Dimensional Reduction of High-Frequency Accelerations for Haptic Rendering

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Abstract. Haptics research has seen several recent efforts at understanding and recreating real vibrations to improve the quality of haptic feedback in both virtual environments and teleoperation. To simplify the modeling process and enable the use of single-axis actuators, these previous efforts have used just one axis of a three-dimensional vibration signal, even though the main vibration mechanoreceptors in the hand are known to detect vibrations in all directions. Furthermore, the fact that these mechanoreceptors are largely insensitive to the direction of high-frequency vibrations points to the existence of a transformation that can reduce three-dimensional high-frequency vibration signals to a one-dimensional signal without appreciable perceptual degradation. After formalizing the requirements for this transformation, this paper describes and compares several candidate methods of varying degrees of sophistication, culminating in a novel frequency-domain solution that performs very well on our chosen metrics.

Keywords: haptic feedback, vibrations, measurement-based modeling.

1 Introduction

Haptic interfaces are designed to let a user touch virtual and distant objects as though they were real and within reach. For many applications, users would like the haptic feedback provided during these virtual and distant contacts to match the feel of real objects as closely as possible. When you touch a real surface with a tool, you feel low-frequency forces that convey shape, compliance, and friction, and you also feel high-frequency vibrations that reflect the texture of the object and its current contact state with your tool \cite{5}. The mechanoreceptors that detect these important high-frequency vibrations are the Pacinian corpuscles (PCs); they are sensitive to vibratory stimuli from 20 to 1000 Hz, with a peak sensitivity between 250 and 550 Hz \cite{12}. PCs are also known to respond to vibrations that occur in all directions, with motion parallel to the skin surface being slightly more easy to detect than motion normal to the skin \cite{3}.

As described in Section 2, high-frequency acceleration measurements have been shown to enable realistic haptic rendering of surface contact. Although tool vibrations
occurs in all three directions, these previous works have simplified the problem by measuring and recreating only a single axis of the vibration, discarding potentially significant haptic information in the other two axes. One could imagine replicating these single-axis techniques in three orthogonal directions, but such an approach would require significantly more complex vibration models and haptic hardware. Instead, we believe we can take advantage of the human hand’s insensitivity to vibration direction by recreating the feel of a full three-dimensional acceleration with a one-dimensional signal. Section 3 lays out our quantitative objectives for this dimensional reduction problem. Section 4 then describes the candidate transformations we have considered, culminating in the presentation of our new approach, DFT321. Finally, Section 5 summarizes the contributions of this paper and lays out future work.

2 Background

Several research teams have succeeded at creating realistic haptic renderings through the use of high-frequency acceleration signals, though all of these efforts have neglected the 3D nature of real vibrations. For teleoperation, Kontarinis and Howe measured uniaxial accelerations at the fingertips of a custom robotic hand and continually played these vibrations for the operator to feel via two inverted audio speakers on the fingers of the master interface [7]. This sensory augmentation improved user performance in bearing inspection and needle puncture tasks. Several other researchers have used uniaxial recordings of real contact accelerations to improve the realism of virtual surface contact, either through parametric models [12,4] or direct playback [8]. In the domain of direct manipulation, Yao, Hayward, and Ellis created a handheld tool that measures accelerations perpendicular to the tool tip and outputs them in the orthogonal direction to improve the user’s sensitivity to small surface features [15].

Inspired by this previous research, work in our own lab has focused on capturing and recreating the feel of real surfaces during tool-mediated contact, a process we call haptography [9]. As part of this project, we added a voice-coil actuator to the handle of a Phantom Omni to allow feedback of a single axis of contact acceleration during teleoperation [10]. Though this system was initially configured to replicate accelerations normal to the contacted surface, it was altered to transmit tangential accelerations for a human subject study focused on texture perception [11]. Subjects rated surface renderings as significantly more real when they included vibrations from the dedicated actuator, but no sample achieved a realism rating as high as the real surface. In fact, the highest rated rendering provided vibrations that were 50% stronger than the measured tangential values, indicating that restricting vibration measurement to a single axis may compromise the fidelity of the resulting interaction. Finally, we have also developed a method for distilling a set of recorded accelerations into a texture model for virtual surface rendering [13]; that work used principal component analysis to reduce 3D sensor signals down to 1D, but it did not closely consider the important role this transformation plays in system performance.