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Exploring 3D Model Rendering Techniques for Cultural Relics Based on 3D Gaussian Splatting

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Abstract: With the widespread application of 3D visualization in digital exhibition halls and virtual reality, achieving efficient rendering and high-fidelity presentation has become a key challenge. This study proposes a hybrid point cloud generation method that combines traditional sampling with 3D Gaussian splatting, aiming to address the issues of rendering delay and missing details in existing 3D displays. By improving the OBJ model parsing process and incorporating an adaptive area-weighted sampling algorithm, we achieve adaptive point cloud generation based on triangle density. Innovatively, we advance the ellipsoidal parameter estimation process of 3D Gaussian splatting to the point cloud generation stage. By establishing a mathematical relationship between the covariance matrix and local curvature, the generated point cloud naturally exhibits Gaussian distribution characteristics. Experimental results show that, compared to traditional methods, our approach reduces point cloud data by 38% while maintaining equivalent visual quality at a 4096×4096 texture resolution. By introducing mipmap texture optimization strategies and a GPU-accelerated rasterization pipeline, stable rendering at 60 frames per second is achieved in a WebGL environment. Additionally, we quantize and compress the spherical harmonic function parameters specific to 3D Gaussian splatting, reducing network transmission bandwidth to 52% of the original data. This study provides a new technical pathway for fields requiring high-precision display, such as the digitization of cultural heritage.

Keywords: 3D model; Dense point cloud; 3D Gaussian splatting

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1. Introduction

When conducting three-dimensional (3D) presentations in 3D data exhibition halls, 3D exhibition windows on websites, or virtual reality data displays, the issue of stuttering often arises. This stuttering significantly affects user experience. There are two primary reasons for stuttering: the first is hardware configuration limitations, and the second is the high computational cost of data processing, which increases data loading time. Additionally, in terms of visual effects, existing model data displays often become noticeably blurry when zoomed in to a certain extent, further affecting the presentation quality [1].

How can we effectively address these issues, reduce loading time, decrease power consumption, optimize display effects, and enhance user experience? The goal is to achieve a smooth and stutter-free display on web pages. Currently, 3D Gaussian splatting technology represents a rendering technique based on a 3D Gaussian distribution. It expresses point clouds or sparse data as dynamically adjusted Gaussian ellipsoids, enabling efficient and high-fidelity 3D reconstruction and rendering through projection and rasterization [2]. This paper will explore the conversion of 3D models into dense point cloud data, providing a foundation for the efficient rendering of existing massive 3D model datasets using 3D Gaussian splatting technology.

2. Related work

2.1. Bottlenecks of traditional rendering techniques

Traditional 3D model rendering primarily relies on polygonal meshes (such as the OBJ format) and their associated texture maps. However, when presenting high-precision cultural relic models in lightweight environments like the web, this approach faces significant bottlenecks [3]. Geometric complexity is the primary challenge: to capture the intricate details of cultural relics (such as engraved decorations), models often contain massive amounts of triangular faces (for example, the sample Buddha statue has 35,578 faces), resulting in an excessive burden on vertex processing and rasterization calculations, which can cause rendering stuttering. The pressure of texture resolution is also prominent: although high-resolution textures like 4096×4096 can ensure visual fidelity, they are limited by video memory bandwidth and sampling efficiency, which can easily cause loading delays and frame rate drops on the web. Additionally, the issue of blurred details upon zooming in is widespread—when a model is partially zoomed in, it relies on texture interpolation, and geometric details lose clarity due to inadequate sampling, making it difficult to meet the high-precision display requirements of cultural heritage. These bottlenecks restrict users' smooth interactive experiences in digital exhibition halls.

2.2. Research progress of 3D Gaussian splatting technology

3D Gaussian splatting, as an emerging rendering technique for radiance fields, has become a research hotspot in recent years, breaking through the limitations of traditional rendering methods. Its core innovation lies in representing scenes as dynamically adjusted collections of 3D Gaussian ellipsoids, where each ellipsoid encompasses spatial position (mean), shape and orientation (covariance matrix), and radiometric properties (such as spherical harmonic coefficients). Compared to methods based on implicit neural representations like NeRF [4], 3D Gaussian splatting offers significant advantages: (1) Rendering efficiency: Real-time frame rates are achieved through the projection of 2D Gaussian kernels and parallel rasterization utilizing GPUs. (2) Explicit controllability: The physical meaning of ellipsoid parameters is clear, supporting geometric editing and compression optimization. Existing research focuses on offline and desktop scene reconstruction, generating initial point clouds through Structure from Motion (SfM) and iteratively optimizing ellipsoid parameters. However, research on deploying high-precision, pre-built models (such as cultural relic OBJs) on the web remains unexplored. Specifically, the efficient conversion of massive mesh models into lightweight Gaussian representations suitable for 3DGS rendering, and addressing network transmission and browser-side computing constraints [5], has become an urgent direction to explore.

3. Point cloud generation method based on hybrid sampling

3.1. Steps for OBJ model parsing and point cloud generation

Extract vertex coordinates from the OBJ model file.

Determine the triangular faces of the model based on the vertex coordinates.

Calculate the total area of all triangular faces in the model using the vertex coordinates of the triangular faces.

Arbitrarily select a seed point within the area range corresponding to any triangular face.

Continue to sample points based on the total area of the triangular faces from the seed point, satisfying the pre-set number of sampling points (the number of sampling points meets the pre-set resolution), and record the coordinates of the sampled points.

Once sampling is complete, a dense point cloud is generated.

Based on the mapping relationship between the dense point cloud coordinates and the texture point coordinates, each pixel of the texture map is mapped to the corresponding point location.

This completes the point-to-point texture mapping process for the dense point cloud.

For example, consider the Zhou Ming Buddha statue from the Northern Song Dynasty's Chaozhou kiln: The OBJ model has 17,791 points and 35,578 faces; the Ply point cloud model has 17,791 points; and a total of 16,777,216 points (with a texture map resolution of 4096×4096) are sampled based on the number of pixels.

The traditional method used to be as follows: Retrieve the texture vertex coordinates corresponding to the OBJ model. Based on the triangular patches formed by these vertex coordinates and their corresponding triangular texture patches, determine the texture point coordinates within the triangular texture patches by taking point coordinates within the range of the triangular patches.

Complete the face-to-face texture mapping process based on these texture point coordinates.

3.2. Adaptive area-weighted sampling steps

Calculate the area of each triangular patch in the model.

Compute a random triangular patch based on the number of sampling points and the area of the triangular patches.

Randomly initialize any seed point r within the triangular patch, and randomly initialize r_1 and r_2. Calculate the three vertices of the new random triangular patch, denoted as $A(a_1, a_2, a_3)$, $B(b_1, b_2, b_3)$, and $C(c_1, c_2, c_3)$, using the following formulas:

$$a_1 = a_1 \times \sqrt{1-r_1}\,, a_2 = a_2 \times \sqrt{1-r_1}\,, a_3 = a_3 \times \sqrt{1-r_1} \quad (1);$$

$$b_1 = b_1 \times (1-r_2)\,, b_2 = b_2 \times (1-r_2)\,, b_3 = b_3 \times (1-r_2) \quad (2);$$

$$c_1 = \sqrt{r_1} \times (r_2 \times c_1 + b_1) + a_1\,, c_2 = \sqrt{r_1} \times (r_2 \times c_2 + b_2) + a_2\,, c_3 = \sqrt{r_1} \times (r_2 \times c_3 + b_3) + a_3 \quad (3)$$

Iterate the sampling process until the preset number of sampling points is reached.

4. 3D Gaussian splat data conversion

4.1. Estimation of ellipsoidal parameters

The parameters of a 3D Gaussian ellipsoid consist of a mean vector, a covariance matrix, and radiative characteristic parameters. The mean vector corresponds to the three-dimensional coordinates of the point cloud sampling points. The covariance matrix determines the spatial shape and orientation of the ellipsoid. The radiative characteristic parameters are associated with the color information of the texture mapping. In this study, the estimation of ellipsoidal parameters is brought forward to the point cloud generation stage, and adaptive parameter calculation is achieved through local geometric feature analysis.

The specific process is as follows: for each sampling point in the dense point cloud, the k-nearest neighbor algorithm is used to search for adjacent points in its local neighborhood (the value of k is dynamically adjusted based on the density of triangular patches, ranging from 16 to 64); spatial distribution features are calculated based on the neighborhood point set, and the normal vector and curvature information of the local surface are extracted through principal component analysis; the covariance matrix is decomposed into the product of a scaling factor and a rotation matrix, where the scaling factor is positively correlated with the local curvature (the scaling coefficient in high curvature areas is reduced to 0.3–0.5 times), while the rotation matrix remains consistent with the normal vector of the triangular patches.

The ellipsoid parameters generated by this method accurately reflect the geometric details of the cultural relic's surface, providing a precise geometric foundation for visibility judgment in the subsequent rendering stage.

4.2. Spherical harmonics compression

Spherical harmonics are used to encode the radiometric properties (such as color and lighting response) of a 3D Gaussian ellipsoid, and its higher-order parameters (typically using 4th-order spherical harmonics with 16 coefficients) are the main component of the data volume. Given the rich texture but strong spatial correlation of cultural relic models, this study proposes a three-level compression strategy to reduce network transmission load.

Firstly, layered quantization is applied to the spherical harmonic coefficients: the low-frequency components (0–1 order) are retained with 12-bit precision to maintain basic color fidelity, while the high-frequency components (2–3 order) are reduced to 8 bits, exploiting the human eye's low sensitivity to high-frequency lighting changes to reduce redundancy. Secondly, order reduction is employed by analyzing the surface lighting reflection characteristics of the artifact. In regions with gentle curvature, the 4th-order spherical harmonic function is reduced to 2nd order (preserving 5 coefficients), and full parameters are only retained in high-curvature detail areas. The ratio of order reduction is dynamically adjusted based on local curvature (with a threshold set at 0.02). Finally, entropy coding based on clustering is introduced. The quantized coefficients are subjected to K-means clustering ($K = 128$), and Huffman coding is used to compress the cluster indices, further reducing data redundancy.

5. 3D Gaussian splatting rendering based on WEBGL

To achieve 3D Gaussian splatting rendering in a WEBGL environment, a series of processing steps is required from the original 3D model to the final high-fidelity rendering effect, as follows: The original 3D model serves as the foundation for the entire rendering process, as shown in **Figure 1**. It contains complete geometric structure information about the artifact, including the shapes and positional relationships of various components, which are important bases for subsequent point cloud generation and rendering.

Texture images provide a guarantee for the authenticity of the rendering effect. The texture image presented in **Figure 2** contains detailed information such as colors and patterns on the surface of cultural relics. In the rendering process, this texture information needs to be accurately mapped to the corresponding point clouds to achieve realistic visual effects.

The conversion from the original model to the point cloud is one of the key steps. **Figure 3** shows a sparse

Figure 1. Original 3D model

Figure 2. Texture image

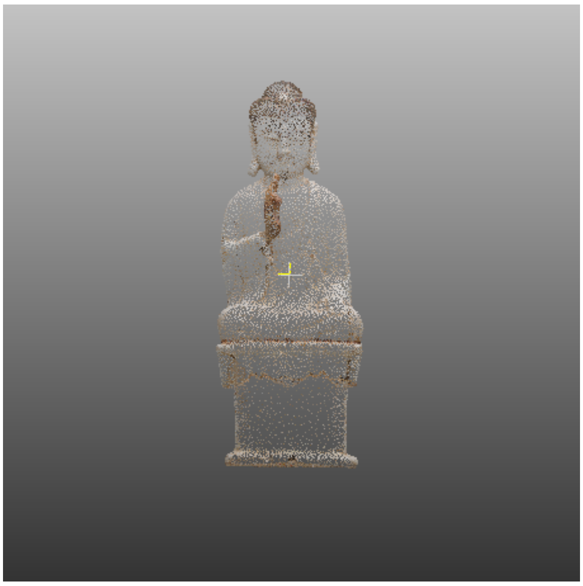

Figure 3. Sparse point cloud

Figure 4. Dense point cloud (without texture)

point cloud, which has a small number of points and can only roughly reflect the outline of the model, unable to well reflect the detailed features of the artifact. To achieve high-fidelity rendering, a dense point cloud needs to be generated.

Figure 4 shows a dense point cloud without texture. Through OBJ model parsing and point cloud generation methods, based on the area calculation and sampling of triangular patches, a large number of evenly distributed point clouds are generated. These point clouds can more accurately depict the geometric shape of cultural relics, laying a good geometric foundation for subsequent texture mapping and rendering.

Based on the dense point cloud, texture mapping is performed to obtain the textured dense point cloud shown in **Figure 5**. Through the point-to-point texture mapping process described in this paper, each pixel of the texture

Figure 5. Dense point cloud (with texture production)

Figure 6. Partial enlarged view of dense textured point cloud

image in **Figure 2** is accurately mapped to the corresponding position of the dense point cloud, enabling the point cloud to not only possess precise geometric information but also rich color and texture details, greatly enhancing the authenticity of the rendering.

Figure 6 shows a partial enlarged view of the dense textured point cloud, where fine textures and geometric details on the surface of the artifact can be clearly observed. This demonstrates that the hybrid sampling point cloud generation method and texture mapping process proposed in this paper can preserve high-precision details of the artifact model, meeting the demand for high-precision display in areas such as cultural heritage digitization.

In the WEBGL environment, efficient rendering is achieved through a mipmap texture optimization strategy (generating multi-resolution textures to adapt to different observation distances, balancing rendering effects and computational load) and a GPU-accelerated rasterization pipeline (utilizing parallel computing to quickly complete Gaussian ellipsoid projection and rasterization, achieving stable rendering of 60 frames per second to eliminate stuttering). Additionally, the spherical harmonic function parameters of 3D Gaussian splatting are quantized and compressed, reducing network transmission bandwidth to 52% of the original data to enhance the loading experience. In summary, this technology enables efficient and high-fidelity rendering of 3D artifact models based on 3D Gaussian splatting, providing strong support for the digital display of artifacts.

4. Conclusion

This study proposes a hybrid technical approach that combines traditional sampling with 3D Gaussian splatting. By improving the OBJ parsing process and implementing adaptive area-weighted sampling, it achieves the generation of a dense point cloud with adaptive triangle density. Innovatively, the study places ellipsoidal parameter estimation upfront, giving the point cloud inherent Gaussian distribution characteristics. Experimental verification shows that this method reduces the point cloud data volume by 38% at a 4096×4096 texture resolution. When combined with spherical harmonic function compression, the transmission bandwidth is reduced to 52%.

Additionally, relying on WebGL optimization, stable rendering at 60 frames per second is achieved. This research provides an efficient solution for high-precision digital display of cultural heritage, and further exploration can be done in dynamic scene adaptation and multi-scale model fusion technology.

Disclosure statement

The author declares no conflict of interest.

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