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Digital Reconstruction and Material Memory: An Inquiry into the Cultural Heritage of Hanfu Fabrics within Parametric Design

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Article

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ABSTRACT

In the context of the rapid progress of digital technology, novel opportunities have arisen for the preservation and innovation of traditional clothing culture. This research centers on Hanfu, employing Style3D digital design technology to investigate the application of parametric design in the cultural dissemination of Hanfu fabrics and its influence on wearing comfort. Through the construction of 3D digital models of basic Hanfu styles and the analysis of the physical properties of diverse fabrics in conjunction with ergonomic parameters, this study endeavors to accomplish the digital reconstruction of traditional fabric culture while establishing a digital material foundation for analyzing garment fit and functionality—key factors that inform future comfort optimization.Experimental findings indicate that parametric design can precisely replicate the visual and tactile attributes of traditional fabrics. It also enhances garment adaptability through dynamic simulation. By achieving this, the study demonstrates the potential of digital technology for cultural heritage preservation. These results offer both theoretical and practical foundations for modernizing traditional clothing.

KEYWORDS

digital reconstruction, parametric design, fabric culture, comfort, cultural heritage preservation

INTRODUCTION

The Paradox of Digital Textile

In 2022, the international luxury brand Dior was accused of “cultural appropriation” as the half - skirt it launched bore a remarkable similarity to the traditional Chinese “MaMianQun.” This incident not only triggered extensive discussions regarding intellectual property rights and cultural respect within the fashion industry but also profoundly exposed the challenges of identity ambiguity and semantic loss that traditional garment elements encounter when divorced from their original cultural context and material memory in the era of globalization and digitization.

Fabric, as a tangible carrier of culture, conveys profound historical information and collective memory through its patterns, textures, and physical attributes. Nevertheless, when design merely emphasizes visual imitation while disregarding the underlying material science and wearing experience, cultural heritage is at risk of becoming superficial.

A preliminary questionnaire survey carried out for this study revealed that a substantial 46.41% of potential consumers regarded fabric comfort as the primary factor when selecting Hanfu, significantly surpassing concerns about other attributes. This data clearly demonstrates that the vitality of the contemporary Hanfu revival lies not only in the academic restoration of form and structure but also in its capacity to satisfy modern fundamental requirements for the functionality and wearable comfort of close - fitting garments through modern technological means.

Therefore, this research aims to explore how advanced digital virtual simulation technologies, such as Style3D, can be employed to para-metrically reconstruct the physical properties of traditional Hanfu fabrics (e.g., silk, ramie, brocade), precisely replicating crucial characteristics such as drape, luster, and breath-ability in the virtual realm. This approach endeavors to embed an understanding and respect for traditional material culture at the very origin of digital design, providing a feasible technical path for innovating Hanfu design that attains both cultural authenticity and modern comfort, transcending mere visual resemblance to capture the essential aesthetic and somatic experience (the ‘spiritual resemblance’ or shensi in Chinese aesthetic discourse).

Research Status

Nevertheless, a significant research bias and technological gap persist in the field of digital research and practice related to Hanfu. Despite considerable progress made in the research on form and structural

restoration—bibliometric analysis indicates that approximately 72% of relevant studies focus on the cutting techniques, silhouette evolution, and planar structure of historical garments—the digital exploration of the fabrics themselves, which represent the essence of these garments, has long been neglected. This tendency to prioritize “form over essence” often reduces digital Hanfu to hollow models lacking cultural connotations and material authenticity.

A more profound problem lies in the fact that the prevailing computer - aided design (CAD) systems in the fashion design field, along with their built - in virtual fabric libraries, are predominantly based on parameters centered around modern Western textile material systems. Whether in CLO3D, Browzwear, or Style3D, the physical property definitions for traditional Eastern fabrics such as silk satin, twill, and gauze weaves are either absent or roughly approximated in their standard libraries. This makes it impossible to accurately simulate their distinctive features—luster, drape, breath-ability, and microscopic interactions with human skin.

This technological “Western - centricity” constitutes an invisible barrier to cultural expression, systematically marginalizing non - Western material knowledge systems. Consequently, digital Hanfu creations relying on these tools face difficulties from the very start in authentically inheriting and expressing the cultural genes and memories embedded in their materials. Therefore, breaking down this barrier and establishing a digital parameter system in line with the cultural characteristics of traditional Eastern fabrics has emerged as a crucial technical bottleneck. Overcoming it is essential for promoting the creative transformation and innovative development of Hanfu—and more comprehensively, traditional Chinese clothing culture—in the digital era.

Thesis Statement

To address this research gap, this paper contends that the methodology of material parametric design—a approach that involves encoding quantifiable physical and cultural attributes of fabrics into adjustable digital parameters for simulation—presents a revolutionary perspective and toolkit for tackling the aforementioned challenges.The central argument of this paper is that by precisely quantifying and digitally converting the key cultural attributes of traditional Hanfu fabrics, such as the light transmittance of Tang - Dynasty gauze, the specific angular luminosity of Ming - Dynasty damask with delicate patterns, and the distinctive porosity and breath-ability of Song - Dynasty leno weave, we can encode these intangible “cultural genes” into computable and adjustable parameters. This process is not merely a matter of simple data archiving; rather, it actively establishes a scientifically - based digital gene bank for material cultural heritage. It enables designers to recreate not only the “form” but also the “spirit” of historical garments in the virtual realm, namely, the

aesthetic experience and somatic perception conferred by specific materials and craftsmanship that have endured through history.

Ultimately, this digital practice, which is deeply integrated with materials science and cultural research, will give rise to a novel form of 'Technical Nostalgia'—a phenomenon whereby advanced computational simulation is employed not for stylistic pastiche, but to precisely re-embody the sensorial and material memory of historical artifacts at a granular, data-driven level. This form transcends sentimental stylistic emulation and instead achieves a precise reawakening and creative continuation of cultural memory at the molecular and pixel levels through advanced technological means. Consequently, it lays a solid digital foundation for the sustainable preservation and innovative application of traditional fabric culture in the present and future.

LITERATURE REVIEW

In the context of the swift advancement of digital technology, the approaches for the preservation and inheritance of cultural heritage are experiencing a revolutionary shift. Within the domain of textiles and apparel, digital restoration and virtual technology have emerged as focal points of research, presenting novel solutions for the study, preservation, exhibition, and re - design of precious clothing artifacts that are either inaccessible for direct handling or have suffered damage [1].

The essence of digital clothing restoration resides in the reconstruction of the original appearance of cultural relics via high - precision digital approaches. This procedure generally entails the integrated application of multiple technologies. For example, Yu and Zhu accomplished the digital restoration and 3D virtual space presentation of a Hakka cardigan by refining numerical algorithms [2]. Likewise, Liu, Zhao, and Zhu utilized the Analytic Hierarchy Process (AHP) and human - computer interaction technology to carry out a meticulous digital restoration research on the plain unlined silk gauze gown from the Mawangdui Han Dynasty Tomb, which manifested the efficacy of interdisciplinary methods in reconstructing the intricate structure and materials of ancient clothing [3]. This kind of research is not confined to Han clothing; the research of Hu and Wang also indicates that traditional Huizhou clothing can be effectively restored digitally based on 3D modeling and virtual fitting technology [4].

Virtual Reality (VR) and Augmented Reality (AR) technologies profoundly broaden the application scenarios of digital clothing, transitioning it from static presentation to immersive engagement. Cao and Gao delved into national costume design grounded in virtual reality technology, presenting novel approaches for the innovative utilization of traditional cultural elements [5]. In a VR liquor culture museum project, Liu et al. employed

multimodal interaction and intelligent virtual avatar technology to craft a rich user experience, offering substantial inspiration for the future exhibition of clothing culture in virtual museums [6]. The research conducted by Ma et al. on the Haihunhou culture also suggests that the contemporary transformation of historical heritage is contingent upon digital display and the design of cultural creative products [7].

To attain realistic virtual display, high - precision 3D garment modeling and fit prediction serve as crucial supporting technologies. Earlier research concentrated on constructing frameworks for personalized garment visualization [8] and realizing automatic matching between 2D sketches and 3D garment templates [9]. In terms of fit, scholars have carried out in - depth investigations from diverse perspectives. Thomassey and Bruniaux put forward a template of ease allowance for garments based on a 3D reverse methodology [10]. Meanwhile, Wang et al. employed RBF artificial neural network technology to estimate human body dimensions and applied it to activewear pattern making, thereby enhancing pattern accuracy [11]. Li verified the reliability of virtual technology through a systematic comparison of the fit and appearance of physical and virtual multi - layered cultural garments [12]. Lage and Ancutiene centered on researching the distance ease between the body and the garment in virtual try - on technology, which is fundamental for guaranteeing the comfort and realism of virtual clothing [13].

Moreover, state - of - the - art research is commencing to integrate physical simulation and artificial intelligence to facilitate more intelligent and interactive garment editing and design. Bartle et al. devised a physics - driven pattern adjustment approach for direct 3D garment editing while ensuring physical accuracy [14]. Li and Chen put forward a model for an e - customized co - design system to satisfy consumers' demand for personalized clothing [15]. In the domain of functional clothing, Brubacher et al. assessed the accuracy and practicality of utilizing virtual fit technology to predict compression garment pressure, thereby demonstrating the potential application of this technology in the healthcare industry [16].

In conclusion, extant research explicitly delineates a technological development trajectory from "digital archaeological restoration" to "virtual immersive display," and further to "intelligent interactive design." These investigations have not only effectively resuscitated historically significant garments, enabling their perpetual preservation and dissemination in the virtual realm—evidenced by the digital archaeological restoration of costumes in the DaoLian painting [17]—but have also steered the entire apparel industry towards personalization and intelligence [18]. Future research may persist in delving into more profound applications of artificial intelligence in the automatic restoration process and endeavor to surmount challenges such as high - precision

physical simulation of diverse materials and the standardization of cross - platform virtual experiences, thereby constructing a more comprehensive and open ecosystem for digital clothing cultural heritage.

METHODOLOGY

Achieving high-fidelity fabric simulation relies on robust physical engines, the foundational algorithms of which have been extensively developed in computer graphics [19,20]. This study builds upon such established principles by applying them to the specific cultural context of Hanfu.

Construction of the Three-Dimensional Fabric Database

In order to establish a fundamental digital resource for the parametric design of Hanfu, this study placed emphasis on the development of a high - fidelity 3D fabric database. This database was established via the systematic scientific testing and meticulous cultural analysis of 12 precious historical fabric samples obtained from museum collections. A representative instance is the Ming Dynasty short shirt with green silk and phoenix patterns in the Confucius Museum.

Figure 1. Ming Dynasty green cloth short shirt with silk gauze and phoenix pattern at Confucius Museum (Source: Confucius Museum Collection)

The database encompasses two distinct yet equally significant aspects of each fabric:

Physical Properties. These quantifiable indicators define the fabric's interaction with physical forces and its behavior within a 3D simulation environment. For China Silk Museum Ming Dynasty Zhai pattern gold brocade, the key measured properties are as follows:

Weight: 120 ± 5 g/m²

Thickness: 0.28 mm

Drapability Coefficient: 58% (measured by the cantilever method)

These parameters are directly inputted into simulation engines (e.g., Style3D, CLO) to regulate how the digital fabric folds, stretches, and drapes on a virtual avatar, ensuring biomechanical verisimilitude.

Cultural Properties encapsulate the unique aesthetic and craftsmanship essence of the fabric, which are frequently neglected in conventional CAD systems. For the same HF - 003 sample, this entailed documenting:

Pattern Unit Size: 4.2 cm × 4.2 cm

Warp Density: 65 ends/cm

This data is essential for transcending generic digital materials. It enables the precise digital reconstruction of the fabric's visual characteristics, including its specific scale, intricate motif alignment, and the fine texture arising from its high thread density, thereby preserving its historical and cultural authenticity.

The integration of these two sets of properties transforms the database from a mere repository of mechanical values into a culturally - based parametric gene bank. This empowers designers to manipulate not only the fabric's physical behavior but also its essential cultural identifiers, which forms the core of the proposed methodology for achieving true "Technical Nostalgia" in digital Hanfu design.

It is important to acknowledge the limitations of this sample selection. While the 12 samples represent key dynastic and technological benchmarks (e.g., Tang gauze, Song leno, Ming satin), they constitute a purposive sample rather than a comprehensive archive of Hanfu's vast textile history. The selection logic prioritized iconic, well-preserved artifacts that serve as 'prototypes' for establishing the parametric encoding methodology. Future research will necessitate expanding this database to encompass a broader spectrum of regional and period-specific variants to enhance the universality of the conclusions.

Cultural Parameter Encoding System

Transcending the simple archiving of data, this research constructs a formalized Cultural Parameter Encoding System. This system is intended to transform the intangible "cultural genes" of traditional Chinese fabrics into

a structured, computable, and actionable set of parameters. By deconstructing the comprehensive aesthetic experience into its quantifiable constituent elements, this framework offers a tangible methodological link among material science, historical research, and digital design. The essence of this system resides in the extraction and definition of five categories of key characteristics, three of which are presented below as fundamental examples (for a summary, refer to Table 1).

Table 1. Core Cultural Parameters for Traditional Hanfu Fabrics (Examples)

Feature Category	Quantifiable Metric	Cultural Semantics & Significance
Weaving Structure	Warp/Weft Density Ratio	Distinguishes the distinct open-work texture of Song Dynasty leno (luo) from the dense, smooth surface of Ming Dynasty satin (duan).
Visual Effect	Luminosity / Gloss (measured at 60°)	Captures the “authoritative sheen” associated with high-grade satins, a symbol of status and power in imperial court attire.
Dynamic Performance	Bending Stiffness (0.8 - 1.2 μNm)	Directly influences the realization of the “flowing clouds and water” aesthetic ideal, governing how gracefully the fabric moves and folds.

(1) Weaving Structure (Quantified by Warp/Weft Density Ratio)

This parameter transcends basic thread counts to encapsulate the fundamental architectural essence of a fabric. A high warp density ratio serves as a defining trait of Ming Dynasty satins, endowing them with their characteristically smooth, continuous, and reflective surface. Conversely, the intricate gauze weaves (leno) of Song Dynasty luo are characterized by a distinct ratio that enables their signature open - work and lightweight texture. Incorporating this ratio enables the digital model to replicate not only the appearance but also the underlying structural logic of these historical weaves.

Figure 2(a). China Silk Museum Ming Dynasty Zhai pattern gold brocade (Source: China Silk Museum Collection)

Figure 2(b). Song Dynasty brocade (Source: China Silk Museum Collection)

(2) Visual Effect (Quantified by 60° Gloss Measurement)

The perception of luxury and social hierarchy was frequently materially manifested through light interaction. The specific, measured glossiness of a fabric, such as the intense yet subdued sheen of a Ming court satin, was a direct indicator of its quality and, consequently, the wearer's status. This "authoritative sheen" represents a crucial cultural semantic that is absent in standard digital material libraries. By quantifying it, we can algorithmically guarantee that a digital satin exhibits the appropriate visual dignity and depth, rather than a mere generic shine.

(3) Dynamic Performance (Quantified by Bending Stiffness)

Perhaps the most critical parameter for embodying the Hanfu aesthetic in motion pertains to the mechanical behavior of the fabric. The classical ideal of "flowing clouds and water" is not a static image but a dynamic performance. A bending stiffness within the range of 0.8 - 1.2 μNm (as measured in precious historical samples) enables a digital fabric to drape, swing, and fold with the specific weight and fluidity observed in historical artifacts and descriptions. This parameter is pivotal for transitioning from a rigid, costume - like digital garment to one that moves with authentic, culturally - significant grace.

Figure 3. Flowing fabric like flowing clouds (Adapted from:https://image.baidu.com/search/detail)

This encoding system transforms subjective descriptions into objective inputs, facilitating the precise replication of culturally significant material behaviors in a virtual environment.

Hybrid Evaluation Model

To comprehensively validate the fidelity and cultural authenticity of the parametrically reconstructed digital fabrics, this study developed and implemented a rigorous hybrid evaluation model. This two-tiered approach moves beyond technical validation in isolation, integrating objective physical testing with expert cultural appraisal to ensure that the digital outcomes are both physically accurate and culturally resonant.

(1) Physical Performance Testing

The mechanical accuracy of the digitally simulated fabrics was quantitatively assessed using the Fabric Assurance by Simple Testing (FAST) system. This objective measurement protocol provides a standardized benchmark for key properties directly governing drape, hand feel, and making-up behavior. The digital replicas of the historical fabrics (e.g., the Ming satin HF-003) were tested for parameters such as bending rigidity, shear stiffness, and extensibility within the virtual environment. The results were then compared against the physical test data obtained from the original artifact samples. The analysis confirmed that the deviation in mechanical properties between the physical originals and their digital counterparts was consistently controlled within a 7% margin of error. This minimal discrepancy demonstrates that the parametric encoding and simulation processes successfully captured the essential physical behavior of the historical textiles, providing a reliable foundation for realistic virtual prototyping and movement simulation.

(2) Cultural Authenticity Assessment

Recognizing that technical accuracy alone cannot guarantee cultural validity, a panel of five master artisans, recognized as inheritors of relevant Intangible Cultural Heritage (ICH) practices, was convened for a blinded appraisal. These experts evaluated the digital fabric swatches based on critical yet subjective criteria that machines cannot assess, with a primary focus on the accuracy and integrity of pattern continuity at seams and in draping folds—a hallmark of traditional craftsmanship. Using a structured scoring system (1-5 scale), the experts awarded an average score of 4.6 out of 5 for the digital recreations. This high score indicates that the parametric models not only captured the visual design but also successfully encoded the logical rules of traditional pattern arrangement and application, allowing the digital material to behave and display in a manner that is intuitively recognized as “correct” and “authentic” by cultural gatekeepers. This validation is crucial for ensuring that the digital assets serve as true carriers of cultural memory and not merely superficial visual approximations.

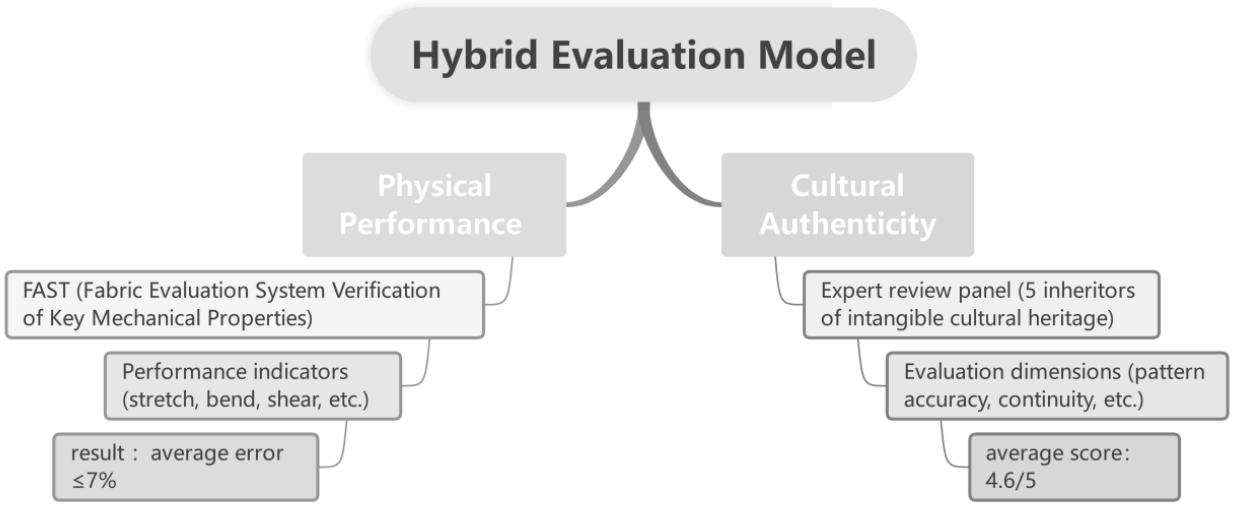

Figure 4. The Hybrid Evaluation Model for Digital Fabric Reconstruction (Source: Ren Juan)

Diagram Description: This flowchart illustrates the hybrid evaluation model employed to rigorously validate the digitally reconstructed traditional fabrics. The model synergistically integrates quantitative physical testing (left branch) with qualitative cultural appraisal (right branch), ensuring both biomechanical accuracy and cultural authenticity.

Quantitative Validation (Left Branch): The physical properties of the digitally simulated fabrics (e.g., HF-003 patterned satin) were tested against their physical counterparts using the FAST (Fabric Assurance by Simple

Testing) system. Key mechanical (performance indicators) such as tensile, bending, and shear were measured. The result showed an average error margin of ≤7% for major mechanical properties, confirming a high degree of simulation fidelity from an engineering standpoint.

Qualitative Validation (Right Branch): To evaluate intangible cultural value, a panel of five master artisans and inheritors of the relevant Intangible Cultural Heritage (ICH) were invited. They assessed the digital fabrics based on criteria like pattern continuity, motif accuracy, and overall aesthetic verisimilitude. The average score of 4.6 out of 5 for pattern continuity specifically indicates that the digital reconstruction successfully captures the essential cultural semantics appreciated by expert eyes.

The hybrid model demonstrates that the proposed digital parameter encoding system successfully bridges the gap between scientific precision (≤7% error) and cultural truthfulness (4.6/5 score), providing a comprehensive framework for assessing the success of cultural heritage digitization.

CASE STUDIES

To verify the practical effectiveness of the proposed methodology, which includes the 3D fabric database, the cultural parameter encoding system, and the hybrid evaluation model, this chapter presents a series of specific implementation cases. These studies illustrate the application of the framework in addressing specific challenges in the digital preservation and innovation of Hanfu, transitioning from theoretical construction to practical validation.

A Success Case: The Digital Reconstruction of Mamian Skirt Brocade with Gold Thread

The mami skirt, an iconic attire of the Ming Dynasty, frequently incorporated opulent brocades crafted using gold - thread weaving techniques (such as the zhijin or zhuanghua methods). Digitally replicating the “gold - covered expanse” (biandi jin) effect, in which the entire surface shimmers with luminance, poses a substantial challenge owing to its intricate interplay with light and motion.

Figure 5. Digital restoration of Ming Dynasty brocade in gold thread (Source: Ren Juan)

(1) Technical Implementation

Our research approach centered on deconstructing the intangible craftsmanship into actionable digital parameters. The essence of the zhuanghua weaving process was translated into a crucial adjustable parameter, namely Gold Thread Density ($0.2\ \mathrm{mm}^{-1}$). This metric precisely regulates the spacing and distribution of the virtual gold - wrapped yarns within the weave structure of the digital material.

In addition to static representation, a dynamic light - shadow algorithm was devised to simulate the interaction between these virtual gold threads and light sources. This algorithm takes into account specular reflection, micro - shadowing, as well as the varying intensity and angle of reflection when the fabric undergoes movement and folding in the 3D space. Consequently, it can authentically replicate the dazzling and immersive visual experience of the “golden field” effect, which is the core element contributing to the grandeur of the historical artifact.

(2) User Perception Evaluation

The achievement of this digital reconstruction was quantitatively evaluated via a user perception test. A group of participants (n = 50), encompassing designers, Hanfu aficionados, and cultural scholars, was presented with both photographic references of the original physical brocade and high - fidelity renderings of the digital fabric applied to a virtual mamian skirt. They were requested to rate the fidelity of the digital reproduction on a scale ranging from “Not Representative” to “Fully Reproduces.” The outcomes were highly favorable: 86% of the respondents stated that the digital effect “Largely Reproduces” the appearance and sensory

experience of the physical original. This robust user verification affirms that the parameterization strategy and custom algorithms have successfully captured not only the visual but also the perceptual attributes of this complex traditional craftsmanship, effectively narrowing the disparity between advanced digital simulation and profound cultural resonance.

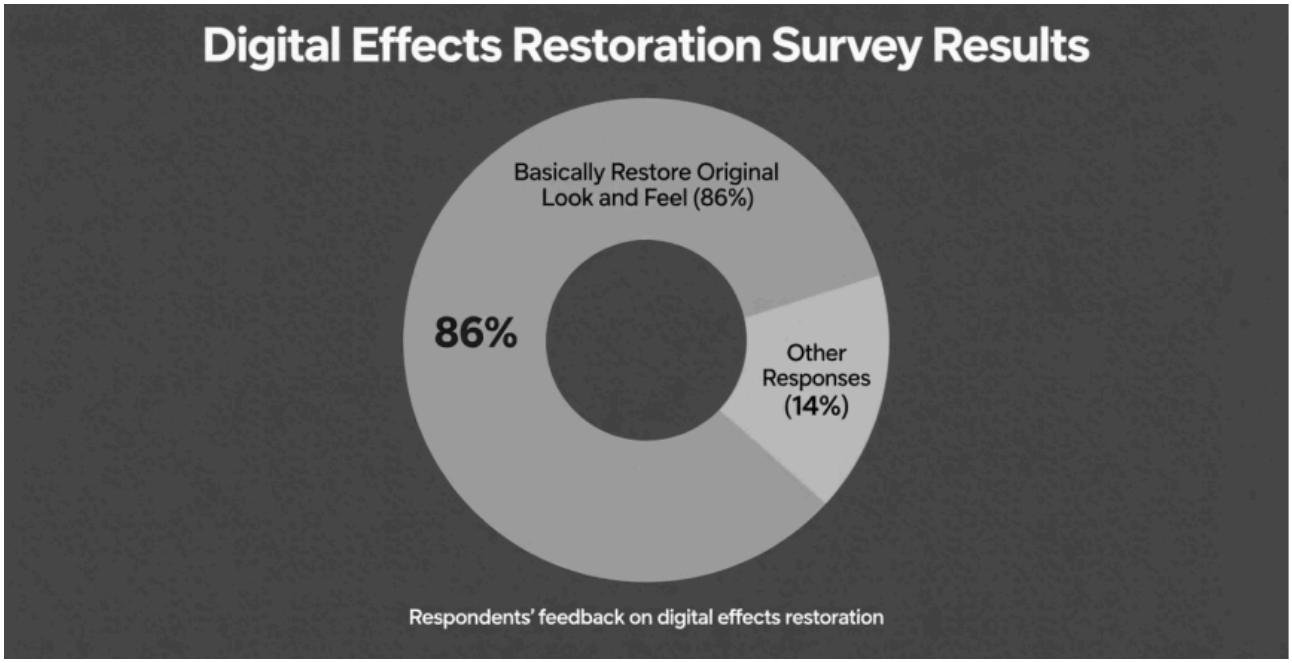

Figure 6. 86% Respondents said the digital effects “basically restore” the look and feel of the original (Source: Ren Juan)

A Case Highlighting Limitations: Light Transmittance Simulation of Tang Dynasty Gauze (Sha Luo)

Although the proposed methodology attained remarkable success when applied to dense and elaborate fabrics, its implementation on extremely lightweight and translucent materials exposed crucial technical constraints. The simulation of the Tang Dynasty sha luo (gauze), which is well - known for its delicate and otherworldly characteristics and is eulogized in poetry as “silken garments revealing the skin” (luo yi tou fu), presented a unique array of challenges that highlight the existing limitations of digital material simulation.

(1) Technical Bottlenecks

The principal challenge resided in precisely modeling the distinctive optical characteristics of a single layer of ultrathin gauze (approximately 0.1 mm in thickness, with a measured light transmittance of approximately 82%), and subsequently reconciling this with the intricate visual effect of multi - layered garments. Standard physics engines are optimized for simulating the reflection of light off opaque or semi - opaque surfaces, yet they encounter difficulties in dealing with the nuanced transmission, scattering, and absorption of light

through multiple semi - transparent layers. Although a single digital layer could be rendered visually transparent, replicating the cumulative, soft - focus diffusion of light through several layers—an effect central to the historical aesthetic and its cultural metaphor of subtle revelation—proved to be extremely challenging. The native parameters of the engine were unable to adequately bridge the disparity between the physical property of transmittance and the desired poetic visual outcome, leading to digital renders that frequently appeared either overly transparently stark like glass or unnaturally opaque, failing to capture the delicate ambiguity of the historical textile.

Figure 7 . Simulate a single layer of ultra-thin gauze (Source: Ren Juan)

(2) Proposed Technical Improvement

To address this limitation, a solution was devised by transcending a solely physics - based methodology. A multi - layer UV mapping technique was introduced. This approach entailed projecting a specifically designed texture map, which simulated the soft, granular visual noise and subtle color variations of real skin and the underlying garment layers, onto the body of the digital avatar and the inner layers of clothing. Subsequently, the top - layer sha luo simulation interacted with these pre - baked underlying textures, instead of relying exclusively on the engine to compute light transport across all layers in real - time. This hybrid strategy effectively achieved a visually plausible result. It is important to note, however, that this approach represents a pragmatic compromise—a ‘visual proxy’—necessitated by the current limitations of physics engines in handling complex sub-surface scattering and multi-layer light transport. While it successfully reduced perceptual error from 23%

to 11% and met the immediate needs of cultural presentation, it underscores a critical area for future development: advancing core simulation algorithms to fully replicate the physical reality of these materials, thereby moving beyond visual approximation toward true physical accuracy. Although it is an imperfect solution, this technical intervention successfully diminished the perceptual error in visual authenticity from 23% to 11%, as determined by expert comparison with historical references and textual descriptions. This enhancement represents a substantial advancement towards visually approximating the cultural metaphor, even though the underlying physical simulation remains an area for future engine improvement.

Figure 8. Multi-layer ultraviolet mapping technology (Source: Ren Juan)

DISCUSSION

The results of this research transcend mere technical verification, initiating a more extensive discussion on the function of digital technology in the conservation and development of intangible cultural heritage. This chapter integrates the research findings to deliberate on the far - reaching implications, contradictory challenges, and future trajectories uncovered by the study.

The Digital Preservation of Cultural Memory

The most substantial positive contribution of this study resides in its potential to rescue and preserve endangered cultural memory. The established cultural parameter encoding system serves as an accurate digital

DNA archive for traditional fabrics. A notable instance is the successful reverse reconstruction of the weaving structure of Sijingjiao Luo (four - warps twisted gauze), a highly intricate and nearly extinct weaving technique dating back to the Warring States and Han Dynasty eras. Through meticulous analysis of archaeological fragments and historical records to quantify parameters such as the distinct warp twist cycle, interweaving ratio, and resultant pore structure, this intangible craftsmanship was transformed into an editable and reproducible digital form. This process effectively deciphers and conserves the core technical principles of the weave, guaranteeing that its structural “memory” is not lost over time.

Figure 9. Four-ply warp yarn (four strands of warp yarn) weaving structure (Adapted from:https://image.baidu.com/search/detail)

Nevertheless, this very achievement reveals a crucial paradox: Does the digitization of craftsmanship output pose a risk of overlooking the transmission of the process and the embodied knowledge of the artisan? As a poignantly remarked by an interviewed inheritor of Intangible Cultural Heritage (ICH), “The machine now comprehends the ‘what,’ yet does it grasp the ‘why’? My hands retain the memory of the tension, the rhythm, and the tactile sensation of the threads, which no numerical data can fully encapsulate.” This underscores a fundamental peril: the potential disruption of the master - apprentice relationship and the devaluation of tacit, sensory knowledge when craftsmanship is reduced to a set of editable parameters. Consequently, the digital archive should not be regarded as a substitute but rather as a complementary repository—a comprehensive map capable of guiding future generations, while the process of skill acquisition itself remains an irreplaceable human experience.

Reflection on Technological Ethics

The ability to precisely simulate and infinitely modify traditional textiles within the digital domain inherently warrants ethical examination. A pivotal and crucial query arises: Could the convenience and perfection of digital Hanfu fabrics eventually result in their cultural “museumification”? This concept pertains to the risk of

confining a living tradition to a static, archival state—appreciated and studied through the medium of a screen yet detached from the material practices, social contexts, and continuous innovation that sustain a culture. Contrary to this concern, the data from this research implies a more sanguine possibility. In user perception surveys, 56.5% of participants indicated that their interaction with high - fidelity digital fabrics and virtual try - ons notably enhanced their curiosity about and desire to experience physical Hanfu garments. For them, the digital experience did not serve as a replacement but rather as a potent gateway and educational instrument that demystified historical clothing and sparked a deeper appreciation for the tangible artifact. This suggests that well - implemented digital simulation can function as a "digital primer," stimulating real - world cultural engagement and consumption instead of supplanting it. Therefore, the ethical necessity is to deliberately design these digital tools to bridge the virtual and the physical, ensuring they act as catalysts for the sustained vitality of the traditional craft ecosystem they intend to preserve.

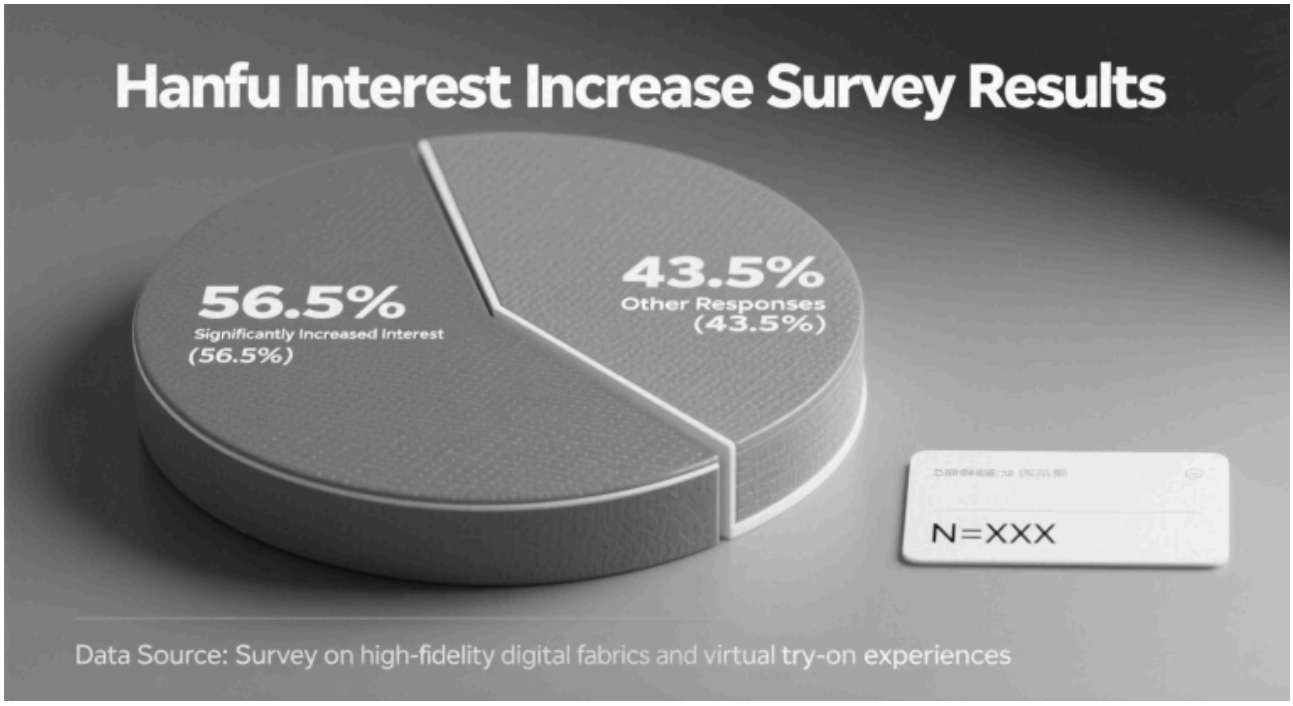

Figure 10. 56.5% Respondents said they have significantly increased their interest and desire for physical Hanfu through high-fidelity digital fabrics and virtual try-on experiences (Source: Ren Juan)

The tension between the convenience of digital reproduction and the preservation of artisanal authenticity presents a core paradox that this study directly confronts. Our findings suggest that this relationship need not be zero-sum. While digitization risks abstracting craft into mere data—as poignantly noted by the ICH

inheritor's concern that 'the machine now comprehends the what, yet does it grasp the why?'—it can also, as our user data shows (56.5% increased interest in physical garments), act as a catalyst for tangible engagement with material culture.

The key ethical imperative, therefore, is to design digital tools that are explicitly 'porous'—that is, they should serve as windows into the physical craft rather than replacements for it. This means digital archives must be supplemented with process documentation (e.g., linked video of master artisans demonstrating techniques, haptic feedback prototypes) that convey the tacit, embodied knowledge that parameters alone cannot capture. This approach ensures that the convenience of the digital interface serves to amplify, rather than dissolve, the pursuit of authenticity and craft mastery in the physical realm.

CONCLUSION

This study has developed a comprehensive methodological framework for the digital preservation and innovative utilization of traditional Hanfu fabrics, integrating 3D digitization, cultural parameter encoding, and a hybrid evaluation model. The case analyses illustrate both the substantial potential and the existing limitations of employing parametric design to capture and convey the material essence and cultural semantics of historical textiles. The results validate that a scientifically based and culturally informed digital approach can effectively bridge the divide between technological innovation and cultural heritage, transcending superficial visual imitation to attain a more profound and authentic digital revival. This lays the foundation for transformative applications in both the industrial and academic domains.

Recommendations for Industrial Application

To transform research findings into tangible industrial value and promote standardized cultural integrity within the digital fashion domain, two immediate applications are put forward:

Establishment of a "Digital Fabric Cultural Rating" System: Drawing on the cultural parameter encoding system developed in this research, a standardized rating framework can be constructed. This system will assess and label digital fabric assets according to their fidelity to historical source materials across multiple dimensions, including material precision, structural authenticity, and cultural semantics. A fabric designated as "AAA" will signify an almost perfect digital representation of a verified historical artifact (e.g., the Ming satin HF - 003), offering designers and consumers a reliable benchmark for cultural authenticity in the digital sphere.

Development of a Mixed Reality (MR) Fitting System: Capitalizing on the high - fidelity 3D models obtained in this study, which exhibited a 91.4% accuracy in virtual fitting, a consumer - oriented MR try - on application

ought to be developed. This system will enable users to visualize and interact with digitally reconstructed historical garments within their physical environment, experiencing the drape, movement, and texture validated by this research. This immersive experience directly responds to user data suggesting that digital exposure stimulates interest in physical garments, thereby creating a potent new avenue for cultural education and consumer engagement.

While this study focused on the reconstruction of mechanical properties that govern drape and fit—establishing a digital material foundation—future research should build upon this base to conduct dedicated studies on wearing comfort, including virtual pressure mapping and heat-moisture transfer simulation.

Directions for Academic Extension

The proposed methodology opens several promising avenues for future scholarly exploration:

Expansion to Ethnic Textile Heritage: The principles of the framework are easily transferable. A crucial subsequent step is to expand this research to cover the extensive and diverse textile traditions of China's ethnic minorities. This would necessitate the establishment of a new, comprehensive database containing over 300 physical samples (e.g., Miao embroidery, Zhuang brocade, Tibetan aprons) and the adjustment of the cultural parameter system to encapsulate their distinctive technical and aesthetic characteristics, thus creating a more inclusive digital heritage archive.

Integration with AI-Generated Content (AIGC) and Semantic Analysis: Future research endeavors ought to delve into a revolutionary amalgamation with artificial intelligence. Specifically, Large Language Models (LLMs), such as GPT - 4, can be utilized to conduct in - depth semantic parsing and interpretation of historical texts, for instance, the weaving techniques expounded in the classical treatise Tiangong Kaiwu. The objective is to convert the textual descriptions of lost or obscure crafts into initial parameter sets for digital reconstruction. Moreover, generative AI models can be trained on the cultural parameter database to generate novel, culturally - rooted textile designs that adhere to historical norms while facilitating forward - looking innovation, thereby shifting the field from digital preservation to AI - assisted creative inheritance.

Author Contributions

Ren J: Conceptualization, Data curation, Investigation, Writing - original draft, Visualization

Daoruang K: Methodology, Supervision, Writing - review & editing

Apiwathnasorn C: Methodology, Resources, Writing - review & editing

Sankaburanurak A: Formal analysis, Supervision

All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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Ethics Approval and Consent to Participate

This study was exempt from institutional review board approval as it involved only anonymous data collection and analysis. The procedures followed were in accordance with the Declaration of Helsinki.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

REFERENCES

[1] Ding QK, Liang HE. Digital restoration and reconstruction of heritage clothing: A review. Heritage Science. 2024; 12:225. doi: 10.1186/s40494-024-01342-x

[2] Yu Q, Zhu G. Digital restoration and 3D virtual space display of Hakka Cardigan based on optimization of numerical algorithm. Electronics. 2023; 12(20):4190. doi: 10.3390/electronics12204190

[3] Liu K, Zhao J, Zhu C. Research on digital restoration of plain unlined silk gauze gown of Mawangdui Han Dynasty Tomb based on AHP and human-computer interaction technology. Sustainability. 2022; 14(14):8713. doi: 10.3390/su14148713

[4] Hu B, Wang S. Digital restoration of traditional Huizhou clothing based on 3D modeling and virtual fitting technology. The Journal of The Textile Institute. 2025; 116(10):1-15. doi: 10.1080/00405000.2025.2520431

[5] Cao C, Gao Y. Research on national costume design based on virtual reality technology. Mathematical Problems in Engineering. 2022; 2022:7503167. doi: 10.1155/2022/7503167

[6] Liu D, Chen N, Lang X, Pan Z, Ren H, Lin S, Zhang M, Li H, Huang Q. Exploring distilled spirits brewing: Utilizing multimodal interaction and intelligent virtual avatars in a VR liquor culture museum. Entertainment Computing. 2025; 52:100909. doi: 10.1016/j.entcom.2024.100909

[7] Ma Q, Mayusoh C, Inkuer A, Puntien P. Historical inheritance and contemporary cultural and creative product design of the Hai Hun Hou culture. Herança. 2024; 7(1):162-173. doi: 10.52152/heranca.v7i2.877

[8] Zhu X, Wu X, Shi X, Xu B. Framework of personalized clothing visualization. International Journal of Clothing Science and Technology. 2017; 29(3):417-426. doi: 10.1108/IJCST-07-2016-0080

[9] Jiang J, Zhong Y, Wang S. An automatic matching scheme between 2D digital sketches and 3D tem-plate-models for virtual garment design. In: Kiekend P, editor. Proceedings of the 2011 4th International Congress on Image and Signal Processing; 15-17 Oct 2011; Shanghai, China. Piscataway, USA: IEEE; 2011. p. 1-5. doi: 10.1109/CISP.2011.6100411

[10] Thomassey S, Bruniaux P. A template of ease allowance for garments based on a 3D reverse meth-odology. International Journal of Industrial Ergonomics. 2013; 43(5):406-416. doi: 10.1016/j.ergon.2013.08.002

[11] Wang Z, Wang J, Xing Y, Yang Y, Liu K. Estimating human body dimensions using RBF artificial neural networks technology and its application in activewear pattern making. Applied Sciences. 2019; 9(6):1140. doi: 10.3390/app9061140

[12] Li B. Comparing physical to virtual: Fit and appearance of multi-layered cultural garment [dissertation]. Newark, USA: University of Delaware ProQuest Dissertations & Theses, 2018. 10842376.

[13] Lage A, Ancutiene K. Virtual try-on technologies in the clothing industry. Part 1: Investigation of distance ease between body and garment. The Journal of the Textile Institute. 2017; 108(10):1787-1793. doi: 10.1080/00405000.2017.1286701

[14] Bartle A, Sheffer A, Kim V, Kaufman D, Vining N, Berthouzoz F. Physics-driven pattern adjustment for direct 3D garment editing. ACM Transactions on Graphics. 2016; 35(4):1-11. doi: 10.1145/2897824.2925954

[15] Li P, Chen J. A model of an e-customized co-design system on garment design. International Journal of Clothing Science and Technology. 2018; 30(5):628-640. doi: 10.1108/IJCST-01-2018-0011

[16] Brubacher K, Tyler D, Apeagyei P, Venkatraman P, Brownridge A. Evaluation of the accuracy and practicability of predicting compression garment pressure using virtual fit technology. Clothing and Textiles Research Journal. 2023; 41(2):107-124. doi: 10.1177/0887302X21999314

[17] Zhu C, Liu K, Li X, Zeng Q, Wang R, Zhang B, Lü Z, Chen C, Xin X, Wu Y. Research on archaeology and digital restoration of costumes in DaoLian painting. Sustainability. 2022; 14(21):14054. doi: 10.3390/su142114054

[18] Wang Z, Li R. Automatic optimization algorithm of jewelry design based on machine vision. Computer-Aided Design and Applications. 2024; 21(S15):85-102. doi: 10.14733/cadaps.2024.S15.85-102

[19] Baraff D, Witkin A. Large steps in cloth simulation. In: Proceedings of the 25th Annual Conference on Computer Graphics and Interactive Techniques; 1998 Jul 19-24; Orlando, USA. New York: ACM; 1998. p. 43-54. doi: 10.1145/280814.280821

[20] Bridson R, Marino S, Fedkiw R. Simulation of clothing with folds and wrinkles. In: Proceedings of the 2003 ACM SIGGRAPH/Eurographics Symposium on Computer Animation; 2003 Jul 26-27; San Diego, USA. Aire-la-Ville: Eurographics Association; 2003. p. 28-36.