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Conductivity-Based Thermal Haptics: Modeling and Perceptual Evaluation for Material Discrimination in Virtual Reality

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I. Introduction

Conventional thermal haptics often rely on static temperature cues, overlooking the dynamic heat transfer governed by thermal conductivity, heat capacity and entropy within a closed system. Therefore, thermal feedback for virtual environments often requires visual and auditory modalities to differentiate objects and materials with similar temperature. This can affect the perception of thermal objects and reduce immersion within the simulated environment. Our work addresses this limitation by exploring the rendering of conductivity-dependent thermal feedback in virtual reality. We investigated two distinct strategies: 1) Modulating the perceived heat flow rate using Pulse Width Modulation (PWM) of the thermal actuator's average power output to simulate apparent conductivity, and 2) Directly simulating transient heat transfer physics to replicate characteristic temperature evolution profiles based on defined material properties during contact. The objective common to both approaches is to generate perceptually distinguishable thermal signatures, enabling users to identify virtual materials through touch alone for tasks such as sorting visually identical objects.

II. Background and Motivation

Although thermal feedback improves VR realism by conveying material properties [1], [2], common static rendering techniques [3], [4] fail to capture the transient heat transfer dynamics crucial for real-world material identification via conductivity and heat capacity [5], [6]. Consequently, static models struggle to differentiate materials such as metal and wood at similar baseline temperatures [6], [7], necessitating large absolute temperature differences [8] or yielding to visual dominance [9], [10]. Although dynamic rendering approaches exist [7], [11], [12], and system-level thermal concepts considering equilibrium and entropy have been discussed (e.g., [13]), practical models specifying the crucial thermal mediation between objects and the scene based on these principles remain underdeveloped. Addressing this gap, our work proposes and evaluates a dynamic thermal rendering model [6], [12], which explicitly handles thermal mediation through conductivity-dependent states and incorporates entropy via a thermal decay factor, aiming for a more physically grounded approach to rendering material-specific thermal cues in Virtual Environments.

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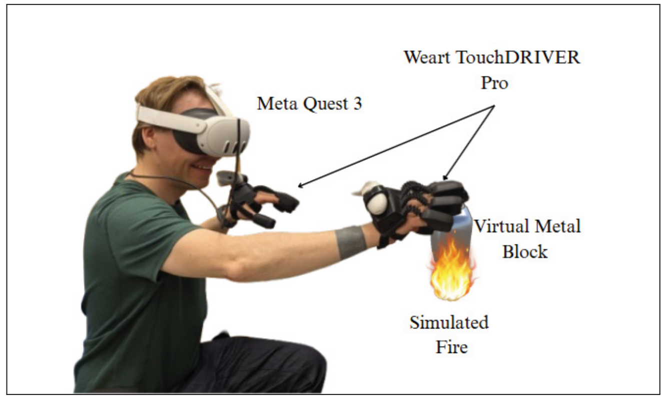

Fig. 1. Experiment Setup, A user wearing the WEART TouchDriver Pro Gloves and Meta Quest 3 to perceive conductivity-based thermal feedback. The scene represents a virtual Metal Block placed on the simulated fire in VR

III. Method

Participants performed a VR classification task using Meta Quest 3 HMD and WeArt TouchDIVER Pro haptic gloves, differentiating three visually distinct virtual objects (metal, glass, wood) based *exclusively* on thermal feedback acquired near simulated heat/cold sources. We initially investigated Pulse Width Modulation (PWM) for rendering apparent conductivity but found it insufficient for reliable perception. We therefore focused on our primary "conductivity curve" approach, which simulates the temporal temperature evolution $T(t)$ based on material characteristics.

The model calculates heating from $T_{initial}$ towards T_{source} using:

$$T(t) = T_{source} - (T_{source} - T_{initial}) * \exp(-k' * t) \quad (1)$$

where k' is the material-dependent heating rate constant (larger for higher conductivity). Cooling from $T(t_{cool})$ towards $T_{ambient}$ follows Newton's Law:

$$T(t) = T_{ambient} + (T(t_{cool}) - T_{ambient}) \exp(-\lambda(t - t_{cool})) \quad (2)$$

where λ is the material-dependent cooling rate constant. The different parameters k' and λ for metal, glass, and wood generated unique $T(t)$ profiles that are intended to be perceptually distinguishable. These profiles were normalized

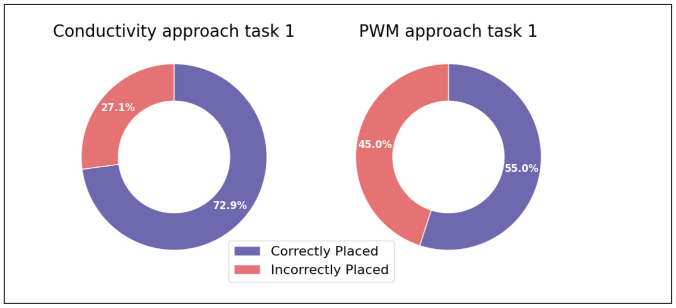

Fig. 2. Comparison of final placement proportions (Correctly Placed vs. Incorrectly Placed) for visually non congruent task using two different thermal rendering methods: the proposed conductivity curve approach (left) and a PWM approach (right)

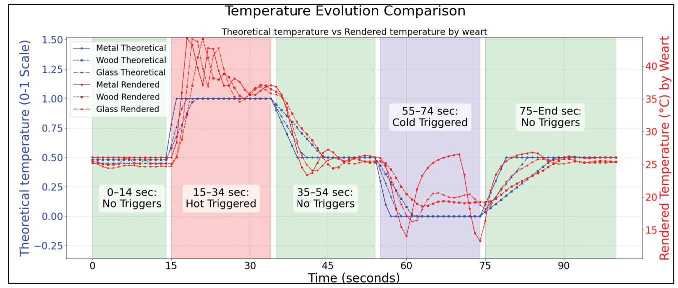

Fig. 3. Encoded (blue) vs Rendered (red) Temperature Validation for conductivity curve method. Comparison of command signals (0-1 scale, left Y-axis) and measured WEART Gloves temperature (°C, right Y-axis) for different material models (Metal, Wood, Glass) across thermal phases.

to the range [0, 1] and sent as command signals to the actuators at 15 Hz.

IV. Results

Our evaluation mainly compared the effectiveness of two thermal rendering strategies for the virtual object sorting task using the WeArt TouchDriver Pro Gloves. Initial tests employing a PWM approach suggested this method did not provide sufficiently reliable cues for perceptual differentiation based on simulated conductivity using the specified hardware.

We subsequently evaluated system performance using the physics-informed conductivity curve model detailed in the section above. Preliminary analysis focused on Task 1 (sorting with non-congruent visual cues) indicates improved performance with this approach. As shown in Figure 2, participants achieved a correct placement accuracy of 72.9% using the conductivity curve method, compared to 55.0% accuracy observed with the PWM approach under the same task conditions. The preliminary findings suggest that rendering dynamic thermal profiles based on simulated conductivity provides more effective discriminatory cues than the tested PWM technique. Analysis of performance across all tasks and conditions is ongoing and will be reported in followup publications.

To validate the thermal feedback, we compared our custom theoretical command signals (0-1 scale) for different materials against the actual surface temperature (°C) rendered by the gloves, measured via thermal imaging and averaged over 15 repeated cycles.Figure 3 illustrates this comparison for ”metal”, ”glass”, and ”wood” models. Each profile was sampled at 15Hz while the resulting surface temperature was measured and averaged. As seen in 3 there are some artifacts while rendering the thermal conductivity curves onto haptic gloves for both hot and cold temperatures. However, for the most part, these artifacts did not affect the conductivity curves for the three materials, except for the larger variation seen for metal at cold temperature seen in 3 from time 60-70 sec. Analysis of performance across all tasks, conditions, and artifacts is ongoing.

V. Conclusion & Future work

The initial results of this research show that the implementation of conductivity can be successfully integrated into a virtual environment, and an optimized method can lead to faster and more accurate material identification of objects and their materials, which have similar temperatures yet different perceptual outputs. Similar to real-world thermal perception, objects may perceive to be hotter or cooler depending on their thermal conductivity (heat transfer), even though the objects may have similar absolute temperature. Our future work will explore the thermal conductivity models discussed in this research using multiple rendering devices across varied VR tasks to further evaluate each model and its limitations.

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