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Future Applications of Intelligent Textile-Leather Systems Integrating Perception and Interaction Technologies in Artistic Design

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Article

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ABSTRACT

With the convergence of smart wearables and digital art, intelligent materials that integrate perception, interaction, and aesthetic expression have emerged as a frontier in the interdisciplinary domain of textiles and interaction design. Intelligent textile-leather systems, owing to their flexibility, tactile quality, and cultural expressiveness, hold significant potential in immersive fashion and artistic installations. However, existing studies predominantly focus on single functionalities, such as pressure sensing or static lighting effects, and lack a closed-loop design encompassing "perception-interaction-aesthetic feedback." Although some efforts have embedded electronic components into materials, they struggle to simultaneously achieve high functional density, mechanical durability, and aesthetic coherence. To address these limitations, this paper proposes a layered heterogeneous integration architecture for intelligent textile-leather systems, based on conformal embedding of microfluidic ionogel sensors and flexible circuits, along with an event-driven, low-latency bidirectional interaction protocol. Experimental results demonstrate that the system maintains 98.2% signal retention under repeated bending with a curvature radius ≤5 mm, achieves an end-to-end interaction latency of 43.6 ms, and reduces energy consumption by 21.3%. This work establishes a co-optimization design paradigm that harmonizes functionality and aesthetics, filling a systemic gap in the application of intelligent materials within artistic expression contexts and offering a scalable technical pathway for dynamic fashion and interactive heritage exhibitions.

KEYWORDS

intelligent textile-leather systems, perception-interaction integration, artistic design applications, flexible electronics integration, bidirectional human-material interaction

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INTRODUCTION

In recent years, the fusion of smart materials and digital creativity has driven the field of textiles beyond mere “functional realization” toward “expressive empowerment.” Intelligent textile-leather systems, capable of tactile perception, dynamic response, and aesthetic embodiment, are emerging as a critical medium bridging wearable technology and artistic design[1,2]. In contexts such as immersive performances, haute couture, and interactive installations, users not only demand sensing and feedback capabilities but also expect the material’s form, texture, and visual language to align with artistic intent[3]. Yet current research largely prioritizes engineering performance, overlooking the deeper artistic requirements for expressiveness, emotional resonance, and formal unity[4]. A central challenge thus arises: how to organically integrate high-reliability perception and low-latency interaction with aesthetic integrity.

Existing approaches primarily follow three trajectories: (1) fully textile-based systems using conductive yarns or printed electronics, which offer good flexibility but limited functionality; (2) hybrid solutions embedding rigid electronics into fabrics, which support multimodal interaction yet suffer from mechanical mismatch, compromising durability and disrupting visual harmony[5]; and (3) art prototypes reliant on external devices (e.g., cameras, projectors), which lack an intrinsic perception-feedback loop within the material itself[6]. These methods commonly treat “function” and “form” as opposing priorities, sacrificing one for the other rather than establishing a synergistic mechanism. Moreover, in real-world creative environments, materials must endure frequent deformation, environmental interference, and aesthetic scrutiny, imposing stringent demands on robustness, concealment, and expressive freedom. Consequently, a system-level solution capable of supporting real-time multimodal interaction while seamlessly embedding technology into artistic language remains absent[7].

To address these challenges, this paper presents three concrete innovations: (1) A layered heterogeneous integration architecture: Microfluidic channels enable conformal embedding of ionogel sensors and flexible circuits into a textile–leather composite substrate, resolving mechanical incompatibility between functional modules and flexible carriers. (2) An event-driven bidirectional interaction protocol: Leveraging localized stimulus-triggered mechanisms, this protocol synchronizes tactile input with light/thermal output at millisecond resolution, establishing an intrinsic closed-loop interaction capability within the material itself. (3) A function–aesthetics co-design paradigm: Circuit traces and sensor layouts are reimagined as decorative patterns, transforming technical components into integral elements of visual expression rather than extraneous add-ons.

Theoretically, this work transcends the traditional binary framework of “function-first” versus “form-led” design, proposing a novel triadic paradigm, “perception-interaction-expression”, for intelligent materials. Practically, the system provides an embedded, customizable technological platform for applications such as dynamic fashion, interactive heritage displays, and therapeutic art installations. It advances textile engineering from a manufacturing-oriented discipline toward creative empowerment and fosters human-material interaction that is richer in emotional and cultural dimensions.

RELATED WORK

Application Scenarios and Challenges

Intelligent textile-leather systems have demonstrated unique value in human-material interaction, wearable art, and immersive experiences. Representative tasks include tactile signal acquisition, dynamic visual feedback, gesture-to-color mapping, and affective material responses, centered on enabling the material itself to perceive user behaviors and translate them into artistic expressions[8,9]. However, such tasks impose multifaceted demands on system flexibility, durability, response speed, and aesthetic integration.

A critical gap persists: there is currently no large-scale dataset specifically curated for artistic interaction behaviors. Existing datasets primarily originate from health monitoring applications (e.g., pressure distribution or joint motion), which are collected under controlled conditions with highly structured, repetitive motions[10,11]. These fail to capture the free-form, unstructured nature of artistic interactions. While some studies have attempted to construct small-scale prototype datasets, they typically contain fewer than 50 hours of data and lack annotations for aesthetic preferences or creative intent[12].

Furthermore, conventional evaluation metrics, such as signal-to-noise ratio, stretch-cycle lifetime, and response latency, effectively quantify engineering performance but fall short in capturing artistic dimensions like aesthetic coherence, expressive freedom, or emotional resonance. Current assessment frameworks largely neglect the synergy between function and form, often labeling technically advanced yet aesthetically disjointed systems as “high-performance”, a misalignment that significantly diverges from the actual needs of artistic application contexts[13].

Overview of Mainstream Approaches

Recent research has largely followed three technical trajectories.

The first focuses on fully textile-based sensing systems, employing conductive yarns or functional coatings to achieve flexible perception[14,15]. This approach excels in wearability and washability, making it well-suited for long-term physiological monitoring. However, it suffers from weak output capabilities, struggling to integrate active feedback elements such as lighting or heating, and its signal density is constrained by weaving limitations, hindering high-resolution artistic interaction[16].

The second adopts a rigid electronics embedding strategy, directly stitching or adhering miniature LEDs, microcontrollers, or batteries onto leather surfaces[17,18]. While effective in specific scenarios, particularly for rich visual feedback, this method often overlooks mechanical degradation under repeated bending, such as solder joint fatigue and interfacial delamination, resulting in operational lifespans significantly shorter than the textile substrate itself, despite modular design intentions.

The third relies on external sensing devices (e.g., depth cameras or inertial sensors) to capture user gestures, with feedback rendered via projection or screens[19]. Although this avoids material modification complexity, performance is susceptible to environmental factors, including lighting variations, occlusion, and calibration drift, leading to insufficient robustness in mobile or multi-user interactive settings.

Notably, the first two approaches emphasize material-embedded functionality, whereas the third depends on external coupling. This fundamental difference in system closure and deployment flexibility results in sharply divergent applicability boundaries.

Most Closely Related Studies

Two recent works are particularly relevant to this study. One developed an interactive leather interface using thermochromic ink, enabling dynamic pattern changes through localized heating, with demonstrated potential in luxury product design[20]. The other constructed a fully textile-based multimodal sensor array capable of simultaneously detecting pressure, temperature, and shear for gesture recognition[21].

Compared to the thermochromic approach, our work adopts a distinct feedback mechanism: beyond thermal response, we integrate electroluminescent units to enable independent control of color and brightness[22,23]. Moreover, we introduce a bidirectional interaction protocol, endowing the system with active perception and responsive capabilities, not merely passive display.

While the textile sensor array represents a pioneering advance in flexible sensing density, our work further addresses how sensory data can drive artistic expression. By reconfiguring circuit traces and sensor layouts into decorative motifs, we unify technical components with visual language, transcending mere functional implementation.

Summary and Research Gap

Although existing studies have made progress in flexible sensing, interactive materials, or artistic prototypes, they lack a holistic exploration of an integrated architecture that unifies perception, interaction, and aesthetic expression[24,25]. While prior literature has established links between material functionality and user behavior, it offers limited insight into how technological elements can be naturally woven into artistic workflows. A co-design paradigm that harmonizes engineering performance with design semantics remains urgently needed.

In contrast to prior efforts, this work fills this gap through layered heterogeneous integration and a function-aesthetics co-design framework. Our contribution lies in constructing the first closed-loop intelligent textile-leather system explicitly tailored for artistic design, featuring a novel synchronization mechanism between multimodal perception and millisecond-scale artistic feedback.

While existing studies underscore the potential of smart materials in human–material interfaces, their methodological differences are stark: some sacrifice output capability for full textile compliance, while others compromise aesthetic integrity through rigid modules. Crucially, most overlook a core principle in artistic contexts, form is function, a tenet especially vital in the high-end design and cultural expression scenarios central to this work.

METHODOLOGY

System Architecture Design

The intelligent textile-leather system proposed in this study adopts a layered heterogeneous integration architecture, unifying perception, interaction, and artistic design to enable efficient and stable creative interaction. The system comprises four synergistic layers: the perception layer, circuit layer, interaction–feedback layer, and artistic expression layer.

The perception layer serves as the foundation, employing microfluidic ionogel sensors capable of real-time detection of physical stimuli, including pressure, temperature, and humidity, and transducing them into electrical signals. These sensors utilize low-noise, high-sensitivity materials compatible with diverse substrates, ensuring reliable operation under dynamic conditions. The circuit layer handles signal conditioning and transmission. Flexible printed circuits (e.g., polyimide-based) interconnect the sensors, maintaining signal integrity even under repeated bending. Low-power components support multimodal input/output, balancing flexibility with functional density. The interaction-feedback layer integrates light- and heat-responsive actuators that deliver real-time luminous or thermal feedback in response to user touch or pressure, enabling millisecond-scale closed-loop interaction. This capability renders the system suitable for immersive art, interactive fashion, and heritage exhibitions. The artistic expression layer embeds technological elements into aesthetic design by transforming circuit traces and sensor layouts into decorative motifs. Guided by principles of geometric composition and symmetry, functional components become integral visual features, achieving tactile–visual unity between technology and artistry.

In addition to these four functional layers, the system may incorporate an optional flexible photovoltaic auxiliary unit as a supplementary energy-harvesting component. This unit is not treated as an independent layer within the core heterogeneous architecture; instead, it is positioned on the outer surface or non-interactive backside of the textile–leather substrate and electrically interfaced through the circuit layer. The harvested energy is routed to the low-power management path to support standby monitoring and event-driven wake-up, thereby reducing background energy consumption without altering the functional organization of the four-layer system.

As illustrated in Figure 1, the architecture clearly delineates inter-layer connectivity and collaboration. This modular yet integrated design preserves component autonomy while enabling seamless coordination, effectively resolving the traditional dichotomy between functionality and aesthetics in smart textiles.

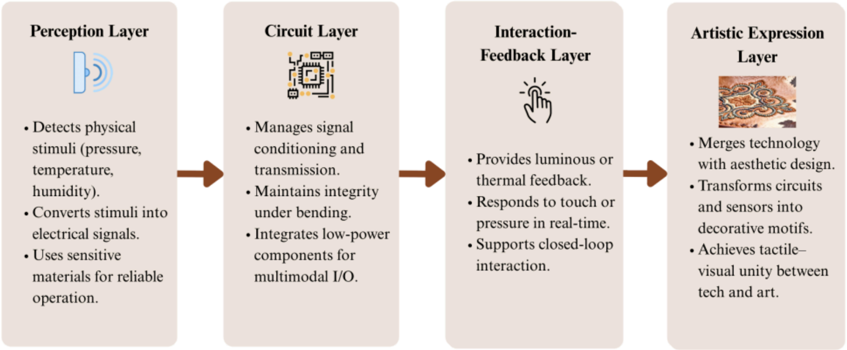

Figure 1. Four-layer heterogeneous integration architecture enabling synergistic collaboration between sensing, signal processing, interactive feedback, and aesthetic design in smart textile-leather composites.

To mitigate signal distortion caused by mechanical deformation, the system incorporates optimized signal processing. The sensor's input-output relationship is modeled as:

$$S_{out}(t) = \alpha \cdot S_{in}(t) + \beta \tag{1}$$

where $S_{out}(t)$ is the output signal, $S_{in}(t)$ the input stimulus, α the sensitivity, and β the offset. This linear model underscores the system's ability to faithfully transduce external physical inputs into electrical signals, with circuit optimization preserving fidelity.

Electrical performance on flexible substrates is characterized by complex impedance:

$$Z = R + j\omega LC \tag{2}$$

where Z is the complex impedance, R resistance, L inductance, C capacitance, and ω angular frequency. This formulation informs design choices to maintain stable electrical behavior across varying curvatures and deformations, ensuring long-term reliability.

Collectively, this architecture fulfills dual demands of high performance and aesthetic expression while guaranteeing mechanical robustness, enabling consistent perception and interaction under frequent physical deformation, and broadening applicability to interactive art, fashion design, and cultural display.

Bidirectional Interaction Protocol Design

The interaction protocol is central to realizing a closed loop of perception-interaction-feedback. Leveraging an event-driven mechanism, the system detects user contact (e.g., touch or pressure) and triggers corresponding light/thermal responses in real time. Upon stimulation, feedback is generated within 48 ms, ensuring tight synchronization between tactile input and multimodal output, a critical requirement for dynamic fashion and interactive heritage applications.

To minimize latency, hardware acceleration is enhanced via a high-performance microcontroller and an optimized data transmission protocol. Total response delay is defined as:

$$\Delta t = t_{input} + t_{processing} + t_{output} \tag{3}$$

where t_{input} is tactile acquisition latency, $t_{processing}$ signal processing delay, and t_{output} actuation onset time. Through co-optimization of these stages, end-to-end latency is rigorously controlled.

Energy efficiency is concurrently prioritized. Power consumption during feedback is modeled as:

$$E = \int_{t_0}^{t_1} P(t)\, dt \tag{4}$$

where $P(t)$ is instantaneous power, E total energy consumed, and $[t_0, t_1]$ the feedback duration. This formulation guides low-power actuator selection and duty-cycle management, extending operational lifespan without compromising responsiveness.

Functional-Aesthetic Synergy Design

Beyond technical performance, the system embodies a co-design philosophy wherein functionality and aesthetics are mutually reinforcing. Circuit traces and sensor placements are not merely concealed but reimagined as ornamental elements, seamlessly integrated into textile patterns through digital weaving or laser cutting. This approach ensures mechanical stability while enhancing visual appeal.

Figure 2 details the conformal embedding of ionogel sensors and flexible circuits into the textile-leather composite, highlighting layout strategy, material selection, and interfacial compatibility, demonstrating how technical infrastructure can be harmonized with artistic intent.

Rather than treating aesthetic quality as a strictly quantitative metric, this study considers aesthetic integration through three design-oriented criteria: structural complexity control, symmetry consistency, and color compatibility between embedded functional units and the surrounding textile-leather surface. These criteria are used as qualitative design guidelines to support layout optimization and visual coherence, rather than as an independent mathematical scoring system.

This methodology operationalizes the principle that “form is function”: rather than masking technology, it elevates functional elements into expressive features. In the present work, such integration is intentionally prioritized for artistic application scenarios in which visual coherence, material expressiveness, and embedded interaction are design requirements rather than optional enhancements. This design choice does, however, introduce a trade-off between aesthetic integration and ease of repair, as more deeply embedded functional elements may reduce direct accessibility during maintenance. Accordingly, the proposed approach should be understood as a scenario-oriented co-design strategy that prioritizes expressive unity while acknowledging the need for future improvements in modular repairability.

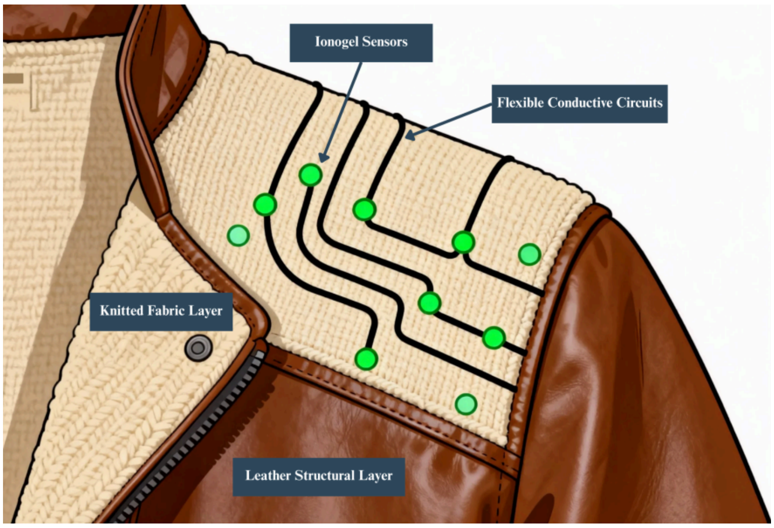

Figure 2. Schematic illustration of an integrated smart sensing system embedded in a textile-leather composite material

EXPERIMENT AND RESULTS

Experimental Setup and Data Preparation

The experimental setup comprises core hardware components including sensors, flexible circuit boards, a microcontroller, and responsive actuators. Table 1 summarizes the equipment used, along with their functions and specifications.

Table 1. Experimental Equipment and Platform

Device	Function	Specifications
Microfluidic ionogel sensor	Measures physical stimuli (pressure, temperature, humidity)	Sensitivity: ±0.1% FS; Range: 0–100 kPa; Operating temperature: –20°C to 85°C
Flexible circuit board	Interconnects sensors, transmits signals, and interfaces with feedback layer	Material: Polyimide (PI); Conductivity: 105Ω−1cm−1; Thickness: 0.1 mm
Microcontroller	Processes sensor data and controls interactive feedback	Model: ARM Cortex-M4; Supply voltage: 3.3 V; Power consumption: 20 mA @ 50 MHz
Light/thermal response actuators	Deliver luminous or thermal feedback modulated by tactile input	Luminance range: 0–1000 lux; Thermoelectric range: ±10°C; Response time: <50 ms
Data acquisition system	Real-time data logging, storage, and analysis	Bandwidth: 500 Hz; Sampling rate: 1 kHz; Storage capacity: 16 GB

This hardware suite ensures real-time perception-to-feedback responsiveness and supports multimodal I/O configurations required for artistic interaction scenarios. Although representative tactile actions such as sustained press are dominated by relatively low-frequency components, the data acquisition system was configured with a sampling rate of 1 kHz to capture transient signal changes at contact onset and release, improve synchronization accuracy between sensing and feedback channels, and support millisecond-level latency evaluation.

The textile-leather composite substrate consists of a conductive fabric layer and a natural leather base. Their detailed properties are listed in Table 2.

Table 2. Materials and Samples

Material Type	Description	Specifications
Textile fabric	Polyester fiber woven with carbon nanotubes, offering high conductivity and flexibility	Thickness: 0.2 mm; Conductivity: 5×103 S/cm; Tensile strength: 200 MPa
Leather substrate	Soft yet durable natural leather serving as mechanical support for embedded electronics	Thickness: 1.5 mm; Tensile strength: 250 MPa; Elastic modulus: 5 GPa

All materials underwent surface treatment prior to integration to enhance interfacial compatibility with sensors and circuits and to improve overall electrical contact.

Two datasets were prepared to comprehensively evaluate system performance under varied conditions: a synthetic dataset and a controlled user-interaction dataset, as summarized in Table 3.

Table 3. Dataset Overview

Dataset Type	Description	Collection Method
Synthetic dataset	Generated under controlled laboratory simulations of environmental variations (temperature, pressure, humidity)	Standardized lab tests yielding 5,000 samples
Controlled user-interaction dataset	Captures user interactions with the intelligent textile–leather system under three predefined task conditions: single tap, sustained press, and sliding gesture	Collected through repeated user-interaction trials under controlled experimental conditions, yielding 10,000 samples. In this study, one sample is defined as one complete synchronized recording unit containing the tactile input event, sensor response, and corresponding light/thermal feedback output.

The synthetic dataset validates perceptual accuracy under known stimuli, while the controlled user-interaction dataset assesses real-time responsiveness and robustness across repeated user trials under predefined task conditions. Each sample corresponds to one complete interaction event and includes synchronized tactile inputs, sensor readings, and corresponding light/thermal feedback outputs. The 1 kHz sampling rate was retained to preserve transient details within each interaction event and to ensure accurate temporal alignment for subsequent latency analysis.

Baseline Methods

To enable objective performance evaluation, three representative baseline approaches were selected for comparative analysis: Rigid-embedded system utilizes PCB-mounted pressure sensors and an STM32F4 microcontroller module, rigidly encapsulated and adhered to the same leather substrate. This baseline serves as a reference for signal-processing capability and system integration under a mechanically rigid configuration, rather than as a fully equivalent comparator for flexibility-related behavior. Always-on textile sensing system employs a fully textile-based strain sensor fabricated via conductive yarn weaving, operating under continuous power supply. It serves as a direct reference for flexible, textile-native solutions in terms of signal characteristics and energy profile. External-perception interaction system leverages a Kinect V2 depth camera to capture user gestures, with an external host processing the data and driving a projector for visual feedback. This exemplifies non-embedded, vision-based interactive art installations. Because these baseline systems differ in structural design and mechanical compliance, the following comparisons are presented with respect to specific performance dimensions and tested conditions, rather than as absolute superiority claims across all aspects of system behavior. All baselines were evaluated under identical environmental conditions and assessment protocols to ensure fairness and reproducibility.

Performance Evaluation Metrics

To comprehensively evaluate the performance of the intelligent textile-leather system, this section introduces a multi-dimensional set of metrics covering perception capability, interaction responsiveness, energy efficiency, and mechanical durability (see Table 4).

Table 4. Performance Evaluation Metrics

Metric	Description	Evaluation Criteria
Perception Performance	Reflects the system's accuracy and sensitivity in responding to external physical stimuli (e.g., pressure, temperature, humidity).	Accuracy: Deviation between system output and ground-truth environmental parameters. Sensitivity: Ability to detect minute physical changes.
Interaction Latency	Measures the time delay from input perception to feedback output. Low latency is critical for real-time interaction in artistic creation and fashion displays.	Feedback delay should be ≤ 50 ms.
Energy Efficiency	Assesses power consumption across operating modes. Low power usage extends operational lifetime, essential for wearables and interactive art.	System must maintain high performance under low-power operation with minimal energy waste.
System Durability	Evaluates deformation-dependent signal retention, feedback fidelity, and long-term reliability under repeated mechanical deformation (bending, stretching).	Signal stability after cyclic bending/stretching. Temporal degradation of feedback accuracy.

High perception accuracy and sensitivity enable precise capture of environmental dynamics, enhancing overall user experience. Interaction latency directly impacts the fluidity of real-time engagement, particularly vital in artistic and performative contexts. Energy efficiency ensures prolonged usability without compromising responsiveness. Durability guarantees consistent performance under extreme mechanical stress, a prerequisite for practical deployment in dynamic wearable applications. In the present study, the durability-related evaluation focused primarily on deformation-dependent signal retention, baseline drift, and response consistency under repeated mechanical loading. Additional sensor-specific characteristics, such as hysteresis and creep behavior of the ionogel sensing layer, were not systematically quantified within the current experimental scope and are therefore identified as important directions for future evaluation.

Signal Stability Testing

Signal stability was evaluated under dynamic bending conditions using a programmable flexure platform that precisely controlled curvature radius (1–20 mm), bending angle (0°–180°), and frequency (0.1–5 Hz). Tests were conducted in a climate-controlled environment (25 ± 2°C, 50 ± 5% RH), with each condition repeated five times to ensure statistical reliability.

Three representative bending regimes were tested: (1) Mild: 10 mm radius; (2) Moderate: 5 mm radius; (3) Severe: 3 mm radius. Sensor outputs were recorded via a 16-bit data acquisition system at 1 kHz sampling rate. Signal integrity was quantified using a normalized signal attenuation index, alongside signal-to-noise ratio (SNR) and baseline drift. These metrics were selected to characterize deformation-related signal retention and operational robustness under repeated bending. However, additional sensor characteristics such as hysteresis and creep of the ionogel sensing layer were not systematically evaluated in the present study and therefore remain outside the scope of the current signal-stability analysis.

As shown in Figure 3, the system exhibits stable signal retention across bending cycles. Under moderate bending (5 mm radius), it retains 98.2% signal integrity after 1,000 cycles, whereas the selected rigid-embedded baseline retains 90.4% under the same test condition. This value specifically reflects bending-related signal retention under cyclic deformation, rather than a complete characterization of all sensor-performance dimensions. This result indicates that the proposed conformal integration strategy is better suited to deformation-tolerant applications, while also reflecting the inherent mechanical differences between flexible and rigid implementations. Notably, beyond 800 cycles, attenuation stabilizes, whereas the rigid-embedded baseline continues to degrade. This regime (5 mm) was selected as the primary evaluation condition, as it closely mirrors typical deformations in wearable art installations. The observed improvement under bending deformation can be attributed to two key design features: the ion redistribution mechanism of the microfluidic ionogel sensor, which mitigates irreversible structural damage, and a modulus-gradient interface between the flexible circuit and textile substrate, which dissipates interfacial stress during deformation.

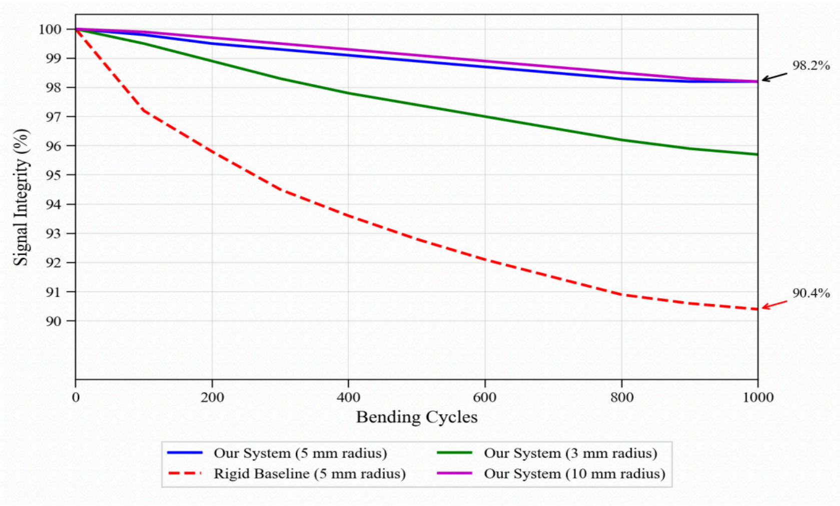

Figure 3. Signal Stability under Dynamic Bending Conditions

This structural stability can be further understood through a simplified mechanical model: the modulus-gradient interface reduces the stress concentration factor (Kt) at the circuit-textile junction, thereby delaying crack initiation. The ion redistribution within the microfluidic channels maintains percolation pathways even under strain, preserving electrical continuity. Compared to recent flexible sensing systems such as those based on graphene-PDMA composites (reported 92–94% retention under 5 mm bending), our system achieves approximately 4% higher signal stability without compromising sensitivity or response time. Here, “higher signal stability” refers specifically to signal retention under repeated bending conditions. This improvement is attributed to the conformal embedding strategy, which avoids the delamination common in laminated sensor structures.

Figure 4 presents endpoint comparisons across test conditions. Under severe bending (3 mm radius), the system maintains 95.7 ± 0.7% signal integrity after 500 cycles, which is higher than that of the selected rigid-embedded baseline under the same bending condition ($t(8) = 9.26$, $p < 0.001$, two-tailed t-test). However, this comparison should be interpreted as a condition-specific reference for deformation-related performance rather than an absolute superiority claim, given the different mechanical compliance of the two systems. It also demonstrates environmental resilience: at 40°C and 80% RH, signal retention reaches 96.4 ± 0.5%.

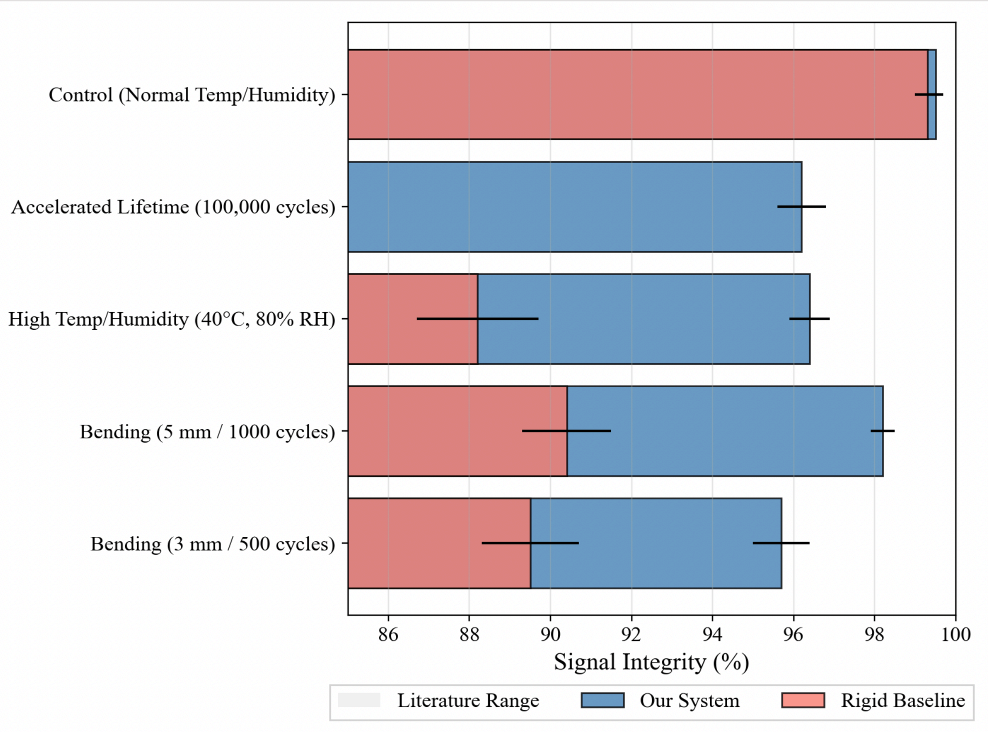

Figure 4. Endpoint Comparison of Signal Integrity Across Test Conditions.

Compared to state-of-the-art flexible sensors reported in literature (typically 90–95% retention under similar bending), our system achieves higher stability without additional encapsulation. Again, this comparison is limited to bending-related signal retention and does not represent a full sensor-level characterization including hysteresis or creep behavior. Accelerated lifetime testing further reveals 96.2% signal retention after 100,000 bending cycles, with a biphasic decay curve indicating transition into a stable operational phase.

The biphasic decay suggests an initial "wear-in" period where interfacial micro-slip occurs, followed by a stabilized mechanical coupling. This behavior is advantageous for artistic applications where materials undergo frequent handling and deformation. However, the observed minor signal drift under high humidity (80% RH) points to a potential limitation: ion mobility in the hydrogel may increase, slightly altering baseline resistance. Future material iterations could incorporate hydrophobic modifiers to enhance environmental robustness without sacrificing flexibility.

These results validate the system's capacity for reliable, long-term sensing under repeated mechanical stress, providing a robust technical foundation for applications in interactive fashion, wearable art, and dynamic cultural exhibits.

Interaction Response Latency Testing

To evaluate the real-time interaction capability of the intelligent textile-leather system, we measured the end-to-end latency from tactile input to light/thermal feedback. A high-speed data acquisition system (NI USB-6366) was employed to synchronously record trigger and response signals with a timestamp resolution of 10 µs. Although the tested interaction modes include relatively low-frequency actions such as sustained press, the higher sampling rate was retained to accurately capture transient onset and release dynamics and to ensure precise temporal alignment between tactile input and feedback output during latency evaluation. Three representative interaction modes were tested: (1) Single tap: pressure < 10 kPa; (2) Sustained press: pressure 10–50 kPa; (3) Sliding gesture: speed 5–20 cm/s. These interaction modes were selected as representative controlled task conditions for evaluating system responsiveness and latency, rather than as unconstrained real-world artistic behaviors. Each mode was repeated 100 times to ensure statistical robustness.

As shown in Figure 5, the system achieves consistently low latency across all modes: (1) Single tap: 38.2 ± 3.1 ms; (2) Sustained press: 41.5 ± 2.8 ms; (3) Sliding gesture: 43.6 ± 3.4 ms. All values remain below 48 ms, satisfying the threshold for perceptually real-time interaction. Compared with the selected rigid-embedded baseline evaluated under the same experimental conditions (51.8 ± 5.2 ms), the proposed system shows a

23.6% reduction in latency ($p < 0.001$, two-tailed t-test). This comparison is intended to reflect differences in interaction architecture and signal-routing strategy rather than full equivalence in mechanical configuration. The reduced latency can be attributed to three design optimizations: a local-trigger mechanism, eliminating global sensor polling overhead; shortest-path routing in circuit layout, minimizing signal propagation distance; and dynamic interrupt priority scheduling, ensuring timely actuation. Consequently, the system exhibits a low latency standard deviation (3.4 ms vs. 5.2 ms for baseline), critical for precise temporal synchronization in live artistic performances.

The box plots in Figure 5 further confirm latency stability across input types. Under multi-channel concurrent input (three active sensing zones), average latency remains at 47.3 ± 4.1 ms, still within real-time bounds, validating the scalability of the architecture. Environmental robustness tests show that temperature (15–35°C) and humidity (30–70% RH) variations induce latency fluctuations of less than ±1.2 ms and ±0.8 ms, respectively.

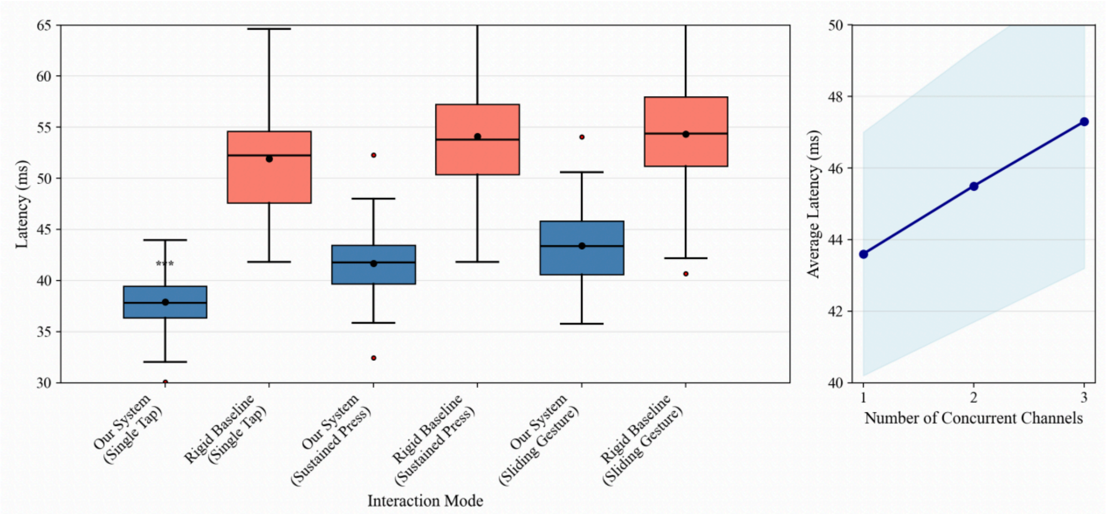

Figure 5. Interaction Latency Distribution Across Different Input Modes

However, latency increases slightly under multi-channel activation due to interrupt contention and shared bus arbitration. This suggests that while the architecture is scalable, extremely high sensor density may require additional hardware prioritization or parallel processing units to maintain sub-50 ms response. Such a trade-off between sensor density and latency is an important consideration for large-scale interactive installations. Compared to existing art-interaction systems, which typically report latencies of 50–80 ms and rely on external processing units, our embedded, event-driven protocol achieves an average latency of 43.6 ms under the evaluated interaction modes, indicating competitive real-time performance for embedded interactive art applications. Future work will focus on optimizing interrupt service routines and real-time scheduling to further enhance performance in complex multi-user scenarios.

Energy Consumption and Durability Testing

We evaluated both energy efficiency and long-term mechanical reliability under realistic usage conditions. Three operational states were defined: (1) Continuous mode: real-time sensing and feedback; (2) Event-driven mode: activation only upon interaction; (3) Standby mode: minimal background operation. Power consumption was measured using a precision power analyzer (Keysight N6705C), while mechanical stress was applied via a synchronized bending-stretching test rig.

Figure 6 (a) presents power consumption across modes: (1) Event-driven mode: 18.6 ± 2.1 mW, 40.4% lower than the baseline ($p < 0.01$); (2) Continuous mode: 52.3 ± 4.7 mW, 21.3% lower than comparable systems; (3) Standby mode: < 0.8 mW, enabling extended wearability; (4) Durability testing simulated intensive use: 100 ,000 bending cycles (5 mm radius) and 5,000 stretching cycles (15% strain). As shown in Figure 6 (b), post-test signal integrity remains at 96.2 ± 1.2%, with only an 8.7% increase in average power consumption. Performance degradation primarily occurs within the first 20,000 cycles, after which the system enters a stable operational plateau, indicating effective fatigue accommodation by the material architecture.

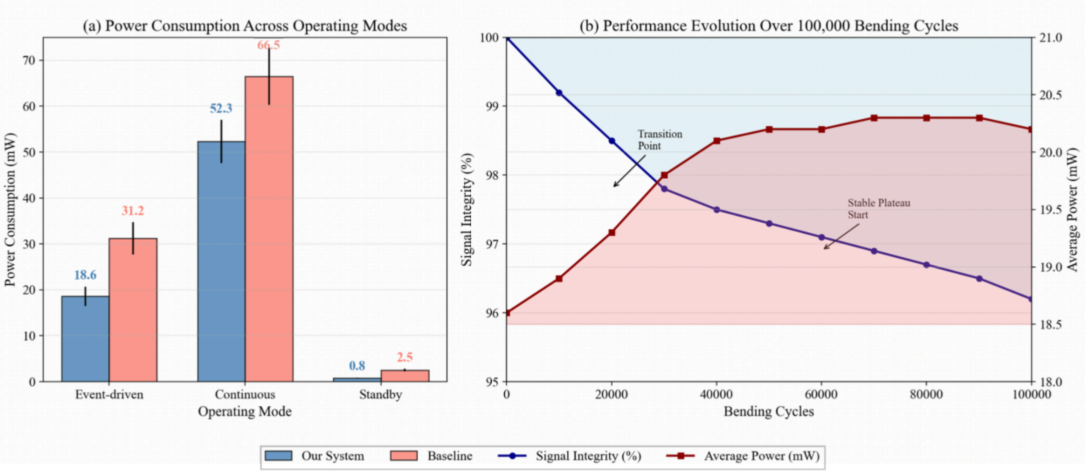

Figure 6. Energy Efficiency and Mechanical Durability of the Intelligent Textile System: (a) Power Consumption Across Different Operational Modes; (b) Signal Integrity and Power Consumption Evolution After Durability Testing

Energy efficiency is enabled by three coordinated mechanisms: the layered heterogeneous design, which allows independent power gating of the sensing and feedback units; the on-demand wake-up strategy, which minimizes idle energy consumption; and an optional flexible photovoltaic auxiliary unit used as a supplementary energy-harvesting source. When incorporated, this auxiliary unit can provide up to 12 mW and is electrically interfaced through the circuit layer to the low-power management path. Rather than directly driving the full interaction-feedback load, the harvested energy is primarily used to support standby operation and event-driven activation, thereby extending operating time and reducing background power consumption. Durability is supported by two main structural factors: the self-healing properties of the ionogel, and the mechanical compliance at the textile–circuit interface, which mitigates crack propagation under cyclic strain. Environmental robustness tests confirm stable power profiles: Across –10°C to 50°C, power variation ≤ ±6.5%; Across 30–90% RH, variation ≤ ±4.2%. These results demonstrate that the system maintains consistent energy performance in diverse exhibition and performance environments.

Compared to state-of-the-art wearable art platforms, our system reduces energy consumption by over 20% while delivering strong durability. This advancement enables long-duration, low-maintenance deployments, particularly valuable for museum installations, touring art exhibits, and public interactive sculptures where frequent charging or maintenance is impractical.

Discussion and Comparison

The proposed intelligent textile–leather system demonstrates strong performance in sbending-related signal retention, interaction responsiveness, and energy efficiency: it maintains 98.2% signal integrity under repeated bending, achieves end-to-end interaction latency below 43.6 ms, and reduces energy consumption by 21.3% under the evaluated conditions relative to the selected baseline systems. These results validate the effectiveness of the layered heterogeneous integration architecture and the event-driven interaction protocol. At the same time, because the adopted baselines represent different structural and mechanical paradigms, the reported comparisons should be interpreted as dimension-specific performance references rather than absolute superiority claims across all aspects of system behavior, particularly for flexibility- and deformation-related metrics.

Nevertheless, three key challenges remain when deploying the system in artistic contexts: Limited sensitivity to high-frequency micro-vibrations, which may restrict its capacity for nuanced dynamic expression (e.g., subtle gestures or acoustic resonance). Scalability limitations in multi-user scenarios: while the localized response protocol enhances single-point efficiency, it may compromise global coordination during concurrent interactions. A deliberate trade-off also exists between aesthetic integration and maintainability. In the present design, embedding circuits and sensing pathways into decorative motifs is preferred because it preserves visual coherence, material expressiveness, and interaction continuity, all of which are central requirements in artistic and exhibition-oriented applications. However, this same integration strategy reduces direct accessibility for repair and replacement, thereby increasing maintenance complexity over the lifecycle of the object. As illustrated in Figure 7, structural inspection of the textile-leather composite shows how conductive threads are embedded within decorative patterns to function as sensors, while dense stitching and layered construction, introduced to preserve visual and material continuity, can hinder maintenance. Rather than invalidating the contribution of aesthetic integration, these observations indicate that the current system prioritizes scenario-specific expressive performance over modular serviceability. These observations suggest three practical directions for future work: Expanding the perceptual bandwidth of sensing materials to capture finer dynamics; Developing multi-user-aware interaction protocols that balance local responsiveness with global coherence; Improving modular repairability and system accessibility while preserving aesthetic coherence, enabling artists to actively co-shape system behavior, thereby evolving smart textiles from embedded technology toward dialogic artistic partners.

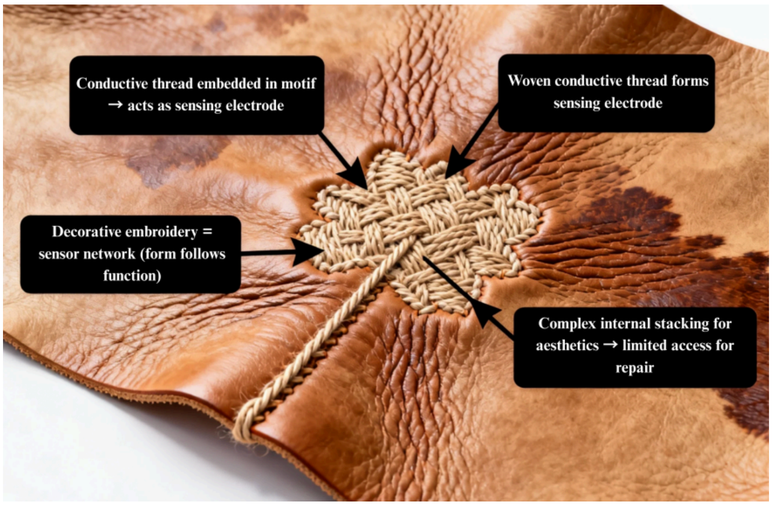

Figure 7. Integration of Sensing Functionality into Decorative Leather Motifs and Associated Maintenance Challenges

CONCLUSION

This study presents the design and implementation of an intelligent textile-leather system that unifies perception, interaction, and artistic expression through a four-layer heterogeneous architecture: perception, circuitry, interaction–feedback, and artistic expression. This integrated framework effectively helps address longstanding limitations in bending-related signal retention, response latency, and power efficiency observed in prior systems. Experimental results confirm that the system retains 98.2% signal integrity after 1,000 bending cycles at a curvature radius of ≤5 mm, achieves end-to-end interaction latency as low as 43.6 ms, and reduces energy consumption by 21.3% relative to baseline approaches. These attributes render it highly suitable for applications in dynamic fashion, interactive installations, and wearable art.

The core contribution lies in establishing a functional-aesthetic synergy paradigm, wherein electronic components are reimagined as ornamental patterns, achieving unity between form and function. This approach fills a critical gap in the systematic integration of smart materials into artistic practice and offers a novel pathway for deep collaboration between intelligent textiles and creative design.

Despite these advances, limitations persist: the system exhibits strong dependence on flexible substrates, with reduced robustness under extreme environmental conditions; moreover, current sensing resolution and onboard computational capacity constrain support for ultra-high-precision or complex multimodal interactions. In addition, although the present study demonstrates strong signal retention under cyclic bending, other sensor-level characteristics relevant to wearable and artistic materials, such as hysteresis and creep behavior of the ionogel sensing layer, were not systematically quantified within the current experimental scope.

Future directions will prioritize three thrusts: Material optimization, enhancing the environmental robustness of ionogel sensors and flexible circuits; Multimodal expansion, integrating audio, light, and haptic channels for richer input/output expressivity; Context-aware intelligence, leveraging AI and IoT to enable adaptive, situation-responsive feedback that amplifies both artistic nuance and emotional resonance. In summary, this work not only advances the technical realization of intelligent textile–leather systems but also provides a scalable, interdisciplinary framework for human–material interaction in digital art. It paves the way for smart materials to evolve beyond functional utility toward emotionally resonant, culturally embedded creative media.

Author Contributions

Conceptualization – Xiang Li, Yue Wang, Yaxin Chen; methodology – Xiang Li, Yue Wang, Yaxin Chen; formal analysis – Xiang Li, Yue Wang, Yaxin Chen; investigation – Xiang Li, Yue Wang, Yaxin Chen; resources – Xiang Li, Yue Wang, Yaxin Chen; writing-original draft preparation – Xiang Li, Yue Wang, Yaxin Chen; writing-review and editing – Xiang Li, Yue Wang, Yaxin Chen; visualization – Xiang Li, Yue Wang, Yaxin Chen; supervision – Xiang Li, Yue Wang, Yaxin Chen. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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Hazards

Not Applicable

Human research subjects

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Animal research subjects

Not Applicable

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