

Strategies and Applications for Constructing Immersive Exhibition Spaces in the Context of Digital Cultural Tourism

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ABSTRACT The rapid development of digital cultural tourism has created increasing demands for immersive exhibition environments that seamlessly integrate cultural expression, intelligent interaction, and real-time information delivery. This study proposes a three-dimensional construction framework for immersive exhibition spaces based on cultural digital reconstruction, immersive experience design, and intelligent interaction optimization. By combining digital twin technology, high-precision 3D reconstruction, and multisensory VR/AR/MR integration, the framework enables accurate preservation and dynamic presentation of cultural heritage while improving user participation through behavior-aware interactive mechanisms. A multidimensional evaluation system covering cultural expression, immersive perception, interaction quality, and technological integration is established to quantitatively assess implementation effectiveness. Experimental results demonstrate notable improvements in cultural perception accuracy, immersive satisfaction, interaction participation, and user engagement compared with conventional exhibition approaches. The proposed strategy also provides a practical reference for next-generation digital exhibition infrastructures supported by wireless communication, electromagnetic signal transmission, and distributed sensing technologies, where low-latency data exchange and reliable spatial information propagation are essential for synchronized immersive experiences.

INDEX TERMS digital cultural tourism, immersive exhibition space, virtual and augmented reality, wireless communication, intelligent interaction

I. INTRODUCTION

A. RESEARCH BACKGROUND

WITH the deep integration of digital technologies such as 5G, artificial intelligence, and virtual reality into the cultural and tourism industry, including the preservation and exhibition of heritage, digital cultural tourism has become a key direction for the industry's transformation and upgrading [1-3]. The "14th Five-Year Plan for Digital Development in Culture and Tourism" issued by the Ministry of Culture and Tourism indicates that by 2025, China's digital cultural tourism industry will exceed 1 trillion yuan in scale, with immersive experience projects becoming the core growth driver of the cultural tourism market. As a key carrier of digital cultural tourism, immersive exhibition spaces have garnered widespread industry attention by leveraging digital technologies to transcend the limitations of traditional display formats and achieve deep integration between cultural content and immersive experiences [4-7].

B. CURRENT STATE OF DOMESTIC AND INTERNATIONAL RESEARCH

1) Research on Immersive Experience Technologies in Cultural Tourism

The application of digital technologies serves as the core driving force behind the development of immersive exhibition spaces. International research has pioneered the integration of multiple technologies with cultural tourism scenarios. The British Museum launched a VR-based immersive exhibition project, using 3D scanning and VR technology to recreate ancient Egyptian pyramids and mummy tombs, enabling users to "step into" ancient cultural settings [8]. France's Palace of Versailles constructed a digital twin system for the palace, achieving real-time mapping between physical and virtual spaces to provide personalized navigation and interactive interpretation services [9].

Domestic research has focused on applying digital technologies like AR and MR to cultural heritage preservation and display. A Tsinghua University team developed an

AR-based cultural relic restoration and exhibition system, using image recognition and 3D modeling to achieve virtual restoration and interactive display of damaged artifacts [10]. Zhejiang University utilized MR technology to construct an immersive experience space for classical Chinese gardens, integrating virtual cultural elements such as historical figures and anecdotes into real garden settings [11]. However, existing applications predominantly concentrate on single-technology integration, lacking systematic multi-technology convergence, which hinders comprehensive upgrades in immersive experiences.

2) Research on Immersive Exhibition Space Construction

International research on immersive exhibition space construction emphasizes user experience and cultural expression. Harvard University professors Pine II and Gilmore proposed the “experience economy” theory, arguing that immersive experiences should be user-centered, achieving emotional connections between users and cultural content through scene construction and interactive design [12]. German scholars developed a user-centric design framework for immersive exhibition spaces based on environmental psychology, emphasizing the impact of spatial layout, lighting, and sound on user experience [13]. Domestic research primarily focuses on design methodologies and innovative models for exhibition spaces. Some scholars propose an “Culture + Technology + Experience” framework for constructing immersive exhibition spaces, emphasizing cultural content as the core, technological support as the means, and user experience as the goal [14]. Other scholars have explored layout design and scene creation for immersive exhibition spaces, proposing principles such as spatial sequencing, visual focal points, and multisensory integration [15]. However, existing research largely remains at the conceptual and theoretical level, lacking concrete implementation strategies and insufficient quantitative evaluation and validation of spatial construction outcomes.

C. RESEARCH QUESTIONS AND INNOVATION POINTS

1) Core Research Questions

1. How to establish a technical methodology system for cultural digital reconstruction to achieve precise transformation and intrinsic value extraction of cultural elements from physical to virtual forms?

2. How to design multi-sensory integrated immersive experience scenarios to enhance users’ sense of presence, immersion, and emotional resonance?

3. How to establish an intelligent interaction mechanism based on user behavior perception to realize personalized interactive services and efficient participation feedback?

4. How can a scientific evaluation system be constructed to quantify the effectiveness and application value of immersive exhibition spaces?

2) Research Innovations

1. Proposes a three-stage reconstruction method—“Cultural Gene Extraction—Digital Modeling—Creative Transformation”—which employs cultural gene mapping and digital twin technology to achieve deep excavation and precise expression of cultural connotations, resolving the disconnect between culture and technology;

2. Establishes a three-dimensional immersive experience design system of “multisensory stimulation—spatial narrative—emotional resonance,” integrating visual, auditory, tactile, and other multisensory technologies with spatial narrative logic to enhance users’ presence and emotional connection;

3. Develops an intelligent interaction mechanism of “user behavior perception—personalized interaction—real-time feedback,” analyzing user preferences through big data and AI technologies to deliver customized interactive services, thereby improving participation efficiency and experience quality;

4. Develop a four-dimensional evaluation framework encompassing cultural expression, immersive perception, interactive participation, and technological integration, providing scientific foundations for quantifying and optimizing immersive exhibition spaces.

D. RESEARCH SIGNIFICANCE

1) Theoretical Significance

1. Enrich interdisciplinary research at the intersection of digital cultural tourism and immersive experience design, revealing intrinsic mechanisms linking cultural digitization, immersive experiences, and intelligent interaction to support theoretical frameworks for immersive exhibition spaces;

2. Establish systematic construction strategies and evaluation methods for immersive exhibition spaces, filling gaps in existing research regarding technology integration, experience design, and effect quantification, and offering new perspectives for related fields.

2) Practical Significance

1. Provide cultural tourism project developers with actionable solutions for constructing immersive exhibition spaces, shortening project R&D cycles, reducing trial-and-error costs, and enhancing the core competitiveness of cultural tourism products;

2. Offer new pathways for the digital preservation and revitalization of cultural heritage, facilitating the transformation of traditional resources, such as intricate craftsmanship, into modern cultural tourism products while amplifying cultural dissemination and influence;

3. Deliver deeper, personalized cultural experiences to users, meeting the evolving demands of cultural tourism consumption in the new era and fostering high-quality development of the digital cultural tourism industry;

4. Provide data support for policy formulation and industry standard refinement, promoting the standardized and sustainable growth of the digital cultural tourism sector.

II. THEORETICAL AND TECHNOLOGICAL FOUNDATIONS

A. CORE THEORETICAL SUPPORT

1) Immersion Theory

Proposed by psychologist Csikszentmihalyi, immersion theory posits that users entering a state of complete engagement in an activity experience heightened concentration, temporary loss of self-awareness, and distorted perception of time [16]. Four conditions must be met for immersive experiences:

1. Clear objectives and immediate feedback;
2. Challenge levels matching user capabilities;
3. High concentration without external distractions;

4. Intrinsic rewards motivating active user participation. Within immersive exhibition spaces, Immersion Theory guides experience design by: defining clear user objectives, designing appropriately challenging tasks, creating distraction-free environments, and providing immediate feedback with emotional rewards to guide users into deep immersion [17,18].

2) Digital Narrative Theory

Building upon traditional narratology, digital narrative theory integrates the interactivity and multimedia characteristics of digital technology to construct a “user-participatory” narrative model [19]. Unlike traditional linear narratives, digital narratives feature non-linearity, interactivity, and multi-sensory engagement. Users are no longer passive recipients of stories but can autonomously choose narrative paths and participate in story development [20].

Within immersive exhibition spaces, digital narrative transforms cultural stories into experiential processes through the integration of “spatial scenes + cultural content + interactive behaviors”: using space as the narrative vessel, cultural elements as narrative symbols, and user interaction as the narrative engine to achieve profound transmission of cultural significance [21].

3) Digital Heritage Preservation Theory

Digital heritage preservation theory emphasizes the use of digital technology for recording, protecting, exhibiting, and disseminating cultural heritage. Its core comprises four key stages: digital acquisition, digital modeling, digital storage, and digital exhibition [22]. The central objective is to accurately restore the physical characteristics of cultural heritage while enabling the excavation and revitalization of its cultural significance [23].

This theory guides the digital reconstruction of cultural elements: precise acquisition through 3D scanning and high-definition photography; digital model construction via 3D modeling and texture mapping; cultural meaning extraction through metadata annotation and knowledge graph construction; and innovative presentation using VR/AR and digital twin technologies [24-26].

B. KEY TECHNOLOGICAL SUPPORT

1) Immersive Experience Technologies

1. VR/AR/MR Convergence Technologies: VR creates fully virtual immersive environments, enabling users to detach from reality via wearable devices and enter virtual cultural spaces; AR overlays virtual cultural elements onto real-world scenes, achieving blended reality; MR integrates VR and AR strengths, supporting real-time interaction between virtual elements and physical environments to enhance immersive authenticity [27,28].

2. Multisensory Interaction Technology: Haptic feedback devices (e.g., data gloves, force-feedback controllers) enable tactile experiences, allowing users to feel the textures and surfaces of virtual artifacts. Odor generators and taste simulators deliver olfactory and gustatory experiences, recreating ancient scents and culinary cultures. Combined with 3D audio technology, these create spatialized soundscapes that heighten presence [29].

3. Spatial Lighting Control Technology: Adjusts light intensity, color, and direction through intelligent lighting systems to simulate historical illumination environments (e.g., candlelight in ancient palaces, dawn sunlight). Combined with projection mapping technology, dynamic scenes are projected onto walls and floors to intensify spatial narrative ambiance [30].

2) Intelligent Interaction Technology

1. User Behavior Perception Technology: Cameras and sensors collect behavioral data (gestures, facial expressions, movement trajectories), combined with computer vision and behavioral analysis algorithms to identify user needs and preferences. For example, facial expression recognition determines user interests to automatically push relevant cultural content.

2. Natural Interaction Technology: Includes gesture recognition, voice interaction, and eye-tracking, enabling users to engage with the exhibition space through natural movements and speech without complex devices. For instance, users can rotate or zoom virtual artifacts via gestures and obtain cultural interpretations through voice queries.

3. Personalized Recommendation Technology: Based on user profiles and behavioral data, algorithms like collaborative filtering and content recommendation deliver tailored experiential content and interaction paths. For instance, historical enthusiasts receive in-depth cultural interpretations, while youth audiences are offered interactive gamified experiences.

C. EVALUATION METRIC SYSTEM CONSTRUCTION

Factor analysis was conducted to verify the structural validity of the evaluation system. The KMO test value is 0.823 (greater than 0.7), and the Bartlett spherical test $P < 0.001$, indicating that the data is suitable for factor analysis. Four common factors were extracted by the maximum variance rotation method, which is consistent with the original four-dimensional framework. The factor loading of each indicator

on the corresponding common factor is greater than 0.75, and the cross-loading is less than 0.3, verifying the independence of the indicators and the rationality of the framework structure.

Aligning with digital cultural tourism characteristics and the core objectives of immersive exhibition spaces, a four-dimensional evaluation metric system is established. The Analytic Hierarchy Process (AHP) determines the weighting of each indicator: To clarify the independence of each evaluation indicator, the core connotation and measurement boundary of key indicators are defined as follows: Cultural Connotation Transmission Efficiency: Focuses on the accurate transmission of cultural knowledge, measured by the pass rate of user cultural cognition tests, reflecting the "information transmission effect at the cognitive level"; Emotional Resonance Degree: Focuses on the degree of emotional impact on users, measured by user emotional feedback questionnaires, reflecting "subjective feelings at the emotional level"; Personalized Interaction Satisfaction: Focuses on the adaptability and convenience of interaction design, measured by user ratings, reflecting the "interaction experience at the behavioral level". The three indicators correspond to the "cognition-emotion-behavior" dimension respectively, and have independent measurement objects and boundaries despite certain correlations. The Evaluation Index System of Immersive Exhibition Space is shown in Table 1:

D. CORRELATION MECHANISM BETWEEN THEORY AND CONSTRUCTION FRAMEWORK

The three core theories of this study form a one-to-one correspondence with the three major components of the construction framework, providing targeted theoretical support for each link of immersive exhibition space construction: Digital Heritage Preservation Theory Supports "Cultural Digital Reconstruction": Guided by the core logic of "digital acquisition-modeling-storage-exhibition", it provides methodological guidance for cultural gene extraction, high-precision modeling, and digital expression of cultural connotations. It solves the problem of precise transformation of cultural elements from physical to virtual forms, ensuring the unity of cultural authenticity and digital accuracy.

Immersion Theory Supports "Immersive Experience Design": Based on the four core conditions of "clear goals-immediate feedback-ability matching-focus and undisturbance" proposed by Immersion Theory, it guides the design of multi-sensory fusion, spatial narrative, and emotional resonance. By optimizing the matching degree between experience difficulty and user capabilities and constructing a distraction-free spatial environment, it helps users enter a deep immersive state.

Digital Narrative Theory Supports "Intelligent Interaction Optimization": Taking "user-participatory narrative" as the core, it guides the design of behavior perception, personalized interaction, and real-time feedback mechanisms. It transforms static cultural stories into dynamic and personal-

ized experiential processes, realizing in-depth transmission of cultural significance through user interaction."

III. STRATEGIC FRAMEWORK FOR IMMERSIVE EXHIBITION SPACE CONSTRUCTION

A. OVERALL CONSTRUCTION FRAMEWORK

This paper proposes a three-dimensional strategic framework comprising "Cultural Digital Reconstruction—Immersive Experience Design—Intelligent Interaction Optimization." Immersive experience design serves as the key vehicle, while intelligent interaction optimization acts as the enhancement method. These three elements synergistically support the construction of immersive exhibition spaces, ultimately achieving continuous optimization through an evaluation feedback mechanism.

The core logic of this framework is: - Grounded in cultural content, with the support of Digital Heritage Preservation Theory, achieving precise expression of cultural essence through digital reconstruction; - Aiming for user experience, guided by Immersion Theory, constructing multi-sensory, narrative-rich spatial environments via immersive experience design; - Supported by technological application, based on Digital Narrative Theory, enhancing user engagement and personalized experiences through intelligent interaction optimization; - Collecting user and expert feedback through an evaluation mechanism to iteratively refine all three components.

B. CULTURAL DIGITAL RECONSTRUCTION STRATEGY

1) Cultural Gene Extraction and Organization

Employ a comprehensive approach combining "literature mining + expert interviews + field research" to extract cultural genes:

1. Literature Mining: Organize historical documents, archaeological reports, and academic papers related to cultural themes to extract key cultural elements (e.g., historical events, figures, artistic styles, craft techniques);

2. Expert Interviews: Assemble a team of cultural heritage preservation specialists, historians, and folklorists to screen and categorize extracted elements, defining core cultural genes;

3. Field Research: Conduct on-site investigations of cultural heritage sites, collecting physical samples and visual materials to supplement intangible cultural genes (e.g., operational procedures of traditional crafts, ritual details of folk activities).

Based on the extracted cultural genes, construct a hierarchical genealogy: Primary Genes → Secondary Genes → Tertiary Genes. Primary Genes represent cultural themes (e.g., "Silk Road," "Tang and Song Poetry"). Secondary Genes denote cultural categories (e.g., historical events, art forms, folk customs). Tertiary Genes specify concrete cultural elements (e.g., "Zhang Qian's Mission to the Western Regions," "Dunhuang Murals," "Paper-cutting Craft").

TABLE 1. Evaluation Index System of Immersive Exhibition Space

First-level Indicator	Weight	Second-level Indicator	Weight	Evaluation Method
Cultural Expression	0.35	Cultural Gene Fidelity	0.45	Expert Rating Method (1–10 points)
		Cultural Connotation Transmission Efficiency	0.35	User Cultural Cognition Test Pass Rate
Immersive Perception	0.30	Cultural Creative Transformation	0.20	User Rating Method (1–10 points)
		Sense of Presence Intensity	0.40	Immersive Experience Scale (1–7 points)
		Multi-sensory Integration	0.35	Sensory Experience Integrity Degree Rating
		Emotional Resonance	0.25	User Emotional Feedback Degree Questionnaire
Interactive Participation	0.20	Proportion of Users Participating in Interaction	0.40	Interactive Participation Rate
		Interactive Command Response Speed	0.30	Interactive Response Delay Time (≤ 100 ms is excellent)
		Personalized Interaction Satisfaction	0.30	User Rating Method (1–10 points)
Technical Integration	0.15	Technical Stability	0.45	Continuous Operation Fault-free Time (≥ 24 h is excellent)
		Technical Adaptability	0.35	Experience Consistency in Different Devices/Network Environments
		Technical Scalability	0.20	Integration Difficulty Rating for New Functions

2) Digital Modeling and Reconstruction

1. Precision Digital Modeling: Employ differentiated modeling approaches for distinct heritage types:

- Cultural artifacts: Utilize laser scanning + photogrammetry to construct high-precision 3D models, restoring form, texture, and material details with 0.01mm accuracy.
- Architectural structures: Apply BIM technology + 3D reconstruction to build structural and exterior models, recreating spatial layouts and decorative elements.

Scenic Sites: Employ digital twin technology to integrate terrain, vegetation, and architectural elements, constructing dynamic scene models that support real-time simulation of environmental factors like weather and time.

2. Digital Expression of Cultural Essence: Link cultural heritage with digital models through metadata annotation, knowledge graph association, and multimedia interpretation: Metadata Annotation: Add cultural attribute tags to digital models (e.g., era, material, historical context, cultural significance); Knowledge Graph Linkage: Establishing relationships between cultural elements (e.g., linking “Dunhuang murals” to “Buddhist culture” and “Silk Road”); Multimedia Interpretation: Providing accompanying audio, video, and text interpretations for digital models, enabling users to access in-depth cultural information through interaction.

To standardize the cultural gene extraction process, a four-step method for constructing cultural gene maps is proposed: Feature Deconstruction: Adopt “morphological analysis + semantic association analysis” to decompose cultural elements. For patterns, they are broken down into four core feature dimensions: basic patterns (geometry/flora and fauna), color matching, composition rules, and craft symbolism. Gene Coding: Assign unique codes to each feature dimension to establish a cultural gene database. For example, the code for “peony pattern-vermilion-symmetrical composition-symbol of wealth and prosperity” is FW-MD-ZH-DC-FG.

Hierarchical Association: Construct an association network of “Primary Genes $\rightarrow$ Secondary Genes $\rightarrow$ Tertiary Genes” through knowledge graph technology, clarifying the inheritance and derivative relationships between cultural genes.

Weight Assignment: Use the Analytic Hierarchy Process (AHP) to assign importance weights to cultural genes. The weight of core symbolic genes is 0.4, morphological feature genes is 0.3, and process feature genes is 0.3.

3) Creative Cultural Transformation

Achieving creative digital expression while preserving cultural authenticity:

1. Scenario Reconstruction: Integrate dispersed cultural elements into cohesive cultural scenes, such as combining Tang poetry, Tang architecture, and Tang attire to create an immersive “Golden Age Chang’an Street” experience;
2. Interactive Transformation: Convert cultural elements into interactive experiences, e.g., transforming traditional paper-cutting craft into a digital paper-cutting game where users complete creations via gesture controls;
3. Visual Presentation: Transforming abstract cultural concepts into intuitive visuals, such as converting Traditional Chinese Medicine meridian theory into dynamic visual models where users can interactively explore meridian pathways and acupoint distributions.

C. IMMERSIVE EXPERIENCE DESIGN STRATEGIES

1) Multi-Sensory Fusion Experience Design

1. Visual Experience Design: Employing a combination of “dynamic scenes + static displays + interactive projections” to create rich visual layers. Dynamic scenes present animated cultural content (e.g., ancient battles, folk performances) via VR/AR/MR technology; static displays feature high-precision digital artifacts and high-definition imagery; interactive projections use projection mapping to display responsive content on spatial interfaces (e.g., petals falling or text appearing when users touch walls).

2. Auditory Experience Design: Construct a three-dimensional soundscape combining “spatial sound effects + thematic music + interactive audio.” Spatial sound effects simulate authentic scene noises (e.g., court ceremonial music, street vendors’ cries); thematic music is customized to cultural themes (e.g., traditional scenes paired with guzheng/flute melodies, modern scenes with electronic beats); interactive sounds respond to user actions (e.g.,

material collision sounds upon touching artifacts, reward sounds for completing tasks).

3. **Tactile/Olfactory/Gustatory Experience Design:** Incorporate multisensory stimuli for specific cultural scenarios. For example, in the “Ancient Teahouse” scene, users can feel the texture of tea ware via tactile devices, smell tea leaves through scent diffusers, and taste ancient tea beverages via taste simulators. In the “Traditional Crafts” scene, users experience tactile feedback from weaving and pottery crafts through data gloves.

2) Spatial Narrative Experience Design

1. **Narrative Structure Design:** Employ a “non-linear, multi-path” narrative structure allowing users to independently choose their experience route. For instance, in the “Silk Road” themed space, users may select the “Merchant Route,” “Envoy Route,” or “Explorer Route,” each corresponding to distinct cultural scenarios and story content.

2. **Narrative Symbol Design:** Cultural elements are transformed into visual narrative symbols that permeate the entire spatial experience. For example, the “dragon pattern” serves as a core symbol of traditional culture, recurring in spatial decorations, interactive interfaces, and virtual elements to enhance cultural recognition.

3) Emotional Resonance Experience Design

1. **Personalized Scenario Adaptation:** Tailor experiential content based on user profiles. For instance, design gamified scenarios (e.g., cultural challenges, artifact restoration games) for youth users, and nostalgic settings (e.g., recreated old neighborhoods, traditional festival atmospheres) for elderly users.

2. **Participatory Emotional Connection:** Design user-participatory cultural creation tasks, such as digital mural painting or traditional music adaptation. Users can display their creations within the space or share them on social platforms, enhancing emotional belonging.

3. **Immersive Role-Playing:** Assign users cultural roles (e.g., ancient merchants, literati, artisans). Users deepen their understanding of the character’s life and emotions by completing role-specific tasks (e.g., procuring goods, composing poetry, crafting artifacts), strengthening cultural identification.

D. INTELLIGENT INTERACTION OPTIMIZATION STRATEGY

1) User Behavior Perception and Analysis

1. **Multi-dimensional Data Collection:** Capture visual data (facial expressions, gestures, gaze points) via cameras; collect motion data (movement trajectories, dwell times) through sensors; gather operational data (clicks, drags, voice commands) from interactive devices.

2. **User Need Identification:** Analyze collected data using machine learning algorithms to identify user interests, behavioral preferences, and experiential requirements. For example, gaze point analysis determines cultural elements

of interest, dwell time analysis identifies engaging scenarios, and operational behavior analysis reveals interaction habits.

3. **User Profile Construction:** Build multidimensional user profiles based on analysis results, including:

- Basic attributes (age, gender, occupation)
- Cultural preferences (history, art, folklore)
- Interaction preferences (gesture-based, voice-based, gamified)
- Experience depth (superficial viewing, deep engagement) .

2) Personalized Interaction Design

1. **Personalized Interaction Content:** Push customized cultural content and interaction tasks based on user personas. For instance, deliver in-depth cultural interpretations and archaeological simulation tasks to history enthusiasts; offer digital creation and aesthetic experience tasks to art lovers; and provide entertaining cultural education and mini-games for children.

2. **Personalized Interaction Methods:** Support users’ preferred interaction methods. For instance, elderly users may choose voice interaction and simplified operations, while younger users may opt for gesture interaction and complex gamified interactions. Dynamically adjust interaction difficulty based on user proficiency—provide guided interactions for novice users and autonomous interactions for experienced users.

3. **Personalized Interaction Pacing:** Adjust experience pacing according to users’ movement speed and operation frequency. For instance, extend scene display times and simplify task flows for slower users, while increasing task difficulty and offering richer content for faster users.

3) Real-Time Feedback and Iterative Optimization

1. **Instant Interaction Feedback:** Provide multisensory feedback immediately after users perform actions.

Examples include:

- Virtual artifacts emitting light effects and sound when tapped, accompanied by cultural information displays;

Upon completing an interaction task, offer visual rewards (e.g., badges, animations) and emotional feedback.

2. **Experience Process Feedback:** Dynamically adjust content based on real-time user behavior data. For instance, if a user lingers too long in a scene, automatically push more detailed cultural interpretations; if a user fails an interaction task multiple times consecutively, provide hints or reduce task difficulty.

E. DATASET CONSTRUCTION

A multidimensional dataset (DCT-2024) was constructed by integrating “project research data + user feedback data + technical test data”:

1. **User Feedback Data:** Collected through online surveys and offline interviews. The online survey yielded 1,500 valid responses, while offline interviews engaged 200 users of

diverse ages and professions to gather evaluations and needs regarding immersive experiences, interaction design, and cultural expression.

2. Technical Testing Data: Conducted technical evaluations through prototype systems, collecting performance metrics (response speed, stability, experiential outcomes) across different technology combinations (e.g., VR + multisensory interaction, AR + digital twins).

The dataset was partitioned into training (2,100 entries), validation (300 entries), and testing (600 entries) sets at a 7:1:2 ratio for training and validating personalized recommendation models and evaluation models.

IV. EXPERIMENTAL DESIGN AND RESULTS ANALYSIS

A. EXPERIMENTAL ENVIRONMENT AND PROTOTYPE SYSTEM SETUP

1. Data Acquisition Devices: Laser scanner (Faro Focus S70), high-definition camera (Sony FX6), 3D camera

(Intel RealSense L515), facial recognition camera (Microsoft Kinect), haptic feedback device (Manus VR Prime II data glove);

2. Computing and Storage Equipment: Intel Xeon Gold 6438 processor, NVIDIA A100 80GB GPU ×2, 256GB RAM, 8TB SSD storage, edge computing gateway (Huawei AR650).

B. COMPARATIVE EXPERIMENT DESIGN

1) Comparison Subjects

Three representative exhibition spaces were selected as comparison subjects to ensure experimental fairness:

1. Traditional Exhibition Space: Utilizes conventional museum displays featuring physical artifacts, textual descriptions, and static images, without digital technology or interactive design;

2. Single-Technology Digital Exhibition Space: Employs only VR technology to construct virtual scenes, lacking multisensory integration and intelligent interaction design;

3. Industry-Standard Immersive Exhibition Space: Its core features are "single VR technology support + basic interaction functions + superficial cultural display". Specifically, it only adopts VR technology to construct virtual scenes, lacking AR/MR multi-technology integration; the interaction method is limited to controller-based clicks, without natural interaction methods such as gestures and voice; cultural display remains at the level of digital model display, lacking in-depth cultural gene extraction and creative transformation. It represents the mainstream technical level of the current cultural tourism industry but has obvious limitations in cultural expression depth and interaction intelligence.

2) Experimental Participants

300 volunteers aged 18–65 were recruited, representing diverse occupations (students, office workers, retirees) and cultural backgrounds (history enthusiasts, general tourists, cultural tourism professionals). Each experimental group

comprised 100 volunteers, ensuring no significant demographic differences among the three participant cohorts. This study was approved by the Ethics Committee of Jilin Animation Institute, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

3) Evaluation Metrics and Testing Process

1. Evaluation Metrics: Employed the four-dimensional evaluation framework developed herein, comprising:

- Cultural Perception Accuracy (measured by cultural knowledge test scores)
- Immersive Experience Satisfaction (user ratings on a 100-point scale)
- Interaction Participation Rate (proportion of users engaging with interactions)
- User Dwell Time (average experience duration)

2. Testing Process:

- Pre-experiment: Volunteers received brief training on the experiment's objectives and experience flow.

During Experiment: After experiencing the exhibition space, volunteers completed the cultural knowledge test and satisfaction questionnaire; the system automatically recorded interaction participation rate and dwell time; Post-Experiment: In-depth interviews were conducted with selected volunteers to gather subjective feedback.

C. EXPERIMENTAL RESULTS AND ANALYSIS

1) Overall Performance Comparison

The experimental results for the four exhibition space types are compared in Table 2:

Table 2 demonstrates that the exhibition space constructed using the proposed strategy achieved the highest scores across all metrics:

1. Cultural perception accuracy reached 92.6%, surpassing mainstream immersive exhibition spaces by 6.9 percentage points and traditional spaces by 30.3 percentage points, proving the strategy's effectiveness in enhancing cultural content transmission efficiency;

2. Immersive experience satisfaction reached 89.3 points, exceeding industry-leading immersive spaces by 6.8 points and single-technology digital spaces by 13.1 points, validating the enhancement of immersive experiences through multisensory integration and spatial narrative design;

3. Interactive engagement rate reached 89.7%, surpassing mainstream industry immersive spaces by 21.2 percentage points and traditional spaces by 74.1 percentage points, demonstrating the effectiveness of intelligent interaction optimization strategies in boosting user participation;

4. User dwell time reached 42.5 minutes—2.3 times longer than traditional exhibition spaces and 11.1 minutes longer than mainstream immersive exhibition spaces—demonstrating that high-quality cultural experiences and interactive design effectively enhance user retention.

TABLE 2. Comparison of Overall Performance of Different Exhibition Space Types

Exhibition Space Type	Cultural Perception Accuracy (%)	Immersive Experience Satisfaction (Points)	Interactive Participation Rate (%)	User Dwell Time (Minutes)	Comprehensive Score (Points)
Traditional Exhibition Space	62.3 ± 4.5	58.7 ± 6.2	15.6 ± 3.1	18.2 ± 2.8	52.3 ± 3.8
Single Digital Technology Exhibition Space	78.5 ± 3.8	76.2 ± 5.1	42.3 ± 4.2	25.7 ± 3.5	68.9 ± 3.2
Industry Mainstream Immersive Exhibition Space	85.7 ± 3.2	82.5 ± 4.3	68.5 ± 3.8	31.4 ± 3.2	77.6 ± 2.9
Exhibition Space Constructed by the Proposed Strategy in This Paper	92.6 ± 2.7	89.3 ± 3.5	89.7 ± 3.1	42.5 ± 3.6	88.9 ± 2.5

To verify the rationality of the correlation between theory and framework, a theoretical adaptability test was added. The results show that the average score of components supported by a single theory is 76.3 points, while the average score of components supported by the three core theories is 88.9 points. The significant performance improvement ($P < 0.05$) confirms that the synergistic effect of multiple theories effectively enhances the overall performance of the framework, verifying the validity of the theoretical-framework correlation.

2) Comparative Analysis of User Experience Across Demographics

Analysis of user experience across different age groups and cultural backgrounds for the proposed exhibition space is presented in Table 3:

TABLE 3. User Experience Comparison of Different Demographic Groups

User Group	Age/Background	Cultural Accuracy (%)	Immersive Satisfaction	Interaction Rate (%)	Dwell Time
Adolescent Group	18–25, Mainly Students	90.2 ± 3.1	92.5 ± 2.8	95.3 ± 2.4	45.7 ± 3.2
Young and Middle-aged Group	26–45, Mainly Office Workers	93.7 ± 2.5	88.6 ± 3.6	88.9 ± 3.3	43.2 ± 3.7
Middle-aged and Elderly Group	46–65, Mainly Retirees	91.5 ± 2.9	86.8 ± 3.8	83.2 ± 3.6	38.9 ± 3.5
History and Culture Enthusiasts	All Ages, Culture-focused	95.8 ± 2.1	91.7 ± 3.2	92.4 ± 2.8	48.3 ± 3.4
General Tourists	All Ages, Random Experience	90.3 ± 2.8	88.5 ± 3.4	87.6 ± 3.2	40.5 ± 3.6

Table 3 demonstrates the proposed exhibition space's strong adaptability across user demographics:

1. The youth demographic exhibited the highest satisfaction with immersive experiences and interaction participation rates, as gamified interactions and multisensory stimulation align more closely with their preferences;

2. Middle-aged and young adults demonstrated the highest cultural perception accuracy, benefiting from their strong learning capabilities and demand for in-depth cultural content;

3. Middle-aged and elderly groups showed slightly lower metrics overall but maintained high levels, proving that intelligent interaction design (e.g., voice interaction, simplified operations) effectively lowered their usage barriers;

4. History and culture enthusiasts exhibited the longest dwell time and highest cultural perception accuracy, reflect-

ing the appeal of deep cultural reconstruction to the target user group.

3) Technical Stability and Adaptability Testing

Testing of the technical stability and adaptability of the proposed exhibition space yielded the results shown in Table 4:

TABLE 4. Technical Stability and Adaptability Test Results

Test Item	Test Indicator	Test Result
Technical Stability	Continuous Operation Fault-free Time (h)	72.5 ± 4.2
	Interactive Response Delay Time (ms)	85.3 ± 12.6
Device Adaptability	VR Device Experience Satisfaction (Points)	90.2 ± 3.1
	AR Device Experience Satisfaction (Points)	88.7 ± 3.3
	MR Device Experience Satisfaction (Points)	91.5 ± 2.8
Network Environment Adaptability	High-speed Network (≥ 100 Mbps) Experience Satisfaction (Points)	92.3 ± 2.6
	Medium Network (20–100Mbps) Experience Satisfaction (Points)	89.6 ± 3.0
	Low-speed Network (≤ 20 Mbps) Experience Satisfaction (Points)	85.4 ± 3.5

Test results indicate:

1. good technical stability, with 72.5 hours of continuous fault-free operation and an average interaction response latency of 85.3ms, meeting real-time interaction requirements;

2. Device compatibility is excellent, with satisfaction scores exceeding 88 points across VR, AR, and MR devices, validating the multi-technology integration strategy's compatibility;

3. Network environment adaptability is strong, maintaining satisfactory performance across varying bandwidths. Even in low-speed networks, satisfaction remains at 85.4 points, making it suitable for complex network scenarios in cultural tourism projects.

4) Analysis of User Subjective Feedback

In-depth interview results indicate that positive user feedback on the proposed exhibition space primarily focuses on three aspects:

1. Cultural Experience Depth: 87% of users stated, "The cultural content is rich and profound. It allows us not only to see artifacts but also to understand the historical stories and cultural significance behind them."

2. Immersive Experience: 92% of users remarked, “The multi-sensory experience makes it feel like we’ve truly stepped into ancient scenes. The addition of tactile and olfactory elements enhances the realism.”

3. User-Friendly Interaction: 85% of users noted that “interaction methods are intuitive and convenient, requiring no complex operations, and personalized recommendations align well with my interests.” Suggestions for improvement primarily include: some elderly users requested larger text prompts and enhanced recognition accuracy for voice interaction; others suggested adding more cultural scenarios and interactive tasks to extend the experience duration.

V. CONCLUSION

Addressing challenges in immersive exhibition spaces within digital cultural tourism, where the lack of tactile feedback and fine detail for intricate patterns leads to weak immersion and low interaction efficiency, this study proposes a three-dimensional strategy: “Cultural Digital Reconstruction—Immersive Experience Design—Intelligent Interaction Optimization.” Experimental validation confirms its effectiveness and practical value. Key findings include:

1. Established a technical methodology for cultural digital reconstruction encompassing three phases: cultural gene extraction and systematization, precise digital modeling, and cultural-creative transformation. This achieves deep excavation and accurate expression of cultural essence.

2. Developed a three-dimensional immersive experience design system integrating multisensory fusion, spatial narrative, and emotional resonance. By integrating VR/AR/MR technologies, multisensory interaction, and spatial light-shadow control, it enhances users’ sense of presence and immersion.

3. Proposed an intelligent interaction optimization strategy based on user behavior sensing, personalized interaction, and real-time feedback, delivering efficient, user-centered interactive services;

4. Developed a four-dimensional evaluation system encompassing cultural expression, immersive perception, interactive participation, and technological integration, providing a scientific basis for quantifying the effectiveness of immersive exhibition spaces;

5. Experimental results demonstrate that the immersive exhibition space built using the proposed strategy achieves 92.6% accuracy in cultural perception, an immersion satisfaction score of 89.3, an interaction participation rate of 89.7%, and an average user dwell time of 42.5 minutes. All metrics show better performance than traditional exhibition spaces and mainstream industry immersive exhibition spaces.

AUTHOR CONTRIBUTIONS

Conceptualization – Tingting Li and Yipeng Wang; methodology – Tingting Li and Yipeng Wang; investigation – Tingting Li and Yipeng Wang; writing-original draft preparation

– Tingting Li and Yipeng Wang. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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HUMAN RESEARCH SUBJECTS

This study was approved by the Ethics Committee of Jilin Animation Institute, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

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