Challenges in Color Reproduction and Historical Representation of 3D Models in Digital Heritage Preservation

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ABSTRACT Digital heritage preservation increasingly relies on high-fidelity 3 D r econstruction technologies to ensure the long-term preservation and dissemination of cultural heritage information. However, accurate color reproduction and historical representation remain major challenges, particularly for organic artifacts such as textiles and leather that undergo color fading and material degradation over time. This study investigates the key factors affecting color reconstruction and age representation in digital heritage models, including the loss of original color information, the difficulty of quantifying aging characteristics, and the balance between technical accuracy and visual authenticity. A restoration framework integrating multi-source data fusion, material aging simulation, and expert–algorithm collaboration is analyzed. The approach combines hyperspectral imaging, spectral reflectance a nalysis, c olor-space r econstruction, and optical property modeling to improve color recovery, while material degradation simulation and texture generation are employed to represent aging features. The results demonstrate that the integration of spectral information processing and intelligent reconstruction strategies can enhance the authenticity and interpretability of digital heritage models. This study provides an engineering-oriented perspective for digital preservation, supporting the development of advanced optical sensing, spectral reconstruction, and virtual heritage visualization technologies.

INDEX TERMS digital heritage, hyperspectral imaging, color reproduction, spectral reconstruction

I. INTRODUCTION

WITH the rapid development of digital technology, cultural heritage has entered the digital age. Three-dimensional modeling technology, a method of digital heritage preservation, can break through the constraints of time and space to achieve the long-term preservation and widespread dissemination of cultural relic information, including the intricate microscopic fibers and structural weaving patterns of historical textiles [1]. By capturing the physical texture and drape of ancient silk and tapestries, this technology ensures that the fragile material heritage of the textile industry remains accessible for future research and global appreciation. However, in the practice of digitization, how to accurately restore the original colors of cultural relics and how to realistically represent the traces of history have become major challenges for researchers and practitioners. Especially for organic cultural relics such as textiles and leather, whose colors undergo complex changes and whose materials exhibit unique aging characteristics over long periods of time, digital reconstruction faces even greater difficulties [2]. Color restoration focuses on the spectral-level recovery of an artifact's chromatic identity, aiming to reverse the chemical degradation of pigments. In contrast, the presentation of a sense of age transcends mere color changes, focusing on the cumulative physical transformations of the material substrate, such as topographical wear and structural decay, which serve as a tangible bridge between the past and the present.

II. THE SIGNIFICANCE OF COLOR REPRODUCTION AND THE PRESENTATION OF THE SENSE OF AGE IN 3D MODELS OF DIGITAL HERITAGE

A. THE AUTHENTICITY OF HISTORICAL AND CULTURAL INFORMATION TRANSMISSION

Color and a sense of age are the carriers of historical and cultural information on cultural relics, and also reflect the authenticity and credibility of digital cultural heritage. The colors of cultural relics generally contain elements of the craftsmanship, aesthetic trends, and cultural connotations of their era; accurate color reproduction is a fundamental guarantee of the integrity of historical information [3]. A sense of age is the trace of time on a cultural relic, reflecting its preservation condition and the process of historical change, and is an important basis for the authenticity of the relic. If digital preservation cannot accurately reproduce color and a sense of age, it will cause distortion and fragmentation of historical information, causing the digital heritage to lose its value as historical witness. Accurate color reproduction can help researchers accurately determine the production date, craftsmanship, and cultural attributes of cultural relics, providing reliable evidence for historical research.

B. ENHANCING THE EDUCATIONAL AND DISSEMINATION VALUE OF DIGITAL HERITAGE

High-quality color reproduction and a sense of age significantly enhance the visual appeal and impact of digital heritage, improving its educational and dissemination effects. In museum digital displays, cultural education platforms, and virtual reality experiences, realistic colors and a sense of age provide viewers with a more immersive experience, allowing for a better perception and appreciation of history and culture. Accurate color reproduction allows viewers to directly experience the artistic beauty and craftsmanship of artifacts, sparking their interest in and exploration of history and culture [4]. A realistic depiction of age deepens viewers' understanding of the historical timeline, enabling them to comprehend the historical context and characteristics of the era in which the artifacts were created, thus broadening and deepening historical education.

C. PROMOTE TECHNOLOGICAL INNOVATION IN CULTURAL HERITAGE PROTECTION

The challenges of color reproduction and the representation of age have spurred innovation in cultural heritage preservation technologies, fostering the integration of multiple disciplines to accurately restore the original luster of natural dyes and the delicate fiber integrity of historical textiles. This interdisciplinary approach combines spectroscopic analysis of ancient weaving with digital modeling to authentically capture the weathering of organic materials over centuries [5]. This research encompasses computer graphics, color science, materials science, archaeology, art history, and many other fields, requiring the comprehensive application of technologies such as spectral analysis, 3D scanning, artificial intelligence, and virtual reality. In overcoming the challenges of color reproduction, researchers have developed innovative achievements such as high-precision color acquisition equipment, color space conversion algorithms, and lighting rendering techniques, thus propelling digital technology forward. Advances in representing age have spurred the development of technologies such as material simulation, aging modeling, and texture generation, providing technical support for the realistic reconstruction of digital artifacts. Technological innovation not only contributes to cultural heritage preservation but also has wide-ranging applications in film and television production, game development, industrial design, and many other fields.

III. PROBLEMS IN COLOR REPRODUCTION AND THE PRESENTATION OF AGE IN 2D MODELS

A. LOSS OF ORIGINAL COLOR INFORMATION AND FADING PHENOMENON

Cultural relics suffer irreversible color fading due to factors such as light, temperature, humidity, and microbial erosion during long-term preservation, resulting in a severe loss of original color information. This becomes the primary problem in color restoration [6]. The decomposition of organic dyes, the oxidation of pigments, and the aging of materials all cause color changes, and the colors of existing cultural relics are now vastly different from their original state. Without historical records or reference objects, researchers find it difficult to accurately determine the original color of a cultural relic, and can only speculate based on residual color traces and the color characteristics of similar artifacts from the same period, which carries significant uncertainty. Color acquisition technology can accurately record the current color condition of a cultural relic, but it cannot solve the fundamental problem of the lack of original color information. Different lighting conditions, different acquisition devices, and different color spaces all affect color data [7]. The complexity of fading lies in its unevenness; different parts of the same cultural relic show significant differences in the degree of fading, making color restoration difficult and hindering researchers from establishing unified restoration standards. As shown in Table 1, color fading is the result of multiple factors working together, and different materials exhibit differentiated fading characteristics under different environments, posing a significant challenge to the accurate inference of the original color.

TABLE 1. Factors and Manifestations of Color Fading in Cultural Relics

Influencing Factors	Mechanism Of Action	Fade Behavior	Affected Materials
Light radiation	Photochemical reactions lead to the destruction of molecular structure	Overall fading, localized bleaching	Textiles, leather, dyes
Temperature and humidity fluctuations	Accelerating chemical reactions and microbial activity	Dull color, spots forming	Organic dyes, natural pigments
Microbial erosion	Enzymatic hydrolysis destroys pigment structure	Mold spots, discolored areas	Textile fibers, leather protein
Oxidation reaction	Pigment components react with air	Hue shift, saturation reduction	Metallic pigments and mineral colorants
Accumulated time	Long-term combined effects of multiple factors	Uneven fading, blurred texture	All materials

B. THE CHARACTERISTICS OF A CERTAIN ERA ARE DIFFICULT TO QUANTIFY AND EXPRESS

The sense of age is defined a s t he m ulti-dimensional physical manifestation of time on a cultural relic. While color shifts are a byproduct, the core of 'age' lies in material-specific t races s uch a s s urface a brasions, micro-fractures, and the evolution of surface gloss (BRDF), rather than the chromatic fading itself. These characteristics are highly complex and subjective, and cannot be quantified using objective parameters. Different materials show different signs of aging, and different preservation environments result in different traces of age; there is no unified quantitative standard or evaluation system. In the process of 3D modeling, the main challenge is how to transform the abstract concept of age into precise digital descriptors such as fractal dimensions for cracks or spatial entropy for stains to bridge the gap between subjective perception and algorithmic execution. Existing material simulation technologies mainly simulate physical properties and are relatively weak in expressing cultural and aesthetic attributes such as age [8]. The presentation of age also involves the observer's subjective feelings; viewers with different cultural backgrounds and aesthetic experiences have different perceptions of age. Balancing objective reality and subjective feelings in the digital model to effectively convey the sense of age requires a deep integration of technology and art. Table 2 establishes a scientific transition from qualitative descriptions to multi-dimensional quantitative indicators. By defining specific metrics like spectral variance and topological connectivity, it provides the necessary mathematical boundary conditions for the intelligent algorithms proposed in the subsequent strategy sections.

TABLE 2. Quantitative Indicators and Technical Dimensionality of Visual Characteristics of Age

Feature Type	Specific Manifestations	Quantification Difficulty	Major Obstacles	Proposed Quantitative Indicators (Technical Dimension)
Stale color	Reduced saturation, hue shift	medium	Lack of original reference standards	Spectral Reflectance Variance &CIELAB Color Difference (ΔE) Analysis
Material wear	Surface gloss reduced, texture blurred	higher	The degree of wear varies depending on the location.	Bidirectional Reflectance Distribution Function (BRDF) & Surface Roughness (Ra)
Crack morphology	Distribution of fine crack network	high	The formation mechanism is complex and variable.	Fractal Dimension Analysis & Topological Connectivity Metrics
stains	Irregular contaminated areas	Very high	Highly random and difficult to predict	Gray-Level Co-occurrence Matrix (GLCM) & Spatial Distribution Entropy
Structural Aging	Internal fiber degradation	Extremely high	Involves subjective aesthetic judgment	Micro-CT Porosity & Fiber Orientation Tensor Analysis

C. THE DILEMMA OF BALANCING TECHNOLOGICAL MEANS AND ARTISTIC AESTHETICS

Color reproduction and the presentation of a sense of age are both technical and artistic issues, requiring a balance between scientific accuracy and artistic expression. Overemphasizing technical precision can result in digital models that appear mechanical and lifeless, failing to capture the artistic charm and historical flavor of cultural relics [9]. Conversely, overemphasizing artistic expression can compromise the authenticity of the relics, reducing the scientific value and credibility of digital heritage. Cultural relic restoration and digital reconstruction involve significant subjective judgment and artistic processing. Restorers must make decisions based on professional knowledge and aesthetic experience, creating an inherent tension between subjectivity and the objectivity and repeatability sought by digital technology. Different researchers and different restoration philosophies will yield different restoration results. Establishing scientifically sound restoration standards and ensuring appropriate artistic processing while maintaining the authenticity of the relics are practical challenges. The balance between technology and art is reflected in the trade-off between efficiency and quality. High-precision color reproduction and the recreation of a sense of age require enormous human and material resources. Finding the best combination of technology and art within limited conditions is a problem that digital heritage preservation must address. Table 3 illustrates the complexity of balancing technology and art [10]. Each dimension requires finding a suitable balance between two extremes. This balance is not fixed, but rather a dynamic process that is adjusted according to the type of cultural relic, its preservation condition, and its intended use.

TABLE 3. Key Dimensions for Balancing Technological Means and Artistic Aesthetics

Balanced Dimensions	Technology-oriented characteristics	Artistic orientation characteristics	Balanced strategy
Color accuracy	Strictly follow the measurement data	Emphasis on visual harmony and aesthetics	Establish an acceptable error range
The sense of age	Accurately simulate the physical process of aging	Creating a historical atmosphere and emotions	The classification reflects the state of different periods.
Restoration concept	Pursuing repeatability and objectivity	Incorporating expert experience and judgment	Establish a transparent decision-making mechanism
Resource input	Automated processing improves efficiency	Manual finishing ensures quality	Key parts should be treated with special attention.
Evaluation criteria	Quantitative indicator system	Subjective aesthetic judgment	Multi-dimensional comprehensive evaluation system

IV. STRATEGIES FOR COLOR REPRODUCTION AND AGE REPRESENTATION IN 3D MODELS

A. COLOR RECONSTRUCTION TECHNOLOGY BASED ON MULTI-SOURCE DATA FUSION

Multi-source data fusion strategy integrates multiple color information sources to improve the accuracy and reliability of color reproduction. First, hyperspectral imaging technology is used to acquire detailed spectral data of the artifact's surface, analyzing the reflectance characteristics of different bands to identify color components and fading levels, providing a scientific basis for inferring the original color. Second, a color knowledge base is established by combining historical documents, artifacts from the same period, and traditional craft data, providing a reference standard for color reproduction [11]. Parallel to these efforts, precision color measuring instruments are utilized to sample multiple surface points to obtain accurate values within the device-independent CIELAB color space. This choice facilitates the precise calculation of color differences (Δ E) between the current state and the predicted original st ate, while also providing a translation path to the CIE XYZ space for high-fidelity spectral reconstruction, thereby ensuring the objectivity and comparability of the color data. During the data fusion process, a structured algorithmic framework is employed to synthesize spectral and historical data. Specifically, a supervised machine learning model is utilized to map the non-linear relationship between current degraded spectral reflectance curves and the chemical composition of original natural dyes. The strategy implements a multi-objective optimization algorithm to resolve data conflicts, where expert-defined historical constraints act as a regularization term. This ensures that the predicted color values remain within the 'physically possible' gamut of the era's craftsmanship. To ensure feasibility, the fusion process assigns dynamic weights to data sources: high-precision spectral data dominates the base hue reconstruction, while historical textual records provide the saturation and brightness boundaries for final calibration [12]. To more clearly demonstrate the complete technical path of multi-source data fusion, Figure 1 presents the entire process framework from data acquisition to color prediction.

B. METHODS FOR REPRESENTING AGE BASED ON MATERIAL AGING SIMULATION

Material aging simulation is a key technical approach to achieving a sense of age. By establishing distinct physical and visual models for material degradation, the 3D modeling process can decouple chromatic restoration from structural aging. The simulation strategy focuses specifically on the kinetic laws governing surface morphology-such as the propagation of crack networks and the erosion of fiber density-ensuring that 'age' is represented as a structural and textural state rather than a simple color variation. Subsequently, procedural texture generation technology is used to automatically generate surface textures with a sense of age based on the aging model. Details such as stain distribution, wear areas, and crack morphology are incorporated to make the 3D model more realistic [13]. Finally, a physical rendering engine is used to simulate the scattering and absorption of light on the surface of aged materials, converting reconstructed CIELAB values into wide-gamut linear color spaces (such as ACEScg or Adobe RGB) for realistic light transport simulation. This process realistically represents changes in the material's optical properties and creates a visual effect of advanced surface weathering. In representing age, realism and aesthetics must be balanced; the artistic value and aesthetic appeal of the cultural relics should not be destroyed in the pursuit of a sense of decay. Furthermore, a parametric control system for representing age is established, allowing researchers to adjust the degree of aging according to actual needs, thus conveniently displaying the condition of cultural relics from different historical periods. Material aging simulation should be combined with knowledge from disciplines such as archaeology and materials science to ensure that the simulation results conform to the actual aging laws of cultural relics and improve the scientificity and credibility of the age representation.

C. REPAIR PATH BASED ON COLLABORATION OF EXPERT KNOWLEDGE AND INTELLIGENT ALGORITHMS

The strategy of collaborating expert knowledge with intelligent algorithms leverages both the advantages of human professional judgment and the characteristics of computer data processing to achieve optimal color restoration and the representation of age. First, an expert knowledge base is established, compiling professional knowledge and experience rules from fields such as cultural relic restoration, archaeology, and art history to provide domain knowledge support for intelligent algorithms. Second, an interactive restoration system allows experts to intervene and modify the digital restoration process in a timely manner, incorporating their opinions into the algorithm's decision-making process and improving the rationality and accuracy of the restoration results. Deep learning methods are used to train the color restoration and age generation models, enabling automatic recognition and restoration after learning from a large amount of labeled data, thus improving efficiency. A human-computer interaction interface is created during the collaboration process, graphically displaying the algorithm's results, which are then reviewed and corrected by experts, forming a cycle [14]. Additionally, an expert evaluation system is developed to assess the authenticity, artistry, and technical aspects of the restoration results, providing feedback for algorithm improvement. The collaboration between expert knowledge and intelligent algorithms is reflected in knowledge transfer, recording the expert restoration decision-making process, extracting tacit knowledge, and converting it into rules that the algorithm can understand, achieving the goal of digitally transferring professional experience. Collaborative approaches have improved the

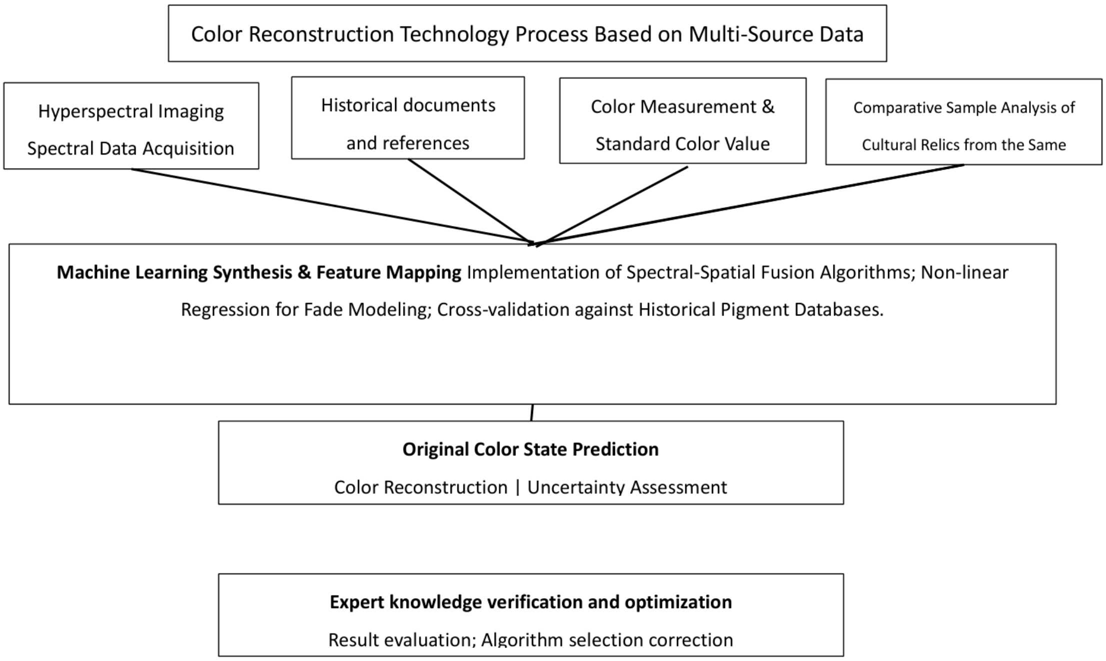

FIGURE 1. Color reconstruction technology process of multi-source data fusion

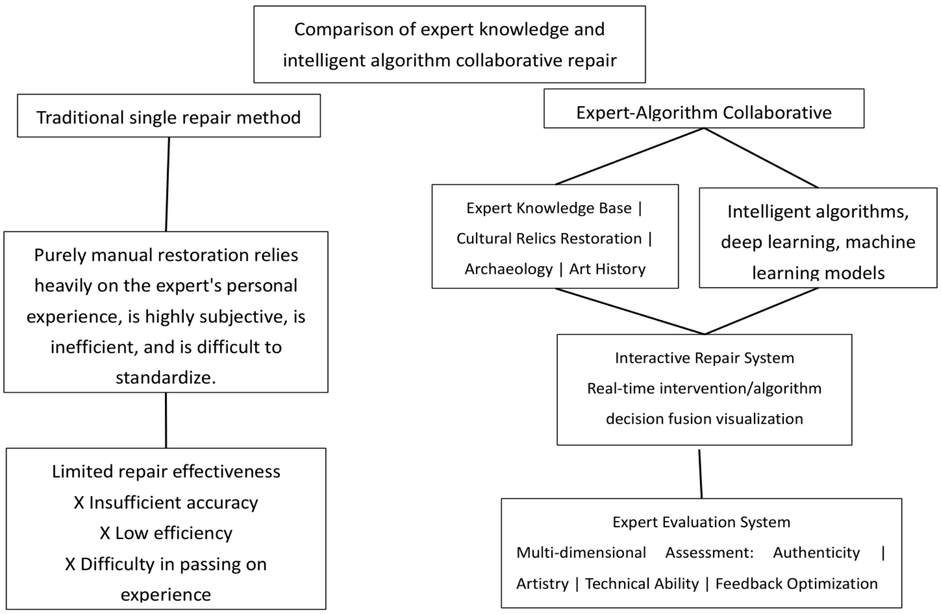

FIGURE 2. Comparison of collaborative repair using expert knowledge and intelligent algorithms

quality of digital heritage preservation and opened up new avenues for the intelligent development of cultural heritage protection [15]. To highlight the advantages of collaborative strategies, Figure 2 compares the differences between traditional single restoration methods and expert-algorithm collaborative models, visually demonstrating the significant improvements in accuracy, efficiency, and knowledge transfer brought about by collaborative approaches.

V. CONCLUSION

The color restoration and aging representation of 3D models in digital heritage preservation are important topics for the authentic transmission of historical information, necessitating the precise digital reconstruction of faded natural dyes and the structural degradation of ancient textile fibers. These technologies ensure that the intricate weaving patterns and material textures of historical fabrics are effectively disseminated while maintaining their cultural and chronological integrity. Color restoration and aging representation face many challenges, including the lack of original information, difficulties in quantifying features, and the balance between technology and art. These challenges require solutions through multi-source data fusion, material aging simulation, and the collaboration of expert knowledge and intelligent algorithms. Future research should continue to promote interdisciplinary collaboration, technological innovation, and theoretical innovation to create a more complete system for color restoration and aging representation, supporting the high-quality preservation of digital heritage. Only by simultaneously advancing science and technology and upholding humanistic values can we achieve the goal of authentically protecting and permanently transmitting cultural heritage, allowing historical culture to radiate new vitality in the digital age.

AUTHOR CONTRIBUTIONS

Zhang Li designed, collected and analyzed the data, and drafted the manuscript. Zhang Li conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Zhang Li participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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REFERENCES

[1] J. Wu, H. Tian, and W. Yan, “Application of GANs in Ancient Architectural Heritage Image Restoration,” npj Heritage Science, vol. 13, no. 1, pp. 655, 2025, doi: 10.1038/s40494-025-02234-4.

[2] Y. Li, “Applications of Diffusion Model Image Restoration in the Field of Heritage Restoration: Overview and Outlook,” Frontiers in Artificial Intelligence and Applications, 2023, doi: 10.3233/faia230895.

[3] F. Rahman and A. Nayak, “Drone-Based 3D Modeling for the Conservation and Restoration of Heritage Buildings,” Architecture Image Studies (AIS), vol. 6, no. 1, pp. 46-55, 2025, doi: 10.48619/ais.v6i1.1090.

[4] J. Li, H. Jawadwala, A. Pan, J. Jeon, Y.-C. Lin, M. Hasheminasab, et al., “Digital Reconstruction and Restoration of Architectural Heritage: Samara House,” Technology|Architecture + Design, vol. 6, no. 2, pp. 232-245, 2022, doi: 10.1080/24751448.2022.2116243.

[5] S. L. K. Siu, “Application of 3d scanning technology in restoration of heritage site damaged by natural disaster,” International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences, vol. XLVI-M-1, pp. 685-691, 2021, doi: 10.5194/isprs-archives-XLVI-M-1-2021-685-2021.

[6] B. Rodriguez-Garcia, L. Corchia, F. Faggiano, D. García-Tejerina, and L. T. De Paolis, “A Tool for the Analysis and Virtual Reality Visualization of the Virtual Restoration of Cultural Heritage 3D Models,” in International Conference on Extended Reality. Cham: Springer, 2024, pp. 173-184, doi: 10.1007/978-3-031-71710-9_13.

[7] A. Mansour, M. Saleh, and A. Serwa, “3D Modeling and Digital Documentation of Heritage Architecture for Preservation and Restoration,” Journal of Engineering Sciences, pp. 54(2), 2026, doi: 10.21608/JESAUN.2025.398784.1581.

[8] E. Diz-Mellado, J. Perez-Fenoy, M. Mudarra-Mata, C. Rivera-Gómez, and C. Galan-Marin, “Enhancing 3D-Printed Clay Models for Heritage Restoration Through 3D Scanning,” Applied Sciences, vol. 14, no. 23, Art. no. 10898, 2024, doi: 10.3390/app142310898.

[9] H. O. Ahmed, T. Alfaqheri, and A. H. Sadka, “Digital Image Inpainting Techniques for Cultural Heritage Preservation and Restoration,” in Data Analytics for Cultural Heritage. Cham: Springer, 2021, pp. 91-122, doi: 10.1007/978-3-030-66777-1_5.

[10] M. Juneja, D. Bajaj, N. Thakur, and P. Jindal, “Reproduction of human dental models using different 3D printing techniques,” Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 2024, doi: 10.1177/09544089241239591.

[11] A. Kroshnin, V. Vasilev, E. Ershov, D. Shepelev, D. Nikolaev, and M. Tchobanou, “On the properties of some low-parameter models for color reproduction in terms of spectrum transformations and coverage of a color triangle,” Journal of the Optical Society of America A, vol. 39, no. 3, pp. 452-458, 2022, doi: 10.1364/JOSAA.447508.

[12] Y. Li and Z. Shi, “Digital Restoration and Reproduction of Historical Monuments Based on 3D Point Cloud Scanning and Model Repair Technology: A Case Study of the Ming Dynasty’s Wooden Memorial Archways,” Proceedings of the 2024 International Conference on Digital Society and Artificial Intelligence, pp. 341-345, 2024, doi: 10.1145/3677892.3677946.

[13] J. Guo, G. Song, C. Zhao, and Y. Bai, “HISTORICAL-IMMERSION – Immersive Memory Reproduction System Based on 3D Scanning and Multi-modal Interaction,” in International Conference on Human-Computer Interaction. Cham: Springer, 2025, pp. 20-30, doi: 10.1007/978-3-031-94165-8_3.

[14] Y. Xu, M. Xie, and S. Xiong, “Application of Virtual Reality Technology in Historical and Cultural Landscape Reproduction,” Applied Mathematics and Nonlinear Sciences, pp. 9(1), 2024, doi: 10.2478/amns-2024-1583.

[15] F. Bianconi, M. Filippucci, F. Cornacchini, M. Meschini, and C. Mommi, “Cultural heritage and virtual reality: application for visualization of historical 3d reproduction,” International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences, vol. 48, no. M/2, pp. 203-210, 2023, doi: 10.5194/isprs-archives-XLVIII-M-2-2023-203-2023.