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A Case Study on the Digital Heritage Application of Embroidered Textile Artifacts in Museum Collections

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Abstract:

This study investigates the digital recontextualization of traditional Korean embroidered textile artifacts from the Gangneung Embroidery Museum, the Onyang Folk Museum, and the Sookmyung Women’s University Museum. Due to their complex physical structure and fabrication techniques, embroidered artifacts present significant challenges for accurate digital reproduction and interactive implementation. To address these, the study focuses on four artifacts that were pre-selected in consultation with the museums based on their potential for digital utilization and commercial scalability. These artifacts, chosen for their diversity in motifs, techniques, and materials, were digitized using HP Captis optical scanning and processed through Adobe Substance 3D tools. The resulting SBSAR-format textures are optimized for use in Unity and Unreal-based WebXR platforms. They replicate embroidery-specific features such as dimensionality, stitch density, luster, and translucency through detailed Physically-Based Rendering (PBR) maps, including Height, Normal, Roughness, and Opacity. Metadata for each artifact was structured in reference to Dublin Core and Europeana standards, forming a labeled dataset applicable to AI training. Key fields such as motif type, embroidery method, and color composition were organized into a schema suitable for semantic search, automated classification, and curatorial tools. This structured approach supports future applications in recommendation engines, multilingual exhibition interfaces, and automated curation systems. Ultimately, the study redefines embroidered artifacts as “Living Heritage” within interactive digital environments and proposes a scalable, human-centered framework for the preservation, interpretation, and creative activation of textile heritage in the era of cultural technology.

1. Introduction

1.1 Research Background and Purpose

Textile-based cultural heritage presents distinct challenges in digital preservation due to the organic and delicate nature of its materials, intricate surface textures, coloration, luster, and complex embroidery techniques. In particular, traditional Korean embroidered artifacts possess material properties—such as silk threads, twisted yarns, and detailed compositions of dots, lines, and surfaces—as well as iconographic symbolism and sensory richness that defy full capture through conventional image scanning or 3D scanning technologies. Yet, it is precisely this complexity that holds potential value: when digitized into a high-fidelity dataset, Korean embroidery can assert unique market differentiation and cultural significance in the global arena.

Advances in generative AI and Physically-Based Rendering (PBR) technologies offer powerful tools to systematically structure the visual characteristics of embroidery into high-resolution digital materials. These tools also enable the transformation of such heritage into usable educational and design resources.

This study aims to establish an integrated method of visualizing Korean embroidery in 3D digital textures, combining high-resolution embroidered data, metadata by technique, and narrative structures based on user experience. The objective is to facilitate practical applications in education, research, exhibition, and industry. To that end, this research employs the Adobe Substance 3D collection for texture design, coupled with AI-driven image analysis and texture generation.

Furthermore, this study aims to develop an AI agent for the digital implementation of traditional Korean embroidery techniques and to propose an immersive virtual exhibition space and interactive museum curation model based on embroidered artifacts, by integrating advanced simulation and virtual reality platforms such as CLO 3D, Unity, and Unreal Engine. This digitalization strategy seeks to integrate advanced artifact data, technique-specific metadata, and user experience-driven narrative structures, with the goal of practical application in education, research, exhibition, and industry. In particular, by designing a generative AI framework capable of reflecting the technical sophistication and symbolism of Korean embroidery, this approach can provide a foundation for the cultural reinterpretation of embroidered artifacts and the expansion of digital creative practices.

1.2 Review of Related Works

Among notable global initiatives, the European Union’s Horizon 2020 project, SILKNOW, represents a benchmark in the digital archiving and creative reuse of European silk heritage from the 18th to 20th centuries. This project digitized motifs, weaving methods, color data, and functional usage embedded in historical silk fabrics, integrating these into a machine-learning-based thesaurus. A key innovation of the project was the development of the “Virtual Loom,” a digital simulation tool that allows users to reconstruct historical weaving practices and generate new designs based on heritage motifs. The project demonstrated both educational and creative potentials, setting a precedent for structured, shareable digital heritage platforms.

Similarly, the “Multimodal Narratives for the Presentation of Silk Heritage in the Museum” project, led by ICS-FORTH in Greece, presented an immersive museum experience through augmented reality and narrative-driven content. Using digital humans, spatial sound, and interactive AR technologies, the project aimed to convey not only the physical artifact but also the cultural memory and context surrounding it, thereby enriching the visitor’s sensory and emotional engagement.

In Korea, interest in the digital representation of textile heritage has grown. For example, research by I Ga-shim and Kim Sook-jin reconstructed Qing Dynasty court robes using CLO 3D and Google Site tools, emphasizing informational value beyond static visuals. Additionally, doctoral work by Wan Yunjun used Adobe Substance 3D Sampler to replicate embroidered textures found in Christian Dior collections, systematically analyzing their digital properties.
Nevertheless, most of these studies remain focused on visual outcomes, and cases based on actual museum embroidery collections are scarce. Attempts to simulate and metadata-encode the materiality of Korean embroidery — its luster, reflectivity, relief depth, and the spatial dynamics of twisted silk threads—remain virtually unexplored.

1.3 Significance of the Study

This research contributes a comprehensive interdisciplinary model by demonstrating how embroidered artifacts can be translated into high-fidelity digital formats using PBR technologies. It enables detailed representations of silk threads, satin, twisted cords, gold and silver threads, and techniques such as metallic stitching and layered embroidery.

Utilizing the Substance 3D pipeline (Sampler → Designer → Painter → Stager), this method ensures interoperability and extends beyond visualization to encompass dataset annotation for generative AI training, XR integration, and exhibition interfaces. Furthermore, it anticipates curatorial transformations within the digital heritage ecosystem.
More than a technical innovation, this study proposes a model for the preservation and utilization of textile heritage across domains. The integration of AI and PBR technologies presents a viable strategy for structuring the visual semantics of embroidery into interactive, high-resolution educational and design tools.

2. Research Scope and Data Collection

2.1 Objects of Study and Scope

The study targets four embroidered artifacts held in Korean institutions—the Onyang Folk Museum, Sookmyung Women's University Museum, and Gangneung Embroidery Museum. Each artifact features distinct motifs, color schemes, fabrics, and stitching methods, offering layered visual data essential for digital texturing, metadata design, AI agent training, and XR content creation.

[Embroidered Artifacts: Digital Texture Mapping and Metadata Framework]

Artifact	Institution	Dimensions	Motifs	Embroidery Techniques	Materials	Texture Generation	3D Mapping	Metadata Tags
Double-Crane Insignia Embroidery with Longevity Motif	Gangneung Embroidery Museum	W 20cm × L 22cm	Double cranes, "寿" (longevity), bats	Flat stitch, vertical stitch	Gold thread, black silk, satin	Scanned with Sampler, height & roughness generated, metallic layer defined	Pattern enhanced in Painter using anchor layer	double-crane, gold, embossed-stitch
Embroidered Dangui	Sookmyung Women's University Museum	W 50cm × L 98cm,	Plum blossom, chrysanthemum	Chain stitch, layered stitch	Silk, gold thread, gauze, purple/green/silver threads	High-res scan, pattern tiled, height/normal/opacity maps	Texture applied in CLO for silhouette rendering	jeogori, chain-stitchroyalty,
Embroidered Pillow End	Gangneung Embroidery Museum	W 45cm × L 30cm	Butterfly, chrysanthemum, peach	Connection stitch, cotton stitch	Cotton thread, unbleached cloth, red/white/green tones	Albedo texture + displacement map	Mapped onto pillow form in Stager, with zoom interaction	bedding, butterfly-flower, domestic-blessing
Five Peaks Embroidered Silk Panel	Onyang Folk Museum	W40cm x L70cm	Five sacred peaks, clouds, dragon	Couched stitch, metallic overlay	Silk, gold thread, blue cotton	Height, normal, roughness, and metallic maps	Pattern scanned in Sampler and tiled	five-peaks, ritual-banner, multi-layered

2.2 Image Acquisition and Preprocessing

High-resolution imagery was captured for each selected artifact to facilitate accurate digital texturing. Prior to use, all images underwent fundamental preprocessing procedures, including focus enhancement, intensity correction, color calibration, thickness adjustment, alignment refinement, and HDR optimization. These corrected images were subsequently imported into Adobe Substance 3D software, where they were automatically decomposed into core texture maps — namely Normal Maps, Height Maps, Roughness Maps, Base Color Maps, and Opacity Maps. This decomposition formed the foundational dataset for digital material reconstruction.

The digitization process captured embroidered textures — including fabric grain, stitching techniques, thread composition, and gold leaf detailing—via both photographic and scanning techniques. Regularly repeated motifs and symmetrical patterns (e.g., peonies, lotuses, mandarin ducks, phoenixes, and longevity symbols) were further processed through parametric pattern transformations. These digital materials were then applied to 3D models using texturing techniques that articulated each embroidery's stitch method, chromatic scheme, and thread sheen through layered visual channels — particularly highlighting needlework styles that convey depth and form through point, line, and surface (e.g., seed stitch, dot stitch, joined stitch, layered gold stitch, and flat stitch).

2.3 Metadata Structuring

To support future integration into generative AI workflows and cultural content platforms, each artifact was systematically annotated with standardized metadata. Core metadata fields included: artifact name, holding institution, date of production, embroidery technique, motif typology, color thread composition, weaving details, stitching method, and preservation status.
This metadata architecture is designed to align with international cultural heritage standards, such as the Dublin Core and the Europeana Data Model (EDM). Structured metadata of this kind will enable scalable applications such as AI-assisted tagging, automated artifact recommendation systems, and semantic search functionalities across digital heritage repositories.

[Example of Applicable Metadata Structure]

{
"dc:title": "오봉문 자수단",
"dc:creator": "미상",
"dc:date": "18 세기",
"dc:subject": ["오봉문", "자수", "조선시대"],
"dc:format": "자련자수, 금사, 비단",
"dc:description": "오봉을 중심으로 구름과 용두문이 배치된 의례용 자수직물",
"dc:provenance": "온양민속박물관",
"dc:coverage": "조선 중기, 한국",
"dc:identifier": "OBM-ON01",
"edm:isShownBy": "https://heritage.korea/model/OBM-ON01.glb",
"edm:hasView": "https://substance.adobe.com/stager/view?id=OBM-ON01"
}

3. Technical Methodology

3.1 Technical Overview and Platform

The technical approach to the digital transformation of embroidered artifacts was conducted primarily using Adobe’s Substance 3D Collection, which enabled the implementation of high-precision texture materials considering Physically-Based Rendering (PBR). Output in SBSAR (Adobe’s procedural texture format) files was designed with potential expansion into Unity, Unreal, AI agents, and WebXR-based interactive exhibitions in mind. This study aims to compare the advantages and disadvantages of recent 3D tools that digitize physical substances (materials) and to explain the rationale for adopting Adobe technology. HP Captis and Adobe Substance 3D technologies were used in this study.

[Comparison Table of Tools for Digital Embroidered Artifact Implementation]

Tool / Solution	Key Functions	Strengths	Limitations
Adobe Substance 3D	PBR-based material texture creation, all-in-one texturing and visualization solution	Adobe ecosystem integration, cross-platform compatibility, photorealistic PBR parameter generation via AI	Requires learning curve
Reality Capture	3D scanning, photo-based mapping	Optimized for photogrammetry, high-speed scanning	Requires post-processing for texture quality
Metashape (Agisoft)	Precision photogrammetry	High-resolution reproduction, suitable for classical artifacts	Limited real-time processing capabilities
Quixel Mixer + Megascans	High-end PBR texture blending	Rich free asset library, strong Unreal Engine integration	Limited in expressing embroidery-level detail
HP Captis	HP scanning device optimized for textiles and reflective materials (optical scanning + AI enhancement)	Automatically detects and refines embroidery texture details such as sheen, grain, and thread thickness	Requires further texturing and rendering

3.2 Texturing Workflow

For each artifact, 3D materials were constructed based on basic texture structures (Base Color, Height, Normal, Roughness, Opacity), and within the Adobe Substance 3D Collection, the surface information of the artifacts was implemented in a state that allows real-time simulation. In particular, the stitch direction of the embroidery, the thickness of the thread, and the sense of depth and three-dimensional reflectivity according to the length of the needlework were precisely implemented through Height Maps and Normal Maps.

In addition, the elegant gloss characteristic of silk fabrics used in hanbok must be expressed, and the transparency of silk gauze (紗) must be represented due to its translucency. Embroidery techniques that express dot-line-surface, such as seed stitch (씨앗수), dot stitch (점수), joined stitch (이음수), layered gold stitch (징금수), flat stitch (평수), continuous stitch (자련수), and seat stitch (자릿수) used in Buddhist embroidered items from the Goryeo Dynasty, require high-resolution capture technologies to be represented in 3D.

In the case of layered gold stitch (징금수), there are various expressive techniques such as thick-threaded layered stitch, left-twisted and right-twisted layered stitch, gold-threaded layered stitch, and “kkal-kkal” stitch (깔깔사). As gold and silver threads are used, it is necessary to utilize the metallic and glossiness map, reverse the roughness map, and implement shading effects according to the direction of the layered stitch reflecting the curvature of the Height Map.

Additionally, for continuous stitches (자련수) used to express motifs such as peonies, lotus flowers, rocks, and birds, it is necessary to reproduce the stitch direction filled with long and short stitches, and to express gradients through color blending based on Gradient Fill, using Noise Mask and Albedo processing techniques that naturally blur the edges.

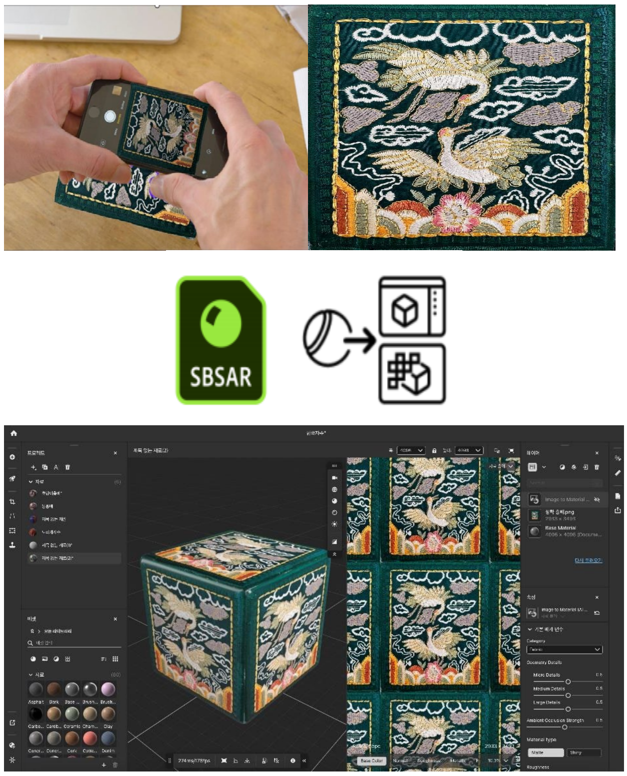

Figure 1. 3D Digital Material Asset Creation from Scanned. (AI-Powered Image-Based 3D Material)
Fabric Photography → 2D Image Assets → 3D Material Assets

3.3 Data Refinement for Generative AI

In the future, textures and metadata can be processed for AI training, and labeling work can be performed so that AI can classify motif types, color arrangements, and technical elements. In this process, a multilayered information structure that enables comparative learning among artifacts can be reflected, and it can be designed to serve as the basis for future AI curation, automatic description generation, and recommendation systems.

[Labeling Schema for AI Training]

Category	Label Key	Example Values
Embroidery Technique	embroidery_technique	layered gold stitch, continuous stitches, seed stitch, joined stitch,

		etc.
Motif Type	motif_type	Longevity Symbol Pattern, Double Crane Motif, Phoenix Motif, Ten Symbols of Longevity, etc.
Thread Material	thread_type	Gold thread, Left-twist thread, Right-twist thread, Kkal-kkal thread
Surface Texture	surface_texture	Shiny, Soft, Rough, Twisted
Gloss Level	gloss_level	High gloss, Medium gloss, Matte
Roughness Value	roughness	0.15 (0 = glossy, 1 = matte)
Image File Path	image_path	textures/emb_texture_001.jpg
Holding Institution	museum	Gangneung Embroidery Museum, Onyang Folk Museum, etc.
Period of Production	period	Late Joseon Dynasty, Korean Empire period, etc.
Source Tool/Format	source	SBSAR, Substance Sampler, Photoscan, etc.

[Example of Smart Material Application]

Smart Material Name	Applied Area	Main Function Description
`SilkBase_Brocade.spsm`	Base fabric	Pearl-like gloss with smooth roughness combination
`GoldThread_Embroidery.spsm`	Five Peaks motif, Dragon head	Characteristic gloss of gold thread, built-in fine normal map
`CottonMatte.spsm`	Cloud motif	Expression of high light-absorption cotton thread
`Ornamental_StitchEdge.spsm`	Outer edges	Embossed stitch effect based on height and ambient occlusion

3.4 XR-Based Application Expansion

The produced textures are mounted onto WebXR platforms based on Unity and Unreal, allowing users to experience the three-dimensionality and texture of the actual artifacts in virtual space. Through adjustment of SBSAR parameters, users can modify color saturation, gloss, and surface curvature in real time, which can be utilized in educational practice, design experimentation, and AI-based explanation functions in curatorial environments.

This technical methodology provides a pathway for traditional embroidered artifacts to be transformed into living heritage within digital environments, demonstrates the potential for a creator-centered interface within the digital cultural technology ecosystem, and can be evaluated as a strategic model for redefining and applying textile heritage.

[Key Parameters to Include in SBSAR Design]
(Example: Based on the Five Peaks Embroidered Banner)

Parameter Name	Description	Example Values
ThreadColor1	Primary embroidery thread color	#D4AF37 (gold)
PatternRepeatX/Y	Pattern repetition count (horizontal/vertical)	1 – 10
StitchHeight	Embroidery height (dimensional depth)	0.0 – 0.5
ShineLevel	Gloss level of gold thread	0.1 – 1.0
FabricRoughness	Roughness of base fabric	0.2 – 0.9
MotifSelector	Motif selection	Five Peaks Motif / Longevity Symbol Pattern / Double Crane Motif
AgeWear	Simulation of aging and fading	none / mild / severe

4. Research Findings and Analysis

4.1 Results of Digital Texture Implementation

Through this study, four embroidered artifacts were converted into digital textures using the SBSAR format. The resulting files were processed into interactive materials that can be simulated in real time within the Adobe Substance 3D Collection. These outcomes precisely reproduced the visual identity of the embroidered artifacts — such as color, glossiness, thread thickness and grain, and dimensional depth.

In particular, the effects of Height and Normal Maps successfully conveyed the raised texture of the threads, the density of the needlework, and the depth of the motifs. By adjusting reflectivity and Roughness values, the visual sparkle of gold and silver threads was also effectively represented. Special attention is drawn to the fact that the distinctive glossiness or translucency of Korean embroidery fabrics — features that require Opacity and Metallic Maps—can only be implemented using Adobe Substance 3D.

Figure 2. An image of continuous stitch (Jaryeonsu) captured in 8K and reconstructed in 3D, with the embroidery technique and fabric grain clearly expressed.

4.2 Metadata Structure for Generative AI Training

The metadata constructed for each artifact can be refined into fields (artifact name, production date, embroidery technique, motif, color, material, holding institution, usage, digitization status), and this structure can be designed to be convertible into a labeled dataset for future AI training. In practice, motif types, color arrangements, and technique-specific embroidery characteristics can be preprocessed into a format that AI can classify, raising the possibility of applying semantic-based search and artifact similarity comparison functions.

High-resolution realistic photography → PBR texture generation (Albedo, Height, Roughness, Normal) The differences between glossy materials like gold thread and cotton thread are separated using a Material ID Mask.

[Example of Metadata Tagging]

```
{
"material_type": "silk + gold-thread",
"motif": "five-peaks",
"thread_type": "gold-silk",
"lighting_reflectivity": "high"
}
```

4.3 Implementation of XR Interactive Exhibitions

Museum 4.0 necessitates the realization of a smart cultural heritage platform based on the integration of metadata, AI, XR technologies, networks, and user data. Specifically, SBSAR textures are digitized through 3D scanning of artifacts to produce digital twins, enabling visitors to experience personalized creation of embroidered rank badges. Through touchscreen interfaces, users can select an embroidered badge, change gold threads to silver, or replace a phoenix motif with a twin crane design, thus engaging in customized embroidery experiences. By employing standardized metadata schemas and ensuring compatibility and extensibility with frameworks such as Dublin Core and Europeana, this platform can automate artifact tagging and provide recommendations for similar patterns. Such services can be globalized, facilitating the international dissemination of K-heritage content and contributing to the spread of Korean cultural assets worldwide.

4.4 Digital Museums and Curating: Reframing the Platform and Redefining the Role

Today’s museum is no longer a static space limited to fixed exhibition content. Rather, it is evolving into a flexible digital environment in which exhibits are continuously rearranged and reinterpreted through user-driven selection, interaction, and exploration. The WebXR-based embroidered artifact content developed in this study stands at the forefront of this transformation by transforming heritage textures into interactive interfaces, thereby fostering a sensory and participatory experience that goes beyond passive information delivery.
Unlike conventional 2D images, SBSAR-based textures allow real-time manipulation of lighting, surface texture, curvature distortion, and color variation, offering a realistic representation of the three-dimensional and tactile qualities of embroidered artifacts. Viewers can explore the layered structure and depth of embroidery motifs, transforming perception into a process of re-sensory engagement.
This shift also fundamentally redefines the role of the curator. While traditional curators functioned primarily as interpreters and conveyors of artifact knowledge, the digital curator now operates as a cultural-technology interface designer — an integrator of technology, content, and user experience. Curating has expanded beyond exhibition planning to encompass narrative design, interaction architecture, and real-time content orchestration.
In particular, XR/AR-based exhibition environments demand spatial and temporal fluidity, immersive scenario development, and data-driven content modulation, all of which require a new generation of digitally literate curators. As a result, the digital museum is being redefined not only as a space of preservation, but as a cultural interface for interpretation, creation, and shared experience. The curator, at this intersection, takes on the role of mediator and designer — bridging humans, technologies, and heritage.
Within this evolving framework, the digital embroidery content model proposed by this study embodies the future potential of platform-based strategies that cultural institutions may pursue. It offers a transformative approach for the creative preservation and global dissemination of textile heritage.

4.5 Beyond Virtual Exhibitions: Industrial Expansion of Digital Textile Heritage through Generative AI

Digital embroidered heritage content—or more broadly, digital textile heritage content—is not limited to virtual exhibitions. Rather, it holds significant potential for expansion into the cultural industry and high-value creative sectors. In particular, when dealing with nationally designated cultural assets, these artifacts can be integrated into generative AI systems in a manner that ensures proper attribution and copyright protection. This enables secondary creative use without compromising cultural identity or historical authenticity.
With refined metadata structures and high-resolution SBSAR textures, traditional embroidery motifs can be extended into a range of practical applications. For instance, embroidery-inspired digital textures can be developed into product design assets—such as limited-edition fashion, accessories, and home décor—which are distributed through e-commerce platforms. This allows traditional craftsmanship to be recontextualized for contemporary consumer markets.

Figure 3. Expansion of interoperability across e-commerce, curatorial systems, and immersive content.

When combined with WebXR or AR technologies, these assets can also be embedded into immersive retail environments that allow users to experience the gloss, texture, and dimensionality of embroidery in real time. Such environments offer multisensory engagement and personalized shopping experiences that enhance interaction between consumers and cultural heritage.

Furthermore, the symbolic and cultural narratives embedded in embroidery motifs can be adapted into marketing content rooted in brand storytelling, helping convey brand identity while fostering emotional resonance with consumers. Additionally, digital assets with clearly defined copyright structures can be licensed for secondary creative use in fields such as education, gaming, interactive media, and exhibition design — creating sustainable models for the circulation and commercialization of digital cultural heritage.

Generative AI enables the rapid prototyping of new designs while preserving essential characteristics such as motif structure, stitching techniques, and material texture. This offers a viable pathway for the simultaneous advancement of cultural preservation and economic innovation. When combined with multilingual AI narration, virtual fitting systems, and user-customizable motif variations, these assets have the potential to evolve into globally scalable, heritage-driven consumer platforms.

5. Conclusion

The key outcomes of this study are as follows.

First, texture assets based on actual artifacts reflecting traditional embroidery techniques and motifs were constructed.

Second, the potential for refining metadata structures and learning labels compatible with generative AI was confirmed.

Third, embroidered artifacts were implemented in an interactive WebXR-based virtual exhibition environment with real-time manipulation capabilities.

Fourth, the potential for the digital utilization of embroidered artifacts and specific application models within the digital cultural heritage ecosystem have been clearly articulated.

As digital and AI technologies continue to advance, humanity’s gaze turns not toward what is common, but toward that which is gradually disappearing — values that exist in daily life yet remain difficult to access: nature, heritage, and objects embodying unique techniques and values born from the human hand. Within this context, this study attempted to reconstruct the intersection of digital, human, and heritage as an “interface.” Technology must function not as an end in itself, but as a tool to provide new accessibility, understanding, and modes of interaction with cultural assets. In particular, artistic heritage such as textile artifacts — characterized by dimensionality, aesthetic depth, and highly skilled craftsmanship — can open new paths for preservation and reinterpretation through digital technologies, ultimately contributing to the expansion of human-centered cultural experiences.

Figure 4. A virtual space constructed based on 3D models of embroidered artifacts.

Future research should expand toward building datasets of broader categories of textile heritage, including costume, various embroidery types (such as Buddhist embroidery, court embroidery, and folk embroidery), dyed craft heritage, and quilted textile heritage. This will require advancements in ultra-high-resolution imaging and dynamic lighting-based data collection, the development of multilingual AI-based interpretation systems for global platform dissemination and commercial use, as well as the design and implementation of a comprehensive cultural technology ecosystem encompassing mobile-based WebXR expansion and museum-linked educational programs.

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