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Does Judgement of Haptic Virtual Texture Roughness Scale Monotonically With Lateral Force Modulation?

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Abstract. We describe experiments that compared the perceived relative roughness of textured virtual walls synthesized with an accurately controlled haptic interface. Texture was modeled as a spatially modulated sinusoidal friction grating. The results indicate that both the modulation depth of the grating (A), and the coefficient of friction (μ) are strongly associated with the perceived roughness when increasing either A or μ. Changing the spatial period of the grating (l), however, did not yield consistent relative roughness judgement results, indicating that there is a weaker association.

Key words: Haptic rendering, haptic textures

1 Introduction

Much work was reported regarding virtual haptic textures and the experience of roughness that results from a variety of synthesis approaches. To our knowledge, however, no previous study addresses the question whether the experience of roughness scales monotonically with synthesis parameters. The property of perceptual monotonicity could greatly simplify the search space for the investigation of equivalent sensations given by different hardware/software combinations. To this end, we use a friction-based algorithm that provides a sensation of texture. Mechanical signals are delivered a high-quality device that is engineered so that its dynamic characteristics are unlikely to interfere with the subjective results. Actuation and sensing resolution of the device allow for a precise reproduction of the texture, and passivity theory is applied to ensure the quality of the synthetic texture.

The perception of the roughness of virtual haptic textures has been extensively explored but the results are difficult to compare. Early work by Lederman and Minsky, [10], showed that the roughness estimate of 2D synthetic virtual textures could be almost entirely predicted by the maximum lateral force. A recent study by Kornbrot et al, [8], explored the psychometric function linking perceived roughness and the spatial frequency of virtual sinuosoidal textures; in their results, the majority of subjects had a descending function (larger pitch correlated with smaller roughness), while other studies indicated either raising or quadratic relationships. A descending trend has been reported, for example by Wall et al. [12], while for physical textures a quadratic function was found [7]. A further complication arises in the very definition of "virtual roughness". This difficulty is apparent in such works as [9], where the authors felt it necessary to clarify what roughness was by comparing the haptic experience with that of a car running on a bumpy road.

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The goal of the present study is to validate the authors' observation that friction-based textured surfaces, synthesized according to a force field of the form (1), feel rougher when either the depth of modulation, A, or the coefficient of friction, μ, increases monotonically.

$$F_{\mathrm{lateral}} = \mu F_{\mathrm{normal}}(1 - A\sin(2\pi x/l)). \qquad (1)$$

To reach this objective, a minimalist definition of roughness was given to the subjects, "roughness is the opposite of smoothness". This definition was thought to minimize subjective bias, yet it prevented confusion. This intuition is consistent with previous findings by Smith et al., [11], since the rate-of-change of the textural force is directly correlated with both quantities. Since the rate of change has the form $\propto A\mu/l$, the effects of the spatial frequency are also explored.

2 Device and Control

We used a Pantograph haptic device, futher described in [2]. It can display forces up to 2 N with a spatial resolution of 0.01 mm in a horizontal workspace of 100×60 mm. It has flat structural response within DC–400 Hz. Simulating dry friction is equivalent to creating high-gain force-feedback [5]. In a sampled-data setting, to guarantee the synthesis to be passive, this gain is limited by the physical dissipation of the device [3]. Our basic device has very little of it, limiting the range of parameters that can be tested. This problem is compounded by the use of 400 Hz cut-off reconstruction filter that adds additional phase lag [1].

We retrofitted the device with eddy-current brakes that add accurately defined viscosity [4]. The magnetic field is produced by C-clamp magnetic circuits terminating with a pair of 11 mm cubic-shaped rare earth magnets (NdFeB, Amazing Magnets LLC, Irvine, CA, USA), as shown in Fig. 1, left panel. Blades, in the shape of annulus arcs, are affixed to the proximal arms of the device and move in the air gap, creating a viscous torque that can be adjusted by tuning the amount of overlap between the gap and the blade. This way, the "base dynamics"of the device feel like a nonuniform viscous field.

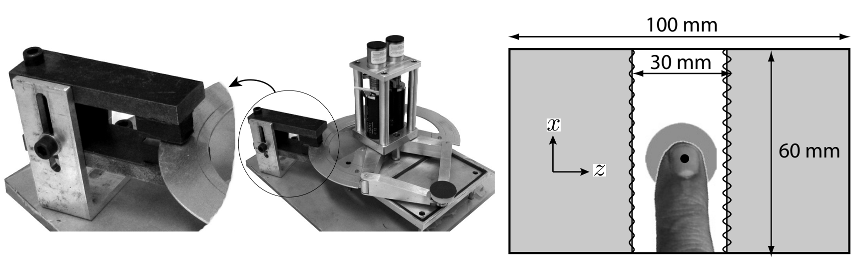

Fig. 1. Left: A direct-driven five-bar mechanism drives a small plate in the horizontal plane. In this version of the Pantograph, each joint has a eddy-current viscous damper. **Right:** Subjects were presented with two textured walls and asked which one was rougher. The virtual interaction point is marked by a black circle, and the free space is in white.

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To compensate for this viscous field in free space, we adopted an approach suggested by Colgate and Shenkel [3]. Assistive virtual damping was used to compensate the extra physical damping; since the sampled data approximation always errs on the side of adding energy, its negation errs on the side of not removing enough of it, preserving passivity. We applied this approach to our hardware. To our knowledge, it is the first report of its successful implementation.

When the interaction point is not in contact with a virtual wall, the motors partially compensate the physical damping. The compensation torques are $\tau_i^j = +B_c\omega_i^j$ for joints $j = 0,1$ at the $i-$th sampling period, where the angular velocities, ω^j, are estimated by backward difference and then averaged over a 24 samples window. The parameter B_c is conservatively set to 4.5 mNms to avoid artifacts arising from the quantization noise in the position measurements, where the actual viscosity given by the brakes is 6.1 nNms. In these conditions, the residual viscosity field is barely perceptible but the range of passive stiffnesses is significantly increased.

3 Texture force field.

The Pantograph device can render planar forces in a z,x plane; thus, the user experiences 1D constraints with 1D textures, see Fig. 1 for the axes definitions. First, a virtual wall is synthesized for $z \leq z_{\text{wall}}$

$$F_z = -Kd^z, \text{ if } \quad z \leq z_{\text{wall}}; \quad F_z = 0\,, \text{otherwise.} \tag{2}$$

where $d^z = z - z_{\text{wall}}$ is the (negative) penetration in the virtual wall and K the stiffness. Then, a time-free, that-is velocity-independent, that is dry-friction algorithm, [6], is used to compute a static friction field with a coefficient μ:

$$F_{\text{friction}} = -\mu \underbrace{K \underbrace{\max(d^z, d^z_{\max})}_{\text{penetration clamp}}}_{\text{normal force}} \underbrace{\frac{\min(d^x, d^x_{\max})}{d^x_{\max}}}_{\text{what the algo computes}} \tag{3}$$

where: $d^x \leq d^x_{\max}$ is the pre-sliding tangential deflection and $d^z_{\max}$ is used to ensure passive synthesis by limiting the maximum friction force. Finally, this friction force field is modulated with a sinusoidal generating function:

$$F_x = F_{\text{textured}} = F_{\text{friction}}(1 - A\sin(2\pi x/l)) \tag{4}$$

where l is the spatial frequency of the texture and $0 \leq A \leq 1$ is the modulation depth of the textural force. The same algorithm is used on both sides of the workspace, $z \geq z_{\text{wall}}$ and $z \leq -z_{\text{wall}}$.

The values $K = 1$ Nmm, $d^x_{\max} = d^z_{\max} = 0.5$ mm were selected because no limit cycles were present when exploring the surfaces, and because they offered a good tradeoff between fidelity of the friction model and maximum lateral force.

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4 Experimental procedure

Design To test our hypothesis, the influence of A, μ, and l is tested independently. Two 1-D virtual walls, facing each other and spaced 30mm ($z_{\text{wall}} = \pm 15$mm), were available to the subjects, Fig. 1, right panel. Each had a sinusoidal texture, and subjects were to identify which of the two surfaces felt rougher: left or right? The two textures differed by the value of exactly one parameter, either A, μ, or l. The answer was entered by a keystroke and the time of each trial was recorded. The two textures were always different.

Stimuli Three sets of stimuli were prepared, one for each parameter. For amplitude $A \in \{0.25, 0.5, 0.75, 1\}$, 6 pairs of textures were presented: $(A_1, A_2) \in \{(1, 0.75), (1, 0.5), (1, 0.25), (0.75, 0.5), (0.75, .25), (0.5, 0.25)\}$. These six amplitude pairs were tested in nine different conditions: $l \in \{1, 2, 3\} \times \mu \in \{1/3, 2/3, 1\}$ for a total of 54 trials for these parameters. With the same procedure, 54 trials were prepared for testing the parameter $l \in \{1, 2, 3, 4\}$ mm in the nine conditions $\mu \in \{1/3, 2/3, 1\} \times A \in \{1/3, 2/3, 1\}$; also the combinations of $\mu \in \{1, 2, 3, 4\}$ were presented in the nine conditions $l \in \{1, 2, 3\} \times A \in \{1/3, 2/3, 1\}$. Each subject performed 162 pairwise comparisons; the surface textures were randomly assigned to the left or right wall.

Subjects Six right handed subjects, two female and four male, volunteered for the experiment; among them were two authors of this paper. Four of the subjects were very familiar with haptic technology. No definition of roughness was given to the subjects except that "roughness was the opposite of smoothness". There was no training and no feedback was provided during the tests. Subjects wore sound isolation headphones (DirectSound EX-29), and white noise was played to mask the sound of the device. Most subjects reported ambiguity when dealing with textures with different frequencies.

5 Results

Figure 2 shows the percentage of times each subject responded in agreement with the hypothesis of monotonicity. In total, the hypothesis was confirmed in almost 97% of the 324 trials for parameter A: only 10 times the surface with smaller A a was identified as rougher. Similar results hold for μ: 9 disagreements over 324 trials. The previous literature indicates that roughness decreases with the spatial period. The experiment confirms it, but the agreement drops to 80%. Equivalently, 20% of times the subject chose the spatial period to be rougher. This effect could be due to the aforementioned ambiguity of the notion of roughness. Only one subject, 3, consistently chose the finer texture as rougher.

Figure 2 shows also the distribution of disagreements as a function of the values being compared. Interestingly, subjects mostly disagreed with the hypothesis when asked to judge pairs of textures with high values of A and μ. More importantly, large differences in parameters were seldom contrary to the hypothesis: $1.00 - 0.25, 0.75 - 0.25$, and $0.5 - 0.25$ had at most 1 error over 54 trials; notice that a similar difference in parameters $1.00 - 0.50$ was misjudged more often. These two results indicate that, even if

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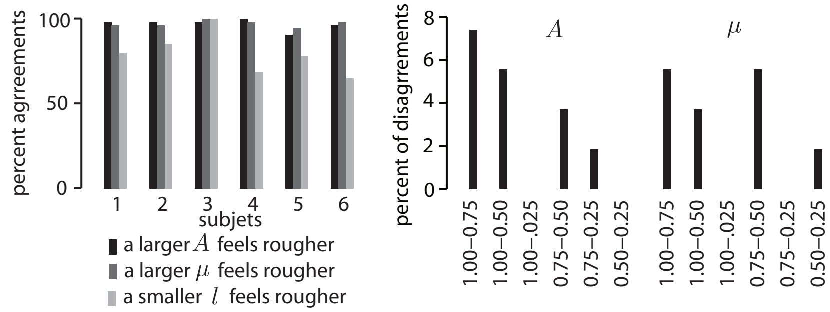

Fig. 2. Intra subject success rate of hypothesis and error rate for A and l as function of their difference. The left panel shows the percentage of times that each subject (1-6) chose the rougher surface in agreement with the hypothesis. The right panel shows an histogram of the percentage of trials that do not agree with the monotonicity hypothesis. For example, in the 7.5% of the comparisons between textures with $A = 1$ and $A = 0.75$ the second was reported rougher. On the contrary, surfaces with $A = 1$ were always perceived rougher than $A = 0.25$, in perfect agreement with the hypothesis.

monotonic, the psychometric function relating roughness with A and μ is probably not linear, because similar differences in parameters did not result in similar error rates.

6 Discussion and Conclusion

Our aim was to validate the hypothesis that there exist more than one parameter which, when increased, also increase the perception of virtual roughness. We employed a texture synthesis algorithm that has a straightforward physical interpretation. When one drags a stylus against an object, if the surface is smooth then the dry friction force does not vary. If the surface is not not smooth, hence “rough”, then this force varies. A natural way to parametrize this variation is to consider that the more a surface deviates from smoothness, the deeper these variations are. It can also be observed that the deeper the grooves are the greater tendency has a stylus has to get caught in the crevices, which *on average*, may be represented by a greater coefficient of friction.

To test this hypothesis we engineered a hardware platform with which we are confident most known haptic synthesis artifacts were eliminated. It has (a) a non-structural response, (b) plenty of resolution, and (c) generates a provably passive mechanical stimulus (like a real surface) under all the needed testing conditions. With this hardware, the results do support our initial hypothesis that increasing either depth of modulation or the coefficient of friction increases monotonically the perception of virtual roughness. It can then be concluded that the underlying psychometric functions are also monotonic. This result was obtained without instructing the participants of what roughness was.

Turning our attention to the effect of the spatial period. It is indeed hard to imagine a simple connection between spatial period and deviation from smoothness, unless innumerable assumptions are made regarding the exact nature of the interaction between a virtual stylus and a virtual surface. It is probable that our volunteers because of their

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varied backgrounds spontaneously utilized different sets of assumptions to answer the question they were asked with respect to changes in spatial period.

Finally, the hypothesis, presented by Smith et al., that the rate of change in the lateral force correlates with roughness is consistent with our analysis of A and μ. Further study is needed, however, to confirm this hypothesis in the virtual world; complete psychometric functions of roughness with respect A and μ needs to be measured, and their joint influence on roughness needs to be investigated.

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