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A Low-Distortion Capturing System for 2D Displacement Measurement of Finger Pad During Tracing on Rough Surfaces*

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I. Introduction

Humans perceive surface features during tactile exploration by detecting mechanical stimuli, such as skin deformation and vibrations, through mechanoreceptors embedded in the skin. Recently, fingertip models have been constructed and deformations simulated to elucidate touch perception [1], improve virtual object grasping performance [2], and provide haptic feedback [3]. We have been constructing a detailed fingertip model based on an individual's finger pad, which incorporates the layered structure of the skin. To validate the accuracy of this model, we believe it's essential to compare its simulated deformations with measured deformation data of real fingertips during object contact. This necessitates a system capable of high-speed, high-resolution measurement of displacements across the finger pad's surface during object interaction.

Levesque et al. proposed an approach for measuring finger pad deformation during tactile exploration using transparent plates with flat or gradually sloped surfaces [4]. However, natural objects do not always have flat surfaces. When using transparent plates with rough surfaces, light refraction can cause image distortion, hindering the optical observation of the finger pad surface. To address this, Kaneko et al. proposed immersing a transparent plate with a rough surface in oil with a similar refractive index to minimize light refraction [5]. Despite this, the friction characteristics between the finger pad and the transparent plate differ significantly between oil-immersed and clean conditions. Optical coherence tomography (OCT) offers another approach for observing the finger pad. It has been used to obtain cross-sectional images containing surface and internal microstructure information while tracing a transparent plate with ridges or grooves. [6]. However, image loss in the finger pad's subsurface can occur depending on the surface shape. Additionally, challenges remain in achieving high-speed, wide-area 2D surface observation.

In this work, we propose an approach that enables 2D observation of the finger pad surface in a clean state while tracing a grooved surface. This is achieved by combining a transparent plate with rectangular wave-shaped surface textures with a telecentric optical system.

II. Low-Distortion Capturing System

To enable optical observation of the finger pad during object tracing, a transparent plate is frequently used as the contact surface. Our system incorporates a telecentric lens, which allows only light rays parallel to its optical axis to pass through. This ensures that objects within the depth of field are captured at a constant magnification, regardless of their distance from the lens. When an air-filled gap exists between the finger pad and textured surface of the transparent plate, light reflected from the finger is refracted at the texture interface, as illustrated in Figure 1(a). This refraction occurs due to the difference in refractive index between the transparent plate and air. As a result, the image exhibits distortion, as shown in Figure 1(b), preventing accurate observation of the finger pad. To mitigate this problem, we use a transparent plate with a rectangular wave pattern (Figure 1(c)). This pattern is specifically designed so that its cross-section is either parallel or perpendicular to the optical axis. This design minimizes refraction at the interface and significantly suppresses image distortion, as demonstrated in Figure 1(d). Figures 1(b) and 1(d) were captured using an imaging setup constructed based on this proposed optical design.

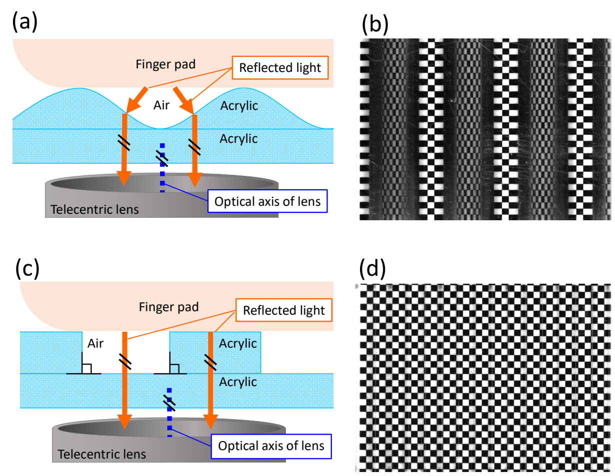

Figure 1. Comparison of light paths and observed patterns with a telecentric lens. (a) Light path when the normal of the textured transparent plate is tilted relative to the optical axis. (b) Observed checkered pattern showing distortion when the normal of the textured transparent plate is tilted. (c) Light path when the normal of the textured transparent plate is parallel or perpendicular to the optical axis. (d) Observed checkered pattern showing reduced distortion when the normal of the textured transparent plate is parallel or perpendicular to the optical axis.

III. Conclusion

From the images acquired using the measurement system developed based on the optical design presented in Section 2, we visually confirmed that our proposed approach successfully suppresses image distortion caused by surface texture. However, the edges of the slits remain visible in the captured images, which may affect the accuracy of the subsequent

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deformation analysis. Additionally, this approach currently restricts the usable surface textures to rectangular wave patterns. Further system development will need to consider the possibility of the finger pad surface catching on the sharp edges of these rectangular waves.

By applying image-based displacement measurement techniques, such as Digital Image Correlation (DIC) or feature point matching, to sequential images of the finger pad surface during tactile exploration of transparent plates with grooved textures, skin displacement can be quantitatively evaluated. We are currently attempting to measure the displacement and strain distributions of the finger pad while tracing a textured surface using the proposed imaging system, employing the open-source DIC software Ncorr [7]. The measurement system setup is shown in Figure 3. The middle finger of a participant (female, 20s) was fixed to a linear actuator via a manual Z-axis stage using a custom finger fixture. The actuator operated at a constant speed of approximately 50 mm/s in the distal direction (i.e., the positive y-axis in Figure 3) to trace over the textured surface. This surface consisted of 0.3 mm wide through-grooves spaced at 1.0 mm intervals. To ensure the structural integrity of the grooved texture during tracing and to prevent deformation that could hinder optical observation, pocket milling was applied around the grooved area, as shown in Figure 2. To create speckle patterns on the subject's right middle finger, purple ink used as a surgical skin marker was diluted with water and sprayed onto the finger pad using an airbrush. The imaging frame rate was 1500 fps (with frame interval of 1/1500 s), and the image resolution was 2048 × 1472 pixels, yielding a spatial resolution of 0.1 mm/pixel. For the DIC analysis, the subset radius was set to 15 pixels, corresponding to a circular area with a diameter of approximately 0.3 mm. As shown in Figure 4, the resulting strain distribution revealed strain patterns along the fingerprint ridges of the finger pad.

As future work, investigating and compensating for the effects of slit edge visibility and brightness differences between concave and convex regions on displacement measurement accuracy will be necessary. Moreover, a method for quantitatively evaluating the performance of this measurement system must be developed. Finally, by applying 3D-DIC techniques with two or more cameras in the proposed optical configuration, we aim to realize a three-dimensional deformation measurement system for finger pad surfaces during tactile exploration of a grooved surface.

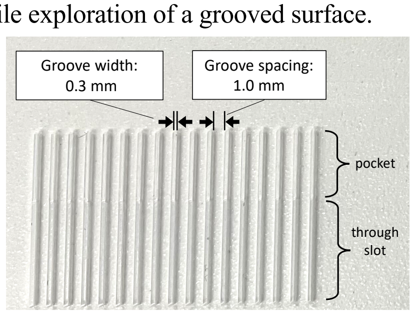

Figure 2. Transparent plates with grooved texture used in the experiment.

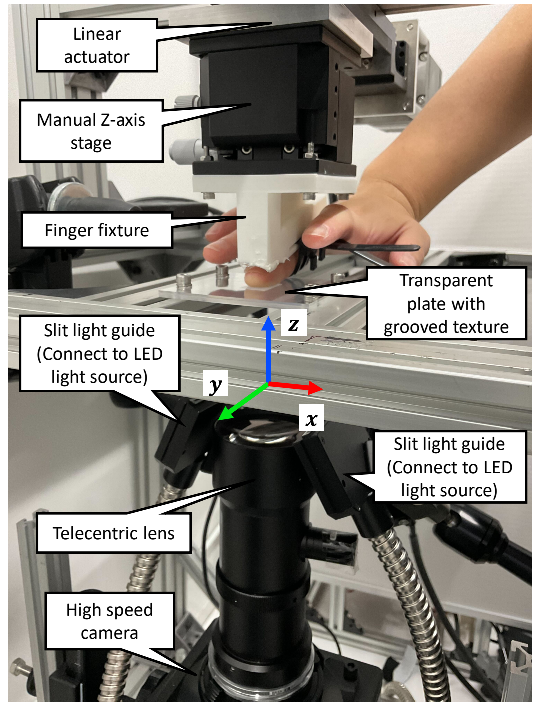

Figure 3. Measurement system setup.

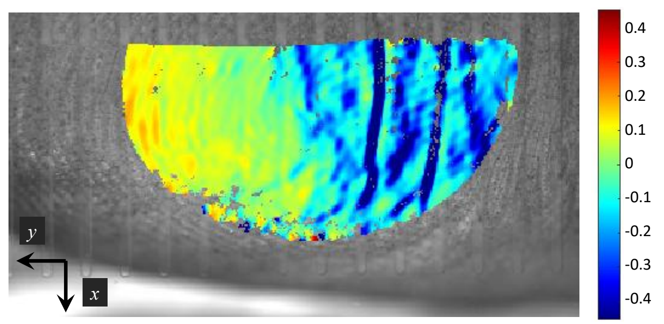

Figure 4. Y-axis strain distribution on the finger pad surface during tracing of a grooved transparent plate. (Red: extension, Green: no strain, Blue: compression)

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