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Key Technologies for the Digitization of Cultural Relics and Their Application in Digital Museums

Ping Li[1,2], Yanqun Liu[1] & Kun Zhou[2]

[1] Shandong University, China

[2] Shandong Museum, China

Correspondence: Ping Li, Shandong University, Shandong Museum, Jinan, Shandong, China.

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Abstract

Cultural relics embody a nation's memory as well as the codes of civilization. As fragile and non-renewable items, they demand novel methods of protection. Digitalization technology is used on cultural heritage, particularly high precision 3D reconstruction of digitization and multilateral data fusion techniques, has opened up new paths to permanently preserving and revitalizing cultural heritage. This journal intends to systematically review the primary technologies of the digitization processes for cultural relics, evaluate their concrete application models and the key bottlenecks facing the construction of digital museums and then the feasible paths of implementation. The ultimate aim is to produce further cultural dissemination and educational credit for the cultural relic digital resources in contemporary society.

Keywords: digitalization of cultural relics, digital museums, revitalization of cultural heritage

1. Introduction

Under the threatening dual hindrance of time erosion and spatial damages, a lot of valuable cultural relics are at risk of antiquating, and the contained culture, inherent artistic qualities are difficult to disseminate far and wide. Traditional preservation means have limitations, while technology has made rapid advances in digital dispositions and this has been a strong positive impetus in the world of cultural heritage. The digitization of cultural relics is more than a replacement for physical preservation, it is positioning to create selective, interactive and infinitely replicable digital twins. It is futurist analogy consisting of many complicated components, like data retrieval, processing, managing, and innovating; but is most essentially transformational allowing cultural relics to dig into the rampant hidden potential in closed acquisitions or glass displays. Digital twins can eventually be seen and studied in another unconventional realm of cultural inheritance.

2. Core Technologies and Processes for Cultural Relic Digitization

2.1 High-Precision 3D Data Acquisition Technology

High-precision 3D data acquisition is the first step in creating a digital model of cultural relics. Use of specialized equipment helps record the geometric forms and surface characteristics of relics with accuracy. Structured light scanners or laser scanning devices project specific light patterns or laser beams onto the relic, and sensors read the information about how the light is altered in terms of deformation of the pattern or reflection off of the relic. These variations are sensed by the equipment and documented and transformed into a collection of points in space to describe the surface contour of the relic. The operators are able to systematically adjust the location and angle of equipment to ensure that the light covers all details remitted from the target area's features involving complexity of the texture or interior structure of the relic. An array of high-resolution reference cameras records a multi-angled image set covering all sides of the relic simultaneously, ensuring true color and texture information. After the equipment completes the initial positioning, it automatically executes the scanning program, generating raw point cloud data containing millions of spatial points and a large number of corresponding images. When the scanned data is imported into the workstation, specialized software automatically aligns and fuses the point cloud and images to construct a 3D model that combines precise geometric shapes with realistic visual appearance, laying the foundation for subsequent work.[1]

2.2 Texture Information Fidelity Processing

Restoring realistic surface textures is a critical stage after 3D high precision construction is completed. Operators will use professional high-resolution digital cameras in a controlled lighting environment to capture thousands of multiple overlapping photographs of cultural relic from various directional perspectives and rotational angles. The angle and distance from which every shot was made with the camera must be calculated exactly; the entire surface of the cultural relic must be covered. The equipment is equipped with a colour management module that monitors in real time changes in ambient light and automatically corrects colour shifts that occur due to ambient light shifts. During the shooting process, operators need to observe the surface gloss features of the cultural relics repeatedly and manually change the angle or intensity of the lighting source so that the details in the highlighted areas or S/B characteristics are not lost, nor consistent textures become lost in shadows.

When the image sequence is imported into the workstation, the dedicated mapping software automatically identifies the model area corresponding to each photo. The intelligent algorithm analyzes the overlapping parts of adjacent images, accurately integrates color differences, and eliminates stitching artifacts. Based on the geometric structure of the model, the software seamlessly maps the optimized images onto the three-dimensional surface, generating texture maps with accurate colors, clear details, and natural transitions. The final output digital model not only has precise morphology but also exhibits a surface texture, color, and subtle historical traces that are highly faithful to the original cultural relic state.

2.3 Lightweight Model Construction

Although high-precision 3D models are rich in detail, their massive data volume makes it difficult to run smoothly on ordinary devices. Engineers use professional modeling software to intelligently simplify the original model. The software algorithm accurately identifies and removes redundant triangular facets on the surface of the object that do not affect the visual contour, while retaining key feature structures. The high-resolution texture mapping on the model surface is re-optimized and processed. Compression tools convert large-sized images into small files suitable for network transmission, while applying color compression technology to maintain texture clarity and color accuracy.[2]

During processing, it’s important to preview the display effects of the model on different devices multiple times and make real-time adjustments to the simplification level to make sure there are no broken surfaces or blobbed out details while loading on mobile devices and web pages. The final output lightweight model, which preserves the primary shape and the surface visual characteristics of the cultural relic, is greatly reduced in data volume and can be efficiently applied in online display platforms, mobile applications, and virtual reality scenes to fulfill the public's need for instant access to digital cultural relics anytime and anywhere.

2.4 Multi-Modal Data Fusion Management

Faced with diverse and heterogeneous data such as 3D point clouds generated by scanners, high-definition images captured by cameras, historical documents, and inspection reports,the technical team of archaeological institutions or institutions of cultural relics and museums must establish a logically rigorous database architecture to achieve unified management. Staff members assign unique digital identifiers to each artifact, and the database automatically aligns and binds the 3D model with the corresponding surface texture based on spatial coordinates. At the same time, it associates repair records, research literature, and other materials with specific structural layers of the model through keyword tagging. The built-in retrieval module of the system supports users to quickly locate the target artifact by date, material, or decorative pattern characteristics, and retrieve all associated multidimensional data with one click. This structured integration model enables fragmented information to form an organic knowledge network, providing a complete data chain support for subsequent research and display.

3. Key Bottlenecks in Digital Museum Construction

3.1 Insufficient Precision in Complex Cultural Relic Digitization

When faced with the complex hollow forms of bronze vessels or the light cracks on ceramic vessels, existing scanning apparatus has great difficulty in fully detecting the geometric characteristics of hidden locations. This is primarily true when artifacts are comprised of deep holes or overlapping structures that result in blind areas, which laser beams are unable to access, resulting in gaps in the point cloud data. Without ability to point cloud values from additional angles through the operator's supplementary scanning, the surface characteristics of some of the special material reflections still caused distortion and distortion to scannot be avoided in the rag retrieval of collected data. The current technical developments represent a major challenge for high-precision reconstruction of the full shape of such complex artifacts.

3.2 High Costs Hindering Widespread Adoption

The procurement costs of high-end 3D scanners and professional-grade cameras often reach tens of thousands of dollars, making it difficult for grassroots museums to afford the core equipment renewal needs within their budgets. The technical team of archaeological institutions or institutions of cultural relics and museums require continuous investment to maintain equipment calibration and software upgrades, and the daily operational and maintenance expenses for high-precision scanning consumables and dedicated storage servers further exacerbate financial pressure. Professional engineers need to customize acquisition plans based on the characteristics of different cultural relics, and the digitization process for a single cultural relic often takes several weeks of work, with labor costs accounting for a significant proportion of total expenditure. The storage of massive amounts of data and the rental costs of cloud computing resources continue to accumulate as the number of cultural relics grows. Limited institutional budgets force a large number of precious cultural relics to remain outside the digitization process for extended periods, urgently requiring the exploration of sustainable cost control solutions.

3.3 Lack of Depth in Interactive Experiences

Most of the interactive functions provided by digital museums only allow for basic operation on the model such as rotation and zooming, making it impossible for visitors to gain deeper insights into the internal structure, craftsmanship details, etc. Most of the commentary systems developed by technical teams pick a linear path through experience lacking the studying ability to dynamically generate personalized content addressing visitors' interest points. Current devices possess a single feedback mode for user behavior without multi-sense response mechanism, while basic touchscreen operations only stimulate fixed graphic descriptions without deeper learning potential- weakening the sense of immersion of historical situations. Usually, systems are unable to detect the cognitive level of the user, although it is quite common for systems to display a variation of standardized information of the same depth for users of different levels of knowledge, meaning both a professional researcher and a somewhat average individual could have a similar superficial reading. Aspects that point towards a hyper-real feel in the virtual environment, rely on the recreation of a macro level of experience reflecting history as opposed to the contextualization, that is social importance, and even definition, of how culture artifacts are 'used,' is very limited in a digital museum context; this makes it difficult for the visitor to relate the object to its intrinsic functional and symbolic meaning in cultural context through interaction.[3]

3.4 Fragmented Interpretation of Historical Information

The 3D models of cultural relics, archaeological site images, and historical documents stored on digital platforms are scattered across independent database modules. When viewers look up a Shang or Zhou Dynasty bronze tripod, the interface only displays basic dimensions and excavation site information. The casting process analysis report and videos of ritual scene reconstructions from the same period need to be manually retrieved across systems. The association rules established by the technical team are limited to material classification and chronological labels. The evolution of the beast-face pattern on this bronze tripod cannot be automatically linked to the pattern lineage of similar artifacts unearthed from other tombs. When viewers try to understand the trade system of the Maritime Silk Road in the Tang Dynasty, the fragmented information provided by the platform includes scattered chemical testing data of ceramic fragments, port site distribution maps, and clothing characteristics of Hu merchants' figurines, lacking a dynamic narrative framework that connects these elements to present the trade routes, kiln production, and the fusion of exotic cultures. This fragmented information supply makes it difficult to fully present stories of cultural evolution, such as the dissemination path of engraving techniques on celadon porcelain from the Yaozhou Kiln in the Northern Song Dynasty and the import chain of cobalt materials for blue and white porcelain in the Yuan Dynasty. Viewers' cognition remains at the level of isolated cultural relics and cannot construct a comprehensive picture of cultural dissemination.

4. Practical Pathways for Key Technologies to Empower Digital Museums

4.1 Construction of Cultural Relic Digital Resource Repositories

Based on a standard of consistency, the technical team of archaeological institutions or institutions of cultural relics and museums standardizes the way to processing the stored cultural relics. When the stored high precision 3D models are created after scanning, the high precision data is kept with key features for further use and lightweight kick parameters are retained. The data administrator will use a color calibration tool to adjust the texture mapping that can produce similar colors in the same object based on different lighting conditions. For the digitalization outcome of a portioned ceramic piece fragmented design, the user has to annotate within the platform the original stitching relationship. The database framework is designed as a multi-tiered system, with the raw point clouds and high-resolution images located at the first tier; lightweight models are located at the second tier, where datasets can be rapidly invoked; and at the top tier, repair records, archaeological reports, and multimedia commentary resources are differentiated and associated. The platform developers create discrete knowledge nodes for each cultural relic, and the spatiotemporal coordinates tether all the mineral composition detection data of the bronze vessels, and all video of the bronze vessels casting process, to the 3D models of the bronze vessels. The data from the Ming Dynasty paintings and calligraphy makes visible the ways that the inscription and seal data are cut from high-resolution partial images adjacent to their locations beside the picture. The system establishes permissions at numerous levels allowing researchers to view the original detection data, educators to invoke streamlined models fit for teaching, and the public to access basic models and guided authoring through the interface. The resource library, updated regularly, is in the process of onboarding cross-institutional digital assets, creating a living knowledge network of how artifacts evolve and their technoscientific genealogy.[4]

4.2 Immersive Virtual Exhibition Hall Applications

In many demonstrative practice case of digitalization of cultural relics in China,the technical team of archaeological institutions or institutions of cultural relics and museums has created a 3D scene of the architectural complex of the West Market in Chang'an during the Tang Dynasty, using archaeological research results. The models of the shop signs, and street props researched by historians have been made interactive objects in the virtual 3D space. Participants can wear VR headsets and have the ability to walk on the stone pavement and interact with the ceramic figures of foreign merchants on each side. Hardware engineers installed an array of motion capture cameras in the physical exhibition hall, which allows participants to engage with the digital holographic projection of a bronze vessel fixed in the exhibit case by gesturing in the air. When the object is rotated, the surface of the projection identifies the casting seams with the pattern of Taotie (a mythical creature). The system developers created a layered anatomy feature for the Han Dynasty silk paintings where viewers can slide their fingers with manipulation to peel off one paint layer at a time to discover the line drawings underneath. A simultaneously played animation of the weaving process demonstrates the mechanism of how paint and silk threads are combined. The cloud server processes multi-user interaction data in real time. When visitors gather in front of the virtual Dunhuang grottoes, the system automatically triggers changes in the lighting and shadows of the murals from different perspectives. The exclamations collected by microphones are processed by algorithms and transformed into ambient sound effects echoing inside the grottoes. The mobile adaptation module compresses large scene data, allowing visitors to scan the QR code in the exhibition hall with their mobile phones to use AR function to overlay the King of War Ding on their own dining table to view the details of the inscriptions. Regularly updated themed virtual exhibitions break through the limitations of physical exhibitions, allowing visitors to enter the special exhibition space online at any time to participate in curator-led nighttime salon activities.

4.3 Construction of Cultural Relic Knowledge Graphs

Data engineers clean and integrate artifact description texts from archaeological reports and museum collection archives, converting professional terminology such as bronze casting techniques and ceramic glaze formulas into standardized entity labels for input into the graph system. Algorithms automatically identify the spatial correlation between the unearthed epitaph records of Tang Dynasty sea beast grape mirrors and the Silk Road route maps of the same period, creating multidimensional attribute nodes for each artifact that include time coordinates, geographical coordinates, and craft schools. Knowledge modelers configure rules based on the functional classification system of bronze ritual vessels, and the system automatically establishes semantic connections between the combinations of Shang and Zhou Dynasty bronze vessels and ritual vessels in sacrificial scenes. When a viewer diagrams a bronze gu, at that moment, the graph moves to other combinations of wine vessels and ritual positions in a simultaneous manner. To create a structure as software developers do, structured data interfaces are opened. And, for instance, after researchers upload reports from new kiln site exploration, the graph can directly auto-match the Song-era iron-bearing celadon shards with sources of a distinct kiln characteristic to update the spatiotemporal network of dynamics in a paths of artifact dissemination. The front-end designers take the relationships from the graph and interpret those into distinct visual dynamic context diagrams. Now as a viewer, you might find themselves in the graph and click on the Jingdezhen kiln node and see an interactive timeline of the cobalt-based blue and white porcelain import route from the Yuan dynasty, with artisan registration management system and patterns taking shapes that have transformed over time and space. Once passed through academic review, the public editing module allows enthusiasts to annotate special patterns onto a lacquerware piece, and knowledge from user-added folk usage records are connected to the knowledge network after data cleaning to become an ever-growing opportunity for civilizational cognition.[5]

4.4 Audience Co-Creation Experience Design

In recent years,the digital technical team of cultural relics in China has developed a digital tool for assembling cultural relic fragments. When visitors assemble fragments of Yuan Dynasty blue and white porcelain plates online, the system compares them in real-time with data from complete vessels in the museum collection. Each correctly matched set of decorative patterns automatically unlocks the story of the pattern's extraterritorial dissemination. The virtual curation module configured by the education specialist opens up some 3D models of Tang Dynasty pottery figurines. Visitors can drag the figurines to different living scenes to create their own music and dance display schemes. The system records high-frequency combinations and automatically generates recommendations for popular theme exhibitions. Technical staff have embedded annotation functions in the digital mural interface. Visitors can circle and select the flying ribbons of the Dunhuang Flying Apsaras and add personal interpretations of dance poses to name them. Once the back-end has reviewed and approved annotation compliance, compliant annotations will be shown as public comments. The system architect built a user creation library. Visitors upload hand-drawn sketches of the Song Dynasty tea ware usage scenes, and the drawings are digitized and attached to models of tea cups stored by the museum to create a digital exhibition wall of living history. After opera enthusiasts matched vocal segments recorded from Kun Opera performances to 3D models of Ming Dynasty costumes, immersive historically-based short dramas were automatically generated that displayed auxiliary subtitles. This open platform regularly publishes design challenges for bronze ornamentations, and after screening, the recreation schemes of the Taotie pattern by visitors are shown as animated light effect sculptures on a holographic projector in the physical exhibition hall for a curated audience. The names of visitors who were selected as participants are permanently recorded in the digital exhibition contribution wall to provide a continuously encouraging co-creation ecosystem.

5. Conclusion

Digital technology for cultural relics, and the application of that technology for digital museums, are augmenting the way the general public engages with and understands cultural heritage. It is an issue that not only breaks through the spatial limitations resulting from the conservation and exhibited space as we have physical cultural relics, but also reconstructs and transforms static historical remains into culturally dynamic stories through digital pumping avenues where virtual exhibition halls can be immersive, knowledge graphs of structured knowledge, and co-creating cognitive experiences. There are still bottlenecks, such as acquisition high-precision, cost-control and deeply interactive engagement that need to be consistently worked on, but also the development of digital resource libraries and searching specific to new application models that are enhanced through technology, have given cultural relics a new life through doing this. Ultimately, as cultural relics continue to gain traction through the digitization of these momentums followed by technology, we will importantly see the depth of our technology innovation rise with humanistic interpretation, allowing public cognition deepened and a memory that transcends time and space is no longer image-utilizing a point of reference, and can be one way an history scholar would see it, a potential bridge linking past and future of human civilization.

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