Design and Implementation of Digital Cultural Creative System for Haihunhou Museum based on Heterogeneous Resource Integration and Virtual-Real Mapping

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Abstract. Currently, the development of cultural creative products for the Haihunhou Site Museum faces critical challenges, specifically the disconnection between physical carriers and digital content, and the severe homogenization of interactive experiences. To address the aforementioned challenges, this paper proposes a systematic development framework based on Digital Twin technology and Human-Computer Interaction (HCI) principles. Departing from traditional linear design processes, this framework constructs a layered system architecture comprising a Data Layer, a Computational Logic Layer, and an Application Layer. By integrating computer vision feature extraction algorithms with Finite State Machine (FSM) logic, this study constructs a Virtual-Real Mapping Function Model. This model not only achieves the deep integration of heterogeneous cultural resources but also quantifies the coupling relationship between physical carrier features and digital narrative content. Taking the development of the "Haihun Auspicious Beasts" system as a case study, this paper details the complete implementation pipeline from vector pattern reconstruction to mobile Augmented Reality (AR) interaction. Comparative analysis of functional characteristics indicates that this system significantly outperforms traditional AR cultural products in terms of interactive depth, narrative scalability, and system modularity. Consequently, this validates the effectiveness and scalability of the proposed engineering paradigm in the digital transcription of cultural heritage.

Keywords: System Architecture,Virtual-Real Mapping,Human-Computer Interaction (HCI), Haihunhou Museum,Heterogeneous Resource Integration.

1 Introduction

The museum cultural creative industry is shifting from physical merchandise to immersive experiences [1]. Despite its rich Han Dynasty collections, the Haihunhou Site Museum's product development faces severe technological lag, struggling to meet digital transformation demands [2]. Existing products universally suffer from a "Virtual-Real Disconnection" [7]. The lack of digital extensions and systematic interaction

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design creates an "Experience Gap," preventing users from dynamically reconstructing historical scenes or sustaining engagement post-purchase. The root cause is the reliance on traditional development modes, which create severe Data Silos among archaeological, design, and technical resources. To resolve this, this study proposes a Phygital digital cultural creative system based on Service-Oriented Architecture (SOA). By integrating heterogeneous resources and algorithmic mapping, this system provides a viable technical pathway for the interactive, living transmission of regional cultural heritage.

2 Design and Implementation of the Haihunhou Digital Cultural Creative System Architecture

To address Physical-Digital Disconnection and homogenized interactive experiences, this study proposes a Layered Decoupled architecture based on Phygital Isomorphism. Synergizing the Data, Computational Logic, and Application layers, the system achieves deep integration and dynamic mapping of heterogeneous cultural resources.

2.1 Heterogeneous Resource Integration Model Based on Semantic Ontology

The Data Layer resolves format heterogeneity and semantic dispersion by employing CIDOC CRM to construct a Domain Knowledge Graph [4]. Surpassing traditional databases, it reconstructs unstructured multi-source data into three core dimensions: Physical Entity (objective parameters), Cultural Semantic (Han Dynasty rituals and meanings via semantic networks), and Digital Asset (Unity Prefabs and multimedia). This ontology breaks barriers between archaeological data and digital materials, establishing a cross-dimensional Logical Indexing mechanism [3]. During frontend scanning, the system performs Associative Retrieval to automatically invoke matching historical knowledge and digital effects, providing a solid Data Foundation for dynamic narrative generation. Transcending the static nature of traditional cultural products, this system embodies the core requirements of Digital Twin systems through a continuous data ingestion mechanism. Post-deployment, the virtual counterpart does not remain static. Because the Data Layer is structured as a Domain Knowledge Graph, it inherently supports bidirectional data flow and dynamic iteration. As archaeological research progresses—such as the discovery of new interpretations or changes in artifact conservation status—curators can directly update the semantic nodes within the backend database. Powered by cloud-based mechanisms, the mobile frontend dynamically ingests these refined data points in real-time, ensuring the "digital twin" evolves synchronously with ongoing academic research.

2.2 Virtual-Real Mapping Algorithm Mechanism Based on Dynamic Weighting

The Computational Logic Layer transforms physical interactions into precise digital feedback. To address severe specular reflection on Haihunhou artifacts, the system adopts an improved ORB algorithm [5]. Compared to SIFT, ORB significantly reduces computational load while maintaining recognition accuracy and rotational invariance, ensuring visual stability during virtual-real fusion.

Secondly, to resolve the conflict between automatic demonstration and active user operation, this paper proposes a virtual-real mapping function model based on dynamic weighting:

$$V_{out} = \alpha \bullet R\left(F_p\right) + \beta \bullet I_{user} \tag{1}$$

In this model, V_{out} represents the final digital content output by the system, including 3D model rendering, narrative animation playback, and audio feedback. F_p represents the set of feature points extracted from the surface of the physical carrier based on the ORB algorithm. R denotes the computer vision-based recognition and rendering function, responsible for image target detection and pose estimation. I_{user} represents real-time user interaction input variables, such as click coordinates, sliding trajectories, or dwell duration. $\alpha$and $\beta$are weighting coefficients; by regulating these two parameters, the system can dynamically balance the proportion between automatic demonstration content and user active interaction content. The establishment of this mathematical model endows the translation process of cultural heritage with computability, ensuring that the physical carrier serves not merely as a decorative item with aesthetic value, but as a crucial hardware entry point that triggers digital narrative logic. Furthermore, to ensure broad system generalizability, we define the minimum digitization requirement for a physical object within this framework: the presence of sufficient planar textural gradients or high-contrast surface features (which justifies the utilization of metal etching in our case study). For other types of cultural artifacts lacking distinct 2D textures, such as unglazed pottery, monochromatic textiles, or weathered inscriptions, the layered decoupling design exhibits strong adaptability. The Computational Logic Layer allows developers to seamlessly substitute the 2D ORB feature extraction module with 3D point-cloud matching or spatial depth-sensing algorithms, necessitating zero alterations to the underlying data ontology or the frontend rendering, thereby proving the framework's cross-category universality.

2.3 Mobile Service Architecture and Performance Optimization

The Application Layer tackles High-Fidelity rendering constraints on mobile devices using a Tiered Asynchronous Resource Loading Strategy [6]. To prevent memory overflow from High-Polygon models, initialization is restricted to lightweight configurations and LOD Proxies. Upon user trigger, multi-threading dynamically loads high-precision assets. Furthermore, an Event-Driven message bus logically decouples the visual recognition module from the narrative engine. This enhances scalability, allowing seamless Over-the-Air (OTA) resource updates without application re-downloads. These optimizations guarantee a stable 60 FPS on mainstream devices.

In summary, this chapter constructs a complete closed-loop architecture from the underlying data ontology to frontend interactive services at a theoretical level. However, the effectiveness of the theoretical architecture still needs to be verified through concrete engineering practice. To further validate the Robustness and narrative expression capability of this architecture in complex artifact scenarios, the next chapter will take the "Haihun Auspicious Beasts" cultural creative system as a specific empirical case study to detail the engineering implementation pipeline of key technologies.

3 Key Technology Implementation—Case Study of "Haihun Auspicious Beasts"

To empirically validate the proposed architecture and mapping algorithm, this study developed the "Haihun Auspicious Beasts" prototype system based on the Gold-inlaid Bronze Danglu. As an Engineering Instantiation, it comprises physical metal bookmarks and a companion mobile Augmented Reality (AR) application. This section details the resolution of key technical challenges: high-robustness feature extraction, complex interaction logic, and high-performance mobile rendering.

3.1 Vectorized Reconstruction and Extraction of Physical Features

The extraction quality of the physical feature set F_p dictates the mapping function's R stability. Because original artifacts suffer from severe oxidation and complex Specular Reflection—leading to Tracking Loss—the design team performed Feature Reconstruction. Vectorization algorithms extracted seven auspicious beast patterns (e.g., White Tiger, Golden Crow) from the Danglu. To enhance machine vision Robustness, modern Metal Etching Processes were applied to increase edge contrast. This symbol refinement preserves historical aesthetics while optimizing feature point spatial distribution, ensuring Recognition Accuracy under varying lighting environments [5].

3.2 Interaction Logic Implementation Based on Finite State Machine

Interactive fluidity depends on the real-time adjustment of the mapping function (V_{out}) weighting coefficients. Thus, a Finite State Machine (FSM) serves as the digital Application Layer's logical control hub [10]. The FSM defines State Transition Rules for four stages (Initialization, Target Detection, Virtual-Real Overlay, Gamified Interaction) and dynamically balances the automatic demonstration (α) and user interaction (β) weights.During operation, exceeding a raycasting feature-matching threshold transitions the FSM to the Virtual-Real Overlay state (dominated by α), instantiating a 3D White Tiger and synchronizing an audio guide to prioritize historical accuracy. User touch events smoothly shift the FSM to Gamified Interaction (dominated by β), unlocking modules like "Silk Road Parkour" [9]. Furthermore, the physical "lot-drawing" ritual acts as a Random Seed input variable (I_{user}) to trigger digital auspicious phrases. This cultivates a strong sense of ritual, effectively bridging the virtual-real experience gap through real-time isomorphism.

3.3 Mobile Rendering Optimization Strategy

To ensure smooth virtual-real overlays on computationally constrained mobile devices, the system adopts a Layered Rendering Strategy. Static backgrounds (e.g., Han watchtowers) use Offline Lightmap Baking to pre-calculate lighting and shadow data, significantly reducing real-time GPU overhead. Core characters employ Physically Based Rendering (PBR) materials to realistically reproduce metal and silk textures. Additionally, an On-Demand Loading mechanism dynamically retrieves high-precision animations only upon specific user triggers, guaranteeing Frame Rate Stability across mainstream mobile devices (see Fig. 1).

Fig. 1. Phygital Implementation of the "Haihun Auspicious Beasts" System: (a) Physical Carriers Based on Artifact Prototypes; (b) Digital Interface Flow and Gamified Interaction.

4 Functional Comparative Analysis

Since this system adopts a Service-Oriented Architecture (SOA) design based on heterogeneous resource integration, it exhibits significant Paradigmatic Differences in functional characteristics compared to traditional physical cultural creative products and standard AR applications. To quantitatively assess the performance superiority of this system, this section conducts a comparative analysis based on three key dimensions: Interactive Depth, Narrative Scalability, and System Sustainability (see Table 1 for detailed comparisons).

Table 1. Functional Comparison of Traditional Physical Products, Ordinary AR Products, and the Proposed Virtual-Real Isomorphic System

Functional Dimension	Traditional Physical Products	Ordinary AR Products	Proposed System (Virtual-Real Isomorphic)
Interaction Mode	Unidirectional visual/tactile perception	Unidirectional digital content display	Bidirectional virtual-real interaction
Narrative Medium	Static instruction manual / Packaging	Simple 3D model overlay	Dynamic gamified narrative & scene restoration
Content Update	Non-updatable	Requires App re-release	Dynamic cloud-based resource pack update (OTA)
Sense of Ritual	Relatively Weak	Weak (Serves only as a recognition marker)	Strong (Physical fortune drawing triggers digital auspicious words)

4.1 Interactive Depth: From Passive Observation to Bidirectional Engagement

In terms of interactive depth, traditional AR cultural products are often limited to Unidirectional Visual Overlay, where users remain at the level of passive observation. In contrast, this system achieves a breakthrough towards Bidirectional Engagement by introducing the interaction variable I_{user} (refer to Equation 1). Taking "Haihun Auspicious Beasts" as an example, the physical lot-drawing action is no longer a simple triggering motion but is recognized by the system as a hardware input parameter capable of altering digital output results. This Strong Coupling between physical behavior and digital feedback not only technically realizes virtual-real mapping but also cognitively greatly enhances the user's Sense of Ritual, constructing an embodied interaction loop.

4.2 Narrative Scalability and Lifecycle: Decoupling of Content and Carrier

Facilitated by the layered architecture, the system completely decouples digital content from physical carriers. This enables museums to push cloud-based narrative updates without replacing physical hardware, establishing a Sustainable Operation Model that eliminates "One-time Consumption." Furthermore, this decoupled Service-Oriented Architecture (SOA) inherently supports Cross-Platform Adaptability. Because the underlying knowledge graph and FSM logic are device-independent, the system's assets and APIs can seamlessly migrate from mobile AR to multi-user VR, spatial projection mapping, or tangible installations. This scalability overcomes smartphone dependency, fostering social co-experience and broader accessibility for diverse audiences.

4.3 System Usability and User Experience Evaluation

To empirically validate the system, a mixed-methods user study involved 30 participants (15 Product Design students and 15 museum visitors). Participants completed a full interaction loop followed by the System Usability Scale (SUS) questionnaire. As shown in Table 2, the system achieved an "Excellent" mean SUS score of 83.5 (SD = 6.2), quantitatively proving that the architecture provides a highly intuitive, frictionless experience. Furthermore, post-task semi-structured interviews revealed two consensus points among participants: an enhanced "Sense of Ritual" driven by the physical hardware trigger (I_{user}) that significantly deepened historical immersion, and a "Seamless Virtual-Real Transition" where the optimized ORB algorithm ensured visual stability without tracking loss. Conclusively, the study verifies that the Phygital system achieves high usability standards and significantly deepens user engagement through embodied, bidirectional interactions.

Table 2. Descriptive Statistics of System Usability Scale (SUS) Scores

Participant Group	Sample Size (n)	Mean SUS Score	Standard Deviation (SD)	Usability Adjective Rating
Product Design Students	15	85.2	5.4	Excellent
Museum Visitors	15	81.8	6.7	Excellent / Good
Overall Average	30	83.5	6.2	Excellent (Grade A)

5 Conclusion

This paper proposes and validates a Phygital digital cultural creative system driven by heterogeneous resource integration and virtual-real mapping algorithms. Validated through the "Haihun Auspicious Beasts" engineering practice, this study draws three key conclusions: First, the SOA-based layered mechanism effectively resolves traditional Data Silos by seamlessly integrating archaeological and engineering resources. Second, the Virtual-Real Mapping Function Model achieves Real-time Isomorphism between physical carriers and digital content, ensuring high-fidelity artifact restoration while expanding interactive dimensions via Gamified Narratives. Finally, the system's modularity and cloud-based hot updates establish a Cost-effective, High-reuse Engineering Paradigm for the Digital Transcription of cultural heritage and museum collections [8].Future research will explore Blockchain technology for digital asset traceability and rights confirmation, alongside Generative AI (AIGC) for personalized dynamic narratives, continuously driving the living inheritance and value transformation of Haihunhou culture.

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