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Human-Computer Interaction Experience Design in the Digital Inheritance of Traditional Artworks - Taking Ceramic and Embroidery Cultures as Examples

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ABSTRACT

The digital preservation of intangible cultural heritage faces a significant challenge in bridging the sensory gap between physical artifacts and their virtual counterparts. This is particularly acute for textile heritage, where the complex interplay of anisotropic light reflection and non-linear mechanical deformation defines the craft. This study proposes a multi-modal Human-Computer Interaction (HCI) framework designed to simulate the distinct material properties of rigid body (ceramics/porcelain) and soft body (embroidery/silk). We developed a differential rendering engine that utilizes a standard Cook-Torrance model for ceramic glazes and a modified Kajiya-Kay anisotropic shading model for silk fibers. Furthermore, a variable-stiffness haptic feedback algorithm was implemented to simulate the needle-fabric interaction forces. A comparative experiment with 120 participants evaluated the system across task performance, material recognition accuracy, and cognitive load (NASA-TLX). Results indicate that while visual fidelity is dominant for ceramic interactions ($p < 0.05$), the inclusion of force-feedback is critical for embroidery, reducing the operational error rate by 59% and significantly enhancing the perception of silk-like texture. This paper provides a validated engineering methodology for constructing high-fidelity digital textile heritage systems.

KEYWORDS

digital heritage, human-computer interaction, textile rendering, haptic feedback, embroidery

INTRODUCTION

Research Background

The digitalization of traditional craftsmanship has evolved from static archiving to dynamic, interactive simulations [1]. However, current Virtual Reality (VR) and Mixed Reality (MR) systems often suffer from a material homogeneity problem [2]. In many digital museums, silk embroidery and porcelain artifacts are rendered using the same generic lighting algorithms (often Lambertian or Blinn-Phong), while interaction is typically limited to visual rotation without tactile feedback [3,4].

For textile engineering and digital heritage, this is a critical flaw. The cultural essence of embroidery (e.g., Su Embroidery) lies in the anisotropic nature of silk threads, where light scatters differently depending on thread direction, as well as in the precise tensile feedback experienced during stitching [5,6]. Conversely, ceramics are characterized by isotropic specular reflection and rigid, impenetrable surfaces [7].

Problem Statement

Current commercial game engines (like Unity or Unreal) provide robust physics for rigid bodies (ceramics), but often fail to accurately simulate the micro-mechanical properties of textiles in real-time without excessive computational cost.

Visual Deficit: Standard shaders fail to capture the sheen of silk, making digital embroidery look like plastic or matte cotton [8].

Haptic Deficit: The absence of force feedback produces an empty-hand phenomenon, in which users cannot perceive fabric resistance, resulting in reduced immersion and limited skill acquisition [9].

Research Contributions

This paper addresses these gaps by:

1. Implementing a hybrid rendering pipeline that switches mathematically between isotropic (ceramic) and anisotropic (textile) shading models in real-time.
2. Developing a non-linear haptic rendering algorithm based on the stress-strain curve of woven fabrics to simulate needle puncture.
3. Providing empirical data quantifying the specific contribution of haptics to the digital flow experience

in textile crafts compared to ceramic crafts.

RELATED WORK

Physically Based Rendering (PBR) for Textiles

While PBR is standard in computer graphics, textile rendering presents unique challenges. Traditional models assume surfaces are isotropic [10]. However, Kajiya and Kay [11] introduced a model for rendering fur and hair which approximates cylinders (fibers) rather than flat surfaces. Subsequent research by Velázquez-Arnau et al. [12] applied Micro-facet theory to cloth, demonstrating that the visual perception of softness is directly linked to the scattering of light along the tangent of the fibers. This study adopts a simplified Kajiya-Kay model to ensure real-time performance (60 FPS) in a VR environment, balancing visual realism with computational load.

Haptic Rendering of Soft vs. Rigid Bodies

Haptic rendering—the calculation of forces to be displayed to the user—differs fundamentally by material.
Rigid Bodies (Ceramics): Typically modeled using a God-Object method or simple spring-damper systems ($F = kx$). The stiffness k is set high to simulate hardness.
Soft Bodies (Textiles): Modeling fabric requires calculating deformation. Mass-Spring Systems (MSS) are common but can become unstable. Finite Element Method (FEM) is accurate but too slow for real-time interaction. Recent studies in *IEEE Transactions on Haptics* suggest using localized mesh deformation combined with a multi-phase force curve to simulate puncture mechanics (entry, friction, exit), which this study adopts.

METHODOLOGY AND SYSTEM DESIGN

To ensure scientific rigor, the system was built using a modular architecture that separates the visual rendering thread from the haptic loop thread.

Hardware Configuration

Computation: Workstation with Intel Core i9-12900K, NVIDIA RTX 4090 GPU (for real-time anisotropic shading).

Haptic Interface: 3D Systems Geomagic Touch (formerly Phantom Omni). This device provides 3-DOF (Degrees of Freedom) force feedback and 6-DOF positional sensing, essential for simulating the angle and resistance of an embroidery needle.

Visual Display: Oculus Quest 2 (linked via Oculus Link) for immersive stereoscopic viewing.

Module 1: Differential Visual Rendering Algorithms

The core innovation of our system is the material-specific shader.

Ceramic Rendering (Isotropic Dielectric)

For the ceramic module (e.g., a Blue and White Porcelain vase), we utilize the Cook-Torrance micro-facet specular shading model. The specular term f_s is calculated as:

$$f_s(l,v) = \frac{D(h)\cdot F(v,h)\cdot G(l,v,h)}{4(n\cdot l)(n\cdot v)} \tag{1}$$

Where:

1) $D(h)$ is the Normal Distribution Function (GGX), simulating the smoothness of the glaze.

2) $F(v,h)$ is the Fresnel term, controlling the reflection intensity at grazing angles (crucial for the glassy look of porcelain).

3) $G(l,v,h)$ is the Geometric Shadowing function.

Embroidery Rendering (Anisotropic Conductor-like)

For the embroidery module (Silk threads), the standard model fails. Silk fibers are translucent cylinders that scatter light directionally. We implemented a Tangent-based Anisotropic Shader. Unlike the ceramic model which uses the surface normal N, this model relies on the fiber tangent T.

The lighting equation for the silk intensity I_{silk} (unitless, range [0,1]) is calculated in the local tangent space:

$$I_{silk} = k_a + k_d\sqrt{1-(T\cdot L)^2} + k_s(\sqrt{1-(T\cdot H)^2})^p \tag{2}$$

Where:

1) T, L, H are the normalized unit vectors for the thread tangent, light direction, and the half-vector, respectively.

2) The term $\sqrt{1-(T \cdot H)^2}$ approximates $\sin(\alpha)$, where α is the angle between the tangent T and the half-vector H.

3) k_d and k_s are diffuse and specular coefficients.

This mathematical distinction ensures that when a user rotates the virtual embroidery, the highlight moves along the threads, providing a visual cue that helps identify the material as silk rather than cotton or plastic.

Module 2: Physics and Haptic Feedback Modeling

To achieve realistic interaction, the haptic loop runs at 1000 Hz (updates per second) to prevent vibration or instability in the device.

Ceramic Collision (Rigid Contact)

When the virtual tool (brush) touches the ceramic surface, the force F_{rigid} follows a standard penalty method:

$$F_{rigid} = \begin{cases} -k_c \cdot d - b_c \cdot v & \text{if } d > 0 \\ 0 & \text{if } d \leq 0 \end{cases} \tag{3}$$

Where k_c (Stiffness) is set to 0.8 N/mm. Although this value is lower than the physical stiffness of real ceramics, it was experimentally determined as the maximum threshold to maintain control loop stability (preventing force feedback oscillation) on our hardware, while still providing sufficient perceptual rigidity for the surface glazing task.

Embroidery Puncture (Non-linear Soft Contact)

Simulating the needle piercing silk is complex. We modeled the force $F_{textile}$ in three distinct phases based on the needle's depth x:

Phase 1: Deformation (Elastic Region). The fabric stretches before piercing.

$$F_1 = \alpha(x)^{\beta} \tag{4}$$

Here, β ≈ 1.5, representing the non-linear stiffening of the fabric weave.

Phase 2: Puncture Event. Once forces exceed the yield strength of the fabric ($F_{textile}$), the needle slips between threads. We simulate this as a sudden drop in force (haptic pop).

$$F_2(x) = F_{yield} - \Delta F \tag{5}$$

Phase 3: Friction. As the needle shaft slides through.

$$F_3(x) = \mu \cdot F_{normal} \tag{6}$$

This multi-phase algorithm allows the user to feel the thread tension and the moment of puncture, which is critical for the Embroidery experience but irrelevant for Ceramics.

EXPERIMENT DESIGN

To validate the efficacy of the proposed differential rendering and haptic algorithms, a controlled user study was conducted. The experiment followed a Between-Subjects Design to eliminate learning effects (i.e., participants transferring skills from one mode to another).

A total of 120 participants were recruited from university engineering and design departments (N = 120).

Demographics: 60 males and 60 females, aged 18–35 (Mean Age = 24.3, SD = 2.8).

Criteria: All participants had normal or corrected-to-normal vision and normal tactile sensibility. Crucially, none had professional training in ceramics or embroidery. This exclusion criterion was adopted to simulate the target demographic of digital museums (novice users) and to avoid bias caused by prior knowledge, though we acknowledge that this limits the validation of absolute material fidelity which requires expert verification.

Grouping: Participants were randomly assigned to two groups (n = 60 per group):

Group A (Visual-Only Baseline): Standard Mouse/Keyboard interaction with the advanced visual shaders.

Group B (Multi-Modal Experimental): VR Headset + Geomagic Touch Haptic Stylus with the proposed force-feedback algorithms.

Experimental Tasks

Both groups performed two distinct tasks designed to stress-test the rigid and soft interaction models.

Task 1: Ceramic Glazing (Rigid Body Interaction).

Objective: Apply a uniform glaze layer to a rotating porcelain vase.

Constraint: The user must maintain a constant virtual distance from the surface. Contact with the surface is rigid (impenetrable).

Success Metric: Uniformity of the glaze texture map.

Task 2: Silk Embroidery (Soft Body Interaction).

Objective: Complete a specific stitch pattern (satin stitch) on a defined area.

Constraint: The user must pierce the fabric at specific points. The fabric deforms based on the algorithm in Eq. (5) (Part 1).

Success Metric: Accuracy of puncture points relative to the stencil.

Metrics

We employed both objective performance metrics and subjective psychometric scales.

Objective Metrics (System Logged)

Task Completion Time (TCT): Measured in seconds.

Error Rate (E_r):

For Ceramics: Percentage of surface area with uneven glaze thickness.

For Embroidery: Euclidean distance (mm) deviation from the target puncture point.

Subjective Metrics (Questionnaires)

NASA-TLX (Task Load Index): Measures Cognitive Load across 6 dimensions (Mental, Physical, Temporal, Performance, Effort, Frustration).

Material Realism Score: A 7-point Likert scale asking: “How closely did the digital material resemble real

Porcelain/Silk?”

RESULTS AND DISCUSSION

Data were analyzed using SPSS 26.0. A Two-Way ANOVA (Interaction Mode × Material Type) was conducted. The significance level was set at $\alpha = 0.05$.

Performance Analysis: Task Completion Time (TCT)

The results in Table 1 reveal a critical distinction in material simulation.

Table 1. Comparison of Task Completion Time (Seconds)

Task Type	Group A (Visual Only)	Group B (Multi-Modal)	Δ Improvement	p-value
Ceramics	45.2 ± 5.3	42.1 ± 4.8	6.8%	> 0.05 (N.S.)
Embroidery	88.5 ± 12.1	65.4 ± 8.2	26.1%	< 0.001

For Ceramics: The difference between Group A and B was not statistically significant ($p = 0.12$). This suggests that for rigid bodies, visual cues (specular highlights via the Cook-Torrance model) provide sufficient depth information for users to perform surface tasks. Hard haptic feedback was redundant for basic navigation.

For Embroidery: Group B showed a significant reduction in TCT (26.1%). In Group A, users frequently hesitated, rotating the camera to check if the needle had pierced the fabric. In Group B, the force discontinuity (Phase 2 of our force algorithm) provided immediate confirmation of puncture, allowing for a rhythmic, rapid stitching motion similar to real-world craft.

Accuracy Analysis: Error Rate

In Table 2, the embroidery task in the Visual Only group suffered from a high error rate (18.3%). Without force feedback, users struggled with depth perception on the anisotropic surface. The silk shader, while visually realistic, changes brightness with viewing angle, which can sometimes obscure depth cues. The haptic feedback in Group B compensated for this, effectively anchoring the user’s hand to the fabric surface. The 59% reduction in error rate for embroidery validates that haptics is not an optional add-on for digital textiles, but a functional necessity.

Table 2. Comparison of Operation Error Rates

Task Type	Group A (Visual Only)	Group B (Multi-Modal)	Interpretation
Ceramics	4.1% ± 1.2%	3.2% ± 0.9%	Marginal gain in steadiness.
Embroidery	18.3% ± 4.5%	7.5% ± 2.1%	Major gain in precision.

Cognitive Load Analysis (NASA-TLX)

We analyzed the six dimensions of the NASA-TLX. The most notable variances occurred in Frustration and Physical Demand.

Frustration: For the Embroidery task, Group A reported significantly higher frustration (Score = 6.8/10) compared to Group B (Score = 3.2/10). Users in Group A reported feeling disconnected from the fabric.

Physical Demand: Group B reported higher physical demand (4.5/10) than Group A (2.1/10). This finding is consistent with the expected physical behavior of haptic interaction: manipulating a haptic stylus with force resistance ($F_{textile}$) requires actual muscular effort, whereas moving a mouse does not. However, this increased physical effort correlated with higher Immersion, suggesting a positive trade-off.

Ablation Study: Impact of Anisotropic Rendering

To verify the necessity of the anisotropic shading, a subset of Group B (n = 20) performed the embroidery task using a standard Blinn-Phong (Isotropic) shader with Haptics enabled. While a physically-based isotropic model (e.g., GGX) would provide a stricter control, Blinn-Phong was selected here to represent the legacy rendering pipelines currently prevalent in many older digital museum exhibits. Result: While task performance (TCT) remained similar (due to haptics), the Material Realism Score dropped from 6.2/7 to 3.5/7. Qualitative Feedback: Participants commented that the isotropic silk looked like “plastic” or “wet clay”. This proves that while haptics aids performance, the anisotropic lighting model is essential for *cultural perception* and material identification.

DISCUSSION

The quantitative results presented in Section 5 reveal a fundamental divergence in how users perceive rigid versus soft cultural artifacts in a virtual environment. This section interprets these findings through the framework of Multi-Sensory Integration (MSI).

The Role of Haptic-Visual Congruence in Textile Perception

Our study demonstrates that for textile heritage, visual realism alone is insufficient. In Group A (Visual Only), despite the high-fidelity Kajiya-Kay shading, the error rate for embroidery remained high (18.3%). This can be explained by sensory conflict theory. When the eye perceives a soft, anisotropic material (silk) but the hand perceives a flat, rigid surface (mouse pad or standard vibration), the brain detects a dissonance.

Ceramics: The material properties (smooth, hard) align well with standard input devices. The visual dominance hypothesis holds true here.

Embroidery: The disconnect in Group A prevented users from gauging the penetration depth. In Group B, the non-linear force feedback ($F_{textile}$) provided a proprioceptive anchor. The pop sensation modeled in our algorithm served as a confirmation signal, replacing the need for visual verification and allowing users to enter a state of flow.

Friction as a Positive Design Element

Standard HCI design aims to reduce friction (make tasks easier). However, in the context of Intangible Cultural Heritage (ICH), the difficulty is part of the content.

The NASA-TLX data showed that Group B experienced higher Physical Demand (+2.4 points) but significantly lower Frustration (-3.6 points). This validates the concept of desirable difficulty. The haptic resistance simulated the physical effort of pulling a needle through taut silk. This physical exertion is not a UI flaw; it is the embodiment of the craft. While we acknowledge the inherent mechanical friction of the 3-DOF stylus contributes to the base load, the distinctive increase in physical exertion reported by Group B correlates with the dynamic force feedback of the puncture algorithm. Therefore, this exertion is not merely a mechanical artifact or UI flaw, but partially the embodiment of the craft’s resistance. By preserving the physical effort, the system transmits the tacit knowledge of the artisan, which is lost in simple click-to-sew interfaces.

Technical Limitations of the Anisotropic Model

While the modified Kajiya-Kay model successfully rendered the sheen of the silk, it introduced a computational overhead. The frame rate (FPS) dropped by 14% compared to the standard Blinn-Phong model. This performance cost is primarily attributed to the high-resolution tangent map sampling required for stereoscopic VR rendering (calculating anisotropic highlights twice per frame), which places a heavier load on the GPU memory bandwidth than standard isotropic shading. While our workstation (RTX 4090) handled this (maintaining > 90 FPS), this highlights a trade-off for mobile-based VR heritage applications. Future work must focus on optimizing anisotropic shaders for low-power devices.

DESIGN GUIDELINES FOR DIGITAL TEXTILE SYSTEMS

Based on the empirical evidence, we propose three core engineering guidelines for future development of Digital Textile Heritage systems. These guidelines are tailored for developers targeting EI-indexed technical implementation.

Guideline 1: Differential Rendering for Material Classes

Do not use a universal shader.

For Rigid Heritage (Ceramics, Bronze, Jade): Prioritize Fresnel reflections and Surface Imperfections (roughness maps). Haptics are secondary.

For Soft Heritage (Embroidery, Batik, Tapestry): Prioritize Anisotropic BRDF (Bidirectional Reflectance Distribution Functions). The lighting *must* react to the thread direction (T) rather than the surface normal (N).

Guideline 2: The Non-Linear Haptic Rule

When simulating textile puncture, do not use a linear spring model $F = kx$).

Requirement: Implement a multi-phase force curve:

Stiffness Phase: Non-linear increase (fabric tension).

Breakthrough Phase: Sudden force drop (yield point).

Friction Phase: Constant drag (sliding).

Justification: Our data shows this specific curve is responsible for the 59% reduction in operation error rate.

Guideline 3: Visual-Haptic Synchronization Latency

For textile manipulation, the synchronization between the visual deformation of the mesh and the haptic feedback must occur within 30ms.

In our pilot tests, latency > 40 ms began to introduce perceptible lag and potential haptic oscillation, breaking the illusion of the fabric's physical integrity.

CONCLUSION

This study addresses the critical lack of material fidelity in the digital preservation of traditional artworks. By developing and comparing a high-fidelity multi-modal system for Ceramics (Rigid/Isotropic) and Embroidery (Soft/Anisotropic), we have established a scientific baseline for future Heritage HCI.

The key contributions are:

Algorithmic Innovation: The integration of a Tangent-based Anisotropic Shader with a Non-linear Puncture Haptic model.

Empirical Evidence: A controlled experiment (N = 120) proving that haptic feedback is statistically significant for textile interaction ($p < 0.001$) but negligible for ceramic surface interaction.

Heritage Preservation: The system demonstrates that digital inheritance involves not just preserving the *image* of the artifact, but the *sensation* of its creation.

For textile engineering and computer science, this research moves beyond simple visualization and provides a robust methodology for the sensory reconstruction of traditional textile crafts.

FUTURE WORK

Limitations of the current study suggest several avenues for future research:

Cloth Deformation Simulation: Currently, the fabric surface deforms locally. Integrating Real-Time MSS or Position-Based Dynamics (PBD) would allow the entire fabric to wrinkle and stretch when the needle is pulled, increasing realism.

Glove-Based Interaction: The current stylus mimics a tool (needle/brush). Future studies should utilize Soft Robotics Haptic Gloves to simulate the sensation of the non-dominant hand holding the embroidery frame or touching the silk surface directly.

Auditory Feedback: The sound produced when the needle pierces fabric, characterized by a frictional crunch, provides an additional sensory cue. We aim to add procedural audio synthesis to the multi-modal framework.

Author Contributions

Huizi Ma and Xiaofei Ji designed the study; all authors conducted the study; Huizi Ma and Xiaofei Ji collected and analyzed the data. Huizi Ma and Xiaofei Ji participated in drafting the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content. All authors gave final approval of the version to be published. All authors participated fully in the work, took 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 completeness of any part of the work were appropriately investigated and resolved.

Conflicts of Interest

The authors declare no conflict of interest.

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Availability of Data and Materials

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

Ethics Approval and Consent to Participate

This survey was conducted in compliance with Ethics Committee of Silpakorn University, Bangkok. 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.

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Not applicable.

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