Research on Key Technologies for Digital Reconstruction of Immovable Cultural Relics

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Abstract: With the continuous advancement of modern optical acquisition technologies, 3D scanning has developed techniques for collecting point cloud data from irregular object surfaces, playing a vital role in cultural heritage preservation. The key technology for digital reconstruction of immovable cultural relics lies in the synchronized processing of color point cloud information, requiring secondary registration of color and artifact positioning data. This study focuses on three aspects: the acquisition and preprocessing of color point clouds, grid reconstruction and parameterization of artifact color point clouds, and the development of 3D digital display platforms. By addressing the unique characteristics of immovable cultural relics, the research aims to provide technical references for achieving digital preservation and utilization of traditional cultural heritage.

Keywords: Digital Reconstruction; Immovable Cultural Relics; Point Cloud Fusion; Virtual Display

1. Introduction

As one of the "Four Ancient Civilizations of the World", China has left behind a wealth of culturally rich and uniquely valuable heritage throughout its 5,000-year civilization. Immovable cultural relics, characterized by their vast scale and exceptional historical-cultural significance, require meticulous preservation. To restore artifact data and document original information, digital reconstruction technology enables in-depth exploration of their value while ensuring protection. These reconstructed models can be presented through interactive displays, virtual reconstructions, and holographic projections, enhancing exhibition impact and improving management efficiency. This approach plays a vital role in safeguarding China's cultural legacy and advancing its cultural development.

2. Acquisition and Preprocessing of Color Point Clouds for Immovable Cultural Relics

2.1 Preprocessing Method for Cultural Relics Image Point Cloud Collection

A 3D point cloud represents a collection of spatial points that characterize the surface features of a target object, containing numerical values of various 3D spatial coordinates. This collection is denoted as E, a 3D spatial domain. Practical applications in digital reconstruction require more sophisticated 3D point cloud representations, which not only include spatial coordinates but also need additional information such as normal vectors, curvature values, and RGB color data. Depending on the acquisition principles, point cloud datasets exhibit distinct spatial distributions, which can be broadly categorized into four types as shown in Figure 1.

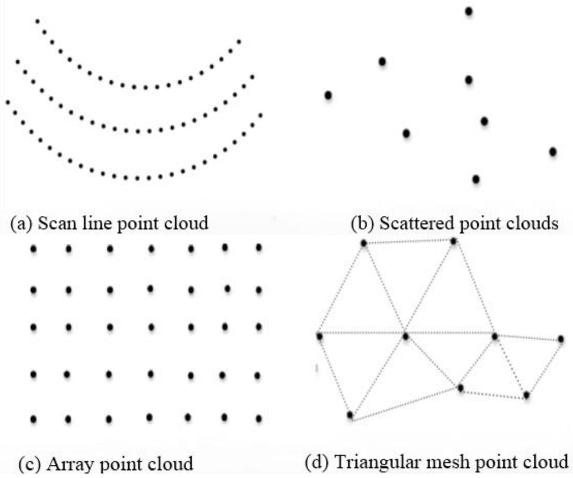

Figure 1. Four Types of Point Cloud Distribution

3D scanning systems still face challenges in systematically organizing point cloud data from immovable cultural relics, with issues like excessive isolated data points and prominent noise. The preprocessing of collected artifact image point clouds involves two key steps: noise removal and data simplification. Most noise points originate from overly smooth material surfaces, operational errors, or environmental interference. Discrete points that deviate significantly from authentic 3D point clouds and exhibit uneven spatial distribution are manually deleted. For mixed points blending with the 3D surface, filtering algorithms such as Laplacian filtering and bilateral filtering are employed [1].

After completing the preliminary processing of noise-contaminated point clouds, the data volume contained in the point cloud significantly decreases, but the complete point cloud still contains a substantial amount of data. To meet processing efficiency requirements, the acquired point cloud data needs to be simplified. For the 3D point cloud collection in digital reconstruction of immovable cultural relics, the definition of simplification calculation is completed. Methods such as mean point distance simplification and centroid-based simplification algorithms can achieve hierarchical decomposition of point samples [2]. Starting from the triangular partition of input sample point clouds, local features of the sampling region are calculated, and linear programming-based simplification is applied to optimize point cloud data. The minimized function objectives sequentially clarify regional information data and local features, enabling targeted simplification of point cloud data [3]. The preprocessing of point clouds is crucial for obtaining positional and color information in digital reconstruction. To preserve the most authentic, high-definition, and faithful color representation of cultural relics, optimized point cloud data undergoes color registration and hole repair processes, ultimately yielding a 3D digital mesh model.

2.2 Colorful Point Cloud Collection and Preprocessing

This study focuses on immovable cultural relics, with the collection system comprising portable scanners, mobile artifact scanning platforms, and high-performance workstations to ensure stable illumination for artifact data acquisition. The color 3D scanner captures surface point cloud data directly, enabling colorized 3D scanning of various immovable artifacts and supporting reverse engineering reconstruction for most 3D objects [9]. The system utilizes an integrated LED white light pattern projector that precisely tracks digital model changes through triangulation principles. Combined with intelligent positioning technology, it rapidly acquires surface data, constructs a numerical coordinate system, and completes data collection via coordinate system conversion (see Figure 2).

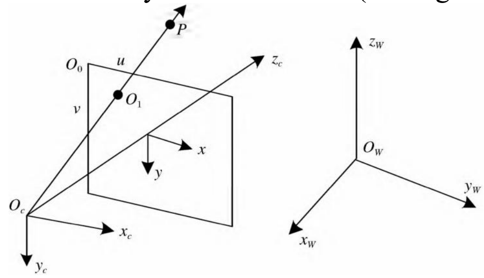

Figure 2. Acquisition of Color Point Clouds of Cultural Relics Images

Figure 2 illustrates the camera coordinate system, world coordinate system, and image origin. By establishing the correspondence between spatial point P and world coordinates, the scanner's data acquisition system converts imaging points into physical projection planes, thereby determining the coordinate relationship between spatial points and model point cloud data. The VX Elements point cloud preprocessing software platform controls scanner parameters including artifact texture resolution, contrast, and color-texture information. For large-scale immovable cultural relics with substantial data acquisition requirements, multi-discrete scanning is employed. While this method sacrifices detail fidelity, it significantly enhances data acquisition efficiency [5]. Three-dimensional resolution settings are determined by the object's structural characteristics, material textures, and color complexity. Immovable artifacts such as historical monuments, architectural landmarks, and stone carvings typically possess rich surface textures. Using 0.3mm 3D point cloud resolution in practical acquisitions achieves optimal results by reducing noise, refining texture representation, and eliminating outliers, ultimately yielding a smooth, uniformly distributed color point cloud dataset.

3. Grid Reconstruction and Parametric Modeling of Colored Cultural Relics Point Clouds

3.1 Colorful Point Cloud Reconstruction of Cultural Relics Using Poisson Grid

The meshing of point clouds is a modeling technique that describes the topological relationships between point clouds, directly manifested as the visualization transformation of point cloud data within the mesh framework. The reconstruction process is inherently linked to the topological relationships of point clouds. Common 3D mesh reconstruction methods include triangulation and surface fitting, but these often fail to meet the mesh construction requirements for immovable cultural relics. Therefore, the Poisson reconstruction method, which is relatively intuitive, was selected. By converting directed point cloud reconstruction into a spatial Poisson problem, we can obtain smooth approximations of object surfaces. This approach reevaluates global point cloud information and also demonstrates effectiveness in noise point removal and data integration, making it highly compatible with digital reconstruction of immovable cultural relics [6]. Given a space M and its boundary ∂M, the function χM is defined as:

$$\chi_M(x)=\begin{cases}1 x\in M\\0 x\notin M\end{cases} \tag{4}$$

The spatial region M denotes the area occupied by the point cloud model. An exponential function is constructed to represent this model, where both internal and external functions are optimized according to the model's surface equipotential surfaces. This process converts the model into a surface representation, specifically the three-dimensional point cloud topology transformation in Poisson reconstruction, as illustrated in Figure 3.

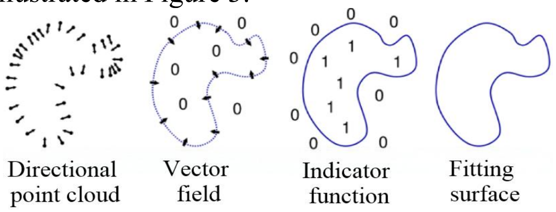

Figure 3. Two-Dimensional Poisson Surface Fitting Description

The implicit function describing the surface represented by a 3D point cloud is directly expressed as a coordinate system in three-dimensional space, i.e., f(x, y, z), where f is the unknown function. During the process of function representation, regions need to be divided and the point cloud data of cultural relics reacquired to obtain the gradient of the indicator function. The unknown function f is directly mapped into the 3D point cloud system to clarify the inner normal represented by the function. The Poisson mesh reconstruction algorithm utilizes adaptive spatial mesh partitioning, adjusting mesh depth based on the vector representation of the point cloud object. To ensure the accuracy of the unknown function, the sampling region and vector field characteristics of sampling points are reconfigured during this process, leading to a redefinition of the unknown function. By continuously optimizing mesh parameters according to different types of cultural relics, an approximate indicator function is obtained. The surface of the cultural relic is then extracted using the isocontour extraction algorithm, with the surface of immovable cultural relics dispersed across each voxel unit [7]. The independent operation of voxel units does not require recomputation of the surface, allowing direct extraction of high-precision geometric features from the overall mesh layout of the cultural relic. These features are connected into triangular surfaces following specific topological patterns, maintaining continuous and smooth transitions to restore the texture and color information of the cultural relic. The Poisson mesh reconstruction process is illustrated in Figure 4.

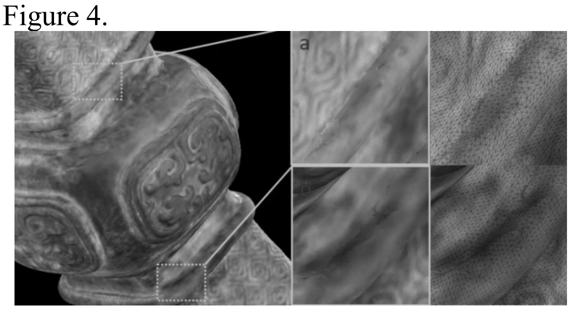

Figure 4. Colorful point cloud Poisson Mesh Reconstruction

3.2 Grid Parametric and Texture Generation

The network model reconstructed through colored point cloud Poisson meshing preserves the original digital information of cultural relics, serving as a valuable source for digital reconstruction. Each point cloud coordinate contains multiple attributes, making efficient output and precise determination of intrinsic characteristics across different point clouds crucial for digital reconstruction. The core of mesh parameterization lies in directly projecting point cloud data onto planar domains, enabling complete mapping of immovable cultural relics 'curved surfaces. By designing planar, cylindrical, and spherical domains, two-dimensional coordinates for meshing can be directly obtained. Texture coordinates provide unique storage locations for color information at each 3D vertex, while also converting color data into specific mapping relationships for 3D mesh vertices. Using open-source 3D software Meshlab for method integration allows rational optimization of regional divisions based on information characteristics, achieving effective parameterization even for relics with complex features or incomplete structures. After preliminary organization of point cloud data, parameterization can proceed directly. When parameterization results lack vertex texture color information, high-precision network models can replicate cultural relics' color data for output as mesh models. This mesh parameterization approach effectively separates cultural relics' textures and colors from point cloud data, generating high-precision mesh models without texture information [8]. The process converts embedded color data into usable 2D texture images through texture coordinates, demonstrating robust transformation capabilities even for complex-structured mesh models.

4. Development of 3D Digital Display Platform

4.1 Simplified Grid Model

The digital reconstruction of immovable cultural relics not only transforms these non-renewable resources into permanent digital records for research and appreciation, but also effectively communicates their historical and cultural significance to the public. By utilizing digital display platforms based on 3D reconstruction, reconstructed relics can be presented through 3D mesh models that preserve authenticity and visual quality [9]. The simplification of 3D mesh models involves optimizing point cloud data and reducing mesh quantities while maintaining essential features, with adjacent triangular faces being eliminated. Specific implementation procedures are illustrated in Figure 5.

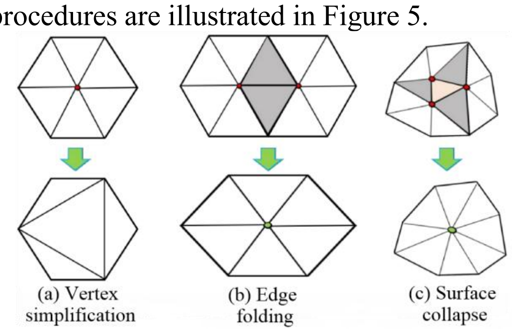

Figure 5. Grid Simplification

After grid simplification, we select processing methods for attached attributes based on cultural relics 'texture characteristics and topological structures. By converting point cloud data into Euclidean distance within the grid framework, we can utilize Euclidean model weights to obtain topological data. Simultaneously, to preserve texture features and precision characteristics, we prioritize model authenticity in simplifying color-textured images. Using quadratic error measurement, we simplify models with texture parameter attributes. This approach effectively retains strong texture colors while meeting targeted simplification requirements for local details. By reasonably controlling the simplification degree of texture network models, we further enhance the platform's rendering efficiency.

4.2 Interactive Platform for 3D Cultural Heritage Models Built on Unity 3D

Unity 3D (U3D) is a mainstream virtual reality development engine compatible with multiple mainstream systems and platforms, supporting various resource interfaces. During digital model presentations, data compatibility issues can be disregarded. The programming process controls the collected digital models, emphasizing human-computer interaction to enhance user immersion and viewing experience, with content adaptable to different exhibits. The area division utilizes HTML's <div> tags to partition the model display space into equal blocks, assigning unique identifiers to each module for efficient synchronized design. Through mouse or button clicks, users can adjust the viewing angle by moving or rotating the model on the platform, transforming physical interactions into screen-based operations that immerse users in virtual coexistence across time and space [10]. The animated model of the artwork "Jian Yun Cang Rui" features a sequence where hidden auspicious creatures emerge upon screen touch, revealing the artifact's true form as shown in Figure 6.

Figure 6. On-site Model Display of "Jianyun Cangrui"

5. Conclusion

In summary, this study focuses on the digital reconstruction of immovable cultural relics. By collecting colored point cloud data and constructing grids, we explore three key technologies: preprocessing of colored point clouds, grid reconstruction of point clouds, and development of digital display platforms. Following the designed digital reconstruction model, we established a stable data collection environment with comprehensive information and built a computer system featuring a cultural relic support platform. Using colored point cloud registration algorithms, we aligned the point cloud data, collected and reconstructed digital models of immovable cultural relics, thereby providing technical support for promoting and publicizing the cultural heritage's value.

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