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Perceived Instability of Virtual Haptic Texture: III. Effect of Update Rate

Abstract

This study investigates the effect of update rate on the quality of haptic virtual textures, with the goal to develop a guideline for choosing an optimal update rate for haptic texture rendering. Two metrics, control stability and perceived quality of the virtual haptic texture, were used. For control stability, we examined the effect of update rate on the "buzzing" of virtual haptic textures. For perceived quality, we measured the discriminability of virtual haptic textures rendered at different update rates. Our study indicates that update rates much higher than the conventional 1 kHz are needed in order to achieve a stable rendering of "clean and hard" textured surfaces. We also found that our ability to distinguish textures rendered with different update rates depends on whether the virtual textures contain perceived instability. Based on these results, we provide a general guideline for selecting an optimal update rate for rendering virtual textured surfaces.

1 Introduction

Haptic update rate refers to the frequency at which force information is computed and sent to the human user via a haptic interface. Given a haptic rendering system consisting of the renderer (algorithm), the haptic interface (hardware), and the user, the update rate is a key parameter that synchronizes the operation of all three components and affects their performance levels. First, the complexity of the virtual environment model that the renderer can process in real time is limited by the update rate. Second, the stability of the haptic interface usually improves with an increase of the update rate (Colgate & Schenkel, 1994). Third, the perceived quality of the haptic virtual environment is also affected by the update rate (Booth, Angelis, & Schmidt-Tjarksen, 2003; Kilchenman & Goldfarb, 2001), because the update rate determines the smoothness of forces delivered by the haptic interface due to the sampled data nature of any haptic rendering system.

In the haptics research community, it is empirically accepted that a minimum update rate of 1 kHz is required for rendering rigid frictionless objects, but lower rates may suffice for soft deformable objects. To the best of our knowledge, however, few general guidelines exist on the selection of an optimal update rate for a specific haptic rendering system. Developing guidelines

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requires considering the effect of update rate on both the control stability and the perceived quality of virtual objects. The guidelines will help designers of haptic virtual environments better understand the tradeoff between more detailed physical modeling (generally requiring lower update rates) and better control stability and improved perceived quality of haptic objects (generally requiring higher update rates).

Our research group has been developing haptic texture rendering systems that deliver "clean and realistic" haptic surface textures. Our previous studies (Choi & Tan, 2004, 2005) have concentrated on the analysis of a widely-used haptic texture rendering system in terms of perceived instability. *Perceived instability* refers to any unrealistic sensations that cannot be attributed to the physical properties of the virtual haptic textures rendered by a force-feedback haptic interface. Three types of perceived instability (buzzing, aliveness, and ridge instability) were observed in our previous studies (Choi & Tan, 2004, 2005). The present study considers the most prevalent type, buzzing, in depth. Details on the other two types of perceived instability can be found in (Choi & Tan, 2004, 2005).

Texture is a key component that defines the identifying characteristics of virtual haptic surfaces. A large number of computational techniques have been developed for haptic texture rendering (e.g., see Costa & Cutkosky, 2000; Fritz & Barner, 1996; C. Ho, Basdogan, & Srinivasan, 1999; P. P. Ho, Adelstein, & Kazerooni, 2004; Kim, Sukhatme, & Desbrun, 2004; Massie, 1996; Minsky & Lederman, 1996; Okamura, Dennerlein, & Howe, 1998; Otaduy, Jain, Sud, & Lin, 2004; and Siira & Pai, 1996; see Choi & Tan, 2004 for a review). Prior to our studies, however, there had been few attempts at evaluating the performance of texture rendering techniques in a quantitative manner (although see a recent study for a theoretical analysis of the fundamental limits of a widely-used haptic interface for simulating periodic gratings, Campion & Hayward, 2005).

The present study investigated the effect of update rate on the quality of virtual haptic textures rendered with a force-feedback haptic interface. The goal of the study was to establish a general guideline for selecting an optimal update rate for a given haptic texture rendering system. Toward this goal, we have developed a haptic texture rendering system that can render textures at a very fast update rate of up to 50 kHz (see the Appendix for details). This capability has made it possible for us to systematically examine the effect of update rate on the quality of virtual haptic textures. Our study was conducted with explicit considerations for both control stability and human perception.

Consideration of the effect of update rate on control stability focused on a type of perceived instability called buzzing. *Buzzing* refers to the high-frequency noise-like force variations emanating from a force-feedback device during haptic texture rendering (Choi & Tan, 2004). It is one of the most-common unrealistic sensations experienced by users of virtual haptic textures (Wall & Harwin, 2000; Weisenberger, Krier, & Rinker, 2000). The existence of buzzing adversely affects the perceived quality of virtual haptic textures. In the present study, we performed two analyses (a simulation and an experiment) in order to understand the effect of update rate on buzzing. In the simulation, we confirmed that buzzing noises could occur due to a combination of the high-frequency mechanical resonances of a force-feedback haptic interface and the relatively low update rates used to render textures. In Experiment I, we assessed the quantitative relationship between update rate and buzzing by measuring the maximum stiffness of textured surfaces that could be rendered without buzzing over a wide range of update rates (250 Hz up to 40 kHz). The results indicated that stiffness thresholds increased with update rates, and that update rates in the range 5–10 kHz, which are significantly faster than the conventional rate of 1 kHz, were needed in order to render perceptually "clean and hard" textured surfaces.

The effect of update rate on human perception was studied with the discriminability of textured surfaces rendered with different update rates as a performance metric. Preliminary experiments (not reported here) led to the hypothesis that virtual haptic textures rendered with different update rates are perceptually equivalent if no perceived instability (buzzing) is involved. In order to test the hypothesis, we designed and conducted two psychophysical experiments. In Experiment II, participants compared two haptic textured surfaces rendered with different update rates. Rendering parameters (including update rate) were chosen so that the virtual textures were perceived to be either stable (without buzzing) or unstable (with buzzing). In Experiment III, we quantified the extent to which participants could discriminate virtual haptic textures of various update rates by measuring the discrimination thresholds of update rates relative to a 10 kHz reference rate. The results were then compared to those obtained in Experiment I. The results of both Experiments II and III strongly supported our hypothesis that virtual haptic textures rendered with different update rates are perceived to be identical if no perceptual artifacts such as buzzing are perceived.

The remainder of this paper is organized as follows. In Section 2, we define the texture rendering model and the rendering methods used throughout the paper. We then provide a brief summary of the physical and perceptual characteristics of buzzing in Section 3, based on our previous studies (Choi & Tan, 2004, 2005). In Sections 4 and 5, we present our investigation of the effect of update rate on control performance. The simulation results are provided in Section 4, and the design and the results of Experiment I in Section 5. In Sections 6 and 7, we present the two psychophysical experiments (Experiments II and III, respectively) that examined our ability to discriminate virtual haptic textures rendered with different update rates. We conclude the paper in Section 8, along with providing a guideline for selecting an optimal update rate for haptic texture rendering.

2 Virtual Haptic Texture

In this section, we introduce the haptic interface, the texture model, and the rendering methods used in our study. We used the PHANToM 1.0A with an encoder gimbal (SensAble Technologies; Woburn, MA, USA) for the simulation and experiments reported in this paper. The user faced a vertical virtual textured surface rendered with the PHANToM (Figure 1) and used the PHANToM stylus to feel the textured surface. The texture was modeled as

$$z = h(x) = A \sin\left(\frac{2\pi}{L}x\right) + A \qquad (1)$$

in the PHANToM world coordinate frame, where A and L denote the amplitude and spatial wavelength of

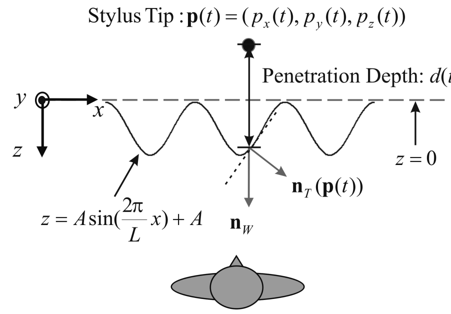


Figure 1. *An illustration of parameters used in haptic texture rendering.*

the sinusoidal textures, respectively. This texture model was superimposed on a 3D plane $z = 0$, forming the textured surface shown in Figure 1.

Given the position of the PHANToM stylus tip, $\mathbf{p}(t) = (p_x(t), p_y(t), p_z(t))$, the penetration depth $d(t)$ was defined as

$$d(t) = \begin{cases} 0 & \text{if } \; p_z(t) > h(p_x(t)) \\ h(p_x(t)) - p_z(t) & \text{if } \; p_z(t) \le h(p_x(t)) \end{cases} \qquad (2)$$

Force was computed using the following two methods:

$$\mathbf{F}_{\text{mag}}(t) = Kd(t)\mathbf{n}_{\text{W}} \qquad (3)$$

and

$$\mathbf{F}_{\text{vec}}(t) = Kd(t)\mathbf{n}_{\text{T}}(\mathbf{p}(t)), \qquad (4)$$

where K was the surface stiffness, $\mathbf{n}_W$ was the normal vector of the underlying wall, and $\mathbf{n}_T(\mathbf{p}(t))$ was the normal of the textured surface at $\mathbf{p}(t)$. These methods were proposed in Massie (1996) and C. Ho et al. (1999), respectively, and produce perceptually disparate virtual haptic textures even for the same model parameters. The constant direction (magnitude-based) method $\mathbf{F}_{\text{mag}}(t)$ generates smooth textures while the varying direction (vector-based) method $\mathbf{F}_{\text{vec}}(t)$ renders textures that feel rougher and sometimes sticky.

3 Characteristics of Buzzing

Our current work focuses on one type of perceived instability called "buzzing" (Choi & Tan, 2004).

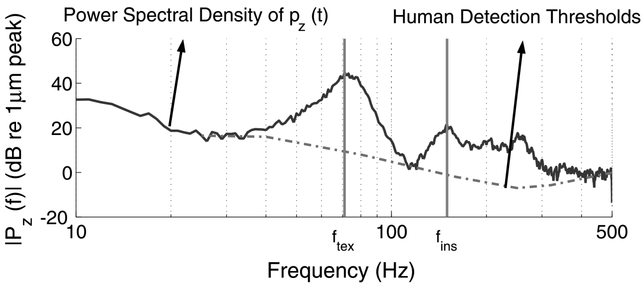


Figure 2. *Frequency domain characteristics of the signals responsible for buzzing.*

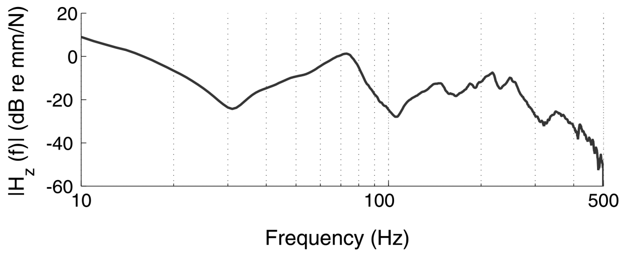


Figure 3. *A z-axis open-loop frequency response of the PHANToM model 1.0A.*

A brief summary of our previous work on the physical and perceptual characteristics of buzzing and its possible sources is provided here. Interested readers may refer to our previous publications (Choi & Tan, 2004, 2005) for further details.

When a virtual textured surface is stroked with a stylus, the user receives texture information (e.g., the sinusoidal bumps in Figure 1) in the form of a vibration resulting from the stylus interacting with the textured surface. In addition to the ever-present vibration due to the texture, the user sometimes feels buzzing that appears to be at a higher frequency. Buzzing can occur with haptic textures rendered with either the $\mathbf{F}_{mag}(t)$ or the $\mathbf{F}_{vec}(t)$ method, and is more apparent when the surface stiffness is relatively high. Buzzing is also more frequently observed than any other types of perceptual instability (such as aliveness or ridge instability) and is usually perceived to be more intense.

An example of the proximal stimuli associated with buzzing is provided in Figure 2. The solid line in the figure shows a typical power spectral density of $p_z(t)$ (the position of the PHANToM stylus tip along the normal direction of the underlying wall; cf. Figure 1) recorded during stroking of the virtual textured surface. The dash-dotted line indicates human detection thresholds at the corresponding frequencies (reproduced from Verrillo, 1963; see Choi & Tan, 2004 for why these thresholds were chosen for the comparison). The first spectral peak at f_{tex} (= 71 Hz) corresponds to the texture-related vibration. The location of f_{tex} can be predicted from the average stroking velocity and the spatial wavelength of the sinusoidal texture model (cf. Choi & Tan, 2004). The vibration at this frequency is responsible for the perception of the virtual texture.

From Figure 2, we can also observe a significant amount of energy in the high-frequency range starting from f_{ins} (= 150 Hz). The spectral components at f_{tex} and at $\geq f_{ins}$ are well separated in frequency, and are well above the corresponding human detection thresholds. As is known in the haptic psychophysics literature (Tan, 1996), vibrations occurring in these two spectral peak regions give rise to distinctive sensations. The user perceives the spectral component at f_{tex} as texture, and the high-frequency vibrations starting from f_{ins} as buzzing (perceived instability).

The high-frequency buzzing noise was most likely caused by the mechanical resonance of the PHANToM, based on its frequency response measured in our laboratory. Figure 3 shows the magnitude of a z-axis open-loop frequency response of the PHANToM (model 1.0A) that was measured with the stylus tip resting at the origin of the world coordinate frame and pointing to the $+z$ direction. The frequency response is defined as

$$H_z(f) = \frac{P_z(f)}{\tilde{F}_z^C(f)}, \qquad (5)$$

where $\tilde{F}_z^{\,C}(f)$ is the Fourier transform of the z-axis force command to the PHANToM $[F_z^{\,C}(t)]$ and $P_z(f)$ is that of the z-axis position of the stylus tip $[p_z(t)]$. This magnitude response plot exhibits significant mechanical resonances at frequencies above 150 Hz. Similar structural resonances have been reported for the PHANToM model 1.5 (Cavusoglu, Feygin, & Tendick, 2002). A comparison of Figure 2 and Figure 3 suggests that the

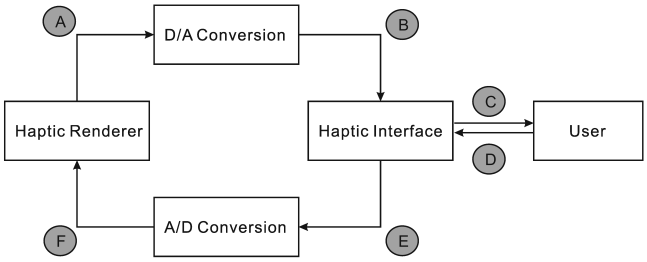


Figure 4. *Structure of a haptic rendering system used in the simulation.*

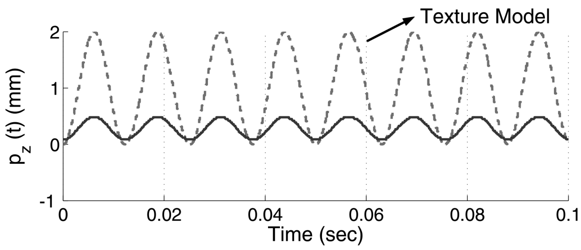


Figure 5. *Stylus position in the z-direction (signal F in Figure 4; solid line) with the corresponding sinusoidal texture model (dashed line).*

high-frequency mechanical resonances in Figure 3 have most likely contributed to the buzzing noise in Figure 2.

In our previous studies on perceived instability of virtual haptic textures (Choi & Tan, 2004, 2005), we tested various values of the texture model parameters (amplitude and spatial period) ranging from 0.5–4 mm. As would be expected, the actual numerical value of the stiffness threshold for stable rendering without buzzing depended on the values of the amplitude and the spatial period used in rendering textures. However, the fundamental characteristics of buzzing discussed in this section were shown to be independent from the values of the rendering parameters. Therefore, we chose one set of texture model parameters (A = 1 mm and L = 2 mm) for the simulation and experiments reported in this article.

4 Simulation: Update Rate versus Buzzing

In this section, we present a simulation demonstrating that using a relatively low update rate can be the main cause of the buzzing noise. The architecture of a haptic texture rendering system used in the simulation is shown in Figure 4. The sampled data nature of the texture rendering system was explicitly considered in the simulation.

The input to the Haptic Renderer (signal F in Figure 4) was the position trajectory of the PHANToM stylus tip along the normal direction to the textured wall [p_z (t)]. An example of signal F is provided in Figure 5 where the stylus trajectory p_z (t) is shown as a solid line and the textured surface height $h(p_x(t))$ is shown as a dashed line. These signals were designed to resemble the typical stylus trajectories measured when a user stroked virtual textured surfaces (Choi, 2003). Specifically, the amplitude (A) and wavelength (L) of the texture model were set to 1 mm and 2 mm, respectively, and the average stroking velocity ($\bar{v}_x$) was assumed to be 160 mm/s. The temporal frequency of the input signal F was thus 80 Hz (= $\bar{v}_x/L$; see Choi & Tan, 2004 for details). The quantization level was set to 0.03 mm, the nominal position resolution of the PHANToM model 1.0A.

The input to the Haptic Interface (force command signal B in Figure 4), denoted by $F_z^C(t)$, was computed using the rendering method $\mathbf{F}_{\text{mag}}(t)$ in Eq. 3 with stiffness K = 0.4 N/mm. Although buzzing could occur with both $\mathbf{F}_{\text{mag}}(t)$ and $\mathbf{F}_{\text{vec}}(t)$, we used $\mathbf{F}_{\text{mag}}(t)$ in the simulation for simplicity. Figure 6 shows the force commands under three digital-to-analog (D/A) conversion conditions. The upper panel corresponds to the force commands computed using an ideal non-causal reconstruction filter.[1] The lower panel shows two force commands reconstructed with zero-order hold (ZOH) at an update rate of 300 and 3000 Hz, respectively. It is apparent that the force command updated at 3000 Hz is quite smooth (and almost indistinguishable from that produced by the ideal reconstruction filter shown in the upper panel of Figure 6), but the force command updated at 300 Hz contains large step changes. This is to be expected for a force signal with a fundamental fre-

1. For the simulation, a very high update rate (100 kHz) was used to generate this force command.

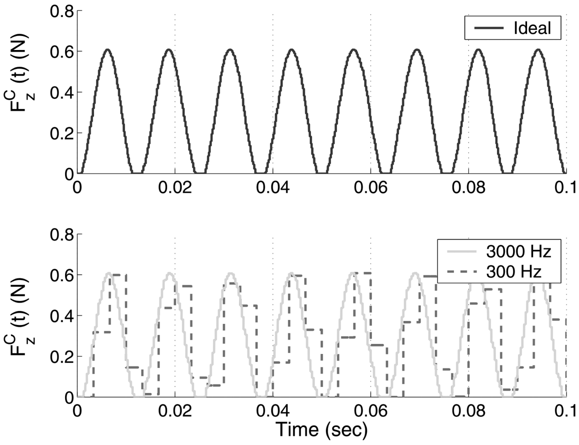


Figure 6. *Force commands in the z-direction (Signal B in Figure 4) updated at 100 kHz (upper panel) and at 300 Hz and 3kHz (lower panel, dashed and solid lines, respectively).*

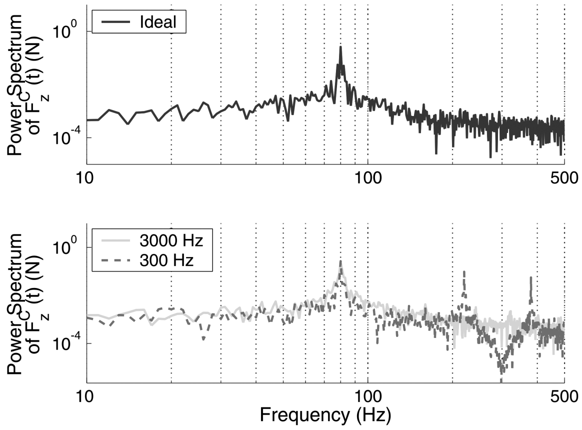


Figure 7. *Power spectral densities of the force commands updated at the three different rates shown in Figure 6.*

quency of 80 Hz. The frequency domain representation of the three force commands is provided in Figure 7. As expected, all three power spectra show a prominent peak at 80 Hz. The spectral density of the force command in the upper panel and that for the 3000 Hz update rate in the lower panel are indistinguishable, but the spectral density for the signal updated at 300 Hz exhibits additional spectral peaks at 220 and 380 Hz.[2]

Finally, we calculated the output of the Haptic Interface (i.e., the input to the user; signal C in Figure 4). We assumed that the PHANToM stylus was moving around the origin of the PHANToM coordinate frame. We then approximated the dynamics of the PHANToM by the linearized magnitude response shown earlier in Figure 3. By multiplying this magnitude response with the power spectral densities of the force commands shown in Figure 7, we obtained the spectral densities of the PHANToM position outputs.

The results are shown in Figure 8 along with the human detection thresholds. As expected, the upper panel showing the PHANToM position signal resulting from the ideal force command has only one spectral peak at 80 Hz which is well above the human detection threshold. We therefore predict that the user will perceive a clean texture from the vibration at 80 Hz. In the lower panel, the same can be said about the position signal generated from the force command updated at 3000 Hz. However, the position signal driven by the force command updated at 300 Hz contains additional spectral peaks at 220 and 380 Hz, and the peak at 220 Hz is well above the corresponding human detection threshold. We therefore conclude that when forces are updated at 300 Hz, the user will perceive not only the texture information from the vibration at 80 Hz, but also the perceived instability of buzzing from the vibration at 220 Hz. The buzzing noise is subsequently fed back to the Haptic Renderer (through the path D-E-F in Figure 4). The behavior of this closed loop usually increases the intensity of buzzing and widens its frequency range, thereby creating the closed-loop response similar to that shown earlier in Figure 2.

In summary, the simulation results suggest that using a higher haptic update rate decreases the high-frequency signal content of the reconstructed force command to the force-feedback haptic interface, and consequently reduces the energy of the signal components that can cause the perception of buzzing. The simulation results

2. Note that the original continuous signal has two spectral peaks at −80 Hz (not shown in Figure 7) and 80 Hz. The spectral density of the same signal sampled at 300 Hz exhibits replicas of the two spectral peaks shifted by 300 Hz, 2 × 300 Hz, 3 × 300 Hz, and so on. (Franklin, Powell, & Workman, 1990). Therefore, we observe prominent spectral peaks at 220 (= 300 − 80) Hz and 380 (= 300 + 80) Hz. We are not interested in the additional spectral peaks beyond 500 Hz (e.g., 520 and 680 Hz) because they cannot be easily perceived by the mechanoreceptors in the hand.

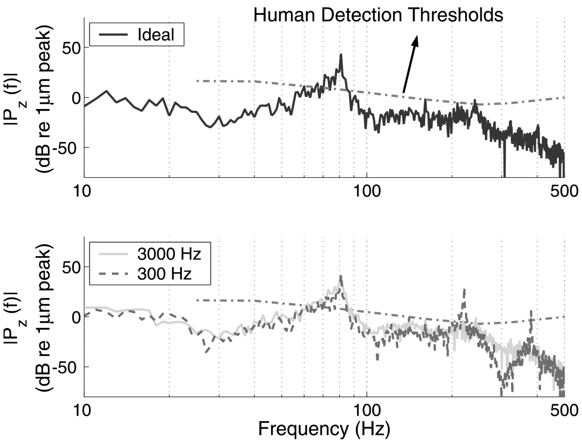


Figure 8. *Power spectral densities of the position outputs of the PHANToM along the z-axis (signal C in Figure 4) at three different update rates.*

support the use of a relatively high haptic update rate with force-feedback devices that have structural resonances at high frequencies, such as the PHANToM.

5 Experiment I: Update Rate versus Buzzing

The simulation results presented in the previous section confirmed that using a low update rate for haptic texture rendering can be a primary cause for the buzzing noise. A psychophysical experiment was conducted to find a quantitative relation between update rate and buzzing. This section reports the design and results of the psychophysical experiment.

5.1 Methods

The PHANToM 1.0A model was used to render virtual haptic textures. The texture was modeled as one-dimensional sinusoidal gratings (Eq. 1). In all experimental conditions, the amplitude and spatial wavelength of the sinusoidal grating were set to 1 mm and 2 mm, respectively. The texture model was rendered using $\mathbf{F}_{vec}(t)$ (Eq. 4), because virtual textures rendered with $\mathbf{F}_{vec}(t)$ exhibit buzzing more often and more intensely than those with $\mathbf{F}_{mag}(t)$ (Choi & Tan, 2004). The independent variable used in the experiment was the haptic update rate for texture rendering. Eight update rates were tested: 250, 500, 1k, 2k, 5k, 10k, 20k, and 40 kHz (see the Appendix for details on how we achieved very high update rates). The dependent variable measured in each experimental condition was the maximum stiffness threshold K_T under which the textured surface was perceived to be stable without buzzing.

The method of limits, a classical psychophysical method (Gescheider, 1997), was employed to estimate stiffness thresholds. The detailed procedure was essentially the same as that used in our previous experiments (Choi & Tan, 2004, 2005). Each experimental condition consisted of 25 ascending series and 25 descending series, resulting in detection thresholds corresponding to the 50-percentile point on the psychometric function. The minimum stiffness (K_{min}) and maximum stiffness (K_{max}) were set to 0.0 and 1.6 N/mm, respectively, based on preliminary experiments. The stiffness increment ΔK was 0.05 N/mm for all conditions. More details can be found in Choi & Tan (2004).

Five participants (three males: S1, S4, S5 and two females: S2, S3) took part in the psychophysical experiment. S1, S3, and S4 were experienced, regular users of the PHANToM device, and S1 and S3 were members of our research team. S1 and S2 had participated in all our previous studies on perceived instability of virtual haptic textures (Choi & Tan, 2004, 2005). S4 was not familiar with virtual haptic textures before his participation in the current study. S5 had not used the PHANToM device prior to the current experiment. All participants were right-handed by self-report and had no known sensory or motor abnormalities with their upper extremities. The age of the participants ranged from 25 to 39 years, and averaged 30.8 years.

During the experiment, the participants were required to stroke the textured surface by moving the PHANToM stylus laterally in the left-to-right direction with their right hands, and to judge whether the surface exhibited any buzzing (see Figure 9). No limitations were imposed on the number of strokes allowed. Buzzing was described to the participants as high-frequency vibratory noise embedded in low-frequency vibrations that they always felt when stroking a textured surface. The participants then became familiarized with the sensation of buzzing after a short

Figure 9. *Experimental setup. The participant stroked the virtual haptic textured surface laterally with the right hand. Only text information was available on the computer monitor to indicate the current trial number and to prompt the participant with the response codes.*

exposure to a particularly unstable condition during training. They were allowed to choose a stroking velocity that was most comfortable to them and were asked to maintain the stroking velocity to the best of their ability throughout the experiment. The participants wore noise-reduction headphones throughout the experiment to block the noises emanating from the PHANToM while they stroked the textured surfaces.

5.2 Results and Discussion

The measured stiffness thresholds for stable texture rendering are shown for individual participants in Figure 10. In general, the maximum stiffness for perceptually stable haptic texture rendering (i.e., without buzzing) increased monotonically with the haptic update rate. On the average, the stiffness threshold increased from 0.411 N/mm (at 250 Hz) to 1.049 N/mm (at 40 kHz) corresponding to a 255% increase. This was a significant increase both numerically and perceptually. The hardest haptic virtual textures that could be stably rendered at 250 Hz were quite soft, whereas the hardest textures rendered at 40 kHz felt hard and crisp (one participant commented that the texture felt like sharp metal blades). A two-way ANOVA with participant and update rate as the independent variables and stiffness threshold as the dependent variable confirmed that both participant and haptic update rate significantly affected the stiffness thresholds [$F(4,1988) = 307.14$, $p < .0001$ for participant; $F(7, 1988) = 189.50$, $p < .0001$ for update rate]. Note that the interparticipant difference was to be expected since each participant applied different mechanical impedance to the PHANToM during the experiment.

The average stiffness threshold measured at the update rate of 1 kHz was 0.640 N/mm. Numerically, this stiffness value is smaller than the stiffness threshold for a flat wall without textures (1.0 N/mm; cf. Choi & Tan, 2004). Perceptually, textures rendered at this stiffness value felt rather soft. The update rates had to be increased to more than 10 kHz before a stiffness threshold close to 1.0 N/mm could be achieved (see Figure 10). Textures rendered at a stiffness value of 0.8–1.0 N/mm with the PHANToM begin to feel as hard as plastic or metal.[3] These results indicate that an update rate much faster than the conventional 1 kHz is necessary in order to render virtual haptic textures that are perceptually "clean and hard" with the PHANToM haptic device.

Our results can be interpreted from the viewpoint of digital control. A unique feature of haptic texture rendering is that the vibration frequency corresponding to texture is determined by both the spatial frequency of the texture model and the user's stroking velocity. A relatively fine surface texture combined with a typical stroking velocity can easily produce force commands with a fundamental frequency of a few hundred Hz. It is well known that humans are most sensitive to vibrations in the frequency range 200–300 Hz and can sense signals at frequencies as high as 700 Hz (Verrillo, 1963). When a ZOH filter is used for D/A conversion, a sampling rate that is 10–20 times faster than the signal bandwidth is usually recommended (Franklin et al., 1990). This results in a preferred update rate in the 5–10 kHz range for haptic texture rendering. Therefore, the widely-accepted haptic-rendering update rate of 1 kHz may not be adequate for perceptually clean haptic texture rendering, as indicated by our experimental results.

3. Some haptic devices can stably render a hard surface without surface textures at 1 kHz with stiffness values higher than 1.0 N/mm (e.g., see Adams & Hannaford, 1998; and Grange, Conti, Rouiller, Helmer, & Baur, 2001).

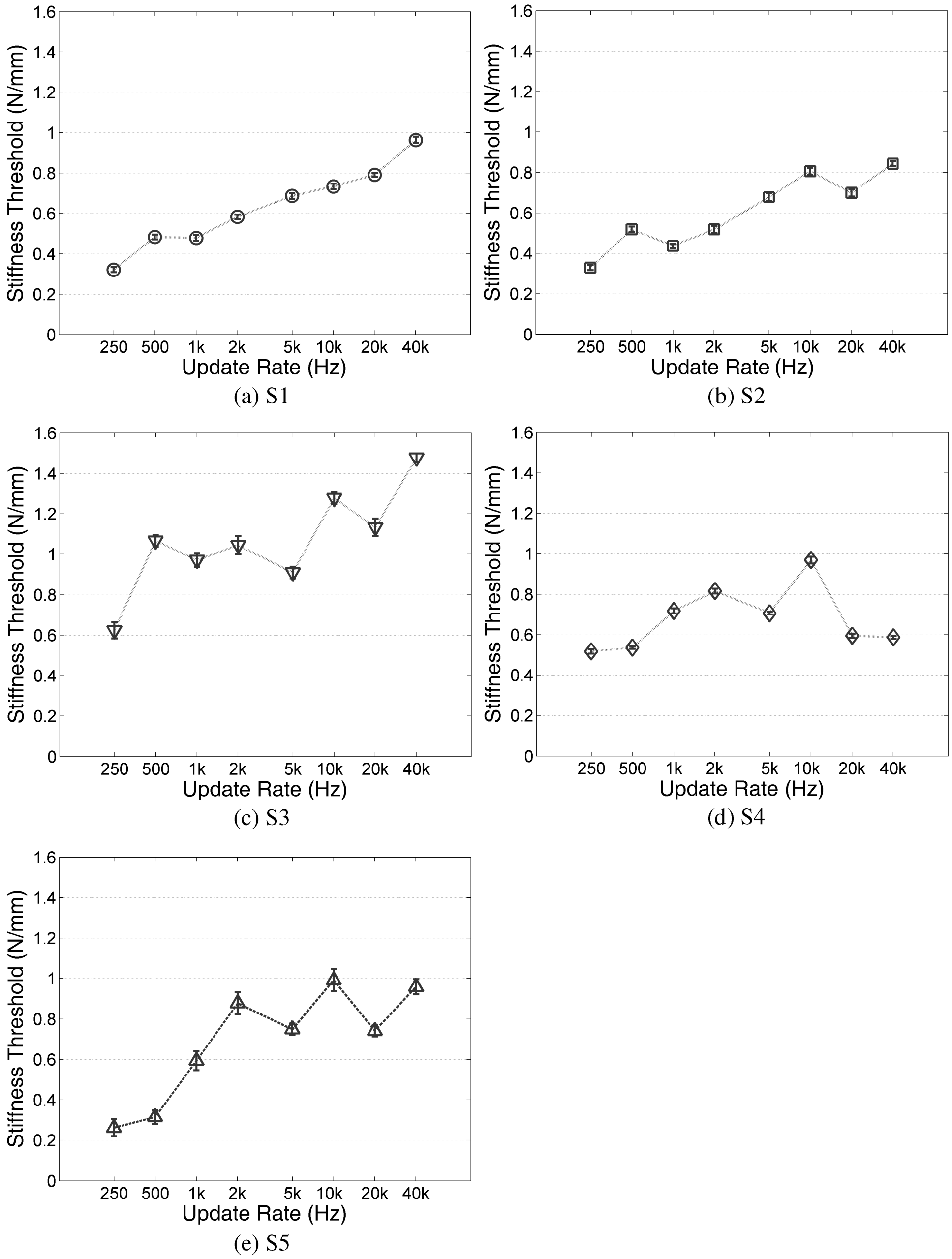
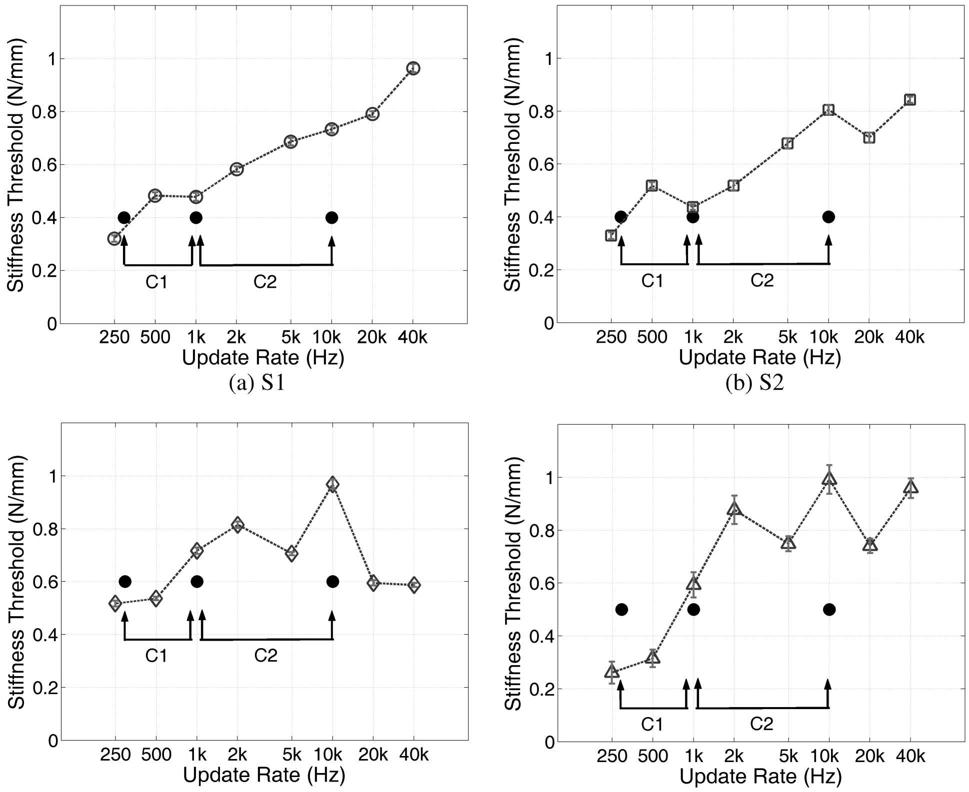


Figure 10. *Stiffness thresholds for perceptually stable texture rendering measured in Experiment I, along with standard errors.*

6 Experiment II: Pairwise Discrimination of Textured Surfaces

In Sections 4 and 5, we have examined the effect of haptic update rate on the perceived instability of virtual textures, with a particular focus on the buzzing noise. The results showed that the control stability of haptic texture rendering was improved (i.e., buzzing was reduced) when the update rate increased. We now turn our attention to the effect of update rate on human perception. In this section, we describe the design and results of a psychophysical experiment where the dis-



(a) S1 (b) S2 (c) S4 (d) S5

Figure 11. *Experimental conditions for Experiment II. See text for details.*

criminability of two haptic textured surfaces rendered with different update rates was examined. The traditional 1 kHz update rate was used as one of the experimental conditions.

6.1 Methods

Four participants (S1, S2, S4, and S5) participated in this experiment. The texture model parameters and rendering method used in the experiment were the same as those used in Experiment I. Two experimental conditions (C1 and C2) were customized to each participant. We used two textured surfaces rendered at 300 Hz and 1 kHz for condition C1, and those rendered at 1 kHz and 10 kHz for condition C2. The stiffness of the surfaces was chosen for each participant such that in condition C1, there was perceived instability associated with the virtual texture rendered at 300 Hz, but not with the one rendered at 1 kHz. In condition C2, there was no perceived instability associated with either the texture rendered at 1 kHz or at 10 kHz. The stiffness value selection was based on the results obtained in Experiment I for the same participant, indicated by dashed lines in Figure 11. In each panel, three filled circles show the two pairs of update rates and the stiffness value used in Experiment II, with the circle in the middle indicating the 1 kHz update rate used in both C1 and C2. The stiffness values chosen for participants S1, S2, S4, and S5 were 0.4, 0.4, 0.6, and 0.5 N/mm, respectively.

Under each experimental condition, a one-interval two-alternatives forced-choice paradigm (Wickens, 2002) was employed. On each trial, the participant felt one virtual texture randomly selected from the two texture alternatives. To explore the textured surface, the participant held the PHANToM stylus lightly like a pen with the right hand and stroked the surface from left to right. The participant was then asked to report which virtual texture was presented by pressing the "1" key on the keyboard for the texture rendered with the lower update rate and the "2" key for the texture rendered with the higher update rate. No trial-by-trial correct-answer feedback was provided during data collection. Each condition consisted of 100 trials. The order of the two experimental conditions was randomized for each participant. At the beginning of each experimental condition, the participants familiarized themselves with the stimuli by entering either "1" or "2" on the keyboard to feel the corresponding texture. Training was terminated by the participants whenever they were ready.

Data from each condition formed a 2×2 stimulus-response matrix consisting of 100 trials. From the matrix, we estimated the sensitivity index d' that provided a bias-free measure of the discriminability between the two textured surfaces, and the standard deviation of d' (Wickens, 2002). With this setup, a large positive d' (>1) indicated that the two textured surfaces could be reliably discriminated. A small d' value (≈ 0) implied that the two surfaces were perceived to be similar.

6.2 Results and Discussion

The values of the sensitivity index d' measured in Experiment II are shown in Figure 12 for each participant, along with the standard deviations represented by error bars. Under condition C1 where there was perceived instability with the texture rendered at 300 Hz but not for the one rendered at 1 kHz, the d' values for all participants averaged 2.2 which were much larger than 0. This indicated that the participants could easily discriminate the two textured surfaces. Under condition C2 where there was no perceived instability with either texture, all of the d' values were close to 0 and averaged -0.1, implying that the two textured surfaces were indistinguishable to the participants.

The results of Experiment II were consistent with our expectations. In condition C1, the texture rendered at 300 Hz contained the buzzing type of perceived instability in the form of high-frequency vibrational noises in addition to lower-frequency vibrations that delivered texture information (cf. Figure 2). This buzzing noise

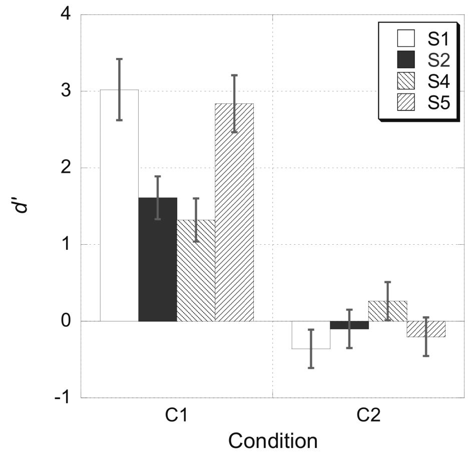


Figure 12. *Sensitivity index d′ values measured in Experiment II, along with their standard deviations.*

must have served as a cue that helped the participant discriminate the textures rendered at 300 Hz and 1 kHz. In condition C2, none of the participants could discriminate the two textures rendered at 1 and 10 kHz. This result indicated that although the textures rendered at 10 kHz contained much smoother force outputs than those rendered at 1 kHz, the participants could not perceive any differences. The results therefore supported our initial hypothesis that as long as the update rate was sufficiently high to eliminate the perceived instability of buzzing, there was no advantage in using a higher update rate.

7 Experiment III: Discrimination Threshold of Update Rate

In this experiment, we measured the discrimination threshold for haptic update rate using a reference rate of 10 kHz. Specifically, we measured how much the haptic update rate could be reduced from 10 kHz until a user could perceive a difference in the quality of the virtual texture. The results were compared to the stiffness threshold versus update rate curve measured in Experiment I. We were particularly interested in whether textures that could be easily discriminated from the reference texture were free of the perceived instability of buzzing.

7.1 Methods

The same four participants (S1, S2, S4, and S5) who took part in Experiments I and II participated in this experiment. The texture model parameters and rendering method used in the experiment were the same as those used in Experiments I and II. The surface stiffness was chosen for each participant such that the reference texture rendered at 10 kHz was perceptually stable for that participant based on the results of Experiment I. The values were 0.4, 0.4, 0.6, and 0.5 N/mm for S1, S2, S4, and S5, respectively (cf. Figure 10).

The discrimination thresholds were measured using a three-interval, forced-choice, one-up three-down adaptive staircase method. This method efficiently estimates a threshold at the 79.4-percentile point of a psychometric function (Leek, 2001). During each trial, the participant felt three instances of virtual textured surfaces. In one randomly chosen interval, the texture was rendered at a varying update rate which was always lower than 10 kHz. The other two textured surfaces were rendered with the reference update rate of 10 kHz. The participant's task was to identify the interval during which the textured surface felt different from those presented during the other two intervals. The initial value of the variable update rate was 250 Hz. An initial step size of 50 Hz was used for the first three response reversals. The step size was then decreased to 10 Hz, and the experiment continued until twelve reversals were obtained at the 10-Hz level.

The update rates at the last twelve reversals were paired and used to calculate six estimates of the discrimination threshold. The average of the six estimates was taken as the discrimination threshold for the condition, and the standard deviation was also computed for error estimation.

7.2 Results and Discussion

The discrimination thresholds measured in Experiment III are shown in Figure 13 for each participant. In each panel, a horizontal line connects the measured discrimination threshold (filled circle at the left end) with the reference update rate of 10 kHz (filled circle at the right end). The line thus represents the interval of update rates that produced perceptually equivalent textures in the experiment. Textures rendered with the two update rates at the ends of the line were barely discriminable to the participant. The values of the update-rate discrimination threshold (i.e., the filled circle on the left side of the solid line segment) were 364 (± 25), 359 (± 28), 279 (± 17), and 434 (± 22) Hz for participants S1, S2, S4, and S5, respectively. Also shown are the results for the corresponding participants from Experiment I (dashed lines). The areas below the dashed lines represent the parameter space (update rate and stiffness value) for virtual textures without the perceived instability of buzzing for the corresponding participant.

For participants S1 and S2, the update rate that could be reliably discriminated from 10 kHz was almost on the stiffness threshold versus update rate curve from Experiment I. The results of these two participants indicated that they were not able to distinguish the reference texture from one that was rendered at a lower update rate until the latter exhibited buzzing. For participants S4 and S5, the update rate that could be reliably discriminated from 10 kHz was slightly lower than the point on the stiffness threshold versus update rate curve from Experiment I at the tested stiffness value. It seemed that these two participants were conservative in their judgments in Experiment III, in the sense that they waited until buzzing was quite apparent with the virtual texture rendered at the lower update rate. Recall that the main difference between the two groups of participants was that S1 and S2 had participated in all previous experiments on perceived instability of virtual haptic textures (Choi & Tan, 2004, 2005), whereas S4 and S5 had not been exposed to virtual haptic textures prior to their participation in the present study. It is likely that the relative inexperience of S4 and S5 with respect to buzzing contributed to their hesitation of declaring the presence of buzzing noise in this experiment.

The results from all four participants support our hypothesis that virtual haptic textures without perceived instability cannot be easily discriminated. The results also demonstrated that the perceptual cue used for discrimination of virtual textures rendered at different update rates was the perceived instability of buzzing.

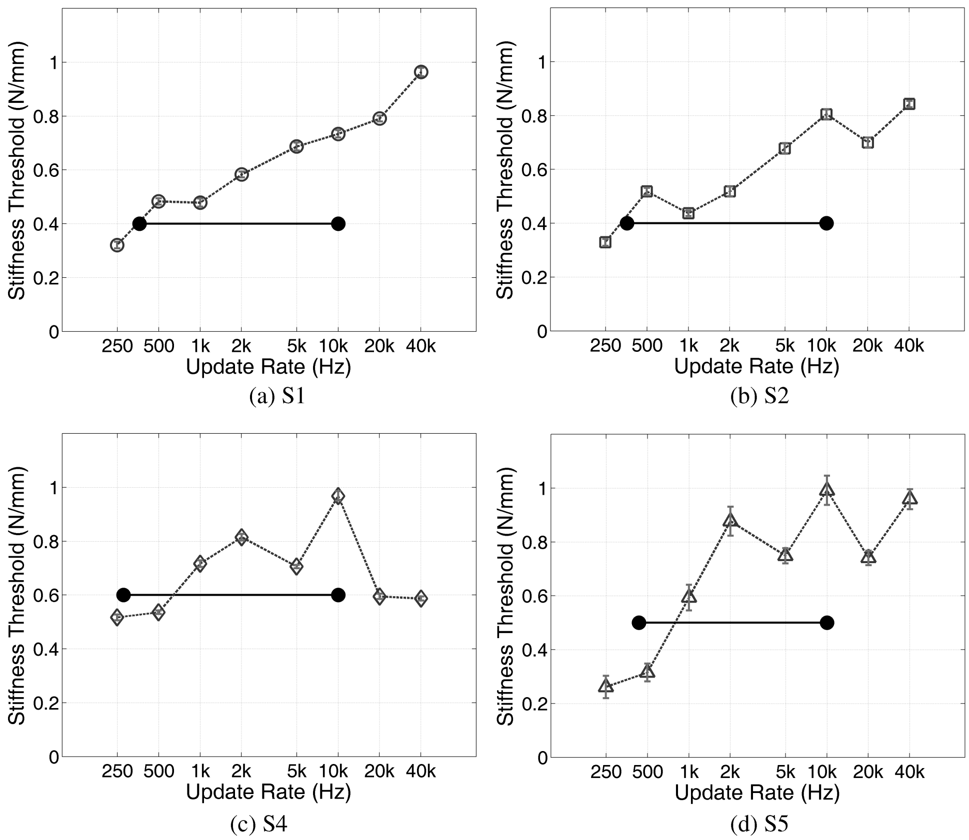


Figure 13. *Discrimination thresholds of update rate measured in Experiment III. See text for details.*

8 Conclusions

In the present study, we investigated the effect of haptic update rate on the perceived quality of virtual textures rendered with a force-feedback haptic interface. Our goal was to develop a general guideline for an optimal update rate. We considered the effect of the update rate on both the control stability of the haptic device and the performance of a perception task by the human user. For control stability, we first presented simulation results in the frequency domain suggesting that buzzing could be caused by an update rate that was too low for the texture model and the stroking velocity under consideration. A subsequent psychophysical experiment (Experiment I) using a wide range of haptic update rates (250 Hz to 40 kHz) showed a nearly linear increase in the stiffness threshold as a function of the logarithm of haptic update rate. Both the simulation and experimental results demonstrated that the haptic update rate was a critical factor in determining the stability of virtual haptic textures. In particular, the experimental results indicated that using a haptic update rate higher than 10 kHz could effectively eliminate the perceived instability of buzzing for most haptic texture rendering applications.

For human perception, we investigated the extent to which users could discriminate virtual haptic textures rendered with different update rates by conducting two psychophysical experiments. Experiment II used the signal detection paradigm and showed that textured surfaces rendered with two different update rates were perceived to be identical if neither texture contained any perceived instability such as buzzing. Two virtual textures rendered at different update rates could be easily discriminated if one exhibited buzzing and the other did not. In Experiment III, we measured the discrimination threshold of update rate using an adaptive staircase method with a reference update rate of 10 kHz. The thresholds were subsequently compared to the stiffness threshold versus update rate curves obtained in Experiment I. The results indicated that our ability to discriminate virtual haptic textures rendered with different update rates was very limited. With the results from Experiments II and III, we were able to quantitatively show that the participants could not discriminate a test textured surface from the reference surface rendered at 10 kHz as long as the test surface did not contain any perceived instability. After the experiments, the participants reported that they indeed concentrated on the detection of buzzing as a way of discriminating textured surfaces. The above results supported our hypothesis that virtual haptic textures rendered with different update rates are perceptually equivalent if no perceived instability exists.

It should be noted that the qualitative findings of the present study can be generalized to other haptic interfaces, but that the quantitative thresholds may be device dependent. The observations attained in Experiment I that the stiffness thresholds for stable texture rendering without buzzing increased with update rate and that update rates much higher than the conventional 1 kHz would be required for clean haptic texture rendering are to be applicable to the majority of force-feedback haptic interfaces. However, the actual numerical values of the stiffness thresholds would depend on the device used for texture rendering. The results of Experiments II and III indicated that when the PHANToM can render clean and stable haptic textures as intended without buzzing, our discriminability of vibratory texture signals rendered with different update rates is very limited. It follows that this fact is also independent from the haptic interface used for the experiment.

Based on the findings of this paper, we have arrived at the following *guideline* for choosing an optimal update rate for rendering virtual textures that are free of perceived artifacts. If the virtual texture feels unstable because of the perceived instability of buzzing, the update rate should be increased until the perceived instability disappears. A further increase of update rate will not improve the perceived quality of haptic virtual textures. In other words, the guideline states that given a textured surface, we can lower the update rate as long as there is no perceived instability, without sacrificing the perceived quality of the virtual texture. This approach allows the virtual environment designer to allocate more computation time to other tasks such as collision detection.

Future research will be pursued in two directions. One is to perform a complete control-theoretic analysis of the effect of haptic update rate on buzzing based on the idea outlined in Section 4. The other is to develop a multi-rate haptic rendering architecture for texture rendering with a very fast update rate (examples of multirate haptic rendering systems can be found in Astley & Hayward, 1998; Barbagli, Prattichizzo, & Salisbury, 2002; and Cavusoglu & Tendick, 2000). In this architecture, the computations for texture rendering (including collision detection and force computation) is performed at a relatively low update rate (e.g., the traditional 1 kHz). The force commands are then upsampled to a higher frequency (e.g., 10 kHz as observed in this paper) and sent to the force-feedback device in order for efficient high update-rate rendering. Our ultimate goal is to develop haptic texture rendering systems with sufficiently high update rates for better perceived quality yet still providing adequate computational time for force computation.

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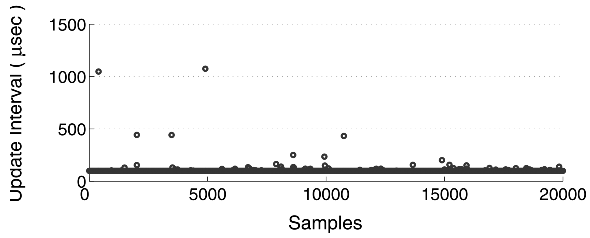

Figure A1. *Haptic update intervals measured with a high-resolution counter at a sampling rate of 10 kHz.*

Appendix

In order to achieve a very fast haptic update rate, we used the high-resolution counter in a Dell Precision Workstation 620 (dual Pentium III Xeon 993 MHz and 512 MB RDRAM) running the Microsoft Windows XP operating system. The high-resolution counter has a time resolution of 1.007 ns, which is much faster than the 1 ms time resolution provided by the Microsoft Windows timer APIs. The input/output (I/O) module used the GHOST programming library v4.0 for the PHANToM. We used the gstDeviceIO class of the GHOST SDK for a non-1-kHz update rate. We hasten to point out that we did not use the I/O functions of the gstDeviceIO class as recommended by SensAble Technologies (the manufacturer of the PHANToM), because with them we could not achieve update rates faster than about 1.5 kHz. This limitation was due to the internal hardware-checking mechanism of the gstDeviceIO I/O functions (personal communication with Billy Chan at SensAble Technologies, 2004). We therefore implemented our own I/O routines that bypassed the internal mechanism and accomplished a maximum update rate of 50 kHz for haptic texture rendering. Update rates below 250 Hz could not be tested due to a safety feature of the PHANToM force-feedback device used in our experiment (personal communication with Billy Chan at SensAble Technologies, 2004). The device renders zero forces for update rates slower than about 250 Hz.

We also examined the timing accuracy of our haptic updating module and confirmed that the resulting update intervals were very consistent. An example of haptic update intervals measured using the high-resolution counter is provided in Figure A1. In this case, the update rate was set to 10 kHz, and 20,000 update intervals were measured. Except for a few large outliers, most of the measured update intervals lay near 100 μs. The mean and standard deviation of the 20,000 datum points were 100 μs and 11 μs, respectively. The relatively large standard deviation was mainly due to the several large outliers as can be seen in the figure. These outliers were suspected to be caused by background system threads such as a virus vaccine program. We also tested the timing accuracy at many other update rates and obtained similar results.