

Heritage Digitization: Conceptual Issues, Research Insights, and Application Practices

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Abstract

With the rapid development of digital technology, heritage digitization has emerged as a transformative approach for the protection, inheritance, and innovation of cultural heritage. This paper traces the conceptual origins of heritage digitization, drawing from UNESCO charters, and elaborates on its definition and scope, emphasizing the importance of digital technology in safeguarding cultural heritage. Next, the paper analyzes the development process of heritage digitization, from its inception to expansion, demonstrating the increasingly sophisticated application of digital technology in heritage preservation. The paper outlines the technical methods for heritage digitization and discusses their applications in heritage documentation, protection, and display. New insights into heritage digitization research are proposed, including the technology-led transformation of Europe's traditional heritage protection systems, a critical reassessment of authenticity and integrity in the digitization process, and the exploration of social dimensions within heritage digitization. Through case studies, the paper demonstrates the significant value of heritage digitization in both international and Chinese contexts. It argues that heritage digitization is not merely an application of technology, but also a reconceptualization of cultural heritage protection, creating greater opportunities for social engagement. It provides new perspectives and strategies for the sustainable development of cultural heritage.

Keywords: digital protection; digital technology; digital platform development; heritage management; practice and enlightenment

In October 2017, the report of the 19th National Congress of the Communist Party of China incorporated "Digital China" into the Party's programmatic document for the first time, marking a new stage in the construction of Digital China. With the arrival of the digital era, the rapid advancement of digital technology has brought unprecedented opportunities for the protection, inheritance, and innovation of cultural heritage. Cultural heritage, as a testament to human history and a crystallization of human wisdom, carries rich cultural connotations and historical value. However, traditional conservation methods face numerous limitations, such as the natural aging and deterioration of tangible cultural heritage and the declining number of inheritors of intangible cultural heritage. Against this backdrop, heritage digitization has emerged, offering new pathways for the protection and transmission of cultural heritage.

In 2022, during the commemorative activities marking the 50th anniversary of the *Convention Concerning the Protection of the World Cultural and Natural Heritage*, under the theme "The Next 50: World Heritage as a Source of Resilience, Humanity and Innovation," digital transformation was identified as one of the five key areas for research and discussion.

Therefore, understanding the research and development status of heritage digitization and analyzing its significant value and practical pathways in contemporary urban and rural development has become an urgent research topic. This endeavor will play a positive role in promoting the protection, inheritance, and sustainable development of historical and cultural heritage in the digital age.

In recent years, digital technology has played an increasingly important role in heritage research. On one hand, merely recording the physical environment of heritage can no longer meet the demands of contemporary heritage protection and management. Relying solely on the preservation of physical remains cannot truly achieve the full excavation of cultural heritage values, thereby making cultural transmission and heritage development difficult to sustain. On the other hand, climate change, greenhouse gas emissions, natural disasters, and human-induced destruction have compounded the challenges of heritage protection. The complexity of heritage imposes higher requirements on research and management practices, making digitization an important trend and field in contemporary heritage research and practice. The development of digital technology has provided new solutions for the protection of cultural heritage.

1 Concept and Manifestations of Heritage Digitization

1.1 Conceptual Origins of Heritage Digitization

The research and discussion of heritage digitization in the international heritage conservation field have a long history. As early as October 15, 2003, UNESCO adopted the *Charter on the Preservation of Digital Heritage*, which stated the need to preserve and maintain "resources of cultural, educational, scientific and administrative information, whether generated digitally or converted from existing analog resources, as well as information in technical, legal, medical, and other fields"[1], thereby expanding the concept and forms of heritage.

Heritage digitization refers to the use of surveying, visualization, and computer technologies to generate or convert digital information about heritage in support of its protection, management, and display, including all forms of digital data capture—from photography, image rectification, and photogrammetry to 3D laser scanning and sound recording[2]. In brief, it is the process of using digital technology to preserve, process, and disseminate the tangible and intangible content of cultural heritage in digital form. This process encompasses not only 3D scanning, digital archiving, and virtual display of tangible cultural heritage such as artifacts, architecture, and books, but also the recording, digital dissemination, and innovative transmission of intangible cultural heritage such as traditional crafts, customs, and oral histories. Heritage digitization is a dynamic process.

Digital cultural heritage refers to cultural heritage that exists in digital form, including documents converted from existing materials into digital formats as well as born-digital materials. These digital cultural heritage assets may

take the form of text, images, audio, video, databases, software, and other formats. Digital cultural heritage emphasizes the content of cultural heritage that has already been digitized—it is a static result.

1.2 Digital Manifestations of Heritage

According to the *Charter on the Preservation of Digital Heritage*, digital heritage "includes text, databases, still and moving images, audio and graphics, software, and web pages, among others." In 2006, the Symposium on "Making 3D Visual Research Outcomes Transparent," initiated by King's College London, adopted *The London Charter for the Computer-based Visualisation of Cultural Heritage* (hereinafter referred to as the *London Charter*). This charter established principles for the digital representation of cultural heritage^①, and its version 2.1 draft stipulated that "published record materials should employ the most effective available media, including images, text, video, audio, digital formats, or combinations thereof"[3–4].

2 Development of Heritage Digitization

2.1 Emergence of Heritage Digitization (1960s–1990s)

European and North American countries had already begun digitizing archival documents and collections as early as the 1960s using techniques such as photography, video recording, and reproduction. The resulting databases initially served internal purposes only and were gradually opened to the public with the advent of the Internet. In the 1990s, 3D technology and virtual reality technology also began to develop and were gradually applied to heritage conservation research, marking the dawn of the digital era in heritage protection.

2.2 Development of Heritage Digitization (1992–2019)

The year 1992 is generally regarded as the inaugural year of digital heritage research. UNESCO launched the "Memory of the World" programme, aimed at using modern information technology and digital means to implement the task of protecting world cultural heritage as stipulated in UNESCO's Constitution, raising awareness of the importance of new forms of documentary heritage including audio recordings, film and television works, and digital media, and promoting the preservation and dissemination of heritage resources worldwide. In the same year, Angkor Wat in Cambodia was inscribed on the UNESCO World Heritage List, and a series of digital technical measures utilizing computer-assisted information management systems were employed for the conservation of Angkor Wat[5].

2.2.1 Collection and Recording of Heritage Digitization

The initial applications of heritage digitization research were relatively simple, primarily focusing on the collection and recording of cultural heritage in digital form. In 1998, the "Digital Michelangelo Project," a collaboration between Stanford University and the University of Washington, employed laser scanners and digital cameras to scan and photograph Michelangelo's sculptures and architecture for digitization.

The role of remote sensing technology in preserving large-scale cultural heritage also led to the widespread application of photogrammetry, particularly for recording immovable heritage such as monumental structures and large-scale archaeological sites. The International Council on Monuments and Sites (ICOMOS) and the International Society for Photogrammetry and Remote Sensing (ISPRS) jointly established the International Committee for Architectural Photogrammetry (CIPA) in 1968. Given the transfer of relevant technologies from the surveying sciences to the discipline of heritage documentation and recording, it was officially renamed CIPA Heritage Documentation in 2007, with the aim of applying surveying, visualization, and computer science technologies to the recording, conservation, and documentation of cultural heritage^②.

2.2.2 Restoration and Display of Heritage

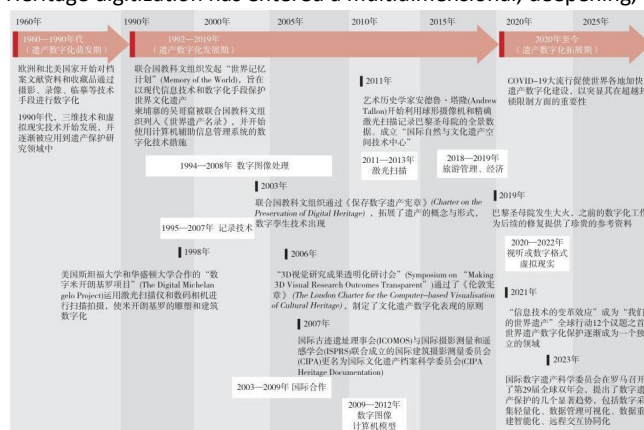
With the development of Virtual Reality (VR) and Augmented Reality (AR) technologies, both have been widely applied in heritage conservation research, including but not limited to the restoration and display of vanished cultural heritage and the reconstruction of connections between heritage and its historical, cultural, and original environmental contexts. Japan used 3D scanners to create a virtual model of the Great Buddha of Kamakura, cast in the 13th century, and employed VR technology to reconstruct the main hall of Kōtoku-in, which was destroyed in the Meiō earthquake of 1498. Meanwhile, due to their capacity to provide users with a deeper sense of engagement and realism, VR and AR technologies began to be applied on a larger scale in exhibition, touring, and visiting contexts, shifting from internal research and restoration applications to public-facing display and education. During this stage, heritage digitization began to emphasize the promotion and dissemination of heritage information, and the application of digital technologies became more oriented toward interactive experiences for users and visitors. For example, IBM's "Eternal Egypt" project (2001–2004) and the University of Chicago's "Sulman Mummy" project both presented heritage through online digital museums on the Internet[6].

2.3 Expansion of Heritage Digitization (2020–Present)

The COVID-19 pandemic prompted countries worldwide to accelerate the development of heritage digitization, highlighting its importance in transcending the limitations imposed by lockdowns. For instance, the Japanese Agency for Cultural Affairs continuously accelerated the development of the "Cultural Heritage Online" website after 2020, including adding electronic information on nationally designated, selected, and registered cultural heritage assets. As of November 2022, data (including images, videos, and textual materials) from 1,045 World Heritage site management agencies, museums, and art galleries had been entered, with information on 273,687 cultural heritage items publicly searchable and viewable^③.

In 2021, "The Transformative Effect of Information Technology" became the first of the 12 themes of the "Our World Heritage" global initiative, and the digital protection of world heritage gradually became an independent field. In 2023, the International Scientific Committee on Digital Heritage held its 29th Global Biennial Conference

in Rome, identifying several new trends in digital heritage protection, including lightweight digital capture, visualization of data management, intelligent data reconstruction, and collaborative remote interaction[7]. Heritage digitization has entered a multidimensional, deepening, and intelligent expansion stage. (See Fig. 1.)



Timeline of heritage digitalization development

Fig. 1 Timeline of heritage digitalization development[8]

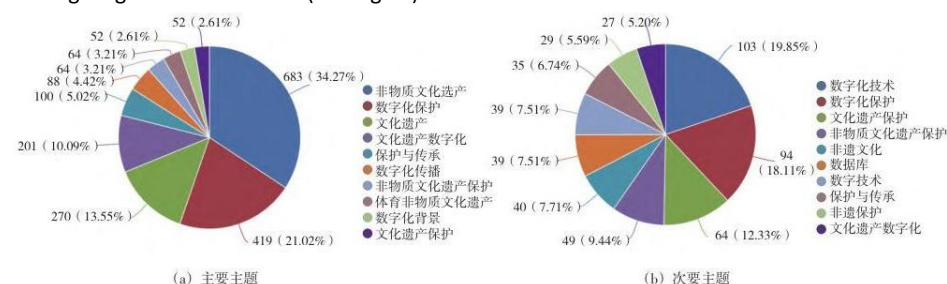
2.4 Heritage Digitization Technologies

Heritage digitization technology has evolved from simple 2D scanning to complex 3D modeling and, further, to intelligent large-model-assisted approaches. Currently, commonly used digitization technologies include: ① **3D laser scanning technology** — acquiring precise 3D data of heritage through laser scanning for reconstruction and archiving. ② **Photogrammetry and remote sensing technology** — utilizing aerial or satellite imagery for large-scale heritage monitoring and management. ③ **Virtual Reality (VR) and Augmented Reality (AR) technology** — providing immersive experiences through simulated and enhanced real environments, capable of recreating vanished traditions to better interpret heritage and facilitate public understanding. ④ **Digital twin technology** — creating digital replicas of heritage for real-time monitoring and assessment. ⑤ **Mobile interaction technology** — mobile interaction and digital media enabling broader public dissemination and facilitating audience expression. ⑥ **Artificial intelligence technology** — AI large models that can comprehensively assist heritage management and research, enabling intelligent heritage protection and planning.

3 Research Issues and Insights of Heritage Digitization

3.1 Research Trends and Themes

A search of the CNKI (China National Knowledge Infrastructure) database using "heritage digitization" as the title keyword yielded a total of 1,451 publications. Bibliometric visualization analysis produced the following results: The number of publications on heritage digitization has been increasing annually since 2000, with a surge beginning in 2010, indicating that research on heritage digitization proliferated after 2010, closely related to the innovation of technical means brought about by the emergence of laser scanning technology in 2011. Another high-growth period appeared after 2020, triggered by the development of virtual reality technology. In 2023, the International Scientific Committee on Digital Heritage held its 29th Global Biennial Conference in Rome, identifying several notable trends in digital heritage protection—lightweight digital capture, visualization of data management, intelligent data reconstruction, and collaborative remote interaction—sparking a new wave of heritage digitization research. (See Fig. 2.)

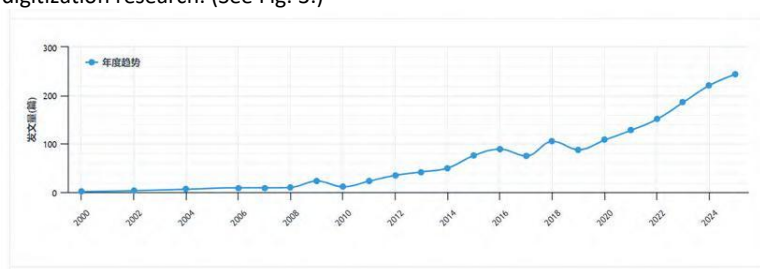


Number of publications on heritage digitalization

Fig. 2 Number of publications on heritage digitalization

In terms of research themes, intangible cultural heritage, digital technology, digital protection, conservation and transmission, and digital dissemination emerged as prominent keywords. Digitization of intangible cultural heritage, requiring relatively simple digital technology, constituted the earliest research topic in heritage digitization. Digital technology, as the decisive factor in heritage protection methods, has remained a consistent research theme, with digital protection correspondingly becoming a frequently discussed topic. The conservation and transmission of heritage is the primary purpose of digital technology-based protection and has become one of the most highly attended topics. In recent years, heritage display and promotion have received unprecedented

attention, facilitating public participation and the sharing of heritage values, and have become a focus of heritage digitization research. (See Fig. 3.)



Distribution of literature themes on heritage digitalization

Fig. 3 Distribution of literature themes on heritage digitalization

3.2 New Insights from Heritage Digitization Research

Through a summary of the aforementioned research hotspots and themes, new insights from heritage digitization for heritage protection can be identified.

3.2.1 A New Perspective: Technology-Led Transformation of Europe's Traditional Heritage Protection System

Digital technology has expanded the means of heritage recording, archiving, and management, while continuously generating new perspectives for heritage protection and research. Based on the authenticity principles established in the *International Charter for the Conservation and Restoration of Monuments and Sites* (1964) and the *Principles for the Recording of Monuments, Groups of Buildings and Sites* (1996) in the field of heritage conservation and restoration, early heritage digitization research primarily focused on heritage recording and site information collection—the most fundamental content of this field. By drawing on digital technology achievements from museums, archives, and other institutions, a methodology analogous to the European traditional heritage protection system is being systematically advanced as the foundation for digital protection, driving the standardization of heritage conservation and restoration processes[9].

In 2007, the Getty Conservation Institute (USA) and its partners published *Recording, Documentation, and Information Management for the Conservation of Heritage Places*, comprising two volumes: *Guiding Principles* and *Illustrated Examples*. This work provided a foundation for understanding, planning, and implementing heritage recording and information system projects, significantly enhancing the capacity of heritage professionals in information collection, processing, and management[2, 10]. In 2008, Martha Demas proposed specific working methods for digital heritage protection and four basic principles for the foundational digital recording of heritage sites[11]. The determination of baseline records serves to standardize heritage site conservation work at either a preliminary or detailed level. Furthermore, this foundation can serve as a starting point for the design and implementation of monitoring programs, enabling the detection of changes that affect the assessment of heritage site values.

3.2.2 A New Concept: Rethinking Authenticity and Integrity in the Digitization Process

Contemporary heritage research involving extensive digital technology applications primarily focuses on recording and simulating the physical environment of heritage—for example, using remote sensing and imaging technologies to document the current state of heritage and its surrounding environment[12–14], employing virtual reality to represent material elements of heritage[15–17], building digital models and virtual restorations and constructing heritage databases from collected information data[18–19], and utilizing augmented reality and gaming technologies for heritage visualization research and the sharing of research outcomes[20].

The issues of authenticity and integrity in the digitization process, and how to balance technological innovation with cultural heritage protection, are current research hotspots that have prompted reflection within the field.

3.2.3 A New Direction: Exploring the Social Dimensions of Heritage Digitization

The social dimensions of heritage digitization primarily involve exploring the foundational architecture of digital heritage archives, seeking optimal models for providing information resources, researching interoperability protocols among digital libraries, testing the most effective user interfaces, addressing the technical challenge of efficiently retrieving desired information from the vast stacks of Internet information, and pursuing more economically viable operation of digital heritage archives and management systems for intellectual property protection. Research on the social dimensions of heritage digitization is not confined to the online sphere; it seeks to effectively store, manage, and make accessible through user-friendly means the vast quantities of information dispersed across different geographic locations and categories, ultimately achieving a high degree of resource sharing and positive social impact.

European Union member states such as Austria and Germany have continuously explored and established comprehensive digital heritage systems, with designated responsible institutions and funding support for the digital advancement of different types of heritage. Faced with an enormous volume of heritage assets, EU countries confront a formidable digitization task and have progressively advanced through successive rounds of iterative project programs over approximately the past 30 years. Platforms composed of governments, administrators, and professionals encourage public sharing and participation, and the use of mobile terminals maximizes the goal of universal access to cultural digitization, serving to promote European integration and foster a sense of belonging among EU citizens.

The "Visualising Ballarat" project in the City of Ballarat, Australia, is a successful case of a heritage digitization sharing research platform[21, 24]④.

4 Application Practices and Positive Value of Digitization in Heritage Protection and Utilization

4.1 Sustainable Heritage Recording: Digital Recording Technologies Creating Open and Shared Platforms

Recording requires accurately capturing the physical characteristics that define the value and defining elements of heritage. Its core objective is to scientifically and effectively capture, represent, and convey the characteristics and values of heritage. Therefore, identifying heritage characteristics is the foundation for discussing recording work. All artificial and natural elements need to be documented through multi-scale, highly flexible means and tools to ensure the completeness of records[21].

Traditional surveying methods are time-consuming and labor-intensive, with long data collection and processing cycles, making regular data updates difficult. New digital technologies have revolutionized the speed and completeness of heritage site recording: new recording technologies represented by remote sensing, scanning, and imaging have innovated the methods of heritage spatial information acquisition, enabling us to observe heritage from unprecedented perspectives and with unprecedented precision, bringing revolutionary advances in the completeness, accuracy, and efficiency of spatial data collection[22]. These records can guide site managers, researchers, and government officials at different levels in their decision-making processes and present the historical knowledge and values of heritage[23].

With the aid of digital recording technologies, heritage recording will become a continuous process, providing ongoing dynamic monitoring and management support. Open sharing is an important characteristic of digital heritage recording—heritage records are no longer constrained by time, location, culture, or format. Although culturally specific, they can be used by anyone in the world. Recording results are shared through platforms, becoming venues for exchange and learning between heritage protection experts and the public, providing rich practical experience and reference materials for heritage protection research, restoration, development, and utilization, and promoting the recognition, protection, and dissemination of the multiple values of heritage.

4.2 Intelligent Heritage Identification: Digital Protection Technologies Preventing Damage to Vulnerable Heritage

In the area of heritage conservation, the objects that can be digitally processed fall into two categories: one comprises various types of indirect analytical data obtained through the analysis of heritage or heritage data itself; the other comprises extended data such as digital models and virtual reality images generated through digital display, digital restoration, or other means.

Heritage sites typically face threats from many quarters. Excessive human interference has left many important world heritage sites and monuments without adequate protection, while environmental changes, natural disasters, and other threats have made more urgent demands on digital protection. Digitization offers a precise and safe means of protecting and studying heritage—once digital information has been collected from a heritage site, research can be conducted remotely away from the site. Digital information collection is both precise and convenient, and off-site research represents the safest approach for fragile heritage. Furthermore, since heritage is a potential component of the sustainable built environment, regular inspections of cultural relic structures are necessary during conservation. Artificial intelligence-based automatic defect detection technologies can be employed to construct automated visual inspection systems.

The permanent preservation and protection of grottoes, murals, and similar heritage represent a major challenge for the international heritage community. Digitization helps counteract natural deterioration such as oxidation, corrosion, aging, and peeling caused by excessive human interference. The Dunhuang Academy (敦煌研究院) began exploring digital protection as early as 1993[25–26].

4.3 Sustainable Heritage Conservation: Digital Archiving Technologies Supporting Reliable Heritage Restoration

The goal of heritage digitization is to create records that can be preserved as permanently as possible, ensuring that heritage information can be passed down from generation to generation and that continuity is maintained even when the values and integrity of heritage are compromised. Therefore, employing digital means to systematically archive recorded heritage entities, various materials, and other related information—establishing scientific heritage archives through a series of standardized collection, processing, storage, and presentation procedures—can support conservation, restoration, development, and utilization efforts. These results represent the foundational information for heritage protection, i.e., information used for the active maintenance of heritage itself. Over time, when heritage entities suffer from sudden disasters, natural erosion, or human destruction, the data generated by digital recording becomes the sole source for obtaining heritage information. Rigorous digital archiving, which systematically organizes various heritage-related information, can serve as a primary means for scholars and the public to understand a fundamentally altered or vanished site[21]. It is a crucial tool in the race against time, preventing heritage from being entirely erased from human memory and ensuring that future generations still have intuitively understandable records.

In 2019, the fire at Notre-Dame de Paris caused significant damage to the heritage. The extensive digital work accumulated prior to the fire became an invaluable reference for the subsequent restoration. In December 2024, Notre-Dame de Paris was successfully restored and reopened to the public, receiving positive professional and public feedback⑤.

4.4 Building Digital Models and Heritage Databases: Digital Information Management Technologies Assisting Professionals in Heritage Management

Heritage information is a comprehensive activity encompassing recording, archiving, and information management. Information integration is also a challenge in heritage recording—fragmented heritage data must be transformed into knowledge that supports heritage decision-making, thereby improving the efficiency of heritage information utilization and more profoundly reflecting heritage values[27]. Therefore, information management—the discovery, classification, storage, and sharing of heritage information for present or future use—plays a pivotal role.

The integrated application of digital twin, HBIM (Historic Building Information Modeling), WebGIS, and other technologies enables the acquisition and integration of heritage information to build digital models and heritage databases. Comprehensive digital analysis methods are employed for digital feature identification, providing a thorough assessment of the authenticity and integrity of heritage sites. The gradual maturation of 3D geographic information systems, intelligent geospatial processing, and machine learning technologies has significantly improved the efficiency and accuracy of heritage feature and element identification, providing an irreplaceable data platform for cultural landscape heritage information management[19]. Applying the latest reality capture and spatial documentation strategies to record heritage, surrounding environments, and other objects worldwide—and creating digital learning tools and library collections based on these data—can facilitate the formulation of planning strategies for heritage conservation, research, education, and tourism. Through hybrid technical approaches, while maintaining respective digital sovereignty, individual storage solutions are aggregated into different cloud products; services and working tools can be accessed or controlled via the Internet, or a heterogeneous approach to data sovereignty can support the processes of copyright, usage rights, and intellectual property protection interpretation in digital development.

As an intangible infrastructure, digital data has now become an integral component of cultural heritage protection. Recording, assessment, monitoring, analysis, planning, and intervention all require digital data. The integrative nature of recording implies that all heritage data should be organized, stored, and managed in the form of databases. The unification of data structures, standardization of data formats, and normalization of data usage will greatly enhance the efficiency of heritage information utilization[19]. Digital information management can meet the widespread demand in the international heritage field for low-cost digital registration systems. Heritage registration systems must be both user-friendly and customizable while leveraging the latest technologies to create and manage rich and diverse heritage information.

The Getty Conservation Institute (USA) and the World Monuments Fund jointly developed Arches in 2013, an open-source software platform for cultural heritage data management, to assist conservation scientists, heritage professionals, and heritage institutions in registering, surveying, and managing various types of heritage resources, as well as securely protecting, retrieving, visualizing, comparing, and sharing scientific heritage data.

4.5 Technological Enhancement of Heritage Display and Interpretation: Digital Education and Dissemination Technologies Innovating Heritage Presentation Formats

After nearly 30 years of development, all sectors of society have placed greater emphasis on cultural heritage, and heritage digitization has advanced rapidly. In terms of display methods in particular, the proliferation of 3D modeling, visualization, virtual reality, augmented reality, and other technologies, along with the emergence of stereoscopic map reproduction, has formed diversified and interactive multimedia presentation tools. These have brought new display and presentation formats for the education and dissemination of heritage site information.

Through virtual reality, 3D modeling, panoramic photography, Bluetooth technology, Near Field Communication (NFC), positioning technology, artificial intelligence, and other means, heritage can be presented through multiple media formats. Heritage site management agencies store and organize large quantities of heritage-related data in the form of digital museums, making it accessible to researchers and users for online retrieval, consultation, and browsing, while providing multimedia presentations related to heritage[28–30]. Many heritage site management agencies are equipped with touch-screen kiosks, tablet computers, multimedia headsets, and VR and AR devices. Mobile applications (apps) related to heritage museums, archaeological sites, cultural relics, and historic buildings have appeared in app stores. Through these applications, visitors can zoom in to observe heritage more clearly and browse historic buildings and museums from a 360° perspective.

As digital education and dissemination technologies develop, heritage site management agencies will increasingly employ new technological means for the excavation and promotion of cultural values. Broadband network technology and multimedia databases are generally used for the comprehensive management of digital content, with information retrieval services provided to the public through Internet platforms and resources integrated accordingly. Utilizing digital methods to develop principles, guidelines, and protocols for documentation, monitoring, interpretation, and dissemination can help heritage site managers enhance the overall application value of digital platforms, create virtual tours and online exhibitions, conduct comprehensive digital cataloging and networked sharing of heritage, and formulate digital heritage development strategies and evaluation standards.

As early as 1996, the French Ministry of Culture (*Ministère de la Culture*) took the lead in launching a digitization program. In 2018, the Ministry launched the *Programme national de Numérisation et de Valorisation des contenus culturels* (National Program for the Digitization and Promotion of Cultural Content, hereinafter "PNV

Program"), a continuation of the aforementioned digitization program that particularly emphasized a more comprehensive implementation of the cultural digitization strategy. The program's content is increasingly oriented toward the use of cultural content, the widest possible cultural dissemination, the development of digital education, and the presentation of new online services, promoting the communication and advancement of the values of cultural heritage, historic buildings, and art collections.

Digital technology-based heritage protection research also contributes to the development of heritage display. Various digital media strive to convey the historical information and values behind heritage to the public in more intuitive and comprehensive ways. For safety reasons, strictly protected historic buildings or ancient sites generally do not make their interior views publicly accessible. Through high-precision VR and AR technology simulations of real scenes, the historical and aesthetic values of heritage can be maximally revealed. Many universities and heritage site management agencies have conducted research on technologies related to heritage digitization in information management, virtual reality, and digital restoration and reconstruction. Examples include the "Virtual Egyptian Temple" project, a collaboration between the University of Pittsburgh and FiatLUX Studio (Canada); the "Digital Giza" project, a collaboration between Harvard University and the Andrew W. Mellon Foundation; and the "Ninna-ji Goten Garden 3D Content" project, a collaboration between Ninna-ji Temple in Kyoto and SUS Corporation.

Since the COVID-19 pandemic, the use of intangible content on heritage social networks has steadily increased[31]. Many heritage site management agencies have begun collaborating with the gaming industry, enhancing the representation of cultural heritage values through serious video game development and partnerships with video game franchises[32], using AR and VR gaming to present history more vividly to the public, particularly younger audiences.

4.6 Heritage Digitization Practices in China

4.6.1 Starting with Designated Cultural Heritage Protection Units

Research on heritage digitization in China began relatively early. It was primarily introduced by cultural heritage research institutions, with major protected cultural heritage sites as the main research objects. Starting in 1993, the Dunhuang Academy implemented the research project "Computer Storage and Management System for Dunhuang Murals," employing close-range photogrammetry on Cave 45 of the Mogao Grottoes to obtain high-quality, high-precision photographic reversal film images of the murals, and using digital scanning to produce digital images of the murals. In late 1998, the Dunhuang Academy, in collaboration with Northwestern University and the Mellon Foundation, conducted the collaborative research project "Digitization of Dunhuang Murals and the International Digital Dunhuang Archive." Through technical cooperation and introduction, a methodological approach to 2D mural digitization was established, and comprehensive digitization was completed for more than 20 representative caves of the Mogao Grottoes that had been previously published[26]. In 2001, the Palace Museum officially launched its website, taking the first step toward establishing a comprehensive database of historical architectural materials. In 2004, 3D laser surveying technology was applied to the digital construction of the Forbidden City. In 2017, Zhejiang University and the Yungang Grottoes Research Institute of Shanxi Province collaborated to produce a 1:1 replica of Cave 3 of the Yungang Grottoes using 3D printing technology—the world's first large-scale heritage replication project achieved through 3D printing. In recent years, the National Cultural Heritage Administration has successively issued departmental regulatory documents on the digital protection of cultural heritage protection units, including Qutansi Temple, the former site of Huaxin Cement Factory, and Fuzhen Temple at Wudang Mountain.

4.6.2 Heritage Digitization Empowering the Protection of Historic and Cultural Cities

The elements of digital heritage protection for historic urban areas are numerous, primarily including heritage data collection and classification, historical resource description and display, long-term storage database organization, query information retrieval, and public interactive dissemination. The heritage digitization process comprises three stages: ① **Digital information.** In historic urban areas, this can be applied to the vectorization of geographic data, cadastral information, and architectural documentation. By comparing cadastral changes, the process of urban transformation can be analyzed. Various urban planning and construction events in historic urban areas are cataloged, recorded, and chronologically sorted. A cognitive framework is used to analyze changes in buildings, roads, urban spatial structure, and functional uses, to assess the conservation and transmission value of cultural heritage, and to directly associate cadastral data, documentary references, and analytical conclusions with physical buildings. ② **Digital platforms.** These integrate the main archival data foundation for the management and protection of historic urban areas, establishing heritage digitization platforms that unify the division of labor and management coordination for heritage digitization protection in historic urban areas. ③ **Digital standards.** Corresponding technical specifications and evaluation standards are formulated for the digital protection of heritage in historic cultural districts or historic urban areas, providing support for the protection and management, planning, landscape, academic research, and community services related to heritage digitization practice[33–34].

At present, China has explored and conducted relatively rich and multi-level heritage digitization practices for historic and cultural cities.

At the **provincial level**, Sichuan Province has constructed a 3D data platform for urban and rural historical and cultural resources, achieving the unified collection, integration, and presentation of basic geographic data, historical and cultural resources, and 3D model data for the entire province. This provides foundational support

and analytical decision-making for historical and cultural resource management, planning and design, protection, and utilization, effectively enhancing Sichuan Province's capacity for historical and cultural resource protection and management⑥.

At the **municipal level**, in 2018, the Enning Road Historic and Cultural District in Guangzhou conducted the first 3D scanning and surveying of its main streets. Building upon this, the "Guangzhou Memory" digital platform was developed—the first government-led urban memory project in China, systematically promoting the public accessibility and popularization of Guangzhou's history and culture. Guangzhou has now entered the intelligent technology stage, developing a sub-model for historic city protection based on the Guangzhou planning large model "CanPlan." Leveraging the City Planning Company's historic and cultural city research platform, a large language model has been formed that encompasses basic information on Guangzhou's historical and cultural resources, conservation planning for historic cultural districts, 3D building and environmental information, and other planning management content[32]. Guangzhou has further explored the compilation of a series of digital protection standards, filling industry gaps and providing scientific and standardized guidance for its work⑥.

Suzhou, meanwhile, has conducted extensive practical exploration in digital twin and digital platform construction. It has built the Suzhou CIM+ Historic City Protection and Renewal Platform, innovatively proposing a digital twin architecture for the Suzhou ancient city. Driven by digital scenarios and technology, it addresses the contradiction between ancient city protection and revitalization development, promotes the sustainable development of the Suzhou ancient city, and explores the digital revival of traditional construction methods, the digital evolution of traditional living patterns, and the digital enhancement of traditional cultural values in the Suzhou ancient city[35].

At the **rural level**, the Digital Museum of Traditional Chinese Villages in Jinzhai County, Anhui Province, serves as an example. Jinzhai County has 5 national-level and 20 provincial-level traditional villages. Centered on the distinctive "mountain–village–field–forest" spatial layout, the museum employs multimedia, panoramic roaming, and other formats to comprehensively present the unique values and connotations of the villages, forming a digital museum that combines educational value, (engaging interactivity), and visual appeal, and achieving the digital protection and transmission of traditional villages⑦.

5 Conclusions and Prospects

5.1 The Demand-Driven Nature of Heritage Digitization Requires Research to Rapidly Respond to Real-World Challenges, Forming Data Research Platforms

Whether confronting climate change, over-tourism, or the recovery in the post-COVID-19 pandemic era, the challenges currently facing heritage sites are closely linked to the constantly emerging changes and crises worldwide. Although digitization can hardly replace the physical heritage entity, it is undeniable that this approach can mitigate or delay various forms of unavoidable damage to heritage, compensate for the shortcomings of heritage dissemination, promote regional integration, and foster cultural belonging. Many heritage site management agencies are maintaining connections with the public through an increasing number of digital initiatives, rapidly responding to real-world challenges to facilitate the formation of data research platforms. National governments are also continuing to implement and strategically plan for heritage and its digital advancement.

5.2 The Technology-Driven Nature of Heritage Digitization Makes the Research Focus on Resolving the Application of Digital Technology in Cultural Heritage Protection, Continuously Advancing Toward Informatization, Intensification, Interactivity, and Intelligence

Digital technology is a powerful tool for heritage recording and visualization. It has evolved from simple digital recording and archiving to 3D modeling and recognition, heritage databases, and information technology integration. The emergence of digital interaction technologies represented by VR and AR is continuously driving heritage digitization research toward informatization, intensification, interactivity, and intelligence. Although heritage digitization research has accumulated decades of valuable experience, with the continuous iterative upgrading of computer networks, big data, and other scientific technologies, this field remains in a stage of accumulating experience while simultaneously adjusting direction in response to technological change. There is still greater room for development and potential in the future.

5.3 Heritage Digitization Brings Transformation to the Traditional Heritage Protection System

The purpose of heritage digitization is to protect and transmit cultural heritage through digital technology, enabling it to be permanently preserved and widely disseminated in the digital space. The technology-led transformation of Europe's traditional heritage protection system has prompted a rethinking of authenticity and integrity issues in the digitization process and opened up new directions for exploring the social dimensions of heritage digitization. Heritage digitization has made positive practical contributions to continuous heritage recording, intelligent identification of heritage vulnerability, reliability of heritage restoration, construction of digital models and heritage databases, and technological enhancement of heritage display and interpretation.

5.4 China Has Relatively Rich Practices in Heritage Digitization for Both Cultural Heritage Protection and Historic and Cultural City Protection, but Urgently Needs National-Level Legislation on Heritage Digitization Protection and the Formulation of Corresponding Technical Specifications and Evaluation Standards for Historic Urban Area Heritage Digitization

Building upon existing practices, efforts should be accelerated to construct interdisciplinary and cross-departmental urban planning databases, build digital protection models for heritage in historic urban areas, and

establish heritage databases for historic urban areas. These should be integrated with the existing historic and cultural city planning system to construct digital heritage protection platforms for historic urban areas, providing authentic and effective data support for the protection of historic and cultural cities. Heritage data for historic urban areas should also be made openly shared among various stakeholders under copyright protection conditions, facilitating public use. It must be emphasized that although heritage digitization has become an extremely important means of preserving and disseminating heritage information, it should not become a substitute for the physical protection and display utilization of heritage.

Going forward, attention must be paid to the challenges of digital heritage data disappearance and cognitive limitations; how to find a balance between the virtual and the real so that the values of heritage can be fully and deeply transmitted; how to establish an ethical framework and codes of practice for digital protection; and how to design intelligent protection strategies[36–37].

Heritage digitization has promoted information exchange among scholars across fields and around the world, revealing the complexity of the contemporary world. This will bring changes and growth opportunities for heritage that align with social development trends, and it will also be an inevitable outcome and practical demand of heritage research development.

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Notes

- ① Some content is drawn from the official website of the London Charter: <http://www.londoncharter.org/>.
- ② Some content is drawn from the official website of CIPA Heritage Documentation: <https://www.cipaheritagedocumentation.org/>.
- ③ Some content is drawn from the official website of Cultural Heritage Online (文化遺産オンライン): <https://japanheritage.bunka.go.jp/ja/>.
- ④ Some content is drawn from the official website of Visualising Ballarat: <http://www.visualisingballarat.org.au/>, the HUL Ballarat official website: <https://www.hulballarat.org.au/>, and the Victorian Heritage Database official website: <https://vhd.heritagecouncil.vic.gov.au/>.
- ⑤ Some content is drawn from the official website of Arches: <https://www.archesproject.org/>.
- ⑥ SHI Yujun. Digital and intelligent practices for the protection and governance of Guangzhou's historic city. The 3rd CIM and Smart City Construction Forum: Digital Technology Empowering the Protection and Transmission of Historic and Cultural Cities, December 29, 2024.
- ⑦ ZHANG Honghui. Digital technology empowering the protection of historical and cultural resources. The 3rd CIM and Smart City Construction Forum: Digital Technology Empowering the Protection and Transmission of Historic and Cultural Cities, December 29, 2024.

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