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Time-Division Multimodal Tactile Perception for Physical AI and Robotic Hands

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Abstract— **Equipping robotic end-effectors with human-like tactile perception is crucial for dexterous manipulation, requiring simultaneous thermal and mechanical sensing at the contact interface. Conventional multimodal sensors often rely on stacked or patterned layers, which increase device thickness, reduce conformability on curved robotic fingers, and introduce response delays. To address this, we present a time-division tactile perception platform tailored for robotic applications that utilizes memristive Ag-Cu_2O core-sheath nanowire networks. This ultrathin artificial skin alternates between thermal and mechanical modalities at 16 Hz via memristive transitions, mirroring the processing of biological mechanoreceptors. In the SET state, sparse silver filaments form a mechanically sensitive network. During RESET, the semiconducting Cu_2O sheath provides high thermal sensitivity. Lacking reactive components, the sensor achieves sub-microsecond mechanical and millisecond thermal responses, ideal for real-time robotic feedback. A deep learning pipeline processing these time-division signals improved object classification accuracy to 95%. Using a wireless module, 20 household objects were recognized with 83% accuracy. This single-layer architecture enables direct, seamless integration onto robotic hands, laying the groundwork for multimodal tactile intelligence in physical AI.**

I. INTRODUCTION

Physical AI systems operating in unstructured environments demand tactile perception capabilities that approach human skin in both spatial resolution and temporal response. When a robotic hand interacts with an unfamiliar object, the ability to simultaneously assess thermal conductivity and mechanical stiffness at the precise point of contact is essential for adaptive, damage-free manipulation [1]. Thermal cues reveal material identity—metal acts as a rapid heat sink, whereas wood insulates [2]. Mechanical cues convey stiffness and texture. Together, these modalities enable robots to distinguish materials accurately without relying solely on vision [3].

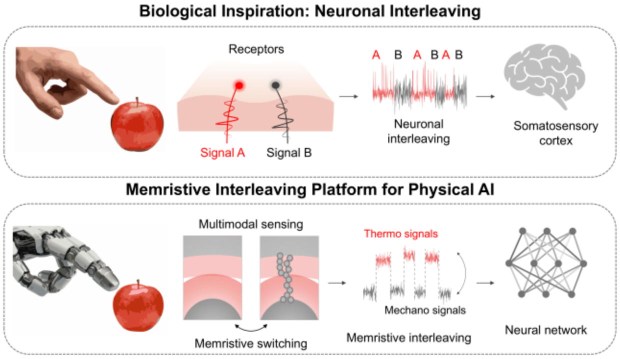
In human skin, overlapping thermoreceptors and mechanoreceptors rapidly alternate signaling, transmitting interleaved stimuli for integrated perception [4]. Replicating this co-located processing on robotic end-effectors remains a significant challenge. Existing multimodal sensors typically employ lateral patterning or vertical stacking of functional layers [5, 6]. Lateral arrangements introduce spatial offsets, preventing true co-located measurement—a critical flaw for localized robotic fingertip contacts. Stacked designs increase device thickness, degrade thermal response times, reduce conformability on curved gripper surfaces, and complicate wiring scalability [7].

In this work, we propose integrating a biomimetic time-division multimodal tactile platform into a robotic system. By leveraging the memristive switching of a core-sheath nanowire network, our system enables co-located thermal and mechanical sensing from a single ultrathin device, perfectly suited for robotic tactile skins.

II. TACTILE SENSOR FOR ROBOTIC INTEGRATION

A. Design Principle

Figure 1. Concept of the biomimetic time-division tactile platform.



Inspired by neuronal interleaving—where single sensory neurons alternate encoding different stimuli before central processing [8]—we implemented a time-division sensing strategy for robotic perception using a memristive Ag-Cu_2O core-sheath nanowire network [9]. The sensor is deposited on a highly flexible polydimethylsiloxane (PDMS) substrate with a thin-film encapsulation layer, ensuring structural integrity during repeated robotic touching. Silver nanowire (AgNW) electrodes provide electrical interfacing across a 60-µm sensing channel. The entire structure remains a single ultrathin layer, avoiding bulky heterogeneous stacking and ensuring high conformability to complex robotic finger geometries.

Triggered by programmed voltage pulses, the device alternates between two resistive states at 16 Hz. In the SET state, Ag ion migration across Cu_2O junctions forms conductive filaments, producing a sparse network (low-resistance state) highly sensitive to mechanical strain (gauge factor of 36). In the RESET state, the filaments collapse, and the semiconducting Cu_2O sheath dominates (high-resistance state), yielding high thermal sensitivity ($B \approx 4{,}500$ K). Each

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state exhibits minimal cross-sensitivity, ensuring clean multimodal feedback for the robot's control system.

B. *Perception Performance*

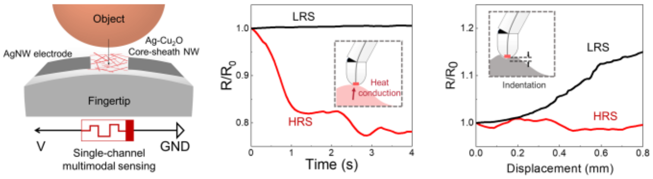

Figure 2. Sensor integration and decoupled perception performance.

Operating entirely through resistive state reconfiguration without slow-relaxing ionic components, the platform achieves sub-microsecond mechanical and millisecond-scale thermal response times—critical for real-time robotic reflex control [7]. Optimized with a sheath-to-core geometric ratio of 1.5, the sensor maximizes the voltage differential for reliable state transitions. The device maintained robust switching under combined thermal (55 °C) and mechanical (10% strain) loading typical of robotic manipulation tasks, demonstrating consistent performance over 500 switching cycles and 7 hours of continuous operation.

III. MULTIMODAL OBJECT RECOGNITION

A. *Classification Framework*

To validate the platform for robotic tactile intelligence, we deployed the sensor in a cyclic time-division scheme during object interaction. Commutating at 16 Hz with a 500 Hz acquisition rate, the system captures eight distinct windows per modality every second. We collected thermomechanical data across diverse material classes (metals, woods, rubbers, polymers) typically encountered by household robots.

A deep learning pipeline, featuring a six-layer LSTM encoder with attention mechanisms, captured the temporal sequences of these alternating channels. A three-layer fully connected decoder then mapped these latent features into discrete material labels. The 128-dimensional LSTM output was concatenated with the original input to preserve raw signal integrity for precise classification.

B. *Results*

Classification accuracy jumped from ~65% (single modality) to 95% with time-division multimodal input, highlighting the advantage of colocated sensing for robot perception pipelines. Impressively, this architecture achieved 94.53% accuracy utilizing only half the temporal data volume, demonstrating the computational efficiency required for untethered robotic systems.

To simulate natural robotic interaction, a wireless switching module with Bluetooth Low Energy was developed. Using a single sensor mounted on a surrogate robotic fingertip, 20 everyday objects were classified with 83% accuracy. Furthermore, the ultrathin design was extended to a multiarray, achieving ~1 mm spatial resolution—matching the spatial resolution of human mechanoreceptors [10] and demonstrating its scalability for large-area robotic skins.

IV. CONCLUSION AND OUTLOOK

This Late Breaking Result introduces a biomimetic time-division tactile platform adapted for robotic physical AI. By achieving co-located thermal and mechanical sensing via memristive switching, the single-channel architecture delivers rapid responses and high resolution while minimizing wiring complexity. These properties are highly advantageous for scaling toward whole-hand robotic skins. Future efforts will focus on directly integrating this sensory skin onto multi-fingered robotic grippers to enable closed-loop grasp adaptation and real-time material-aware manipulation in unstructured environments.

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