Discrimination of Virtual Haptic Textures
Rendered with Different Update Rates

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Abstract

This paper addresses the discriminability of virtual haptic textures rendered with different update rates. Two psychophysical experiments were conducted. In the first experiment, we examined the pairwise discriminability of textured surfaces rendered with different update rates. In the second experiment, we measured the discrimination threshold of update rate for a reference textured surface rendered at 10 kHz. The results indicated that as long as the virtual textures were perceived to be stable (i.e., free of perceptual artifacts), subjects judged them to be perceptually equivalent. These findings, when taken together with our previous findings regarding the effect of update rate on perceived instability of virtual haptic texture [1], provide a general guideline for choosing an optimal update rate for haptic texture rendering, with explicit consideration for both control and perception performance.

1. Introduction

Haptic update rate refers to the rate 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, update rate is a critical factor that determines the performance of all three components. Firstly, the complexity of the virtual environment model that the renderer can process in real-time is limited by the update rate. Secondly, the stability of the haptic interface usually improves with an increase of the updated rate [2]. Thirdly, the perceived quality of the haptic virtual environment is affected by the update rate [3, 4], 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 minimum update rate needed for a specific haptic rendering system. Finding such guidelines requires considering the effect of update rate on both control stability and perceived quality of virtual objects. Such guidelines will help designers of haptic virtual environments better understand the tradeoff between more detailed physical modeling (requiring lower update rates) and better control stability and perceived quality of haptic objects (generally requiring higher update rates).

In the past several years, we have been working towards haptic rendering systems that guarantee perceptually "clean" surface textures. Towards this goal, we introduced the concept of *perceived instability*, which refers to any unrealistic sensations that cannot be attributed to the physical properties of the virtual haptic textured surfaces being rendered by a force-feedback haptic interface [5]. Perceived instability is a frequently occurring phenomenon in virtual haptic textures rendered with current techniques (for example, see [6, 7]; see also [8] for a review). Our previous studies examined the effects of various factors (texture model parameter, rendering method, collision detection algorithm, and exploration mode) on the perceived instability of virtual haptic textures, and revealed the characteristics and sources of several primary types of perceived instabilities [5, 8-10].

Our most recent study [1] investigated the effect of haptic update rate on the perceived instability of virtual haptic textures. We focused on one type of perceived instability called buzzing, which refers to high-frequency noise-like forces (or vibrations) emanating from a force-feedback device during haptic texture rendering. In the study, we first showed that buzzing noises were due to the unstable high-frequency modes of a force-feedback haptic interface and relatively low update rates of haptic texture rendering. This study thus corresponds to an investigation of the effect of update rate on the *control stability* of haptic texture rendering systems. We have since developed a haptic texture rendering system capable of updating forces at a rate of up to 50 kHz. Using the system, we measured the maximum stiffness of textured surfaces that could be rendered without buzzing over an update rate range 250 Hz – 40 kHz when the subjects stroked the textured surfaces. We confirmed that stiffness thresholds increased with update rates, and found that update rates significantly faster than the conventional rate of 1 kHz (e.g., 5 – 10 kHz) were needed in order to render perceptually "clean and hard" textured surfaces.

In the current study reported in this paper, we examine effect of update rate on the *perceived quality* of virtual haptic textures. We selected the discriminability of virtual haptic textured surfaces rendered with different update rates as a measure of perceived quality. Our hypothesis, based on extensive preliminary experiments, was that *virtual haptic textures rendered with different update rates are perceptually equivalent if there is no perceived instability involved.* To test the hypothesis, we designed and conducted two psychophysical experiments. In the first experiment, we had subjects compare two haptic textured surfaces rendered with different update rates and measured the pairwise discrimination performance. Rendering parameters including the update rate were chosen based on our previous work [1], so that they resulted in either perceptually stable or unstable textures. In the second experiment, we quantified the extent to which we can discriminate virtual haptic textures of various update rates by measuring the discrimination thresholds of the update rate. The discrimination thresholds were then compared to the surface stiffness vs. update rate curve for perceptually stable rendering measured in [1]. The results of both experiments strongly supported our hypothesis for update rates above 250 Hz[1]. The findings presented in this paper, when taken together with those of our previous work [1], provide a guideline of choosing an optimal update rate for haptic texture rendering, with explicit considerations for both device control and human perception.

2. General Methods

In this section, we describe the experimental methods that are common to both experiments. Experiment-specific details are presented later when the corresponding experiment is discussed.

2.1. Apparatus

We used the PHANToM 1.0A with an encoder gimbal (SensAble Technologies; Woburn, MA, USA) in all experiments reported in this paper.

2.2. Subjects

Three subjects (S1 – S3) participated in the experiment. S1 is male, and is an experienced user of the PHANToM device. S2 is female, and had not used any haptic interfaces prior to her participation in our previous experiments on perceived instability of virtual haptic textures. S1 and S2 participated in all of our previous experiments [1, 8-10]. S3 is male, and is an experienced PHANToM user. However, S3 was not familiar with virtual haptic textures before his participation in our most recent study [1]. All are right-handed, and did not report any known sensory or motor impairments with their hands or arms. The age of the subjects ranged from 25 to 33 years old, and averaged 30 years.

2.3. Stimulus

The haptic texture was modeled as 1D sinusoidal gratings and defined by

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

in the PHANToM world coordinate frame, where A and L denoted the amplitude and spatial wavelength of the sinusoidal textures, respectively (see Fig. 1). This texture model was superimposed on a 3D plane $z = 0$ to form the textured surface as shown in the figure.

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

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

We then computed forces as

$$\mathbf{F}(t) = Kd(t)\mathbf{n}_T(\mathbf{p}(t)),$$

where K was the surface stiffness and $\mathbf{n}_T(\mathbf{p}(t))$ was the normal of the textured surface at $\mathbf{p}(t)$. This method was

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[1] Update rates below 250 Hz could not be tested due to a safety feature of the PHANToM force-feedback device used in our experiment (see Sec. 2.1). The device renders zero forces if force update becomes slower than about 250 Hz [personal communication with Billy Chan at Sensable Technologies].

proposed in [7], and produced virtual haptic textures that felt rougher and sometimes stickier than other rendering methods.

This force computation was repeated at a specified update rate. Therefore, the stimulus used in the experiments were uniquely defined by four variables, A, L, K, and update rate. Throughout the experiments, A and L were kept at 1 mm and 2 mm, respectively.

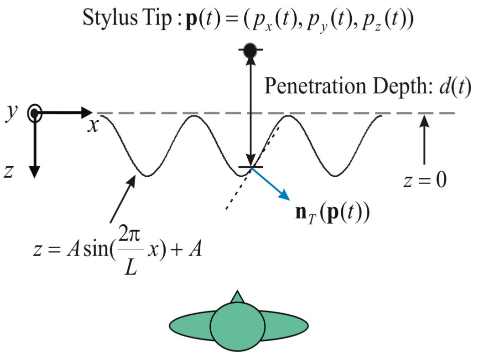


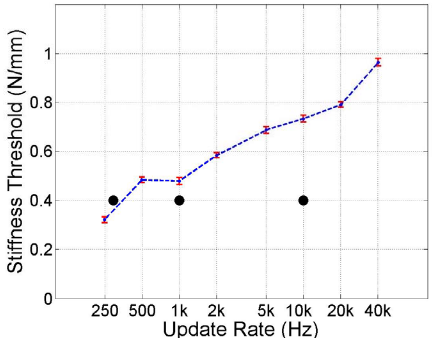
Fig. 1. An illustration of parameters used in haptic texture rendering.

3. Exp. I: Pairwise Discrimination

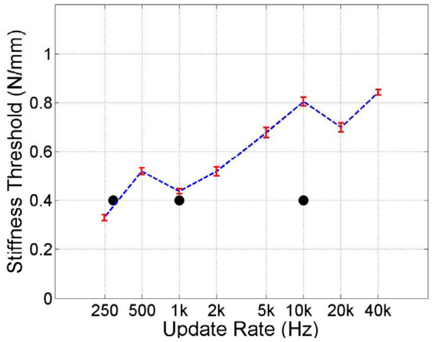
In this experiment, we examined the discrimination performance of two virtual haptic textures rendered with different updates rates. The traditional 1 kHz update rate was included in all experimental conditions.

3.1. Methods

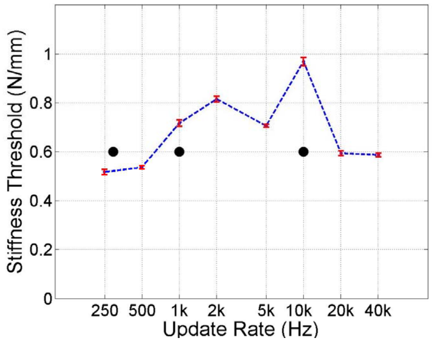
For each subject, two customized experimental conditions (C1 and C2) were selected. We used two textured surfaces rendered at 300 Hz and 1 kHz for condition C1, and those rendered at 1 kHz and 10 kHz for condition C2. Under both conditions, the textured surface with the lower update rate was named Signal 1, and the other Signal 2. The stiffness of the surfaces was chosen for each subject such that in condition C1, the stiffness value resulted in perceptually unstable (300 Hz) and stable (1 kHz) textures, and in condition C2, both perceptually stable (1 and 10 kHz) cases. The stiffness value selection was based on the update rate vs. stiffness threshold curve under which the textured surfaces were perceived to be stable without buzzing. The curves for individual subjects measured in our previous work [1] are shown in separate panels in Fig. 2 by dashed lines, along with the error bars representing the standard errors of the stiffness thresholds. In the curves, the stiffness threshold for an update rate is the largest stiffness value that could render stable textures without buzzing for the corresponding subject. Using higher stiffness than the threshold resulted in unstable textures exhibiting buzzing. In each panel, three filled circles show the two pairs of update rate and stiffness value used in Exp. I, with the circle in the middle indicating the 1 kHz update rate used in both C1 and C2. The stiffness values used for subjects S1, S2, and S3 were 0.4, 0.4, and 0.6 N/mm, respectively.



(a) Subject S1



(b) Subject S2



(c) Subject S3

Fig. 2. Experimental conditions for Exp. I. See Sec. 3.1 for details.

Under each experimental condition, a one-interval two-alternative forced-choice paradigm was employed. On each trial, the subject felt either Signal 1 or 2 randomly selected by a computer program. To explore the textured surface, the subject held the PHANToM stylus lightly like a pen with his/her right hand and stroked the surface from left to right. The subject was then asked to report whether Signal 1 or Signal 2 was presented on that trial by pressing "1" for Signal 1 and "2" for Signal 2. 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 subject.

At the beginning of each condition, subjects familiarized themselves with the stimuli by entering either "1" or "2" on the keyboard to feel the corresponding signal. Correct-answer feedback was also provided. Training was terminated by the subjects whenever they were ready. During the main experiment, no visual feedback was provided except for text information about trial numbers. The subjects wore noise-reduction headphones throughout the experiment to block the aural noises emanating from the PHANToM while they stroked the textured surfaces.

Data from each condition formed a 2 by 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′* [11].

3.2. Results and Discussion

The values of *d′* measured in Exp. I are shown in Fig. 3 for each subject, along with the standard deviations represented by error bars. Under condition C1 where the perceptually unstable texture rendered at 300 Hz and the stable one rendered at 1 kHz were compared to each other, all subjects produced *d′* values that were much larger than 0. This result indicated that the subjects could reliably discriminate the two textured surfaces. Under condition C2 where the two textures rendered at 1 and 10 kHz contained no perceived instability, the *d′* values were all close to 0, implying that the two textured surfaces were indistinguishable to the subjects.

The results of Exp. I were consistent with our expectations. In C1, the texture rendered at 300 Hz contained the buzzing type of perceived instability in the form of high-frequency noises in addition to (relatively) low-frequency vibrations that delivered texture information (see [1, 8] for details). An example of signals that cause the perception of buzzing is provided in Fig. 4, which shows a power spectral density of the stylus position ($p_z(t)$) normal to the underlying wall of the textures. One can clearly observe high-frequency buzzing noises starting from f_{ins}, in addition to a low-frequency spectral component at f_{tex} that was responsible for the texture information (see [8] for further details). This buzzing noise must have served as a perceptual cue that helped the subject discriminate the textures rendered at 300 Hz and 1 kHz. In C2, none of the subjects could discriminate the two textures rendered at 1 and 10 kHz. This result indicated that although the texture rendered at 10 kHz contained much smoother force outputs than that rendered at 1 kHz, the subjects could not perceive the differences. The results therefore supported our initial hypothesis that as long as the update rate was sufficiently high to eliminate perceived instability, there was no advantage in using a higher update rate.

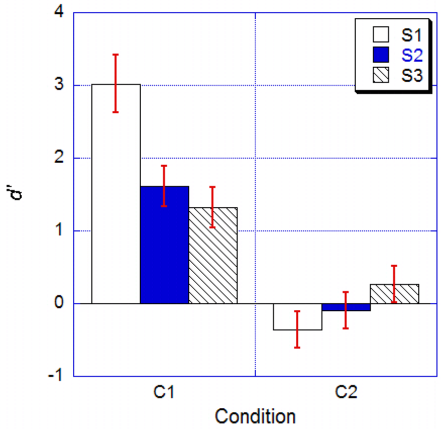


Fig. 3. *d′* values measured in Exp. I.

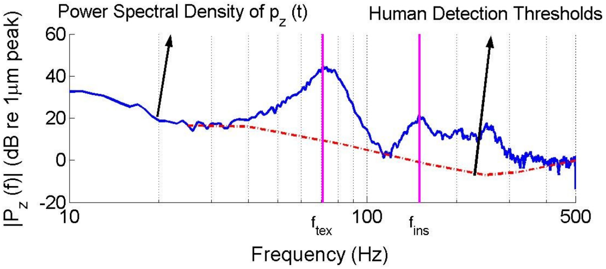


Fig. 4. Frequency-domain illustration of buzzing.

4. Exp. II: Discrimination Threshold for Update Rate

In this experiment, we measured the discrimination threshold for haptic update rate using a reference rate of 10 kHz. We were particularly interested in whether textures that could be easily discriminated from the reference texture were free of the perceived instability of buzzing.

4.1. Method

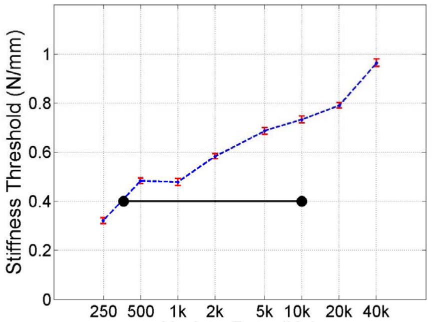
The surface stiffness was chosen for each subject such that the reference texture rendered at 10 kHz was perceptually stable for that subject based on [1]. The values were 0.4 N/mm, 0.4 N/mm and 0.6 N/mm for subjects S1, S2 and S3, respectively (see Fig. 2).

The discrimination thresholds were measured using a three-interval, forced-choice, one-up and three-down adaptive staircase method. This method efficiently estimates a threshold at the 79.4%-correct performance level [12]. During each trial, the subjects felt three instances of virtual textured surfaces. In one randomly chosen interval, the texture was rendered at the varying update rate. The other two textured surfaces were rendered with the reference update rate of 10 kHz. The subject's task was to identify the interval during which the textured surface felt different from those perceived during the other two intervals. The initial value of the variable update rate was always 250 Hz. An initial step size of 50 Hz was used for the three initial 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.

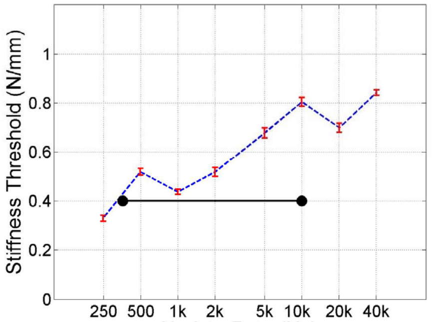
The update rates at the last twelve reversals were paired and used to calculate six estimates of the discrimination threshold. The average of the six estimates was taken as the discrimination threshold for the condition, and the standard deviation was also computed for error estimation.

4.2. Results and Discussion

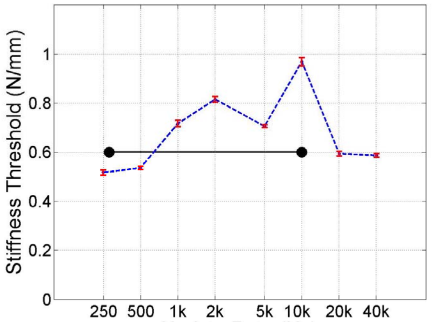
The discrimination thresholds measured in Exp. II are shown in Fig. 5 for each subject. In each panel, a horizontal line with filled circles connects the measured discrimination threshold at the left end with the reference update rate of 10 kHz at the right end. The line thus represents the interval 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 just discriminable to the subject. The standard deviations of the discrimination thresholds were 25, 28, and 17 Hz for subjects S1, S2 and S3, respectively. Also shown are the update rate vs. stiffness curves for perceptually stable rendering measured in our previous work [1]. The update rates and stiffness values below the curves represent the parameter space for perceptually stable virtual textures for the corresponding subject.



(a) Subject S1



(b) Subject S2



(c) Subject S3

Fig. 5. Discrimination thresholds of update rate for virtual haptic textures measured in Exp. II. See Sec. 4.2 for details.

For subjects S1 and S2, the estimated discrimination threshold of update rate (for the surface stiffness value of 0.4 N/mm) was almost on the update rate vs. stiffness curve for perceptually stable texture rendering. The results of these two subjects indicated that the subjects were not able to distinguish the reference texture from one that was rendered at a rate below 10 kHz, unless the latter exhibited perceived instability. For subject S3, the estimated discrimination threshold crossed the update rate vs. stiffness curve measured earlier. It was possible that subject S3 was conservative in his response in Exp. II. The results from all three subjects demonstrated that the perceptual cue used for discrimination of virtual textures rendered at different update rates was perceived instability (i.e., buzzing).

5. Conclusions

In this paper, we investigated the extent to which human users can discriminate virtual haptic textures rendered with different update rates by two psychophysical experiments. Exp. I used the signal detection paradigm and showed that textured surfaces rendered with two different update rates were perceived to be identical if both textures were perceptually stable (i.e., without buzzing). They could be easily discriminated if one texture exhibited buzzing and the other did not. In Exp. II, we measured the discrimination threshold of update rate using an adaptive staircase method. The threshold was subsequently compared to the update rate vs. stiffness curve for perceptually stable texture rendering measured in our previous study [1]. The results indicated that our ability to discriminate virtual haptic textures rendered with different update rates was very limited. It was shown quantitatively that the subject could not discriminate a test textured surface from the reference surface rendered at 10 kHz as long as the test surface was perceptually stable. After the experiments, the subjects reported that they concentrated on the detection of buzzing as a way of discriminating two textured surfaces. All these results supported our hypothesis that *virtual haptic textures rendered with different update rates are perceptually equivalent if they are perceptually stable*.

For the designer of haptic virtual environments, our studies provide the following guideline for rendering virtual textures that are free of perceptual artifacts. If the virtual texture feels unstable, one can increase the update rate until the texture is perceived to be stable. 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 tasks such as collision detection and response force computation.

Acknowledgement

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