibration display was disconcerting, while others did not find the vibrations unnatural. For textures, subjects indicated that the vibration-based texture was most realistic, although it did not necessarily feel like the patterned texture used in data acquisition. Several subjects said that both the damping and vibration textures felt like the teeth of a comb. Those subjects familiar with force-feedback and virtual environment design noted that the vibrations would be their first choice for a texture display algorithm. Some subjects also noticed the force-vibration amplitude relationship and appreciated that aspect.

For puncture the small trend observed for vibration feedback is attributed to the fact that vibrations were not truly absent during the force-feedback only algorithm. The discontinuity that occurs when the force on the motor was removed at the instant of puncture causes some vibrations.

5.1 Future Work

Future work includes modeling of more vibrotactile tasks, and consideration of the device used in the task (i.e. the effects of stylus mechanics on the vibration signal). Additionally, experimental verification should be used to show that the vibrations displayed correctly reflect the desired vibrations from the waveform library. Refinement of our current approach will also be investigated. A general research question investigates the direction of the applied vibration. Since the use of puncture simulation is useful for medical training, simulations, and hence identification at this stage should be designed that mimic human or animal tissue. Furthermore there is a need to develop a repeatable model and display for general textures.

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