Discriminability of Real and Virtual Surfaces with Triangular Gratings

Matthew Kocsis[*] Hong Z. Tan[*] Bernard D. Adelstein[†]
(*)Haptic Interface Research Laboratory, Purdue University, USA
(†)Human Systems Integration Division, NASA Ames Research Center, USA
Email: {mkocsis, hongtan}@purdue.edu, Bernard.D.Adelstein@nasa.gov

Abstract

Human sensitivity to height differences in textured surfaces is on the order of microns. Research on human texture perception requires texture samples with precisely controlled micro-geometry. This can be achieved with an electrical discharge machining (EDM) procedure, but the process is time consuming and labor intensive. An alternative approach is to simulate textured surfaces with a haptic interface with high position resolution. The present study measured the amplitude discrimination thresholds for surfaces with triangular gratings using real EDM textured samples and virtual textures rendered with a high-precision force-feedback device called the ministick. The results indicated that the just noticeable differences for real and virtual textures, respectively 3.69±0.65 and 4.94±0.96 μm, were of similar magnitude. Therefore, we propose that this device is suitable for the study human perception of surface micro-geometry with features on the scale of human perceptual resolution.

1. Introduction

The need for high-precision texture samples for studies of texture perception is well illustrated by an earlier study by Lederman in which two grooved aluminum surfaces with identical dimensional specifications but with different fabrication processes (machined with a cutting tool, and electrical discharge machining, or EDM) and, therefore, different surface micro-geometry, were judged different in a magnitude estimation task [1]. The surfaces consisted of square gratings with a groove width of 0.125 mm and a land width of 0.25 mm. More recently, sinusoidal gratings with an amplitude of 12.8-51.3 μm and a wavelength of 2.5 μm, fabricated by EDM on stainless steel bars, were used in an amplitude discrimination task and the resulting thresholds were on the order of single microns [2].

We have been interested in duplicating these prior studies with sinusoidal as well as triangle- and square-wave gratings. However, fabrication of stainless steel surfaces with well-defined sinusoidal and triangular gratings by wire EDM entails a post-machining polishing step. This process, which requires a highly skilled machinist, is both time-consuming and expensive. An alternative to fabricating precision surface gratings in a machine shop is the use of force-feedback technology to generate precision virtual haptic surfaces, as we did for a previous study comparing perception of real and virtual sinusoidal gratings [3]. That study demonstrated similar amplitude (i.e., height) discrimination thresholds, whether obtained via exploration of real EDM textures or with virtual textures rendered with a high resolution (~1 μm) 3-DOF force display (the "ministick"). This outcome was encouraging not only because the individual high-precision virtual textures produced by the ministick were perceptually comparable to real samples, but also because their production was much more efficient in terms of time and fiscal cost than machining actual physical specimens.

The present work is a follow-on to the sinusoidal gratings study reported by Tan et al. [3]. Our goal is to extend the previous study in order to determine whether discrimination thresholds would be similarly comparable for real and virtual triangular gratings, as was the case with sinusoidal gratings. The choice of triangular gratings is based on our interest in examining this comparison for texture waveforms with greater spectral complexity and consequently higher spatial frequency content than the previous sinusoidal gratings.

Two experiments are presented below. Exp. I examines particpants' ability to discriminate the height of two real triangular gratings directly with their fingertips. Exp. II involves exploration of virtual textures with a stylus. We present the methods

Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)
0-7695-2738-8/07 $20.00 © 2007 IEEE

common to both experiments in Section 2, followed by the specifics of the two experiments in Sections 3 and 4, and a discussion of the results in Section 5.

2. Methods

This section explains the data collection and analysis methods common to both experiments. Differences between methods for the two experiments are explained in Sections 3 and 4. Since the methods used in the present study are very similar to those that we reported previously [3], only a brief summary is presented here.

2.1. Stimuli

The triangular gratings used in this experiment had a fixed fundamental spatial wavelength of 2.5 mm. The amplitudes of the triangle gratings (1/2 of peak to trough) were either 50 µm (A_0, reference), 55 µm (A_1), 60 µm (A_2), 65 µm (A_3), or 70 µm (A_4).

2.2. Procedure

The experiments followed a two-interval two-alternative forced choice paradigm based on signal detection theory. Four pairs of stimuli were used in each experiment. Each pair included A_0, the reference stimulus, and either A_1, A_2, A_3, or A_4, the test stimulus. The paired stimuli were presented in the manner described in Sections 3 and 4. The participants could stroke the pair of textures laterally (perpendicular to the texture ridges) for as long as they wished, before they responded as to which of the pair had the larger height amplitude. Individual texture pairs were presented repeatedly as a block of trials. Training and trial-by-trial correct-answer feedback were provided. A total of 200 trials were conducted for each reference-test texture pair.

2.3. Data analysis

Data from each participant were analyzed individually to obtain the discriminability, d_i' for each test stimulus level (A_i, i = 1,…,4) [4]. The slope, k, of the best fit line passing through the origin was created by averaging the ratios of individual d' (ordinate) over the respective difference between the reference and test stimulus levels, $\Delta_i = A_i - A_0$ (abscissa), as defined by:

$$k = \frac{1}{4}\sum_{i=1}^{4}\frac{d_i'}{\Delta_i}$$

The discrimination threshold (also known as the just noticeable difference – JND) is calculated as the amplitude difference $\Delta = A - A_0$ at which $d' = 1$. From the slope of the linear fit ($k = d'/\Delta$), it follows that $d' = 1$ when $\Delta = 1/k$. Further details can be found in [3].

3. Exp. I: Discrimination of stainless steel surfaces with triangular gratings

3.1. Participants

Four participants, two females and two males, took part in Exp. I. All were right handed and none reported any conditions that would compromise their sense of touch. Two of the four participants (S3 and S4) had previous haptic experiments experience. The number of participants was limited because data collection was time-consuming for the real texture experiment. In general, it took about nine hours per participant to complete Exp 1.

3.2. Validation of real textures

The triangular grating texture samples were fabricated from stainless steel blocks by a wire EDM process. The blocks were 100 mm (L) × 30 mm (W) × 15 mm (H). Surface profilometry data for one sample (A_3=65 µm) is shown in Fig. 1 (top trace) along with its Fourier transform (bottom trace). Mathematically, the Fourier series of a triangular waveform is

$$A\left(\frac{8}{\pi^2}\right)\left\{\sin\frac{2\pi x}{\lambda}+\left(\frac{1}{3}\right)^2\sin 3\frac{2\pi x}{\lambda}+\left(\frac{1}{5}\right)^2\sin 5\frac{2\pi x}{\lambda}+\cdots\right\}.$$

It can be seen that the triangular profile contains a fundamental component (unity normalized magnitude), plus a third and fifth harmonic with normalized magnitude of 1/9 and 1/25, respectively. Other than side lobes due to finite sample length, there was no discernable noise in the Fourier spectrum.

A three-dimensional raster-scan image of the same sample, shown in Fig. 2, confirms that the triangular surface profile was consistent along the width of the texture sample.

Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)
0-7695-2738-8/07 $20.00 © 2007 IEEE

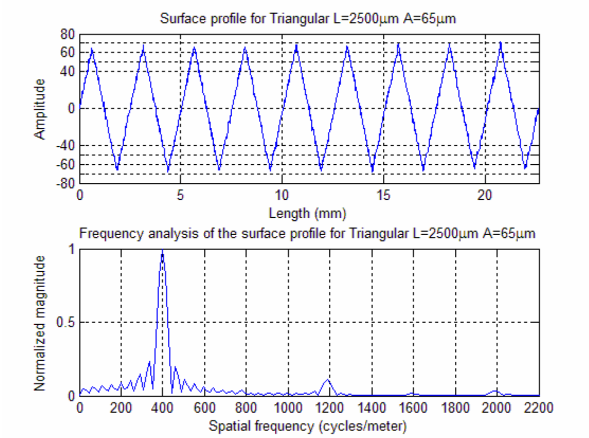

Figure 1. (top) Surface height along the length of a texture sample with A_3 = 65 mm. (bottom) Fourier transform of the top height trace.

3.3. Procedure

During Exp. I, each run consisted of 50 trials of the same reference-test stimulus pair, with a total of 4 runs conducted per reference-test stimulus pair so that a total of 200 trials could be collected. The ordering of the 16 experimental runs (4 reference-test stimulus pair × 4 runs per pair) was randomized for each participant. Before starting, participants were instructed to wash their hands thoroughly with soap to reduce excess oils from the fingertips. Participants sat at a table across from the experimenter, separated by a curtain. The participant slid his or her hand under the curtain where the experimenter would present the texture samples

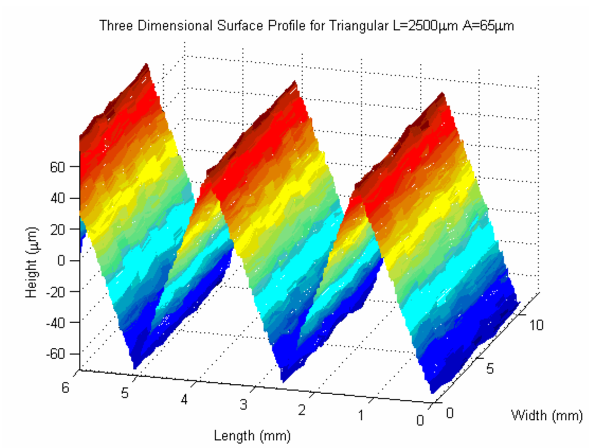

Figure 2. 3-D raster image of the surface of the texture sample with a triangular amplitude of 65 μm. Multiple length-wise profilometer scans taken at several positions along the width are combined to form the image.

Figure 3. Test apparatus used in Exp. I. It housed two stainless steel texture samples. The numbers "1" and "2" were used by the experimenter to determine the orientation at which the texture samples were presented to the participant.

that were hidden from the participant's view. Before each run started, the experimenter inserted the reference and probe stimuli (A_0 and A_1-A_4, depending on the stimulus set being presented) into the texture apparatus (Fig. 3). The apparatus was rotated behind the curtain by the experimenter between trials such that the participant was never aware in advance of contacting the specimens as to whether the left or right window contained the probe stimulus. Trial-by-trial correct-answer feedback was provided to the participant. A typical visit comprised either one or two runs, depending on the participant's comfort. Because of this experiment's duration (~9 hr/participant), multiple sessions were needed to complete data collection.

3.4. Results

Table 1 shows the texture discrimination thresholds (JNDs) from Exp. I. On average, the participants were very sensitive to the amplitude difference between two triangular surface profiles. The average discrimination threshold for the reference amplitude of 50 μm was 3.69 μm (7.4%). After the experiments, the participants commented that a great deal of concentration was needed to perform the discrimination task.

Table 1. Discrimination thresholds from Exp. I

Participant	Threshold (μm)	Avg±SD (μm)
1	3.72	3.69±0.65
2	4.17	
3	4.12	
4	2.76	

Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)
0-7695-2738-8/07 $20.00 © 2007 IEEE
IEEE COMPUTER SOCIETY

4. Exp. II: discrimination of virtual surfaces with triangular gratings

4.1. Participants

Ten participants, five female and five male, including S1-S4 from Exp. I who were assigned the same S number, took part in Exp. II. All participants were right handed and none reported any condition that would compromise their sense of touch. Four of the participants (S3, S4, S5 and S6) had previous haptic experimentation experience.

4.2. Virtual textures

The virtual textures were rendered by the ministick, a 3-DOF high position-resolution force display [5, 6] (see Fig. 4). The ministick has a nominal displacement resolution of 1 μm with a force update rate of 2 kHz.

The layout of the virtual textures was very similar to that of the stainless steel texture blocks used in Exp. I. The height map was defined by

$$h(x) = (-1)^n \left(\frac{2A}{D}\right)\left[x - D\left(n + \frac{1}{2} - \frac{1}{2}(-1)^n\right)\right],$$

where x was the x-axis displacement of the stylus tip in mm (Fig. 4), D the half period of the triangle wave (1.25 mm), and A the amplitude of the particular test texture sample, and $n = x \bmod D$ determined the sign of the slope of the line segments making up the triangular waveform. The resulting height profile $h(x)$ had the same appearance as the top trace in Fig. 1. The restoring force was calculated as

$$F = \begin{cases} K \times [h(x) - p_y] & \text{when } p_y < h(x) \\ 0 & \text{otherwise} \end{cases},$$

where the restoring force F always pointed up along the y axis (Fig. 4), and p_y was the y-axis displacement of the stylus tip. The stiffness constant K was always 2.0 N/mm. No force was generated along the tangential (x and z) directions.

4.3. Procedure

The procedure used in Exp. II was very similar to that of Exp. I, with the key difference that 100 trials were collected during each run because data collection was easier and therefore faster with the virtual

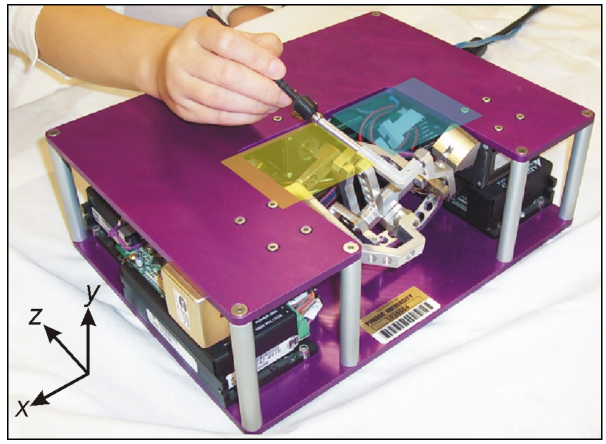

Figure 4. The 3-DOF force-feedback device used to render virtual textures in Exp. II. The two rectangular patches (cyan and yellow in color) indicate (roughly) the locations of the two virtual textured surfaces.

textures. The ordering of the 8 experimental runs (4 reference-test stimulus pair × 2 runs per pair) was randomized for each participant. Participants typically completed four runs per session. The experiment control software assigned the sides on which the reference and test gratings were presented during each trial (see the shaded patches shown in Fig. 4). Data collection in Exp. II took approximately three hours per participant.

4.4. Results

Discrimination thresholds from Exp. II are shown in Table 2. The average threshold for the 50 μm reference amplitude was 4.94 μm (9.9%).

Table 2. Texture discrimination thresholds from Exp. II

Participant	Threshold (μm)	Avg±SD (μm)
1	5.07	4.94 ±0.96
2	6.24	
3	5.13	
4	4.71	
5	4.12	
6	2.98	
7	5.71	
8	6.06	
9	4.55	
10	4.81	

Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)
0-7695-2738-8/07 $20.00 © 2007 IEEE

Discussion

The present study investigated the amplitude discrimination threshold for textured surfaces with triangular gratings. Exp. I showed an average ($N = 4$ participants) threshold of 3.69±0.65 μm (Avg±SD) using stainless steel real texture samples with triangular gratings that were explored directly with the finger. The result is very similar to that reported by Tan et al. [3] in which a similar experiment was conducted on real textured samples with sinusoidal gratings (3.90±0.77 μm, $N = 4$). A Student's t-test did not show significant differences between the two real texture experiments ($t_6 = 0.401$, $p_{\text{two-tail}} > 0.7$). From Exp. II in the present study, we obtained a discrimination threshold of 4.94±0.96 μm with virtual triangular gratings rendered on the ministick. This is again not significantly different than the thresholds (5.05±1.07 μm, $N = 10$) obtained in a similar experiment reported by Tan et al. [3] for virtual sinusoidal gratings (t-test: $t_{18} = 0.235$, $p_{\text{two-tail}} > 0.8$).

These results can be examined in several ways. First, the discrimination thresholds obtained in the present two experiments (3.69 and 4.94 μm for real and virtual triangular gratings, respectively) are of the same order of magnitude as was the case (3.90 and 5.05 μm) in Tan et al. [3], supporting the use of the ministick as a tool for studying human texture perception. Nevertheless, these differences between real and virtual texture thresholds are significant for both the sinusoidal (t-test for unequal variances: $t_8 = -2.24$, $p_{\text{one-tail}} < 0.028$) and triangular (t-test for unequal variances: $t_8 = -2.79$, $p_{\text{one-tail}} < 0.013$) gratings. The slightly lower real threshold may, in part, reflect the subtle differences between stroking a surface directly with one's own finger (real) versus indirectly via a grasped stylus (virtual).

Second, the similarity between the results obtained in the present triangular grating study and those reported previously for sinusoidal gratings [3] suggests that for either real or virtual textures the discrimination of triangular gratings was based mainly on the fundamental sinusoidal component of the waveform. Given the sharp roll-off of the Fourier coefficients for the triangular waveform (1/9 for the third harmonic, 1/25 for the fifth harmonic, etc.), it is quite possible that the harmonic components of the triangular gratings were below human detection thresholds and therefore did not contribute to the amplitude discrimination task.

A possible explanation for the slightly better performance with real textures would be that participants had access to both spatial-intensive as well as temporal information while stroking a real surface with a bare fingertip [7, 8]. Therefore, further studies will also examine amplitude discrimination for real textures with a grasped stylus so that only temporal information is available to the participants, as was the case with virtual textures.

Moreover, to evaluate the frequency-decomposition conjecture, future work will examine the physical attributes (e.g., forces, accelerations, etc.) of the proximal stimuli resulting from stroking virtual sinusoidal and triangular gratings on the ministick. The data will be analyzed in the (temporal) frequency domain to gain insight into which attributes the participants might use to perform such amplitude discrimination tasks.

What is emerging from this study as well as our previous one is the extraordinary sensitivity of human skin to the vibrations resulting from stroking a surface with micro-geometric height variations; i.e., on the order of microns. By conducting parallel experiments with high-definition real textures and virtual surfaces rendered by a high spatial-resolution force-feedback device, we have shown that the ministick is a useful experimental platform for studying human texture perception. Finally, in addition to repeated upfront costs associated with the fabrication of new stimuli at the initiation of a perceptual study, the use of *real* surface textures also entails the relatively cumbersome manual exchange of specimens during the experiment. Thus, very high performance *virtual* haptic interfaces such as the ministick open the door to a wide range of studies that otherwise could not have been conducted easily, quickly, or economically.

Acknowledgments

This work was supported in part by a National Science Foundation Award under Grant No. 0098443-IIS, and in part by NASA under award no. NCC 2-1363. MK was also supported by a Fellowship from the School of Electrical and Computer Engineering at Purdue University. BDA was supported by NASA's Space Human Factors Engineering Program.

References

[1] S. J. Lederman, "Tactile roughness of grooved surfaces: The touching process and effects of macro- and microsurface structure," *Perception & Psychophysics*, vol. 16, pp. 385–395, 1974.

[2] H. T. Nefs, A. M. L. Kappers, and J. J. Koenderink, “Amplitude and spatial-period discrimination in sinusoidal gratings by dynamic touch,” *Perception*, vol. 30, pp. 1263-1274, 2001.

[3] H. Z. Tan, B. D. Adelstein, R. Traylor, M. Kocsis, and E. D. Hirleman, “Discrimination of real and virtual high-definition textured surfaces,” *Proceedings of the 14th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS '06)*, pp. 3-9, 2006.

[4] N. A. Macmillan and C. D. Creelman, *Detection Theory: A User's Guide*, 2nd ed. New York: Lawrence Erlbaum Associates, 2004.

[5] R. Traylor, D. Wilhelm, B. D. Adelstein, and H. Z. Tan, “Design considerations for stand-alone haptic interfaces communicating via UDP protocol,” *Proceedings of the 2005 World Haptics Conference (WHC05): The First Joint EuroHaptics Conference and the Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Pisa, Italy, Mar. 18-20, 2005, pp. 563-564.

[6] R. Steger, K. Lin, B. D. Adelstein, and H. Kazerooni, “Design of a passively balanced spatial linkage haptic interface,” *ASME J. Mech. Des.*, vol. 126, pp. 984-991, 2004.

[7] C. E. Connor and K. O. Johnson, “Neural coding of tactile texture: Comparison of spatial and temporal mechanisms for roughness perception,” *Journal of Neuroscience*, vol. 12, pp. 3414–3426, 1992.

[8] S. J. Lederman, R. L. Klatzky, C. L. Hamilton, and G. I. Ramsay, “Perceiving roughness via a rigid probe: Psychophysical effects of exploration speed and mode of touch,” *Haptics-e: The Electronic Journal for Haptics Research*, vol. 1, 1999. (http://www.haptics-e.org)

0-7695-2738-8/07 $20.00 © 2007 IEEE