

A Museum Digital Twin Model for Exhibit Services

Authors: Li Xuhui, Fan Jingya, Peng Weiyu, Chang Menglong, Wang Xiaoguang, Yujue Wang, Li Xuhui

Date: 2025-08-08T11:11:33+00:00

Abstract

[Purpose/Significance] Digital museum applications that incorporate digital twin technology present new requirements for the content organization and service modalities of exhibit services. Research on digital twin models oriented toward museum exhibit services can provide a theoretical framework for constructing next-generation digital museum applications that embody the advantages and characteristics of digital twin technology, and can offer practical guidance for museums to achieve high-quality informatization transformation and provide diversified, personalized public digital services. [Method/Process] First, we analyze the main characteristics of museum exhibit services based on digital twin technology and their principal differences from traditional twin systems; second, we propose a foundational conceptual model for multi-granularity digital twin, summarizing the structure and characteristics of the digital twin environment from a multi-granularity information perspective; then, we propose a digital twin model for museum exhibit services, and design information recommendation services as its primary content along with functions for exhibition content organization; finally, using the Palace Museum tour as an example, we introduce the implementation mechanism of the digital twin process for related cultural heritage exhibit services. [Results/Conclusion] We propose a digital twin model for museum exhibit services from the perspective of multi-granularity information modeling and discuss the design mechanisms of its core functions, providing reference for the construction of digital museums in the new era.

Full Text

A Digital Twin Model for Museum Exhibit Services

Li Xuhui^{1,2}, Fan Jingya^{1,2}, Peng Weiyu¹, Chang Menglong³, Wang Xiaoguang^{1,2}, Wang Yujue^{1,2}

¹School of Information Management, Wuhan University, Wuhan 430072

²Intellectual Computing Laboratory for Cultural Heritage, Wuhan University, Wuhan 430072

³The Palace Museum, Beijing 100009

Abstract

[Purpose/Significance] The application of digital twin technology in digital museums imposes new requirements on the organization of content and service forms for exhibit services. Researching a digital twin model for museum exhibit services can provide a theoretical framework for building next-generation digital museum applications that reflect the advantages and characteristics of digital twin technology, and can also offer practical guidance for museums to achieve high-quality digital transformation and provide diversified, personalized public digital services. **[Method/Process]** First, this paper analyzes the main features of museum exhibit services based on digital twin technology and their distinctions from traditional twin systems. Second, it proposes a foundational conceptual model for multi-granularity digital twins, summarizing the structure and characteristics of the digital twin environment from a multi-granularity information perspective. Then, it presents a digital twin model for museum exhibit services, designing information recommendation services and functions for organizing display content as its core components. Finally, using the example of touring the Palace Museum, it introduces the implementation mechanism of the digital twin process for related cultural relic exhibits. **[Result/Conclusion]** From the perspective of multi-granularity information modeling, this paper proposes a digital twin model for museum exhibit services and discusses the design mechanisms of its core functions, providing a reference for the construction of digital museums in the new era.

Keywords: Digital twin, Exhibition Services, Multi-granularity, Digital museum

1 Introduction

With the rapid development of information technology, digital museums have gradually become an important platform for cultural heritage and innovation. In recent years, museums have progressively introduced digital twin technology based on the digital processing of their collections. Digital twin is an emerging industrial management technology originating from Industry 4.0, whose main idea is to achieve the goal of using digital twins to reflect and control physical entities through spatial information modeling of physical details and real-time process modeling of manufacturing processes. Based on this technology, exhibit information can be combined with museum daily management and exhibition service information to gradually form a digital twin environment covering all aspects of museum services. With the support of digital twin and virtual re-

ality technologies, users can tour museums, view collections, and interact with them through various methods such as on-site information recommendations, virtual exhibitions, and online guides, greatly enriching the content and forms of museum information services.

Museums belong to the service industry oriented toward the public, with their main content being the provision of touring and exhibit viewing services for audiences. The goal of museum digital twin systems (hereinafter referred to as twin systems) is to support the full lifecycle management of museum public services, with service provision methods and management means that differ from traditional digital twin applications that are purely oriented toward physical entity modeling and simulation. While some museums have made preliminary attempts to digitize/virtualize exhibits and venues based on traditional digital twin methods, primarily focusing on building 3D models, the question of how to apply digital twin thinking to the information processing and management of their core business—public exhibit services—remains an issue that requires in-depth exploration.

The public exhibit service process is an information exchange and interaction process between people (visitors) and objects (exhibits), which is a frequently changing process that is difficult to deterministically simulate. It requires describing and managing the interaction methods and behavioral characteristics of people and objects, and improving service quality through personalized information recommendations for users. To this end, twin systems need to establish exhibit services that can reflect the characteristics of digital twin technology based on a unified information conceptual model and twin process modeling method, collecting and organizing information on physical objects such as visitors, exhibits, and the environment, and meeting visitors' personalized touring needs. This enables the information exchange and interaction processes in services to be accurately perceived, predicted, and managed by the twin system, thereby enhancing service quality and visitor experience. However, current museum digital twin systems lack appropriate theoretical models to describe this process, making it difficult for systems to analyze the viewing process from the perspective of digital twin technology based on the characteristics of exhibit services, hindering the design and implementation of relevant business digital twins in the system.

This paper analyzes the basic characteristics and content of museum digital twins and finds that the fundamental task of twin systems lies in the hierarchical organization and representation of semantic information of various entities in the system, and establishing a twin feedback loop for data acquisition, content organization, and information recommendation based on the actual needs of the exhibit service process. To this end, this paper starts from multi-granularity semantic information description, summarizes the main semantic information of people and objects during the museum touring process, establishes a basic architecture model for museum digital twins and discusses its key technologies, and then uses the Palace Museum's digital twin system, which integrates mu-

seum, tourist attraction, and world heritage site, as an example to discuss the construction method of museum digital twin exhibit services. The main contributions of this paper are: (1) analyzing the main features of museum exhibit services based on digital twin technology and their distinctions from traditional twin systems, pointing out the direction and ideas for subsequent research; (2) proposing a foundational conceptual model for multi-granularity digital twins, systematically summarizing the structure and characteristics of the digital twin environment from a multi-granularity information perspective; and (3) proposing a digital twin model for museum exhibit services and designing the relevant mechanisms of information recommendation services and display content organization functions as its main content, laying a theoretical foundation for building the core capabilities of museum digital twin systems.

2 Related Research

Digital twin is a technology that establishes multi-dimensional, multi-temporal-scale, multi-disciplinary, and multi-physical dynamic virtual models of physical entities in a digital manner to simulate and characterize the attributes, behaviors, and rules of physical entities in real environments. Its main characteristics are manifested as virtual-real integration, iterative operation and optimization, and full-element/full-process/full-business data-driven operations, emphasizing information synchronization and sharing between physical and virtual entities. The concept of digital twin was first proposed by Grieves and immediately attracted widespread attention from multiple industry sectors, with manufacturing as a representative. Models are an important component of digital twin and an important prerequisite for implementing digital twin functions, and have also received considerable attention in digital twin research. Researchers from industry and academia have conducted extensive research and discussions on digital twin modeling from various aspects including model architecture, core technology, application architecture, and industrial practice.

Digital twin modeling research has strong domain-specific characteristics. Early digital twin modeling methods mainly focused on product manufacturing, with corresponding modeling research and practice being relatively abundant. In the industrial manufacturing field, Grieves proposed a three-element model including physical products, virtual products, and connections between them, which has been widely recognized and applied. Tao Fei et al. constructed a five-dimensional model including physical entities, virtual entities, services, twin data, and connections during their research on digital twin workshops, and discussed its application ideas and solutions in ten fields including ships and vehicles. Wang Jianjun et al. proposed a digital twin model applied to spacecraft engineering manufacturing and built a digital twin system architecture based on model definition. Thomas H et al. proposed a three-layer digital twin modeling process conceptual framework for industrial production consisting of physical entities, data layer, and information processing and optimization layer. In addition, digital twin has expanded from industrial scenarios to smart cities,

agricultural production, cultural education, and other fields. Qiu Baoxing et al. described and modeled urban physical space based on data, mapping geometric, physical, and rule models in digital twin city systems to behavior layer, connection layer, data layer, and decision layer to synchronize perception and reflect real city systems and improve urban management efficiency. Zhang Xuyi et al. proposed an agricultural digital twin technology framework including device layer, data layer, service layer, communication layer, business layer, application layer, and interaction layer. Wang Jing et al. constructed a data governance model from a digital twin perspective in the library field based on the DCMM model, consisting of ten core components including data strategy, data architecture, and technology platform, providing strong support for promoting the open sharing of university library data resource systems. Li Haifeng et al. proposed a framework model for digital twin smart learning spaces, designing teaching activities and supporting technologies from three logical levels: physical space, cloud services, and digital space.

The cultural heritage digitalization process also requires the integration of large amounts of data and the construction of virtual simulation entities, which has certain technical dependencies and correlations with digital twin technology. With the continuous emphasis on digitalization and intelligent development in the cultural industry, scholars have conducted a series of studies on exhibit services from the perspective of digital museums. Hu Ying explained the value co-construction between museums and audiences during digital product development from three dimensions: co-narrative of cultural knowledge production, interactive link of cultural field construction, and emotional care of cultural value communication. Fang Liyu constructed a key quality framework for museum online collection databases using the Palace Museum's digital cultural relics library as an example to control and improve the quality of online collection databases. Meanwhile, knowledge graphs, 3D digital technology, VR technology, and the Internet of Things have been applied to digital exhibit services. On this basis, digital twin applications are also being introduced into the cultural heritage field, triggering discussions around theoretical model construction, technical element application, and actual deployment scenarios. At the theoretical construction level, Kong Xiangzheng et al. emphasized the need to break through the spatial and temporal limitations in museum management, protection, and services to form associations between people, culture, and fields. At the technical support level, current digital cultural heritage protection and management are significantly driven by the Internet of Things, artificial intelligence, machine learning, and AR/VR technologies, which dramatically disrupt traditional visiting patterns. In addition, scholars have conducted research on the practical application of digital twin in museums, such as the reconstruction and reproduction of the Pingliangtai site based on digital twin technology, the protection and revitalization of historical and cultural heritage in the ancient city of Suzhou, and energy management in the Nanyue King Museum.

Overall, research on the integration and application of digital twin and cultural heritage has made certain progress, mainly focusing on the reconstruction of

museum 3D scenes, the digital transformation of exhibit services, and the construction of collection knowledge networks. However, there are also problems of limited research content and insufficient research depth, mainly manifested in the following three aspects. First, existing research focuses on static scene reconstruction and reproduction, lacking modeling of dynamic business processes in digital museums. Unlike the industrial field, current related research in the cultural heritage field mostly focuses on the single “scene reconstruction” link, with little attention paid to dynamic business processes within digital museums such as collection management, cultural relic protection, exhibition planning, public services, and educational research. Second, existing research focuses on the modeling of exhibit artifacts themselves, lacking modeling of museum public service processes. Domestic and foreign scholars have conducted relatively rich research on 3D scanning and modeling of cultural relics, as well as knowledge organization and visual presentation, but there has not been in-depth targeted research on the entire process of museum public services, such as the specific paths of simulation prediction, virtual-real comparison, and information feedback during the visitor touring process. Third, existing research has not deeply reflected the characteristics of dynamic interaction among “people-environment-objects” in the modeling process. Digital twin technology emphasizes “full-process” and “full-element” data-driven operations, which in the museum context means the dynamic interaction and data flow among “people-environment-objects.” However, current research mostly focuses on a certain node or dimension, lacking a holistic discussion of the dynamic interaction among the three.

3 Characteristics of Digital Twin Modeling for Museum Exhibit Services

Digital twin modeling for exhibit services is the foundation for building museum twin systems. The main content of digital twin modeling is to establish digital twins for physical objects to describe their evolution process and conduct simulation control. Generally, digital twin models have main functions such as virtual-real mapping and real-time synchronization, reflecting characteristics such as system co-evolution and closed-loop optimization. Virtual-real mapping achieves digital representation and bidirectional mapping between virtual space and physical objects; real-time synchronization function realizes state change interaction between physical objects and their twins. Co-evolution reflects the evolution and update of twins in the system along with the lifecycle process of their physical objects; closed-loop optimization reflects the system’s ability to form optimization instructions or strategies for the physical world based on analysis and simulation, achieving closed-loop decision optimization functions for physical entities.

Museum public service is a symbiotic system composed of people (visitors), objects (exhibits), and the environment. Compared with traditional industries, an important difference in its digital twin system is that people have autonomy: in traditional industry twin systems represented by manufacturing, only manufac-

turing objects are modeled as digital twins, and the twin process is controlled through simulation prediction of the twins; however, during the touring process, visitors' autonomy leads to behaviors that can only be predicted and intervened but not completely controlled, and their autonomous behaviors directly affect the content organization and presentation forms of exhibit services. Museums usually have many types and large quantities of exhibits, and the visitor touring process is a process where visitors select viewing objects and touring paths based on museum exhibit themes and their own preferences. From a digital twin perspective, this is an interactive process between visitors and exhibit services. The goal of twin system exhibit services is to dynamically adjust their display content and forms during the interaction process with visitors to meet their personalized needs.

This paper will analyze the interactivity and personalization characteristics of the museum exhibit service process by combining the basic functional characteristics of digital twin modeling to establish an appropriate twin system model. On the one hand, this paper will analyze the human-object interaction process in twin systems from the basic characteristics of the digital twin process mentioned above, and discuss its key modeling tasks. On the other hand, this paper innovatively proposes treating personalized organization of display content as the "product" of exhibit services, thereby drawing on existing product-oriented digital twin methods and integrating them into the twin modeling tasks for exhibit services.

3.1 Human-Object-Environment Interaction in Twin Systems

The digital twins of audiences and exhibits need to model, simulate, and predict the human-object interaction process between the two parties. During the interaction process, audiences view exhibits through prompts and recommendations from the service system. The audience twin serves as their digital agent, providing system services to the audience on the one hand, and feeding back behavioral details to the system management and control module on the other hand, for analysis to obtain further personalized exhibit services. During this process, the twin and the service system complete the co-evolution of various twins through the system's virtual-real mapping and real-time synchronization functions. The system intervenes in audience behavior through information recommendation, environmental control, and other auxiliary management means to complete closed-loop optimization throughout the entire lifecycle of audience tours.

The information recommendation service in twin systems is the foundation for realizing human-object-environment interaction. Traditional information recommendation services mainly focus on the relevance characteristics of recommended content, while the information recommendation in twin systems has more obvious multi-granularity characteristics on this basis. Museum exhibits usually have rich, multi-level connotations, such as calligraphy, sculptures, utensils, etc., containing multiple categories of information at different granularity

details and forming complex associations with other related things. For example, when viewing calligraphy cultural relics, audiences may be interested in the calligrapher and thus want to obtain more information about their life experiences and other literary works, or they may be interested in calligraphy details (such as each typical character type in the calligraphy, the calligraphy inscriptions, etc.) and thus want to understand more calligraphy works and other works from the same era and type; professional-level audiences may further want to understand the excavation and preservation of specific cultural relics. Therefore, appropriate models are needed to organize and manage the multi-granularity, relational semantic information of exhibits for information recommendation.

Based on the user historical behavior information fed back by twins, the twin system analyzes the current interest preferences of audiences and simulates and predicts their subsequent touring behaviors in combination with external environmental factors, thereby providing personalized enhanced interest guidance and knowledge supplementation for audiences to optimize their museum experience. At the same time, it achieves traffic optimization and safety assurance purposes through influencing and intervening in user behavior. Due to the uncertainty of user behavior, prediction results usually have multiple possibilities. Fine-grained simulation prediction will greatly increase computational complexity and even cause combinatorial explosion problems. Therefore, twin systems also need to introduce the information granularity characteristics of various physical objects and their twins when conducting simulation predictions, selecting appropriate information granularity based on real-world contexts to complete real-time simulation prediction tasks.

3.2 Personalized Organization of Display Content in Twin Systems

Digital twin systems in traditional industries are usually used for product manufacturing process management. For museum digital twin systems, their main “product” is not a physical entity but personalized exhibit services and their display content provided to audiences. Therefore, twin systems need to establish personalized organization models for exhibit content to achieve dynamic generation and management of exhibit content, reflecting the unique application forms and values of digital twin technology in the museum field.

The organization of display content can be designed from multiple aspects including exhibit type, display method, and technical means. From the perspective of exhibit type, museum exhibits can usually be divided into movable and immovable categories. From the perspective of display method, exhibits can be divided into thematic display and navigation display: the former involves sorting, categorizing, and thematically organizing display content to provide audiences with centralized display around themes; the latter follows the audience touring process for exhibit content navigation. From the perspective of technical means, exhibit content display methods can be divided into physical display and virtual display: traditional exhibit services mainly involve viewing services for physical entities of exhibits, while with the support of network and virtual/augmented

reality technologies, museum digitalization can provide virtual display services for digital images of exhibits.

Compared with the real museum touring process, audiences can more flexibly and conveniently achieve customized organization and presentation of touring content when touring museums online or in virtual reality environments. Twin systems need to comprehensively consider the factors and characteristics of the above three aspects, designing corresponding display content organization structures and forms to achieve exhibit services that meet audience personalized needs and reflect digital twin characteristics.

Furthermore, the content organization method of virtual exhibits provides new ideas for the development of digital twin technology. Different from general digital twin systems, in digital twin systems for virtual museums, entities with twins include not only physical objects represented by audiences but also digital landscapes and exhibits in virtual/augmented reality environments. Digital landscapes and exhibits, as data images of corresponding physical entities in the real world, their twins (becoming data twins) are data views dynamically generated specifically for audience tours. During the virtual space touring process, data twins interact with audience twins, and under the control of the twin system, dynamically generate user-viewable exhibit data based on original data, customizing touring content, themes, and processes throughout the entire lifecycle of the touring process.

4 Multi-Granularity Digital Twin Model for Exhibit Services

4.1 Foundational Concepts and Model of Multi-Granularity Digital Twins

This paper studies the main functions and mechanisms of museum digital twins based on entity multi-granularity information. The granularity concept is usually used to describe the degree of subdivision or fineness of details of things. This paper defines granularity-related concepts from the characteristics of semantic modeling of thing extensions. Semantic information describing thing extensions usually presents a hierarchical structure, manifested as a “whole-part” membership relationship.

We define granularity as a set based on specific granular elements for the extension structure of things. Granularity can completely cover the extension of things at a certain level, mainly manifested as: when using a certain granularity to examine things, the corresponding parts of things can be covered by the extensions of things referred to by certain granular elements in the granularity. Specific granules in granularity can introduce sub-granularity to be further subdivided into sub-granules, forming multi-level granularity. Composite semantics formed by different semantic information combinations can introduce granularity among their members to form multi-granularity.

Virtual/augmented reality technologies can be introduced in digital museum systems to form digital images of corresponding things. Therefore, the examination of real things is no longer limited to physical entities in the real world but can also include data images of original physical entities in virtual reality contexts. To this end, this paper introduces the concept of “entity image” to represent the information collection of entity objects at a specific granularity, reflecting the attribute state of entity objects at a certain moment. Physical entities in twin systems usually continuously change: for example, parts change from blanks to finished products during processing, and the part blanks and finished products cannot be considered the same object; equipment may undergo decomposition, assembly, or even reorganization during production, and thus cannot be considered as stable and unchanging objects.

Therefore, in digital twin models, we pay more attention to entity images rather than physical entities. The concept corresponding to entity image is “virtual image,” which is the data image in digital twin space corresponding to a certain entity object, generated by the twin system according to simulation prediction and other computational purposes. Entity objects have rich detailed information, but their data images in twin space only need to represent and process information at specific granularity. An entity can correspond to multiple “virtual images” to meet different computational purposes, with its information granularity controlled and adjusted by the twin system.

During system operation, entity images and virtual images will continuously evolve. The evolution process of entity images is completed based on external control information and their own physical mechanisms, while virtual image evolution is based on simulation processes. To this end, this paper introduces the concept of “granularity-preserving change” for images: granularity-preserving change is a binary relation on sets with granularity. For sets A and B, if element a in A can granularity-preserving change to element b in B (this change is not one-to-one), then the granule of b at a certain specific granularity is composed of corresponding granules of a at that granularity. Based on this concept, the evolution process in twin system operation can be manifested as a series of granularity-preserving change processes in entity/virtual images, during which the system controls granularity change through control information to make entity image changes develop toward expected goals.

The model structure of multi-granularity digital twin systems is divided into four parts: multi-granularity information organization, virtual-real mapping between entity images and virtual images, simulation prediction, and entity intervention. As shown in Figure 1 [Figure 1: see original paper].

Figure 1. Schematic diagram of multi-granularity digital twin model

Multi-granularity information organization organizes data of various physical entities in the target domain based on the granularity concept mentioned above. The twin system defines corresponding granularity patterns based on the original data of physical entities stored in the domain database, combines original

data with corresponding granularity information to form granular entity images of various domain objects, provides image data under specific granularity views for various functional modules within the twin system based on entity image information, manages granularity change results of each entity image during system operation and virtual image information generated by simulation processes, and maintains the relevance and local consistency of virtual-real image data.

The virtual-real mapping of twin models is achieved through a series of mappings and granularity changes between entity images and virtual images. Virtual-real mapping, as a basic function of digital twin, lays the foundation for co-evolution between the real world and virtual space. In this model, the mapping from entity image to virtual image is a homomorphism mapping on granularity structures, which can be transformed on specific granularity of entity images according to the computational needs of the virtual image by the simulation prediction module. Different computational needs can generate different virtual images.

The simulation prediction function module uses discrete simulation or hybrid simulation based on virtual image information to complete evolution process simulation and result prediction of entities (such as audiences) under specific environmental influences (such as system intervention). The processing and transformation of virtual images form a series of granularity-preserving changes of images, and the resulting images can be regarded as evolution results of virtual images. When new virtual images meet expectations, the reverse mapping from virtual images to entity images constructs expected evolution results of entity images, while transmitting corresponding control information to the entity intervention control module to promote entity objects to evolve.

The entity intervention function module intervenes in or controls the behavior of real physical entities based on simulation prediction results. This function provides various optional intervention measures for the simulation prediction function based on current physical environment conditions, evaluates various possible situations based on simulation prediction results, selects optimal intervention measures to intervene in real physical entities, compares the evolution result entity images with expected entity images from simulation prediction after physical entities evolve under intervention in the real world, conducts intervention effect evaluation after obtaining comparison results, and forms new intervention plans for subsequent system evolution processes, thereby achieving the control closed loop of the entire system.

4.2 Digital Twin Model for Museum Exhibit Services

The main content of museum exhibit services is context-based exhibit introduction and touring recommendations. Based on the above multi-granularity digital twin model, we further constructed a digital twin model for museum exhibit services, including audience entity images/virtual images, touring simulation prediction, touring process intervention mechanisms, and other parts to adapt to the dynamic interaction needs of the “people-cultural relics-environment”

trinity in the digital twin environment, as shown in Figure 2 [Figure 2: see original paper]. The core advantages of digital twin systems in museum exhibit services lie in their real-time nature, dynamism, and comprehensiveness. Compared with traditional static solutions, digital twin systems can capture and analyze audience behavior in real time and dynamically adjust recommendation content and display methods. The system obtains relevant information about audiences during the touring process based on environmental sensors and audience personal auxiliary devices to establish audience entity images. Audience virtual images are multi-granularity audience information established based on audience entity images, serving as the foundation for simulation prediction of audience behavior in virtual space. The simulation prediction module simulates and predicts their subsequent viewing objects and touring paths based on current audience virtual images and venue environment-provided relevant information. The touring intervention function indirectly or directly intervenes in users' later behaviors by providing various types of information to users.

The above exhibit service process mainly relies on the unique granularity-based information recommendation service and multi-granularity display content organization function and implementation in museum twin systems.

Figure 2. Digital twin model for museum exhibit services

4.2.1 Granularity-Based Information Recommendation Service In museum twin systems, main physical entities such as exhibits and audiences exhibit obvious multi-granularity characteristics. First, for cultural relics, “multi-granularity” means that exhibit content forms different granularities according to its inherent hierarchical structure, and based on this, corresponding virtual-real mapping is carried out according to service requirements in different scenarios. For example, a calligraphy work can be structurally divided into granularity levels such as main content and inscriptions from a content perspective, and can be further decomposed to the granularity of individual characters or strokes. Second, for visitors, during the touring process, factors such as their affiliated groups, geographical location, field of view, and personal background determine their “multi-granularity” demand characteristics for exhibit content. Third, “multi-granularity” of the environment means that museum venues can be divided into exhibition areas/venues, museum buildings, areas within buildings, exhibit viewing areas, etc., and different granularity environmental twins generated from this participate in virtual-real interaction and simulation prediction according to corresponding scene requirements.

Twin systems establish granularity-based information recommendation services based on the above multi-granularity characteristics, using corresponding processing mechanisms on the basis of multi-granularity organizational structures of exhibit content to achieve real-time personalized multi-granularity information recommendations for audiences during the touring process.

The multi-granularity organizational structure of exhibit content is an exhibit

content data service that constructs exhibit content with granularity feature identification based on content information at different granularity levels of exhibits, supporting query and association analysis of exhibit content at different granularity levels.

Content granularity association patterns are rules for associating exhibit content at related granularities. Twin systems can pre-specify association patterns of content at specific granularities, or analyze audience viewing behavior records during operation to mine frequent patterns of content granularity associations. These association patterns are the foundation for twin systems to conduct related content recommendations and display content organization, and are also used to establish underlying storage indexes for exhibit content-related data, helping the system achieve efficient data access.

Based on multi-granularity exhibit content, twin systems can conduct more targeted multi-granularity information recommendations. For example, when audiences tour the Palace Museum and walk toward the Hall of Mental Cultivation (Yangxin Dian), the system judges the visible granularity situation of the Hall of Mental Cultivation, surrounding buildings, and other immovable exhibits in their field of view based on the audience's real-time location and orientation, and provides real-time key content introduction for users. During the touring process inside the Hall of Mental Cultivation, the system can also judge the focus granularity of the exhibits they are viewing based on user touring paths, location, and other information, and recommend information with appropriate granularity. In addition, twin systems can also combine collaborative filtering recommendation methods for granularity information recommendation, directly recommending exhibit information that audiences with similar preferences are interested in to audiences based on touring scenarios according to the analysis and mining results of large amounts of user preferences, and collaboratively completing subsequent touring content recommendation and organization with display content organization services.

Information recommendation services can also design more flexible recommendation schemes and content according to audience group granularity. Common museum audience groups can be distinguished by granularity such as groups, families, and individuals, with different group granularities having specific touring preferences and corresponding differences in exhibit content presentation granularity. Based on the analysis and mining of audience information, twin systems design corresponding content granularity recommendation schemes according to group touring characteristics, balancing personalized services with group touring organization. For example, when tourist groups tour the Hall of Mental Cultivation, the recommendation service recommends exhibit information suitable for individual preferences to each audience, while simultaneously selecting autonomous touring paths and times for each audience in the hall based on simulation results of the group's touring process from the simulation prediction module, enabling team members to complete the touring process synchronously.

4.2.2 Multi-Granularity Organization Mode of Display Content Display content organization in the digital twin environment is based on touring path construction associated with multi-granularity content of exhibits. With the support of digital twin and other computer technologies such as virtual/augmented reality, museum display content can achieve on-demand planning and organization, and can be automatically reorganized according to audience real-time needs to form “display products” with characteristics of both museum public services and digital twin technology, demonstrating broad development prospects for digital museums.

As mentioned above, twin systems can design flexible display content organization modes based on factors such as exhibit type, display method, and technical means. Typical organization modes include thematic content organization for movable exhibits, navigation-based content organization for fixed exhibits, and dynamic content organization for virtual exhibits.

The thematic content organization mode for movable exhibits constructs special exhibitions by selecting and aggregating movable exhibits based on proposed display themes. The simulation module of the twin system designs exhibit placement positions in the venue environment virtual image based on analysis of exhibit content granularity and association patterns, and introduces audience intelligent twins with typical preference characteristics to simulate touring paths and evaluate simulation results to optimize physical exhibit positions, design recommended touring paths for display content, and generate corresponding multi-granularity exhibit content for recommendation services.

The navigation-based content organization for fixed exhibits is an upgrade of traditional fixed touring path mode in the digital twin environment, which plans appropriate touring paths for audiences in real time based on their exhibited granularity content preferences for current location fixed exhibits and provides dynamic navigation. The twin system dynamically screens and arranges subsequent touring content and forms recommended fixed exhibit touring paths based on real-time analysis of audience background information and preferences and interaction with multi-granularity information recommendation services during the touring process.

Audiences can dynamically adjust their preferences based on interaction with information recommendation services in navigation mode. The twin system compares audience entity images with simulation results in navigation mode to adjust touring paths in real time, and collaborates with information recommendation services to complete recommendations for audiences' subsequent viewing exhibit content, enabling audiences to make full use of touring time to achieve expected goals and obtain better touring experiences.

The dynamic content organization for virtual exhibits combines the characteristics of the above two modes and is mainly used for touring path construction in online museums or virtual museums in virtual/augmented reality environments. The twin system screens exhibit content and granularity in real time

based on audience preferences, forms exhibit touring graphs based on specific associations between various exhibit contents, uses audience intelligent twins to conduct touring process simulation in the exhibit touring graph, dynamically generates current virtual venue environment and exhibit content display forms after analyzing simulation results, and recommends appropriate touring paths for users. During the touring process, behavioral information formed by audience interaction is captured by their entity images and compared with existing simulation prediction results. When deviations occur, the system timely adjusts and reorganizes subsequent touring content and exhibit forms.

4.2.3 Digital Twin Mechanism for Exhibit Services The implementation of the above information recommendation and display content organization functions requires close cooperation among various functional modules of the digital twin system.

During the user touring process, the twin system simulates user behavior through the simulation prediction module and indirectly or directly influences users' later touring behavior through recommendation services or display content organization services, achieving mapping and evolution of virtual-real images in the twin system. The system simulation prediction module completes user interest prediction based on parameters such as user information, environmental information, exhibit content, and granularity. The recommendation system selects appropriate content to complete recommendation services based on prediction results. From the perspective of the twin model, information recommendation achieves control over user physical entities by providing information to users. After users accept pushed information (such as confirming recommendation options), their behavioral information is fed back to the twin system's simulation prediction module for subsequent behavior simulation calculations.

The main goal of simulation is to predict users' subsequent viewing objects and touring path results. The simulation prediction results are further transmitted to information recommendation services and environmental management services to complete subsequent twin management work.

In the virtual image space, the simulation prediction module predicts the current user's subsequent behavior through analysis of user touring historical data, forming several possible virtual images of the user at the next time point and forming the evolution of virtual images. Based on user characteristics reflected by virtual images, the system jointly conducts judgment of user behavior intervention levels with the environmental management module to determine recommendation or guidance information for user behavior orientation. After receiving recommendation or navigation information from the twin system, users autonomously adjust their own touring behavior, and then new dynamic touring information is obtained by sensors and personal touring auxiliary devices to update entity images and complete their evolution. Entity images generate new virtual images through real mapping, and after comparing with previous prediction results, the

system enters state monitoring and simulation prediction for the next step. This process achieves the closed loop of virtual-real mapping and evolution of user objects during the touring process.

Based on audience touring record behavior data analysis, museum digital twin systems can build intelligent twins specifically for simulating typical audience behavior, serving as the foundation for digitalized and precise management of twin systems. Audience intelligent twins are virtual audience images with typical backgrounds (age, gender, interest preferences, etc.). Based on statistical analysis of behavior preferences such as touring paths, viewing objects, and content focus of audience groups matching these backgrounds during the touring process, interactive simulation models for museum management can be formed. On this basis, in the museum venue environment virtual image of the digital twin system, simulation analysis of audience viewing paths is conducted through virtual audience intelligent twins. After evaluating simulation results, the physical positions of exhibits in display venues are determined, and active recommendation information for display content is designed based on exhibit topology. At the same time, environmental simulation can select multiple granularities of simulation according to system computing power: coarse-grained simulation can directly use prediction models induced from historical data for regional environment prediction; medium-grained simulation can introduce tourist intelligent twins to simulate current tourist behavior information to obtain prediction results more consistent with real-time environments; fine-grained simulation achieves more accurate simulation prediction results through real-time analysis and simulation of current tourists' entity/virtual images, thereby achieving precise environmental management.

4.2.4 Comparison with Typical Models The above model is a twin model for museum exhibit services built according to the needs and characteristics of the public service field. Compared with typical digital twin models, the model proposed in this paper can better adapt to the personalization and interactivity characteristics of service-oriented digital twin systems. For example, early three-dimensional models focused on depicting physical entities, virtual entities, and bidirectional mapping connections among the three, suitable for tasks such as industrial product design, testing, and maintenance, but lacking support for services. The currently popular five-dimensional model integrates five dimensions of physical entities, virtual entities, twin data, connections, and functional services, mainly focusing on entity data synchronization and functional service encapsulation in the industrial manufacturing process. Existing models lack in-depth analysis of digital twin processes and characteristics in the service industry and are difficult to directly apply to process modeling in museum twin systems. On the other hand, current research on digital twin models in the museum field usually focuses on basic elements of entity data and content mapping of entity data, but lacks analysis and modeling of exhibit service processes, missing the characterization of real-time personalized knowledge service processes based on simulation prediction and feedback optimization, making twin models unable

to form closed loops. The twin model proposed in this paper can effectively represent the interaction process among people, objects, and environment in service-oriented twin systems.

In addition, existing models usually focus on entity data content but often lack consistent means in data organization. Discussions on “digital twin” in the cultural heritage field mostly remain at 3D information display, historical scene reconstruction, and simple knowledge transmission, with information organization methods insufficient to support complex twin process data needs. The twin model in this paper uses multi-granularity semantic information organization methods to establish multi-level structures of entity data and depicts various information evolutions in twin processes based on this foundation, enabling the personalized demand characteristics of museum exhibit services to be conveniently represented and processed based on granular information in twin models.

5 Case Study: Digital Twin Example of the Palace Museum

Based on the multi-granularity digital twin model for exhibit services described above, this section conducts case analysis using the Palace Museum’s Hall of Mental Cultivation (Yangxin Dian) and the exhibit “Wen Zhengming’s Running Script ‘Inscription on the Humble Room’ Scroll” as examples.

5.1 Data Standards

The Palace Museum developed the “Ancient Chinese Movable Cultural Relics Conceptual Reference Model” (hereinafter referred to as CRM-ACA) based on CIDOC-CRM to reconstruct cataloging information of collection cultural relics and serve the information organization of ancient Chinese movable cultural relics.

Digital museum applications form multi-dimensional and multi-level semantic data of cultural relics through these two aspects of information: space and structure. The model in this research also follows the basic structure of the Palace Museum’s CRM-ACA when conducting multi-granularity information organization. Based on this ontology model, the concept of “granularity” is added, and multi-level granularity is divided from two aspects of spatial structure and events. Classes in CRM-ACA belong to different granularity levels according to their characteristics, among which the same class can appear in multiple granularity levels according to needs. In digital museum applications represented by exhibit services, spatial structure information is granularized to support the dynamic and extensible processing needs for cultural relic data in digital twin systems.

5.2 Model Architecture

Taking the Palace Museum as an example, the overall architecture of the Palace Museum digital twin model is constructed based on the “Digital Twin Model for Museum Exhibit Services” built in Chapter 4.

The reality layer mainly relies on interactive devices, sensors, personal auxiliary devices, etc. to collect data, organizes tourist information based on granularity patterns, and forms tourist entity images. In the Palace Museum scenario, to segment and collect information from visiting audiences and establish their entity images, on the one hand, visiting audiences are granularly distinguished from three levels: groups, families, and individuals; on the other hand, fixed devices such as sensors and cameras and the “Palace Museum in Your Palm” application portal are used to automatically collect and process basic audience information such as age, gender, and number of visits, as well as various dynamic data generated during the touring process, including grid passenger flow, audience real-time location and orientation, touring paths, and dwell time. The above content is uploaded to the virtual carrier to form audience virtual images for information recommendation services and content organization services.

The virtual layer establishes multi-granularity audience virtual images based on entity images provided by the reality layer, combines environmental information and exhibit information, and simulates and predicts tourists’ viewing objects and touring paths through simulation modules. For example, based on the types of cultural relics visitors view in the Palace Museum, the dynasties of cultural relics, current location, and current orientation, it real-time predicts their subsequent visiting behavior, plans touring routes, and conducts real-time comparison and feedback optimization of simulation effects between predicted virtual images and newly formed virtual images.

The control layer includes environmental management systems, multi-granularity information recommendation systems, and multi-granularity content organization systems, and intervenes in the behavior of physical tourists in the reality layer based on the above functional modules. Specifically, it conducts content organization of cultural relics in the Palace Museum based on granularity patterns to accurately capture the interest points of different audiences. At the same time, based on simulation prediction results from the virtual layer, it conducts proactive or passive exhibit introduction and touring recommendations to improve audience matching accuracy and dynamic interactivity.

Through the above layers, this model possesses basic functions such as multi-granularity organization of exhibits, simulation prediction, entity intervention, feedback optimization, and dynamic environmental updates.

5.3.1 Exhibit Description: Multi-Granularity Information Organization Taking “Wen Zhengming’s Running Script ‘Inscription on the Humble Room’ Scroll” (cultural relic number: Xin 00054693) as an example to illus-

trate the “exhibit description” function. Combining the characteristics of calligraphy works themselves, granularity types can be determined as three levels: work granularity, single character granularity, and stroke granularity. For a calligraphy work, content at the work granularity level mainly includes author, content, font, carrier, period, style, inscriptions, and theme. At the single character granularity level, it can be described from aspects such as character content, character structure, and character font. Further refined to single stroke granularity, there are stroke name, stroke category, stroke artistic style, etc. On this basis, corresponding granularity features are extracted from physical entities to form virtual images, and same-granularity cultural relic associations are conducted to form preset association patterns at different granularity levels. For example, at the work granularity level, the “theme” of “Wen Zhengming’s Running Script ‘Inscription on the Humble Room’ Scroll” is Tang Dynasty Liu Yuxi’s “Inscription on the Humble Room,” which can be associated through “theme” to “Taibuhua’s Seal Script ‘Inscription on the Humble Room’ Scroll” (cultural relic number: Xin 00176117). At the single character granularity, one of the typical characters in “Wen Zhengming’s Running Script ‘Inscription on the Humble Room’ Scroll” in terms of artistic style is the character “是” (shi), which is running script with top-bottom structure and can be associated with other calligraphy works with the same character shape and font. At the stroke granularity, the horizontal fold stroke uses Wang Xizhi’s twisting brush technique at the turning point, which can similarly be associated with his running script works, as shown in Figure 3 [Figure 3: see original paper].

Figure 3. Schematic diagram of exhibit knowledge organization and association

In the description process of immovable cultural relics, granularity division is also required, including building overall granularity, sub-building granularity, and building component granularity. After determining specific granularity levels, content at different granularities is described and associated from multiple dimensions such as functional use, construction technology, associated figures, and associated events. Taking the Hall of Mental Cultivation as an example, at the building overall granularity, there are metadata contents such as form, layout, area, and theme: the Hall of Mental Cultivation is located on the west road of the Inner Court, built during the Jiajing period of the Ming Dynasty, with building form as “palace,” form as yellow glazed hip roof, layout as I-shaped palace, themes including “palace,” “Ming Dynasty,” “Qing Dynasty,” and “emperor,” and area of 7,707 square meters. It can be further refined into sub-building granularity such as main hall, east warm pavilion, west warm pavilion, Yanxi Hall, and Tishun Hall, and the Three Rarities Hall (Sanxi Hall) for description, including their location, area, use, building structure, decorative technology, and indoor furnishings. It can be further decomposed to the granularity of individual building components such as tiles, beams, and inscriptions for description. For example, the structure of the “beam” component of the Hall of Mental Cultivation’s outer eave is “post-and-beam structure,” the decoration is “golden dragon and imperial seal,” and the theme is “emperor.”

5.3.2 Exhibit Recommendation: Simulation Prediction and Feedback Optimization

Taking “Wen Zhengming’s Running Script ‘Inscription on the Humble Room’ Scroll” as an example for distinguishing different audiences and personalized information recommendation. For instance, audience group A is a tour group visiting the museum, who are more likely to focus on metadata information at the “work” granularity level compared to professional perspectives. Therefore, the system pushes basic information such as the creation period, font style, carrier material of “Wen Zhengming’s Running Script ‘Inscription on the Humble Room’ Scroll,” as well as basic information about Wen Zhengming’s life and achievements, and generates recommended touring routes based on other collection calligraphy works by Wen Zhengming (such as “Wen Zhengming’s Running Script ‘Five-character Regulated Verse’ Scroll”) and works by related figures (such as his teacher Wu Kuan’s works). By collecting audience data through sensors, monitors, and applications, the system discovers that audience B focuses on calligraphy theme content, and pushes the original text and interpretation of Liu Yuxi’s “Inscription on the Humble Room” to audience B, and intelligently retrieves other calligraphy works with “Inscription on the Humble Room” as content or theme (such as Taibuhua’s “Taibuhua’s Seal Script ‘Inscription on the Humble Room’ Scroll”). Audience C focuses on calligraphy appreciation, particularly on the twisting brush technique from Wang Xizhi at bending strokes, and is recommended typical works by Wang Xizhi with such brush techniques with corresponding route navigation. In addition, when the twin system discovers that multiple audiences visit another unassociated work after viewing “Wen Zhengming’s Running Script ‘Inscription on the Humble Room’ Scroll,” it records and analyzes this to mine associations at different granularity levels.

Taking the Hall of Mental Cultivation as another example, the provided information recommendation services are mainly divided into location-based information recommendation, focus-based information recommendation, and path-based information recommendation. For instance, for offline touring audience D, when the system detects their continuous approach to the Hall of Mental Cultivation, it pushes basic information about the “Hall of Mental Cultivation” and direction navigation to the audience through the application. After receiving the information recommendation, the audience enters the Hall of Mental Cultivation range to begin visiting according to navigation information, focusing on the plaque calligraphy in the main hall of the Hall of Mental Cultivation and watching the “Zhongzheng Renhe” (Impartial and Benevolent) inscription by Yongzheng for a longer time. Data collected by fixed devices and applications is returned to the twin system, and combined with the audience’s previous touring paths and query records, the system infers that the user’s interest points have a high probability of being “Yongzheng” and “calligraphy,” calculates that the user’s virtual image will next enter the Qinzheng Hall in the west warm pavilion where there are also calligraphy works by Yongzheng, and will first briefly stop at the east side room when passing through the east room to briefly view other imperial calligraphy works, then enter the Qinzheng Hall in the west warm

pavilion to carefully view the “Qinzheng Qinxian” (Diligent in Governance and Close to the Worthy) plaque and couplets written by Yongzheng. After completing the above prediction simulation, the twin system pushes information and locations of the above cultural relics to the audience through the application, enables navigation, guides the audience’s next visiting behavior, and conducts real-time virtual-real comparison and feedback, with real-time optimization of recommended routes based on tourist behavior, as shown in Figure 4 [Figure 4: see original paper].

Figure 4. Schematic diagram of dynamic touring interaction process

5.3.3 Exhibit Organization: Exhibition Layout and Environmental Updates One application scenario of digital twin in exhibit content organization is thematic content organization for movable cultural relics. Taking the Hall of Mental Cultivation as the scene, when planning a special exhibition on “Daily Life of Qing Dynasty Emperors,” the digital twin system can assist in exhibition hall planning and design. Specifically, using past audience data recorded by the digital twin technology system, including viewing counts, dwell time, and query records for different exhibits such as thrones, imperial inscriptions, and palace furniture in the Hall of Mental Cultivation, the system analyzes past audience preferences for different exhibit content, and combines this with policy orientation for the inheritance of Qing Dynasty historical culture to screen and determine core exhibits for the exhibition. After exhibit selection, when arranging exhibit positions, based on analysis of previous audience touring sequences through different inner rooms and touring paths within each inner room in the Hall of Mental Cultivation, the system uses audience intelligent twins to simulate touring behavior, and optimizes physical exhibit positions based on simulation results of audience viewing sequences, designs recommended touring paths for display content, and generates corresponding multi-granularity exhibit content for recommendation services.

Another application scenario of digital twin in exhibit content organization is dynamic content organization for virtual exhibits. When audience E visits the Hall of Mental Cultivation virtual exhibition hall online, the system discovers that audience E has spent a long time in the “In front of the Hall of Mental Cultivation” and “Main Hall of the Hall of Mental Cultivation” areas, and has repeatedly zoomed in and dragged to view details of the top painted beam areas multiple times. The system sends data such as audience E’s viewing angle, selected points, and cursor hover time to the prediction simulation module, infers that the user’s interest point is “colored painting art,” and based on the Hall of Mental Cultivation beam decoration data and user query records, determines that the user is concerned about the “imperial seal colored painting” type. It automatically pushes relevant information to the user and queries that the Hall of Supreme Harmony, Palace of Compassion and Tranquility, and Hall of Union around the Hall of Mental Cultivation also use imperial seal colored painting as beam decorations. Based on this, it forms a virtual environment

including the above venues and conducts dynamic organization of corresponding exhibit content to form a virtual exhibition hall themed “Imperial Seal Colored Painting,” and pushes the recommended touring route to audience E in real time, as shown in Figure 5 [Figure 5: see original paper]. After completing the above information recommendation, the system will continue to obtain the user’s actual touring behavior and compare it with existing simulation prediction results.

Figure 5. Schematic diagram of exhibit content organization mode

6 Conclusion

Digital museum systems have gradually introduced advanced technologies represented by digital twin in recent years, imposing new requirements on the forms and content of exhibit services as their core functions. To this end, this paper proposes a digital twin model for exhibit services that 刻画 s the core functions and processes of museum digital twin system exhibit services from the perspective of multi-granularity information organization, and specifically designs core functions of exhibit services such as information recommendation and display content organization supported by digital twin technology to meet the actual needs of building digital museum digital twin systems. Due to space limitations, this paper only proposes relevant ideas for the basic problems of exhibit service modeling and preliminarily discusses the implementation mechanisms of related functions according to the characteristics of digital twin technology. The application of digital twin technology in the cultural heritage field involves theoretical and technical issues such as multi-granularity semantic data computational models, user behavior simulation prediction, and environmental management digital twin, which we will explore in subsequent research.

References

- [1][26] Tao F, Zhang M, Cheng J, et al. Digital twin workshop: a new paradigm for future workshop[J]. *Computer Integrated Manufacturing Systems*, 2017,23(01):1-9.
- [2] Wahbeh W, Kunz D, Hofmann J, et al. Digital twinning of the built environment: An interdisciplinary topic for innovation in didactics[J]. *2020 ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2020(1):231-237.
- [3] Tao F, Zhang H, Qi J, et al. Theory of digital twin modeling and its application[J]. *Computer Integrated Manufacturing Systems*, 2021,27(01): 1-15.
- [4] Liu Q, Liu B, Wang G, et al. Research on Models, Problems, and Progress of Digital Twins[J]. *Journal of Hebei University of Science and Technology*, 2019,40(01): 68-78.

- [5][31] Grieves, M. Product Lifecycle Management: Driving the Next Generation of Lean Thinking[M]. New York, McGraw-Hill, 2006.
- [6][32] Tao F, Liu W, Zhang M, et al. Five-dimension digital twin model and its ten applications[J]. Computer Integrated Manufacturing Systems, 2019,25(01):1-18.
- [7] Wang J, Xiang Y, He Z. Spacecraft System Engineering Model and Implementation Based on Digital Twins[J]. Computer Integrated Manufacturing Systems, 2019,25(06):1348-1360.
- [8] Thomas H., J. Uhlemann., Christian Lehmann., Rolf Steinhilper. The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0[J]. Procedia CIRP, 2017, 61:335-340.
- [9] Qiu B, Chen M. Digital twin cities and its applications[J]. Urban Development Studies, 2022,29(11):1-9.
- [10] Zhang X, Sun X, Yang P, et al. The conceptual connotation, technical framework, and application progress of agricultural digital twin[J]. Chinese Journal of Agricultural Resources and Regional Planning, 2025.
- [11] Wang J, Wang P. Research on data governance model of smart university libraries based on digital twin[J]. Research on Library Science, 2023,(11):41-50.
- [12] Li H, Wang Y, Digital Twin Smart Learning Space: Connotation, Model, and Strategy[J]. Modern Distance Education Research, 2021,33(03):73-80+90.
- [13] Qin X, Zhang X. The Application of Digital Twin Technology in the Digital Construction of Material Cultural Heritage[J]. Information and Documentation Services, 2018,(02):103-111.
- [14] Hu Y. The development of museum digital collection: Discussed from the perspective of culture value[J]. Southeast Culture, 2023,(03):185-190.
- [15] Fang L. On-line museum collection database key-quality framework design with the case study of the Palace Museum digitized cultural relics library[J]. Palace Museum Journal, 2024,(05):13-23+139-140.
- [16] Wu Y, Zhou S, Tan S, et al. Research on the Construction of Knowledge Graph and Knowledge Discovery of Ancient Chinese Decorative Patterns[J]. Archives & Construction, 2025,(04):77-86.
- [17] Hu H, Deng S, Application of knowledge graph in the construction of bronze digital collection[J]. Digital Library Forum, 2024,(05):13-23+139-140.
- [18] He J, Sun Y, Zhang Y, The application of 3D digital technology in museum displays of costume collections[J]. Southeast Culture, 2024,(05):155-161.
- [19] Zhang J, Research on the Security Strategies of Digital Museums for Cultural Relic Protection and Global Communication[J]. Information Science, 2022,40(02): 59-64.

- [20] Kong X, Cong S, Li M, et al. Construction and development extension of culture and museum field design under digital technology[J]. *Packaging Engineering*, 2024,45(04):158-165.
- [21] Luther W., Baloian N., Biella D., Sacher D. Digital Twins and Enabling Technologies in Museums and Cultural Heritage: An Overview[J]. *Sensors*. 2023, 23(3):1583.
- [22] Schott, Ephraim and Makled, Elhassan Belal and Zoepig, Tony Jan and Muehlhaus, Sebastian and Weidner, Florian and Broll, Wolfgang and Froehlich, Bernd UniteXR: Joint Exploration of a Real-World Museum and its Digital Twin[J]. *Association for Computing Machinery*, 2023.
- [23] Hu Y, Li X, Wang D, et al. Digital twin-driven virtual reconstruction and scene reproduction of the Pingliangtai site[J]. *Furniture & Interior Design*, 2024,31(10):140-144.
- [24] Yang T, Li J, Li M. Digital twins method for protecting and revitalizing the urban historic and cultural heritage of Suzhou ancient city[J]. *Urban Planning Forum*, 2024,(01):82-90.
- [25] Li B. Building a smart & green museum with its digital twin: Practice in building energy consumption system for the site of King's Tomb of the Nanyue King Museum[J]. *Chinese Museum*, 2024,(01):82-90.
- [27] Miao T, Zhang X, Xiong H, et al. The Application and Prospect of Digital Twin Technology in the Product Lifecycle[J]. *Computer Integrated Manufacturing Systems*, 2019,25(06):1546-1558.
- [28] KRAFT E M. The US air force digital thread/digital twin - life cycle integration and use of computational and experimental knowledge[C]. *Proceeding of the 54th AIAA Aerospace sciences Meeting*. Reston:AIAA Press, 2016:0897.
- [29] Wang C, Some Thoughts on the Smart Museum Construction[J]. *Museum Management*, 2020,(03):4-15.
- [30] Li X, Peng W, Ye Y, et al. Multi-granularity knowledge organization and service of cultural relics in digital museums based on events[J]. *Library and Information Service*, 2025.
- [33] Ma Y, Study on the Construction of Museum Intelligent Operation Center Based on Digital Twin[J]. *MUSEUM*, 2022,(06):6-12.
- [34] Wei Y, Ren L. Design Transformation of Intangible Cultural Heritage from the Perspective of Digital Twin[J]. *PACKAGING ENGINEERING*, 2023,44(06):302-310.
- [35] Ye Y. Ontology Construction: Ancient Chinese Artifacts Conceptual Reference Model[J]. *Digital Humanities Research*, 2023,3(03):37-48.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.