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Protection and Utilization of Historical Sites Using Digital Twins

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Abstract: Historical sites are incomplete relics left by human activities and are also valuable resources for human society, with most of them buried deep underground. Because the protection of original historical sites is difficult, very few sites choose this method. Many funerary objects that have been in historical sites are scattered in museums, losing their original context and complicating their utilization. Thus, using digital technology to protect and utilize historical sites and to explore their outstanding value from historical, aesthetic, and anthropological perspectives is a foremost concern. Therefore, this study aims to develop a comprehensive method for the protection and utilization of historical sites, that is, digital protection and utilization based on a digital twin. We constructed a historical site digital twin model using qualitative and vertical methods, including a physical entity, virtual entity, twin data center, digital twin service, and connection. We also established a technical framework of data acquisition and processing, digital protection, and digital utilization, forming a layered management and application of digital resources. In digital protection, information in the real world and the virtual world are connected to monitor risks, collect data, create simulations, and propose protection strategies, quickly and accurately. In digital utilization, the knowledge graph is constructed to associate seemingly unrelated information, explore potential knowledge, and improve information sharing. In addition, the method is validated by means of case studies of historical sites in China. In this paper, the historical sites of the Northern Qi Dynasty in Taiyuan, Shanxi, especially the Xuxianxiu Tomb and Lourui Tomb, are discussed in detail. The results indicate that this method is effective for the protection and utilization of historical sites.

Keywords: historical sites; digital twin; protection; utilization

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1. Introduction

Historical sites are relics of human civilization, including buildings built for different purposes, as well as places affected by human utilization and the processing of the natural environment. Historical sites are the important material and spiritual heritage of a nation, as well as a witness to the development of a nation and even a civilization. They include archaeological sites with outstanding universal value from a historical, aesthetic, ethnological, or anthropological perspective [1]. The preservation of historical sites is related to the future, and it is our unshirkable responsibility to protect them. We should understand the profound historical and cultural implications behind them so as to cultivate a new modern culture based on tradition [2]. However, the rapid development of society has complicated the protection of historical sites, but fortunately, the development of digital technology, such as terrestrial laser scanning, close-range photogrammetry, and satellite remote sensing, has created new opportunities for the protection and utilization of historical sites with fragile and perishable characteristics [3,4]. In the past three decades, technical improvement has led to digital protection becoming a mainstream trend in the protection of historical sites, through digital archaeology, 3D modeling, geographic information systems, etc. [5,6]. Digital media technologies such as virtual reality and augmented reality have also revitalized the inheritance of historical sites [7]. Breaking time and geographical restrictions, people can easily access global history and culture, enhance understanding between different cultures, and promote the diversified development of modern culture [8].

Overall, digital technology has pushed the protection and utilization of historical sites to a new level. However, the increasing number of digital resources has also introduced new problems and opportunities, such as how to integrate and link digital resources and excavate heritage value. Additionally, digital protection and utilization involve mostly static data collection, storage, and processing, which lack a consideration of real-time intelligence and interactivity, as well as the intelligent diagnosis and prediction analysis of risks. Fortunately, digital twin (DT), a new technology, provides a new approach to solving the above problems.

The digital twin prototype was proposed for Product Lifecycle Management (PLM) by Michael Grieve at the University of Michigan in 2003 [9]. In NASA's 2010 technical report, digital twin was officially proposed as a system of aircraft simulation processes that integrate multiple physical quantities, scales, and probabilities [10]. It was defined by Grieve as a digital replica used for virtual expression and real description, and he conducted model simulation tests of real environments, conditions, and states [11]. As of 2023, research has made substantial progress in theory and application. The study field has gradually shifted from aerospace and the military to industrial manufacturing, heritage protection, etc. It has been expanded from designing and planning to modeling and manufacturing, management and maintenance, etc.

Especially in the past three years, digital twins have become a hot topic in cultural heritage research in theory and application. The focus of theoretical research is mainly on the models, frameworks, technologies, and management of digital twins. For example, a digital twin model was created by means of motion photogrammetry and depth camera mapping to generate a four-dimensional space of cultural heritage [12]. A digital twin provided an accurate digital model for performing finite element analyses for preserving valuable assets, which was the structural vulnerability assessment of heritage structures and the pivotal part of a risk mitigation strategy [13]. A digital twin research framework combined with the HBIM model is used for managing the preventive protection of heritage buildings and identifying the threats associated with their integrity, the corresponding mitigation strategies, the value assessment process, etc. [14]. The function of digital twins is to support on-site managers in the preventive protection of their assets, predict threats to site integrity based on the DT environment, and propose corresponding prevention plans [15]. The digital twin paradigm has significant advantages in integrating knowledge, protecting, restoring, and managing cultural heritage.

In applied research, the focus is mainly on the protection and utilization of key cultural heritage sites. A digital twin was used for the protection and utilization of the Great Wall through evidence-based analysis and scientific deduction using the information technology methodology framework [16]. A digital twin method was constructed to consider the connotation of the whole life cycle and applied to the Great Wall to evaluate the application effects [17]. The application of a digital twin was combined with artificial intelligence and 5G technology in the art design of digital museums [18]. A protocol for the graphic and constructive diffusion with the digital twin method of building heritage was created to guarantee universal accessibility through AR and VR [19]. The maintenance and preservation of art objects in a museum with digital twins highlighted the great advantages of the integration of traditional and novel procedures in the conservation of artistic assets [20]. The Parco Archeologico dell'Appia Antica in Rome has been digitized in multi-temporal digital twins integrated with historical documentation, connecting physical and virtual models to provide an immersive experience beyond traditional reality [21].

Based on the above research, this study aims to introduce digital twins into the digital protection and utilization of historical sites and build a digital twin system. With the characteristics of virtual–real integration and real-time interaction, it solves the problem of poor real-time intelligent interactivity and explores the coexistence of the physical entities and virtual twins of historical sites to produce a new protection and utilization mode for historical sites with intelligent interaction and management. This paper provides a comprehensive method for the protection and utilization of historical sites based on digital twins. This paper is organized as follows. Section 2 describes the composition and function of this method in detail. Section 3 is an introduction to the case study of the historical sites of the Northern Qi Dynasty in Taiyuan, Shanxi, China. Section 4 provides a detailed analysis of the experimental results of the historical sites investigated by our team. Section 5 discusses the methods and results of this study. Finally, Section 6 reports the conclusions.

2. Methods

To achieve our goal, a new method needs to be built in this study, namely, the protection utilization and method validation of historical sites based on digital twin technology. This section describes its model and technical process. This model is a five-dimensional model using digital twin theory and digital technology, including physical entity, virtual entity, service, twin data, and connections. The technical process involves the basic work, protection, and utilization The method validation is used to verify its effectiveness in protection and utilization as follows.

2.1. Digital Twin Model

A digital twin model was constructed. The original model of this digital twin was proposed by Grieves in 2017 in the USA, which was a three-dimensional model including the physical entity, virtual entity, and connections between them [22]. On this basis, in China, Tao proposed the five-dimensional model, which contained a physical entity, virtual entity, service, twin data, and the connections among them [23]. In this study, according to the previous models and features of historical sites, the digital twin model of historical sites was constructed. The equation is as follows:

$$DT_{(HS)} = \left(PE_{(HS)}, VE_{(HS)}, DTS_{(HS)}, TDC_{(HS)}, CN_{(HS)}\right) \quad (1)$$

where $PE_{(HS)}$ is the physical entity of historical sites, and $VE_{(HS)}$ is the virtual entity of historical sites. $DTS_{(HS)}$ is the digital twin service, $TDC_{(HS)}$ is the twin data center, and $CN_{(HS)}$ is the connection among them. According to Equation (1), the structure of the digital twin model is shown in Figure 1.

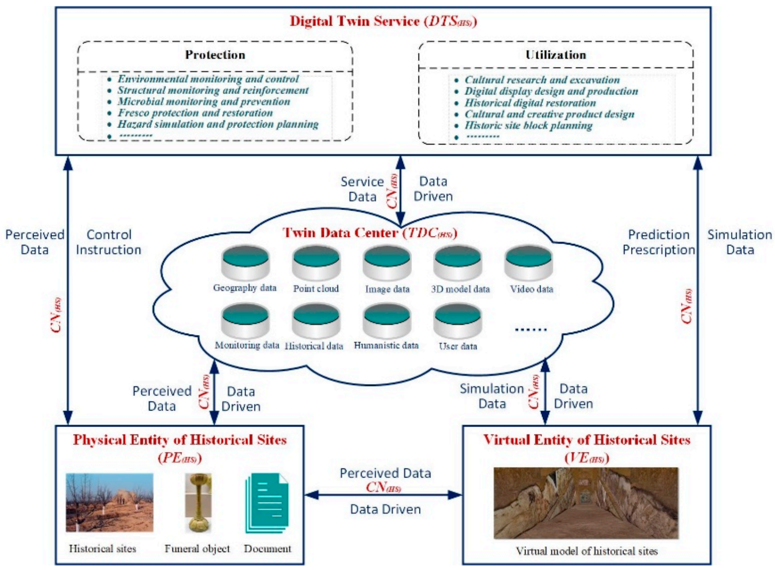


Figure 1. The digital twin model of historical sites.

2.1.1. Physical Entity

The physical entity of historical sites ($PE_{(HS)}$), the related entities of historical sites in the real world, is the foundation of the digital twin system of historical sites ($DT_{(HS)}$), serving as a link and bridge connecting the physical and virtual worlds and completing the twin tasks of historical sites through control and execution system collaboration. The main role and function of digital twin physical entities lies in collecting the real data information and demonstrating decision-making deployment execution management of historical sites such as site ontology, funerary objects, literature, various sensors distributed on the site ontology, etc. The accurate analysis and effective maintenance of the physical space are the premise of the $DT_{(HS)}$ model. For example, the physical space of a tomb site includes tombs, funerary objects, tomb murals, historical materials, etc.

2.1.2. Virtual Entity

The virtual entity of historical sites ($VE_{(HS)}$) is the digital mirror of the digital twin system of historical sites ($DT_{(HS)}$), and it gathers the three model layers of real-time status, historical restoration, and prediction management. "Real-time status" refers to the full digital restoration of the current status of historical sites, including the site itself, funerary objects, and the surrounding environment. "Historical restoration" refers to the digital virtual restoration of historical sites and the digital restoration of the original appearance of the sites according to historical data and existing conditions. Through the real-time monitoring of the site environment and simulation, "predictive management" predicts possible threats to historical sites, provides a basis for scientific decision-making, and thus realizes planning upgrade and decision-making analysis.

2.1.3. Digital Twin Service

The digital twin service for historical sites ($DTS_{(HS)}$) is a user-oriented service terminal that encapsulates the data, models, algorithms, and simulations required in the process of digital twin application, including the protection and utilization of historical sites. In protection, there is environmental monitoring and control, structural monitoring and reinforcement, microbial monitoring and prevention, fresco protection and restoration, hazard simulation and protection planning, etc. In digital use, there is cultural research and excavation, digital display design and production, historical digital restoration, cultural and creative product design, historic site block planning, etc.

2.1.4. Twin Data Center

The twin data center of the historical site ($TDC_{(HS)}$) is the computing center of the digital twin system, including the original data, process data, and result data generated in the process of digital twin application. The details include the geography data, point cloud, image data, 3D model data, video data, monitoring data, historical data, humanistic data, user data, etc.

2.1.5. Connection

The connection to the historical site ($CN_{(HS)}$) enables the interconnection of all components of the model, as shown in Equation (2):

$$CN_{(HS)} = (CN_{PE-VE},\ CN_{PE-TDC}, CN_{VE-TDC}, CN_{PE-DTS}, CN_{VE-DTS}, CN_{TDC-DTS}) \tag{2}$$

where CN_{PE-VE} is the connection between the physical entity and virtual entity, CN_{PE-TDC} is the connection between the physical entity and the twin data center, CN_{VE-TDC} is the connection between the virtual entity and twin data center, CN_{PE-DTS} is the connection between the physical entity and digital twin service, CN_{VE-DTS} is the connection between the virtual entity and digital twin service, and $CN_{TDC-DTS}$ is the connection between the twin data center and digital twin service.

2.2. Technical Process

The technical process is shown in Figure 2 and is mainly divided into three parts. The second is the protection of historical sites, which refers to protecting the original site of historical sites using a digital twin. The third is the utilization of historical sites, which refers to the revitalization and utilization of historical sites with a digital twin.

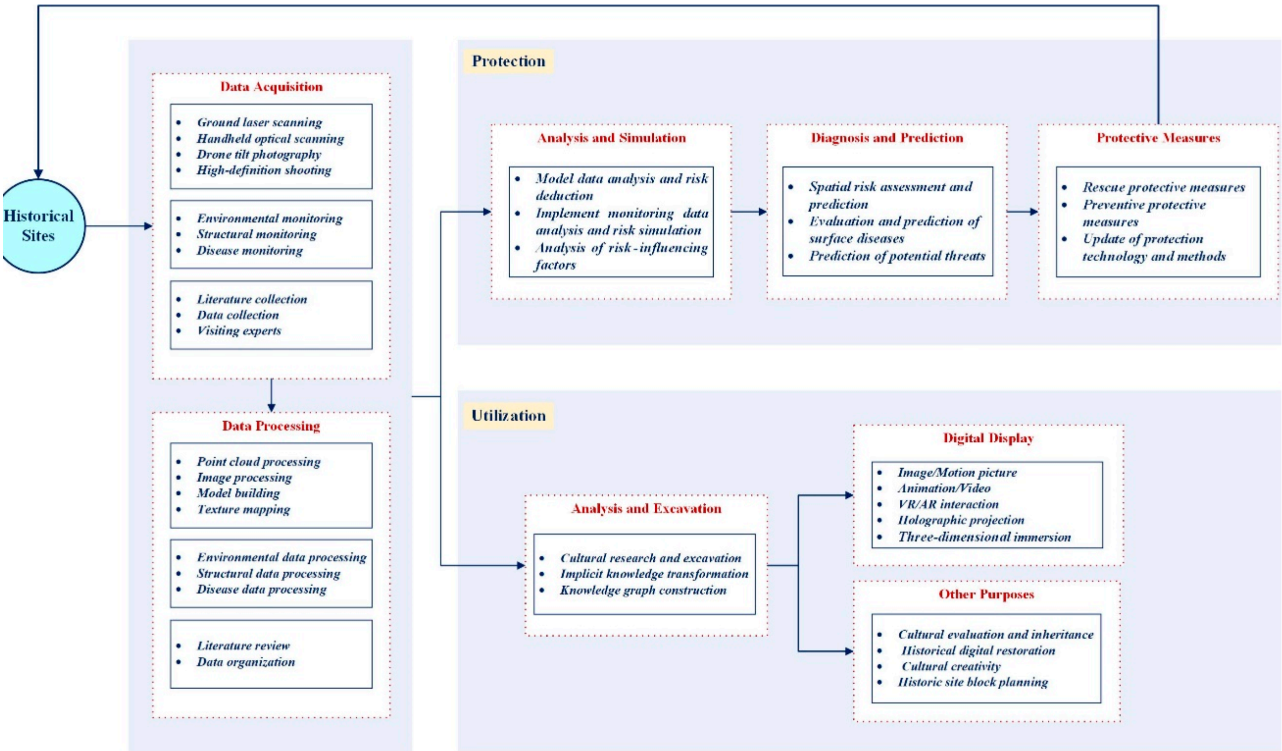


Figure 2. The digital twin technical process for historical sites.

2.2.1. Basic Work

This part outlines the basic work of the digital twin, and the goal is obtaining digital information about the physical entity of the historical site. It is divided into two phases: data collection and data processing.

The objects of the digital twin data collection in historical sites mainly include the site itself, scattered funerary objects in museums, and relevant literature materials. In particular, the site itself not only needs digital collection but also real-time monitoring.

The spatial information of the site itself is mainly obtained using TLS to generate point clouds with 3D coordinates, color information, and echo intensity. For the funerary objects and the detailed part of the site, handheld scanners can be used for fine scanning with at least 0.1 mm accuracy. The surrounding environmental information of the historic site is obtained using UAV photogrammetry, which directly generates a textured 3D model with sharply expressed spatial location and geographical environment. The surface textural information of the site itself and burial objects is obtained by means of high-definition photography.

Real-time monitoring data are mainly used for the protection of the site itself, the timely identification of risks, and the improvement of protection measures, such as the environmental monitoring of the temperature, humidity, etc.

2.2.2. Protection

The main objective of the protection process is to protect historical sites by creating a digital twin implemented in three stages: analysis and simulation, diagnosis and prediction, and protection measures.

Firstly, in the analysis and simulation stage, a statistical analysis is conducted on the temperature, humidity, color, atmosphere, etc., obtained from the physical entities of the site. It is necessary to analyze the influencing factors of site protection, construct simulation models to simulate potential risks, analyze model data and derive risks, implement monitoring data analysis and simulation risks, and analyze risk-influencing factors.

Secondly, in the diagnosis and prediction stage, based on simulation data, risk factors such as temperature, humidity, and color in the site space are evaluated and predicted. This stage also evaluates and predicts potential surface disasters such as earthquakes, floods, and wind disasters that may occur at the site, as well as potential threats.

Finally, during the protection measures stage, based on the simulation analysis, diagnosis, and prediction results mentioned above, the rescue and protection measures, preventive protection measures, and protection techniques and methods of historical sites are devised.

2.2.3. Utilization

The utilization of digital twins in historical sites refers to fully utilizing the data to activate the utilization of historical sites, which mainly involves digital twin services, the twin data center, and virtual entities. The potential information on historical sites is excavated via analysis, and then it is used for the digital display, digital restoration, planning, and development of historical sites.

Analysis and mining are the foundation of digital utilization, and there are multiple ways to utilize digital twins to explore the potential information of historical sites. In this study, the deformation and surface changes of historical sites can be detected from point clouds, such as changes in building surfaces indicated by rebuilt point clouds [24]. They also transform professional vocabulary into public language through knowledge visualization, such as depicting the protection and utilization of architectural sites based on knowledge visualization [25]. It is also possible to construct knowledge maps, such as knowledge maps of cultural relics, to connect seemingly unrelated information [26].

By using digital media technologies such as animation, VR/AR, etc., the digital twin data can be presented digitally, effectively expressing abstract professional knowledge through visualization. The complex and profound cultural knowledge of historical sites is disseminated in a simple and understandable way, enabling cultural inheritance. In this study, these are mainly digital displays such as image/motion picture, animation/video, VR/AR interaction, holographic projection, 3D immersion, etc.

In addition, utilization includes cultural evaluation and inheritance, historical digital restoration, cultural creativity, historic site block planning, etc. In the digital restoration of historical sites especially, as many historical sites no longer exist in the real world, scientific judgments are made based on the literature to restore the original appearance of the sites in the virtual world, such as the digital restoration of the Old Summer Palace in China [27].

2.3. Method Validation

The effectiveness of this method is mainly reflected in the role of digital twin systems in the protection and utilization of historical sites, as shown in Figure 3.

2.3.1. Protection

After establishing the digital twin system, there is a protection module in the digital twin service for protection. It protects historical sites from two aspects: phased information protection and real-time monitoring protection.

Periodic information protection regularly generates digital protection data of historical sites through 3D scanning, photogrammetry, model construction, etc., and stores them in the twin data center. This cycle can be six months, one year, or several years, recording the geometric and texture information of historical sites from different periods. These data can not only permanently preserve the site information, but also be used for activation and utilization.

Real-time monitoring protection dynamically obtains real-time data through temperature and humidity sensors in the physical entities of the site, simulates and predicts risks, and provides scientific evidence for proposing protection measures. By comparing predicted risks with actual risks, or implementing protective measures based on predicted risks, this determines the accuracy of risk prediction and the effectiveness of the method.

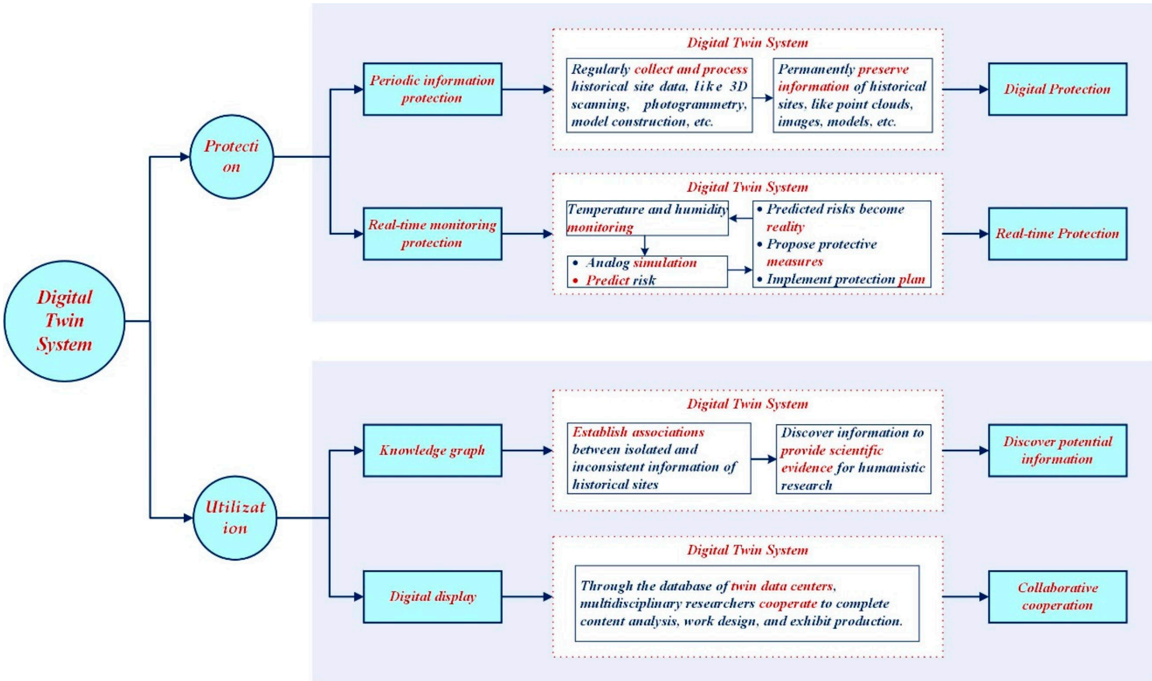


Figure 3. The digital twin method validation for historical sites.

2.3.2. Utilization

The utilization of historical sites is the re-development and re-excavation of the basic data in digital twins, and the discovery of new knowledge through the association of entity models and semantic information, so as to understand the culture of historical sites more deeply in essence. The utilization module in digital twin services realizes this function, mainly including a knowledge graph and digital display.

The knowledge graph, relying on the powerful data of twin digital centers, establishes associations and explores potential information for independent and inconsistent historical sites.

In digital display design, multidisciplinary researchers collaborate through databases in twin data centers to achieve content parsing, work design, and display production.

3. Case Study Introduction

In this case study, we investigated a historical site of the Northern Qi Dynasty (557–587 AD) in Taiyuan, Shanxi, China, because of the diversity and complexity of its historical sites with high symbolic and cultural value, as shown in Figure 4. These features make it a relevant case study for explaining and analyzing the results of digital twin.

Taiyuan is the capital city of Shanxi Province in China, with an area of about 7000 km^2 and a population of 5.4 million. It is the political, economic, cultural, and international exchange center of Shanxi. Taiyuan is a national historical and cultural city, an ancient city with a history of more than 2000 years. In 557–587 AD, Taiyuan was the alternate capital of the Northern Qi Dynasty, which was also important for commercial exchanges and cultural integration. World economic and cultural exchanges were unprecedentedly prosperous, with envoys and merchants from various Asian and Mediterranean countries gathering [28]. Foreign religious ideas and cultural arts were widely absorbed, greatly enriching China's traditional culture and art [29]. In an era of great ethnic and cultural integration, a rich historical and cultural heritage was left behind, such as the Xuxianxiu Tomb, Lourui Tomb, Tongzi Temple, etc. However, due to natural or human factors, most of the sites are not completely preserved, and the original history cannot be completely presented.

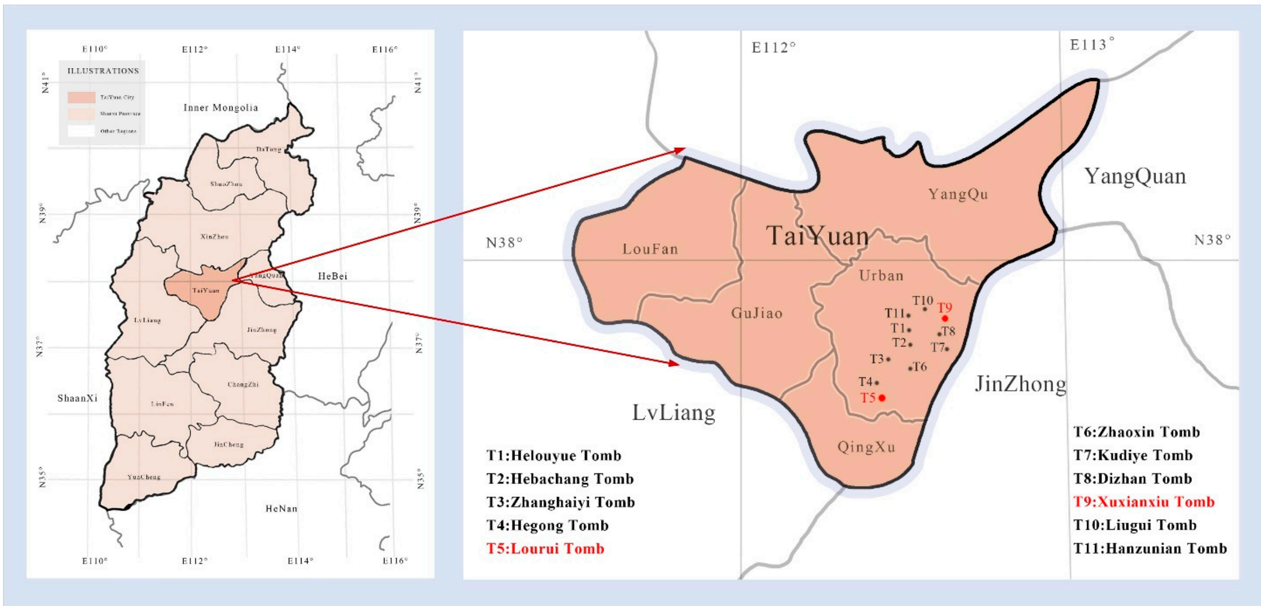


Figure 4. The historical sites of the Northern Qi Dynasty in Taiyuan.

3.1. Xuxianxiu Tomb

The Xuxianxiu Tomb, the only original protected historical site in China, is located in Wangjiafeng Village in the southeast of Taiyuan City. It was one of the most representative historical sites and the best preserved mural tomb of the Northern Qi Dynasty (550 A.D–577 A.D), excavated in 2000 and rated among "China's Top Ten Archaeological Discoveries" in 2002, as shown in Figure 5a. In 2006, it was designated as a key cultural relic protection unit in China and is one of the few burial sites protected in its original location [30]. The owner of the tomb, Xuxianxiu, was the King of Wuan in the Northern Qi Dynasty. Therefore, it was a royal mural tomb with a grand scale and rich contents, a brick chamber tomb with a square surface facing south, dome-shaped brick coupons, and a single-room long slope. The tomb was composed of a corridor, tunnel, patio, and tomb, measuring 30 m long and 8.5 m deep. The 330 m^2 painted murals on the tomb wall are well preserved, magnificent, and spectacular, with vivid and realistic imagery, retaining their original color [31]. They were a masterpiece in the history of Chinese art, representing the highest level of painting at that time, and containing much historical and cultural information. In addition, there are more than 550 buried objects, including pottery figurines, porcelain, etc. [32]. At present, most of them are placed in the Shanxi Provincial Museum, Taiyuan Museum, and Shanxi Provincial Archaeological Institute. As shown in Figure 5b, the Xuxianxiu Tomb, under original protection, is located in the Taiyuan Northern Qi Dynasty Mural Museum.

Since its discovery, the Xuxianxiu Tomb has received much attention from academia and society. In particular, its protection concepts and practices have been highly recognized by experts and various sectors of society, such as protection during excavation, minimal intervention protection, environmental control protection, scientific monitoring and preventive protection, digital protection, and scientific protection of the original site. At present, it is the only mural tomb in China that has been scientifically protected through building a museum on its original site after archaeological excavation, and its digital protection and utilization have become a new focus of attention. Therefore, we conducted research on the digital protection and utilization of historical sites based on a digital twin and took the Xuxianxiu Tomb as a case study.


(**a**)

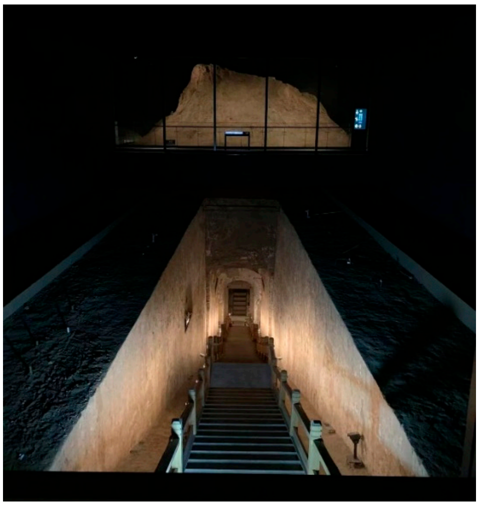

(**b**)

Figure 5. The historical sites of the Xuxianxiu Tomb. (**a**) Xuxianxiu Tomb site [30]. (**b**) Xuxianxiu Tomb under original site protection.

3.2. Lourui Tomb

The Lourui Tomb is located in the southwest of Wangguo Village, southwest of Taiyuan City, and was excavated in 1979, as shown in Figure 6a. It is another well-preserved mural tomb and a representative historical site of the Northern Qi Dynasty (550 A.D.–577 A.D.) [33]. The owner of the tomb, Lourui, was the Dongan King of the Northern Qi Dynasty. Therefore, it is a grand and rich royal tomb, consisting of a tomb passage, courtyard, corridor, and tomb chamber, over 22 m in length and over 12 m in depth. It is over 200 m^2 and contains 71 picture murals in the tomb, mainly distributed in the tomb passage and chamber. The content of the mural is a grand and colorful large scroll, depicting the magnificent scenes of the tomb owner's life before his death [34]. It can be regarded as a representative work of the Northern and Southern Dynasties period, filling a gap in the history of art. Due to the low-lying and humid terrain, the tomb murals have been exposed and are now preserved in the Northern Qi Dynasty Mural Museum, as shown in Figure 6b. In addition, there are over 870 funerary objects, including pottery figurines, porcelain, etc., which are the most excavated tomb artifacts of the Northern Qi Dynasty [35]. Most of them are stored in the Shanxi Provincial Museum, Taiyuan City Museum, and Shanxi Provincial Institute of Archaeology.


(**a**)


(**b**)

Figure 6. The historical sites of the Lourui Tomb. (**a**) Lourui Tomb site [33]. (**b**) The murals of the Lourui Tomb in the museum.

Since its discovery, the Lourui Tomb, like the Xuxianxiu Tomb, has received much attention from the academic community and society, not only focused on its painting, but also focused on research on the Northern Qi Dynasty culture. However, due to the backfilling of the Lourui Tomb and the distribution of funerary objects in various museums, research on it is restricted. Therefore, we researched the digital protection and utilization of historical relics based on a digital twin and used the Lourui Tomb as an example for digital restoration and VR/AR display.

4. Results

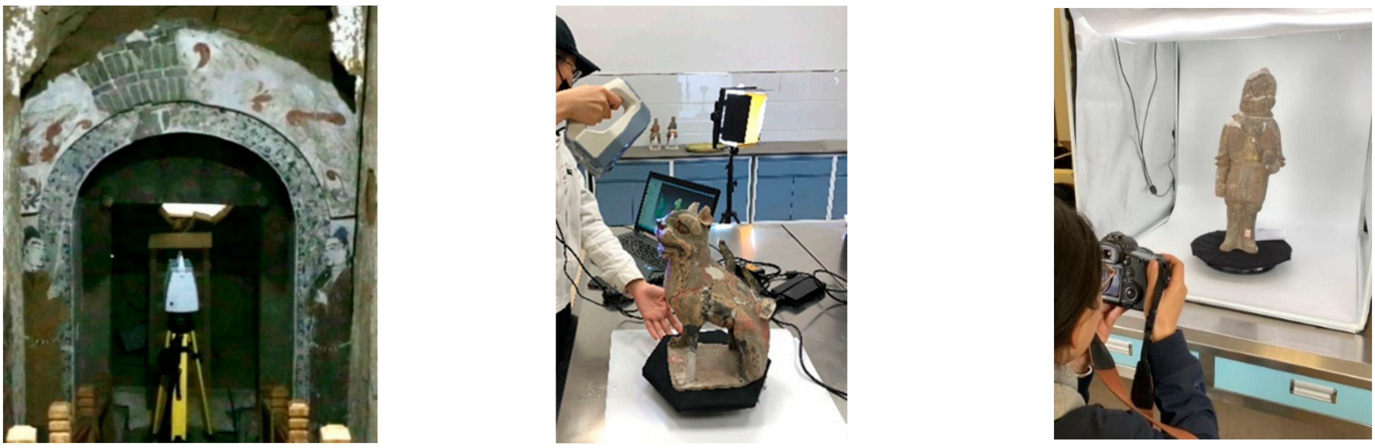
Based on the above methods, the Xuxianxiu Tomb and Lourui Tomb of the Northern Qi Dynasty were chosen as examples for research regarding the digital protection and utilization of a historic site.

4.1. Basic Work

4.1.1. Data Acquisition

The digital twin objects of historical sites mainly include the site itself, scattered funerary objects in museums, and relevant literature materials. The site itself not only needs digital collection but also real-time monitoring.

There are three main types of data acquisition for historical sites. Firstly, the data collection of the original protection site was conducted through three-dimensional scanning and high-definition shooting, as shown in Figure 6 for the Xuxianxiu Tomb data collection. The spatial point cloud information of the site was obtained using a Leica C10 (Wetzlar, Germany), and the spatial texture image information of the site was obtained by taking photos, as shown in Figure 7a. The excavation information, site space, and historical information of the sites that have been backfilled, such as the Lourui Tomb and Hanzumian Tomb, were obtained through archaeological excavation reports or briefs and other documents. Third, the funerary objects were scattered in the Shanxi Museum, Taiyuan Museum, etc. Information was obtained through handheld scanning or photographing, as shown in Figure 7b,c.



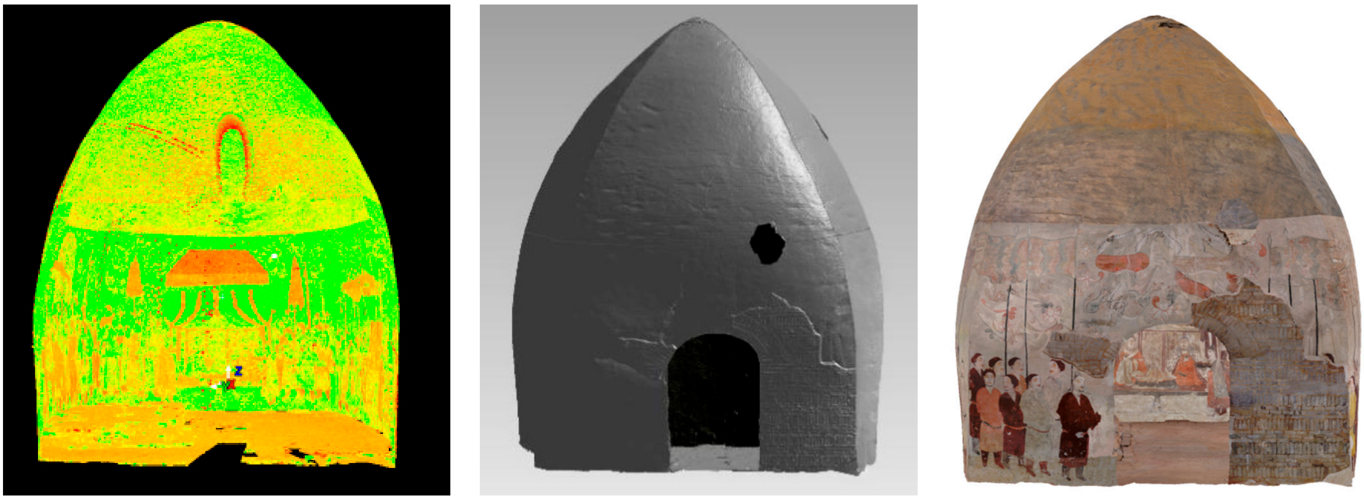
(**a**) (**b**) (**c**)

Figure 7. Data collection. (**a**) Terrestrial laser scanning. (**b**) Handheld scanning. (**c**) UAV photogrammetry.

4.1.2. Data Processing

Data processing focuses on the processing of point clouds, images, and models.

The point cloud accurately records the three-dimensional spatial information of historical sites, which is opened in the scanner. In our research, we mainly focused on the site protection of the Xuxianxiu Tomb and the 3D geometric information of the funeral wares. There are two types of point cloud data: one is the original data, which can be opened in Leica and Artec, and the other is the point cloud after drying, registration, fusion, and other processing. General point cloud formats include .dxf, .pcd, and so on. Figure 8a is the point cloud of the Xuxianxiu Tomb site. The image records the texture information of the surface of the site, such as the murals. The formats are not only .jpg, .png, etc., but also .raw records containing the metadata of the original information of the image.



(**a**) (**b**) (**c**)

Figure 8. Data processing. (**a**) Point cloud. (**b**) Triangular mesh model. (**c**) Textured 3D model.

The three-dimensional model is a triangular mesh model generated from the point cloud, which more intuitively reflects the geometric information of the site but has no texture information, also known as the prime model, as shown in Figure 8b. When the image of the corresponding position is mapped onto the model, the triangular mesh model becomes a model with texture. At this time, the three-dimensional model not only includes geometric information but also texture information, as shown in Figure 8c.

4.2. Protection

The biggest difficulty in in situ protection of historical sites is the protection process. The complex environment and high difficulty result in a very small number of sites suitable for in situ protection. The Xuxianxiu tomb in Taiyuan is the only site-protected burial site in Shanxi Province. In the protection of the Xuxianxiu tomb site, the digital twin was used to realize the real-time monitoring of the site. In the virtual entity, the risk was predicted through simulation, to propose and adjust the protection measures of the site.

As shown in Figure 9, observation points were set at the entrance, tuyere, corner, and other key positions of the site, thermometers and hygrometers were placed to record temperature and humidity in real time, and mural images were taken every quarter for image color detection. The data were fed into the total analysis model to predict risks and propose protective measures. We found that the temperature fluctuation of the tomb chamber was more obvious than that of the tomb passage. The relative humidity of the tomb passage fluctuated most sharply, but the environment of the tomb chamber tended to be stable. During the rainy season, the humidity inside the site tends to increase. When the external temperature is extremely cold or hot, the internal temperature is easily affected. Therefore, the addition of drainage ditches around the site along with pumping and exhaust equipment, and the opening in summer precipitation are conducive to the internal ventilation of the tomb chamber. The reduction in the internal humidity of the tomb by means of air conditioning equipment, reducing hot air pressure and the heat and humidity exchange inside and outside the tomb driven by the humidity difference, caused temperature and humidity fluctuations.

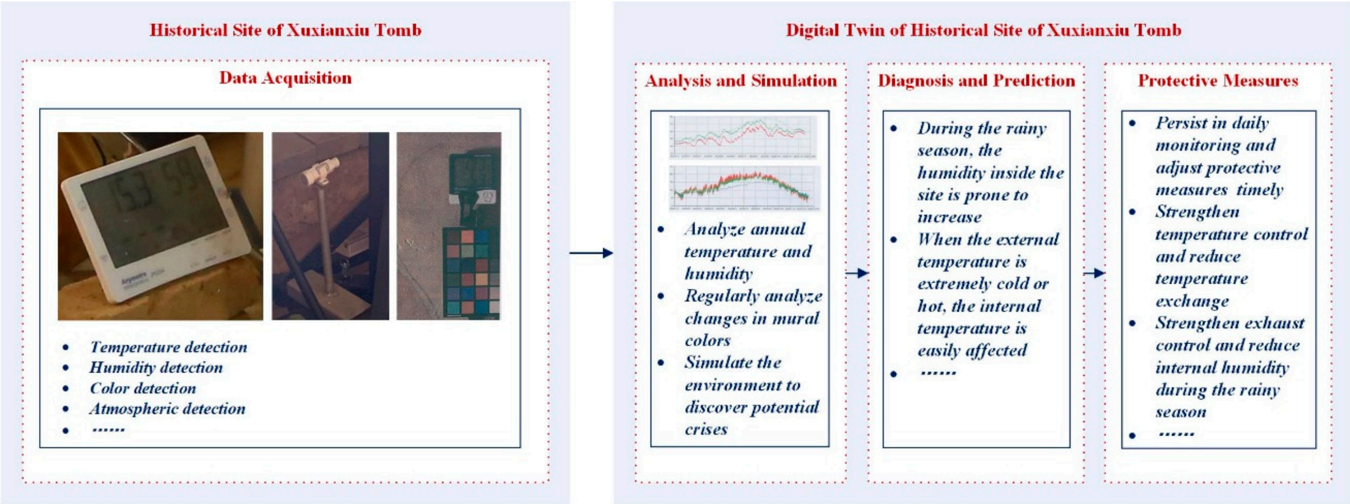


Figure 9. The protection of the Xuxianxiu Tomb based on digital twin.

4.3. Utilization

There are two main forms of digital utilization. One is the knowledge graph, which establishes connections among all the elements of historical sites. The second is the digital display, which presents historical sites through video, animation, VR/AR, etc., and disseminates culture to the public.

4.3.1. Knowledge Graph

The historical sites of the Northern Qi Dynasty in Taiyuan contain many murals and funerary objects; highly valued for their history, art, and social significance, the various historical sites contain complex relationships. Therefore, in the digital twin model, various types of data from the historical sites are linked through knowledge maps. Taking the Taiyuan Northern Qi historical sites as the main thread, we can connect various cultural elements such as the site, murals, and funerary objects, transforming scattered and unstructured historical site information into structured knowledge and presenting it in the form of graphs. When we use knowledge graph multimodal data to achieve a multi-channel display of historical sites, the public can quickly and inexpensively obtain a deeper knowledge of historical sites by touching three-dimensional models of cultural relics, watching videos and images, listening to audio and sound testing, etc. It is possible to obtain undiscovered and hidden knowledge based on semantic reasoning, break down information silos in exhibitions, and use non-linear, hypertext, and even information clouds to allow audiences to see both "trees" and "forests".

By normalizing the knowledge classification, conceptual system, data property, and the relationships between aspects within the site, we can discover potential information about the site through the knowledge map, and the knowledge structure can be identified. Hence, it is suitable for knowledge sharing and reuse and provides a good solution for the protection and inheritance of the site. In this case, to build the knowledge map of the Northern Qi Dynasty's historical sites, we used Protégé software (5.5.0), an ontology editing software developed by Stanford University using Java [36]. The map was constructed by combining the site knowledge, designing and constructing an ontology, instantiating the ontology, and other steps. The specific steps were as follows.

First of all, the information on historical sites was sorted and classified. It mainly included basic information, spatial structure, murals, and funerary objects.

Secondly, the ontology of knowledge graphs was designed, as well as the core class hierarchy and core property. The core class hierarchy included basic information, spatial structure, and mural and funerary objects. The core property included the data property and object property.

Thirdly, the ontology was constructed in Protégé. Classes and subclasses were added. For example, the subclass of "basic case" includes person, time, and place; the spatial structure includes the tomb passage, through-hole, raised rock hole, corridor, coffin chamber, etc. Funerary objects include tomb-suppressing and evil-warding objects, shown in Figure 10a. Then, the data property hierarchy was added, incorporating profile, gender, etc., as seen in Figure 10b. The object properties, such as where they were excavated from, time, and other properties, were added (Figure 10c).

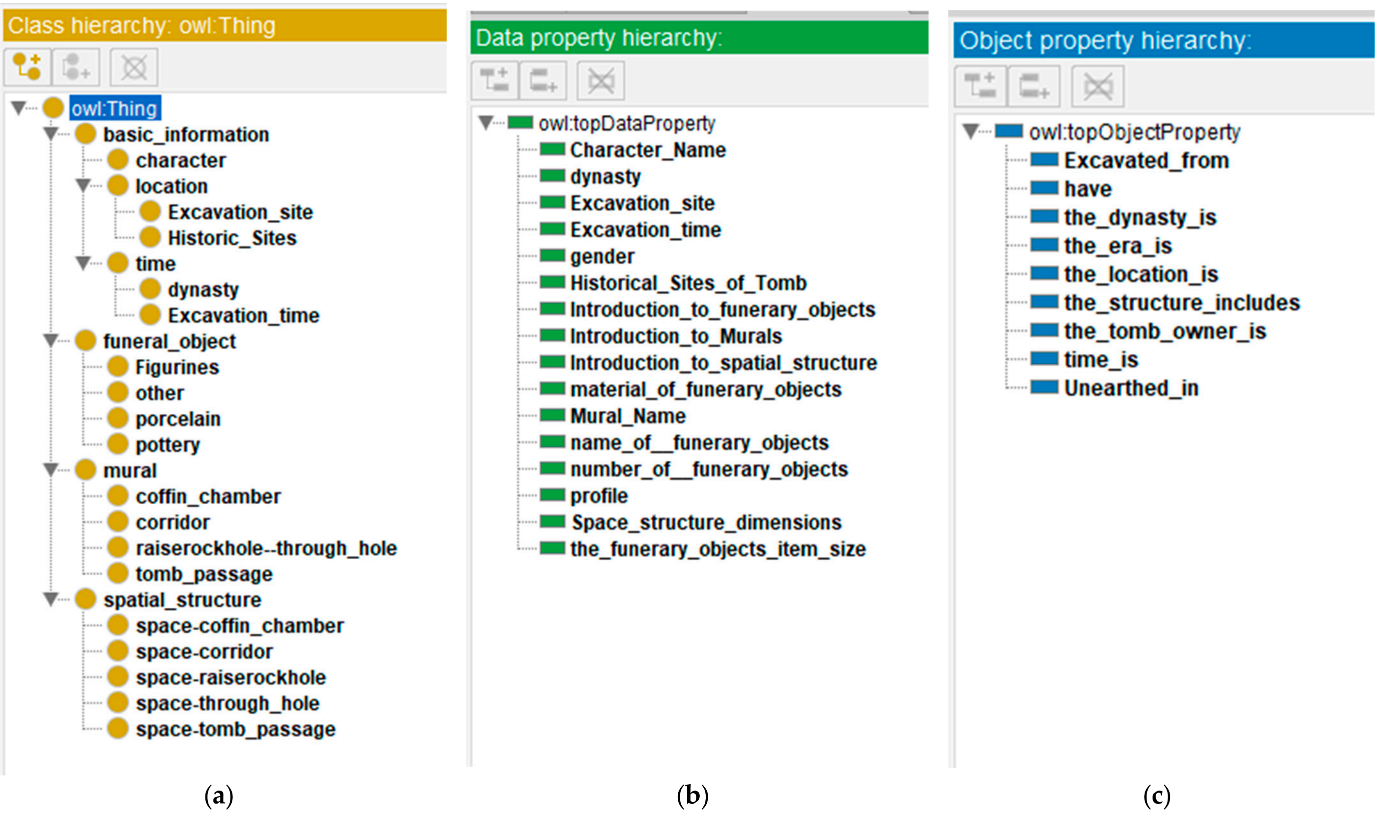


Figure 10. The construction of a knowledge graph of historical sites based on digital twin. (**a**) Class hierarchy. (**b**) Data property hierarchy. (**c**) Object property.

Fourthly, we added individuals from each category to the ontology model to generate knowledge maps of the historical sites in the Northern Qi Dynasty, as shown in Figure 11.

4.3.2. Digital Display

Historical sites contain a large number of murals, funerary objects, etc., with high cultural, artistic, and scientific value. In digital twins, using the digital twin data of historical sites and new media technologies such as video, animation, and virtual reality, the profound cultural information of the sites can be digitally displayed and disseminated to transmit traditional culture. The main display methods include animation, video, VR/AR, graphics, images, etc.

In the digital twin system, the design process of the digital display is different from the previous method. As all data are placed in the database of the twin data center, designers from different disciplines only need to retrieve the data in the database to obtain preliminary research results and complete their work. As shown in Figure 12, the design is divided into three phases. Firstly, in data collection and processing, the digital protection of historical sites is carried out by archaeology and surveying researchers. Secondly, in cultural analysis, researchers from history, sociology, art, and anthropology analyze the space, murals, funerary objects, etc., of the site based on models, images, documents, and other data, forming the historical data, the humanities data, etc. In the third stage, designers carry out the design and production based on all the previous results, such as images, models, history, and culture. Technical issues such as VR/AR require the assistance of computer personnel. The entire process involves multidisciplinary personnel working together, connected mainly through data centers. In addition, the data in the twin data center can be used as design materials for multiple related digital works, which greatly improves the efficiency of digital work creation.

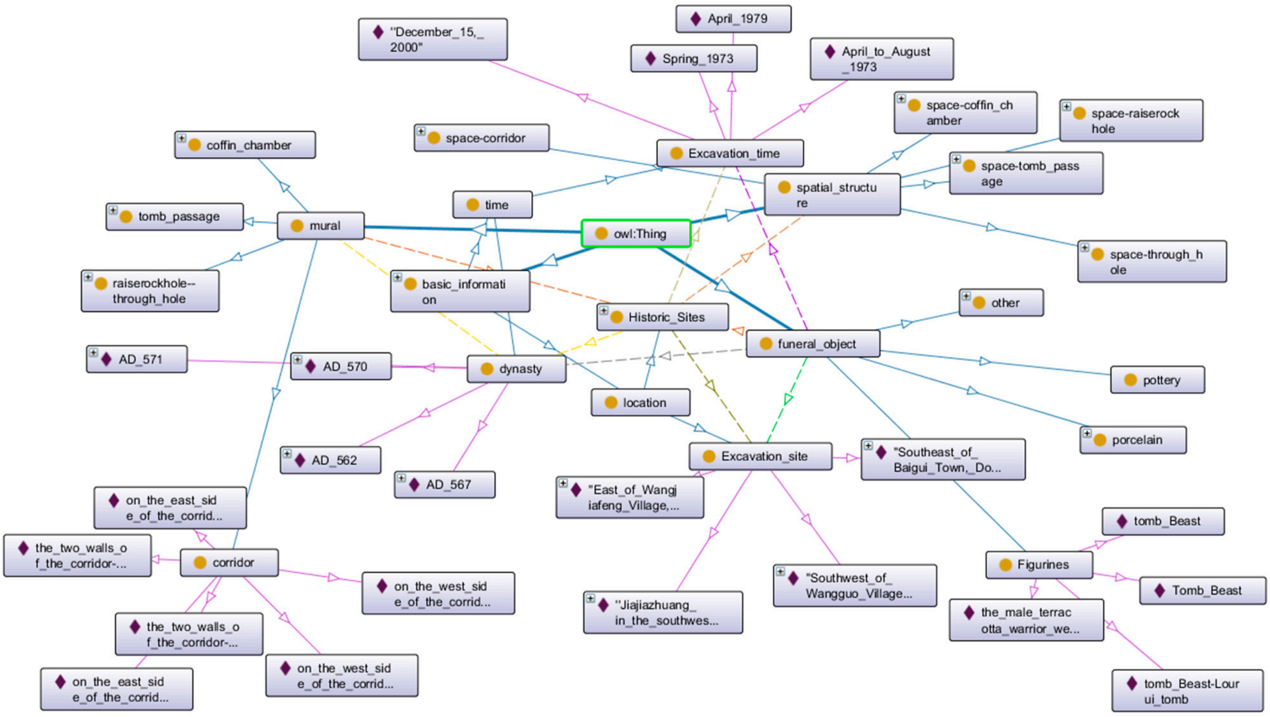


Figure 11. The knowledge graph of the historical sites of the Northern Qi Dynasty in Taiyuan based on digital twin.

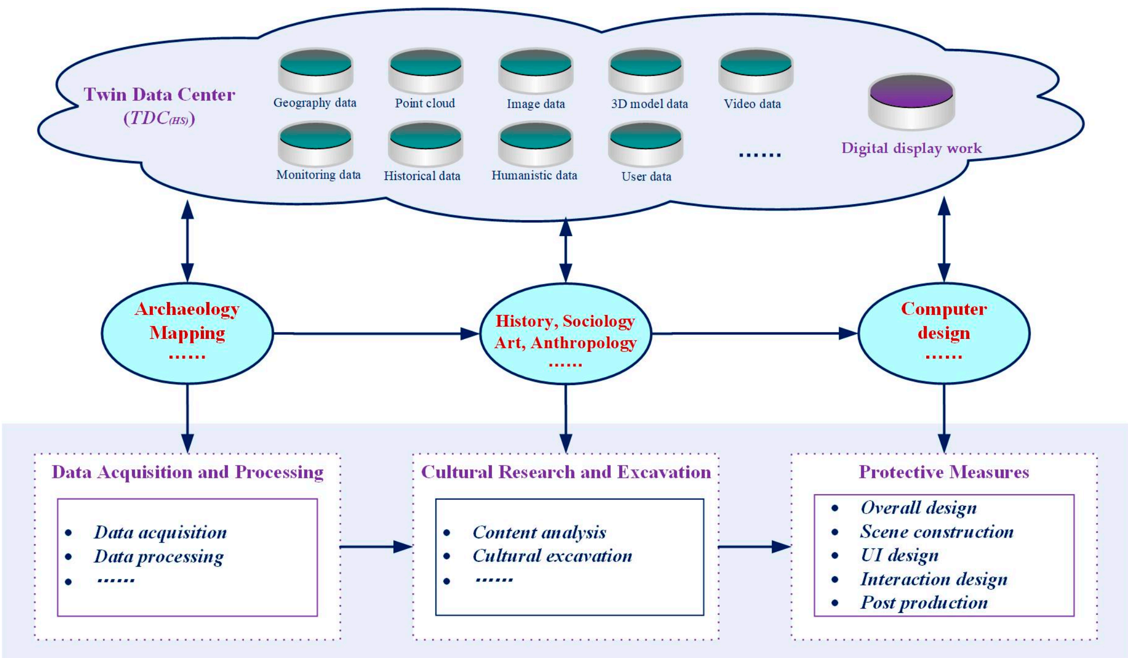


Figure 12. The design process of the digital display based on digital twin.

For the digital restoration of the historical sites that have disappeared, the virtual reality display is the best, allowing people to experience the original appearance of the historical sites. For the Lourui Tomb site, we used digital technology to restore it based on historical data. Based on the digital restoration model and PICO VR glasses, we displayed the ruins of the Lourui Tomb virtually with Unity3D. Experiencers only need to wear VR glasses and shake hands to "walk" in the space of the Lourui Tomb site, "touch" any part of it, and look at murals, funerary objects, etc. They can observe and study as if they were traveling back more than 1000 years. This combination of VR technology and culture breaks the limitations of time and space, enabling the public to visit anytime and anywhere immersively, enhancing the user experience. As shown in Figure 13a, this is the VR interactive experience of the Lourui Tomb.

(**a**) (**b**)

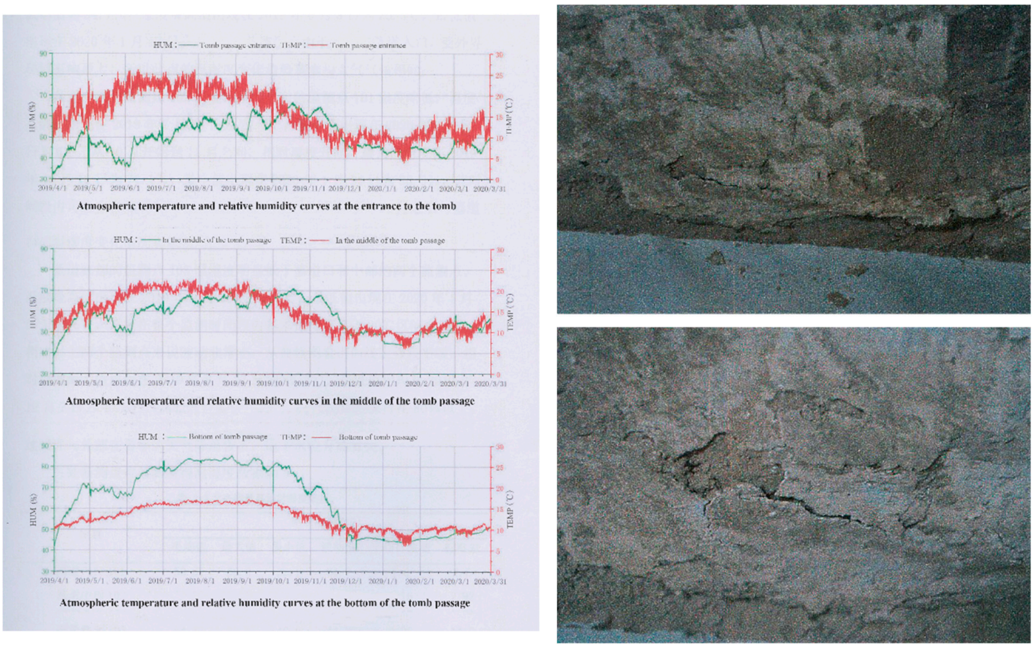
Figure 13. Digital display of the Lourui Tomb. (**a**) VR interaction. (**b**) AR interaction.

AR interaction is another type of interactive display, which uses a mobile app to display 3D models of sites and funerary objects, allowing users to intuitively understand information about historical sites. As shown in Figure 13b, when scanning images of funerary objects, a 3D model of the site appears, and users can freely view the structure, decoration, and other information about the objects by sliding, rotating, and moving the model on the screen. AR makes the display more convenient, autonomous, and experiential.

5. Discussion

This approach emphasizes the process of preserving and utilizing historical sites through digital twins. Through digital twins, the historical site information of the real world is mapped to the virtual world, providing support for preventive protection and cultural transmission, and facilitating interdisciplinary collaboration. In practice, it was found that this method has certain advantages in protection and utilization.

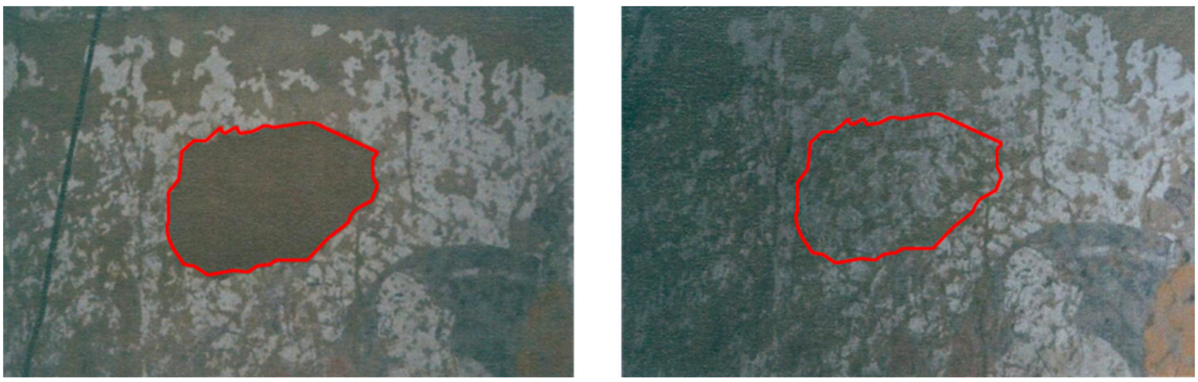
In the case of the Northern Qi Dynasty historical sites in Taiyuan, a five-dimensional digital twin system was established to form the hierarchical research on protection and utilization. By collecting a large number of monitoring data and protection cases, the system can simulate and predict possible risks based on the current monitoring data and give protection suggestions. For example, in Figure 14a, through an analysis of the temperature and humidity monitoring data at the entrance, middle, and bottom of the Xuxianxiu tomb passage in the digital twin system, the change trend of monitoring temperature and humidity was found to be greatly affected by the external environment. Due to the rainy season, the humidity at the entrance and bottom of the tomb remains high, which easily causes plaster disruption, flaking, detachment, and other symptoms. Figure 14b shows the symptoms of plaster disruption, flaking, and detachment found at the bottom of the east and west walls of the tomb passage, consistent with the mural symptom warning issued by the system.



(**a**) (**b**)

Figure 14. Monitoring and protection of the Xuxianxiu Tomb. (**a**) Monitoring of temperature and humidity. (**b**) Symptoms of plaster disruption, flaking, and detachment.

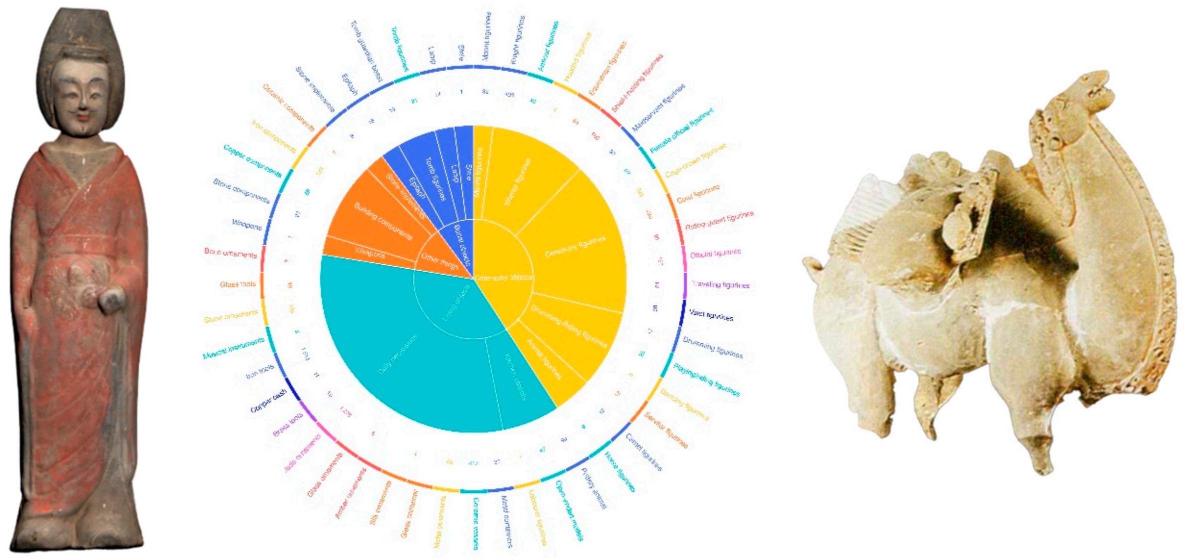
In 2021, we relied on the temperature and humidity monitoring data from 2018 to 2020 to conduct risk assessment simulation calculations on the site, predict risks, and put forward corresponding protection suggestions. We implemented a fully enclosed, constant temperature and humidity protection system for the Xuxianxiu Tomb site, with a temperature of 15–16° and a humidity of 55–60%. More than a year after the adjustment, the temperature and humidity of the ruins were still controlled and monitored. The preservation results of the ruins' space and murals were good, and no hollowing, crispness, or cracking occurred again. As shown in Figure 15a, a mural on the east wall of the tomb passage suffered from hollowing and fell off due to alkali damage in 2019. Figure 15b shows that after restoration, protective measures were taken to maintain the effect to this day.



(**a**) (**b**)

Figure 15. Protection of the Xuxianxiu Tomb. (**a**) Caustic alkali and hollowing diseases before repair. (**b**) No disease after repair.

In addition, the knowledge graph constructed from digital twin data brought us a significant amount of information. Taking the funerary objects of historical sites as an example, due to the different excavation times of historical sites, some of which were nearly 30 years apart, they are all stored in different museum warehouses and recorded in different ways. For example, the Lourui Tomb was excavated in 1979, and the Xuxianxiu Tomb was excavated in 2003, and their funerary objects were stored in different museums. As a result, it was difficult for us to determine the correlation between different artifacts, and it was also difficult to explore the information behind them. However, all funerary objects can be identified and mapped through digital twins, and we can discover much hidden information. For example, we were pleasantly surprised to find that the "Cage-crown figurine" from the Xuxianxiu Tomb and the " Maidservant figurine" from the Lourui Tomb were exactly the same in shape, color, texture, and size material and were fired in the same kiln, as shown in Figure 16a. In addition, we found some regular features. For example, in Figure 16b, which depicts a sunburst chart of funerary objects, ceremonial objects are the most common, accounting for 53%, and burial objects are the least common, accounting for 3%. Among the caravans, there are already more camel figurines and fewer horse figurines in the western regions, indicating that multi-ethnic integration had become very prosperous. A camel figurine from the Hanzunian Tomb is shown in Figure 16c. The discovery of numerous potential sources of information provides a scientific basis for research in history, sociology, religion, and philosophy.



(**a**) (**b**) (**c**)

Figure 16. Discovery of potential information. (**a**) The same figurine from the Xuxianxiu Tomb and Lourui Tomb. (**b**) Sunburst chart of funerary objects. (**c**) Camel figurine from the Hazunian Tomb.

However, this method still lacks many functions. In protection, we have only achieved simulation and the prediction of risks, whereas how to use digital twins to repair damaged historical sites has not yet been achieved. In utilization, we have only implemented knowledge graphs and digital displays, while other areas such as planning and development, cultural and creative design, etc., need to be implemented. In addition, this method has limitations. For example, we have only achieved text recognition but not image recognition, so the knowledge graph can express the physical characteristics of funerary objects, but it is difficult to describe their symbolic characteristics and environmental characteristics. This will inhibit them from becoming integrated into an overall scheme in the correlation comparison [37]. The image features of objects can only be compared based on textual descriptions, such as image elements in murals and decorative elements in utensils. Therefore, in future research, more functions and more effective methods need to be researched and developed.

6. Conclusions

Current methods of historic heritage conservation and utilization lag far behind advances in digital technology, and this study provides an innovative approach to the digital preservation and utilization of historic sites. Through the digital twin method, it realizes the preservation and utilization of historical sites from three aspects. Firstly, the simulation and prediction of historical sites are realized in the data twin virtual entity. Secondly, in digital twin, knowledge maps are constructed to mine potential connections between sites that appear to be unrelated on the surface. Finally, through digital twin, historical sites that have disappeared can also be restored and displayed through VR/AR and other technologies, and multidisciplinary researchers can collaborate efficiently to create digital display works.

By investigating the historical sites of the Northern Qi Dynasty in Taiyuan, Shanxi, the method was further applied to the protection of historical sites. The results show that the digital twin method is effective. It can also be applied to different types of cultural heritage. These digital achievements can be widely disseminated through websites, mobile phones, and museums and galleries.

In the future, we will further improve this method in terms of interactive display, simulation, digital repair, cultural mining, pattern recognition, etc. We will also survey more historical sites to form a giant digital twin system that integrates site protection and cultural inheritance. In addition, AI has grown, and we can also integrate it into our innovation research, which is an important task for our future work.

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Data Availability Statement: All the data that support the findings of this study are available from the corresponding author upon reasonable request.

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