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Integrating Ethnic Art Elements into Smart Textile Interaction Design for Cultural Expression and User Experience

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ABSTRACT

Smart textiles enable embodied interaction by integrating sensing, actuation, and computation into textile-based systems. In culturally oriented design contexts, however, many existing smart textile applications emphasize technical demonstration or surface-level visual adaptation, providing limited methodological support for translating cultural content into systematically evaluable interaction experiences. To address this limitation, this study develops and empirically examines a structured design-and-evaluation framework for integrating ethnic art elements into smart textile interaction design, with a focus on cultural expression and user experience.

The framework consists of three sequential layers: cultural decomposition, experience mapping, and adaptive optimization. Ethnic art elements are first decomposed into explicit, design-relevant parameters across visual, material, and narrative dimensions. These parameters are then translated to embodied interaction behaviors through constrained and parameterized rules, enabling cultural attributes to be expressed via tactile, temporal, and material-based interactions. A user-feedback-driven optimization mechanism further refines interaction parameters to accommodate individual differences in perception and interpretation within predefined bounds.

To examine the effectiveness of the proposed framework-guided cultural interaction strategy, a smart textile prototype inspired by Miao embroidery was designed and fabricated using integrated textile sensors and actuators. A mixed-method user study ($N = 60$) with controlled comparison conditions evaluated cultural narrative recognition and experience satisfaction. Results show that the framework-guided interactive design yields significantly higher cultural narrative recognition accuracy ($F(2,57) = 92.51$, $p < .001$, $\eta^2 = .76$) and experience satisfaction ($F(2,57) = 87.66$, $p < .001$, $\eta^2 = .75$) compared to static cultural and non-cultural interactive baselines.

This study demonstrates a reproducible, engineering-oriented approach for embedding cultural expression into smart textile interaction systems through the integrated use of cultural analysis and interaction design, rather than isolated visual or technical augmentation.

KEYWORDS
smart textiles, interaction design, cultural expression, ethnic art, user experience

INTRODUCTION

Smart textiles integrate sensing, actuation, and computation directly into fabric structures and have emerged as a promising medium for embodied human–computer interaction. By leveraging the softness, flexibility, and close physical proximity of textiles to the human body, smart textile systems support forms of interaction that are difficult to achieve with rigid interfaces, enabling applications in wearable sensing, immersive interaction, and responsive environments [1,2]. Recent advances in textile-based sensors, digital embroidery, and flexible electronics have further improved the scalability and customizability of smart textile interfaces, broadening their potential application domains [2,3].

In parallel, the digital preservation and dissemination of cultural heritage has attracted increasing attention across design, engineering, and human–computer interaction research. Prior studies have explored tangible and interactive interfaces as a means to enhance public engagement with cultural heritage, highlighting physical interaction as an effective complement to screen-based representation [4]. Despite this growing interest, many existing approaches remain centered on visual reproduction or static ornamentation. Consequently, deeper cultural meanings—such as embodied knowledge, narrative structures, and material practices—are often insufficiently translated into interactive experiences that users can actively perceive, interpret, and evaluate.

Smart textiles offer a distinctive opportunity to address this limitation. Owing to their materiality, tactility, and temporal expressiveness, textile-based interfaces are particularly well suited for conveying culturally grounded experiences. This research aims to foster dynamic, diverse interpretations of cultural content, recognizing that cultural meanings are fluid and can evolve based on individual and contextual factors. Nevertheless, research on smart textile interaction has predominantly emphasized technical integration and performance optimization, including sensor fabrication, signal processing, and system robustness [1,2].

Studies that systematically examine how cultural elements can be operationalized within smart textile interaction design—and how such design decisions affect user experience—remain relatively scarce [5].

This situation gives rise to three interrelated challenges in existing “culture + smart textile” design practices. First, cultural symbols are frequently applied at a superficial level, functioning primarily as visual motifs rather than as carriers of embodied and narrative meaning. Second, interaction behaviors across culturally themed smart textile systems often converge toward similar forms of feedback, resulting in homogeneous user experiences. Third, most existing systems lack mechanisms for adapting cultural expression to individual users, despite well-documented variations in perception, interpretation, and affective response during interaction [6]. Together, these challenges limit the potential of smart textiles to function as a medium for deep cultural expression rather than decorative augmentation.

To address these challenges, this study develops a systematic and implementable framework for integrating ethnic art elements into smart textile interaction design. The framework is conceived as a design-oriented engineering method that bridges cultural analysis, technical implementation, and empirical evaluation. It comprises three stages: (1) cultural element decomposition, which operationalizes visual symbols, material techniques, and narrative structures of ethnic art into explicit design parameters; (2) parameterized interaction mapping, which translates these parameters into tactile, temporal, and material-based interaction behaviors within smart textile systems; and (3) user-feedback-driven personalization, which adaptively adjusts interaction parameters based on individual user responses.

Using Miao embroidery as a representative case, the framework is instantiated through the design and fabrication of a smart textile prototype integrating textile-based sensors and interactive feedback via digital embroidery techniques. A mixed-method user study evaluates whether the proposed approach enhances users’ recognition of cultural narratives and overall interaction experience in comparison with baseline designs. Through this investigation, the study demonstrates how smart textile interaction can function as an embodied medium for cultural expression and provides a reproducible engineering pathway for culturally grounded interaction design.

RELATED WORK

This section reviews prior research on smart textile interaction, interactive cultural heritage systems, and cultural experience evaluation. Rather than providing an exhaustive survey, the review focuses on identifying methodological limitations that motivate the framework proposed in Section "The Proposed Framework: Cultural-aware Embodied Interaction".

Smart Textile Interaction Technologies

Smart textiles have been widely studied as a platform for integrating sensing, actuation, and computation into fabric-based interfaces. Early research demonstrated the feasibility of embedding sensors directly into knitted or woven textiles for physiological monitoring and interaction [1]. Subsequent advances in textile strain sensors, conductive yarns, and fabrication techniques have further improved robustness, scalability, and signal quality, enabling a broad range of interactive textile applications [2].

Beyond sensing, smart textiles have increasingly been explored as interactive interfaces in immersive and augmented environments. Prior studies have investigated wearable smart textiles for gesture-based control and augmented reality interaction, highlighting their potential for embodied and unobtrusive interaction [3]. More recent work has focused on digitally fabricated e-textiles, showing that techniques such as digital embroidery support rapid customization and the seamless integration of functional elements within textile structures [7].

Despite these advances, most smart textile research remains primarily technology-driven, emphasizing performance metrics such as sensitivity, durability, and signal fidelity. Cultural meaning and experiential interpretation are seldom treated as primary design objectives. Consequently, interaction behaviors across smart textile systems often converge toward similar functional feedback patterns, leaving limited room for culturally differentiated expression.

Interactive Cultural Heritage and Tangible Interfaces

In the field of cultural heritage, interactive and tangible interfaces are widely recognized as effective means for enhancing public engagement. Prior research suggests that physical interaction can improve technology acceptance and deepen users' understanding of cultural content in museums and heritage institutions [4].

Through tangible and embodied interaction, users engage with cultural artifacts via action and perception rather than passive observation.

However, many existing interactive cultural heritage systems rely on rigid devices or screen-based installations, which constrain the range of embodied experiences that can be supported. Although such systems are effective for information delivery, they often struggle to convey materiality, tactility, and bodily engagement—qualities that are central to many forms of ethnic and craft-based cultural heritage.

Recent studies have begun to explore wearable and textile-based approaches to cultural expression, particularly within smart fashion and design contexts [5]. While these efforts demonstrate increasing interest in integrating ethnic art elements into interactive systems, they often remain focused on visual styling or symbolic representation, with limited attention to how cultural meaning can be systematically translated into interaction behaviors that unfold over time through bodily engagement.

Cultural Experience and User Experience Evaluation

Evaluating cultural experience presents methodological challenges due to its subjective, interpretive, and context-dependent nature. Research on user experience (UX) evaluation offers a wide range of quantitative and qualitative methods for assessing usability, affect, and satisfaction [6]. These methods are well established for functional systems but are not always well suited to capturing culturally situated meanings.

In response, recent work has proposed frameworks for affective and emotional interaction with smart textiles, emphasizing the role of materiality and temporal dynamics in shaping user experience [8]. Such approaches underscore the value of combining quantitative metrics with qualitative inquiry to better understand how users perceive and interpret interactive textile systems.

Nevertheless, relatively few studies explicitly examine how cultural semantics can be evaluated in relation to interaction design decisions. In particular, there remains a lack of approaches that systematically link cultural analysis, interaction implementation, and user evaluation within a unified methodological framework. This limitation complicates efforts to assess whether interactive systems genuinely support cultural understanding or primarily offer novel sensory experiences.

Summary and Research Positioning

The reviewed literature reflects substantial progress in smart textile technologies, interactive cultural heritage systems, and user experience evaluation. However, these research strands largely evolve in parallel rather than converging within a unified methodological framework. Smart textile studies primarily emphasize technical integration and performance optimization, cultural heritage research often relies on visual or static forms of interaction, and user experience evaluation methods are rarely tailored to culturally situated semantics.

As a result, existing approaches provide limited methodological guidance on how cultural elements can be systematically translated into interaction behaviors that are both technically implementable and empirically evaluable. In particular, few studies specify how cultural symbols, material practices, and narrative structures can be operationalized as design parameters, instantiated through smart textile technologies, and assessed in terms of their impact on user experience.

In contrast to prior work, this study positions cultural expression as a core design and evaluation objective within smart textile interaction. Rather than treating ethnic art elements as decorative references or relying solely on interpretive analysis, the proposed framework introduces an explicit, parameterized pathway that links cultural analysis, interaction implementation, and user evaluation. By integrating cultural decomposition, embodied interaction mapping, and user-feedback-driven optimization within a single workflow, the framework aims to support reproducible and evaluable design processes for culturally expressive smart textile systems.

THE PROPOSED FRAMEWORK: CULTURAL-AWARE EMBODIED INTERACTION

Framework Overview

To support reproducible and empirically evaluable integration of ethnic art elements into smart textile interaction design, this study proposes a three-layer parameterized design-and-evaluation framework, termed cultural-aware embodied interaction. In this study, “embodied interaction” refers to sensory and material-based engagement rather than full-body motion. Accordingly, the prototype adopts a wall-hanging format to ensure stable and controlled interaction, improving consistency and comparability across participants.

The framework is formulated as a methodological pipeline that defines cultural parameters, mapping rules, and bounded adjustment strategies. This structure enables cultural analysis to be implemented as concrete smart textile interaction behaviors, rather than remaining at a purely conceptual level.

The framework links cultural analysis, technical implementation, and user evaluation within an iterative design and evaluation process, following design-oriented and material-driven interaction design principles [7,9]. By operationalizing ethnic art elements as interaction-relevant parameters rather than static decorative references, cultural expression can be instantiated, evaluated, and refined through smart textile interaction in a systematic and repeatable manner.

As illustrated in Figure 1, the framework consists of three interconnected layers: Cultural Decomposition, Experience Mapping, and Adaptive Optimization, which collectively enable the integration of ethnic art elements into smart textile interaction design.

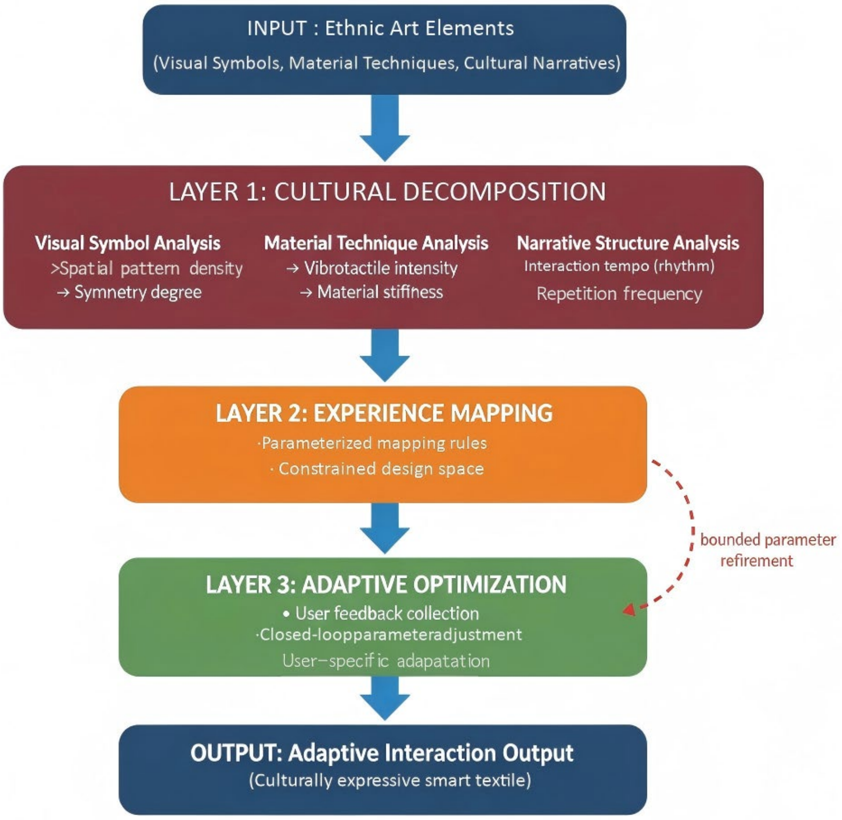

Figure 1. Overall framework of the cultural-aware embodied interaction design process, illustrating the three main layers: cultural decomposition, experience mapping, and adaptive optimization

The Cultural Decomposition Layer translates culturally situated ethnic art knowledge into an explicit, design-relevant representation. Ethnic art elements are analyzed across visual symbolism, material and technique characteristics, and narrative structures, and are decomposed into semantic attributes that are directly actionable in smart textile interaction design. This layer serves as an intermediate representation that bridges qualitative cultural interpretation and technical development, enabling coordination between interaction designers and engineers [9].

The Experience Mapping Layer establishes relationships between cultural semantics and interaction behaviors, mapping cultural attributes to tactile, temporal, and material-based interaction variables, ensuring technical feasibility and perceptual clarity. All mapping rules are defined and fixed prior to evaluation to ensure technical feasibility, perceptual distinguishability, and reproducibility, while avoiding metaphorical or purely symbolic correspondences [8].

The Adaptive Optimization Layer accounts for individual differences in perception and interpretation through a user-feedback-driven, closed-loop adjustment strategy. In this study, the term “adaptive” does not refer to autonomous or real-time sensor-driven intelligence, but to a bounded and controlled parameter refinement process guided by user experience feedback. Instead of employing data-intensive learning models, interaction parameters are incrementally refined based on user response data collected during or after interaction, operating strictly within the parameter bounds defined in the Experience Mapping Layer to preserve experimental control and reproducibility. This process does not alter the underlying cultural representations established during decomposition, thereby maintaining experimental control and comparability across conditions [6].

Together, these three layers constitute a design-oriented engineering framework that supports the creation, implementation, and empirical evaluation of culturally expressive smart textile interactions. Although instantiated through a specific case study in this work, the framework is transferable to other ethnic art forms and smart textile configurations, provided that comparable cultural attributes, interaction variables, and parameter constraints can be defined.

Cultural Decomposition Layer: Operationalizing Ethnic Art Elements

Rather than attempting to encode the full cultural meaning of ethnic art, this layer focuses on identifying culturally salient attributes that can be directly expressed through smart textile interaction.

Drawing on material-driven and craft-informed design approaches, ethnic art artifacts are treated as structured sources of visual, material, and narrative attributes. These attributes are abstracted into parameters that can be directly referenced during interaction mapping and system implementation [7,9].

In this study, Miao embroidery is selected as a representative case due to its rich symbolic system, material diversity, and well-established narrative traditions. To ensure methodological consistency and avoid purely interpretive decomposition, the selection of cultural attributes is constrained by interaction feasibility: only attributes that can be perceived, enacted, or differentiated through spatial, tactile, or temporal interaction are considered. Accordingly, three complementary dimensions are defined: (1) visual symbolism, (2) material and technique characteristics, and (3) cultural narrative structures. Together, these dimensions provide a structured and reproducible basis for translating qualitative cultural knowledge into parameters usable for interaction mapping and system implementation.

To maintain transparency and reproducibility, each cultural dimension is explicitly mapped to interaction-relevant semantic attributes and corresponding design parameters that can be directly referenced during implementation. Table 1 summarizes this operationalization process by linking cultural inputs to semantic attributes and parameterized interaction variables. Importantly, these links represent design-oriented abstractions intended to support interaction implementation, rather than direct or exhaustive representations of cultural meanings.

Table 1. Operationalization of ethnic art elements into design-relevant parameters for smart textile interaction design

Decomposition Dimension	**Cultural Input (Example: Miao Embroidery)**	**Extracted Semantic Attributes**	**Design-Relevant Parameters**
Visual symbols	Motifs (e.g., butterfly patterns), geometric composition, symmetry	Motif complexity, repetition, visual hierarchy	Pattern density, spatial distribution, symmetry ratio
Material techniques	Stitching methods, textile texture, yarn reflectivity	Surface roughness, flexibility, gloss perception	Tactile feedback intensity, material stiffness, visual reflectance

Cultural narratives	Myths, ritual symbolism, temporal storytelling	Narrative rhythm, emotional intensity, cyclic structure	Interaction tempo, feedback duration, repetition frequency

It should be noted that the narrative-related parameters listed in Table 1 (e.g., rhythm, repetition, or cyclic structure) do not aim to encode specific mythological content or ritual meanings of Miao embroidery. Instead, these parameters function as temporal interaction abstractions that reflect how narrative structures may be perceptually experienced through interaction, rather than as literal representations of cultural narratives.

Visual symbolism refers to the compositional characteristics of embroidery patterns, including motif types, symmetry, repetition, and spatial organization. In Miao embroidery, iconic motifs such as butterfly-inspired forms and geometric arrangements are analyzed in terms of contour complexity, symmetry level, and visual focal distribution. These attributes are abstracted as shape-related parameters that inform spatial layout and visual emphasis in smart textile interaction, consistent with prior work on material experience and interaction-oriented feature extraction [9].

Material and technique characteristics capture tactile and visual qualities arising from traditional embroidery practices, including stitch density, surface relief, yarn material, and reflectivity. Prior research shows that textile techniques and material choices directly shape tactile perception and embodied interaction experience [7]. Accordingly, techniques such as raised stitching and the use of lustrous threads are translated into specifiable material attributes—including surface roughness, softness, elasticity, and reflectance—which can be referenced during textile substrate selection and actuation design.

Cultural narrative structures refer to symbolic themes and temporal logic commonly associated with embroidery practices, such as mythological references and cyclical storytelling. In Miao embroidery, recurring narratives related to origin myths and migration histories are characterized by gradual unfolding and repetition. These properties are abstracted into temporal interaction parameters—including interaction rhythm, feedback duration, and repetition frequency—that later guide the design of dynamic, time-based interaction behaviors.

The outcome of the Cultural Decomposition Layer is a bounded set of cultural design parameters that bridges qualitative cultural interpretation and technical implementation. By constraining how cultural elements are translated into interaction-relevant parameters, Table 1 supports reproducibility, reduces reliance on implicit designer intuition, and facilitates multidisciplinary collaboration [9]. This decomposition does not aim to represent the full cultural complexity of ethnic art, but prioritizes attributes that are operationally actionable within smart textile interaction systems. The resulting parameter set serves as the input to the Experience Mapping Layer.

Experience Mapping Layer: From Cultural Parameters to Interaction Behaviors

Its primary function is to define rule-based and bounded mappings between cultural parameters and interaction variables, ensuring reproducible, technically feasible, and perceptually interpretable interaction behaviors.

Mapping Principles and Rule Definition

Mapping rules were formulated according to three principles.

First, mappings are parameterized rather than one-to-one symbolic correspondences, allowing a single cultural attribute to be expressed through a controlled range of interaction behaviors.

Second, all mappings are constrained by perceptual distinguishability and system feasibility, based on pilot testing and hardware limitations.

Third, all mapping rules and parameter ranges were defined and fixed prior to the main user study, ensuring experimental control and preventing post-hoc tuning effects.

Based on these principles, cultural parameters are mapped to three categories of interaction variables: spatial, tactile, and temporal, corresponding to visual symbolism, material/technique characteristics, and narrative structures, respectively.

Spatial Mapping of Visual Symbolism

Visual-symbolic parameters, including motif complexity, repetition, and symmetry (Table 1), are mapped to spatial interaction variables that govern the distribution and activation of interactive zones within the textile. Rather than reproducing visual motifs directly, spatial mapping expresses symbolic balance and hierarchy through interaction structure.

Specifically, motif density and visual hierarchy determine the number and arrangement of active interaction zones, while symmetry parameters influence synchronized or mirrored activation patterns. In the implemented prototype, spatial activation was constrained to 2–6 predefined interaction zones aligned with major embroidered motifs to maintain perceptual clarity and avoid interaction overload.

Tactile Mapping of Material and Technique Characteristics

Material- and technique-related cultural parameters—such as surface roughness, softness, and reflectance—are mapped to tactile interaction variables, primarily vibrotactile feedback amplitude and frequency. Prior studies indicate that low-frequency, higher-amplitude vibrations are more effective for conveying perceptions of material weight and texture in textile-based interfaces. Here, vibrotactile feedback is not intended to reproduce the physical texture of embroidery stitches, but to function as an interaction-level perceptual proxy that modulates perceived tactile intensity and salience during interaction.

Accordingly, tactile feedback intensity was discretized into five levels, corresponding to vibration amplitudes ranging from 0.2 to 1.0 g, with a fixed step size of 0.2 g. Feedback frequency was constrained to a low-frequency range suitable for textile interaction to maintain comfort and perceptual differentiation. These bounds were determined through pilot testing to balance perceptibility and user comfort.

Temporal Mapping of Cultural Narrative Structures

Cultural narrative parameters—such as narrative rhythm, emotional intensity, and cyclic structure—are mapped to temporal interaction variables that govern the timing and duration of feedback. Narrative rhythm informs interaction tempo, while cyclic storytelling structures guide repetition patterns and temporal sequencing.

In the implemented system, interaction tempo was constrained to a frequency range of 0.5–2.0 Hz, discretized in steps of 0.25 Hz, enabling gradual transitions and repeated interaction loops without inducing fatigue or confusion. Feedback duration and repetition frequency were similarly bounded to ensure that temporal patterns remained interpretable across users.

Summary of Mapping Parameters and Constraints

Table 2 summarizes the mapping between cultural parameters and interaction variables, including predefined ranges and step sizes used in the prototype implementation.

Table 2. Parameterized mapping rules between cultural attributes and interaction variables

Cultural Attribute	Interaction Variable	Range	Step Size
Motif density / hierarchy	Spatial activation zones	2–6 zones	1
Surface roughness	Vibration amplitude	0.2–1.0 g	0.2 g
Narrative rhythm	Interaction tempo	0.5–2.0 Hz	0.25 Hz
Cyclic structure	Repetition frequency	1–4 cycles	1

Note: The mapping between surface roughness and vibration amplitude represents a perceptual abstraction for interaction design, rather than a direct physical equivalence.

These parameterized mapping rules directly inform prototype implementation and serve as the initial configuration for the Adaptive Optimization Layer. By constraining mappings within predefined ranges and fixing rules prior to evaluation, the Experience Mapping Layer ensures that cultural expression through interaction remains systematic, reproducible, and empirically testable.

Adaptive Optimization Layer: User-Feedback-Driven Personalization

The Adaptive Optimization Layer introduces a user-feedback-driven bounded parameter refinement mechanism to account for individual differences in perception, interpretation, and affective response during smart textile interaction. Prior research in user experience evaluation and human–textile interaction indicates that users may respond differently to identical tactile or temporal stimuli due to variations in sensory sensitivity, prior experience, and cultural familiarity [6,10]. To prevent such variability from undermining experimental consistency, adaptive refinement in this study is explicitly constrained and controlled.

In this study, the term “adaptive” does not refer to continuous or data-driven learning, but to controlled, incremental adjustment within predefined parameter ranges, prioritizing experimental control and interpretability.

Adaptive optimization was applied only after an initial standardized interaction phase, during which all participants experienced identical interaction settings. All subsequent parameter adjustments were performed within the predefined bounds established in the Experience Mapping Layer (Section “Experience

Mapping Layer: From Cultural Parameters to Interaction Behaviors”), ensuring functional equivalence across participants and experimental conditions.

Rather than employing data-intensive learning models, the framework adopts a lightweight, closed-loop adjustment strategy suitable for small-sample, design-oriented smart textile studies. Here, the closed-loop mechanism operates at the level of post-interaction user experience feedback rather than real-time sensor-driven autonomous adaptation. Interaction parameters generated by the Experience Mapping Layer—such as feedback intensity, temporal rhythm, and spatial activation patterns—serve as the initial configuration. User response data are collected through quantitative and qualitative channels, including self-reported ratings of cultural clarity and experience satisfaction, as well as brief post-interaction prompts [6].

Parameter refinement follows an incremental and bounded adjustment strategy. When users report insufficient clarity or weak cultural resonance, selected parameters (e.g., feedback amplitude or temporal contrast) are increased by one predefined step per iteration to enhance perceptibility. Conversely, when interaction is perceived as overwhelming or distracting, parameters are attenuated using the same step size to maintain comfort and coherence. To preserve experimental control, a maximum of three adjustment iterations was allowed per participant.

This iteration limit was intentionally selected to balance limited personalization with cross-participant comparability, rather than to achieve convergence toward an optimal or fully personalized solution.

Importantly, the bounded personalization optimization process does not introduce new interaction variables or modify mapping rules, nor does it alter the underlying cultural semantics defined in the Cultural Decomposition Layer. Instead, it refines how predefined cultural parameters are expressed through interaction within controlled bounds.

The outcome of the Adaptive Optimization Layer is a personalized yet comparable interaction configuration that improves alignment between perceived user experience and intended cultural expression. The effectiveness of this bounded personalization strategy is evaluated in the user study through measures of cultural narrative recognition and experience satisfaction.

PROTOTYPE IMPLEMENTATION AND SYSTEM ARCHITECTURE

This section describes the design rationale, fabrication process, and system architecture of the smart textile prototype developed to instantiate and evaluate the proposed framework. The prototype serves as a controlled experimental implementation of the cultural decomposition, experience mapping, and bounded adaptive refinement mechanisms described in Section “The Proposed Framework: Cultural-aware Embodied Interaction”.

Prototype Design and Form Factor Selection

The prototype was designed as a narrative smart textile artifact intended to support culturally expressive interaction under controlled experimental conditions. Rather than adopting a wearable form factor, a wall-hanging smart textile was selected as the primary configuration. This choice reflects the traditional display and ceremonial roles of embroidered textiles in cultural contexts, while also enabling stable integration of sensing and actuation components.

From an engineering perspective, the wall-hanging form factor minimizes variability associated with continuous wear, such as body movement, fit differences, and motion-induced signal noise. By reducing these confounding factors, the prototype provides a controlled interaction environment in which the effects of interaction mapping and parameterized feedback can be more reliably evaluated. This design decision therefore balances cultural relevance with experimental controllability.

The prototype layout was directly informed by the design-relevant parameters derived in the Cultural Decomposition Layer (Section “Cultural Decomposition Layer: Operationalizing Ethnic Art Elements”). Embroidered motifs were arranged according to extracted symmetry and focal distribution characteristics, and interactive zones were spatially aligned with these motifs. In the implemented prototype, a fixed number of interaction zones was defined and embedded beneath or adjacent to culturally salient motifs, ensuring that interaction behaviors were structurally coupled to cultural elements rather than added as external or generic feedback.

By explicitly aligning the physical layout of sensing and actuation components with decomposed cultural parameters, the prototype functions as a material instantiation of the proposed framework, allowing cultural semantics, interaction behavior, and user response to be examined within a unified and reproducible system configuration.

Digital Fabrication and Textile Integration

The prototype was fabricated using a digital embroidery–based e-textile workflow that integrates functional textile components directly into traditional embroidery patterns. Conductive yarns were employed as both structural embroidery elements and electrical interconnects, enabling signal transmission while maintaining visual continuity with surrounding non-conductive threads. This approach allows sensing and actuation elements to be embedded within the textile surface without introducing rigid components or disrupting the visual integrity of the embroidery.

Two types of textile-based sensors were integrated: capacitive touch sensors and pressure-sensitive textile sensors. Sensors were embedded within embroidered regions corresponding to culturally salient motifs, and their placement followed the spatial distribution parameters defined in the Cultural Decomposition Layer (Section “Cultural Decomposition Layer: Operationalizing Ethnic Art Elements”). By aligning sensing locations with visual and narrative focal areas, interaction inputs were structurally coupled to cultural elements rather than arbitrarily distributed across the textile.

Actuation was implemented using a combination of addressable light-emitting elements and low-profile vibrotactile motors, enabling both visual–temporal and tactile feedback. Light-based feedback supported spatial and temporal expression of visual symbolism, while vibrotactile feedback conveyed material- and texture-related attributes through controlled amplitude and rhythm, as defined by the parameterized mapping rules in Section “Experience Mapping Layer: From Cultural Parameters to Interaction Behaviors”. All actuators were selected to ensure low profile and compatibility with flexible textile substrates.

All functional components were mounted on a flexible textile base layer and interconnected through embroidered conductive pathways, forming an integrated e-textile structure. Electrical connections between sensors, actuators, and control electronics were realized through stitched conductive traces, minimizing the need for discrete wiring. The fabrication process emphasized modularity at the component level, allowing individual sensors or actuators to be replaced or reconfigured without altering the overall textile layout or embroidery pattern.

This modular and embroidery-integrated fabrication strategy supports reproducibility and adaptability. By maintaining a clear correspondence between cultural parameters, interaction zones, and embedded textile components, the prototype can be readily adapted to alternative ethnic art patterns or interaction scenarios while preserving the underlying framework structure. To support reproducibility and facilitate engineering-oriented evaluation, key implementation parameters of the prototype are summarized in Table 3.

Table 3. Implementation details of the smart textile interaction prototype

Component Category	**Specification**
Microcontroller Unit (MCU)	32-bit microcontroller (e.g., Arduino Nano 33 IoT–class), operating at 48 MHz
Sensor Types	Capacitive touch sensors; pressure-sensitive textile sensors
Sensor Sampling Rate	50 Hz
Signal Processing	Moving average filtering (window size = 5 samples); threshold-based event detection
Actuators (Tactile)	Low-profile vibrotactile motors
Vibration Amplitude Range	0.2–1.0 g (step size: 0.2 g)
Actuators (Visual)	Addressable LED elements embedded via digital embroidery
Temporal Control Range	Interaction tempo: 0.5–2.0 Hz (step size: 0.25 Hz)
Power Supply	External 5 V DC supply
Textile Integration Method	Digital embroidery with conductive yarns for sensing and interconnection
Adaptive Optimization	Bounded parameter adjustment; maximum of three iterations per participant

System Architecture and Data Flow

The system architecture adopts a modular and layered design consistent with the proposed framework. As illustrated in Figure 2, the system comprises four main modules: (1) sensor input, (2) interaction mapping logic, (3) feedback actuation, and (4) user feedback collection.

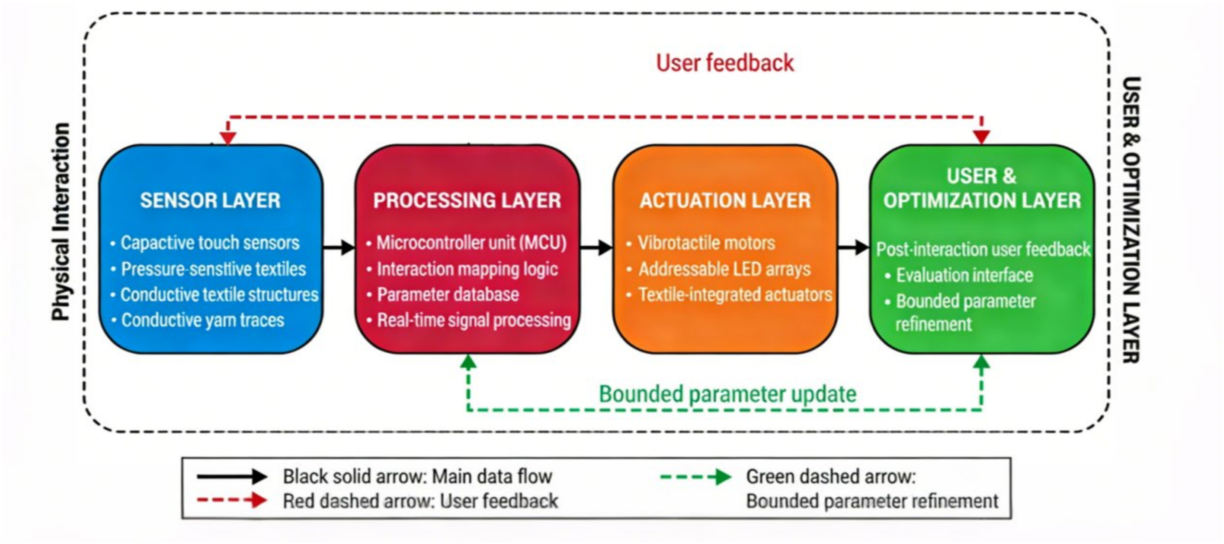

Figure 2. System architecture of the smart textile interaction platform, illustrating data flow from sensor input through interaction mapping to feedback actuation, with bounded user-feedback-driven parameter refinement.

Sensor input data, including touch location and interaction duration, are sampled by a microcontroller unit (MCU) and forwarded to the interaction mapping module. This module implements the parameterized and rule-based mapping logic defined in Section “Experience Mapping Layer: From Cultural Parameters to Interaction Behaviors”, translating sensor events into real-time control signals for visual and tactile feedback. Mapping parameters—such as feedback intensity scaling, temporal modulation, and spatial activation patterns—are stored as adjustable but bounded variables, rather than fixed constants, enabling controlled refinement while preserving experimental consistency.

The feedback actuation module drives light-based and vibrotactile outputs according to the generated control signals, enabling interaction behaviors that unfold over time in accordance with the predefined cultural mapping rules. All actuation parameters operate strictly within the predefined ranges established in the Experience Mapping Layer, ensuring perceptual stability and preventing uncontrolled variation during interaction.

User feedback is collected through short post-interaction questionnaires and optional verbal prompts. As described in Section “Adaptive Optimization Layer: User-Feedback-Driven Personalization”, this feedback is used to support bounded parameter refinement within the same predefined ranges. Importantly, user-feedback-driven adjustment does not introduce new interaction variables, modify mapping rules, or alter cultural semantics; instead, it functions as a controlled micro-adjustment of existing parameters, ensuring comparability across participants and experimental conditions.

Overall, the architecture supports a constrained closed-loop interaction process that links cultural intent, interaction behavior, and user experience. By separating sensing, mapping, actuation, and feedback handling into distinct modules, the system maintains transparency, reproducibility, and experimental controllability, while remaining adaptable to alternative cultural artifacts or smart textile configurations. The prototype employs standard textile-based sensors and low-profile actuators operating within bounded parameter ranges to ensure stable system performance during evaluation.

USER STUDY AND EVALUATION

Study Design and Participants

A mixed-method evaluation approach was adopted, combining quantitative measures with qualitative inquiry, in line with established user experience research practices [6]. Sixty participants (20 per condition; 32 female, 28 male; age range: 20–35 years, M = 26.4, SD = 3.8) were recruited. All participants reported normal or corrected-to-normal vision and no known tactile impairments. The study protocol followed institutional ethical guidelines, and informed consent was obtained from all participants.Participants were recruited from a general university population with diverse academic backgrounds, and none reported professional training or formal education in textile design, embroidery, or Miao cultural studies.

To ensure comparable cultural starting points across experimental groups, participants completed a brief pre-study questionnaire assessing familiarity with Miao embroidery and related cultural patterns using a 5-point Likert scale. A one-way ANOVA indicated no significant difference in cultural familiarity among the three groups ($F(2,57) = 0.42$, $p = .66$), suggesting that subsequent group differences could be attributed primarily to the experimental conditions rather than prior cultural knowledge.

A between-subjects experimental design was employed. Participants were randomly assigned to one of three conditions:

- **Condition A (Framework-based interaction):** Participants interacted with the smart textile prototype implemented using the proposed cultural-aware embodied interaction framework, including parameterized interaction mapping and bounded user-feedback-driven refinement.

- **Condition B (Static cultural textile):** Participants interacted with a non-interactive embroidered textile displaying identical visual motifs to Condition A, without sensing, actuation, or dynamic feedback.
- **Condition C (Non-cultural interactive textile):** Participants interacted with an interactive textile prototype featuring generic interaction behaviors (e.g., uniform light patterns and random vibrotactile feedback) that were not derived from cultural parameters.

To control for potential confounding effects of adaptive refinement, user-feedback-driven parameter adjustment was applied only within Condition A and only after an identical initial interaction phase. All parameter adjustments were constrained within predefined bounds specified in Section “Experience Mapping Layer: From Cultural Parameters to Interaction Behaviors”, with a maximum of three adjustment iterations per participant. No cross-condition adaptation was performed. As a result, observed differences among conditions can be attributed to framework-level design strategies rather than unequal exposure duration or system responsiveness.

Each participant interacted with the assigned prototype in a quiet indoor laboratory environment with stable ambient lighting and minimal external disturbance for approximately 10 minutes. Each session consisted of an initial familiarization phase (~2 min), a guided interaction phase (~3 min), and a free exploration phase (~5 min). Following the interaction session, participants completed a questionnaire and participated in a brief semi-structured interview to capture both quantitative evaluations and qualitative impressions.

Measures and Data Collection

Cultural narrative recognition accuracy was assessed using a structured interpretation task in which participants were asked to identify and describe the cultural meaning conveyed by the textile interaction. While cultural interpretation is inherently subjective and fluid, 'recognition accuracy' in this study does not refer to determining a fixed 'correct' interpretation of culture. Instead, it evaluates how effectively the interaction design facilitates engagement with cultural content and encourages diverse interpretations. This measure reflects the degree to which the design supports meaningful cultural engagement, recognizing that cultural narratives are dynamic and can be interpreted in multiple valid ways. Therefore, recognition accuracy is seen as an indicator of how well the design enables users to connect with and interpret cultural elements, rather than a strict alignment with predefined narrative criteria.

A coding guide derived from the Cultural Decomposition Layer (Table 1) was developed prior to the user study to operationalize recognition criteria. The guide specified key narrative elements, symbolic references, and temporal characteristics expected to be recognized through interaction. Participant responses were independently coded by two research assistants who were blind to experimental conditions. For each participant, recognition accuracy was calculated as the proportion of correctly identified narrative elements relative to the total number of predefined elements:

$$\mathrm{RecognitionAccuracy}=\frac{N_{\mathrm{correct}}}{N_{\mathrm{total}}}\times 100$$

Inter-rater reliability was assessed using Cohen's κ and indicated high agreement between coders ($\kappa = 0.82$), supporting the reliability of the coding procedure.

Cultural experience satisfaction was measured using a 5-point Likert-scale questionnaire adapted from prior work on user experience and cultural interaction evaluation [6,11]. The questionnaire assessed perceived cultural clarity, emotional engagement, and overall interaction satisfaction. An overall satisfaction score was computed as the mean of all items. The adapted scale demonstrated good internal consistency in a pilot test (Cronbach's $\alpha = 0.89$).

In addition to quantitative measures, qualitative data were collected through post-interaction semi-structured interviews and think-aloud observations. These data focused on participants' interpretive strategies, perceived alignment between interaction behavior and cultural meaning, and overall experiential impressions. Qualitative findings were used to contextualize and interpret the quantitative results rather than as standalone evaluative metrics.

Results

Quantitative Results

As shown in Table 4, Condition A (framework-based interaction) achieved higher cultural narrative recognition accuracy and experience satisfaction scores than both baseline conditions.

Table 4. Summary of quantitative evaluation results

Condition	**Recognition Accuracy Mean ± SD (%)**	**Satisfaction Mean ± SD (1–5)**
A (Framework-based)	78.50 ± 6.43	4.33 ± 0.26
B (Static textile)	52.50 ± 6.26	3.35 ± 0.24
C(Non-cultural interactive)	58.15 ± 6.38	3.54 ± 0.25

All statistical analyses followed standard assumption checks. A one-way ANOVA revealed a significant main effect of condition on cultural narrative recognition accuracy, $F(2, 57) = 92.51$, $p < .001$, $\eta^2 = 0.76$. Post-hoc Tukey comparisons indicated that Condition A significantly outperformed both Conditions B and C (all *ps* < .001), and that Conditions B and C also differed significantly ($p < .01$).

Pairwise effect size analysis indicated large between-group differences. For cultural narrative recognition accuracy, Cohen’s *d* values were 4.17 for Condition A vs. Condition B and 3.20 for Condition A vs. Condition C. For experience satisfaction, Cohen’s *d* values were 4.02 (A vs. B) and 3.35 (A vs. C), indicating large effects according to conventional benchmarks.

A similar pattern was observed for experience satisfaction. The main effect of condition was significant, $F(2, 57) = 87.66$, $p < .001$, $\eta^2 = 0.75$, with post-hoc comparisons showing that Condition A received significantly higher satisfaction ratings than both baseline conditions (all *ps* < .001).

Exploratory Analysis

An exploratory ANCOVA was conducted with cultural familiarity score included as a covariate. The main effect of condition remained significant for both cultural narrative recognition accuracy, $F(2, 56) = 85.34$, $p < .001$, and experience satisfaction, $F(2, 56) = 80.12$, $p < .001$. Cultural familiarity did not emerge as a significant covariate for either measure (*ps* > .10), and no significant interaction between condition and cultural familiarity was observed.

Qualitative Results

Qualitative observations from post-interaction interviews and think-aloud protocols revealed systematic differences across conditions. Participants in Condition A frequently described the interaction as “telling a story through rhythm and touch” and “making the embroidery feel alive.” In contrast, participants in

Condition B primarily focused on visual appearance, while participants in Condition C described the interaction as engaging but culturally ambiguous. These qualitative observations are consistent with the quantitative performance patterns across conditions.

DISCUSSION

Summary of Key Findings

This study demonstrates that the proposed framework supports the systematic translation of ethnic art elements into smart textile interaction behaviors. The empirical results indicate that framework-guided interactive designs yield significantly higher cultural narrative recognition and experience satisfaction than both static cultural textiles and non-cultural interactive baselines.

The observed effect sizes should be interpreted in relation to the experimental design, which employed contrasting baseline conditions to compare different culturally themed textile interaction strategies, rather than to fully disentangle the isolated effects of interactivity novelty and cultural framing.

In this study, “embodied interaction” refers to sensory and material-based engagement rather than full-body motion. The wall-hanging prototype was adopted to ensure stable and controlled interaction, thereby improving experimental consistency across participants.

Recognition accuracy refers to the alignment between a user’s interpretation of the cultural content and a predefined set of cultural narrative criteria. While cultural interpretation is inherently fluid and subjective, this measure is not intended to assess a single “correct” interpretation. Instead, it reflects how effectively the interaction supports user engagement with culturally relevant content within a structured design framework.

Overall, the findings suggest that smart textile interaction, when structured through parameterized cultural mapping and bounded user-feedback-driven refinement, can function as an embodied medium for cultural expression through material and sensory engagement, rather than merely as a responsive technical interface.

Theoretical and Practical Implications

From a theoretical perspective, this research contributes to the literature on cultural computing and embodied interaction by advancing a design-oriented methodological approach to cultural expression in smart textiles. By operationalizing ethnic art elements as interaction-relevant parameters and embedding them within a rule-based mapping and evaluation pipeline, the proposed framework-guided design approach complements existing interpretive and design-led approaches with an engineering-oriented, empirically evaluable methodology. The inclusion of a bounded Adaptive Optimization Layer further suggests that individual differences in cultural perception can be addressed through controlled parameter refinement, without reliance on data-intensive learning models.

From a practical perspective, the framework provides actionable guidance for the design and evaluation of culturally expressive smart textile systems. Potential application domains include interactive museum installations, cultural education tools, and smart fashion or interior textiles, where cultural meaning must be conveyed through material properties, temporal dynamics, and embodied interaction rather than visual representation alone. By supporting reproducible implementation and empirical evaluation, the framework offers a transferable foundation for future smart textile applications across diverse cultural contexts.

Limitations and Future Work

Several limitations of this study suggest directions for future work. First, the participant sample consisted primarily of young and highly educated individuals, and the overall sample size was moderate. Although sufficient for controlled experimental evaluation, future work could validate the proposed framework with larger and more demographically and culturally diverse populations to further assess its generalizability.

Second, while cultural decomposition is necessary for systematic engineering implementation, it inevitably involves abstraction and simplification of complex, context-dependent cultural knowledge. In this study, such abstraction is intentionally confined to interaction-level and perceptual parameters, and does not aim to represent or reconstruct the full symbolic, mythological, or ritual meanings of the original cultural artifacts. Future work could incorporate insights from anthropology and material culture studies to refine decomposition strategies and support more nuanced parameter definitions without compromising technical feasibility.

Third, although cultural familiarity was measured and statistically controlled, subtle variations in individual cultural interpretation remain difficult to quantify. In addition, the laboratory-based evaluation environment may not fully reflect authentic cultural engagement contexts. Future research could therefore consider insitu studies in museums, exhibitions, or public cultural spaces to examine how culturally expressive smart textiles are perceived and interpreted in real-world settings.

An additional limitation concerns the experimental comparison design. As the framework-based condition integrates both interactivity and culturally grounded mapping, the present study does not fully disentangle the isolated effect of interaction novelty from that of the proposed framework itself. Rather than aiming for strict causal separation, this study prioritizes evaluating the effectiveness of a framework-guided cultural interaction strategy in contrast to static cultural presentation and non-cultural interactive designs. Future work will introduce finer-grained experimental conditions to further separate novelty effects from framework-level contributions.

An additional limitation concerns the bounded nature of the adaptive optimization mechanism, which prioritizes experimental control and comparability over convergence and therefore should not be interpreted as a fully adaptive or learning-based system.

Finally, the current prototype implementation relies on a specific set of sensing and actuation technologies. While sufficient for validating the proposed framework, future work could examine its applicability across a broader range of smart textile materials, sensing modalities, and actuation mechanisms, as well as its integration with emerging textile fabrication technologies.

CONCLUSION

This study examined how ethnic art elements can be systematically integrated into smart textile interaction design to support cultural expression and user experience. To address limitations of prior approaches that primarily treat cultural elements as static visual references, a reproducible three-stage framework was proposed, comprising cultural decomposition, parameterized experience mapping, and bounded user-feedback-driven refinement. By operationalizing cultural symbols, material characteristics, and narrative structures as explicit design parameters, the framework enables cultural intent to be translated into implementable and empirically evaluable interaction behaviors.

A smart textile prototype inspired by Miao embroidery was developed as a material instantiation of the proposed framework and evaluated through a controlled user study. The results indicate that framework-based interaction designs lead to significantly higher cultural narrative recognition accuracy and experience satisfaction compared with both static cultural textiles and non-cultural interactive baselines. Within the scope of the experimental design, these findings suggest that smart textile interaction, when structured through parameterized cultural mapping and controlled refinement, is capable of supporting cultural expression as an embodied interaction medium rather than functioning solely as a responsive technical interface.

While parameterizing cultural experience inevitably involves abstraction and simplification, the proposed framework provides a practical, design-oriented engineering pathway for balancing cultural expressiveness with technical realizability in smart textile systems. By emphasizing reproducible implementation and empirical evaluation, this work offers a transferable methodological foundation for future research and applications in areas such as cultural heritage presentation, interactive exhibitions, and wearable or spatial smart textile environments.

Author Contributions

Yingfang Xu designed, collected and analyzed the data, and drafted the manuscript. Yingfang Xu conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Yingfang Xu participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Conflicts of Interest

The authors declare no conflict of interest.

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Ethics Approval and Consent to Participate

This survey was conducted in compliance with Ethics Committee of Zhejiang Fashion Institute of Technology. Participants were informed of the study's purpose and data usage prior to participation, and responses were collected anonymously. No personally identifiable information was stored.

Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

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