

Research on the Modern Digital Restoration and Construction of Yongle Palace Murals

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Abstract: The murals in Yongle Palace possess extremely high artistic and historical value. Its protection work is facing huge challenges. Traditional repair methods have limitations. Digital technology offers a new direction for the protection of murals. This article aims to construct a digital restoration technology system. This system is specifically applied to the protection of the murals in Yongle Palace. The study first reviews the existing technologies. Digital acquisition technology can obtain high-precision information. Intelligent algorithms can automatically identify diseases in murals. Virtual repair technology can digitally restore the damaged area. This paper proposes a three-layer technical framework. The first layer is the precise collection of digital information. Combining high-resolution scanning with multispectral imaging. The second layer is intelligent disease recognition and diagnosis. Analyze using deep learning models. The third layer is virtual restoration and digital reproduction. Restoration is carried out using artificial intelligence technology. The research also discussed the current challenges faced. And specific implementation suggestions were put forward. It is suggested to establish an interdisciplinary collaboration mechanism. It is suggested to improve the construction of digital archives. It is suggested to develop intelligent auxiliary tools. This system provides a systematic solution for the protection of the murals in Yongle Palace. It helps to achieve scientific protection and sustainable inheritance of cultural relics.

Keywords: Yongle Palace murals; digital restoration; image processing; deep learning; digital protection.

1. Introduction

The murals of Yongle Palace are outstanding representatives of ancient Chinese art. Located in Shanxi Province, they possess extremely high historical value. These murals were created during the Yuan Dynasty, are of grand scale and exquisite craftsmanship. With smooth lines and rich colors, they demonstrate the superb painting skills of ancient times. They are important physical materials for studying ancient Chinese art and social culture. However, the preservation of the murals at Yongle Palace faces challenges. The previous overall relocation project had an impact on the murals. Environmental factors such as humidity changes and air pollution can also cause damage to the murals. Common diseases include pigment detachment and surface cracking. Traditional restoration methods are important but have certain limitations. Physical restoration operations are irreversible and may carry potential risks.

Therefore, modern digital technology offers a new direction for mural protection. Digital technology can achieve non-contact measurement and analysis. It can effectively reduce intervention to the cultural relics themselves. Digital technology can also permanently preserve the current state information of the cultural relics. This paper aims to explore a systematic solution for applying digital restoration technology to the protection of the murals at Yongle Palace. This study will review existing technologies and construct an integrated digital protection framework to support the scientific protection and long-term inheritance of the murals at Yongle Palace.

2. Literature Review

2.1. Research Status of Digital Acquisition and Disease Identification Technology for Murals

Modern digital technologies are first applied to the comprehensive collection of cultural relic information. High-resolution scanning technology is a fundamental recording method. This technology can obtain fine texture information on the surface of murals. Multispectral imaging technology goes further, as it can detect hidden information that is invisible to the human eye. The research by Lei Tong and Wei Xiaoyang (2022) shows that this technology can effectively identify the draft and faded traces of murals[6]. The common advantage of these technologies is their non-contact nature, which completely avoids protective damage.

Based on information collection, the automatic identification of diseases has become a research hotspot. Digital image processing technology plays a key role in this field. Han Guoxun (2025) pointed out that through algorithms such as image filtering and segmentation, the cracking and moldy areas of murals can be effectively identified. Traditional algorithms are being enhanced by more advanced deep learning methods[4]. Zhang Shuang's (2023) research used Generative Adversarial Networks (GAN) to improve the accuracy and efficiency of identification. This indicates that research is evolving from traditional methods to intelligent analysis[5].

2.2. Development of Digital Virtual Restoration Technology and Concept of Holographic Protection

After completing the diagnosis of the disease, virtual restoration is the core point. Computer graphics provides various restoration algorithms. These algorithms can intelligently fill in the missing parts based on the texture of the surrounding intact areas. Han Jianwu et al. (2014)'s research successfully simulated the traditional manual restoration process and achieved the virtual restoration of murals[7]. Deep learning technology has promoted the development of restoration capabilities. Zhang Shuang (2023) applied a two-stage generative adversarial network, effectively solving the problems of disordered structure and loss of details in the restoration area, making the restoration effect more natural and accurate[5].

The holographic replication concept expands the connotation of protection. Ma Yujuan (2024) proposed that this is an innovative non-ontological protection method. It combines traditional techniques and digital technology. Its goal is not to directly handle the mural itself, but to produce high-precision replicas for display and dissemination[1]. Hu Yan and Zhang Tianling (2023) also believe that digital replication technology is an important part of cultural relic protection[2]. This concept extends protection from simple technical restoration to the dissemination and utilization of cultural value.

2.3. Summary of Literature Review

In conclusion, the existing technologies have achieved remarkable results in their respective fields. High-precision acquisition, intelligent recognition, and virtual restoration form the main technical line. The "holographic reconstruction" concept enriches the extension of protection. However, there is a significant deficiency in current research. Most studies focus on optimizing a single technical link. Some studies only concern acquisition, while others only study algorithms. There is a lack of a systematic framework to connect these technologies together. Specifically for the murals of Yongle Palace, the problem is more prominent. Currently, there is a lack of customized solutions for its unique artistic features and preservation conditions. An integrated, process-based technical system covering "acquisition - diagnosis - restoration - reproduction" has not yet been established.

Therefore, this research is highly necessary. This study aims to bridge the gaps between existing technologies. The goal is to build a digital restoration technology system specifically designed for the murals of Yongle Palace. This system will integrate all links from information acquisition to final presentation. Ultimately, it is hoped to provide a complete solution for the scientific protection and sustainable utilization of the murals of Yongle Palace.

3. Construction of Digital Restoration Technology System for Yongle Palace Murals

The murals of Yongle Palace, as the pinnacle of art in the Yuan Dynasty, face significant challenges in terms of their protection. Although traditional restoration methods are important, they have limitations such as strong intervention and irreversibility. With the development of technology,

digital technology has provided a new solution for the protection of murals. Based on the research gaps identified in the previous analysis, this chapter proposes a systematic digital restoration technology system. This system integrates all the technologies from information collection to final presentation, and is specifically designed to address the artistic characteristics and preservation status of the murals of Yongle Palace.

3.1. Precise Collection of Digital Information

Digital information collection is the fundamental part of the entire technical system. High-resolution scanning is the preferred technical method, which can capture the fine texture information and color characteristics of the mural surface. This technology uses professional large-format scanning or high-resolution remote sensing imaging systems, capable of achieving resolutions of several hundred DPI or even higher, sufficient to record the subtle brushstrokes and pigment layers that are difficult to be noticed by the naked eye. For the murals of the Longmen Palace, high-resolution scanning can completely record its unique iron-line drawing technique and rich color transitions, establishing an accurate benchmark for subsequent restoration.

Multispectral imaging technology is another key technology. This technology, by capturing the reflection of light from different wavelengths, can reveal hidden information that is invisible to the human eye. Ma Yujuan (2024) successfully detected the draft lines beneath the murals and the original patterns that were later covered using multispectral imaging in her research[1]. In the digitalization collection of the murals in the Yongle Palace, multispectral imaging can be used to discover early drawing traces, identify restoration marks from different periods, and detect initial diseases that are difficult to detect with the naked eye.

Three-dimensional laser scanning technology offers another dimension of information recording. This technology, based on the principle of laser ranging, can precisely record the geometric shape and surface micro-deformations of murals. Lv Jie (2021) demonstrated in the digital research of bronze artifacts the effectiveness of this technology in recording complex surface forms[3]. For the murals of the Yongle Palace, three-dimensional laser scanning can quantitatively record the undulating state of the murals, minor cracks, and deformations caused by material aging, which are crucial for evaluating the structural stability of the murals.

The combined application of these three technologies constitutes a three-dimensional information collection system. In actual operation, it is necessary to first conduct three-dimensional laser scanning to obtain geometric data, then perform high-resolution scanning to record texture information, and finally use multispectral imaging to supplement hidden information. All data need to undergo strict calibration and registration processing to ensure that data from different sources can accurately correspond, forming a complete digital archive.

3.2. Intelligent Identification and Diagnosis of Diseases

After completing the data collection, the next step is to conduct intelligent recognition and diagnosis of the mural damages. The core of this process is the multi-source data fusion technology, which integrates and analyzes data from different collection devices. Data fusion not only includes simple data overlay but also involves deep integration at the

feature level. For example, combining the geometric data obtained from 3D scanning with the material data obtained from multispectral imaging can more accurately identify potential areas of detachment risk.

Deep learning technology plays a crucial role in disease identification. Generative Adversarial Networks (GAN) is one of the most effective techniques currently. Zhang Shuang (2023) used this technology in a study to achieve high-precision identification of mural diseases. In the protection of the murals of Yongle Palace, a specialized deep learning model can be trained to identify specific types of diseases[5]. First, a labeled training dataset needs to be established, including various typical disease samples such as cracking, peeling, and mold growth. Then, these data are used to train the neural network, enabling it to automatically identify and classify the diseases.

Image processing algorithms provide another important tool for disease diagnosis. The research of Han Xun (2025) demonstrated the application of image segmentation algorithms in the quantitative analysis of mural diseases[8]. For the murals of Yongle Palace, edge detection algorithms can be used to identify cracks, clustering analysis algorithms can be used to distinguish different pigment areas, and change detection algorithms can be used to monitor the development trend of diseases. These algorithms not only can identify the existence of diseases but also can quantify and assess the severity of the diseases, providing a basis for prioritizing restoration.

The ultimate goal of the intelligent diagnosis system is to establish a digital disease archive. This archive should include the location information of each disease point, type classification, severity assessment, and historical change records. Based on these data, the system can generate restoration suggestions, recommending the most suitable treatment methods and materials. At the same time, the system should also have predictive capabilities, capable of predicting potential risks in the future based on environmental data and disease development trends, achieving preventive protection.

3.3. Virtual Restoration and Digital Recreation

Virtual restoration is the most innovative part of the digital technology system. Traditional image restoration algorithms remain an important technical foundation. These algorithms are based on principles such as adjacent pixel analysis and texture synthesis, and can effectively handle small-scale damages. The research by Han Jianwu et al. (2014) proved that these traditional algorithms have practical value in virtual restoration of murals[7]. For the murals of Yongle Palace, these algorithms can be used to handle minor scratches and stains, maintaining the natural harmony of the restoration results.

Generative artificial intelligence technology has pushed virtual restoration to a new height. Advanced algorithms such as Partial Convolution (PConv) can handle larger areas of missing regions. Zhang Shuang (2023) conducted research using deep learning methods and successfully restored large-scale missing parts of the murals[5]. In the virtual restoration of the murals of Yongle Palace, a specialized generative model can be trained to learn the artistic style and technical features of the murals, thereby generating more content that is in line with the original work. This AI-based restoration not only considers the continuity of textures but also maintains the uniformity of artistic style.

Digital reproduction is the final output stage of the technology system. Virtual Reality (VR) and Augmented Reality (AR) technologies provide new display methods. Lei Tong and Wei Xiaoyang (2022) demonstrated the advantages of these technologies in the display of cultural relics[6]. For the murals of Yongle Palace, a specialized VR system can be developed to allow viewers to have an immersive experience of the details and overall spirits of the murals. AR technology can provide enhanced information during on-site visits, such as displaying hidden details or showing the state before restoration.

Holographic replication technology offers another possibility for the digital dissemination of cultural relics. Ma Yujian (2024) proposed a holographic replication system that combines digital technology and traditional craftsmanship, capable of producing high-precision physical replicas[1]. For the murals of Yongle Palace, a proportional replica can be made for touring exhibitions, protecting the original work while achieving cultural dissemination. Digital reproduction is not only a display of technology but also a manifestation of the concept of cultural protection, allowing cultural relics to gain new life through digital means and achieving sustainable protection and utilization.

The implementation of the entire technology system requires the establishment of standardized operation procedures and quality control systems. Each stage needs to have detailed technical specifications, including data collection standards, processing procedures, and output requirements. At the same time, a cross-disciplinary cooperation mechanism needs to be established, involving cultural heritage experts, computer scientists, and art historians to ensure the scientific and rationality of the technology application. The final result is not only a technical solution but also a sustainable new model of cultural heritage protection.

4. Discussion and Recommendations

Digital technology has brought new opportunities for the conservation of the murals in Yongle Palace. This study has established a technical system that provides a systematic solution. This solution covers the entire process from information collection to the display of results. However, in practical application, it still faces many challenges. These challenges require the joint efforts of all parties to solve. This chapter will discuss the current main issues and propose specific suggestions.

4.1. Promote Establishment of Cross-disciplinary Collaborative Working Mechanism

Currently, there is a phenomenon of professional isolation in the field of cultural heritage protection. Technicians are not aware of the needs of art conservation. Conservation experts are not familiar with the latest technological advancements. This isolation seriously affects the effectiveness of the protection work. Establishing interdisciplinary teams is the top priority. It is suggested to establish a special working group for the digital protection of Yongle Palace. The team should include cultural heritage protection experts and computer scientists. Art historians and traditional mural artisans should also participate. The cultural heritage protection experts are responsible for formulating protection principles. They ensure that all operations comply with the

ethical standards of cultural heritage protection. Computer scientists provide technical support. They are responsible for algorithm development and data processing. Art historians provide academic guidance. They ensure that the restoration work conforms to the historical style. Traditional painters provide technical support. They help understand the mural painting techniques.

The team needs to establish unified working standards. Data formats should be standardized. Processing procedures need to be standardized. Quality evaluation should be established in a unified system. These standards ensure the orderly connection of all tasks. The team should also establish a regular communication mechanism. Sharing the latest progress through seminars. Communicating work results through collaboration platforms. This collaborative model can improve work efficiency. Cross-disciplinary cooperation requires institutional support. Institutions should provide financial support. Universities can cultivate interdisciplinary talents. The government needs to introduce incentive policies. These measures can promote the in-depth development of cross-disciplinary cooperation. Eventually, a sustainable protection model can be formed.

4.2. Improve Construction of High-precision Digital Archives

Digital archives form the foundation of the protection work. Currently, there is a problem of insufficient comprehensiveness in data collection. Some data formats are not uniform. Data management lacks systematic planning. The construction of digital archives needs to be further improved. It is suggested to carry out systematic supplementary data collection work. Focus on collecting areas that were previously overlooked. Use more precise equipment to re-collect. Special attention should be paid to the data recording of vulnerable parts. The collection process should follow unified standards. Equipment parameters should remain consistent. Lighting conditions need to be fixed. Coordinate systems must be unified. These measures ensure the comparability of data. Data management requires professional system support. It is suggested to establish an exclusive database management system. The system should have large-capacity storage capabilities. It needs to support access to multiple data formats. It should also provide a fast search function. Data security is of utmost importance. A multiple backup mechanism must be established. Off-site backup can prevent accidental losses. Access permissions need to be strictly managed.

Data sharing deserves special attention. It should be limitedly open under the premise of ensuring security. Researchers can apply for data usage. Students' education can utilize some data. Public display requires special handling of versions. Sharing promotes the improvement of research levels. At the same time, it expands the influence of cultural relic protection. The database should have expansion capabilities. New data types generated by future technologies should be compatible with the system. It leaves interface space for technological development. In this way, it can maintain long-term usability value.

4.3. Develop Intelligent Repair Assistance Technologies

The development of artificial intelligence technology is rapid. However, its application in the field of cultural relic protection is still in its early stages. It is necessary to steadily

promote the application of the technology. The focus should be on developing auxiliary tool systems. In the near future, the development of disease identification tools will be the priority. Based on deep learning algorithms, training identification models will be carried out. Firstly, for common disease types, such as cracking and chalking, typical problems will be targeted. A large number of sample images will be collected for training. The algorithm's recognition accuracy will be continuously optimized. The tool can automatically mark the location of the disease. It can also assess the severity of the disease. This significantly improves the efficiency of the census.

In the medium term, the exploration of virtual restoration assistance systems will be carried out. A specialized mural restoration software platform will be developed. Multiple image processing algorithms will be integrated. Interactive restoration tools will be provided. The restorationist can try different solutions. The system will record all operation steps. This provides a digital laboratory for the restoration work. It avoids the risks brought by direct operation.

In the long term, the research direction is intelligent generation assistance. Training a dedicated model that understands the style of the mural. The model will learn the features of lines and colors. It can generate suggestions in the missing areas. The generated results need to be reviewed and confirmed by experts. Artificial intelligence always plays an auxiliary role. The final decision-making power lies with the human experts. The development of technology should focus on practicality. Avoid pursuing overly complex technologies. Choose mature and reliable technical solutions. Ensure the long-term stable operation of the system. At the same time, strengthen talent training. So that technicians can master the new tools proficiently.

5. Conclusion

The murals of Yongle Palace are precious cultural heritage. Protecting these murals is of great significance. Digital technology provides new protection methods. This article systematically studies the digital restoration technology system. The research first analyzes the current technical situation. It points out the main problems existing at present. Then a systematic technical framework is constructed. The framework consists of three main levels. The first is the information collection layer. The second is the intelligent diagnosis layer. The third is the virtual restoration layer. This framework covers the entire process of protection. The research also proposes implementation suggestions. Suggestions include establishing interdisciplinary teams. Improving digital archive construction. Developing intelligent auxiliary tools. These suggestions have practical guiding value. Digital technology cannot replace traditional protection. It is an important supplement and improvement. Technology helps people make better decisions. Ultimately, protection still requires human wisdom. It is hoped that this research can promote the development of protection work. Further research is needed in the future. More technical possibilities need to be explored. The technical standard system needs to be improved. A professional talent team needs to be cultivated. Through the joint efforts of all parties, the murals of Yongle Palace will surely receive better protection. These artistic treasures will be passed down to future generations and continue to display their brilliant brilliance.

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