Augmented Reality Integrated with Flexible Electronic Skin: Multi-Sensory Experience for Digital Inheritance of Hong Kong Yulan Festival Intangible Cultural Heritage

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Abstract: This study proposes a multi-sensory Augmented Reality (AR) system integrated with custom flexible electronic skin technology, focusing on addressing the lack of haptic feedback in the digital inheritance of the Hong Kong Yulan Festival (Hungry Ghosts Festival) intangible cultural heritage (ICH). The goal is to enhance the authenticity of user experience and cultural perception when interacting with virtual cultural relics of the Yulan Festival. By integrating AR's scene reconstruction capabilities with customizable haptic feedback technology, the system simulates the vibration physical properties and material pressure sensations of characteristic cultural relics of the Yulan Festival, compensating for the deficiency of physical interaction experience in the digital communication of ICH by traditional AR technologies. The flexible electronic skin adopts a modular design, featuring excellent wearing adaptability and environmental compatibility. Combined with the audio-visual immersion brought by AR technology, it constructs an efficient augmented reality interaction framework for technology-empowered traditional culture. Comparative experiments were conducted using the interaction with virtual cultural relics of the Hong Kong Yulan Festival as a standardized scenario, verifying the key role of haptic feedback in improving users' spatial presence, sense of participation, and cultural authenticity. This research provides an extensible technical solution for the digital inheritance of ICH, which can be widely applied to ICH interactive exhibition scenarios requiring enhanced haptic experience.

Keywords: Augmented Reality, Flexible Electronic Skin, Haptic Feedback, Intangible Cultural Heritage, Hong Kong Yulan Festival, Digital Inheritance of ICH, User Experience.

1. INTRODUCTION

1.1. Research Background

With the rapid development of AR technology, its applications in the digital inheritance of ICH and cultural exhibitions have become increasingly widespread. As an important ICH project carrying the folk culture of the Lingnan region, the Hong Kong Yulan Festival incorporates cultural carriers—such as hand-crafted paper effigies, lanterns, and ritual utensils—that possess not only visual aesthetics but also distinct haptic qualities essential to their cultural meaning.

Existing digital representations of the Yulan Festival mostly rely on 2D images or static 3D models, which fail to convey the haptic experiences integral to ritual and craft interactions, thus limiting user engagement and cultural understanding. For example, in current virtual exhibitions, users may view 3D models but cannot perceive the texture of paper pulp, the rigidity of bamboo frames, the softness of lantern fabric, or the cold solidity of metal ritual objects. This sensory gap restricts cultural interaction to visual appreciation and hinders deeper participatory experience. To address this, integrating haptic feedback with AR offers a promising path. Flexible electronic skin, as a wearable customizable haptic device, can simulate vibrations to replicate pressure and texture sensations of cultural artifacts, thereby supporting both physical interactivity and cultural transmission. Recent advances in skin-integrated electronics have demonstrated the feasibility of reproducing complex tactile sensations for diverse materials. Combined with AR’s scene-reconstruction capability, this technology can overcome spatial and temporal limits in ICH inheritance—enabling immersive, multisensory interaction with virtual artifacts in reconstructed traditional settings.

Based on this "technology empowering culture" integration idea, this study constructs a haptic feedback AR system based on flexible electronic skin, focusing on exploring the optimization effect of haptic feedback on the AR interaction experience and cultural perception of the Yulan Festival ICH.

1.2. Research Questions

1.2.1. Multidimensional Perceptual Needs of Virtual Interaction

The interactive experience of virtual ICH relics involves the collaborative effect of multiple sensory

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dimensions, including vision, hearing, and touch. The cultural characteristics of Hong Kong Yulan Festival relics are precisely reflected in "multi-sensory collaboration"—the drumbeats during rituals, the touch of paper effigies, the light and shadow of lanterns, and the heaviness of ritual utensils together form a complete cultural experience. In the interactive scenario of virtual Yulan Festival relics, users not only need clear visual presentation to obtain visual information such as the patterns of ritual utensils and the shapes of paper effigies but also need to perceive key information such as the material toughness of paper effigys and the surface texture of ritual vessels (e.g., the matte texture of bronze tripods and the smooth glaze of ceramic bowls) through touch, thereby understanding the production techniques and folk uses behind these relics. Different types of Yulan Festival relics have unique physical properties and cultural implications, and their corresponding haptic feedback needs also vary: the gentle vibration of paper effigies corresponds to the flexible cultural connotation of "praying for blessings and prosperity," the steady vibration of metal ritual vessels aligns with the folk context of "solemn rituals," and the warm touch of ceramic offerings conveys the devout intention of "respecting ancestors." These all require the design of precise haptic feedback modes tailored to the Yulan Festival cultural scenario.

1.2.2. Interaction Experience Bottlenecks of Existing Technologies

Traditional AR interaction systems face numerous experience challenges in the inheritance of Yulan Festival ICH. On one hand, when users interact with virtual paper effigies, lanterns, and other relics, the lack of haptic feedback makes it difficult to obtain authentic technical perception—for example, they cannot understand the process characteristics of paper effigies through touch, nor can they feel the shape design of "three-legged stability" and the solid texture of ritual bronze tripods by holding them, leading to a superficial understanding of ICH techniques. On the other hand, existing digital technologies focus more on the visual beautification of Yulan Festival scenes, neglecting the collaborative matching of touch and vision, resulting in asymmetric sensory information and further reducing the authenticity of cultural experience. For example, when users "touch" virtual Yulan lanterns or ritual blue and white bowls in AR scenes, the vision shows the state of finger contact, but there is no tactile response. This sensory conflict not only weakens users' interest in interaction but may also lead to cognitive deviations in the cultural meanings of "lanterns as guiding symbols and ritual vessels as offerings."

These challenges establish specific and measurable research objectives: in the haptic dimension, to quantitatively evaluate the impact of haptic feedback on users' perception of material authenticity and experimentally measure its effect on improving the retention rate of cultural information; in the interaction dimension, to develop "visual-haptic" consistency metrics to assess how multisensory integration reduces cognitive load and enhances presence. Grounded in the "touch + culture" design philosophy, the integration of AR technology with flexible electronic skin enables users to engage in tangible interactions with virtual Yulan Festival relics. Through tactile feedback, users can not only perceive the physical attributes of the relics but also deepen their understanding of cultural connotations such as prayer and commemoration in the "Yulan Grand Gathering," thereby significantly enhancing the authenticity of the interaction experience and the depth of cultural engagement.

1.3. Main Contributions

Addressing the problems of poor experience and weak cultural perception caused by the lack of haptic feedback in AR technology for Yulan Festival ICH inheritance, this study proposes a digital interaction strategy of "haptic priority + cultural adaptation," providing an extensible solution for ICH interaction scenarios requiring enhanced haptic experience. The research contributions are mainly reflected in the following two aspects:

1.3.1. Theoretical Aspect

Establishing a multi-sensory collaborative paradigm for technology-empowered traditional culture in ICH digitalization, expanding the application boundary of AR technology in the field of ICH inheritance. By deeply integrating haptic feedback with AR technology and customizing interaction modes based on the cultural characteristics of Yulan Festival relics, it redefines the experience logic of ICH digitalization—shifting from "visual appreciation" to "multi-sensory cultural participation," realizing active interaction between users and ICH, and providing a new theoretical reference for the digital inheritance of similar ICH projects.

1.3.2. Practical Aspect

Providing a replicable dynamic interaction solution for Yulan Festival ICH, especially suitable for ICH exhibition scenarios requiring enhanced haptic participation. The modular design of flexible electronic skin can quickly adapt to the interaction needs of different types of Yulan Festival relics. Only by adjusting haptic feedback parameters can it match the characteristics of paper effigies, lanterns, ritual vessels, and other relics without large-scale modifications to the hardware structure, providing a practical example for the engineering application of AR technology in ICH venues and folk activities.

2. LITERATURE REVIEW

2.1. Application and Limitations of AR Technology in ICH Inheritance

With its core feature of integrating virtual and real elements, Augmented Reality (AR) technology has become a key support for the digital inheritance of ICH. Its advantages of breaking physical temporal and spatial limitations and enhancing user participation have been widely verified in global ICH projects. (Labadi *et al*. 2013) pointed out that the UNESCO ICH protection framework explicitly regards digital technologies such as AR as important tools for "living inheritance," emphasizing that technology should serve the transmission of cultural connotations rather than mere formal display. In specific applications, the combination of 3D modeling and AR has realized the leap of ICH from static archiving to dynamic interaction. Wang *et al*. (2018) and Lang *et al*. (2019) constructed an AR-based display mode for the Li nationality's ICH in the Areca Valley. Their system allows users to intuitively feel the operation process of brocade weaving technology through virtual scene reconstruction, effectively solving the problem of "invisible technology" in traditional museums.

Recent studies have further expanded the application boundary of AR. Hou *et al*. (2022) mentioned in a review of ICH digitalization that AR technology has covered multiple scenarios such as technology display, ritual reproduction, and educational communication. However, Tong & Hee-Gyun (2022) pointed out in their study on Shadow Play that although AR technology has entered people's lives, due to the shortage of technology and personnel, "no good solution has been found, and little gain has been achieved" in the broader context of ICH protection. Their experiment confirmed that while AR-based Shadow Play is more popular and offers a better viewing effect than traditional methods, the development of such systems remains challenging.

Existing applications still have significant limitations. Multiple studies (Skublewska *et al*. 2022) show that most AR ICH projects in the past decade focus on visual presentation, with only a few involving multi-sensory collaboration, resulting in superficial experiences. Taking Yulan Festival AR applications as an example, although users can view 3D models of paper effigies, they cannot perceive the toughness of paper materials and the texture of bamboo frames. As Chan (2018) pointed out, this "visual-only" experience is difficult to convey the core cultural value of the Yulan Festival as "collective memory and identity recognition."

Technical bottlenecks are also prominent. Related research indicates that the stability of AR ICH systems is greatly affected by environmental light and spatial positioning accuracy, and virtual cultural relics are prone to "drift" in dynamic scenarios such as outdoor Yulan Festival processions. In addition, the disconnection between content design and cultural adaptation is common. Some AR projects only use ICH elements as visual symbols without designing interactions based on folk logic. To address this, Gheorghiu & Ștefan (2020) proposed a method at the Kallatis site to "link tangible and intangible heritage." They argued that unlike simple visual overlays, a Mobile Augmented Reality (MAR) application must define specific points of interest to trigger an "immersive and holistic experience," thereby helping visitors understand the complexity of civilization rather than just viewing isolated artifacts. These limitations collectively point to a core problem: AR technology has not yet achieved an essential transformation from "technical tool" to "cultural carrier" in ICH inheritance, and there is an urgent need for multi-sensory technology supplementation to enhance the authenticity of experience.

2.2. Development of Haptic Feedback Technology and Flexible Electronic Skin

Haptic feedback technology provides "physical authenticity" for virtual interaction by simulating the physical properties of objects (such as hardness, texture, and vibration frequency). Its development process can be divided into two stages: traditional mechanical feedback and flexible electronic feedback. Traditional haptic devices such as force feedback joysticks can provide simple vibration sensations but have the disadvantages of large size and poor adaptability, making them difficult to apply to scenarios such as ICH that require fine touch experiences (Kim *et* *al*., 2019). The emergence of flexible electronic skin has broken this limitation. With its characteristics of thinness, wearability, and high sensitivity, it can fit the curves of human limbs and realize the precise simulation of complex haptic sensations.

The core advantage of flexible electronic skin lies in its "skin integration" capability, that is, through the combination of Micro-Electro-Mechanical Systems (MEMS) actuators and flexible substrates, haptic signals are directly transmitted to the skin surface, forming an "immersive" perceptual experience. Yu *et al*. (2019) developed a skin-integrated wireless haptic interface, which realized the haptic simulation of various materials such as paper, metal, and wood through MEMS actuators with a diameter of only 10mm, and its frequency response range of 0-200Hz is sufficient to cover the haptic characteristic requirements of ICH relics. On this basis, Huang *et al*. (2023) optimized the technical scheme, enabling the flexible electronic skin to simulate three haptic dimensions—pressure, vibration, and temperature—simultaneously through multi-module collaborative design, providing the possibility for "comprehensive perception" of virtual cultural relics.

In the field of cultural inheritance, the application of haptic feedback technology is still in its infancy but has shown great potential. Recent studies have further highlighted the importance of "technology-culture" adaptation. The AR + flexible electronic skin system for the Hong Kong Yulan Festival (Ke *et al*., 2025) set the haptic parameters of paper effigies to 40-60Hz low-frequency vibration and metal ritual vessels to 120-150Hz high-frequency pulses by measuring the physical data of real ICH relics, ensuring the consistency between haptic feedback and cultural cognition. At the same time, research on smart portable devices shows that the low-power design of flexible electronic skin (such as BLE wireless communication) can meet the long-time experience needs of ICH exhibitions and outdoor processions, and its breathable material is also suitable for the high-temperature and high-humidity environmental characteristics of Hong Kong. Nevertheless, the field still faces challenges: the cost of micro-actuators is relatively high, and the algorithm optimization of multi-modal feedback still needs support from more ICH scenario data. However, overall, flexible electronic skin has become a core technical support for multi-sensory ICH inheritance, providing a feasible path for the experience upgrade of AR-based ICH.

3. AR TECHNOLOGY BASED ON FLEXIBLE ELECTRONIC SKIN

The multi-sensory immersive AR system proposed in this study realizes the upgrade of virtual interaction experience and the enhancement of cultural perception through the deep integration of custom flexible electronic skin and AR technology, combined with the cultural and physical characteristics of Hong Kong Yulan Festival ICH relics. Breaking the limitation of haptic interaction of traditional AR technology in ICH inheritance, the system complements the physical simulation capability of flexible electronic technology with the scene presentation advantage of augmented reality technology, constructing a high-precision, high-immersion virtual-real interaction framework that fits folk culture.

3.1. Design of Flexible Electronic Skin

The hardware implementation adopts a flexible electronic device integrated with Micro-Electro-Mechanical Systems (MEMS) actuators. The actuators have a diameter of 10mm and a thickness of 2.5mm, which can conform to the curvature of the palm, specifically designed to simulate the material characteristics of Yulan Festival relics (see Figure **1**) — such as the slight deformation vibration of paper effigies, the texture friction vibration of bamboo lantern frames, and the steady touch pressure of ceramic ritual bowls, with a frequency response range of 0-200Hz. Compared with traditional ERM motors, this design significantly reduces energy consumption, ensuring that users do not have to worry about performance degradation during long-time experiences such as participating in the "Yulan Grand Gathering" themed interaction.

Based on skin-integrated electronic technology, the device realizes the wireless transmission of haptic signals through vibration actuators, and all haptic parameters are calibrated based on the measured data of real Yulan Festival relics—for example, the vibration frequency of paper effigys is set to 40-60Hz to simulate paper toughness, metal ritual vessels to 120-150Hz to convey hardness, and ceramic offerings to 70-90Hz to restore the warm touch of the glaze. The low-power Bluetooth (BLE) wireless communication protocol is adopted to ensure low latency and stable connection, meeting the real-time interaction needs of "touching a lantern for immediate feedback," "grabbing a paper effigy for immediate perception," and "holding a ritual bowl for immediate experience" in dynamic AR

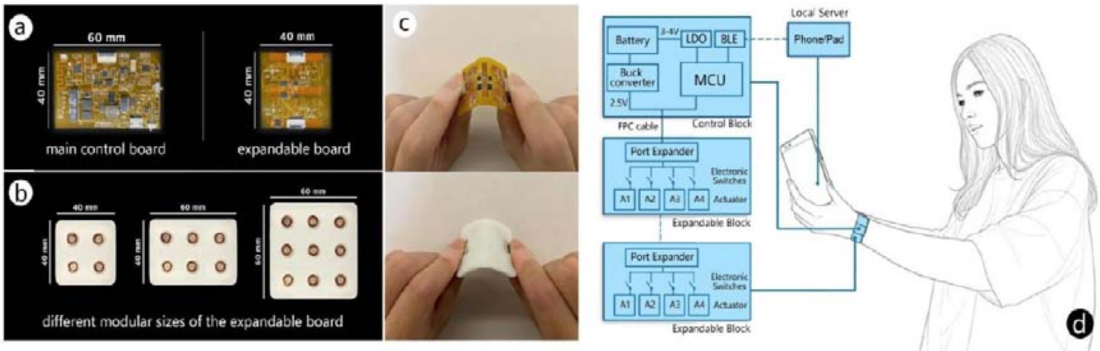

Figure 1: Flexible electronic skin and its characteristics (**a**) Main control board (left) and multiple expandable boards (right) of the device. (**b**) Three different modular sizes of the expandable board. (**c**) The electronic devices have properties similar to physical skin. (**d**) System architecture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

environments. The key quantitative performance parameters of the flexible vibrotactile actuator system are summarized as follows: Communication and response performance: The Bluetooth communication latency between the PC and MCU is 12–18 ms, the overall system response time from PWM signal input to actuator vibration onset is 5–8 ms, and the controllable vibration frequency ranges from 20 Hz to 500 Hz. Actuator performance metrics: The commercial linear resonant actuator (LRA) achieves a maximum output amplitude of 0.8 mm at its resonant frequency of 180 Hz; the custom micro-electro-mechanical system (MEMS) actuator has a maximum amplitude of 0.3 mm with a low power consumption of 0.12 W.

The flexible substrate integrates electronic components such as circuits, chips, and electrodes to simulate the stretchability and deformability of skin. The substrate material is a hybrid polymer-silicone composite material, which ensures the durability of electronic components while maintaining mechanical flexibility, ensuring that the device can be reused under various environmental conditions such as ICH venues and outdoor folk activities.

3.1.1. Environmental Adaptability

The device is made of lightweight and breathable materials to ensure comfort during long-time wearing, suitable for various indoor and outdoor scenarios such as ICH venue exhibitions and Yulan Festival themed activities. The materials can adapt to the interaction needs in Hong Kong's high-temperature and high-humidity summer environment, avoiding the impact of environmental factors on the effect of users' virtual experience of the Yulan Festival.

3.1.2. Multi-Sensory Feedback Collaboration

The system realizes the synchronous presentation of vision, hearing, and touch, and all sensory elements are in line with the Yulan Festival cultural scenario—visually restoring the paper effigies, ritual offering tables, ritual vessels, etc., of the "Yulan Grand Gathering"; audibly superimposing the sound of bronze bells and drumbeats during ritual ceremonies; and haptically matching the touch of corresponding cultural relics, such as the solid vibration of bronze tripods and the warm feedback of ceramic bowls. The triple sensory collaboration enhances users' immersion and cultural presence in AR interaction.

3.1.3. Modular Haptic Feedback

To meet the interaction needs of different types of Yulan Festival relics, the flexible electronic skin is designed as a modular structure that can be adapted to different parts of the body (palm, fingers, forearm, etc.), supporting independent control of vibration intensity and frequency to achieve high-fidelity multi-sensory feedback (see Figure **2**). For example, the finger module is used to perceive the fine lines of paper effigies, the palm module to feel the overall texture of lanterns and the solidity of ritual bronze tripods, and the fingertip module to experience the delicate glaze of

Figure 2: Modular design can be worn on different positions of the body.

ceramic bowls. The hardware adopts a modular design (see Figure **3**), which is easy to disassemble and reassemble, and the configuration can be quickly adjusted according to specific interaction scenarios without large-scale modifications to the hardware structure, flexibly matching the diverse cultural experience needs of the Yulan Festival.

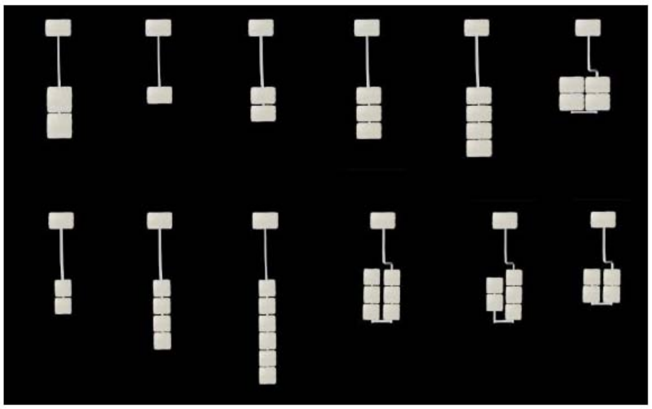

Figure 3: Modular hardware architecture enabling reconfigurable system integration.

3.2. Multi-Sensory Integration of AR and Haptic Feedback

3.2.1. System Integration

Photogrammetry and structured light 3D scanning technology are used to collect 3D data of real Hong Kong Yulan Festival cultural relics (such as the century-old paper effigy "Dashi Wang," traditional bamboo-frame lanterns, blue and white ritual bowls, bronze ritual tripods, etc.), and the models are processed and optimized through 3D reconstruction and modeling technology (see Figure **4**). The photogrammetry process integrates machine learning-based texture enhancement technology to accurately restore cultural characteristics such as the pattern details of paper effigies, the fabric folds of lanterns, and the rust texture of ritual tripods; the structured light scanning accuracy reaches 0.1mm, ensuring the geometric accuracy of the 3D models of virtual cultural relics—such as the knots of bamboo lantern frames, the cutting traces of paper effigies, and the decorative carvings of ritual tripods are clearly distinguishable, laying the foundation for the matching of real haptic feedback and the transmission of cultural characteristics (see Figure **5**).

3.2.2. Virtual-Real Superposition Technology

AR visualization technology is used to project characteristic virtual Yulan Festival cultural relics (such as "Yulan Grand Gathering" themed lanterns, paper effigy "carriages and horses," ritual tripods, blue and white offering bowls, etc.) into real environments—either next to display cabinets in ICH venues or at community Yulan Festival events. Users interact with virtual scenes or cultural relics through the UI interface, such as touching the texture of paper effigies, lifting the hanging ropes of lanterns, placing ritual utensils, and holding blue and white bowls. AR superposition adopts Simultaneous Localization and Mapping (SLAM) technology to ensure the stable anchoring of virtual cultural relics in physical space, maintain spatial consistency, and enhance the sense of interaction of "participating in real Yulan activities."

3.2.3. Haptic-Visual Synchronization

Based on the characteristic Yulan Festival interaction events in the AR scene, the flexible electronic skin triggers precise vibration feedback in the corresponding areas—outputting low-frequency, low-intensity vibration when touching paper effigies to simulate paper toughness; generating high-frequency strong pulses when tapping ritual bronze tripods to restore metal texture and solidity; transmitting continuous low-frequency vibration when stroking

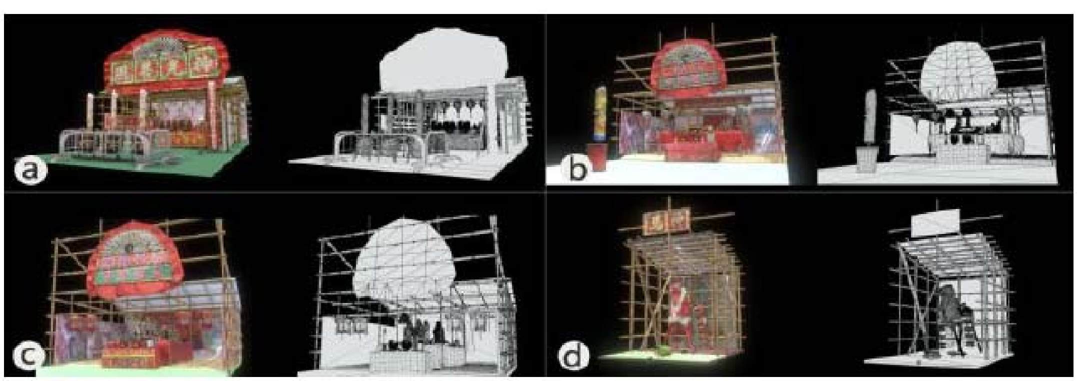

Figure 4: Yulan Festival shrine model realized through the integration of photogrammetry, structured light 3D scanning, and 3D modeling technologies.

lantern fabrics to convey the drape of the fabric; and simulating the warm touch of ceramic glaze with medium-frequency gentle vibration when holding blue and white ritual bowls. The haptic feedback parameters are all determined based on the measured physical properties of real Yulan Festival cultural relics and calibrated with the participation of ICH inheritors, ensuring the dual consistency of haptic experience with cultural relic attributes and folk cognition, and avoiding deviations between technical feedback and cultural cognition.

Figure 5: Detailed 3D model of virtual cultural relics acquired via multiple 3d scanning technology.

4. SYSTEM ARCHITECTURE AND IMPLEMENTATION

4.1. System Architecture

The proposed multi-sensory AR system adopts a modular and extensible architecture design to ensure the seamless integration of AR technology and flexible electronic skin, while adapting to the cultural characteristics of Yulan Festival ICH relics. Developed based on the Unity engine, it adopts a layered design concept, including three core modules: the perception layer, the interaction layer, and the service layer, realizing efficient data transmission, real-time processing, and an immersive user experience of "technology + culture."

4.1.1. Perception Layer

As the foundation for data collection, the perception layer captures real-time environmental data and user-Yulan Festival cultural relic interaction data through AR cameras (scanning AR postcards) and flexible electronic skin sensors. The AR camera has image recognition and depth perception functions. It first identifies the exclusive marker code on the AR postcard, triggers the loading of the corresponding virtual Yulan Festival cultural relic model, and thus realizes the precise placement of the virtual cultural relic around the postcard—"placing" the ritual bronze tripod on the real offering table in front of the postcard, for example, or "arranging" the paper effigy on the real exhibition platform corresponding to the postcard; the flexible electronic skin sensor embeds MEMS actuators, which can simulate the touch of various real objects, such as the haptic sensations of materials of Yulan Festival cultural relics like paper, bamboo, metal, and ceramic.

4.1.2. Interaction Layer

As a bridge connecting AR postcards, the physical world, and virtual Yulan Festival cultural scenes, the interaction layer undertakes the core function of processing user input and rendering and synchronizing multi-sensory feedback. Its integrated key technologies first include the AR postcard recognition and scene construction function based on the ARCore framework, which can quickly read the postcard marker code, match the corresponding virtual cultural relic resources, and realize motion tracking. At the same time, the haptic feedback logic engine built into the interaction layer parses Yulan Festival interaction events triggered by touching paper effigies, lifting lanterns, etc., through custom drivers, and maps these events to actuator commands matching the cultural relic materials—such as outputting 40Hz low-frequency vibration when touching paper effigies, 150Hz high-frequency pulses when tapping bronze tripods, and 80Hz medium-frequency vibration when holding ceramic bowls. The engine supports dynamic adjustment of the intensity, duration, and rhythm of vibration modes to accurately match the interaction characteristics and folk usage scenarios of different cultural relics.

Scene Recognition and Postcard Parsing: Realize AR postcard marker code recognition, motion tracking, etc., based on the Unity engine. For example, when users scan AR postcards with different themes, the system automatically identifies the marker code and anchors the corresponding virtual cultural relic to the surface around the postcard.

Haptic Feedback Logic Engine: Custom drivers parse interaction events (such as touching virtual objects, operating virtual tools, etc.) and map them to actuator commands. The engine supports the setting and adjustment of vibration modes (intensity, duration, rhythm) to match the interaction characteristics of different objects.

4.1.3. Service Layer

The service layer is mainly responsible for coordinating high-level functions such as content management, user analysis, and cultural inheritance. Among its core subsystems, AR content transmission stores 3D models of virtual Yulan Festival cultural relics and cultural marker AR tags based on the Unity engine—the models are attached with process details annotated by ICH inheritors, such as the paper-pasting skills of paper effigies and the casting process of ritual tripods; the tags are associated with cultural information such as "the historical origin of the Yulan Grand Gathering," "the inheritance story of paper effigy craftsmanship," and "the folk implications of ritual utensils." Users can access relevant content through the cloud storage library, a design that ensures the scalability of the system for users worldwide concerned about Yulan Festival culture; the interaction database stores attribute data of Yulan Festival cultural relics in the form of a structured knowledge graph, including both descriptive information about the cultural relics and cultural connotation information such as "lanterns symbolize reunion," "paper effigies are used for praying," and "ritual tripods represent solemnity." During AR interaction, it provides users with timely contextual perception prompts—such as popping up the cultural annotation "traditional Yulan lanterns mostly use bamboo frames and paper surfaces, symbolizing illuminating the way home for ancestors" when touching a lantern, and displaying the explanation "Yulan ritual bowls are mostly blue and white, symbolizing purity and respect" when touching a blue and white bowl. In future versions, this layer will further integrate blockchain technology to realize the authentication and tracking of user-generated content, build a "Yulan Festival ICH digital asset library," and promote the sharing and ecological construction of ICH.

4.2. Digital Implementation of Virtual Interaction Scenarios

The actual deployment of the system focuses on several typical immersive interaction scenarios of the Hong Kong Yulan Festival, verifying the user experience effect and cultural perception degree under different folk links respectively.

4.2.1. Virtual Object Touch Interaction

This scenario focuses on "AR postcard triggering + touch experience," simulating the touch of core Yulan Festival cultural relics and recreating the cultural scene of "closely feeling ICH craftsmanship." Its technical implementation is first reflected in the collaboration between hardware and carriers. Users need to wear flexible electronic skin gloves integrated with palm and finger actuators and hold AR postcards with corresponding themes—the postcards are printed with 2D patterns of target cultural relics and AR identification codes. The actuators have a diameter of 10mm and a thickness of only 2.5mm, and the flexible substrate ensures comfort during long-time wearing, facilitating the fine touch of virtual cultural relic details. In terms of the AR interaction process, users scan the AR postcard through a tablet device, and the system quickly identifies the marker code and presents a high-precision virtual cultural relic (such as the "centennial paper effigy Dashi Wang," "traditional bamboo-frame lantern," etc.) in the space around the postcard. When the user "touches" the virtual cultural relic, the actuator emits vibration of the corresponding frequency according to the cultural relic material: 40-60Hz low-frequency vibration when touching paper effigies to simulate paper toughness, 80-100Hz vibration when touching bamboo lantern frames to restore bamboo grain friction, 70-90Hz vibration when touching ceramic bowls to convey the warm glaze, and 120-150Hz vibration when touching bronze ritual tripods to present metal solidity. At the same time, the system renders light and shadow changes through particle effects—such as the lantern emitting a faint light when touched, forming a visual link with the AR postcard.

Hardware Configuration: Users wear flexible electronic skin gloves integrated with palm actuators. The actuators have a diameter of 10mm and a thickness of 2.5mm, and the flexible substrate ensures comfort during long-time wearing.

AR Interaction Process: Users scan Yulan Festival themed AR postcards through AR devices. After identifying the postcard marker code, the system loads the corresponding virtual cultural relic and anchors it to the planar area around the postcard (such as a desktop) as a virtual display platform. Users can switch the display angle of the cultural relic through the UI menu. When the user "touches" the cultural relic on the virtual display platform, the palm actuator emits vibration of the corresponding frequency according to the cultural relic material, and at the same time, visual feedback is rendered through particle effects, forming an "entity-virtual" echo with the AR postcard.

Interaction Authenticity: The haptic feedback parameters are determined based on the physical measurement data of real objects to ensure the authenticity of the haptic experience.

4.2.2. Virtual Tool Operation Interaction

This module aims at "AR postcard triggering + craft operation," recreating the cultural process of "participating in the production of Yulan Festival cultural relics." Its core innovations are reflected in multiple aspects. In terms of feedback coverage, modules are bound to the user's limbs and trunk, and each module's actuator is independently controlled to accurately match different flexible electronic skincraft actions—such as the finger module simulating the light pressure of "pasting paper" (low-frequency weak vibration) and the forearm module simulating the force of "binding bamboo frames" (medium-frequency medium vibration). At the same time, dynamic soundscape technology is integrated to adjust the audio based on the user's position relative to the virtual workbench, synchronously playing sound effects such as "bamboo strip friction sound."

Full-Body Wearing Feedback: flexible electronic skin modules are bound to the limbs and trunk, and the actuator of each module is independently controlled to match different operation actions (such as 150Hz pulses simulating tool tapping, low-frequency vibration simulating movement, etc.).

Motion-Haptic Mapping: Based on a biomechanical model, the user's joint angle data (from ARKit) is converted into corresponding vibration sequences. For example, when simulating tool swinging, the actuator dynamically adjusts the intensity during the movement to simulate the force transmission sense of real operations (see Figure **6**).

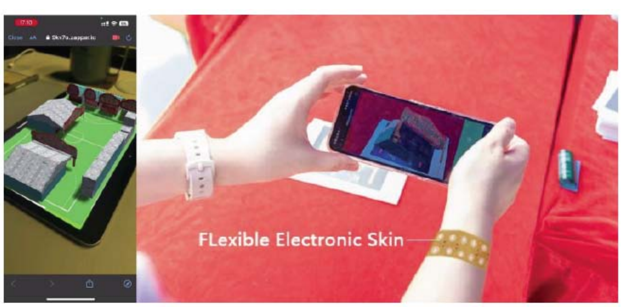

Figure 6: The AR system based on flexible electronic skin realize the protection and inheritance of intangible cultural heritage.

Dynamic Soundscape: Adjust binaural audio based on the user's position relative to the virtual operation platform, and haptic feedback enhances direction prompts (such as increased vibration of the left module when operating on the left side).

4.2.3. Virtual Space Navigation Interaction

In the future, it is planned to extend the digital experience to the actual folk scenes of the Hong Kong Yulan Festival and develop the function of "AR postcard navigation + procession experience." A series of "procession route" AR postcards will be designed. After scanning the postcards, users trigger AR navigation to guide them to explore along the traditional procession route. Scanning specific landmark postcards along the way can "encounter" virtual ICH inheritors explaining and historical scene reproductions. The flexible electronic skin provides vibration feedback according to GPS data and the content triggered by the postcards—for example, when scanning the "lantern array" postcard and approaching the virtual lantern array, the arm module emits rhythmic vibration to simulate the swaying of lantern light and shadow; when scanning the "ritual platform" postcard and reaching the destination, the palm module emits steady vibration to match the solemnity of the etiquette. Combined with the AR-overlaid "historical and modern comparison" effect, it enhances the perception of cultural inheritance and realizes a new ICH inheritance model of "AR postcard triggering + online experience + offline participation."

5. EXPERIMENTAL DESIGN AND RESULT ANALYSIS

5.1. Experimental Design

This experiment aims to evaluate the independent contribution of "haptic feedback" in AR systems to improving users' spatial presence, sense of participation, and authenticity (i.e., the core dimensions of "presence"). The touch interaction with typical virtual Hong Kong Yulan Festival cultural relics (such as paper effigy models, blue and white ritual bowls, bronze ritual tripods) was used as a standardized interaction scenario to ensure the cultural representativeness and repeatability of the experimental scenario.

The study employed a within-subjects design with counterbalancing to control for potential order effects. Given the common sample size range in immersive human-computer interaction research and the feasibility constraints of exploratory research(Faulkner, 2003; Macefield, 2009.), Twelve participants were randomly assigned to different experimental condition sequences and experienced the two conditions in turn. The participants included ICH enthusiasts, college students majoring in design, and community residents, ensuring the diversity of the sample's cognitive levels of Yulan Festival culture. Among them, two participants had prior experience with haptic feedback technology, and six participants had prior experience with augmented reality technology. To minimize carryover effects between conditions, each participant entered a washout period of at least 15 minutes after completing one condition, during which they performed a neutral task unrelated to the experiment to reduce residual cognitive or perceptual interference. Experimental Condition 1 (AR + Haptic) was an AR system with haptic feedback: participants wore flexible electronic skin integrated with palm modules, and after scanning the marker image printed with Yulan Festival cultural elements through a tablet device, high-precision virtual cultural relics (reconstructed based on photogrammetry and structured light scanning technology of real works) were presented on the screen. When the user's hand touched the virtual cultural relic on the screen, the flexible electronic skin module would generate corresponding haptic feedback according to the material characteristics of the cultural relic (the soft vibration of paper effigies, the steady vibration of ritual bowls). Experimental Condition 2 (AR Only) had exactly the same AR visual effects, with identical virtual cultural relic models, scene layouts, and interaction logic, but no haptic feedback was provided. Participants also used tablet devices to view and touch the same virtual Yulan Festival cultural relics, but the palm module did not generate vibration.

To eliminate the order effect, a counterbalancing procedure was adopted: 6 participants first experienced Condition 1 and then Condition 2, and the other 6 experienced the conditions in the reverse order, ensuring the overall balance of the presentation order of the two conditions and purely comparing the differences brought by haptics.

5.2. Experimental Process

The experiment was conducted in a controlled laboratory environment. After arriving, participants were explained the standardized process by researchers and then started the first round of experience according to the randomly assigned order.

For virtual Yulan Festival cultural relics, participants were encouraged to focus on touching the characteristic parts of different cultural relics—such as the pattern details of paper effigies, the decorations of ritual tripods, the rim and body of blue and white bowls, and especially to evaluate the haptic feedback of ritual utensils. Under both conditions, participants were encouraged to freely explore the virtual Yulan Festival cultural relics in the AR scene, focusing on touching the characteristic parts of different cultural relics. After each round of experience, participants were required to immediately fill out a questionnaire focusing on spatial presence, sense of participation, and cultural authenticity. In addition to conventional perceptual items, the questionnaire specially added cultural-related items (such as "I can feel the handcrafted temperature of Yulan Festival cultural relics through the experience"). The questionnaire used a 7-point Likert scale (1=strongly disagree, 7=strongly agree). After completing the experience and questionnaire for both conditions, a brief semi-structured interview was conducted to focus on understanding the participants' subjective perception differences between the two conditions in terms of "cultural sense of substitution" and "perception of ICH techniques," such as "Which experience made you better understand the value of Yulan Festival paper effigy craftsmanship."

5.3. Experimental Results

Analysis of the questionnaire data using paired-sample t-tests showed that the AR + Haptic condition was significantly superior to the AR Only condition in the three measurement dimensions and the additional cultural perception items ($p<0.05$). The mean scores (M) and standard deviations (SD) of each dimension are shown in the following Table **1**:

In terms of spatial presence, the score of the AR + Haptic condition (M=6.1) was significantly higher. In the interview, participants generally stated that haptic feedback gave the virtual Yulan Festival cultural relics a "tangible sense of temperature." One participant mentioned: "The steady vibration when touching the ritual tripod made me experience the solemnity during the ritual, which is more immersive than just looking at pictures"; an ICH enthusiast described: "The haptic sensation when touching the cultural relics made me feel as if I could really hold these cultural relics in my hands"; in the AR Only condition, although the cultural relics were visually three-dimensional, they were still perceived as "soulless pictures," making it difficult to trigger associations with Yulan Festival ritual scenes.

Table 1:

Measurement Dimension	Example Items	Condition 1 (AR + Haptic)	Condition 2 (AR Only)
Sense of Presence	- I feel that the virtual cultural relics (such as lanterns, paper effigys) seem to really exist in the physical space where I am. - I have the feeling that I am in the world created by the AR system, not just looking at a screen.	M = 6.1, SD = 0.8	M = 4.5, SD = 1.1
Sense of Participation and Influence	- I feel like an active participant in the virtual environment, not just an observer. - I can freely explore virtual cultural relics and touch different parts of them through hand movements. - The process of exploring cultural relic materials through haptic feedback feels natural and intuitive to me.	M = 6.4, SD = 0.7	M = 4.8, SD = 1.2
Authenticity	- The feedback provided by the system makes me feel that the virtual cultural relics are real objects. - The feelings generated by different feedbacks are synchronous and consistent. - When touching cultural relics of different materials, the difference in feedback is obvious and in line with my expectations of real materials.	M = 6.2, SD = 0.8	M = 4.3, SD = 1.3

There was a significant difference in the sense of participation and influence: under the AR + Haptic condition, haptic feedback stimulated participants' desire to actively explore. They would repeatedly touch different parts of the paper effigy to compare textures, carefully feel the material of the cultural relics, and even try to simulate actions such as "placing the ritual tripod" and "holding the bowl to present offerings." Many people took the initiative to ask during the interview, "How are these utensils specifically used during Yulan Festival rituals" and "Where can I see real ritual ceremonies"; in the AR Only condition, the lack of physical feedback from touching led participants to mostly simply slide the screen to browse, and they also lacked the desire to inquire about the craftsmanship and cultural stories behind the cultural relics.

In the authenticity evaluation, the AR + Haptic condition (M=6.2) had a decisive advantage. Participants particularly emphasized that the differentiated vibration modes designed for different materials allowed them to "feel the cultural details of the Yulan Festival through their hands"—for example, the steady vibration of the ritual tripod made people feel the solemnity of the ceremony, and the gentle vibration of the paper effigy conveyed the delicacy of handcrafted techniques. On the contrary, in the AR Only condition, participants believed that the experience "stayed at looking at pictures," making it difficult to connect the virtual cultural relics with "folk carriers carrying the meanings of praying and respecting," resulting in weak cultural perception.

5.4. Experimental Analysis

The experimental results clearly indicate that on the same AR visual basis, haptic feedback that fits the cultural characteristics of the Yulan Festival is a key increment to improve users' ICH perception. By providing physical signals synchronized with vision and consistent with folk cognition, it solves the core problem of virtual ICH relics being "form without spirit" in pure visual AR—not only endowing the cultural relics with physical presence but also giving them cultural temperature, thereby significantly enhancing users' spatial perception and cultural identity of Yulan Festival cultural relics.

Secondly, haptic feedback transforms the interaction between users and Yulan Festival cultural relics from "passive viewing" to "active cultural exploration," which greatly strengthens users' sense of participation and cultural interest. Data shows that touch is not only a physical feedback but also a "cultural trigger" that stimulates users to understand ICH backgrounds and explore folk connotations—when users feel the handcrafted texture of paper effigies through touch, they will naturally generate inquiries about cultural issues such as "who made them" and "why they are made." This desire for cultural exploration triggered by sensory experience cannot be achieved by pure visual experience.

Finally, the contribution of touch to cultural authenticity lies in realizing the "consistency between sensory experience and cultural cognition." The brain's judgment on the authenticity of ICH culture relies not only on visual information but also on multi-sensory collaboration consistent with life experience and cultural memory. When haptic feedback provides material information consistent with the cultural attributes of Yulan Festival cultural relics—such as the gentleness of paper effigies and the solemnity of ritual utensils—the cultural authenticity of virtual cultural relics is greatly improved, and users' cognition will shift from "this is a virtual model" to "this is part of Yulan Festival culture."

In addition, the counterbalancing design ensures the reliability of the experimental results. Data analysis shows that regardless of the experience order, participants gave significantly higher scores to the AR + Haptic condition, proving that the experience advantage brought by touch is robust and not derived from order effects or novelty.

In summary, through rigorous comparison, the experiment confirms that integrating flexible electronic skin into AR systems and providing haptic feedback that fits the cultural characteristics of the Hong Kong Yulan Festival can significantly improve users' spatial presence, sense of participation, and cultural authenticity by enhancing multi-sensory consistency and stimulating cultural exploration behaviors. It provides key empirical support for the application of haptic technology in the digital inheritance of ICH and also provides new technical ideas for the living inheritance of folk ICH such as the Yulan Festival.

6. DISCUSSION AND LIMITATIONS

The AR haptic feedback system based on flexible electronic skin provides an innovative solution for the optimization of virtual interaction technology, especially suitable for scenarios requiring enhanced haptic experience. However, the system still has certain limitations that need to be further addressed in future research.

6.1. Technical Feasibility and Scalability

The modular design of flexible electronic skin endows it with cross-scenario adaptability, but its scalability is still limited by material durability and manufacturing costs. Although the MEMS actuators and skin-integrated electronic technology adopted in the current prototype have good effects, further optimization is needed for large-scale production. For example, the 10mm diameter actuator still has room for improvement in simulating fine touch, and miniaturization design needs to be explored in the future to adapt to more refined interaction scenarios. In addition, it is necessary to develop more cost-effective materials and manufacturing processes to ensure the accessibility of the technology in more scenarios, especially in resource-constrained application environments.

6.2. User Experience and Interaction Authenticity

Drawing on sensory anthropology and embodied interaction theory, the system extends beyond technical immersion by positioning haptic feedback as a mechanism for cultural evocation.Touch functions not only as a sensory channel but also as a medium for cultural memory and meaning transmission. In this context, the tactile simulation of Yulan Festival artifacts—such as the coarse texture of handmade paper or the solid coolness of bronze tripods—can serve as a sensory trigger that deepens cultural engagement and authenticates intangible heritage experience. However, excessive reliance on virtual elements may compromise interaction intuitiveness. For example, although "haptic-visual" digital files are easy to share, they are difficult to fully reproduce the complex haptic details of real objects. In the future, more user experience-based iterative testing needs to be carried out, and haptic feedback parameters should be optimized in conjunction with user feedback to further improve interaction authenticity. In addition, long-term user tracking research needs to be conducted to evaluate whether the improvement in user experience brought by the system is sustainable rather than a short-term novelty. On another note, the system's introduction of multimodal feedback (haptic, visual, and potentially auditory) may increase cognitive load in certain scenarios, particularly for users unfamiliar with the technology or older adult populations. Future interaction designs should consider the pacing and layering of information presentation to avoid perceptual channel overload, which could negatively impact the user experience and the effective reception of cultural content.

6.3. Challenges of Interdisciplinary Collaboration

This project integrates multi-disciplinary knowledge such as AR technology, haptic engineering, and user experience design, emphasizing the importance of interdisciplinary collaboration. However, terminology differences and methodological divergences between different disciplines may affect design efficiency. For example, engineering and technical personnel may focus on the accuracy of technical parameters, while user experience designers are more concerned about the intuitiveness and comfort of interaction. In the future, it is necessary to establish a unified design context and collaboration framework, and promote effective communication among experts in different fields through joint workshops, co-design, and other methods to ensure the consistency between technical implementation and user needs.

6.4. Practical Application Limitations

The system's reliance on wearable devices brings certain practical application limitations. During long-time outdoor use, the device faces challenges in battery life and environmental adaptability. For example, Hong Kong's high-temperature and high-humidity summer environment may affect device performance. Although the current design has considered features such as lightweight construction and breathability, more rigorous testing under diverse environmental conditions is still required. Particular attention should be paid to the material durability and signal stability of the flexible electronic skin in real-world usage scenarios involving repeated bending, sweat exposure, and similar factors. Although the current design has considered characteristics such as light weight and breathability, more rigorous outdoor environment testing is still needed. In the future, alternative energy solutions such as solar power supply and kinetic energy collection can be explored to further improve the practical application capabilities of the device.

7. CONCLUSION

This study constructs a multi-sensory virtual interaction system through the deep integration of custom flexible electronic skin and AR technology, effectively solving the problem of poor interaction experience caused by the lack of haptic feedback in traditional AR technology. The modular design of the flexible electronic skin adopted by the system has good environmental adaptability and interaction flexibility. Combined with the audio-visual immersion of AR technology and the physical authenticity of haptic feedback, it realizes an all-round upgrade of virtual interaction experience.

Comparative experimental results confirm that haptic feedback plays a key role in improving users' spatial presence, sense of participation, and authenticity, providing a clear direction for the optimization of AR interaction technology. The technical system proposed in this study not only demonstrates practical value in virtual interaction scenarios for intangible cultural heritage but also contributes a versatile “haptic-augmented” paradigm to the broader field of immersive media research. This paradigm can advance interaction design theory in extended reality (XR) domains—including virtual reality and mixed reality—particularly in scenarios requiring high-fidelity multi-sensory integration, such as training simulations, remote collaboration, and advanced visualization, offering significant technical reference and methodological insights.

Future research will further expand the multi-sensory simulation capabilities of flexible electronic skin (such as olfactory simulation) and optimize the environmental adaptability and cost-effectiveness of the system, continuously promoting the development and application of virtual interaction technology. This study provides a practical example for the innovation of multi-sensory interaction technology and is expected to promote the in-depth application of AR technology in more fields.

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