Open Access Library Journal
2026, Volume 13, e14970
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Research on the Design and Dissemination of a Digital Twin Based English Virtual Exhibition Hall for the Longshan Cultural City Wall Ruins in Jinan

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How to cite this paper: Xu, X.Y. and Zou, D.P. (2026) Research on the Design and Dissemination of a Digital Twin Based English Virtual Exhibition Hall for the Longshan Cultural City Wall Ruins in Jinan. *Open Access Library Journal*, **13**: e14970.
https://doi.org/10.4236/oalib.1114970

Received: February 1, 2026
Accepted: March 1, 2026
Published: March 4, 2026

Abstract

In the context of the deepening implementation of the national cultural digitalization strategy, the international dissemination models for large-scale archaeological sites urgently require innovation. The Jinan Longshan Cultural City Wall Site serves as crucial evidence for tracing the origins of Chinese civilization. Its traditional display and dissemination have long been constrained by three core issues: low physical accessibility, insufficient international interpretation, and a lack of interactive experience. Supported by digital twin technology and cross-cultural communication theory, this research combines high-precision 3D reconstruction, real-time rendering engines, and interactive narrative methods to construct a fully English virtual exhibition hall for a global audience. By establishing a three-dimensional design framework of "Perception Layer-Behavior Layer-Experience Layer," and integrating pathways for data acquisition, model construction, interactive implementation, and multi-platform dissemination, the study utilizes user testing and effectiveness evaluation for continuous optimization. This achieves the digital preservation and international interpretation of the site, promoting the global cognitive enhancement and value dissemination of early Chinese civilization achievements.

Subject Areas

Digital Humanities, Cultural Heritage Studies, Cross-Cultural Communication

Keywords

Digital Twin, Virtual Exhibition Hall, Cross-Cultural Communication

1. Introduction

At the end of 2025, the construction of Jinan Metro Line 6 led to a historic archaeological discovery: well-preserved city walls and moats from the Longshan Culture period were uncovered southwest of Daming Lake. Dating indicates these walls are approximately 4200 years old, pushing back the documented history of Jinan's city establishment by about 1500 years. This discovery not only provides physical evidence confirming the existence of early states in the lower Yellow River region but also, with its continuous cultural layer accumulation, serves as a vivid "underground chronicle" of China's uninterrupted civilization spanning over five millennia [1]. However, contradicting this immense academic value is its extremely limited public awareness and international influence. The development of digital cultural heritage abroad is relatively mature, mainly presenting two paths: one focuses on high-precision data acquisition and restoration, such as using laser scanning and photogrammetry for sub-centimeter digital reconstruction of the Pompeii ruins in Italy; the other emphasizes contextual narrative and experiential design, for example, the British Museum's use of VR technology to recreate ancient Egyptian life scenes, enhancing emotional connection and historical understanding. In contrast, while domestic projects like "Digital Forbidden City" and "Digital Dunhuang" have set industry benchmarks, the digital interpretation of prehistoric city sites—especially earthen sites—mostly remains at basic forms like 3D model reconstruction of the site, aerial panorama tours, or explanatory short videos [2]. Although relevant research is emerging, it often shows significant limitations in deeper dimensions such as immersive spatial narrative, dynamic simulation of construction techniques, and cross-cultural communication adaptation, or fails to form a complete project practice with a closed "technology-content-dissemination" loop [3]. To break through this bottleneck, this paper proposes and implements a solution integrating cutting-edge technology and communication theory: designing and constructing a fully English digital twin virtual exhibition hall for the "Jinan Longshan Cultural City Wall Site" and systematically researching its overseas dissemination pathways. This study aims to accomplish two core tasks: First, utilizing high-precision 3D modeling, real-time rendering engines, and interactive narrative technology to create an immersive, explorable, and understandable online exhibition hall, transforming specialized archaeological findings into an immersive experience transcending language and cultural barriers; Second, planning its systematic dissemination strategy within overseas academic communities and social media platforms, and establishing a scientific effectiveness evaluation system to tangibly enhance the site's international visibility. The paper will follow the logic of "problem proposal-theoretical framework construction-technical solution design-dissemination strategy planning," employing interdisciplinary research methods, aiming to explore an effective new path for the international digital dissemination of early Chinese civilization heritage represented by Longshan Culture.

2. Virtual Exhibition Hall Design Framework Based on Interactive Experience

Based on the core characteristics of the Longshan Cultural city wall site as a large-scale immovable earthen site, this study constructs a three-layer progressive design framework of "Perception Layer, Behavior Layer, Experience Layer" [4], serving as the overarching guideline for the overall design of the virtual exhibition hall. It should be noted that the virtual exhibition hall constructed in this paper strictly falls within the category of "high-fidelity virtual reconstruction" as it has not yet achieved real-time sensor data synchronization with the physical site. However, in the context of cultural heritage digitization, this study meets the core criteria of digital twins: 1) Geometric accuracy reaching the centimeter level; 2) Achieving structured linkage of multi-source archaeological data; 3) Supporting interactive deduction based on real-time rendering engines. This constitutes an "approximate digital twin" application paradigm for immovable earthen heritage sites.

2.1. Perception Layer

This layer serves as the starting point for international users to access the digital space of the site, aiming to create an immersive first impression that transcends cultural backgrounds. The goal is to utilize the Nanite virtual geometry technology and Lumen global dynamic lighting system of Unreal Engine 5 (UE5) to meticulously reproduce the stratified texture of the rammed earth of the city wall, tool excavation marks, historical erosion conditions, and the original topography of the settlement environment. By integrating environmental sound effects (such as simulated ancient wind sounds, flowing water, and labor sounds) with carefully designed scene lighting changes (simulating day and night, and seasonal transitions), an atmosphere of a grand, profound, and vibrant prehistoric settlement during the Longshan Culture period is created. This immersive audio-visual experience aims to instantly shorten the psychological distance between modern audiences and the civilization of 4000 years ago, laying an intuitive emotional and cognitive foundation for subsequent in-depth exploration.

2.2. Behavioral Layer

This layer serves as the core bridge connecting users with the virtual archaeological environment, with a focus on providing an intuitive and in-depth interactive paradigm aligned with internationally recognized conventions. It aims to shift users from passive information reception to active exploration and discovery. In terms of spatial navigation, multimodal controls (keyboard/mouse or VR controllers) are supported, allowing users to freely roam within reconstructed settlements and inside or outside city walls from either a first-person or bird's-eye perspective, while independently planning their exploration paths. For interaction with archaeological objects, users can perform actions such as clicking, selecting, or dragging to conduct a "virtual dissection" of the city wall—for example, peeling away layers of rammed earth to observe the construction sequence or clicking on spe-

cific areas to trigger a 360-degree examination of related artifacts (such as excavated pottery or stone tools). In the realm of simulated practice, a simplified "construction simulation" tool is provided, enabling users to intuitively experience key processes—from planning baselines to ramming and final wall completion—by combining virtual tool modules and allocating resources (represented by icons). This interactive system is designed to fundamentally transcend the limitations of static images, texts, or video observation, transforming users into active participants in the virtual archaeological site.

2.3. Experience Layer

Built upon perceptual immersion and behavioral interaction, the ultimate goal of this layer is to guide users toward a cognitive leap from "viewing the site" to "understanding the civilization." This is primarily achieved through two core narrative modules. The first is the Decoding of Engineering Wisdom, which features a dynamic demonstration animation of the "complete construction process of the city wall." This transforms archaeological research findings into a visual continuous narrative, clearly presenting key technical steps—from site selection and foundation preparation to formwork setting and layered ramming—while explaining the early engineering wisdom and collaborative models embodied within. The second module is Socio-Cultural Interpretation, which organically integrates explanations of the wall's functions (defense, regulation, and symbolism of social stratification), the social organization reflected in the settlement layout, and comparative perspectives with contemporaneous civilizations during interactive exploration. It guides users to contemplate the social mobilization capabilities, resource management levels, and power structures required for large-scale public projects, thereby fostering a deep appreciation of the underlying value that "the city wall is a milestone of civilization" and an understanding of the pivotal role of the Longshan Period in the origins of Chinese civilization.

3. Digital Reconstruction and Dynamic Narrative Technology for the City Wall Site

3.1. High-Precision 3D Modeling and Geographic Scene Reconstruction

To achieve precise digital archiving and highly immersive presentation of large-scale immovable sites, this study establishes an integrated aerial-ground-space 3D reconstruction workflow. First, The specific acquisition parameters are as follows: UAV oblique photogrammetry was conducted using a DJI Mavic 3E at a flight altitude of 80 m, with an 85% forward overlap and 75% side overlap, capturing 1260 images at a ground sampling distance (GSD) of 2.1 cm. Terrestrial laser scanning employed a FARO Focus S350 with a resolution of 1/4 (*i.e.*, point spacing of 6.1 mm at 10 m), and registration using spherical targets and the ICP algorithm achieved an RMS accuracy of ≤3 mm. Georeferencing was based on six ground control points (GCPs, measured by RTK), yielding an overall root mean square

error (RMSE) of 2.8 cm for the integrated model, meeting the accuracy requirements for archaeological site archiving. is used to acquire millimeter-precision point-cloud data of key wall sections and archaeological features, compensating for data gaps in vertical surfaces and details of the aerial model. In professional software such as Blender, multi-source data are integrated with reference to archaeological maps and typological research to construct a high-detail 3D model that balances macroscopic geographic fidelity and microscopic archaeological accuracy. Through a PBR (Physically Based Rendering) material workflow, base-color maps restore the hues of different soil types such as rammed earth and ash; roughness maps represent differences in weathering and tool marks; and normal/displacement maps finely depict micro-geometric features such as rammed-earth laminations, post-holes, and tool impressions. Ultimately, a high-fidelity digital twin model reflecting both the current state and historical traces of the site is generated.

3.2. Construction of a Multi-Source Site Database and Information Linkage

In-depth interpretation of the site relies on systematic integration of multidimensional, multi-type archaeological information. Therefore, the database adopts a simplified cultural heritage core metadata model, referencing the CIDOC CRM conceptual framework with five custom core entity types: SiteUnit, Artifact, Image, Document, and TimeSpan. Each entity is assigned a globally unique identifier (UUID) and indexed with spatiotemporal relationships. At runtime in UE5, attribute storage is driven by DataTables, and dynamic queries are performed via Blueprint's "GetDataRow" node by ID, triggering the UI panel to load corresponding texts, models, and dating data. All 3D models are streamed with LOD levels to ensure real-time linkage rendering efficiency of multi-source data. The database integrates not only the aforementioned geometric-spatial information (3D models, high-resolution orthophotos, point clouds) but also systematically links multi-level data from archaeological excavations: the geographic information layer (trench locations, elevation); the feature layer (IDs, stratigraphic relationships, plans/sections of walls, ash-pits, tombs); the artifact layer (3D models, line-drawings, photographs, materials, dating data of excavated pottery, stone, bone tools); and the documentation layer (excavation diaries, preliminary research results, relevant historical texts). All data are linked through unified spatiotemporal coordinates and ID identifiers, forming a queryable, analyzable, and visually retrievable knowledge network that provides solid underlying data support for front-end interactive storytelling and in-depth exploration [4].

3.3. Spatiotemporal Dynamic Narrative Design and Implementation

To bring static site models to life, this study focuses on building dynamic narrative capabilities across time. A clear evidence-inference distinction rule is established for scene reconstruction: 1) Direct evidence layer: features such as rammed-earth

layering, post-hole locations, and ash-pit boundaries are directly derived from excavation reports based on plan and section drawings and typological data. 2) Interpretive reconstruction layer: elements such as above-ground building forms, vegetation cover, and human activity scenes are inferred through analogy with contemporaneous sites (e.g., Chengziya, Liangchengzhen) and ethnographic references. The system transparently communicates the confidence level of each element via a three-tier "evidence strength indicator" (high/medium/low) in the UI, and annotations such as "archaeological inference" or "based on typological analogy" are provided in knowledge cards to ensure academic rigor.

1) Visualization of Stratigraphic Accumulation and Settlement Evolution: Based on archaeological stratigraphic sequences, the accumulation of cultural layers and changes in settlement layout across different periods (e.g., late Dawenkou, Longshan, Yueshi cultures) are produced as key-frame animations. Users can drag a timeline slider to intuitively observe the dynamic evolution of the site area over millennia—topographic changes, construction and abandonment of city walls, and shifts in settlement boundaries.

2) Visualization of Stratigraphic Accumulation and Settlement Evolution: Based on stratigraphic relationships and radiocarbon data from key excavation units (e.g., T0203, T0405), a stratigraphic unit–historical period mapping is established: Layer 6 → Hougang Phase (4600 - 4500 BP); Layer 5 → Early Longshan (4500 - 4200 BP); Layer 4 → Middle Longshan (4200 - 4000 BP); Layer 3 → Yueshi Culture (4000 - 3600 BP). Each period's determination is based on typological comparison, stratigraphic superimposition, and artifact evolution. Key-frame animations are produced accordingly; when users drag the timeline slider, each switching node displays the "trench number + dating data + determining basis" for narrative transparency.

3) Reconstruction of Key Historical Scenes and Simulation of Construction Processes: Core historical nodes (e.g., initial wall construction, peak period, abandonment phase) are selected, and 3D animation techniques are used to reconstruct their possible macroscopic appearance in the virtual scene. Specifically for wall construction, the archaeologically inferred "rammed-earth formwork technique" is decomposed into key steps—planning baselines, setting formwork, layering and ramming, wall tapering—and produced as playable process-explanation animations. This dynamic narrative is not pre-rendered video but an interactive, real-time engine-rendered sequence that allows users to pause, skip, and observe from multiple angles, thereby translating complex archaeological inferences into accessible visual language and deeply revealing the social mobilization capacity and engineering skill witnessed by the site.

4. Engine Architecture and Core Interaction Implementation for the English Virtual Exhibition

4.1. Engine Selection and Prehistoric Environment Creation

Based on the imperative need for high-precision restoration and real-time inter-

action with large-scale archaeological scenes, this study selects Unreal Engine 5 (UE5) as the core development platform. Its key advantages lie in fully supporting the project's technical goals: leveraging Nanite virtualized geometry technology, high-precision scanned models of the city wall consisting of tens of millions of polygons can be imported losslessly, maintaining extreme visual detail while ensuring smooth scene performance; through the Lumen global dynamic illumination system, the complex light behavior of prehistoric natural light (e.g., sunlight, moonlight) and artificial light (e.g., bonfires) on rammed-earth surfaces and settlement environments can be accurately simulated, efficiently creating immersive atmospheres from dawn to dusk simply by designing lighting. The engine's built-in Blueprint visual scripting system enables the construction of complex interaction logic via node-based wiring, significantly lowering the development threshold for interdisciplinary teams and facilitating rapid iteration of interactive features according to archaeological interpretation needs.

In actual scene construction, the spatiotemporal characteristics of the site are strictly restored based on archaeological data. Spatially, referring to the archaeological plans of semi-subterranean building clusters, a virtual exhibition space is built with an enclosed, centripetal layout, positioning the reconstructed wall segment as the core narrative anchor. In terms of material and lighting, all surfaces adopt physically-scanned materials such as rammed earth and daub, and dynamic lighting is used to create narrative visual effects—for instance, a narrow beam of evening light passing through a virtual "gateway" structure, casting elongated shadows on the passage floor, thereby hinting at spatial openness and the passage of time, and imbuing the scene with emotional tension and an epic sense beyond visual realism.

4.2. Design and Implementation of Core Interactive Features

To facilitate the cognitive shift from "viewing" to "exploring," the exhibition designs and implements the following key interactive modules centered on the characteristics of the city wall site:

For free spatial exploration, users can roam within the archaeologically-inferred reconstructed settlement via a first-person perspective or switch to a bird's-eye view to survey the macro-relationship between the site and its environment. Navigation follows intuitive interaction principles, supporting keyboard, mouse, and mainstream VR device controls to ensure international users can explore comfortably without specialized training.

For in-depth analysis of site structure, a signature "virtual archaeological investigation" interaction is developed. Users can perform non-destructive virtual sectioning of the digital wall: by dragging a cutting plane, clear internal layered structures of the wall are generated and observed in real time; clicking on any rammed layer or contained artifact triggers a non-modal information panel that dynamically loads and presents carbon-14 dating data, soil-granularity analysis, and high-resolution models of associated artifacts. For key archaeological features such as

wall foundation trenches or post-holes, the system provides focused observation modes and virtual measurement tools, enabling users to conduct independent spatial-scale analysis to meet the deep inquiry needs of educational and professional users.

For dynamic process simulation and participation, reconstruction research is transformed into interactive experiences. The core is the "City Wall Construction Simulator": in designated interactive zones, users can follow contextual prompts to sequentially select and place virtual formwork tools and rammers; the system then triggers real-time animations of each step while synchronously accumulating and visually displaying key estimated data such as labor hours and earthwork volume. Another core feature is the "Temporal Slider": operating the timeline control on the interface drives dynamic evolution of the scene, smoothly presenting the macro-transition of the settlement from initial construction, prosperity, to abandonment—realizing the visualization of "deep time"—and allowing quick switching between reconstructed landscape views of different archaeological-culture periods [5].

4.3. Full-English Interface and Cross-Cultural User Experience Adaptation

Given the core objective of international dissemination, the entire user interface and interactive system have undergone comprehensive English localization and cross-cultural design adaptation. All textual content—including guide labels, operation prompts, artifact explanations, and complete audio narration—has been professionally translated and crafted by a team with archaeology and communication backgrounds to ensure academic accuracy and cultural accessibility, avoiding misunderstandings due to literal translation or culture-specific expressions. Interaction logic and visual-symbol system design deeply reference international mainstream digital museum and serious-educational-game paradigms to ensure cognitive consistency. Considering audience diversity, the system offers switchable "Guided Narrative Mode" and "Open Exploration Mode," as well as adjustable "Information Density" options, allowing users to highly customize their experience path and learning pace based on their prior knowledge, interests, and language proficiency. This effectively covers and deeply serves a broad user spectrum, from general international visitors and students to professional researchers.

5. Multilingual Testing and Global Dissemination Value Assessment of the Virtual Exhibition

5.1. International User Testing and Iterative Optimization

To ensure global usability and cross-cultural acceptance of the full-English virtual exhibition, this study conducted multiple rounds of international user experience testing. The testing groups included not only domestic students and scholars in archaeology and digital media but also specifically invited international students, scholars, and museum enthusiasts from English-speaking countries with diverse

cultural backgrounds as core testers to simulate real overseas usage scenarios [6].

Testing employed mixed methods with 42 participants (28 native English speakers, 14 non-native; backgrounds: archaeology 12, museology 8, digital media 10, general public 12). Tasks included free exploration + three specified interactions (virtual sectioning, construction simulation, timeline switching) + pre/post questionnaires. Evaluation used SUS usability scale, ITC-SOPI presence scale, and self-designed cultural cognition gain questionnaire. Results: SUS mean 82.3 (Grade A-); ITC-SOPI spatial presence mean 4.2/5; cultural cognition accuracy improved from 38% to 79% ($p < 0.01$). Qualitative feedback: 87% of native English speakers agreed "layered knowledge card design reduces cognitive load"; 75% of archaeology users affirmed "evidence strength indicator enhances academic credibility." Based on this feedback, key optimizations focused on improving cross-cultural user experience: First, regarding performance and accessibility, multiple quality presets from "Performance-First" to "Visual-Fidelity" were implemented, and the scene's dynamic-streaming mechanism was optimized to ensure smooth access across different terminal devices. Second, for interaction and cognitive guidance, a visual-guidance system aligned with international user habits was strengthened, such as using pulsing halos for non-verbal cues on interactive objects and designing concise full-English interactive tutorials. Finally, for multimodal content adaptation, lengthy academic explanations were restructured into a modular, selectable "Knowledge Card" system; each entry provides concise text-image summaries paired with professionally recorded English audio, and a floating Glossary function for key terms was added, allowing users to autonomously control the pace and depth of information reception based on their language proficiency and interest level.

5.2. Comprehensive Value and Global Significance of the Project

The English virtual exhibition built in this project demonstrates value across a complete chain from digital archiving to global dissemination, with profound multi-dimensional significance.

Value for Digital Preservation and Global Sharing of Cultural Heritage: The project creates a digital twin archive compliant with international cultural-heritage digital-recording standards, comprising centimeter-precision 3D site models, a structured multilingual archaeological database, and authoritative academic interpretation. This not only constitutes permanent digital preservation of fragile earthen sites but, crucially, transforms Chinese early-civilization archaeological achievements into a globally accessible, understandable, and researchable digital public good in open, interoperable formats, providing a high-quality data foundation for cross-civilization comparative research and dialogue.

Value as an Innovative Global Education Platform: The project establishes an immersive archaeological education international platform that transcends geographic and language barriers. Through highly interactive exploratory learning, it translates complex knowledge about early urbanism and state origins into intui-

tive experiences. For students, educators, and lifelong learners worldwide, it offers a "field-visit" entry point to key Chinese archaeological sites without requiring visas, serving as an innovative tool to promote global public understanding of shared human civilizational journeys, particularly the developmental landscape of early East Asian civilizations, with significant public-education and international-education value.

Methodological Value in Technological Integration and Cross-Cultural Design: As a practice deeply integrating archaeology, digital engineering, interaction design, and cross-cultural communication, this project validates a complete workflow for applying cutting-edge game-engine technology to the international dissemination of large-scale immovable heritage. The accumulated experience and solutions in handling multi-source data fusion, real-time large-scene rendering, and designing interaction interfaces aligned with non-native-speaker cognitive habits provide transferable interdisciplinary methodologies and practical cases for the digital presentation and international storytelling of similar heritage worldwide.

Bridge Value for International Communication and Civilizational Exchange: Through cross-platform publishing technologies like WebGL, the project can be embedded with low thresholds into various global websites, educational platforms, and social media. It proactively delivers the significant archaeological discovery of Jinan Longshan culture in a digitally accessible form to global cyberspace, directly addressing the practical need to enhance the international visibility of Chinese archaeology. It is not merely one-way information dissemination but constructs an online international cultural space that can stimulate interaction, questioning, and discussion, effectively serving as a digital bridge promoting academic exchange and mutual learning among civilizations, with positive practical significance for shaping a credible, appealing, and respectable image of China.

Funding Statement

Research Project on the Cultivation of Basic Education Teaching Reform of Qilu Normal University in 2025: Research on the Construction Path of New Forms of English Textbooks Integrating "Paper" and "Digital" from the Perspective of Smart Education for Primary Schools (Project Number: JP202409).

Conflicts of Interest

The authors declare no conflicts of interest.

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