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Application of Digital Twin Technology in the Restoration of Traditional Residential Architectural Paintings

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Abstract: In the protection of traditional residential buildings, for the color painting restoration faces the high covertness of the disease, the restoration process is lost, and the material matching efficiency is low, so the traditional detection relies on manual experience, and cannot accurately investigate the grass-roots level of the hollow drum, the pigment layer chalking and other microscopic diseases; the restoration material is mostly based on the empirical preparation, that is, lack of quantitative assessment of the strength of the role of the environmental corrosiveness, so that the restoration layer is not sufficiently durable and there is a large color difference; and the traditional techniques are limited. Inheritance growth capacity is limited, young craftsmen can not accurately understand the "leaching powder gold" "three alum nine dyeing" and other complex processes through the physical copy. Therefore, through the introduction of digital twin technology, this paper aims to build a full-factor digital twin to realize quasi-diagnosis of diseases, virtual simulation to create restoration solutions, and AR to recreate traditional skills, and ultimately to form a verifiable and inheritable digital protection system, which will provide a technical guarantee for the perpetual survival of traditional residential architectural paintings.

Keywords: digital twin, traditional houses, architectural paintings, restoration

Introduction:

For the protection of traditional residential buildings, color painting, as a carrier of regional culture and historical memory, is facing multiple difficulties in its protection and restoration: traditional testing methods are difficult to judge the grass-roots level disease and microscopic damage of pigment layer due to the accuracy problem, so it is not possible to formulate corresponding restoration plan according to the type of damage of material layer; restoration materials rely on the experience of trial mixing and are not able to withstand the environment and seasonal contraction and expansion, which are often prone to secondary damage such as cracking and fading of the restoration layer; more realistically, the inheritance of traditional skills may be interrupted. Repair layer cracking, fading and other secondary damage; more realistic is that the traditional skills inheritance may be interrupted by the fault, many complex processes such as "leaching powder gold", "three alum nine dyeing" and other processes are on the verge of being lost. The emergence of digital twin technology provides a new way to solve the restoration difficulties, through the whole element of digital twins to accurately trace the disease, virtual simulation optimization restoration program, AR technology can also reproduce the traditional technology, etc., for the protection of the traditional residential architecture painting injected into the digital vitality.

1. Application Scenarios of Digital Twin Technology in Painted Restoration

1.1 High-precision data acquisition

The application of digital twin technology in the field of traditional residential building painting restoration, especially in the high-precision data collection of this link has obvious advantages.

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Traditional painting restoration causes drawing to rely on manual mapping and empirical judgment. Low data accuracy, one-sided information records are unavoidable drawbacks. Digital twin technology through three-dimensional laser scanning, multi-spectral imaging, high-resolution photogrammetry and other means of painted patterns, color levels, the degree of material aging and other details of millimeter-level precision capture. Construct a digital archive of spatial coordinates, color spectra, material properties and other multi-dimensional information. This new data collection method is not bound by physical space and reaches the level of holographic data collection. Then using multi-source data fusion algorithms, intelligently integrate data of different spectral bands and different imaging angles to be spliced in the virtual simulation environment to form a holographic, high-fidelity three-dimensional digital model. Not only to provide an accurate basis for the development of the target restoration program, but also to use virtual simulation technology to preview and evaluate different restoration paths to avoid the consequences of secondary damage (Wang & Luo, 2023).

1.2 3D model construction

The 3D model construction process of digital twin technology in traditional residential building painting restoration fully embodies the powerful function of digital twin technology empowerment. Due to the lack of accurate spatial data support for traditional painting restoration, the restoration program is often unable to accurately restore the original historical appearance. Digital twin technology combined with three-dimensional laser scanning, structured light measurement, drone tilt photography and other multi-source data acquisition means, rapid access to the architectural painted surface geometry, texture details, spatial distribution and other characteristics, so as to build a three-dimensional point cloud model with millimeter-level accuracy. On this basis, with the help of computer vision and graphics algorithms, the point cloud data can be transformed into a highly realistic 3D mesh model, and the material mapping technology will achieve a high degree of reproduction of the pattern color and texture. Not only breaks through the two-dimensional limitations of traditional mapping, point cloud mapping technology can also highly retain the complete form and spatial relationship of the painted works, and because of the development of parametric modeling techniques, can realize the virtual stripping and restoration simulation. Restorers can interactively verify different restoration schemes in the digital environment, explore the impact of different pigment ratios and painting methods on the visual effect, and ultimately formulate a restoration scheme that harmonizes historical authenticity and on-site art (Sima, 2018).

1.3 Real-time data interaction

Digital twin technology breaks through the location of cultural heritage protection space by interacting these complex and variable information in real time through digital data interfaces, providing a real-time data interaction method for the restoration of painted cultural heritage. Conventional monitoring tests or on-site data updates are usually delayed than the work and cannot be targeted for restoration according to the site conditions, while through the combination of IoT sensor networks and 3D digital models, digital twin technology unfolds a real-time sensing system for the whole process of the painted ontology, environmental parameters and restoration operations. For example, temperature and humidity sensors, strain gauges and spectral analyzers are deployed on the painted surface to measure micro-environmental changes with delayed updates per second, and realize data pre-processing and anomaly warning through edge computing. The digital twin platform can also be superimposed onto the 3D model for real-time monitoring with the help of augmented reality (AR) technology, and the imaging monitoring of the restored results can be completed in close proximity, so that the restorers can grasp the dynamic information of deformation of the painted grassroots layer and peeling of the pigment layer. Environmental parameters exceed the safety threshold, automatically start the protection plan, linkage control temperature and humidity control equipment or start masking and so on (Li, 2021).

2. The Advantages of Digital Twin Technology

2.1 Accurate restoration

Because of its digital mapping of all elements of the whole process characteristics, digital twin technology is suitable for the accurate restoration of the painted surface and key components. Compared with traditional technology, digital mapping through high-precision three-dimensional scanning and multi-spectral imaging and other technical means, up to millimeter-level surface morphology and color information, while obtaining the characteristics of the material aging or oil film changes, to achieve the geometric morphology of the paintings, the color distribution and the material information of the digital holography, the integration of the spatial coordinates of the surface of the paintings, the spectral reflectance, the distribution of pigment molecules, and many other information. This holographic data model not only makes the restoration more accurate at the molecular level, but also returns to the essence of the painting process through parametric modeling techniques. In the restoration process, the digital twin system through the virtual simulation module, can be different restoration materials, process parameters for millions of secondary simulation experiments, accurate prediction of the rate of pigment fading, painting between the layers of adhesion and other key indicators, thus helping restorers to screen out the restoration path with the highest degree of match with the original historical appearance. At the same time, the use of augmented reality (AR) technology, restoration personnel through the helmet were obtained from the digital model and the actual painting of the superposition of information, to ensure that each stroke of painting are strictly follow the spatial trajectory set by the digital twin and color parameters.

2.2 Efficient collaboration

The reason why digital twin technology can significantly improve the collaborative efficiency of traditional residential building painting restoration work, the key is that it breaks the traditional information asymmetry and collaboration difficulties in space and time barriers. The digital twin realizes the fusion of multi-source data through the cloud collaboration environment, and the archaeologists, material scientists, restoration engineers and other multi-party teams collaborate in real-time in a multi-scale, multi-angle digital environment. In the digital twin model, experts in different fields can directly mark disease characteristics and make restoration suggestions in 3D space through semantic annotation and other functions, and all operations are stored in the form of structured data, forming a traceable process and decision-making chain. In the restoration execution phase, the digital twin system based on BIM (Building Information Modeling) technology can automatically generate a standardized construction process, disassembling the restoration task into a digital work order containing material ratios, process parameters, quality standards and other elements, paired with Internet of Things (IoT) equipment, real-time tracking of construction progress. When restorers encounter technical difficulties, the system automatically calls up its own database of historical restoration cases to provide solutions for the same disease. The virtual capability of the digital twin system supports remote diagnosis and guidance by off-site experts through VR equipment "in person" on-site. This real sense of "cloud collaboration-intelligent scheduling-remote support" collaboration mode, so that the restoration cycle is shortened by 40%, while reducing human error, cultural heritage protection in this field ushered in the efficient digital collaboration (Jia, 2020).

2.3 Sustainable maintenance

The sustainable maintenance advantage of digital twin technology in the restoration of color painting is mainly manifested in the digital twin technology for cultural heritage to build a full life cycle of digital guarding system mentioned above. First of all, the traditional restoration mode lacks the monitoring and intervention on the long-term deterioration of the paintings due to the consideration of the single restoration investment. Digital twin system through the integration of Internet of Things sensor network, real-time collection of painted surface temperature and humidity, light intensity, micro-environmental gas composition and other key parameters, to build a dynamic update of the environment - disease associated database. Secondly, based on machine learning algorithms, the system can autonomously identify early signs of disease through the law of expected sites with weak signals, predict the deterioration trend in the next 5-10 years, and formulate preventive protection programs 6-12 months in advance. Furthermore, after the restoration is completed, the digital twin model directly and continuously performs the function of "digital archive", automatically recording the time, process, materials and other details of each maintenance operation, forming a traceable maintenance log. For example, when there is a sudden change in the environmental conditions or the development of the disease exceeds the expected range, the system can automatically trigger the emergency response mechanism to control the temperature and humidity control equipment or start local isolation protection. The digital twin data encrypted and stored using blockchain technology not only guarantees the security of cultural heritage information, but also provides authentic and credible historical credentials for intergenerational inheritance. This "preventive monitoring-intelligent decision-making-digital evidence" type of sustainable maintenance model, so that the protection of colored paintings from passive restoration to active intervention, the life of cultural relics significantly extended (Xu, 2021).

3. Digital Twin Technology in the Traditional Residential Building Color Painting Restoration Way

3.1 Technical measures

Digital twins and related technical countermeasures need to build a "data acquisition - model construction - intelligent decision-making - real-time monitoring" system. In the data collection stage, with the help of multi-spectral camera and three-dimensional laser scanning and other means to obtain the building geometry, chromatographic spectrum, color pigment composition, fading degree and other elements of data. Such as Shanxi Qing Dynasty houses painted repair, scanner rack station and drone tilt photography combined to obtain the building facade 120 million three-dimensional coordinates, combined with 16-band hyperspectral imager, the color distribution and fading of painted color, the formation of more than 20 types of parameters including spatial coordinates, spectral reflectance and color, pigment molecular structure and other parameters of the digital archives. Using the model construction link of parametric modeling technology, the collected data are transformed into interactive digital twins. For example, in a 30-year environmental erosion test case, this system simulated the performance comparison of 12 different restoration materials, which were actually screened based on virtual simulation. For example, in the case of a courtyard restoration in Beijing, the team tested the performance of 12 restoration materials in the digital model, and finally chose nano-modified mineral pigments, which improved the weather resistance of the restoration layer by 40%. Intelligent decision-making system, supported by machine learning algorithms, automatically matches the historical disease case base and generates executable work orders. When real-time monitoring detects humidity exceeding the standard, i.e., through the sensor network of the Internet of Things (IoT), under the guidance of the environmental data collected in seconds, the intelligent triggering of the AR glasses displays the three-dimensional annotation information, which automatically makes dehumidification equipment work and guides the localized restoration. This full-process digital control mode, which improves the restoration efficiency by more than 60%, is a real innovation of technological change in the field of cultural heritage restoration (Jin, 2021).

3.2 Application countermeasures

The application of digital twin technology in the restoration of traditional residential architecture painting needs to be based on the countermeasures, that is, we need to build a closed-loop system around the "accurate diagnosis-intelligent restoration-cooperative control". Accurate diagnosis, multimodal data fusion technology has technical means, such as three-dimensional laser scanning to obtain the painted geometry and hyperspectral imaging to analyze the pigment composition of the application of technology, combined with infrared thermal imaging to detect grass-roots level disease. For example, in Anhui, a Huizhou residential restoration, the team through the "laser scanning + multi-spectral + infrared" to complete the composite acquisition, found that there are environmental humidity changes under the painted layer of the line into the hollow drum disease, in different acoustic wave test has a different pattern, can not be identified through traditional means of detection. This result provides a basis for subsequent restoration. Intelligent repair link relying on the virtual simulation function of the digital twin model of the repair program for ten million secondary accelerated aging experiments. The system can also simulate the long-term performance of different material changes under environmental erosion, and automatically generate digital work orders containing material ratios, process parameters, quality standards. In Fujian, an earth building painting repair, the team found through digital twin simulation, the original program selected organic cementing material hygroscopic deterioration, changed to nano-modified mineral glue, the repair layer weathering enhancement of 35%, the repair layer to match the degree of 92%. Collaborative control requires a cloud-based collaboration platform to carry out real-time interdisciplinary team interactions. Digital twins enable archaeologists to mark the characteristics of the disease, material engineers recommend repair materials, repair technicians feedback construction parameters and other operations are stored structured data to form a traceable decision-making chain. In Zhejiang, an ancient house restoration, off-site experts through VR equipment "in person" on-site, guiding the restorers to use digital model coordinate system to refine the treatment of species disease accuracy accuracy of 0.1mm level, the restoration cycle is shortened by 40%. The whole process of digital management model, cultural heritage protection from experience-driven to data-driven (Li, 2018a).

3.3 Cultural countermeasures

The cultural countermeasures of digital twin technology in the restoration of traditional residential architecture painting need to take "technology-enabled cultural inheritance" as the ontology, and construct a three-dimensional protection system of "digital evidence - technology reproduction - public participation". In digital evidence, the establishment of high-precision cultural heritage digital gene bank, the use of nanometer precision scanning, multi-spectral imaging technology, systematic recording of color pattern, chromatography, brush stroke and other cultural elements. For example, in the restoration project of a Bai residential house in Yunnan, the use of macro photography and fluorescence spectral analysis technology not only analyzes the mineral color components in the color painting, but also analyzes and restores the characteristics of the "three alums and nine dyes" process of the Qing Dynasty painter through the trajectory of the brush, and the data is permanently preserved in the blockchain distributed ledger, which has become a cultural memory that can not be tampered with. Memory. For the reproduction of traditional skills, it is necessary to build a digital twin technology inheritance platform to transform traditional crafts into editable digital assets. The computer automatically generates digital chemical sheets containing material ratios, drawing order, temperature control and other process parameters, and uses augmented reality technology to realize virtual teaching. Such as a Qiang village in Sichuan towers painted restoration, the research team developed a digital twin technology-based "traditional craft simulator", young craftsmen wearing AR glasses, you can repeatedly practice in virtual space "leaching powder gold" process, the system provides real-time feedback on the strength of drawing The system provides real-time feedback on the drawing strength, pigment dosage and other parameter deviations, increasing the efficiency of inheritance by 40%. The public participation mechanism needs to build the interactive scene of digital twin technology, develop lightweight digital twin applications, and design a "digital archaeology" for the public to participate in the restoration of paintings, so that the public can obtain a cultural interpretation based on historical documents through the identification of diseases and the selection of restoration programs in the virtual space. Thus, the protection of cultural heritage is expanded from professional to universal, and the living inheritance of traditional skills is truly realized.

3.4 Cost countermeasures

The cost countermeasures of digital twin technology in traditional residential building painting restoration should focus on the three dimensions of "precise input - efficiency enhancement - long-term control" to build a full-cycle cost optimization system. At the level of precise input, quantitative assessment of restoration plan should be realized through digital twin model. For example, the digital twin system equipped with high-precision three-dimensional scanning and spectral analysis functions can accurately calculate the area of the disease, the amount of materials and the complexity of the process, and generate a dynamic budget table containing more than 10 cost elements such as material costs, labor costs, equipment costs, and so on. For example, in the case of restoration of a Gan residential house in Jiangxi, the team found through digital twin simulation that in the original program, the use of the "whole uncovered restoration" will lead to 30% ineffective material loss, the actual cost of materials is 42% higher, and the construction period is 25% higher. At the level of efficiency improvement, it relies on the intelligent scheduling function of the digital twin platform. For example, the system maintains real-time monitoring of repair progress, material inventory and equipment status, and autonomously optimizes resource allocation through algorithms. The IoT sensor network not only realizes offline environmental control, but also comes a step closer to long-term control. In the restoration of an earthen building in Fujian, the IoT sensor network deployed in the project team automatically collects the temperature and humidity, light intensity and other data at the restoration site. When the environmental conditions are detected to deviate from the optimal restoration zone, the system directly adjusts the construction plan and links the temperature and humidity equipment, increasing the effective working hours by 18% and indirectly reducing the labor cost by 15%. Long-term control realizes cost savings through continuous updating of the digital twin. The system automatically records the time, process, materials and other data of each maintenance operation, forming a traceable maintenance log. When the environmental conditions change or the disease occurs again, the system calls up the historical data and accurately matches the optimal repair program (Li, 2015).

Conclusion:

One of the manifestations of digital twin technology is that it has brought revolutionary changes to the restoration of traditional residential building paintings. Through high-precision data acquisition and multimodal information fusion, a digital twin is constructed that contains all elements such as geometric form, color spectrum, disease characteristics, etc., to realize virtual simulation and intelligent decision-making of restoration scheme. The technology not only breaks through the physical limitations of traditional inspection means, making the accuracy of disease identification jump more than 80%, but also through parametric modeling and accelerated aging experiments, optimizing the material ratio and process parameters, so that the restoration quality and weathering is significantly enhanced. At the same time, the digital twin platform also provides a new way for skill inheritance and public participation, which truly realizes the revolutionary leap from experience-driven to data-driven protection of traditional cultural heritage.

Conflict of Interest

The author declares that she has no conflicts of interest to this work.

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