Synthesizing the Roughness of Textured Surfaces for an Encountered-type Haptic Display using Spatiotemporal Encoding

Yaesol Kim, Siyeon Kim, Uran Oh, and Young J. Kim, *Member, IEEE,*

***Abstract*—Encountered-type haptic rendering provides realistic, free-to-touch, and move-and-collide haptic sensation to a user. However, inducing haptic-texture sensation without complicated tactile actuators is challenging for encountered-type haptic rendering. In this paper, we propose a novel texture synthesizing method for an encountered-type haptic display using spatial and temporal encoding of roughness, which provides both active and passive touch sensation requiring no complicated tactile actuation. Focused on macro-scale roughness perception, we geometrically model the textured surface with a grid of hemiellipsoidal bumps, which can provide a variety of perceived roughness as the user explores the surface with one's bare hand. Our texture synthesis method is based on two important hypotheses. First, we assume that perceptual roughness can be spatially encoded along the radial direction of a textured surface with hemiellipsoidal bumps. Second, perceptual roughness temporally varies with the relative velocity of a scanning human hand with respect to the surface. To validate these hypotheses on our spatiotemporal encoding method, we implemented an encountered-type haptic texture rendering system using an off-the-shelf collaborative robot that can also track the user's hand using IR sensors. We performed psychophysical user tests with 25 participants and verified the main effects of spatiotemporal encoding of a textured model on the user's roughness perception. Our empirical experiments imply that the users perceive a more rough texture as the surface orientation or the relative hand motion increases. Based on these findings, we show that our visuo-haptic system can synthesize an appropriate level of roughness corresponding to diverse visual textures by suitably choosing encoding values.**

***Index Terms*—Encountered-type haptic, Haptic texture, Texture roughness, Human robot interaction**

I. Introduction

In recent years, a great deal of research has been carried out on effectively delivering virtual reality (VR) experiences. In particular, due to the rise and availability of low-cost VR technology [1], disseminating and commercializing VR devices for general mass has drawn a lot of attention from both academic and industrial sectors, which makes the interest in immersive VR research grow more than ever. To realize fully immersive VR experience for the users, various types of body-mountable sensors and actuation devices have been developed [1]. However, the use of these devices mounted on a user's body need to be minimized since it may hinder the user's VR immersion and cause unnecessary physical fatigue to the user.

On the other hand, an encountered-type haptic display or robotic graphics enables a fully immersive experience by utilizing a robotic manipulator to deliver haptic feedback to the user [2], [3]. Such an encountered-type haptic system allows users to experience "free-to-touch" and "move-and-collide" haptic sensation without requiring the user to wear a device nor mount it on the user's body.

An encountered-type haptic device is often designed as a hybrid of kinesthetic and cutaneous mechanisms [4]. Through this device, various physical characteristics of a virtual object can be delivered to the user's bare hand, *i.e.*, a direct touch, which allows users to haptically explore virtual objects and feel haptic feedback properly and instantly. Meanwhile, when a user's bare hand is used for haptic interaction, the tactile information of a physical object can be immediately recognized by the user's nervous system. Therefore, for generating a truly immersive VR experience with haptic feedback, the encountered-type haptic display should provide not only force feedback but also proper tactile sensation to the VR users.

A general approach for providing tactile feedback through an encountered-type haptic device can be taken by (1) preparing various physical textures in advance, (2) attaching one of the textures to the end-effector of a haptic device, and (3) switching the different haptic textures on demand [5], [6]. For this purpose, a special module can be attached to the end-effector such as a tool changing gripper [6] or an extra tactile displaying device [7]. Although these methods are feasible texture-rendering methods for an encountered-type haptic system, there have been no studies reported in the literature that do not rely on adding extra modules to the manipulator or modifying the manipulator. Instead, in our approach, we attempt to deliver haptic-texture sensations by synthesizing tactile feedback through spatiotemporal encoding of textures as shown in Fig. 1.

In this paper, we propose a novel approach for synthesizing the surface roughness which is one of the most prominent dimensions of perceptual space for tactile texture [8]. We model a textured surface by spatially encoding roughness along the radial direction of the surface. Based on the theory of roughness perception, we encode the roughness by using embossed bumps and modulating bump width and distance between bumps depending on the direction on the surface. Considering that ellipses vary in width and distance between them depending on their direction, we employ a grid of hemiellipsoidal bumps to model the surface texture, whose radius is used as a modeling parameter. We conducted an experimental study with 25 subjects to test our hypotheses that our roughness-encoded spatial model can render a variety

The authors are with the Department of Computer Science and Engineering, Ewha Womans University, Seoul, South Korea (e-mail: yaesol91@ewhain.net; syunni33@ewhain.net; uran.oh@ewha.ac.kr; kimy@ewha.ac.kr).

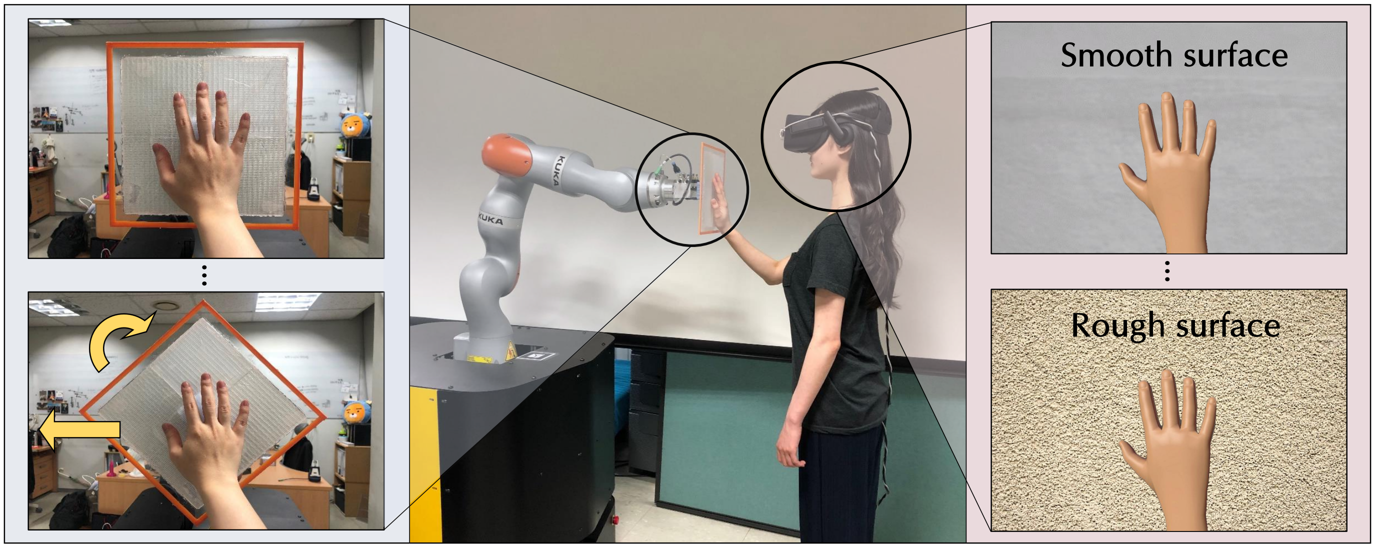


Fig. 1. Our encountered-type haptic rendering system can synthesize texture roughness using a collaborative robot manipulator (center). A rigid surface with spatially encoded bumps (top left) can give the VR user an illusion of touching surfaces with different levels of roughness from smooth (top right) to rough (bottom right) by changing the surface orientation and velocity (bottom left).

of perceptual levels of roughness and the roughness can be temporally encoded by varying the velocity of a spatial model relative to the user's hand motion.

As a result, we show that our encountered-type haptic system render diverse roughness by properly choosing the values of spatial (orientation) and temporal encoding (velocity) as rendering parameters. Texture roughness is provided both in a passive perceptual sense - *i.e.,* the manipulator is dynamic while the user's hand is static - and in an active perceptual sense - *i.e.,* the user's hand is dynamic while the manipulator is dynamic [9]. The main contributions of this paper are summarized as follows:

- A novel spatiotemporal texture roughness encoding of geometric grids using hemiellipsoidal bumps, which does not require complicated tactile actuation for encountered-type haptic display.
- Empirical evidence from psychophysical user studies showing that various levels of perceptual roughness can be rendered in a passive and active manner by controlling the orientation and velocity of the surface.
- Applications of our visuo-haptic system for synthesizing an appropriate level of perceived roughness corresponding to diverse visual textures in VR.

The rest of this paper is organized as follows. In Sec. II, we summarize previous researches relevant to encountered-type haptics and texture roughness perception. We describe our textured surface synthesizing method in Sec. III, and explain the details of our system in Sec. IV. In Sec. V and Sec. VI, empirical experiments are presented to support our texture-encoding hypotheses, and our discussion is described in Sec. VII, and the paper is concluded in Sec. VIII.

II. Previous Works

In this section, we survey works relevant to encountered-type haptics and human perception on texture roughness.

A. Encountered-type Haptics

Encountered-type haptics or robotic graphics, originally conceived by McNeely [2], directly delivers haptic feedback to the user by physically presenting an object proxy unlike conventional haptic devices relying on motor actuation. Tachi *et al*. [10] proposed a similar concept using haptic shape display. Yokokohji *et al.* [3], [11] proposed a method for realizing visual/haptic interfaces, called what-you-see-is-what-you-feel (WYSIWYF) display, using a PUMA 560 manipulator as an encountered-type haptic interface. They also used vision-based tracking for controlling the robotic manipulator with a motion-command type haptic rendering algorithm.

Recently, in order to expand the limited workspace of encountered-type haptics, some works were proposed using drones or quadcopters, such as HapticDrone [12] and VRHapticDrones [13]. As an extension of HapticDrone, Abdullah *et al.* presented a method for simulating the stiffness and weight of a virtual object [14]. To present the texture information of a virtual object, HoverHaptics [5] attached multiple textures to a quadcopter and can render a limited number of haptic textures. However, due to the current drone technology, these works using drones have some limitations including a limited magnitude of exertable force feedback and inflexibility of representable virtual objects. Moreover, the number of representable haptic textures should be kept to small and discrete whereas our haptic system can represent diverse haptic textures continuously.

Vonach *et al.* [15] presented a fully immersive VR system, called VRRobot, providing prop-based encountered-type haptic feedback. Their system utilizes robot actuation to provide haptic feedback for static virtual objects in a passive sense. Using a seven-DoF collaborative robot as a haptic manipulator, an encountered-type haptic display was proposed to provide both passive and active haptic feedback for static and dynamic virtual objects [16]. However, surface texture information was not utilized in these works even though the texture is a salient feature for object perception [17]. Araujo *et al.* [6] proposed the "snake charmer" system in the context of VR, where the user with a head-mounted display (HMD) on can experience haptic feedback of various objects with tactile properties such as shape difference, surface characteristics, and even temperature. However, the system uses a fixed size of palette of textures, and the number of usable textures is limited. Moreover, since the system relies on tool change to provide different textures, it may not provide a real-time response to the user when she/he reacts too quickly. In contrast, our system can provide more diverse range of haptic textures in real-time.

B. Roughness Perception of Textures

When the user touches a virtual object, it is known that the object's position alone is not sufficient to provide reliable tactile feedback without using additional physical cues [18]. Surface texture is important for a human to perceive the property of an object that is constructed multi-dimensionally [17], [19]. Three prominent psychophysical features of tactile texture, including roughness (rough/smooth), hardness (hard/soft) and warmness (warm/cold), are used to define the perceptual dimensions of a tactile texture [8]. Among these dimensions, roughness is the most prominent one and thus has been intensively studied [20], [21].

Since the natural and rich texture information can be rendered by the vibration of a haptic device, the vibration based-method is more widely used than other tactile rendering methods such as modulating static pressure, skin stretch, or friction [22]. To render the texture roughness with a tool, Romano and Kuchenbecker proposed a method for recording, modeling, and recreating texture contact vibration using a tablet-based haptic device [23]. Ujitoko *et al.* presented a cross-modal modulating method of vibrotactile roughness perception using pseudo-haptic effect [24]. For bare finger interaction, touchscreen with electrovibration [25] or conjunction of vibrotactile and electrostatic display [26] are proposed to render the texture roughness. These tactile displays could be integrated into the encountered-type haptic system but it may increase the system's complexity and cost.

In the roughness perception study, the size and the spacing of tactile elements have been shown to play a crucial role in the subjective sensation of roughness. Lederman and Taylor showed that an increase in the width of *texton* leads to a decrease in perceived roughness [27]. The relationship between the texton spacing and the magnitude of subjective roughness is depicted as an inverted U-shaped curve [28], and peaks near at $3.5mm$. Dépeault *et al.* [29] showed that one critical measure of roughness is the *dot spacing* along the scanning direction. Connor and Johnson showed that the perceived roughness increases as the dot spacing increases along the scanning axis or across the scanning axis [21]. These results allude to a possibility that a single object can encode multiple roughness values by arranging elements with different inter-distances according to the scanning direction. Later in Sec. VI, we will exploit this possibility to present and prove hypotheses and leverage them to spatially encode haptic textures for our system.

Although it is argued that the user movement has a negligible effect on subjective roughness perception [30], [31], the influence of a temporal cue on roughness has been demonstrated in recent works. Gamzu and Ahissar showed that temporal cues may provide an alternative channel of information for bare-finger texture perception [32]. Smith *et al.* showed that kinetic friction, governed by a ratio of normal forces to tangential forces, is a significant determinant of roughness perception and implied that the temporal cues play a role in roughness perception of macro-texture [33]. Under a precisely-controlled condition of passive linear motion, Cascio and Sathian demonstrated that the perceived roughness also depends on a scanning velocity [20].

Optimal roughness perception depends on the user's hand motion [34], [35], and is indispensable to neural activation in space and time [20]. The relative motion produced by an object or user's hand is required for roughness perception [30]. Lederman found that the estimated magnitude of roughness does not depend on whether the associated hand motion is active or passive [9]. In our system, we will take advantage of both active and passive motion of the user's hand to generate a different magnitude of roughness.

III. Proposed Method

A. Goal and Hypotheses

The main goal of this study is to synthesize the perceptual roughness through a rigid surface attached to the end-effector of an encountered type haptic device using only the degrees of freedom that the device originally has. Extending the idea of using a collaborative robot as an encountered-type haptic device [16], this study proposes both haptic-texture modeling and rendering methods to synthesize a variety of texture roughness.

By spatially encoding roughness along the radial direction on a planar rigid surface, the textured surface can represent various roughness as a change of touch orientation with respect to the surface when a user explores the surface with one's bare hand. For instance, a user will feel different roughness whether she/he is rubbing the surface up and down, or left and right. In addition to the spatial encoding of roughness, a textured surface model tangentially moves at a certain velocity maintaining its contact with the hand to create temporally-varying roughness. In other words, roughness can be rendered by modulating the orientation and velocity of the rigid surface as the user grazes over the surface model. Our encountered-type texture modeling and rendering method are based on the following hypotheses:

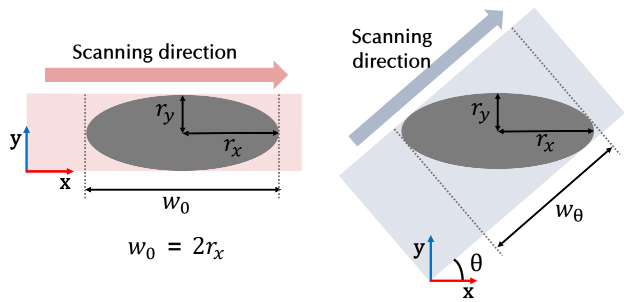
Hypothesis 1: When a user grazes over a rigid planar surface embossed with a grid of hemiellipsoidal bumps, the user can feel different levels of roughness depending on the **orientation** of the surface.

Hypothesis 2: When a user grazes over a rigid planar surface embossed with a grid of hemiellipsoidal bumps, the user can feel different levels of roughness depending on the **velocity** relative to the user hand motion.

We validate these hypotheses in Sec. VI and explain how to implement our haptic texturing system based on our results in Sec. IV.

B. Textured Surface Modeling

Arranging an embossed dot[1] pattern on a flat surface is a general and simple modeling method for spatially encoding tactile roughness. Similar to [36], we may use four parameters to dictate a dot pattern for representing perceived roughness: dot spacing, dot height, dot width, dot angle. However, in our case, we select the dot width w_θ and the dot spacing d_θ as our main modeling parameters that can be modulated in runtime to generate difference roughness.



(a) When the scanning direction is parallel to the x axis (i.e. $\theta = 0$)

(b) In general case when $\theta \neq 0$

Fig. 2. Perceptual width (w_θ) of an elliptic texton according to the scanning direction parameterized by θ.

Meftah et al. [37] suggested that the human perception of surface roughness is a function of the spatial characteristics of the scanned surface along the scanning axis. Based on this observation, we define the texton width along a scanning direction, affecting roughness perception. When a circular texton such as a truncated cone or hemisphere is used for a dot pattern, the user would experience a constant perceptual width regardless of the scanning direction. In our case, however, we select an elliptically-shaped texton to control the texton width, as illustrated in Fig. 2. To define the dot width along the scanning direction w_θ, we consider the length of the texton projected onto the scanning direction. Then, w_θ is a function of the angle of scanning direction $\theta \in [0, \frac{\pi}{2}]$ as follows:

$$w_\theta = 2\sqrt{{r_x}^2 \cos^2\theta + {r_y}^2 \sin^2\theta}, \tag{1}$$

where r_x and r_y are the x-radius and y-radius of an elliptical texton with $r_x > r_y > 0$, without loss of generality.

It is well known in the psychophysics field that the psychometric relationship between texton spacing and perceived roughness forms an inverted U-shape graph [28]. Since the perceived roughness increases with reduced texton spacing along the scanning axis when the inter-distance between textons is greater than 3 mm, we set the shorter axial radius of an elliptical texton to 1.5 mm so that the distance between textons is at least 3 mm.

In order to increase the effectiveness of the perceived roughness as θ increases, textons should be arranged in such a geometric way that their inter-distance (or spacing) d_θ decreases as θ increases. As illustrated in Fig. 3, we arrange the textons in a rectangular grid so that the encoded roughness increases as θ increases. Here, the distance d_θ is defined as a *ray distance* that is measured from the center of an ellipse to the nearest ellipse along the scanning direction with an angle of $\theta \geq \theta_{min}$. We designed the texton as hemiellipsoid since the textured surface model with hemiellipsoids provides a wider range of roughness compare to the model with elliptical truncated cones. We verified it by our additional user experiment and the result will be discussed in Sec. VII.

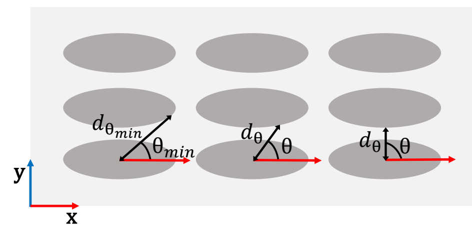


Fig. 3. Variation of distance between top of tactile elements (d_θ) according to a scanning direction parameterized by θ.

3D modeling software such as 3DS MAX was used for this spatial encoding of textons and we print this model using a Form2 3D printer with 50 micrometer resolution. We will perform a user study and verify our spatial encoding scheme providing different roughness relative to the scanning direction in Sec. V.

C. Haptic Texture Rendering

Haptic texturing is rendered to the user via an impedance-controlled robotic manipulator as an encountered-type haptic device. A textured surface, as designed in Sec. III-B, is attached to the end-effector of the haptic device and interacts with the user's bare hand. In runtime, the haptic system tracks the user's hand motion and controls the orientation and the velocity of the manipulator's end-effector depending on the roughness of an object that is expected to be touched.

In order to haptically render the roughness of virtual objects, we encoded their roughness and mapped to virtual roughness in our system. Specifically, for n objects' virtual textures that will interact with VR users, their roughness are first sorted in increasing order, and n distinguishable roughness are selected in increasing order from the m encoded roughness (assuming that $m \geq n$) and mapped to the virtual textures. Here, the exact roughness mapping from virtual to encoded textures is not crucial as long as the mapping is one-to-one, since our objective here is to make the user feel different roughness of textures.

The encoded roughness is associated to orientation and velocity of the end-effector relative to the user's hand scanning direction in the offline process. At runtime, the orientation and velocity value corresponding to the virtual object's texture that the user intends to touch is chosen by our system and rendered to the user via the manipulator to deliver haptic feedback. As shown in Fig. 4, the end-effector rotates and translates a textured surface model to provide a proper relative velocity between the user hand and the surface, representing the roughness of a virtual object that the user is touching in VR.

[1]We interchangeably use *dot* and *texton* to refer to the same tactile unit throughout the paper.

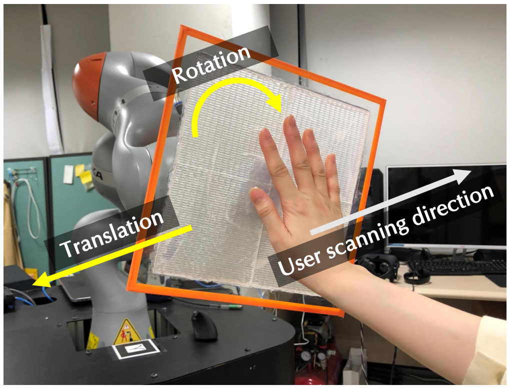


Fig. 4. Tactile rendering by rotating and translating the surface model relative to the user's scanning direction.

IV. Encountered-type haptic texturing system

In this section, we describe the overall architecture of our haptic texturing system.

A. System Overview

We implemented our encountered-type texture rendering system based on the H-wall system [16]. The H-wall allows users to have visuo-haptic interaction with static and dynamic virtual objects using a robotic manipulator but has two major limitations: (1) limited motion-tracking space and (2) lack of haptic-texture information for virtual objects. To address the first problem, we expand the tracking space by mounting an infrared (IR) motion sensor on the user's HMD. Also, a textured surface model, attached to the end-effector of a robotic manipulator, synthesizes different surface roughness and serves as a proxy of the virtual object.

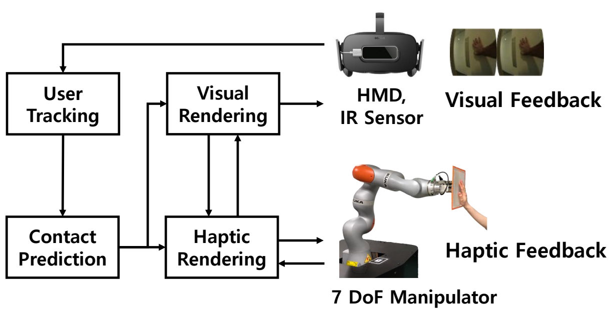


Fig. 5. Overview of encountered-type haptic texturing system.

An overview of our encountered-type haptic texturing system is shown in Fig. 5. A virtual environment consisting of objects with various textures and a user's virtual proxy hand is visually rendered to the HMD based on a real-time rendering engine. A seven-DoF off-the-shelf collaborative robot operates as a haptic device to provide tactile feedback to the user. By tracking a user's hand, our system predicts when and which virtual object is most likely to collide with the user, and a contact configuration of the object relative to the user is estimated. A textured surface model attached to the end-effector of the manipulator serves as a proxy of the virtual object following human hands. The manipulator relies on contact forces exerted by the user to synthesize the texture roughness of a virtual object being in contact with the user. The states of an avatar in VR and of a user in the physical world are shared by haptic and visual rendering components. The overall system works asynchronously under real-time constraints of tens of milliseconds using a message-passing protocol.

B. User Movement Tracking

In order to provide visuo-haptic interaction, the user's head and hand are tracked in real-time and represented in the same frame in which the configuration of the haptic manipulator is represented. The user's head position is tracked by an HMD tracker and transformed from the tracking sensor frame to the robot's base frame. The user's hand position and direction of movement are tracked by an IR motion sensor mounted on the HMD and transformed from the motion sensor frame to the robot's base frame.

The midpoint smoothing algorithm [38] is used for reducing tracking noise and generating a smooth robot motion. By referencing earlier four hand positions, two positions are determined after two steps of midpoint smoothing are performed and yield a direction vector, which is used as an estimate for the user scanning direction.

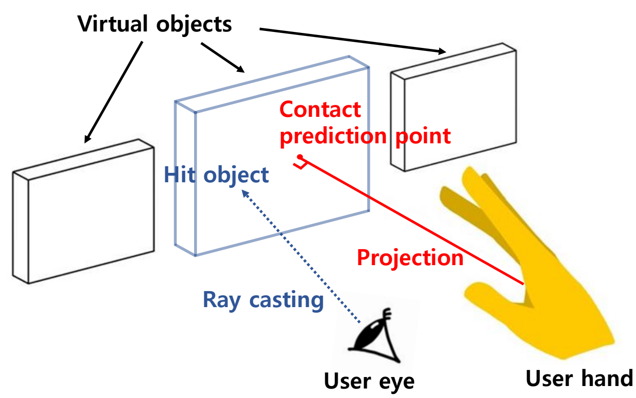


Fig. 6. Contact prediction using raycasting and projection.

C. Contact Prediction

To realize encountered-type haptic feedback, our system needs to predict when the user's hand will contact virtual objects. However, this problem poses a significant sensing and control challenge: predicting where the user will want to touch in the virtual environment as the hand approaches an object, such that the haptic device can position and shape itself as needed in order to provide the desired haptic experience [4].

In our system, contact prediction is performed in a virtual world using user tracking data while contact detection is done in a physical world using joint torque sensors embedded in the robot. To predict an object with a high probability of collision, we employ the concept of *a region of interest*. As shown in Fig. 6, we utilize ray casting for predicting the user's region of interest by shooting a virtual ray along the user's gazing direction. The hit object is considered as a collision-imminent object and its configuration along with associated surface texture roughness are retrieved. Then, the user's virtual hand is projected to the colliding object's surface so that the system can determine the contact position and orientation.

D. Haptic Rendering

Contact is detected using the haptic manipulator. Torque sensors embedded in the manipulator's joints are used to measure the user contact force $\mathbf{f}$ with the manipulator Jacobian $\mathbf{J}$. When $\mathbf{f}$ is higher than the pre-defined threshold ($3N$ in our implementation), the manipulator considers the state as a contact.

Once the contact configuration is determined, the robotic manipulator is controlled in such a way that the manipulator needs to follow the contact-predicting points while pointing at the predicted object. When the user's contact is detected by the manipulator, the manipulator stops following the contact-predicting point and starts to provide the roughness of the texture of the virtual object to the user. This is achieved by adjusting the orientation and velocity of the haptic manipulator as described in Sec. III-C.

E. System Implementation

We implemented our encountered-type haptic texturing system using two independent computing platforms: One is for visual rendering with Windows 10 64bit operating system equipped with a 4.0GHz Intel Core i7 CPU, GeForce GTX 970 GPU and 24GB RAM. The other is for haptic and robotic control with Ubuntu 14.04 LTS 64bit operating system equipped with a 2.1GHz Intel Core i7 CPU and 8GB RAM. We used Leap motion as a motion sensor to track the user's hand. As a haptic manipulator, we used KUKA LBR IIWA 7 R800 which has seven degrees of freedom and torque sensors are integrated into all seven joints. ROS indigo framework and Sunrise OS are used as software robotic platform to perform haptic and tracking calculation, and control the robot, respectively. Each of these components is programmed in C++ and Java programming languages, and is communicated over Ethernet via a message-passing protocol. Unity3D and Oculus Rift CV1 are used to visually render a 3D virtual scene and track the user's head. Our rendering unit in Unity3D is implemented in C# and communicates with a ROS unit over an Ethernet connection.

The response time of the robot manipulator was measured to 22 ms including 0.125 ms controller PC latency and the latency of stereo visual rendering was 11.7 ms. The Leap motion frame latency was 8.33 ms while the network latency is negligible. As a haptic proxy for a virtual object, a textured surface model is attached to the IIWA's end effector and follows the human hand in highly real-time providing a sense of illusion of touching a virtual object.

V. Preliminary Study

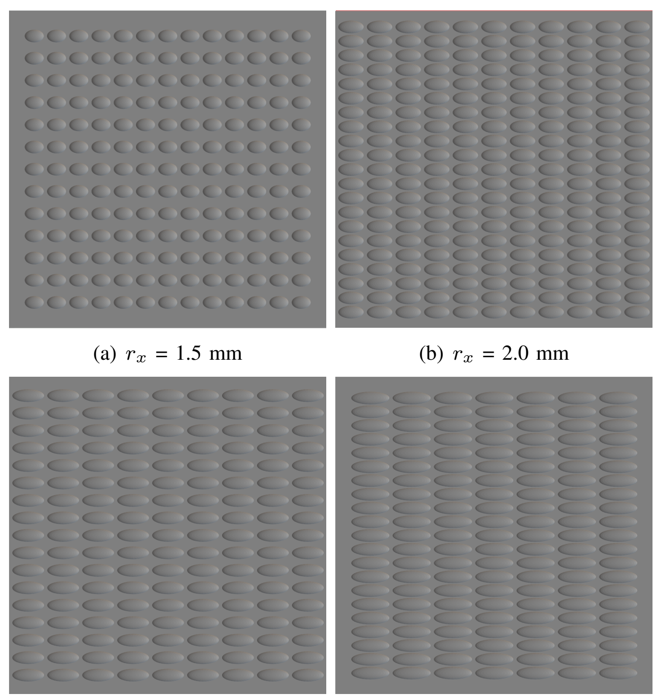
Prior to testing our hypotheses that our surface textured model with various scanning direction and velocities can provide a wide range of perceived roughness, we conducted a preliminary user study to (1) examine if altering users' roughness perception by changing scanning direction of our model is feasible and (2) to decide on the design of surface texture model, specifically the radius in x-axis of each bump, for simulating a range of perceived roughness as wide as possible.

A. Participants

For this study, we recruited 7 volunteers (all female) from a women's university that the paper authors are affiliated with. All the participants were right-handed, and their average age was 26.1 ranged from 24 to 29.

B. Experimental Conditions

To provide as wide a range of perceived roughness as possible with the varying scanning directions, we find the most effective radius of hemiellipsoidal bumps on a surface. We investigated four different radii in x axis (denoted as r_x) starting from 1.5 mm to 3.0 mm with the interval of 0.5 mm while the radius in y axis is fixed to 1.0 mm as shown in Fig. 7. As for scanning directions, the tested angles were chosen in terms of the linearly-increasing slope of scanning direction as shown in Fig. 8, which were: $0(\arctan 0), 45(\arctan 1), 63.43(\arctan 2), 71.57(\arctan 3)$, and $90(\arctan \infty)$ degrees.



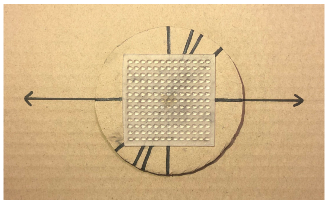
(a) r_x = 1.5 mm (b) r_x = 2.0 mm

(c) r_x = 2.5 mm (d) r_x = 3.0 mm

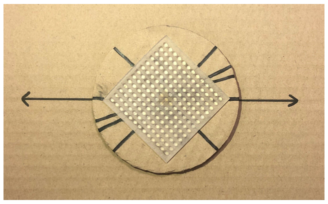
Fig. 7. Four different roughness encoded models with various radii in x axis used in our preliminary study.

C. Apparatus

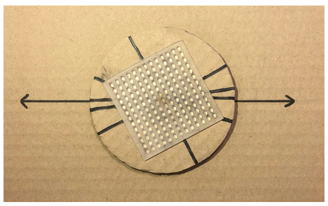
For each of the four roughness encoded models, we prepared a rigid polymer surface patch (5 $cm\times$ 5 cm) using a 3D printer. Then each patch was firmly attached to a round cardboard with tacks. As for testing different scanning directions, an experimenter rotated each patch to change its orientation accordingly based on the marked lines with 5 predefined angles as mentioned above on the cardboard instead of asking subjects to change their scanning directions. In addition, we had an opaque cloth for covering the patch area during the experiment to help subjects to focus on their sense of touch while preventing them from seeing the surface texture details.



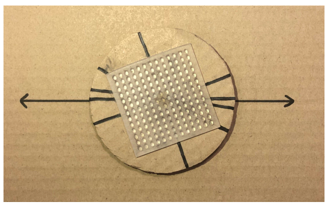
(a) θ = 0



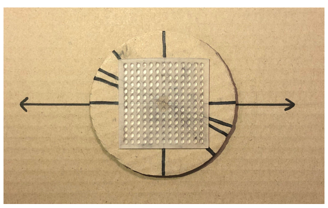
(b) θ = 45



(c) θ = 63.43



(d) θ = 71.57



(e) θ = 90

Fig. 8. Five different scanning angles used for the preliminary study.

D. Procedure

After a brief introduction about the study procedure, we asked subjects to use their index finger of the dominant hand and rub a patch with a specific scanning direction as shown in Fig. 9. We follow the ratio scaling method of magnitude estimation which allows subjects to select their range of numbers and make a numerical estimation of perceived magnitudes [39]. Subjects were asked to rate the perceived roughness with any positive number where a higher value indicates a rougher texture. Subjects were allowed to choose their own scale when reporting their subjective roughness. The presentation order was first randomized by patches with different radii, then by scanning directions for each round and it was repeated three times. In total, each subject performed 60 trials (four radii in x axis $\times$ five scanning orientations $\times$ three rounds).

E. Data Analysis

Since subjects are free to choose any numerical value for reporting the magnitude of perceived roughness, the captured raw data need to be normalized for relative comparisons. Thus, following the magnitude estimation method [40], [39], perceived roughness for each patch and orientation across three trials per subject was averaged and normalized by dividing each subject's responses by the grand mean of all subjects' averaged data. The normalized averaged data were then rescaled by being multiplied by the grand mean of all subjects' averaged data.

Fig. 9. Experimental setup for the preliminary study. Subjects were asked to graze each of the 4 patches in horizontal direction under 5 different orientations while each patch was covered by an opaque cloth.

F. Results

As shown in Fig. 10, our results suggest that it is feasible to change the perceived level of roughness by varying the scanning direction using our model. Moreover, it seems that the perceived level of roughness tends to increase as the scanning angle increases from 0 to 90 degrees except when r_x was set to $1.5mm$. Although further investigation is needed, it could be that the impact of increasing the scanning angle is relatively small and the difference between the radii of x and y is smaller than a certain threshold. Based on the results, we chose a textured surface model with $r_x = 3.0mm$ for our encountered-type haptic system which showed the widest range of average perceived roughness to maximize the effect.

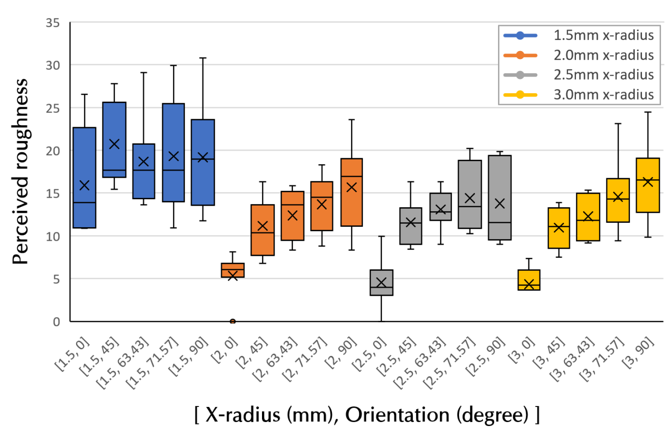


Fig. 10. The normalized roughness estimates varying in surface patch with different x-radius (r_x) and scanning direction.

VI. Main Study

To test our hypotheses that a surface textured model with various grazing orientation and velocity can provide a wide range of perceived roughness, we designed and conducted a within-subject study where participants were asked to report perceived roughness after scanning using our encountered-type haptic texturing system.

A. Participants

Twenty five human subjects including 20 females and 5 males participated in our main study. The ages of the subjects vary between 19 and 50, with an average age of 26.6. All subjects were right-handed and four of them had participated in our preliminary study.

B. Experimental Conditions

The orientation conditions were the same as our preliminary study: 0, 45, 63.43, 71.57, 90 (degrees). As for the velocity, the conditions include 0, 20, 40, 60, 80 (mm/sec) which were distinguishable velocities observed from an internal study. The x-radius of the hemiellipsoidal bump (r_x) was set to $3.0mm$ based on findings from the preliminary study.

C. Apparatus

We prepared a rigid polymer surface patch (20 cm×20 cm) with $r_x = 3.0mm$ using a 3D printer. As the printable size of patches is limited by hardware constraints, we divided the model into four sub-patches of a squared shape (10 cm×10 cm) and printed them separately. Then we attached the surface models to a rigid acrylic panel that was fastened to the end-effector of the manipulator. Also, we printed a custom, robotic gripper model that can be connected to the end-effector by bolts to firmly attach the acrylic panel to the robot.

We used HMD and IR sensor for tracking user's head and hand motions and preventing the subject from seeing the surface detail. In order to focus on the haptic effect on roughness perception, subjects were asked to wear an HMD during the experiment as shown in Fig. 11, and no visual images are provided through the HMD. The sequence of experimental conditions was programmatically set per subject in advance so that the experimenter can prepare for the next trial remotely using an Oculus controller.

D. Procedure

Before the experiment began, the subjects had been informed that their task is to rate roughness of each series of system conditions without considering other texture attributes such as warm/cold, soft/hard or flat/bumpy. The magnitude estimation method in Sec. V was used to numerically represent an estimation data for subject's perceived roughness.

The subjects were comfortably seated on a chair facing the haptic manipulator and wore an HMD that was displaying nothing. IR motion sensor was mounted on top of the HMD to track users' hand movement as described in Sec. IV. Then, they were asked to raise their dominant hand by shoulder height and extend the hand forward to touch a textured surface model. When they felt contact with the model, they were instructed to touch the surface from side to side while maintaining both the contact force and the scanning speed constant during the entire experiment. Since keeping these parameters constant depends on the user's capabilities, the users went through the exercises until they could experiment correctly. The subjects evaluated surface texture roughness using only a positive number, with a higher number indicating a rougher texture. The textured surface was cleaned with alcohol after each subject completed her/his experiment.

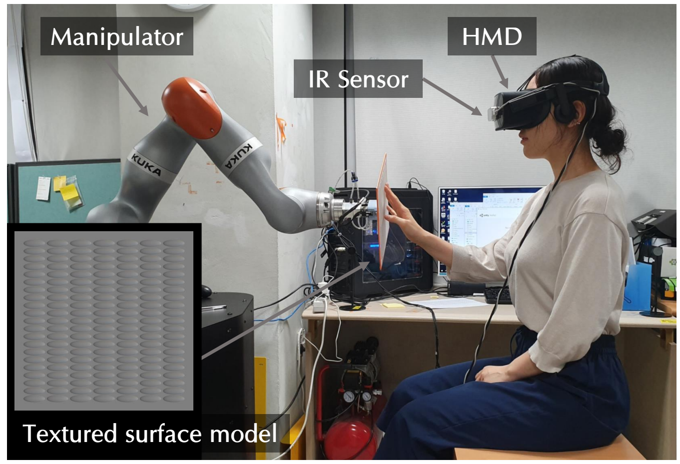


Fig. 11. Experimental setup for the main user study.

E. Data Analysis

By combining five different orientations and five different velocity values for the surface texture, 25 different levels of conditions were tested for each subject. In total, each subject performed 150 trials (five orientations × five velocity levels × six rounds). Each subject spent 36.3 minutes for the entire experiment procedure on average. Each subject's reported perceived roughness were normalized across rounds as in our preliminary study as described in Sec. V-E.

Not to violate the sphericity before conducting analysis, we apply Aligned Rank Transform (ART) [41] to our non-parametric data. Then we conduct a two-way repeated measures ANOVA with factors of orientation (5-level) and velocity (5-level). Pairwise t-tests were performed for posthoc analysis with Bonferroni adjustments.

F. Results

Fig. 12 shows the results of the roughness estimation experiment using our texture synthesizing system. The x-axis in the graph represents the combinations of orientation and velocity values, and the y-axis represents the rescaled normalized roughness. The curves in the graph are shown in distinct color to distinguish the different conditions on orientation.

Overall, subjects perceived the surface to be rougher as orientation angle and velocity increase. Moreover, changes in orientation seem to have a greater influence on perceived

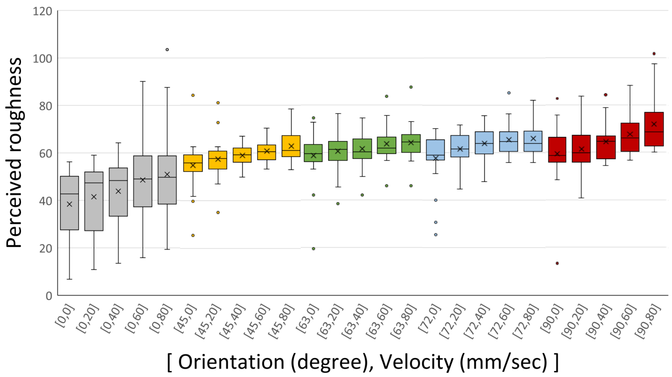
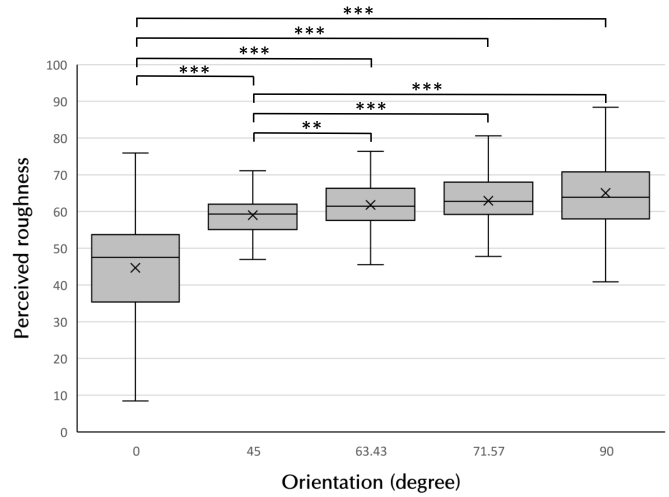
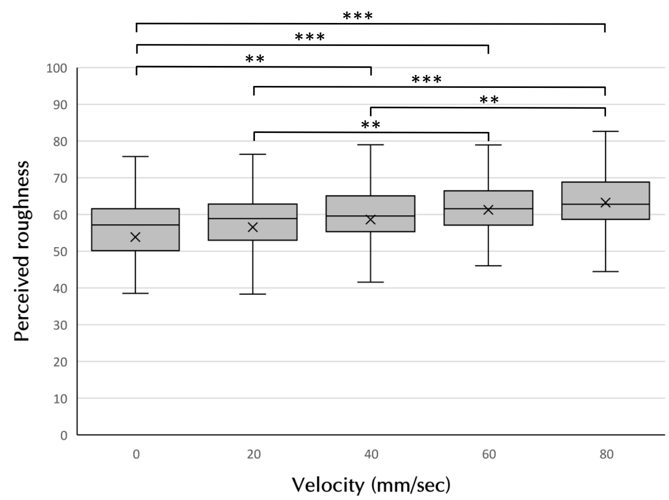


Fig. 12. The normalized magnitude estimation of roughness with respect to the orientation and velocity of an end-effector.



(a) Perceived roughness with respect to the end-effector orientation.



(b) Perceived roughness with respect to the end-effector velocity.

Fig. 13. Boxplots showing users' perceived roughness on average varying orientation and velocity. Stars were indicate p values from pairwise posthoc analysis results: '*' for $p < .05$, '**' for $p < .01$ and '***' for $p < .001$.

roughness compared to changes in velocity. To investigate the impact of orientation and velocity on perceived roughness and their interaction effect, we performed two-way ANOVA with repeated measures. As a result, we found significant main effect and large effect size of orientation ($F_{(4)}$ = 71.67, p <.001, η_p^2 = .3323) and significant main effect and medium effect size of velocity ($F_{(4)}$ = 15.87, p <.001, η_p^2 = .0993) on roughness estimation confirming both of our hypotheses.

As shown in Fig. 13(a), posthoc analysis with Bonferroni adjustments show that the perceived roughness was significantly greater as the orientation angle increases in general. For example, the perceived roughness of the scanning orientation angle of 0 and 45 is significantly less than other angles ($p \leq .001$ for all). However, there was no statistically significant difference in perceived roughness among 63.43, 71.57, and 90 degrees.

Similarly, subjects tend to perceive our surface model to be rougher as the velocity increases as shown in Fig. 13(b). While no significant differences in perceived roughness between every pair with 20 mm/sec differences (*e.g.*, 20 and 40 mm/sec and 60 and 80 mm/sec) were found, the perceived roughness differences between all pairs with at least 40 mm/sec difference were statistically significant. This suggests that our surface model can be used to simulate various levels of perceived roughness by tuning either of the parameters of orientation and velocity. Meanwhile, no interaction effect between orientation and velocity was found to be significant.

VII. Discussion

In this section, we discuss how our results can contribute to the implementation of roughness synthesis and suggest potential applications for virtual environments.

A. Supporting Roughness Changes with One Surface

Our results demonstrate that our encountered-type textured surface model with hemiellipsoidal bumps can be used for changing users' perception of roughness levels, simply by changing orientation and velocity without using body-mounted or hand-held devices. Moreover, compared to other encountered-type haptic systems with an additional tactile display, our simple method can represent various levels of perceived roughness using one rigid surface model. Therefore, we can dynamically change the level of roughness in realtime without switching a different textured surface each time for altering perceived levels of roughness. Our method is expected to reduce the system complexity and the cost of an encountered-type haptic system that provides textural information.

To vary the range of perceived roughness, hemiellipsoid is used as an elliptical texton in our texture model. We also conducted user experiments for cross verification using the truncated-cone model [21] and our model using hemiellipsoid and verified that our model more clearly shows the increase in roughness with respect to increasing angle and provides a wider range of roughness. In this experiment, r_x, r_y, and the height of elliptical truncated cones are constant and set to the same as our hemiellipsoid model and the dot angle of truncated cones is set to 45 degrees. These experiments follow the same procedure as the main user study with eight subjects.

The increasing effect of roughness proportional to increasing angle is more evident in our hemiellipsoid model. In particular, when a user scans the surface of the model with truncated-cone along its sharp edge, the proportional relationship between the orientation and perceived roughness may not be maintained.

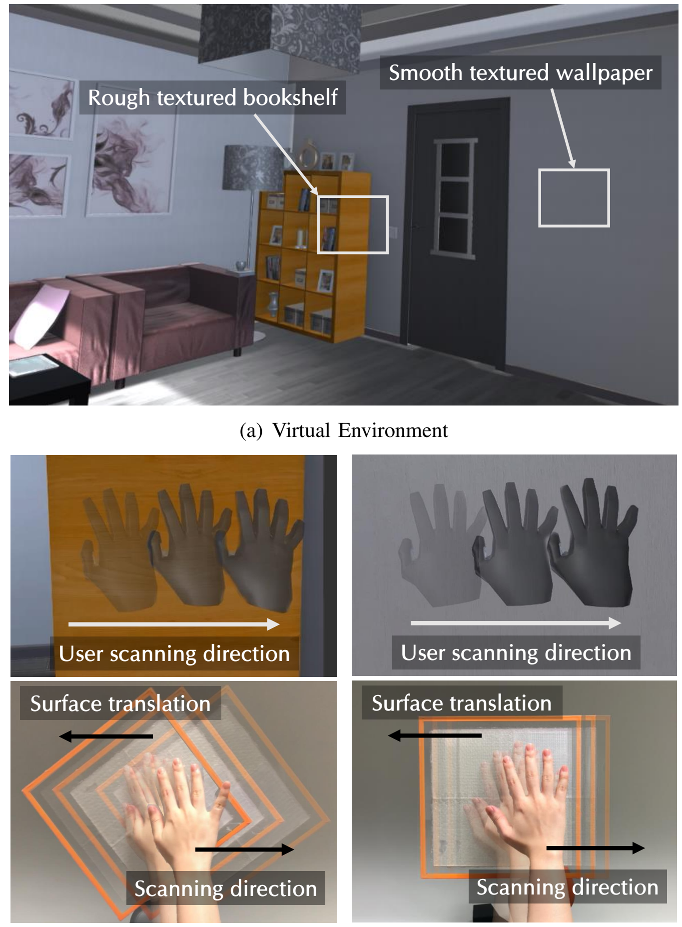
B. Simulating Various Levels of Roughness

Our finding confirms that roughness perception is affected by temporal cues which depend on scanning velocity, similarly to a prior work [20]. As our textured model have large inter-distance between textons, experimental conditions with larger velocity resulted in higher roughness which is consistent with the result of Connor and Johnson [21]. Whereas the earlier work was focused on a passive touch experiment for studying the effect of temporal cues under a precisely controlled condition, our result shows that the temporal cues also have a significant influence on roughness perception during active touch. In addition, we show that spatial cues offered by our encountered-type texture surface model with different orientations can also be used to alter users' perception of texture roughness. Most of all, we demonstrate our model can simulate a particular level of perceived roughness by tuning two parameters: orientation angle and velocity. For instance, gradual changes in perceived roughness can be implemented by changing the velocity which is almost linear in terms of roughness level as shown in Fig. 12. Thus, once we identify the range I of roughness change a priori, we can continuously map a certain level of roughness to an orientation-velocity pair (θ, v) in two steps: first we find an orientation θ_I that contains the roughness range I and change the velocity value v continuously to cover I.

C. Active and Passive Touch

Our texture roughness rendering method provides both active and passive touch simultaneously. The encoded spatial cue of roughness is represented by the user's active touch. As the haptic manipulator holds its orientation relative to the user's hand motion, there is no relative rotational motion between the user hand and the textured surface model. On the other hand, both passive and active touch is involved in delivering temporal cue. While the user actively scans the surface of the model, a haptic manipulator translates the model with a predefined velocity determined by the roughness of the virtual object. That is, the textured surface moves in the opposite direction of the user's scanning direction regardless of the user's scanning speed.

While previous studies demonstrated the little effect of relative speed [30], [31], our finding shows the significant effect of scanning speed on perceived roughness. Based on the human brain research [42] that shows roughness perception differs depending on the scanning velocity during a passive touch, we conjecture that the simultaneous active and passive touch makes the experimental result differ from previous researches. When the haptic system provides passive feedback during the user's active touch in VR, the system might deceive the human perception process and substantiate the effect of scanning speed. To identify the exact cause and neural process, additional in-depth research in the sensory and neural recognition field should be needed, which we leave as future work.



(a) Virtual Environment

(b) Rough Texture (c) Smooth Texture

Fig. 14. Prototype VR application using our roughness synthesizing method.

D. Potential VR Applications

While deepening our understanding of how we can manipulate roughness perception with a spatiotemporally encoded surface model, our findings suggest implications for potential VR applications with bare hand interaction in particular. An encountered-type haptic system with a limited number of textures can use our nine levels of distinctive roughness. If the order of texture roughness is determined in the target application, one can use our spatiotemporal encoding of textures to cover the variation of roughness. For example, the player of immersive VR game can feel the distinctive roughness corresponding to the texture of the game object using the encountered-type haptic system. Fig. 14 shows our VR prototype implementation of the indoor environment consisting of furniture such as a door and bookshelf. As the user gazes at the surface of the furniture with different texture in the virtual environment, she or he can feel different levels of roughness while scanning the textured surface attached to the encountered-type haptic display.

Although we limited the user's movement to a straight line in a user study, our prototype implementation can provide the user with a non-linear movement. Further study on verifying the significance of roughness rendering supporting non-linear scanning could contribute to improving VR realism. We also refer the reader to check our accompanying video to see this showroom scenario. This system will be even more powerful if the manipulator is mobile, which is our base implementation platform, to extend the limited haptic workspace, even though our current haptic system does not exploit the mobility.

E. Limitations and Future Work

As a single-session controlled lab study, limitations exist. First of all, since we imposed motion constraint to control the contact force and velocity of hand motion, the subjects were not completely free in their hand motion during the experiment. However, users should be able to freely change the contact force and the speed of rubbing in virtual environments with tactile feedback. Thus, the uncertainties caused by the active movement of the user should be considered when applying our method to an actual VR application. Another limitation is that our results, the ranges of perceived roughness for instance, may have differed if we recruited a different population; the majority of our subjects were female in their twenties. Although a previous work [43] shows that there is no difference in tactile spatial acuity by gender, one should note that there could have been a gender or age difference that we have not considered.

Moreover, we did not consider synthesizing the surface of an actual object since the goal of the main study was to maximize the range of roughness synthesis with a single encoded model. As a next step, we plan to study an analytical model that can be mapped to a specific object to simulate the same texture but with a relative difference in terms of roughness. Also, other modeling parameters such as texton height could be studied for providing a more realistic texture.

Although we focused on macro-scale roughness perception, a further study for synthesizing fine roughness would be interesting. In order to do this, a micro-scale modeling method and finer velocity control during texture rendering will be needed. Also, beyond the distinctive level of roughness, a more serious study on a continuous level of roughness synthesis is deserved to represent the diverse range of visual or physical textures. In this case, the realtime system reaction is much more critical. Although no subject complained about the abnormality of system latency during the user experiment, reduction in reaction time both in haptic rendering and visual rendering is still desirable.

VIII. Conclusion

We propose a macro-scale roughness-synthesizing method for an encountered-type haptic display using spatiotemporal encoding of roughness. The encoding scheme is based on a geometric grid of hemiellipsoidal bumps with the capability of changing the orientation and velocity relative to user motion using an off-the-shelf collaborative robot. Our psychophysical experiments show that both the orientation and the velocity have impacts on perceived roughness, which suggests that users feel the same surface of our model differently in terms of roughness when scanning orientation or velocity changes. Moreover, we demonstrate that simulating a wide range of perceived roughness with a specific target roughness level is possible through both active and passive touch sensation. We expect our system to synthesize an appropriate level of roughness on demand that corresponds to diverse visual textures in VR by manipulating the encoding values for a given textured surface.

References

[1] P. Cipresso, I. A. C. Giglioli, M. A. Raya, and G. Riva, "The past, present, and future of virtual and augmented reality research: A network and cluster analysis of the literature," *Frontiers in Psychology*, vol. 9, p. 2086, 2018. [Online]. Available: https://www.frontiersin.org/article/10.3389/fpsyg.2018.02086

[2] W. A. McNeely, "Robotic graphics: a new approach to force feedback for virtual reality," in *Proc. of IEEE Virtual Reality Annual International Symposium*, Sep 1993, pp. 336–341.

[3] Y. Yokokohji, R. L. Hollis, and T. Kanade, "What you can see is what you can feel-development of a visual/haptic interface to virtual environment," in *Proceedings of the IEEE 1996 Virtual Reality Annual International Symposium*, March 1996, pp. 46–53.

[4] H. Culbertson, S. B. Schorr, and A. M. Okamura, "Haptics: The present and future of artificial touch sensation," *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 1, no. 1, pp. 385–409, 2018.

[5] P. Abtahi, B. Landry, J. J. Yang, M. Pavone, S. Follmer, and J. A. Landay, "Beyond the force: Using quadcopters to appropriate objects and the environment for haptics in virtual reality," in *Proc. of the CHI Conference on Human Factors in Computing Systems*, 2019, pp. 1–13.

[6] B. Araujo, R. Jota, V. Perumal, J. X. Yao, K. Singh, and D. Wigdor, "Snake charmer: Physically enabling virtual objects," in *Proc. of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, 2018, pp. 218–226.

[7] P. Abtahi and S. Follmer, "Visuo-haptic illusions for improving the perceived performance of shape displays," in *Proc. of the CHI Conference on Human Factors in Computing Systems*, 2018, pp. 1–13.

[8] S. Okamoto, H. Nagano, and Y. Yamada, "Psychophysical dimensions of tactile perception of textures," *IEEE Transactions on Haptics*, vol. 6, no. 1, pp. 81–93, First 2013.

[9] S. J. Lederman, "The perception of surface roughness by active and passive touch," *Bulletin of the Psychonomic Society*, vol. 18, no. 5, pp. 253–255, Nov 1981. [Online]. Available: https://doi.org/10.3758/BF03333619

[10] S. Tachi, "A construction method of virtual haptics space," *Proc. of the ICAT'94 (4th International Conference on Artificial Reality and Tele-Existence)*, pp. 131–138, 1994.

[11] Y. Yokokohji, R. L. Hollis, and T. Kanade, "Wysiwyf display: A visual/haptic interface to virtual environment," *Presence*, vol. 8, no. 4, pp. 412–434, Aug 1999.

[12] M. Abdullah, M. Kim, W. Hassan, Y. Kuroda, and S. Jeon, "Haptic-Drone: An encountered-type kinesthetic haptic interface with controllable force feedback: Initial example for 1d haptic feedback," in *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology*, ser. UIST '17. New York, NY, USA: ACM, 2017, pp. 115–117.

[13] M. Hoppe, P. Knierim, T. Kosch, M. Funk, L. Futami, S. Schneegass, N. Henze, A. Schmidt, and T. Machulla, "VRHapticDrones: Providing haptics in virtual reality through quadcopters," in *Proc. of the 17th International Conference on Mobile and Ubiquitous Multimedia*, 2018, pp. 7–18.

[14] M. Abdullah, M. Kim, W. Hassan, Y. Kuroda, and S. Jeon, "Haptic-Drone: An encountered-type kinesthetic haptic interface with controllable force feedback: Example of stiffness and weight rendering," in *2018 IEEE Haptics Symposium (HAPTICS)*, 2018, pp. 334–339.

[15] E. Vonach, C. Gatterer, and H. Kaufmann, "Vrrobot: Robot actuated props in an infinite virtual environment," in *2017 IEEE Virtual Reality (VR)*, March 2017, pp. 74–83.

[16] Y. Kim, H. J. Kim, and Y. J. Kim, "Encountered-type haptic display for large vr environment using per-plane reachability maps," *Computer Animation and Virtual Worlds*, vol. 29, no. 3-4, p. e1814, 2018.

[17] S. J. Lederman and R. L. Klatzky, “Relative availability of surface and object properties during early haptic processing,” *Journal of Experimental Psychology: Human Perception and Performance*, vol. 23, no. 6, pp. 1680–1707, 1997.

[18] K. S. Hale and K. M. Stanney, “Deriving haptic design guidelines from human physiological, psychophysical, and neurological foundations,” *IEEE Computer Graphics and Applications*, vol. 24, no. 2, pp. 33–39, March 2004.

[19] L. A. Jones, *Haptics*. The MIT Press, 2018.

[20] C. J. Cascio and K. Sathian, “Temporal cues contribute to tactile perception of roughness,” *Journal of Neuroscience*, vol. 21, no. 14, pp. 5289–5296, 2001.

[21] C. Connor and K. Johnson, “Neural coding of tactile texture: comparison of spatial and temporal mechanisms for roughness perception,” *Journal of Neuroscience*, vol. 12, no. 9, pp. 3414–3426, 1992.

[22] S. Choi and K. J. Kuchenbecker, “Vibrotactile display: Perception, technology, and applications,” *Proceedings of the IEEE*, vol. 101, no. 9, pp. 2093–2104, 2013.

[23] J. M. Romano and K. J. Kuchenbecker, “Creating realistic virtual textures from contact acceleration data,” *IEEE Transactions on Haptics*, vol. 5, no. 2, pp. 109–119, April 2012.

[24] Y. Ujitoko, Y. Ban, and K. Hirota, “Modulating fine roughness perception of vibrotactile textured surface using pseudo-haptic effect,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 25, no. 5, pp. 1981–1990, May 2019.

[25] Y. Vardar, A. İşleyen, M. K. Saleem, and C. Basdogan, “Roughness perception of virtual textures displayed by electrovibration on touch screens,” in *2017 IEEE World Haptics Conference (WHC)*, June 2017, pp. 263–268.

[26] K. Ito, S. Okamoto, H. Elfekey, H. Kajimto, and Y. Yamada, “A texture display using vibrotactile and electrostatic friction stimuli surpasses one based on either type of stimulus,” in *2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, Oct 2017, pp. 2343–2348.

[27] S. J. Lederman and M. M. Taylor, “Fingertip force, surface geometry, and the perception of roughness by active touch,” *Perception & Psychophysics*, vol. 12, no. 5, pp. 401–408, Sep 1972.

[28] C. Connor, S. Hsiao, J. Phillips, and K. Johnson, “Tactile roughness: Neural codes that account for psychophysical magnitude estimates,” *Journal of Neuroscience*, vol. 10, no. 12, pp. 3823–3836, 1990.

[29] A. Dépeault, E. M. Meftah, and C. E. Chapman, “Tactile perception of roughness: raised-dot spacing, density and disposition,” *Exp. Brain Res.*, vol. 197, no. 3, pp. 235–244, Aug 2009.

[30] M. M. Taylor and S. J. Lederman, “Tactile roughness of grooved surfaces: A model and the effect of friction,” *Perception & Psychophysics*, vol. 17, no. 1, pp. 23–36, Jan 1975.

[31] S. J. Lederman, “Tactual roughness perception: Spatial and temporal determinants.” *Canadian Journal of Psychology/Revue canadienne de psychologie*, vol. 37, no. 4, pp. 498–511, 1983.

[32] E. Gamzu and E. Ahissar, “Importance of temporal cues for tactile spatial- frequency discrimination,” *Journal of Neuroscience*, vol. 21, no. 18, pp. 7416–7427, 2001.

[33] A. M. Smith, C. E. Chapman, M. Deslandes, J. S. Langlais, and M. P. Thibodeau, “Role of friction and tangential force variation in the subjective scaling of tactile roughness,” *Exp. Brain Res.*, vol. 144, no. 2, pp. 211–223, May 2002.

[34] M. Meenes and M. J. Zigler, “An experimental study of the perceptions roughness and smoothness,” *The American Journal of Psychology*, vol. 34, no. 4, pp. 542–549, 1923.

[35] S. J. Lederman and R. L. Klatzky, “Hand movements: A window into haptic object recognition,” *Cognitive Psychology*, vol. 19, no. 3, pp. 342 – 368, 1987.

[36] J. M. Goodman and S. J. Bensmaia, “A variation code accounts for the perceived roughness of coarsely textured surfaces,” *Scientific Reports*, vol. 7, p. 46699, Apr 2017.

[37] E. M. Meftah, L. Belingard, and C. E. Chapman, “Relative effects of the spatial and temporal characteristics of scanned surfaces on human perception of tactile roughness using passive touch,” *Exp. Brain Res.*, vol. 132, no. 3, pp. 351–361, 2000.

[38] D. Cohen-Or, C. Greif, T. Ju, N. J. Mitra, and H. Zhang, *A Sampler of Useful Computational Tools for Applied Geometry, Computer Graphics, and Image Processing*. CRC Press, 2015.

[39] L. A. Jones and H. Z. Tan, “Application of psychophysical techniques to haptic research,” *IEEE Transactions on Haptics*, vol. 6, no. 3, pp. 268–284, July 2013.

[40] S. S. Stevens, “On the psychophysical law,” *Psychological Review*, vol. 64, pp. 153–181, 1957.

[41] J. O. Wobbrock, L. Findlater, D. Gergle, and J. J. Higgins, “The aligned rank transform for nonparametric factorial analyses using only anova procedures,” in *Proc. of the SIGCHI Conference on Human Factors in Computing Systems*, 2011, pp. 143–146.

[42] S. Ballesteros, F. Munoz, M. Sebastian, B. Garcia, and J. M. Reales, “Erp evidence of tactile texture processing: Effects of roughness and movement,” in *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2009, pp. 166–171.

[43] R. M. Peters, E. Hackeman, and D. Goldreich, “Diminutive digits discern delicate details: Fingertip size and the sex difference in tactile spatial acuity,” *Journal of Neuroscience*, vol. 29, no. 50, pp. 15 756–15 761, 2009.

Yaesol Kim is a PhD student of computer science and engineering at Ewha Womans University. She received her BS in computer science and engineering in 2016 from Ewha Womans University. Her research interests include human robot interaction, haptics and virtual reality.

Siyeon Kim is a MS student of computer science and engineering at Ewha Womans University. She received her BS in physics in 2018 from Ewha Womans University. Her research interests include robotics, motion and task planning.

Uran Oh is an assistant professor of computer science and engineering at Ewha Womans University. She received her PhD in Computer Science from University of Maryland, College Park. Before joining Ewha, she was a postdoctoral research fellow at Carnegie Mellon University. Her research goal in Human-Computer Interaction is to enrich user experience with novel interaction technologies with minimum physical and cognitive loads. She is particularly interested in improving information access by redesigning and augmenting state-of-art technologies (e.g., wearables, VR/AR) for individuals with various needs, especially for people with visual impairments.

Young J. Kim is an Ewha fellow professor of computer science and engineering at Ewha Womans University. He received his PhD in computer science in 2000 from Purdue University. Before joining Ewha, he was a postdoctoral research fellow in the Department of Computer Science at the University of North Carolina at Chapel Hill. His research interests include interactive computer graphics, computer games, robotics, haptics, and geometric modeling. He has published more than 100 papers in leading conferences and journals in these fields. He also received the best paper awards at the ACM Solid Modeling Conference in 2003, the International CAD Conference in 2008 and the HCI Korea Conference in 2016, and the best poster award at the Geometric Modeling and Processing conference in 2006.