2025 IEEE World Haptics Conference (WHC)
Suwon Convention Center, Suwon, Korea
July 8 ~ 11, 2025

Modular Haptic Texture Rendering System Using a Wearable Piezoelectric Ring

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***Abstract*—This work presents a modular haptic texture rendering system designed for freehand interaction in immersive environments. The system synthesizes real-time vibrotactile feedback from finger speed and contact force, enabling texture perception without reliance on stylus-based tools or visual interfaces. Its modular architecture integrates motion tracking, force sensing, and signal generation components, supporting flexible deployment across platforms such as tablets and augmented reality systems. To provide localized haptic feedback, a wearable thimble-type ring equipped with a multilayer piezoelectric actuator is employed, delivering high-frequency vibration directly to the fingertip during natural interaction.**

I. Introduction

Vibrotactile feedback enables users to perceive the material properties of virtual textures through touch [1]. A common method for generating such feedback involves recording vibration signals during real surface interactions using sensor-equipped tools. These signals depend on interaction variables like movement speed and applied force. Data-driven approaches are widely adopted to model these signals due to their ability to capture fine-grained texture characteristics. The modeled signals are then reproduced via high-frequency actuators to evoke corresponding tactile sensations [2].

Traditionally, virtual textures are rendered using stylus-based systems where a vibration motor is embedded in a handheld device that interacts with a touchscreen. These systems offer stable control and can be integrated with visual interfaces, but they often require structured environments and graphical user interfaces [3]. More recent studies have explored wearable thimble-like devices that attach to the fingertip, but many of these rely on actuators such as eccentric rotating mass motors or linear resonant actuators, which limit the frequency range and responsiveness of the feedback.

This work introduces a thimble-type wearable device that delivers fingertip-localized texture rendering using a multilayer piezoelectric actuator, which enables fast and precise reproduction of rapidly changing tactile signals. The system is designed to function without reliance on a graphical user interface, making it suitable for both tablet-based and augmented reality setups. In the proof-of-concept implementation, finger speed is captured using a motion tracking camera, and contact force is measured via a load cell placed beneath a rigid acrylic surface. These inputs are processed by a rendering algorithm that synthesizes texture-specific vibrations in real time. We believe this GUI-free configuration enables focused evaluation of tactile perception and may also be extended to overlay textures in mixed or augmented environments.

This research was supported by the National Research Council of Science & Technology (NST) grant by the Korea government (MSIT) (CRC23021-000) and in part by IITP under the Ministry of Science and ICT Korea through the IITP program No. 2022-0-01005

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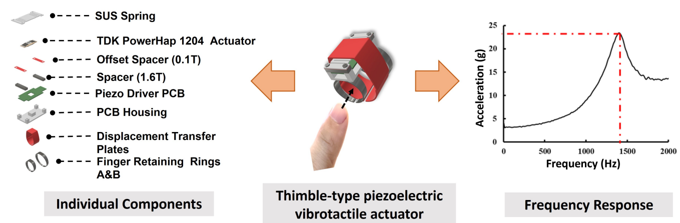

Fig. 1. Overview of the developed thimble-type piezoelectric actuator, including its internal components and frequency response profile.

II. Haptic Texture Rendering with Piezoelectric

This section describes the complete texture rendering pipeline used in this study, including the design of the wearable ring actuator, the texture rendering algorithm, and the hardware setup for input sensing and signal actuation.

A. Wearable Piezoelectric Ring for Vibrotactile Feedback

The proposed haptic device features a compact, thimble-type piezoelectric ring designed to deliver localized vibrotactile feedback to the fingertip. As shown in Fig. 1, the actuator integrates a multilayer piezoelectric element (TDK PowerHap 1204) within a mechanically optimized housing. A stainless steel (SUS) spring provides pre-compression, which enhances displacement output and ensures contact stability. Upon voltage excitation, the actuator generates high-frequency out-of-plane vibrations, which are transmitted to the user's skin through a displacement transfer plate. The ring is secured using finger retaining components, and the onboard driver circuit supplies the required excitation signals. The accompanying frequency response of the piezoelectric actuator, showing a sharp resonance peak at approximately 1450 Hz and a maximum acceleration exceeding 22 g, confirming its suitability for high-fidelity texture rendering.

B. Texture Rendering Algorithm and Hardware Integration

For texture rendering, this study adopts a data-driven library and algorithm that synthesize acceleration or vibration waveforms based on recordings from real textures [3]. The rendering algorithm generates vibration patterns modulated in

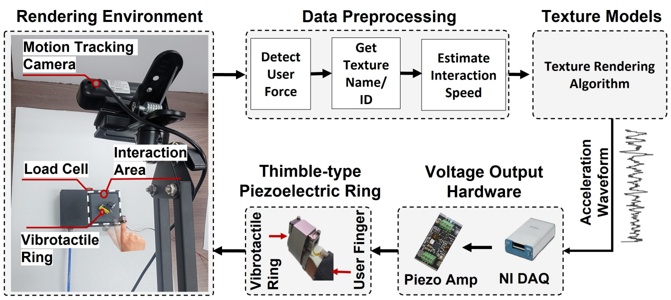

Fig. 2. User study setup (left) and the interface presented to participants during the psychophysical experiment (right).

real time by the user's interaction dynamics, specifically finger speed and applied force. The overall system architecture is illustrated in Figure 2.

In the current implementation, finger speed is captured using an overhead camera (webcam HCAM01L), and contact force is measured using a 3 kg load cell embedded beneath a rigid acrylic surface. The camera is connected via USB, while the load cell communicates through an Arduino-based ADC. Both input streams are sent to a common host computer, where data are resampled to 120 Hz and forwarded to the rendering module, which synthesizes vibration signals at a 1 kHz update rate. To compensate for the resonant behavior of the piezoelectric actuator, a dynamic compensation filter is applied using the inverse transfer function of the ring. The filtered signal is then transmitted to a data acquisition device (NI USB-6351), amplified using a high-voltage amplifier (Pdu100B), and delivered to the actuator for tactile feedback.

This implementation operates without a graphical user interface, enabling isolated evaluation of tactile perception without visual cues. While optimized for GUI-free use in AR environments, the system architecture is also compatible with touchscreen-based setups, where interaction speed and force can be captured via stylus or capacitive sensing, with the rest of the pipeline remaining unchanged.

III. Expriemtment Results and Discussion

Procedure: A pilot perceptual study was conducted with eight participants (six male, two female, mean age 33.6) who interacted with textures selected from a published texture library [2], illustrated in Fig. 3. Two conditions were tested: physical versus physical textures for baseline consistency, and physical versus virtual textures rendered by the piezoelectric ring. Trial order was randomized. Participants wore the haptic ring and headphones playing white noise, with visual access to the textures blocked. During real texture trials, the vibration output was disabled, as no artificial feedback was required.

Results and Discussion: Participants rated the perceptual similarity between pairs of textures using a numerical scale from 0 to 100, where 100 represented a perfect perceptual match. As mentioned earlier, ratings were collected for both physical and rendered texture comparisons, and averaged across participants for each texture. The results are presented in Figure 4.

Bumpy Wood received the highest average rating, suggesting that its temporally structured tactile features are effectively

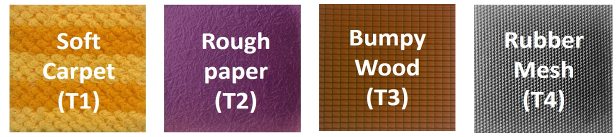

Fig. 3. Real texture samples used in this study.

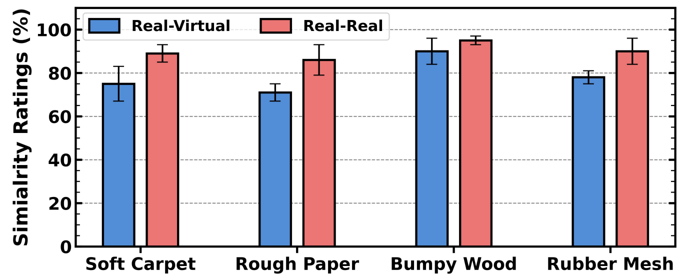

Fig. 4. Average perceptual similarity ratings across textures.

reproduced by the rendering pipeline. Rubber Mesh and Soft Carpet achieved moderately high ratings, indicating partial perceptual alignment between physical and virtual experiences. In contrast, Rough Paper produced the lowest similarity score, likely due to its complex, anisotropic surface patterns and broadband frequency content. These features are challenging to synthesize using current methods that rely solely on speed and force as input parameters. Incorporating interaction direction as an additional input for signal modulation may improve realism for textures with directionally uneven features.

These results demonstrate that the proposed piezoelectric ring can convey key texture-specific cues, enabling users to perceive virtual textures with a reasonable degree of fidelity. However, the observed variability across materials indicates that further refinement of signal modeling and actuation strategies may be necessary to improve rendering accuracy for fine-grained or directionally complex textures.

IV. Conclusion and Future Work

This study introduced a compact piezoelectric ring actuator for real-time texture rendering using finger speed and contact force as inputs. The system provides localized vibrotactile feedback through high-bandwidth actuation and signal synthesis. A pilot study showed promising similarity between real and virtual textures, with variability across materials such as soft carpet and rigid wood mesh. Future work will expand the texture dataset, refine rendering algorithms, and evaluate performance in tablet-based and augmented reality environments with more participants.

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