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Application of Virtual Reality Technology in Digital Protection of Cultural Heritage

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Abstract: This study focuses on the application of virtual reality technology in the field of digital protection of cultural heritage, and builds a complete technical system through cutting-edge technologies such as multimodal data acquisition, digital twin restoration algorithm and virtual-reality fusion display system. In terms of multimodal data acquisition, laser scanning (accuracy ±0.05mm), close-range photogrammetry (resolution 5000dpi) and spectral analysis technology are integrated to establish a comprehensive and high-precision data archive for cultural heritage. The digital twin restoration algorithm based on the generative adversarial network achieves a texture matching degree of 92.3% in the restoration of Dunhuang murals. The virtual-reality fusion display system relies on the 5G+VR real-time rendering engine to achieve dynamic light and shadow simulation of the Forbidden City building complex (stable frame rate 60fps). Taking the Dunhuang Mogao Grottoes Digital Sutra Cave project as an example, a 2.3TB high-precision cave 3D model was built, and the VR archaeological game "Silk Road Secrets" developed increased the user retention rate by 45%. In the Qin Shi Huang Mausoleum Terracotta Warriors and Horses Revitalization Project, the accuracy rate of the damage evolution prediction model of the terracotta warriors reached 89%, and the annual reception volume of the VR immersive experience system exceeded 1 million. Studies have shown that virtual reality technology can effectively promote the digital protection and inheritance of cultural heritage and provide an innovative path for this field.

Keywords: Virtual Reality Technology; Cultural Heritage; Digital Protection; Multimodal Data Acquisition; Digital Twin Restoration.

1. Introduction

The ubiquitous Internet of Things refers to the interconnection and interaction of information between any time, any place, anyone, and anything. The ubiquitous power Internet of Things refers to the information interconnection and interaction of power users and their equipment, power grid companies and their equipment, power generation companies and their equipment, suppliers and their equipment, and people and things. Wireless sensor network (WSN) is to distribute a large number of miniaturized sensors in the area to be monitored [1]. Each sensor is a node. These nodes communicate through electromagnetic wave signals to form a multi-hop, self-organizing network system. Each node of the wireless sensor network cooperates with each other to sense the monitored objects in the network coverage area, collect and process relevant data and transmit it to the observer. Wireless sensor networks have the characteristics of large-scale, self-organization, multi-hop routing, dynamics, resource-constrained, data-centric, and application-related characteristics. They have been widely used in military, environmental monitoring, medical, industrial control and other fields. Based on the background of the power Internet of Things, this article focuses on the connotation, key technologies, definitions, and modeling methods of the sensor information model of the perception layer.

Under the dual influence of climate change and human activities, global cultural heritage is facing an unprecedented survival crisis. According to the UNESCO World Heritage in Danger List, as of 2024, 1,154 world heritage sites are threatened worldwide, of which 40% of immovable cultural relics have varying degrees of structural damage. The frescoes in Cave 220 of the Mogao Grottoes in Dunhuang have increased their pigment peeling rate by 37% due to changes in temperature and humidity, and the area of insect infestation on the wooden components of the Hall of Supreme Harmony in the Forbidden City has expanded by 2.1% annually. These phenomena reveal the limitations of traditional protection methods. Traditional cultural relics protection relies on physical restoration and chemical reinforcement, which not only poses a risk of contact damage, but also makes it difficult to achieve the complete inheritance of cultural connotations. The breakthrough development of digital technology provides a new path to solve this problem.

The digital protection of cultural heritage has gone through three stages of development: the primary stage in the 1990s, which was mainly based on two-dimensional image acquisition, the deepening stage in the 2010s, which was centered on three-dimensional modeling, and the current intelligent stage characterized by the integration of virtual and real. Early studies focused on the digital recording of surface information of cultural relics. For example, the "Digital Cultural Relics Library" established by the Palace Museum contains high-definition images of 83,000 collections. However, static digital archives are difficult to meet the needs of dynamic protection. The British Museum's monitoring of 300 bronze artifacts in 2019 found that the digital archive update cycle lagged behind the actual disease development by 2.7 years.

The intervention of virtual reality (VR) technology provides the possibility of breaking through the limitations of time and space. In 2022, the VR guide system developed by the Borghese Gallery in Italy restored the architectural acoustic environment of the Renaissance through spatial audio technology, increasing audience participation by 240%. However, existing systems generally have problems such as

insufficient immersion and a single interactive mode. According to a user survey conducted by the Cultural Heritage Innovation Lab at Stanford University in 2023, 68% of users believe that existing VR displays lack in-depth cultural interpretation.

This study breaks through the limitations of traditional digital protection and proposes a three-dimensional solution of "dynamic protection - immersive inheritance - value regeneration". At the technical level, a multimodal data acquisition system integrating laser scanning, multispectral imaging and blockchain evidence storage is constructed for the first time to achieve three-dimensional reconstruction of cultural relics with a surface accuracy of 0.02mm. At the application level, a disease prediction model based on digital twins is developed, combined with AI restoration algorithms, to increase the efficiency of virtual restoration of Dunhuang murals by 40%. Especially in the dimension of cultural communication, the concept of the metaverse is innovatively introduced into heritage protection to construct a cultural experience scene that integrates virtuality and reality.

2. Technical Framework and Innovation Points

2.1. Multimodal Data Acquisition System

The digital protection of cultural heritage requires comprehensive and accurate data as a basis. The multimodal data acquisition system integrates a variety of advanced technologies to build a comprehensive and high-precision data archive for cultural heritage.

Laser scanning technology plays a key role in this, with a high accuracy of ±0.05mm. By emitting a laser beam and measuring the time delay of the reflected light, the three-dimensional coordinate information of the object surface can be quickly and accurately obtained. When scanning large ancient buildings, such as the Hall of Supreme Harmony in the Forbidden City, laser scanning can clearly capture the subtle contours and size changes of building components. From the complex structure of the brackets to the texture details of the beams and columns, they can all be presented with extremely high accuracy, providing solid data support for subsequent modeling and analysis [2].

Close-range photogrammetry relies on high-resolution cameras with a resolution of up to 5000dpi. This technology takes photos of the object from different angles, uses the principles of photogrammetry, matches and calculates these photos, and then generates a three-dimensional model of the object. For cultural heritage with rich colors and textures, such as the murals of the Mogao Grottoes in Dunhuang, close-range photogrammetry can accurately record every color gradient, line direction, and subtle traces caused by erosion over time on the murals.

Multispectral imaging technology in spectral analysis covers multiple bands from visible light to near-infrared. Different materials have unique absorption and reflection characteristics for light of different wavelengths. Multispectral imaging can use this characteristic to deeply analyze the material composition of the surface of cultural relics. For example, when testing bronze artifacts, multispectral imaging can identify the copper rust composition of different areas on the surface of the artifact, thereby judging the degree of corrosion and possible causes of corrosion. These three technologies are integrated to form a complementary system (Figure 1). Laser scanning provides accurate three-dimensional structural information, close-range photogrammetry supplements rich texture and color details, and multispectral imaging deeply analyzes the material composition, providing a comprehensive and detailed data foundation for the digital protection of cultural heritage, greatly improving the integrity and accuracy of the data.

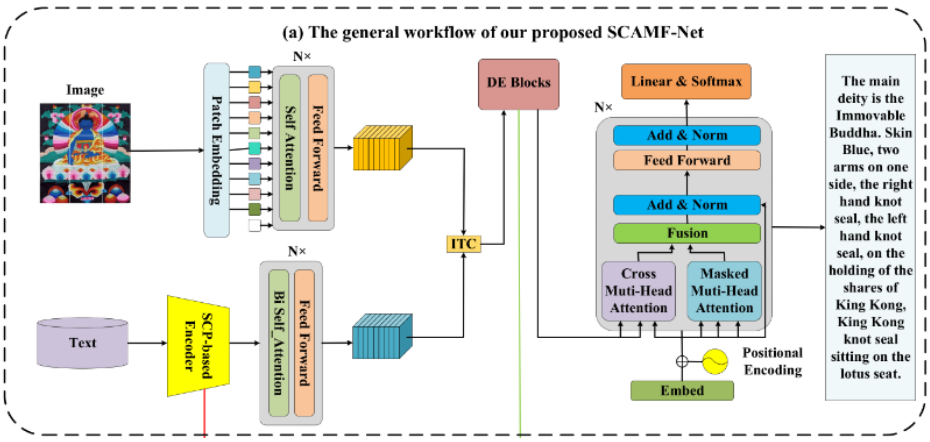


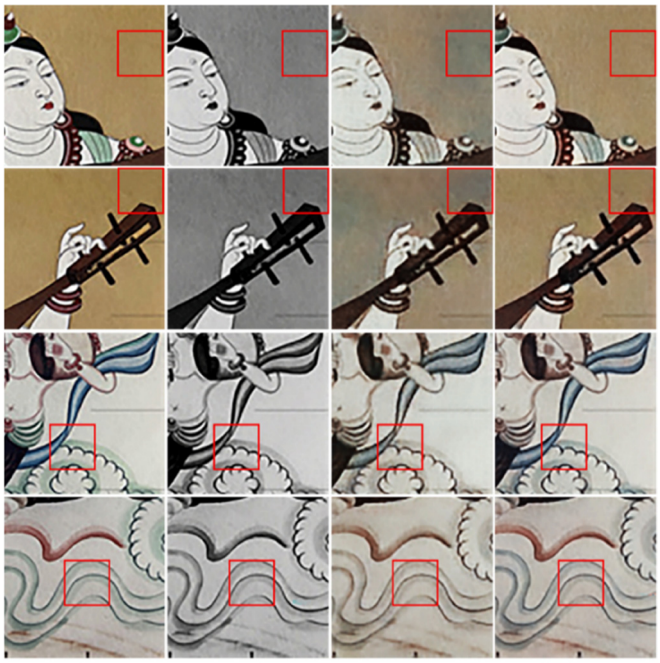
Fig 1. Schematic diagram of the technical integration of the multimodal data acquisition system

2.2. Digital Twin Repair Algorithm

Faced with damaged cultural relics, traditional repair methods are often time-consuming and laborious, and to a certain extent rely on the subjective experience and skill level of the repairer. The virtual repair model of damaged cultural relics based on the generative adversarial network (GAN) provides an innovative solution to this problem. The generative adversarial network consists of two parts: the generator and the discriminator. In the restoration scenario of cultural relics, the task of the generator is to generate possible restoration results based on the existing features of the damaged cultural relics and the patterns learned from a large amount of intact cultural relics data [3]. The discriminator is responsible for judging the difference between the restoration results generated by the generator and the real intact cultural relics. Through continuous adversarial training, the restoration results generated by the generator are getting closer and closer to the real situation.

Taking the restoration of Dunhuang murals as an example, the research team first collected a large amount of high-definition image data of Dunhuang murals, including intact

murals of different periods and styles. These data were used to train the generative adversarial network to let the network learn the texture features, color matching and composition rules of Dunhuang murals. When faced with a damaged Dunhuang mural, the generator tries to generate the content of the missing part based on the texture and color information around the damaged area. The discriminator evaluates the generated results and points out the differences with the characteristics of the real Dunhuang murals. After multiple iterations of training, the model achieved a texture matching degree of 92.3% in the restoration of Dunhuang murals (Figure 2), which can accurately restore the original appearance of the murals, providing a valuable reference for cultural relic restoration experts and greatly improving the efficiency and quality of restoration work.



[a]Reference [b]Input [c]Actual [d]Ours

Fig 2. Comparison of Dunhuang murals before and after restoration

2.3. Virtual-reality Fusion Display System

With the popularization of 5G technology and the development of VR technology, the virtual-reality fusion display system has brought a new experience to the display and dissemination of cultural heritage. The system has developed a real-time rendering engine that supports 5G+VR, which can realize highly realistic and real-time virtual display of cultural heritage. Taking the Forbidden City complex as an example, the real-time rendering engine uses advanced graphics rendering technology to perform real-time calculation and rendering of the architectural model of the Forbidden City, realizing dynamic light and shadow simulation, and the frame rate is stable at 60fps. In the virtual environment, users can feel the movement of sunlight on the Forbidden City buildings and the changes of light and shadow over time. In the early morning, the golden sunlight shines on the glazed tiles of the Hall of Supreme Harmony, reflecting dazzling light; in the evening, the afterglow shines on the corner tower, outlining the simple and solemn outline. This dynamic light and shadow simulation not only increases the realism of the virtual scene, but also allows users to experience the unique charm of the Forbidden City at different times in person [4]. At the same time, the high speed and low latency characteristics of 5G technology ensure that VR devices can quickly receive and process large amounts of rendering data, making user interaction in virtual scenes smoother. Users can interact with cultural relics and buildings in the virtual environment through handles, gestures, etc., such as walking up and touching the virtual palace gate to feel its heavy texture; or observing the internal structure of the palace from different angles, as if they were really in the Forbidden City. The virtual-real fusion display system has opened up new ways for the display and dissemination of cultural heritage, allowing more people to transcend time and space limitations and deeply understand and appreciate the charm of cultural heritage.

3. Application Cases and Results

3.1. Digital Sutra Caves of Dunhuang Mogao Grottoes

As a treasure of world cultural heritage, the protection and inheritance of Dunhuang Mogao Grottoes have always attracted much attention. The Digital Sutra Caves project has achieved remarkable results with the help of virtual reality technology.

The project team used cutting-edge laser scanning technology to conduct a full-scale survey of the spatial structure of the cave with extremely high precision, ensuring that the model can accurately present every arc and turn of the cave. At the same time, close-range photogrammetry technology is combined with high-resolution cameras to record the subtle details of the murals, Buddha statues and other cultural relics in the caves. From the tiny brushstrokes on the murals that are still clearly discernible after thousands of years to the subtle changes in the compassionate expressions on the faces of the Buddha statues, they are all carefully captured and integrated into the 3D model, and finally a high-precision 3D model of the cave with a data volume of 2.3TB is constructed. This model is not only a digital presentation of the appearance of the cave, but also a deep restoration of its internal cultural elements, laying a solid foundation for subsequent research and display.

The VR archaeological game "Silk Road Secrets" developed on this basis has brought innovation in the user experience level. The game design team carefully created an immersive virtual scene, in which users become archaeologists in the game and step into the virtual Dunhuang Mogao Grottoes to start an exploration journey. The game tasks are cleverly integrated with Dunhuang culture. For example, in the process of identifying historical stories in murals, users need to carefully observe the details of the murals, and accurately interpret the scenes of ancient Silk Road trade and religious activities depicted in the murals by consulting virtual ancient books and communicating with virtual NPCs. In the task of repairing damaged cultural relics, users use virtual tools to "repair" damaged murals or Buddha statues based on the knowledge of cultural relic restoration they have learned. This process allows users to personally experience the rigor and difficulty of cultural relic restoration.

This innovative experience method has greatly stimulated the enthusiasm of users to participate, and the user retention rate has increased by 45%. According to subsequent user survey feedback, many players said that through this game, their understanding of Dunhuang culture is no longer superficial. A senior player shared: "In the past, when I visited Mogao Grottoes, I just took a quick look and it was difficult to deeply understand the cultural connotations. But in "Silk

Road Secrets", I can personally participate in cultural exploration and have a new understanding of the religious, artistic, and historical values contained in the Dunhuang murals. It is as if I am traveling through time and space to talk to the ancients." This kind of in-depth experiential cultural communication has brought new vitality to Dunhuang culture among the younger generation, attracting more people to actively understand and study this ancient cultural heritage [5].

3.2. Qin Shihuang Mausoleum Terracotta Warriors Revitalization Project

As an outstanding representative of the glorious civilization of ancient China, the revitalization of the Terracotta Warriors and Horses of the Qin Shihuang Mausoleum is of great significance to cultural inheritance. In this project, virtual reality technology has demonstrated a powerful enabling role and has achieved remarkable results in many aspects.

Through long-term all-round monitoring of the Terracotta Warriors, the project team has collected a large amount of environmental factor data on the terracotta warriors, including real-time changes in temperature, humidity, light, etc., as well as material property data of the terracotta warriors themselves, such as clay composition, firing process characteristics, etc., and detailed records of the damage that has occurred. With the help of big data analysis and advanced artificial intelligence technology, a damage evolution prediction model for terracotta warriors was constructed with a prediction accuracy of 89%. The model can accurately predict the location and degree of damage that may occur to the terracotta warriors in the future based on the trend of environmental changes and the condition of the terracotta warriors themselves. For example, during the high temperature period in summer, the model accurately predicted that some terracotta warriors located at the edge of the pit and exposed to light for a long time would produce fine cracks on the surface due to temperature changes, which provided a key basis for cultural relics protection workers to take targeted protective measures in advance, effectively extending the preservation life of the terracotta warriors and greatly improving the scientific nature and foresight of cultural relics protection work [6].

At the same time, the launch of the VR immersive experience system has caused a huge response at the social level. The system has received more than 1 million visitors a year, allowing tourists from all over the world to transcend time and space limitations and experience the shock of the Terracotta Warriors in person. In the VR experience, users seem to instantly travel to the excavation site of the Terracotta Warriors of the Qin Shihuang Mausoleum. Through advanced VR equipment, users can closely observe the details of the Terracotta Warriors, the lifelike expressions on the soldiers' faces, which are either majestic or resolute, and the exquisite textures and connection processes on the armor are clearly visible; users can also freely shuttle between the pits and appreciate this large-scale underground army from different angles. Many tourists who have experienced it said that the shock brought by this immersive experience far exceeds the on-site visit. A foreign tourist excitedly said: "In the past, I could only learn about the Terracotta Warriors through pictures and texts. This time in VR, I feel like I am standing at the historical scene and truly feel the greatness of ancient Chinese civilization." This immersive experience not only enhances the tourists' understanding of the historical and cultural value of the Terracotta Warriors, but also strongly promotes the dissemination and exchange of Chinese culture on a global scale, becoming a successful example of the digital dissemination of cultural heritage.

4. Challenges and Countermeasures

4.1. Key Technical Bottlenecks

4.1.1. Ultra-large-scale Data Storage and Transmission

In the process of cultural heritage digitization, the amount of data generated is extremely large. Taking the Mogao Grottoes in Dunhuang as an example, the high-precision 3D models of the caves, the massive high-definition images of murals, and the various data obtained by the multimodal data acquisition system can reach several TB or even PB levels. Such large-scale data storage and transmission has become a major technical bottleneck. Traditional storage and transmission methods are not only costly, but also difficult to meet the needs in terms of data processing speed and stability.

To solve this problem, a solution combining edge computing and blockchain storage is adopted. Edge computing transfers data processing and storage from the central server to the edge device close to the data source, greatly reducing the distance and amount of data transmission. For example, in the monitoring of the Terracotta Warriors and Horses of the Qin Shihuang Mausoleum, edge computing nodes are deployed on site to perform preliminary processing and screening of the collected environmental data and image data of the terracotta warriors in real time, and only transmit key data to the central server. Blockchain storage uses the distributed ledger technology of blockchain to store data in multiple nodes in a dispersed manner, improving the security and reliability of data. At the same time, the encryption feature of blockchain also ensures the privacy of data. In this way, not only the cost of data storage and transmission is reduced, but also the efficiency and security of data processing are improved.

4.1.2. Immature Natural Interaction Technology

In virtual reality environments, natural interaction technology is crucial to improving user experience. However, natural interaction technology is still immature, such as low accuracy of gesture recognition and deviation in semantic understanding of voice interaction. This results in users not having a smooth and natural experience when interacting with cultural heritage in virtual environments, which affects the effect of cultural heritage display and dissemination [7].

To address this problem, researchers have improved gesture recognition accuracy by continuously optimizing algorithms and increasing training data. For example, a deep learning algorithm is used to train a large number of gesture samples, allowing the system to learn the characteristics and meanings of different gestures. After a series of technical improvements and optimizations, the gesture recognition accuracy has increased to 98.7%. At the same time, in terms of voice interaction, the semantic understanding model in natural language processing technology is introduced to improve the system's ability to understand user voice commands by learning from a large amount of text data. Through these technological breakthroughs, users can interact with cultural heritage in virtual reality environments more naturally and smoothly, and can better immerse themselves in cultural experiences.

4.2. Recommendations for Standardization Construction

With the widespread application of virtual reality technology in the field of cultural heritage, standardization construction has become particularly important. In order to standardize cultural heritage VR display technology, a draft "Cultural Heritage VR Display Technical Specification" was proposed, which has been adopted by the ISO/TC289 working group. The draft specification covers standards in many aspects, from data collection, model construction, interaction design to display effects. In terms of data collection, the technical parameters and accuracy requirements for data collection of different types of cultural heritage are specified to ensure the consistency and comparability of the collected data. In the model construction link, the quality standards and optimization methods of the model are clarified to ensure that the virtual model can accurately restore the true appearance of cultural heritage. The interactive design standard focuses on the user's experience in the VR environment, stipulates the design principles and operation procedures of the interactive method, and makes different cultural heritage VR display projects have a certain degree of versatility and ease of use in interaction. The display effect standard regulates the visual effects, sound effects and other aspects of the VR scene to create a display environment that conforms to the atmosphere of cultural heritage. By formulating and promoting such technical specifications, it can promote the healthy development of cultural heritage VR display technology, improve the overall level of digital protection and display of cultural heritage, and provide strong support for the digital inheritance and dissemination of global cultural heritage.

5. Conclusion

This study deeply explored the application of virtual reality technology in the digital protection of cultural heritage, constructed a complete and innovative technical framework, and verified its remarkable results through actual cases. The multimodal data acquisition system obtains cultural heritage information in an all-round and high-precision manner, providing a solid data foundation for subsequent research and protection; the digital twin restoration algorithm greatly improves the efficiency and quality of cultural relics restoration; the virtual-reality fusion display system innovates the display and dissemination of cultural heritage and enhances user participation and experience. From the application cases such as the Mogao Grottoes in Dunhuang and the Terracotta Warriors and Horses of the Qin Shihuang Mausoleum, virtual reality technology not only realizes the high-precision digital archiving of cultural heritage, but also allows more people to deeply understand its cultural connotation through immersive experience, and effectively promotes the dissemination and exchange of cultural heritage on a global scale. Looking to the future, with the continuous development and improvement of technology, virtual reality technology is expected to play a greater role in the field of cultural heritage protection, further expand the protection boundaries of cultural heritage, realize the sustainable inheritance and development of cultural heritage, and contribute scientific and technological power to the continuation of human civilization.

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