Haptic Texture Modeling Using Photometric Stereo

Sunghwan Shin and Seungmoon Choi

***Abstract*— In this paper, we propose a new image-based haptic texture modeling method using photometric stereo that has much higher accuracy that previous image-based haptic texture modeling methods. Our method uses multiple images of a texture sample taken under precisely controlled lighting conditions and extracts a height map using a reconstruction method in photometric stereo. Our preliminary evaluation results show promising performance for the modeling and rendering of both homogeneous and inhomogeneous surface textures.**

I. Introduction

Accurate modeling and rendering of surface texture is one of the most important and challenging topics in haptics. Since texture sensation depends on many different physical properties such as stiffness, viscoelasticity, friction, and surface microgeometry, many different methods have been proposed to model and render realistic texture to the user. Among them, the data-driven modeling approach using contact acceleration data has recently achieved notable progress [1], [2], [3], [4], [5]. This approach can provide realistic texture sensations by synthesizing a signal that includes similar spectral content to the real texture. However, this approach has been applied mainly to homogeneous texture, in which the local texture property is independent of contact position. Using contact acceleration data for modeling inhomogeneous texture is fundamentally difficult. Contact acceleration data need to be collected locally as a function of contact position, and this exponentially increases the amount of data required for interpolation function training. In addition, data-driven models mainly focus on fine textural features mediated by the PC channel. Coarse textural features (e.g., particle size $> 100\ \mu$m) are not adequate for the data-driven approach since they are encoded in terms of spatial layout (the duplex theory of texture perception [6]).

In this work, we revisit an alternative approach using vision for inhomogeneous texture modeling and coarse texture modeling. Some early haptic texture modeling methods used the image-based approach [7], [8], but it became less popular because of its low modeling resolution and accuracy. Instead, the method we present here relies on photometric stereo. Although the highly accurate acquisition of object geometry using multiple images is still a challenging problem in computer graphics, photometric stereo is regarded as one of the most accurate methods [9]. In this approach, the surface geometry is estimated by correlating the correspondence among different images that are photographed under precisely controlled lighting conditions using a fixed camera.

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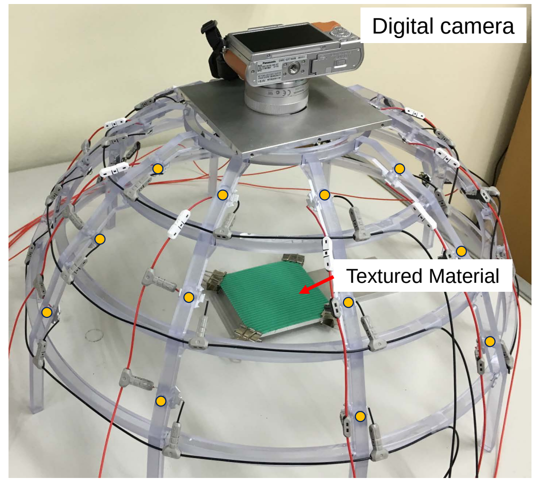


Fig. 1: Apparatus for texture modeling. LEDs are installed inside the polycarbonate dome (marked by orange circles).

To achieve such lighting conditions, we designed a lighting-dome structure that is appropriate for haptic texture modeling. Multiple photographs taken using the lighting dome are fed to our haptic texture modeling algorithm to build the height map of the target surface using photometric stereo. The modeled textures were rendered using the estimated height maps and Force Dimension Omega.3 device to demonstrate the feasibility of modeling and rendering haptic texture using photometric stereo.

Our texture modeling method supports both homogeneous and inhomogeneous textures. In terms of textural density, our method is limited to relatively coarse textures (resolution $100\ \mu$m). For finer textures, one can use commercial 3D profilometers (resolution 10–100 nm), but they are usually very expensive.

II. Height Map Estimation

General photometric stereo algorithms in computer graphics require dedicated and expensive apparatus to cover a large workspace and support objects of arbitrary shape. For haptic textures, however, we can assume relatively small and almost flat texture samples. We also use an ordinary digital camera for better reproducibility [10].

A. Apparatus

To accurately locate lighting instruments, we designed and built a dome-shaped lighting structure (Fig. 1). Placing multiple light sources at the fixed locations is effective for the precise control of lighting conditions, which is the most important requirement of photometric stereo. To this end, lighting-dome structures are commonly used in the research for photometric stereo algorithms. Unlike other lighting-domes, ours is much smaller in size, and the camera position is fixed at the top of the dome to focus more on almost flat texture materials.

The detailed structure of the lighting dome was designed considering the relationship between illumination angle and reconstruction error. An empirical experiment in [11] showed that the modeling error is the lowest when the lighting source has the illumination angle (elevation) of 55° for general surfaces but the error rate is almost flat between 40° and 70°. Therefore, our design places light sources at three elevations of 40°, 55°, and 70°. This configuration is repeated for every 36° in azimuth, resulting in 30 different lighting conditions.

As light sources, we use power LEDs (1W) to provide sufficient illumination to the object surface. The power supplied to each LED is accurately controlled by an LED driver circuit.

B. Photometric Stereo Algorithm

We use the photometric stereo algorithm presented in [10] to construct the height map of a texture sample. This method works well with a regular DSLR camera and flash lights and also has resulted in many successful examples that model 3D features on a flat surface.

Before height map construction, we estimate the radiance (incident light intensity) function $L(x,y)$ for each position (x,y) on the surface. For this, we use a blank white paper as the surface material. This allows us to assume that the normal vector and the albedo (reflection coefficient) are constant over the surface. Therefore, a photographed image of the paper represents the radiance function.

Using the radiance function $L(x,y)$, the photographed light intensity $I(x,y)$ can be represented by

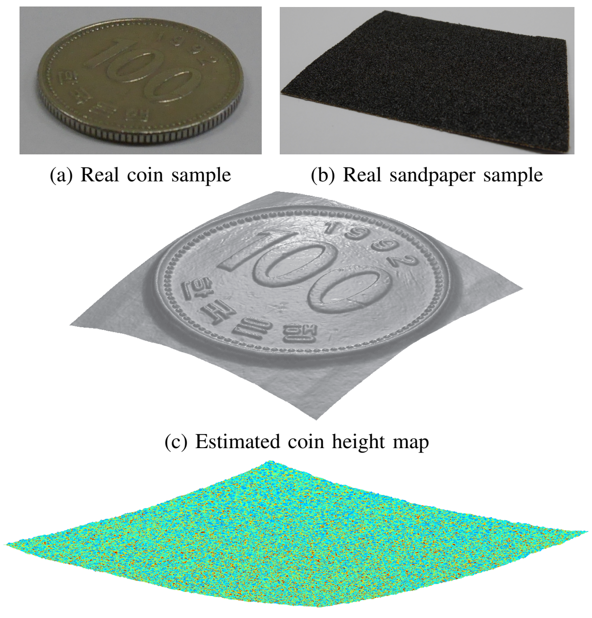
$$I(x,y) = f(x,y)L(x,y), \tag{1}$$

where $f(x,y)$ is a BRDF (Bidirectional Reflectance Distribution Function). The BRDF is a function that defines the light reflectance and depends on surface parameters such as albedo, normal vector, incident light vector, and view vector. Many different models exist for the BRDF. Among them, we use the Lambertian model since it is effective for perfectly diffuse surfaces[1] in spite of its simple form [10]. Specifically,

$$f(x,y) = a(x,y)\mathbf{n}(x,y)^T\mathbf{l}(x,y), \tag{2}$$

while a is the albedo, $\mathbf{n}$ is the normal vector, and $\mathbf{l}$ is the incident light vector. $\mathbf{l}$ is known by the use of the lighting dome. Thus, a and $\mathbf{n}$ are the only unknowns in (1) and (2), and they need to be determined for each point (x,y).

[1]Diffuse reflection occurs on a non-glitter and irregular surface, which is the main target of haptic texture modeling and rendering.



(a) Real coin sample (b) Real sandpaper sample

(c) Estimated coin height map

(d) Estimated sandpaper height map (Color coded)

Fig. 2: Comparison between real samples and estimated height maps. Height maps are illuminated and rendered using MATLAB for better recognition.

For robust estimation of a and $\mathbf{n}$, we use multiple photographs taken under N different lighting conditions ($N = 30$). Then the problem can be formulated as an optimization problem as follows:

$$(a(x,y), \mathbf{n}(x,y)) = \operatorname{argmin} \sum_{i=1}^{N} \left| I_i(x,y) - a(x,y)\mathbf{n}(x,y)^T \mathbf{l}_i(x,y)L(x,y) \right|^2. \tag{3}$$

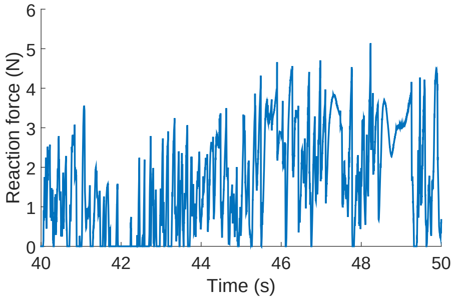
To solve this optimization problem, we initialize $\mathbf{n} = (0,0,1)$ and then find a using singular value decomposition (SVD). Then a new $\mathbf{n}$ is found with this a using SVD. This procedure is terminated until the changes in $\mathbf{n}$ and a become negligible. Twenty iterations are generally sufficient in our implementation.

Finally, the normal vectors $\mathbf{n}(x,y)$ are integrated over the surface to construct the height map $h(x,y)$ [12].

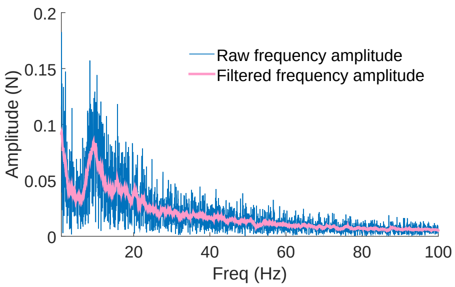
III. Results

A. Modeling

To evaluate the modeling accuracy of our method, we constructed the height maps of a coin and a sandpaper and then compared them with the photographs of the real samples. These results are shown in Fig. 2. For the coin, the grooves on the coin are fully expressed in the estimated height map. For the sandpaper, accurate comparison between the real sample and the height map is too difficult, but by



(a) Force profile in the time domain



(b) Force profile in the frequency domain

Fig. 3: Force command computed when the sandpaper model was scanned by a user. In the time domain signal, similar patterns are repeated. In the frequency domain, the signal power is concentrated in the low-frequency band (0–50 Hz), conveying rough sensations.

visual observation, the rough surface of the sandpaper seems to be well reconstructed in the height map. These examples demonstrate that our height map estimation apparatus and algorithm can build the height map of both homogeneous and inhomogeneous haptic textures with high accuracy.

B. Rendering

We also rendered the two reconstructed height maps to deliver their texture sensations. The two height maps were converted to high-resolution meshes, and these meshes were rendered using the conventional virtual proxy algorithm implemented in the open-source haptic rendering library CHAI 3D. The haptic device used was Force Dimension Omega.3, which has high stiffness and position resolution suitable for texture rendering.

We could confirm that the rendering well preserves the texture sensations of the real samples. An example in Fig. 3 shows a force profile computed from the sandpaper model while a user was stroking on its surface.

IV. On-going and Future Work

At present, we are working on more rigorous evaluation of the modeling performance of our haptic texture modeling system. We have fabricated texture samples that have surface features with known dimensions and plan to use their modeling results to quantify the accuracy and resolution of our image-based modeling system.

It is still likely that the modeling resolution of our approach is inferior to that using other sensors such as a high-resolution accelerometer. We are particularly interested in a hybrid modeling and rendering approach that combines the vision-based approach presented in this paper and the contact acceleration-based approach. The former allows modeling of inhomogeneous texture geometry, while the latter can be advantageous for the expression of very fine surface material property due to the superior sensitivity of accelerometers.

V. Conclusions

In this paper, we have described an image-based haptic texture modeling method using photometric stereo. This approach resolves the low-resolution problem of previous imaged-based haptic texture modeling methods to a large extent. The performance of our method is demonstrated using the promising results of two examples, although a more formal evaluation is on-going. Our plan for future work towards hybrid texture modeling and rendering is also introduced briefly.

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