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Augmented Reality System with Flexible Electronic Skin for Intangible Cultural Heritage Preservation: A Case Study of Hong Kong Yu Lan Festival

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Abstract

This study presents an innovative multisensory augmented reality (AR) system integrated with flexible electronic skin technology to address the challenges of preserving intangible cultural heritage (ICH), focusing on the Hong Kong Yu Lan Festival. The system combines AR's contextual reconstruction capabilities with customizable haptic feedback to recreate immersive cultural experiences. By simulating tactile sensations such as ritual implement vibrations and incense temperature variations, the technology bridges the gap between traditional practices and modern digital preservation methods. The modular design of the electronic skin allows for adaptable wearability, while AR enhances visual and auditory immersion. This research contributes a scalable framework for ICH preservation, with potential applications in other tactile-dependent cultural practices worldwide.

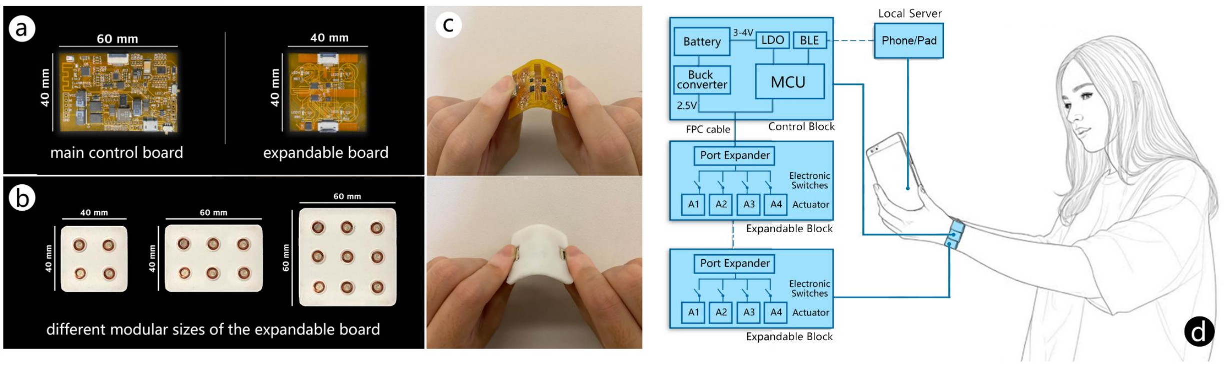

Figure 1. Flexible electronic skin and its characteristics (a) Main control board (left) and multiple expandable boards (right) of the device. (b) Three different modular sizes of the expandable board. (c) The electronic devices have properties similar to physical skin. (d) System architecture diagram

1. Introduction

1.1 Research Background

As a traditional festival integrating religious rituals, community culture, and performing arts (Chan, 2015, 2018), the core value of Hong Kong Yu Lan Festival resides not only in its material manifestations like ceremonial procedures and ritual operas, but more crucially in participants' multisensory immersion and emotional connections. The festival's rituals, such as incense offerings and ritual operas, are deeply rooted in the collective memory of Hong Kong's Chaozhou community, serving as a bridge between generations. However, rapid urbanization and shifting societal values have disrupted these traditions, leading to a decline in active participation, particularly among younger demographics. Studies indicate that part of Hong Kong's youth perceive traditional rituals as outdated or irrelevant, citing a lack of interactive engagement (Chan et al., 2023). This disconnection threatens the sustainability of intangible cultural heritage (ICH), as the essence of Yu Lan Festival lies not in static observation but in dynamic, multisensory participation.

Current digital preservation methods predominantly rely on 2D recordings or static models, failing to recreate dynamic ritual interactions and tactile perceptions, resulting in inefficient transmission of cultural essence. For instance, archival videos of ritual operas capture visual and auditory elements but omit the tactile feedback of holding ritual implements or the warmth of incense burners. This sensory gap undermines the emotional resonance of the festival, reducing it to a passive spectacle rather than an immersive experience.

Flexible electronic skin, as a wearable customized haptic feedback device, simulates vibration intensity and frequency to generate multi-level epidermal pressure, enabling precise transmission of physical interaction realism. Recent advancements in wearable technology, such as skin-integrated electronics (Yu et al., 2019), have demonstrated the potential to replicate complex tactile sensations, from subtle vibrations to pressure gradients. When integrated with AR's contextual reconstruction capabilities, this technology can transcend spatiotemporal constraints to revitalize cultural scenarios through virtual-physical integration. For example, AR can overlay virtual altars in real-world environments, while electronic skin simulates the tactile feedback of ritual actions, such as striking a gong or handling ceremonial objects. Focusing on the preservation needs of Yu Lan Festival, this study proposes an AR system framework based on customized electronic skin, exploring innovative approaches for ICH transmission through tactile-visual-auditory multisensory synergy.

1.2 Research Problem

1.2.1 Multidimensional Expression of Cultural Symbols

The Hong Kong Yu Lan Festival embodies profound cultural significance through multidimensional rituals and activities (Chan et al., 2023). Religious ceremonies, such as the "Feeding the Hungry Ghosts" ritual, are not merely performances but acts of spiritual communion, reflecting Confucian values of filial piety and ancestral veneration. Community-driven activities, like the distribution of "Peace Rice," reinforce social cohesion by fostering reciprocity among neighbors—a practice increasingly rare in modern urban settings. Meanwhile, the Shengong opera, a fusion of Cantonese opera and puppetry, preserves traditional artistry while adapting to contemporary tastes. These elements collectively form a rich tapestry of cultural symbols, each requiring nuanced preservation strategies.

1.2.2 Transmission Challenges and Requirements

The festival's transmission faces multifaceted challenges in evolving social contexts. Younger generations often perceive rituals as inaccessible due to their complexity and lack of interactivity. Current digital archives, such as the Hong Kong Heritage Museum’s Yu Lan exhibition, prioritize visual documentation but neglect tactile and proprioceptive feedback, which are critical for authentic ritual replication (Hou et al., 2022). For instance, the act of offering incense involves not only visual and olfactory cues but also the tactile sensation of holding and placing incense sticks—a detail lost in conventional digitization. Modern lifestyle-context disjunction further exacerbates the issue, as rituals are increasingly performed as symbolic gestures rather than meaningful practices.

These challenges necessitate a core solution: reconstructing immersive multisensory experiences in the digital age to integrate Yu Lan's spiritual essence into contemporary cultural memory. A "tactile-first" approach, combining AR with electronic skin, could bridge this gap by enabling users to physically interact with virtual ritual elements, thereby fostering deeper emotional connections.

1.3 Main Contributions

As a Chinese national-level ICH element, Yu Lan Festival's tactile ritual practices face a transmission crisis. This study pioneers a "tactile-first" digitization strategy, providing scalable solutions for global ICH elements with tactile semantics (e.g., Chinese water-splashing festival, Korean Gangneung Danoje Festival). Our research advances beyond single-sensory digitization through dual innovations:

1.3.1 Theoretical

Establishes a new technological paradigm for multisensory interaction in ICH preservation, expanding cultural heritage digitization boundaries. By integrating haptic feedback with AR, we redefine how ICH is experienced and transmitted, moving from passive observation to active participation.

1.3.2 Practical

Provides replicable solutions for dynamic ritual-based ICH transmission, particularly effective for scenarios requiring enhanced tactile engagement and community connectivity. For example, our modular electronic skin design can be adapted to other tactile-dependent rituals, such as Japanese tea ceremonies or Balinese dance.

2. Collaborative Innovation of Customized Electronic Skin and AR Technology

In this paper, we propose a multisensory immersive AR system integrating customized flexible electronic skin with AR technology for ICH digitization. The system represents a paradigm shift in cultural heritage preservation by bridging the gap between virtual representations and physical interactions. By leveraging advancements in flexible electronics and augmented reality, our approach addresses the limitations of traditional preservation methods, which often fail to capture the tactile and participatory dimensions of intangible cultural heritage.

2.1 Customized Electronic Skin Design

Our hardware implementation features MEMS-based actuator-integrated flexible electronic device, with 10mm-diameter, 2.5mm-thick actuators conforming to palm curvature to simulate paper craft deformation vibrations (0-200Hz frequency response). The actuator design was optimized through iterative testing to ensure fidelity in replicating the subtle vibrations associated with ritual implements, such as the tremors of burning incense or the reverberations of ceremonial gongs. Compared to traditional ERM motors, this design reduces energy consumption, enabling extended cultural experiences without compromising performance.

Utilizing skin-integrated electronics (Yu et al., 2019; Huang et al., 2023), the device wirelessly transmits sensory stimuli through vibration actuators. The wireless communication protocol, based on Bluetooth Low Energy (BLE), ensures low latency and robust connectivity, critical for real-time haptic feedback in dynamic AR environments. The flexible substrate integrates electronic components (circuits, chips, electrodes) to mimic skin properties like stretchability and deformability (see Figure 1). Key innovations in the substrate material include a hybrid polymer-silicone composite, which balances mechanical flexibility with electronic durability, ensuring the device withstands repeated use in diverse environmental conditions.

2.1.1 Environmental Adaptability

Lightweight, breathable materials ensure long-term wear comfort, suitable for outdoor activities. The material selection was informed by ethnographic studies of Yu Lan Festival participants, who often engage in prolonged rituals under varying weather conditions. The device’s moisture-wicking

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properties and UV-resistant coating further enhance its suitability for outdoor cultural events.

2.1.2 Multisensory Feedback

Synchronized rendering of visual, auditory, and tactile sensations enhances user immersion and presence during AR-based intangible cultural heritage experiences. Our system employs a proprietary algorithm to dynamically adjust feedback intensity based on user proximity to virtual objects. For example, the tactile feedback intensifies as users approach a virtual altar, creating a gradient of sensory engagement that mirrors real-world ritual dynamics.

2.1.3 Modular Tactile Feedback

Tailored to the interaction scenarios of the Yu Lan Festival (e.g., holding incense, striking gongs), flexible electronic skin modules are designed to fit different body parts (palms, arms), supporting independent vibration intensity and frequency control for high-fidelity multisensory feedback (see Figure 2). The modular design allows for rapid customization, enabling the system to adapt to other cultural heritage contexts with minimal hardware modifications. Each module features a magnetic coupling mechanism for easy attachment and reconfiguration, ensuring seamless integration with user movements.

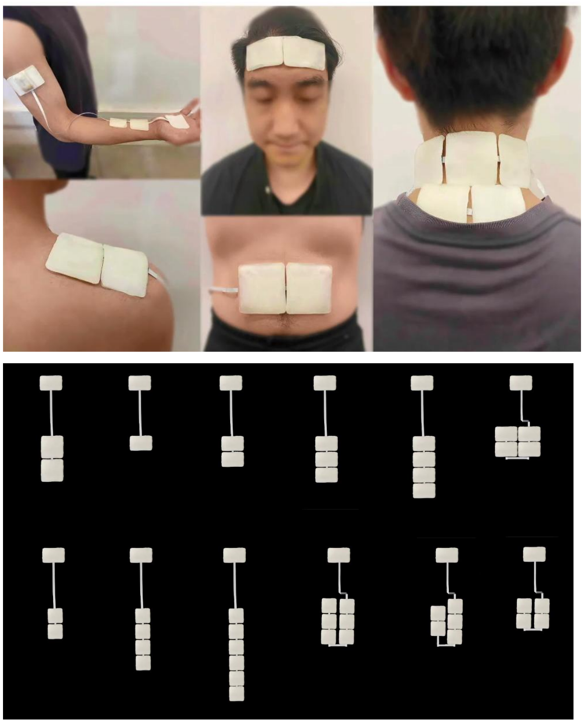

Figure 2. Modular design enables flexible vibration equipment to be worn in different positions of the body

2.2 Multisensory Fusion of AR and Haptic Feedback

2.2.1 System Integration: We employ photogrammetry and structured light 3D scanning for 3D acquisition, and use 3D reconstruction and modeling technology to process and optimize the model (see Figure 3). The photogrammetry pipeline incorporates machine learning-based texture enhancement to preserve intricate details of ritual artifacts, such as the carvings on incense burners or the embroidery on ceremonial costumes. Structured light scanning, with an accuracy of 0.1mm, ensures geometric precision in virtual reconstructions.

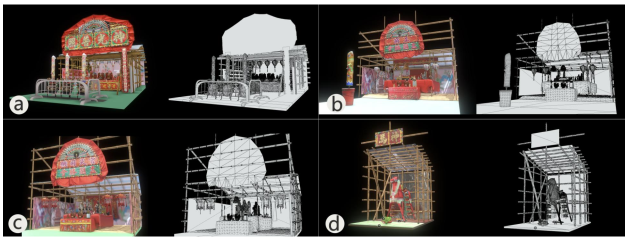

Figure 3. Combining photogrammetry, structured light 3D scanning technology and 3D modeling technology to realize the Yulan Festival shrine model

2.2.2 Virtual-Physical Overlay: Using AR visualization technology, virtual altars and Shengong opera stages are projected into real environments. Users can interact with scenes or artifacts through a UI interface, such as lighting virtual incense or manipulating puppets. The AR overlay employs SLAM (Simultaneous Localization and Mapping) to anchor virtual objects stably in physical space, even in dynamic environments with moving participants. This ensures that virtual rituals remain spatially coherent, enhancing the illusion of presence.

2.2.3 Haptic-Visual Sync: The electronic skin triggers vibration feedback in corresponding regions based on AR events (e.g., drumming, incense offering), such as low-frequency vibrations simulating sutra chanting or high-frequency pulses mimicking gong strikes. The haptic feedback profiles were empirically derived from recordings of actual ritual performances, ensuring anthropological accuracy. For instance, the 15Hz vibration pattern for sutra chanting replicates the rhythmic cadence of monastic recitations.

2.2.4 Soundscape Integration: Environmental audio (e.g., chanting, percussion rhythms) is combined with spatiotemporal tactile feedback to create a multisensory immersive experience. The audio-tactile synchronization is achieved through a temporal alignment algorithm, which dynamically adjusts for latency discrepancies between auditory and haptic channels. This ensures that the strike of a virtual drum, for example, is perceived simultaneously as sound and vibration.

2.3 User-Driven Cultural Co-Creation

2.3.1 Interactive Narratives Design: Users can participate in various activities of the Yu Lan Festival (such as burning incense to honor ancestors, distributing "Peace Rice," and watching Shengong opera) through AR. They can assume different roles (e.g., worshipper, performer) to trigger storylines and interactions with personalized tactile feedback (see Figure 4, 5). The narrative framework is grounded in participatory design principles, with branching storylines adapted from ethnographic interviews with festival practitioners. For example, choosing the role of a "rice distributor" unlocks tactile feedback simulating the weight and texture of rice bags, while the "opera performer" role emphasizes dynamic full-body vibrations synchronized with stage movements.

Figure 4. Digital narratives are used to increase users' understanding of festival-related knowledge.

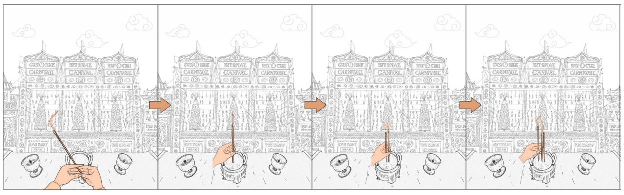

Figure 5. Immersive narrative design storyboard of intangible cultural heritage based on multisensory feedback

2.3.2 Digital Content Generation: Users can record customized ritual processes, with the electronic skin capturing tactile parameters to generate "tactile-visual" digital talismans. The talismans encode haptic signatures as JSON files, enabling interoperability with other AR platforms. Future extensions will integrate blockchain technology to authenticate and trace user-generated content, fostering a decentralized archive of cultural practices. In the future, users can even share these creations on community platforms, forming a chain of cultural dissemination.

3. System Architecture and Implementation

3.1 System Architecture

The proposed multisensory AR system is designed with a modular and scalable architecture to ensure seamless integration of augmented reality (AR) and flexible electronic skin technologies. Built on the Unity engine, the system adopts a layered design philosophy, comprising three core modules: the perception layer, interaction layer, and service layer. This hierarchical structure ensures efficient data flow, real-time processing, and immersive user experiences.

3.1.1 Perception Layer: The perception layer serves as the foundation for data acquisition, capturing real-time environmental and user interaction data through a combination of AR cameras and electronic skin sensors. Key components include:

(1) AR Cameras: Equipped with depth-sensing capabilities, these cameras scan the physical environment to detect surfaces, objects, and spatial anchors. This enables precise virtual object placement and interaction tracking.

(2) Electronic Skin Sensors: Embedded with MEMS-based actuators, these sensors detect user gestures (e.g., hand movements, pressure applied during rituals) and transmit tactile feedback signals. The sensors are calibrated to respond to frequencies ranging from 0–200 Hz, simulating realistic tactile sensations such as incense vibrations or drumbeat impacts.

(3) Environmental Sensors: Additional sensors, such as ambient light and temperature detectors, enhance contextual awareness, allowing the system to adapt feedback intensity based on real-world conditions (e.g., dim lighting in ritual spaces).

Data from these sensors is preprocessed to filter noise and normalize input signals, ensuring robustness in dynamic environments.

3.1.2 Interaction Layer: The interaction layer bridges the physical and virtual worlds by processing user inputs and rendering synchronized multisensory feedback. The layer integrates the following technologies:

- ARCore for Scene Recognition: This framework enables motion tracking, environmental understanding, and light estimation. For example, when a user scans a ritual altar, ARCore identifies planar surfaces and anchors virtual objects (e.g., incense burners) to them.

- Tactile Feedback Logic Engine: A custom-developed driver parses interaction events (e.g., virtual gong strikes) and maps them to actuator commands. The engine supports dynamic adjustment of vibration patterns (intensity, duration, rhythm) to reflect cultural semantics (e.g., sutra chanting = low-frequency pulses).

- Gesture Recognition: Machine learning algorithms classify user gestures (e.g., incense insertion, puppet manipulation) using data from the electronic skin's inertial measurement units (IMUs). This ensures accurate triggering of AR animations and haptic responses.

3.1.3 Service Layer: The service layer orchestrates high-level functionalities, including content management, user analytics, and community features. Notable subsystems include:

(1) Vuforia for AR Content Delivery: This platform hosts 3D models of cultural artifacts (e.g., ritual puppets) and geotagged AR markers. Users access these via a cloud-based repository, ensuring scalability for global audiences.

(2) Cultural Database: A structured knowledge graph stores metadata about Yu Lan Festival rituals (e.g., historical context, procedural steps), enabling context-aware tooltips during AR interactions.

(3) User Profiling: Anonymous analytics track engagement metrics (e.g., time spent in virtual rituals, feedback preferences) to iteratively refine tactile feedback algorithms.

Future iterations will incorporate blockchain technology to authenticate user-generated content (e.g., digital talismans) and foster community co-creation.

3.2 Digital Implementation for Yu Lan Festival

The system’s practical deployment focuses on three immersive scenarios, each addressing distinct aspects of the Yu Lan Festival’s cultural transmission.

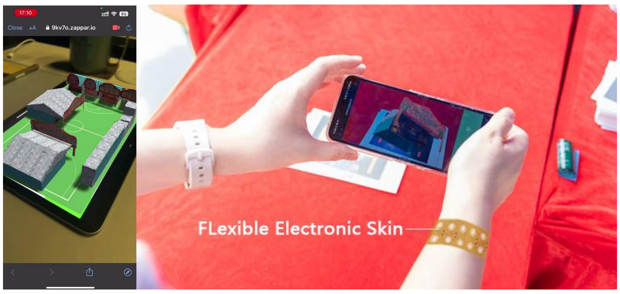

Figure 6. The Concept diagram showcase the AR system based on electronic skin will realize the protection and inheritance of intangible cultural heritage

3.2.1 Virtual Rituals Ceremony: This scenario recreates the incense-offering ritual, a core spiritual practice. Technical implementation details:

(1) Hardware Setup: Users wear electronic skin gloves with palm-mounted actuators (10 mm diameter, 2.5 mm thickness). The actuators’ flexible substrate ensures comfort during prolonged use.

(2) AR Interaction Flow: The AR camera scans the user’s surroundings, identifying a flat surface (e.g., table) as the virtual altar. Users pick a virtual incense stick from a UI menu. Hand-tracking algorithms detect pinch gestures to "grasp" the object. Upon "inserting" the incense into a virtual burner, the palm actuators emit a 120 Hz vibration (mimicking resin crackling), while particle effects render rising smoke.

(3) Cultural Fidelity: The vibration profile is derived from field recordings of actual ritual implements, preserving tactile authenticity.

3.2.2 Shengong Opera Interactive Theater: This module transforms users into performers of traditional Cantonese opera. Key innovations:

(1) Body-Worn Feedback: Electronic skin modules are strapped to limbs and torso. Each module’s actuators are independently controlled to reflect stage actions (e.g., 50 Hz pulses for sword clashes, 180 Hz for drumrolls).

(2) Motion-to-Tactile Mapping: A biomechanical model translates joint angles (from ARKit) into vibration sequences. For leaps, actuators ramp up intensity mid-air to simulate weightlessness.

(3) Dynamic Soundscapes: Binaural audio adjusts based on user position relative to the virtual stage, while haptic feedback reinforces directional cues (e.g., vibrations shift leftward for offstage dialogue).

3.2.3 Community Cultural Map: In the future, we plan to extend the digital experience to offline spaces through a community cultural map. AR navigation guides users to explore historical sites of the Yu Lan Festival, while the electronic skin triggers regional vibrations based on GPS data. For example, when users approach the century-old "Yu Lan Association" site, rhythmic vibrations in the arm module, combined with AR-overlaid historical imagery, create a sense of time travel, using tactile feedback to awaken deep cultural memories.

Ritual Scenario	Core Haptic Experience Requirements	Adapted Electronic Skin Module	Typical Feedback Parameter Examples
Virtual Incense Offering	Slight trembling sensation when holding incense; confirmation feedback when inserting into the burner	**Palm Module**	High-frequency vibration (~100Hz, low intensity); short click (insertion)
Simulating Ritual Instrument Striking	Impact force at the moment of striking; reverberation of the instrument	**Palm Module**	High-intensity pulse (~150Hz, <100ms); low-frequency aftershock
Watching Ritual Opera (Martial Scene)	Physical vibration from gongs and drums; impact transmission from martial movements	**Forearm Module**	Low-frequency resonance (~30-50Hz, synchronized with drum beats)
Receiving "Peace Rice"	Weight sensation of the rice bag landing in the hand; slight squeezing sensation from the grains	**Palm Module**	Medium-intensity sustained vibration (~80Hz, simulating weight); superimposed slight random fluctuations
Community Map Navigation	Proximity-based vibration prompts near historical sites	**Forearm Module**	Regular low-frequency pulses (~25Hz), intensity/frequency varies with distance

Table 1. Key Scenarios of the Yu Lan Festival and Corresponding Haptic Feedback Module Designs

4. Discussion & Limitation

The proposed AR system integrated with flexible electronic skin presents a novel approach to intangible cultural heritage (ICH) preservation, particularly for tactile-rich traditions like the Hong Kong Yu Lan Festival. While the system demonstrates significant potential, several critical discussions and limitations must be addressed to contextualize its contributions and guide future research.

4.1 Technological Feasibility and Scalability

The modular design of the flexible electronic skin allows for adaptability across various cultural scenarios, yet its scalability remains contingent on material durability and manufacturing costs. Current prototypes rely on MEMS-based actuators and skin-integrated electronics, which, while effective, require further optimization for mass production. For instance, the 10mm-diameter actuators, though suitable for simulating ritual vibrations, may need miniaturization for finer tactile feedback in other ICH applications, such as traditional crafts or dance. Future work should explore cost-effective materials and fabrication techniques to ensure broader accessibility, especially for communities in developing regions where ICH preservation is often underfunded.

4.2 User Experience and Cultural Authenticity

The system’s success hinges on its ability to balance technological immersion with cultural fidelity. While multisensory feedback (e.g., synchronized vibrations during incense offerings) enhances engagement, over-reliance on virtual elements risks diluting the ritual’s spiritual essence. For example, the "tactile-visual" digital talismans, though innovative, may not fully replicate the emotional weight of physical artifacts. Ethnographic studies with ritual practitioners could refine feedback parameters to align with authentic sensory experiences. Additionally, longitudinal user testing is needed to evaluate whether the system fosters sustained cultural connection or merely transient novelty.

4.3 Interdisciplinary Collaboration Challenges

The project’s integration of AR, haptics, and cultural studies underscores the importance of interdisciplinary collaboration. However, differences in terminology and methodology between engineers and cultural heritage experts can hinder cohesive design. For instance, engineers may prioritize technical precision (e.g., vibration frequency accuracy), while anthropologists emphasize symbolic meaning (e.g., the cultural significance of gong rhythms). Establishing a shared lexicon and co-creation frameworks, such as participatory design workshops with community stakeholders, could bridge these gaps.

4.4 Ethical and Preservation Paradoxes

Digitizing tactile rituals introduces ethical dilemmas. On one hand, the system democratizes access to ICH; on the other, it may inadvertently commodify or standardize practices that are inherently fluid and context-dependent. For example, AR-guided ritual reenactments could oversimplify regional variations of the Yu Lan Festival. Future iterations must incorporate adaptive algorithms to accommodate cultural diversity and avoid homogenization. Moreover, data privacy concerns arise from user-generated content (e.g., recorded tactile parameters), necessitating robust protocols for ethical data ownership and usage.

4.5 Environmental and Practical Constraints

The system’s reliance on wearable technology poses practical limitations. Extended use of electronic skin in outdoor settings, such as community cultural maps, may be constrained by battery life and environmental factors (e.g., humidity during Hong Kong’s summer festivals). While the current design emphasizes lightweight, breathable materials, real-world deployment requires rigorous testing under varied climatic conditions. Alternative energy solutions, such as solar-powered modules or kinetic energy harvesting, could mitigate these challenges.

5. Conclusion

This study constructs a multisensory digital preservation system for the Yu Lan Festival through the deep integration of customized electronic skin and AR technology, addressing bottlenecks such as the lack of tactile feedback and insufficient participation in traditional methods. Future work will explore multi-sensory extensions of electronic skin (e.g., olfactory simulation) and adapt the framework to more intangible cultural heritage scenarios (e.g., traditional dances, crafts), providing a reusable technical framework for the living transmission of cultural heritage.

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