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A Parameter Space for Perceptually Stable Haptic Texture Rendering *

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1 Introduction

After Minsky's pioneering work on synthetic texture rendering using a two-dimensional force feedback joystick [5], the research on haptic texture rendering has received much attention in the recent years, with a majority of work focusing on the development of texture rendering algorithms. Several successful implementations of texture rendering methods using various texture geometry models have been reported so far (for examples, see [1][2][4][6]). These studies focus on the computational aspects of texture rendering. Our research program is more concerned with the perceptual aspects, in additional to the computational aspects of texture rendering. Specifically, we are developing a research program for a better understanding of the perceptual dimensions associated with texture perception, and the development of algorithms for rendering synthetic textures with desired perceptual qualities.

The first challenge we face is the stability problem of synthetic texture rendering. In particular, there is a need for the specification of the parameter space within which perceptually stable texture rendering can be achieved. Most studies on stability uses a virtual wall as a benchmark of stability performance in haptic rendering. In this case, a haptic interaction can be modeled by a 1 DoF (Degree-of-Freedom) system due to the locally homogeneous geometry of a flat wall. The rendering objective is to make the wall feel as hard as possible without unintended vibrations. Theoretical analysis of stability for interactions with textured surfaces is a much more complex problem. In practice, many authors, such as [8], have commented that the stable range of surface stiffness ensuring *perceptually* stable texture rendering can be quite small. The goal of texture rendering is to evoke sensations related to various aspects of texture perception such as roughness and stickiness [3]. The PHANToM uses the paradigm of feeling through a probe, which means that surface textures are transmitted via temporal cues (as compared to spatial and intensive cues while the bare finger pad is used). From a theoretical points of view, it is difficult to predict what kinds of vibrations would be perceived to be related to texture attributes and what would be perceived as unrealistic. Therefore, we propose to study the parameter space for perceptually stable haptic texture rendering by conducting psychophysical experiments. In this paper, we report results of our study on the range of stiffness parameter that ensures perceptually stable texture rendering, using the method of limits as the experimental paradigm. In Section 2, we describe the experimental design in terms of the rendering methods and the exploration modes employed. The results of the experiments conducted so far are summarized in Section 3, followed by a discussion in Section 4.

2 General Methods

2.1 Apparatus

The hardware setup consists of a PHANToM (Model 1.0A, with encoder gimbals) and a Pentium II PC (400MHz, 128MB RAM). This model of PHANToM has a maximum stiffness of 3.5 N/mm and a workspace of 13 cm × 18 cm × 25 cm.

2.2 Stimuli

The textured surfaces chosen for the stimuli of the experiments are one-dimensional sinusoidal gratings superimposed on an underlying surface. A flat wall is used as the underlying surface in the current study. It is always positioned such that it coincides with the xy plane located at $z = 0$ in the PHANToM coordinate frame. We regard sinusoidal gratings as the basic building blocks for textured surfaces, since any surface profile can be modeled by the weighted sum of sinusoidal functions (see, for example, [7]). The sinusoidal gratings used in this study are described by $z = A\sin(\frac{2\pi}{L}x) + A$, where A and L are the amplitude and the (spatial) wavelength, respectively (see Figure 1).

Two kinds of texture rendering methods are used in the current experiments. Both use a spring model to calculate the magnitude of the rendered force. The first method, introduced by Massie, always generates a force, denoted by $\mathbf{F}_1(t)$, that is normal to the underlying surface [4]. This

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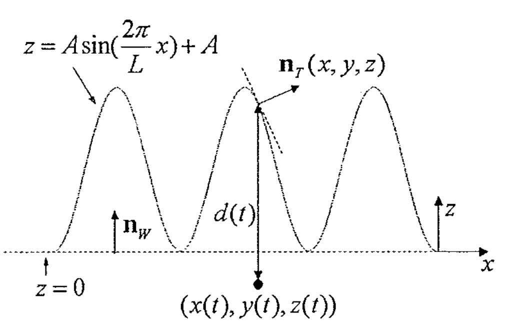

Figure 1: An illustration of the textured surface and its associated variables. See the text in Section 2.2 for details.

method generates forces with a constant direction when the underlying surface is a flat wall. The second method, proposed by Ho, Basdogan and Srinivasan, calculates a force, denoted by $\mathbf{F}_2(t)$, that is normal to the textured surface [2]. This method generates forces that change directions depending on the local micro-geometry of the surface texture.

For both methods, $d(t)$, the penetration depth of the stylus into the textured surface at time t, and the force vectors $\mathbf{F}_1(t)$ and $\mathbf{F}_2(t)$, can be calculated as follows.

$$d(t) = \begin{cases} 0 & , \quad z(t) > 0 \\ A\sin\left(\frac{2\pi}{L}x(t)\right) + A - z(t) & , \quad z(t) \leq 0 \end{cases},$$

$$\begin{aligned} \mathbf{F}_1(t) &= K\,d(t)\,\mathbf{n}_W, \\ \mathbf{F}_2(t) &= K\,d(t)\,\mathbf{n}_T(x(t), y(t), z(t)). \end{aligned}$$

where K is the stiffness of the surface, $(x(t), y(t), z(t))$ are the coordinates of the stylus, $\mathbf{n}_W$ is the normal vector of the underlying flat wall, and $\mathbf{n}_T(x,y,z)$ is the normal vector of the textured surface at (x,y,z) (see, again, Figure 1).

2.3 Psychophysical Method

As explained in Section 2.2, the relevant physical parameters are amplitude(A) and spatial period(L) of a sinusoidal grating, and stiffness(K) of the surface.

The goal of our experiments is to quantify the range of the stiffness parameter K where haptically rendered textures feel stable. The method of limits is used for all the experiments reported here. In a typical run, the values of A and L are kept constant, and the value of K is systematically changed (in either ascending or descending order) from trial to trial. The subject's task is to report whether the textured surface feels stable. Each run is terminated when the subject reverses the response from stable to unstable or vice versa. For each experimental condition (i.e., the same pair of A and L values), there are a total of 100 runs with 50 ascending and 50 descending runs. The order of ascending and descending runs is randomized. An ascending run starts with a trial with K_{min}, whose value is chosen to be small enough to ensure a perceptually stable rendering of a textured surface. The subject is instructed to press '1' if the textured surface feels stable, and '2' if it feels unstable. If the subject presses '1', K is increased by a pre-determined value, ΔK, on the next trial. This continues until the subject presses '2'. The value of $K + \Delta K/2$ is then recorded as the estimated threshold for this run. Descending runs are conducted in a similar fashion.

For each experimental condition, the mean and standard deviation of the estimated thresholds of K for the 50 ascending runs (K_A), the 50 descending runs (K_D), and all 100 runs (K_T) are computed and stored separately. Let the lower and upper bounds be $K_L = \min\{K_A, K_D\}$ and $K_U = \max\{K_A, K_D\}$, respectively. The ranges $[0, K_L]$, $[K_U, \infty]$ and $[K_L, K_U]$ correspond to perceptually stable, perceptually unstable, and perceptually 'gray' regions, respectively.

2.4 Experimental Conditions

Four experiments were conducted using the two texture rendering methods and the two exploration modes described below (Table 1):

- **Texture Rendering Methods:** The two texture rendering force computation methods proposed by Massie and Ho et al. (Section 2.2) are used in the experiments. It was observed during preliminary experiments that the two methods produced perceptually distinctive textured surfaces, given the same parameter values. It is therefore necessary to compare their stability characteristics quantitatively.
- **Exploration Modes:** It was also observed during the preliminary experiments that perceived stability of textured surfaces depended on the manner with which the stylus interacted with the surfaces. During the main experiments, the subject is allowed to use two exploration methods: free exploration, or stroking. In the free exploration mode, the subjects can explore the surface in whatever patterns they think are appropriate to discover unrealistic vibrations. In the stroking mode, the subjects are only allowed to move the stylus laterally across the textured surfaces. The stroking mode is particularly interesting because it is the most natural (and the most frequently used) way for gathering texture information through a probe, and because it seems to result in a more stable rendering of textured surfaces.

For each of the four experiments, three values of A (0.5, 1.0, 2.0 mm) and three values of L (1.0, 2.0, 4.0 mm) are used. This results in nine conditions per experiment. The order of the experimental conditions are randomized. For each combination of A and L values, K can vary from 0.0 N/mm (K_{min}) to 0.6 N/mm (K_{max}). This value of K_{max} is chosen to be the maximum stiffness for simulating a stable (not textured) virtual wall, as recommended in the GHOST Programmer's Guide [9]. For ascending or descending runs, K starts from 0.0 N/mm or 0.6 N/mm, respectively. The same increment of ΔK (0.02 N/mm) is used for both ascending and descending runs. Throughout the experiments, the subject is instructed to look away from the PHANToM, and wore headphones through which white noise was played.

Experiment Number	Texture Rendering Method	Exploration Mode
1	$\mathbf{F}_1(t)$	Free Exploration
2	$\mathbf{F}_1(t)$	Stroking
3	$\mathbf{F}_2(t)$	Free Exploration
4	$\mathbf{F}_2(t)$	Stroking

Table 1: Experimental conditions

2.5 Subject

So far, data have been collected for one subject, the first author. This subject has no sensory abnormalities and has considerable experience with haptic interfaces, especially the PHANToM.

3 Results

Typical data for one experimental condition is shown in Figure 2. As is expected with the method of limits, ascending runs tend to generate overestimated thresholds (top panel), and descending runs underestimated ones (middle panel). A combined histogram for ascending and descending runs usually shows a bimodal distribution. This tendency of $K_A > K_D$ has been observed for most of our data, except when both K_A and K_D are very small. The means of the data in Figure 2 are 0.26, 0.19, and 0.23 N/mm for the ascending, descending, and combined runs, respectively. The corresponding standard deviations are 0.04, 0.03, and 0.05 N/mm, respectively. For the remainder of this paper, only the mean and standard deviation for the combined runs are reported.

Data for Experiments 1 and 2 are shown in Figure 3. The same data are plotted as a function of L (top panel) and as a function of A (bottom panel). The two plot symbols, squares and crosses, correspond to data from Experiments 1 and 2, respectively. Equivalently, the same two symbols correspond to data collected using the free exploration and stroking modes, respectively. Several observations can be made from Figure 3. First, the range of K values for stable rendering is consistently larger for the stroking mode than for the free exploration mode. This can be seen from the fact that the crosses are above the squares in both panels of Figure 3. Second, the mean K for stable rendering depended on the values of A, but not L, for the range of A and L tested. Third, the values of K_T for the free exploration mode (i.e., the squares) are less than 0.15 N/mm. This results in a much smaller parameter range for the stable rendering of textured surfaces as compared to that for the rendering of (not textured) flat walls. Data for Experiments 3 and 4 are shown in similar fashion in Figure 4. The main difference between Figures 3 and 4 are that the former used $\mathbf{F}_1(t)$ for rendering, and the latter $\mathbf{F}_2(t)$. Again, the stroking mode results in a larger K range for stable rendering than the free exploration mode. However, there is no clear evidence of strong dependence of data points on either L or A.

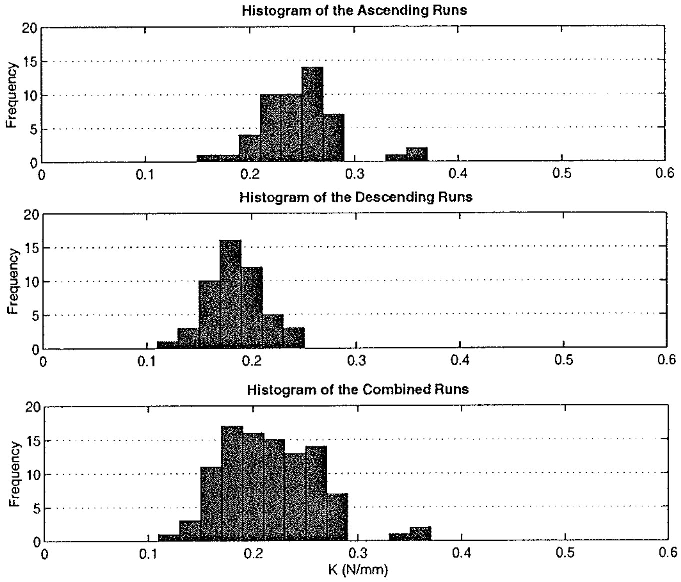

Figure 2: Histogram of the estimated thresholds of K (Experiment 2, $A = 2.0$ mm, and $L = 2.0$ mm)

4 Discussion

In this paper, the method of limits was used to measure the range of K for stable rendering of textured surfaces, using two rendering methods and two exploration modes. Overall, the data demonstrate that the stroking mode results in a more stable rendering of textured surfaces than the free exploration mode, although the effect is much bigger when $\mathbf{F}_1(t)$ was used than when $\mathbf{F}_2(t)$ was used. Basically, the range of K that can be used for stable rendering is very small for the free exploration mode, whether $\mathbf{F}_1(t)$ or $\mathbf{F}_2(t)$ was used. However, for the stroking mode, the use of $\mathbf{F}_1(t)$ results in a larger stable range of K than the use of $\mathbf{F}_2(t)$.

It should be pointed out that the decision to call a particular rendering stable or unstable can be highly subjective and depends greatly on the subject's expectation of how the PHANToM should feel like. It also seems to be the case that different strategies can be employed to determine a perceptual criterion for different combinations of rendering methods and exploration modes. For example, in Experiment 1 where $\mathbf{F}_1(t)$ and free exploration mode were used, the subject judged instability by detecting a vibration when the stylus barely contacted the peaks of the sinusoidal gratings. In Experiment 3 where $\mathbf{F}_2(t)$ and free exploration mode were used, the subject judged instability by paying attention to vibrations when the stylus was in contact with the peaks, or deep inside the valleys of the sinusoidal gratings. It was believed that when the stylus was deep inside the valley, instability could result from the continually changing force directions. For Experiment 2 and 4 where stroking mode was employed, the subject judged instability by whether the perceived bumpiness was mixed with additional vibrations.

Future work will assess the range of stable rendering for

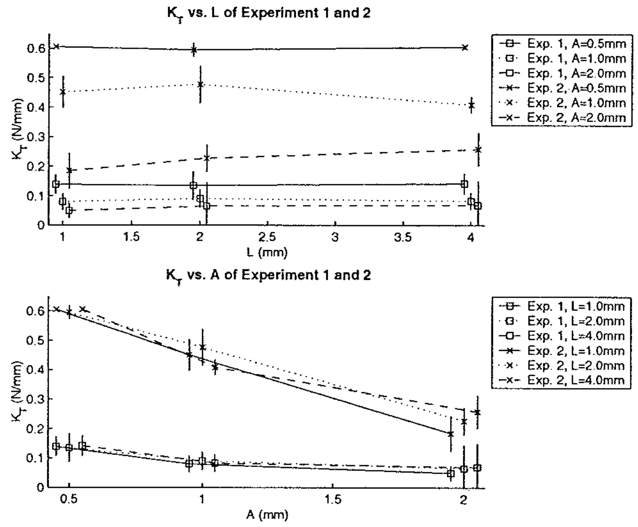

Figure 3: Results of Experiment 1 and 2.
Datum points are slightly offset for a particular L or A value for clarity. Vertical bars show ±1 standard deviation.

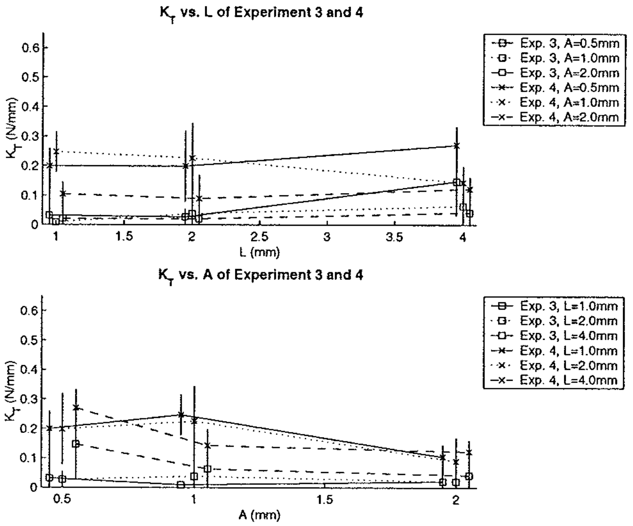

Figure 4: Results of Experiment 3 and 4.
Datum points are slightly offset for a particular L or A value for clarity. Vertical bars show ±1 standard deviation.

the parameters A and L with additional subjects. Our goal is to define the volume within the three-dimensional space (A, L, and K) where stable rendering of textured surfaces can be achieved.

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