Method of Observing Finger Skin Displacement on a Textured Surface Using Index Matching

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Abstract. Relationship between skin displacement and subjective sensation is indispensable for the design of tactile feeling display. Previous works on the observation of the skin displacement mainly used flat glass plate and a camera. However, the flat glass is not a representative tactile texture that we daily touch. We developed a system that can observe interaction between textured surface and finger skin by using technique known as index matching. The textured plate is immersed in the oil with the same refractive index, so that the texture became invisible. The finger skin is printed with markers, and its movement is analyzed by image processing. We also show a preliminary result of the observation when finger strokes on 0.5 mm interval grating.

Keywords: Haptic interface · Index matching · Optical observation · Skin displacement · Textured surface

1 Introduction

Tactile displays that present realistic sensations have been intensively studied in the fields of virtual reality, teleoperation, and remote palpation. To realize a realistic tactile sensation, the relationship between skin displacement and associated sensation must be clarified. There have been numerous attempts to observe this relationship, typically using a glass plate and high-speed camera that captures the finger skin from under the plate.

However, the surface of a flat glass plate is not typical of surfaces that we touch on a daily basis. We need ways of observing skin deformation when skin strokes across a rough surface. Levesque et al. reported skin displacement for a glass plate having bumps and holes [1], but in this case, the shapes were relatively large and did not greatly hinder optical observation. If, for example, the surface of the glass plate has a texture like sandpaper, we cannot optically observe the skin displacement from beneath the plate.

To solve the above issue, we propose using a technique called index matching. We use an oil that has almost the same refractive index as the plate. The measurement system is immersed in the oil so that the plate is “invisible”, even if it has a finely textured surface. We stroke the plate with a finger on which optical markers are printed, and the markers are detected using a high-speed camera.

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2 Related Work

The process of the tactile perception of a textured surface is as follows. First, skin displacement is generated by contact with a physical object (textured plate). The subsequent mechanoreceptor activity is then perceived by our brain as a tactile feeling. Various studies have been conducted to clarify this whole process.

Several works on nerve recording have aimed to clarify the relationship between the texture of a plate and mechanoreceptor activity. LaMotte et al. [2] and Srinivasan et al. [3] conducted an experiment to read the neural activity of slowly adapting and rapidly adapting receptors of monkeys when their fingers were stroked across a flat, dot-plotted, or line plotted surface. Connor et al. [4, 5] measured activities of slowly adapting and rapidly adapting receptors when a matrix of dots was presented, and found the relationship between the tactile roughness and mechanoreceptor activity.

Skin displacement has been intensively measured, especially for the purpose of developing tactile displays. In most cases, an optical measurement was made using a glass plate and camera. Levesque et al. [1] measured the finger surface behavior using feature points of the finger such as sweat ducts. Soneda et al. [6] measured the contact surface area using a glass prism. Several studies measured the relationship between the grip status and skin moisture using a similar optical measurement setup [7]. An optical measurement was also employed as the mechanism of a computer–human interface. Kurita et al. [8] used the contact area to determine the finger force and direction, while Holz et al. [9] used a fingerprint image to identify each finger.

Meanwhile, vibrations have been measured when a finger strokes a rough surface. Martinot et al. [10] used an acceleration sensor to detect fingertip vibration when the fingertip stroked a rough surface. Romano et al. [11] obtained contact acceleration data for numerous textures. Sato et al. [12] proposed a method of measuring the finger surface displacement using a change in the finger side. Yuan et al. [13] used a GelSight Tactile Sensor to detect shear forces and incipient slip on flat and curved surface.

Against the background of the above studies, the direct measurement of the displacement of finger skin on a textured surface is rare. As previously noted, Levesque et al. used a non-flat surface, but the features on the surface were relatively large so as not to hinder optical observation. Clarification of skin behavior when skin comes into contact with a wide variety of textured surfaces is essential for the future development of tactile displays.

3 System

3.1 Principles

We generally cannot observe an object clearly when a textured plate is placed between the object and a camera, owing to refraction at the surface of the plate (Fig. 1).

If the surface shape is accurately known, the refracted image can be reconstructed, but this is generally difficult, especially when the plate has fine texture.

We use index matching to solve this issue. Index matching is frequently used for optical measurements, especially in the field of fluid mechanics [14, 15]. A transparent

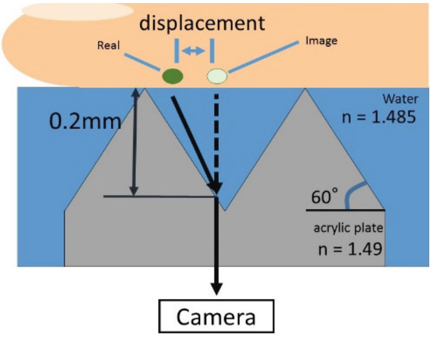

Fig. 1. Displacement of a marker image by surface texture

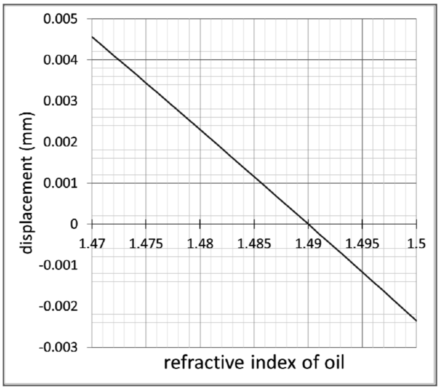

Fig. 2. Relationship between refractive index of oil and displacement

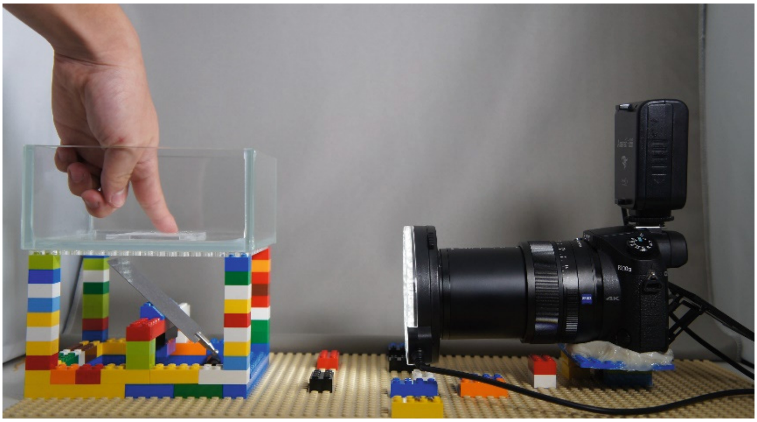

Fig. 3. Photograph of the experimental setup

object is submerged in transparent liquid having the same refractive index, making the object optically invisible. In our case, the textured plate is submerged in liquid so that the texture does not hinder optical observation of the skin of the contacting finger (Fig. 8).

In the described method, the accurate matching of the refractive index is important. We estimated the mismatch allowance of the refractive index in simulation. We used an acrylic plate with a refractive index 1.490, which is readily available commercially and for which it is easy to add texture using a laser beam machine. Figure 1 shows the situation of the simulation, assuming convex protrusions with a 60-degree slope and height of 0.2 mm. Figure 2 shows the simulated displacements of the marker image for different values of the refractive index of the liquid. It is seen that liquid with a refractive index between 1.485 and 1.495 results in error less than 0.001 mm, which is acceptable considering the human perception threshold of vibration [16].

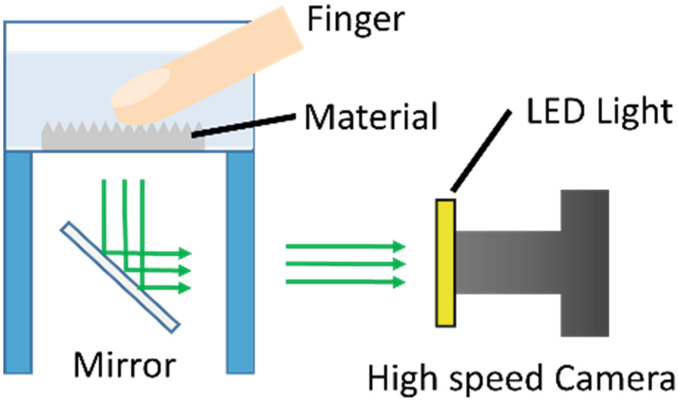

Fig. 4. Overview of the experimental setup

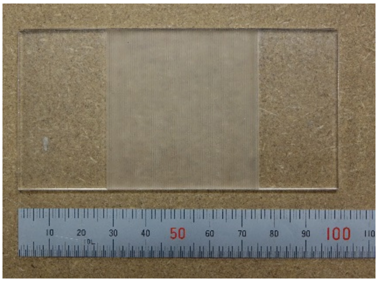

Fig. 5. Rough surface image

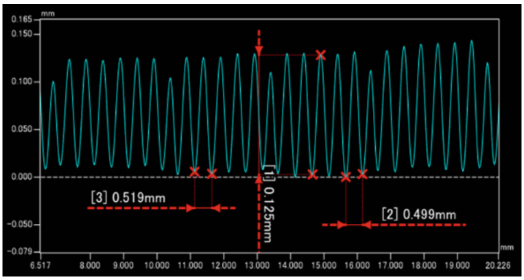

Fig. 6. Cross-sectional view of the rough surface

3.2 Hardware

Figures 3 and 4 show the experiment setup. Optical markers (in a 10 × 16 array, each having a diameter of 0.5 mm, with center-to-center intervals of 1.0 mm) are printed on the fingertip with a waterproof stamp. The test texture on the acrylic plate is a series of lines at intervals of 0.5 mm and depth of 0.125 mm, which were carved with a laser beam machine and measured with a three-dimensional microscope (Keyence VR-3000) (Figs. 5 and 6). The markers are observed by a high-speed camera (SONY, RX10 II) that can take 1920 × 1080-pixel images at 1000 fps. A light-emitting diode is used to illuminate the fingertip. The acrylic plate and fingertip are submerged in silicone oil having a refractive index of 1.485 (Shinetsu Silicone KF-53), on the basis of the results of the previous simulation.

3.3 Software

Figure 7 is a diagram of the image processing. We used the OpenCV library (http://opencv.org) for image processing and Python as the front-end environment. The software is used to obtain the accurate positions of markers on the finger.

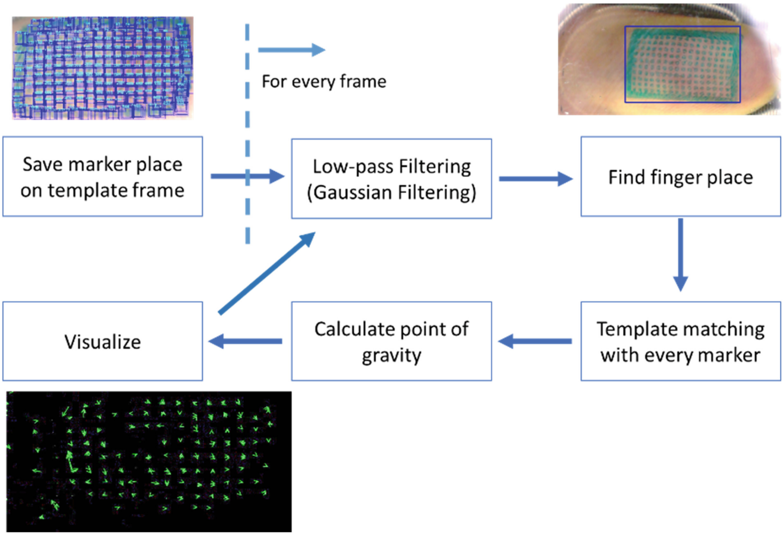

Fig. 7. Image processing flow

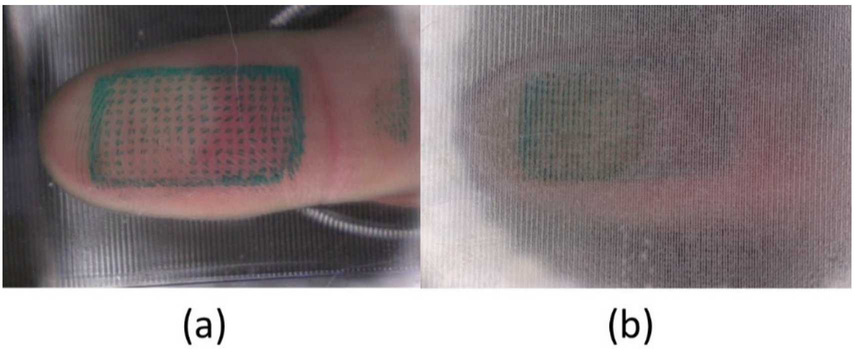

Fig. 8. The picture of finger (a) with oil and (b) without oil

Two image templates are manually obtained from the video. The finger template has a rectangular shape and contains all printed markers, while the marker template has a square shape and contains one marker (Fig. 9). The global fingertip position is obtained by template matching using the finger template. The position of each marker is roughly obtained by template matching using the marker template. Then, by

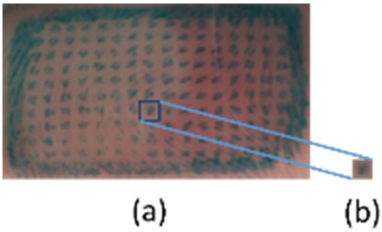

Fig. 9. Example of (a) the finger template and (b) marker template

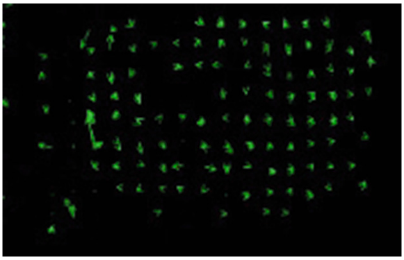

Fig. 10. Example of the flow field

calculating the cross-correlation between two sequential images around each marker, the displacement of the marker between the two sequential frames is obtained with sub-pixel accuracy. This "flow field" is visualized using arrows (Fig. 10).

4 Experimental Results

Figure 11 shows frames from the video captured by the high-speed camera. We see that by index matching, the finger marker is clearly observed without distortion. By looking at each marker, tiny movement was also observed, mostly at the tip of the finger because the base of the finger was not firmly attached to the plate.

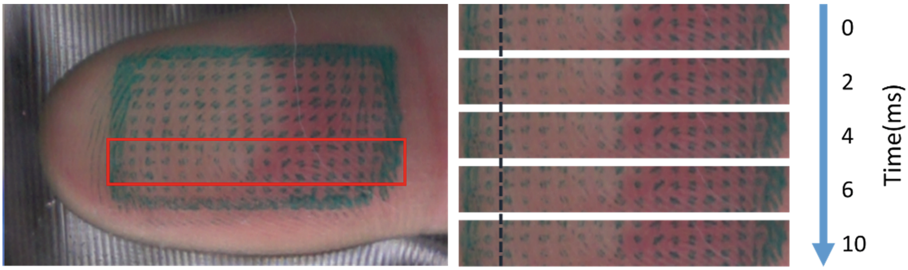

Fig. 11. Continuous photographs of the finger marker

Next, we show the results of image processing. Figure 12 shows how each marker of finger was labeled. Figure 13 shows the behavior of the marker that is red marked in Fig. 12 relative to the finger coordinate system. Averaging using sequential three frames data was conducted. The marker was chosen because it showed characteristic vibratory behavior.

The result showed that vibration around 66 Hz was observed between 0.031 s and 0.121 s, which can be considered as a stick-slip movement.

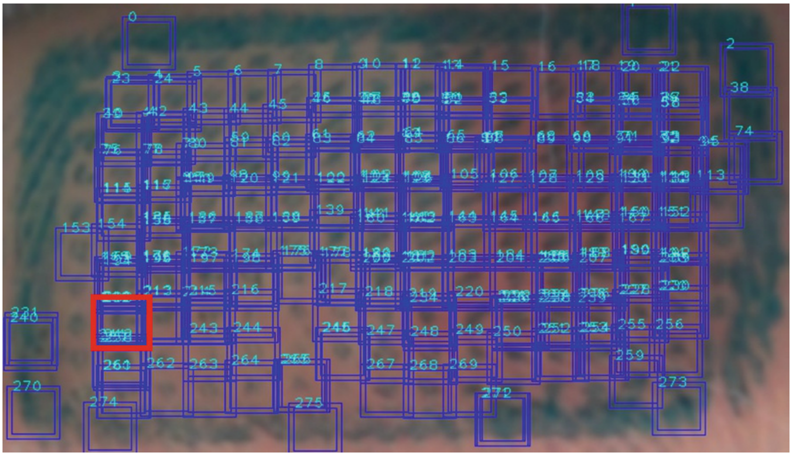

Fig. 12. Result of finger marker detection (Color figure online)

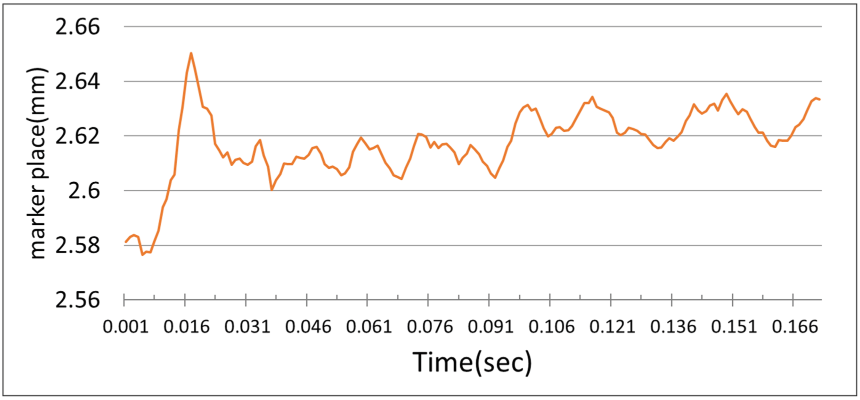

Fig. 13. Movement of one marker relative to the finger coordinates

5 Conclusion

To observe the temporal and spatial behavior of skin when a finger strokes a textured surface, the present study proposed using a technique called index matching. We showed by simulation that a difference in refractive index between the oil and textured object of around 0.005 is acceptable considering the threshold of human perception. On this basis, we constructed a measurement system that allowed clear observation.

One possible question that arises for our approach is that the texture feeling is altered by the oil. However, the purpose of our approach is not to find the relationship between daily objects and tactile feeling but to find the relationship between finger skin displacement and tactile feeling, since the latter relationship is more important for the design of a tactile display, which is a device that deforms skin and presents a tactile feeling. The use of oil is thus not a problem in the present context.

Our next step is to lower the noise in image processing, by applying filtering and using clearer markers. We will also use numerous types of materials, such as those having rough and smooth surfaces, bumps and holes, and soft and hard materials, in observing skin behavior. Furthermore, we will make a subjective evaluation of the tactile feeling during the measurement, to clarify the relationship between the skin displacement and tactile feeling.

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