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GAUSSIAN SPLATTING FOR CULTURAL HERITAGE DIGITIZATION: TECHNICAL POSITIONING, APPLICATION SCENARIOS, AND FUTURE PROSPECTS

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Abstract: Cultural heritage digitization is increasingly shifting from static geometric recording toward immersive, interactive, and scene-based representation. Within this technological transformation, Gaussian Splatting has emerged as a promising approach for image-driven three-dimensional visualization, offering photorealistic rendering, spatial continuity, and real-time free-viewpoint navigation. This article examines the role of Gaussian Splatting in cultural heritage digitization by situating it within the broader evolution from manual modeling, laser scanning, photogrammetry, and SfM-MVS reconstruction to neural rendering. It argues that Gaussian Splatting should be understood primarily as a rendering-oriented scene representation rather than as a substitute for measurement-oriented point clouds, mesh models, BIM/HBIM, or GIS-based heritage information systems. On this basis, the article discusses its potential applications in architectural heritage, archaeological sites, caves and grottoes, museum collections, virtual museums, and digital cultural tourism. It further analyzes key methodological stages, including data acquisition, pose estimation, Gaussian representation and optimization, quality evaluation, semantic segmentation, multi-source fusion, and platform deployment. While Gaussian Splatting provides strong advantages in visual realism and interactive access, its limitations in geometric measurability, semantic organization, long-term interoperability, and conservation-grade documentation must be carefully addressed. The article concludes that the future value of Gaussian Splatting lies not in replacing established digitization methods, but in connecting visual scenes with measurement data, semantic annotation, archival systems, and public-facing platforms, thereby contributing to more integrated, accessible, and sustainable cultural heritage digital infrastructures.
Keywords: Gaussian splatting; Cultural heritage digitization; Three-dimensional reconstruction; Neural rendering; Virtual museums; Digital cultural tourism; Heritage visualization

1 INTRODUCTION

Cultural heritage serves as an important carrier of historical memory and social identity. Under the combined effects of natural weathering, environmental pollution, climate change, geological hazards, and other factors, the risks faced by cultural heritage conservation have become increasingly complex. Heritage digitization has therefore emerged as an important technological pathway in conservation practice [1]. By digitally recording information related to heritage assets, it provides a foundation for preservation, restoration, research, display, interpretation, and dissemination.

Gaussian Splatting, characterized by image-driven reconstruction, explicit scene representation, and real-time rendering, offers new technological possibilities for the three-dimensional digitization of cultural heritage [2]. It can generate navigable scenes with spatial continuity and a high degree of visual realism through a relatively streamlined workflow. In recent years, Gaussian Splatting has become an important development in the fields of 3D reconstruction. Conventional 3D digitization methods typically rely on point clouds, meshes, texture mapping, or parametric components as their primary forms of representation. Compared with implicit neural radiance fields such as NeRF, Gaussian Splatting represents scene appearance through explicit 3D Gaussian primitives [3]. Compared with traditional point cloud and mesh models, its main advantages lie in photorealistic rendering and free-viewpoint navigation, rather than in replacing measurement-oriented geometric models.

In simple terms, Gaussian Splatting decomposes a scene into some spatial primitives with attributes such as position, orientation, color, and opacity. By optimizing the distribution and appearance of these primitives, it enables users to observe a highly realistic three-dimensional scene in real time from different viewpoints. For heritage objects characterized by complex textures, irregular surfaces, reflective materials, or low-light environments, Gaussian Splatting can effectively preserve the color, lighting, shadow, and material impressions captured in images. It has also demonstrated considerable application potential in research on virtual museums and the digital documentation of cultural relics [4].

2 THE EVOLUTION OF THREE-DIMENSIONAL DIGITIZATION TECHNOLOGIES FOR CULTURAL HERITAGE AND THE RISE OF GAUSSIAN SPLATTING

Early practices of cultural heritage digitization largely relied on CAD, three-dimensional modeling software, and virtual reconstruction methods. Researchers or technical specialists manually constructed models on the basis of survey drawings, historical images, archaeological records, and on-site observations. These practices promoted the transformation of heritage objects from two-dimensional images, textual descriptions, and planar survey drawings into three-dimensional visual representations. However, manual modeling depends heavily on the experience of the operator. The resulting models are often shaped by the completeness of available sources and by subjective judgment. They are therefore more suitable for visual presentation and spatial imagination than for fine-grained measurement.

With the development of terrestrial laser scanning, close-range photogrammetry, structured-light scanning, and related techniques, the three-dimensional digitization of cultural heritage gradually entered a measurement-driven stage [1]. Terrestrial laser scanning can rapidly acquire high-density point clouds and is well suited to recording the geometric forms of historic buildings, historical districts, large sculptures, archaeological sites, and cave spaces [1]. Close-range photogrammetry can generate point clouds, meshes, and textured models from multi-view images, offering advantages in cost, flexibility, and texture representation [5]. Structured-light scanning is commonly used for the high-precision acquisition of small movable cultural relics, finely carved objects, ornamental components, and complex surfaces.

Compared with manual modeling, measurement-driven three-dimensional digitization provides cultural heritage models with clearer data sources and more explicit spatial scales. It also enables 3D models to support condition documentation, dimensional measurement, damage identification, restoration design, and long-term monitoring. At this stage, a basic workflow for cultural heritage digitization was gradually established. Raw data are first acquired through laser scanning, photogrammetry, or structured-light scanning. The data are then processed through point-cloud denoising, registration, fusion, segmentation, and coordinate unification. Subsequently, triangular meshes, textured models, orthophotos, or engineering drawings are generated, before being applied to display, archiving, research, or restoration.

At the same time, this stage also revealed new problems. Point clouds are usually unordered and unstructured data. Although mesh models are suitable for rendering, they do not inherently carry component names, historical attributes, material information, types of deterioration, or restoration records. After format conversion and platform migration, three-dimensional outputs are prone to data fragmentation, semantic loss, and difficulties in long-term reuse.

The widespread adoption of photogrammetry represents a critical turning point in the technological evolution of three-dimensional digitization for cultural heritage. Traditional photogrammetry relies on camera calibration, control-point measurement, and specialized computational procedures, which impose relatively high technical requirements. The introduction of the Scale-Invariant Feature Transform, commonly known as the SIFT algorithm, substantially improved the stability of image feature extraction and matching, thereby providing an important foundation for the automatic matching of multi-view images [6]. Building on this basis, Structure from Motion (SfM) can recover camera positions, orientations, and sparse three-dimensional points from multiple overlapping photographs, while Multi-View Stereo (MVS) further generates dense point clouds and surface details.

With the development of tools such as COLMAP, Agisoft Metashape, RealityCapture, and Pix4D, photogrammetry has gradually expanded from a specialized surveying procedure into a widely used method in cultural heritage digitization [5]. For medium- and small-scale artefacts, building façades, local areas of archaeological sites, sculptures, exhibition spaces, and vernacular architecture, researchers can acquire images using conventional cameras, unmanned aerial vehicles, or mobile devices, and then generate three-dimensional models through automated algorithms. This approach effectively compensates for some limitations of laser scanning, including high equipment costs, complex deployment, and insufficient texture acquisition. It has also enabled a wider range of cultural heritage institutions, local museums, and research teams to undertake three-dimensional digitization practices.

The three-dimensional outputs generated through photogrammetry typically include sparse point clouds, dense point clouds, mesh models, textured models, orthophotos, and digital elevation models. These outputs can support spatial documentation, visual presentation, and certain measurement needs. Nevertheless, SfM-MVS remains fundamentally centered on geometric reconstruction and surface modeling. It requires sufficient image overlap, stable illumination, and matchable visual features. For low-texture surfaces, reflective materials, transparent objects, repetitive patterns, low-light spaces, and severely occluded scenes, reconstruction results may contain holes, mismatches, floating noise, and texture distortion.

The emergence of neural rendering represents another important milestone. NeRF represents a continuous volumetric radiance field through a neural network, mapping spatial positions and viewing directions to volume density and view-dependent color, thereby synthesizing novel views from multi-view images [3]. Compared with conventional mesh-based models, NeRF places greater emphasis on learning scene appearance, illumination, and view-dependent variations from images, and is capable of generating photorealistic images in scenes with complex geometry and materials. In the field of cultural heritage, this shift means that three-dimensional digitization can move beyond the browsing of static models toward a free-viewpoint experience that more closely approximates on-site observation.

The limitations of NeRF are also evident. Its training and rendering processes usually involve high computational costs, and its capacity for real-time interaction remains limited. Since its scene representation is implicit, geometric structures, semantic objects, and editable components are difficult to extract directly. As a result, NeRF outputs are more suitable for novel-view synthesis and visual presentation than for directly replacing point clouds, meshes, and BIM/HBIM models in measurement, structural analysis, and heritage management.

Gaussian Splatting has attracted increasing attention against this technological background. It inherits the pursuit of photorealistic novel-view synthesis from neural rendering, while representing scenes through explicit 3D Gaussian primitives. Gaussian Splatting usually takes sparse point clouds derived from camera pose estimation as its initialization. It represents a scene as a large number of Gaussian primitives with attributes such as position, scale, orientation, color, opacity, and view-dependent appearance [2]. Through differentiable rendering, density control, and anisotropic covariance optimization, it enables high-quality real-time rendering.

3 THE TECHNICAL POSITIONING OF GAUSSIAN SPLATTING WITHIN THE SPECTRUM OF THREE-DIMENSIONAL DIGITIZATION

The advantages of Gaussian Splatting are mainly reflected in three aspects. First, it can generate spatially continuous and navigable scenes from multi-view images. Second, it can effectively preserve the color, illumination, texture, and view-dependent appearance captured in images. Third, it supports real-time or near-real-time free-viewpoint rendering while maintaining relatively high visual quality. For these reasons, Gaussian Splatting is particularly suitable for heritage presentation, virtual tours, exhibition hall reconstruction, historical district walkthroughs, remote access to archaeological sites, and digital cultural tourism experiences.

In terms of input data, Gaussian Splatting is naturally connected to photogrammetry. It usually relies on multi-view images which are often provided by SfM or SLAM pipelines. In this sense, Gaussian Splatting does not depart completely from conventional three-dimensional reconstruction workflows. Instead, it develops a new rendering representation on these basis. Existing photogrammetric datasets, UAV images, exhibition hall photographs, and video-captured data can all serve as potential input sources for Gaussian Splatting-based modeling.

In terms of output form, Gaussian Splatting should be positioned as a rendering-oriented scene model, rather than as a measurement model or a semantic management model. Point clouds, meshes, BIM/HBIM, and GIS respectively undertake functions such as spatial sampling, surface representation, component management, and geographic organization. Gaussian Splatting organizes visual information through 3D Gaussian primitives, with its advantages concentrated in photorealistic presentation and free-viewpoint navigation. Accordingly, Gaussian Splatting is better suited to tasks at the level of presentation, guidance, and interaction, while precise measurement, structural assessment, deterioration analysis, and long-term management still need to rely on measurement-oriented models and semantic models.

The evolution of three-dimensional digitization for cultural heritage reflects, at a deeper level, a shift in the understanding of digital heritage itself. Manual modeling, measurement-based modeling, and photogrammetry have primarily focused on recording the form of heritage objects, whereas neural rendering and Gaussian Splatting further enhance scene representation and free-viewpoint observation. As a result, cultural heritage digitization has begun to address continuous scenes such as exhibition halls, courtyards, historical districts, archaeological sites, grotto spaces, and cultural landscapes. For public communication, this shift helps reposition heritage objects within their spatial contexts, viewing routes, and narrative relationships.

4 REPRESENTATIVE APPLICATIONS OF GAUSSIAN SPLATTING IN CULTURAL HERITAGE DIGITIZATION

The application of Gaussian Splatting in the field of cultural heritage remains in a stage of rapid development. Existing explorations have mainly focused on architectural heritage, archaeological sites, caves and grottoes, museum collections, damaged heritage, virtual museums, and digital cultural tourism. Different types of heritage objects vary in spatial scale, material characteristics, acquisition conditions, conservation constraints, and display objectives. These differences also determine the applicable modes and risk boundaries of Gaussian Splatting.

4.1 Architectural Heritage

Ancient buildings, palaces, temples, religious architecture, historical districts, and modern and contemporary architectural heritage usually involve large spatial scales, complex component hierarchies, and rich surface details. Traditional three-dimensional digitization often combines terrestrial laser scanning, UAV oblique photogrammetry, close-range photogrammetry, and HBIM modeling. Through multi-source data acquisition and registration, these methods generate point clouds, mesh models, textured models, or component-level semantic models. Such approaches have clear advantages in geometric documentation, restoration management, and long-term maintenance. However, the process from data acquisition to model publication often requires a relatively long production cycle, and high-fidelity visualization and real-time interaction still depend on additional rendering optimization.Gaussian Splatting can serve as a display-oriented complement for architectural heritage. It is well suited to generating navigable scenes from UAV images, ground-based photographs, mobile video, and existing photogrammetric datasets, and can be applied to online tours, digital exhibitions, cultural tourism promotion, and immersive education.

4.2 Archaeological Sites and Open Scenes

Archaeological sites, ancient city remains, ruin landscapes, burial complexes, and cultural landscapes are characterized by openness, large spatial scales, and multiple levels of spatial organization. Compared with individual buildings or museum collections, the digitization of archaeological heritage is more challenging because such sites often cover extensive areas, involve varied topography, contain dispersed remains, and present complex stratigraphic relationships. They also require the simultaneous documentation of archaeological remains, geomorphological settings, excavation conditions, trench relationships, and surrounding landscapes.

The value of Gaussian Splatting in site-based scenes is first reflected in remote access and immersive reconstruction. Many archaeological sites are difficult for the public to access fully due to conservation requirements, transportation conditions, access management, and safety regulations. Some sites are still under excavation, conservation, or restoration, and are therefore unsuitable for conventional tourism. Based on UAV and ground-level imagery, Gaussian Splatting can generate navigable scenes that allow users to understand the spatial layout, relationships among remains, topographic setting, and viewing routes of a site within a digital environment. Compared with static photographs, two-dimensional plans, or fixed-viewpoint videos, it provides a more continuous sense of space and helps make archaeological interpretation more intuitive.

Gaussian Splatting can be used for staged archaeological documentation and multi-temporal presentation. Archaeological sites are inherently processual: the exposure, cleaning, consolidation, backfilling, and display of remains often occur at different stages. Through multi-temporal imagery and Gaussian Splatting reconstruction, digital records of the site can be produced for different phases and used in teaching, public communication, and the explanation of conservation processes. For site conditions that have disappeared, been backfilled, or are no longer displayed for conservation reasons, Gaussian Splatting can help preserve their visual and spatial information.

4.3 Caves, Grottoes, and Low-Light Spaces

Caves, grotto temples, mural spaces, underground sites, and tomb spaces are among the most challenging object types in three-dimensional cultural heritage digitization. Such heritage sites are usually characterized by enclosed or semi-enclosed spaces, insufficient illumination, complex wall undulations, dense texture details, fragile color preservation, and strict conservation constraints. In the case of grotto temples, three-dimensional digitization must document not only the spatial structure of the cave but also wall images, sculptural forms, deterioration and damage, and historical traces.

Gaussian Splatting has distinctive potential for caves and grotto heritage. Based on images, it can preserve on-site lighting, wall textures, spatial depth, and viewing atmosphere, thereby transforming the presentation of grotto heritage from conventional two-dimensional image display into a digital space that users can enter, turn within, and observe at close range. For caves that are difficult to open to the public because of conservation restrictions, or for areas where prolonged visitation is constrained by lighting, passage conditions, or safety requirements, Gaussian Splatting can serve as a technological complement for digital access. It helps present the spatial continuity of cave interiors and enables viewers to understand the relationships among sculptures, murals, inscriptions, and cave-chamber structures.

4.4 Museum Collections and Small-Scale Artefacts

Museum collections and small movable artefacts represent one of the more readily implementable application areas for Gaussian Splatting. Ceramics, bronzes, jade objects, gold and silver artefacts, Buddhist statues, sculptures, wooden objects, textiles, and excavated archaeological objects are usually relatively small in scale and can be documented under more controllable imaging conditions. They are therefore well suited to data acquisition through turntable-based imaging, multi-view photography, controlled lighting, and background isolation. Traditionally, such artefacts have been digitized using structured-light scanning, close-range photogrammetry, or a combination of both. Structured-light scanning is suitable for acquiring high-precision geometry, while photogrammetry is effective in recording texture and color.The introduction of Gaussian Splatting provides a new option for the photorealistic presentation of museum collections. It can effectively preserve the appearance information contained in multi-view images and is therefore suitable for online exhibitions, detailed artefact browsing, virtual display cases, educational courses, and cultural creative presentation.

In the future, the digitization of museum collections may not rely solely on high-end scanning equipment. A lightweight digitization workflow may also emerge through the process of “exhibition-space capture—object recognition—single-object extraction—semantic annotation—online presentation.” However, such methods remain exploratory. When applied to highly protected or high-value artefacts, they must be validated in terms of geometric accuracy, color reproduction, and compliance with conservation standards. Accordingly, the digitization of museum collections may adopt a “dual-model” strategy: structured-light scanning or photogrammetric meshes can serve as research and archival models, while Gaussian Splatting can function as a presentation and interaction model. The former ensures the reliability of dimensional measurement, deterioration analysis, and restoration records, whereas the latter improves the experiential quality of online exhibitions, close-up observation, and public interaction.

Existing research has applied Gaussian Splatting to the three-dimensional visualization of a damaged statue and its integration into a web-based interface. Taking a statue of an Egyptian Ptolemaic queen as a case study, the research compares photogrammetry, Gaussian Splatting, and an integrated laser scanning–photogrammetry method, and evaluates geometric fidelity using Hausdorff distance [7]. The study suggests that Gaussian Splatting offers advantages for rapid and resource-efficient visualization, especially in scenarios with limited computational resources and a need for web deployment [7]. This case indicates that Gaussian Splatting can provide a lightweight pathway for restoration-oriented display, making the digital presentation of damaged heritage more accessible to online platforms and public-facing interfaces.

4.5 Virtual Museums and Digital Cultural Tourism

Virtual museums and digital cultural tourism represent some of the most communicatively valuable application areas for Gaussian Splatting at present. Traditional virtual museums often rely on panoramic photographs, two-dimensional exhibition panels, web-based images, video tours, or mesh models. Panoramic photographs are relatively inexpensive to produce and can provide high visual clarity, but they restrict users' movement paths and offer limited spatial interaction. Conventional mesh-based exhibition halls can support a certain degree of navigation, but they often require long production cycles, model optimization, and considerable effort to achieve visual realism. Positioned between image acquisition and three-dimensional interaction, Gaussian Splatting can generate photorealistic exhibition spaces that support free navigation through a relatively streamlined workflow. It is therefore suitable for online exhibitions, remote visits, digital education, and cultural tourism experiences. Although Gaussian Splatting has already demonstrated strong experiential advantages in virtual museums, it still needs to be combined with traditional web interfaces, high-resolution images, and information visualization in areas such as exhibition labels, textual interpretation, detailed reading, and interface design.

The application of Gaussian Splatting in virtual museums should not be limited to the replication of exhibition spaces. Its greater value lies in its integration with curatorial narratives, artefact knowledge, guided routes, and interaction design, enabling users to obtain object interpretation, temporal clues, detailed images, and related knowledge links during free exploration. In this sense, Gaussian Splatting provides a spatial entry point, while a complete museum experience still requires the support of collection information systems, knowledge graphs, and interactive narratives. In digital cultural tourism, Gaussian Splatting can be used for heritage-site previews, scenic-area guidance, historical district walkthroughs, study-tour courses, immersive theatre, and online communication.

5 KEY TECHNOLOGIES AND METHODS THROUGH WHICH GAUSSIAN SPLATTING EMPOWERS CULTURAL HERITAGE DIGITIZATION

The introduction of Gaussian Splatting into cultural heritage digitization has brought changes not only in rendering quality but also in the reorganization of digitization workflows. Traditional three-dimensional digitization of cultural heritage is usually structured around the sequence of "acquisition—processing—modeling—presentation—archiving," with core procedures including data acquisition, point-cloud processing, mesh reconstruction, texture mapping, multi-level detail representation, and the development of data standards [8]. Gaussian Splatting continues the basic logic of image-driven three-dimensional reconstruction, but its output is not a conventional triangular mesh. Instead, it produces a real-time renderable scene composed of a large number of 3D Gaussian primitives. In general, the application of Gaussian Splatting to cultural heritage digitization involves seven key stages: data acquisition, pose estimation and initialization, Gaussian representation and optimization, quality evaluation, semantic segmentation and object extraction, multi-source fusion, and platform deployment.

5.1 Data Acquisition

Gaussian Splatting typically relies on multi-view images or video frames and requires relatively stable camera pose estimation as a prerequisite. Therefore, image quality, viewpoint coverage, lighting conditions, texture clarity, and occlusion control during the acquisition stage directly determine the stability of subsequent reconstruction and the quality of rendering. Compared with ordinary scene capture, cultural heritage data acquisition must also take into account conservation requirements, site-management constraints, and scholarly documentation standards. For heritage objects that cannot be touched, moved, exposed to strong light, or kept open for extended periods, acquisition strategies must strike a balance between technical effectiveness and conservation ethics.

Different types of cultural heritage require differentiated acquisition strategies. For ancient buildings, historical districts, archaeological sites, and cultural landscapes, UAV imagery, ground-based photography, mobile video, and control-point measurement can be combined to ensure continuous coverage of roofs, façades, courtyards, streets, alleys, and topographic relationships. For museum exhibition halls and indoor heritage spaces, particular attention should be paid to glass display cases, low-light environments, visitor occlusion, reflective materials, and narrow circulation routes. Data acquisition should, where possible, be conducted during closed hours, with stable lighting and planned capture routes. For small museum artefacts, turntables, multi-camera arrays, orbiting photography, and controlled lighting can be used to obtain images that are uniform, clear, and sufficiently overlapping across the object surface. For grottoes, murals, tombs, and cave spaces, special attention should be given to lighting control, color calibration, and conservation-sensitive acquisition, so as to avoid introducing new risks to the heritage fabric during the capture process.

From the perspective of Gaussian Splatting-based modeling, the acquisition stage should prioritize continuous viewpoint coverage, image sharpness, stable illumination, and controllable dynamic interference. Adjacent images need to have sufficient overlap in order to avoid holes, floating Gaussians, or discontinuities in viewpoint transitions during free-viewpoint navigation. Image blur, uneven exposure, excessive noise, and dynamic occlusion can all affect pose estimation and appearance optimization.

Cultural heritage data acquisition also requires the establishment of a metadata documentation system. The recorded information should cover key elements such as acquisition conditions, equipment parameters, capture routes, control-point information, color calibration methods, and data versions. For high-value artefacts and important heritage sites, original images, RAW files, camera calibration information, and processing logs should also be preserved.

5.2 Pose Estimation and Initialization

Gaussian Splatting typically requires camera poses and a sparse point cloud as the basis for initialization. In practice, a common workflow first uses SfM software or related algorithms to perform feature extraction. The resulting outputs are then used to initialize 3D Gaussian primitives. SfM/MVS systems such as COLMAP have become widely used tools in image-based three-dimensional reconstruction. Their fundamental task is to recover camera parameters and scene structure from unordered or ordered image collections. In cultural heritage applications, pose estimation determines not only whether a model can be successfully generated, but also the reliability of spatial scale, local detail, and multi-view consistency.

Pose estimation in cultural heritage scenes often faces particular challenges. Repetitive patterns, continuous wall surfaces, symmetrical components, and low-texture areas are common in historic buildings and grottoes, and these features may lead to unstable feature matching. Metal objects, glass, glazed ceramics, and display-case surfaces often produce reflections and specular highlights, causing the same area to appear differently from different viewpoints and thereby affecting the matching of corresponding points. Indoor exhibition halls and cave spaces may suffer from insufficient lighting, restricted movement routes, and severe occlusion, resulting in inadequate camera baselines or uneven viewpoint distributions. In archaeological sites and historical districts, large areas of sky, vegetation, and moving crowds may also weaken the reliability of pose estimation.

To address these problems, Gaussian Splatting workflows for large-scale archaeological sites and architectural complexes should be combined with GNSS RTK, total-station control points, UAV POS data, or existing surveying results in order to establish a unified coordinate system. For indoor and low-light environments, pose stability can be improved through artificial markers, enhanced use of natural features, supplementary capture routes, and the stitching of locally reconstructed sections. For projects that already include laser-scanning point clouds or structured-light scanning data, these point clouds can serve as geometric references, constraining the spatial position of the Gaussian model through coarse and fine registration.

In multi-source data fusion scenarios, point-cloud registration is also an important preliminary step. The Iterative Closest Point (ICP) algorithm has long been used for point-cloud registration [9]. In cultural heritage projects, coarse registration can first be achieved through control points, targets, or manually selected points, followed by fine registration using ICP or related methods. If a Gaussian Splatting model can remain coordinate-consistent with laser-scanning point clouds, photogrammetric point clouds, or structured-light scanning data, subsequent work can include error assessment, semantic annotation, change comparison, and cross-platform presentation. This means that Gaussian Splatting should contribute to the spatial consistency and reusability of cultural heritage digital assets.

5.3 Gaussian Representation and Optimization

The core of Gaussian Splatting lies in representing a scene with a large number of 3D Gaussian primitives. Compared with traditional point clouds, Gaussian primitives are not merely discrete sampling points; rather, they are renderable units with spatial extent and directionality. Compared with conventional triangular meshes, Gaussian Splatting does not rely on a complete continuous surface and does not require the explicit construction of surface topology. Starting from sparse points generated through camera calibration, it represents the scene using 3D Gaussians and enables real-time radiance-field rendering through density control, anisotropic covariance optimization, and fast visibility-aware rendering [2].

During training, Gaussian primitives continuously adjust their position, scale, orientation, opacity, and color parameters according to image reprojection errors. Through densification, pruning, and optimization, they gradually form a renderable scene. For cultural heritage applications, this representation has two major advantages. First, it can effectively preserve the lighting, texture, and material impressions captured in images, making it suitable for presenting painted surfaces, stone carvings, wooden structures, metal objects, glazed surfaces, murals, and complex spatial atmospheres. Second, it offers high rendering efficiency and is therefore suitable for real-time browsing in web-based platforms, VR environments, and immersive exhibitions.

Because Gaussian primitives are optimized primarily for rendering, their geometric boundaries, occluded areas, and semantic hierarchies are not inherently reliable. Therefore, in conservation measurement, component identification, and deterioration analysis, Gaussian Splatting needs to be used in combination with point clouds, meshes, and semantic annotation. The optimization stage of Gaussian Splatting should therefore be adapted to the specific requirements of cultural heritage applications. For presentation-oriented projects, priority should be given to visual consistency, rendering speed, and viewpoint completeness. For conservation documentation projects, point clouds or meshes should be introduced as geometric references in order to reduce excessive dependence on image appearance. For projects focused on artefact details, high-resolution photography, normal estimation, and local enhancement should be combined to ensure that patterns, inscriptions, and areas of deterioration can be clearly observed. For large-scale archaeological sites and architectural complexes, partitioned training, hierarchical organization, and LOD strategies should be adopted to prevent excessive model size from hindering deployment.

5.4 Quality Evaluation

The quality evaluation of Gaussian Splatting for cultural heritage applications can be divided into six dimensions. The first is visual quality, including sharpness, color consistency, texture continuity, artefact control, viewpoint stability, and the naturalness of lighting and shadow. The second is geometric quality, including scale error, spatial registration error, surface deviation, boundary completeness, and missing information in occluded areas. The spatial reliability of a Gaussian model can be assessed by comparison with laser-scanning point clouds, structured-light point clouds, photogrammetric meshes, or control points. The third is heritage information quality, which concerns whether decorative patterns, inscriptions, materials, and technical details can be observed and interpreted. The fourth is interactive performance, including frame rate, loading speed, latency, device compatibility, and the stability of browsing paths. The fifth is documentation quality, including the completeness of original data, processing procedures, algorithm versions, parameter settings, manual modifications, and quality reports. The sixth is long-term usability, including format openness, metadata completeness, version management, migration capacity, and copyright licensing.

Quality evaluation should also distinguish between different application objectives. Models intended for public presentation may place greater emphasis on visual realism, interaction fluency, and narrative experience. Models used for restoration research must give greater priority to geometric accuracy, preservation of original data, and error reporting. Models designed for online museum exhibitions need to balance detail readability, interface design, and artefact interpretation. Models used for digital twins of archaeological sites should focus on coordinate systems, multi-temporal registration, and data update mechanisms.

5.5 Semantic Segmentation and Object Extraction

For Gaussian Splatting to be effectively applied in cultural heritage contexts, semantic mechanisms need to be established on top of visualized scenes. The key task is to transform continuous three-dimensional visual scenes into heritage and museum objects that can be named, retrieved, and interpreted. For example, in architectural heritage scenes, it is necessary to identify bracket sets, beam frames, roofs, painted decorations, doors and windows, inscriptions, and traces of restoration. In museum collection scenes, it is necessary to distinguish rims, bodies, bases, inscriptions, decorative patterns, cracks, and restored areas. In archaeological site scenes, it is necessary to annotate excavation squares, archaeological features, stratigraphic relationships, findspots, and interpretive areas. Only when object-level organization is achieved can Gaussian Splatting scenes move beyond simple browsing interfaces and enter processes of knowledge production and heritage service delivery.

More specifically, the semantic enrichment of Gaussian Splatting can proceed through three pathways. The first is two-dimensional semantic annotation based on input images. Artefacts, components, deterioration areas, or restored regions can first be annotated in photographs or video frames, and the annotation information can then be mapped into the 3D Gaussian scene according to camera poses. The second is object clustering and segmentation based on three-dimensional space. Components, artefacts, or regions within a scene can be grouped by using the position, color, opacity, and spatial adjacency of Gaussian primitives. The third is semi-automatic recognition supported by foundation vision models. Models such as Segment Anything can assist in the recognition of artefact parts, segmentation of deterioration areas, and extraction of three-dimensional objects. However, their outputs need to be refined through domain-specific data training and expert verification in order to avoid mismatches between general visual categories and heritage-specific semantics. The semantic enrichment of Gaussian Splatting should therefore not rely solely on general-purpose visual classification, but should be combined with heritage classification standards and expert validation.

5.6 Multi-Source Fusion

The main challenges of multi-source fusion lie in coordinate consistency, data granularity, and semantic mapping. Gaussian Splatting models need to maintain consistent scale and coordinates with point clouds, meshes, and GIS scenes. The object granularity of different models also needs to be coordinated: Gaussian primitives are visual primitives, HBIM components are architectural elements, and entries in heritage databases are management objects. Different systems also require unified naming conventions, identifiers, and metadata. Addressing these issues requires not only registration and transformation at the algorithmic level, but also the establishment of data governance standards by museums and heritage institutions. Only when Gaussian Splatting models can be incorporated into an institution's digital asset system can they acquire long-term value.

5.7 Deployment and Application

The application value of Gaussian Splatting is ultimately realized through deployment and service delivery. Cultural heritage digitization outputs usually serve multiple types of users. Conservation professionals require high-precision data and analytical tools; researchers require retrievable objects and evidence; curators require narrative organization and exhibition interfaces; and the public requires a smooth, intuitive, and accessible viewing experience. Therefore, the deployment of Gaussian Splatting models must also take into account device compatibility, network transmission, interaction design, and information organization.

Web-based deployment currently represents the direction with the greatest potential for broader adoption. Web platforms can lower the threshold for public access and facilitate online exhibitions, remote tours, and educational communication by museums and heritage institutions. The web-based deployment of Gaussian Splatting needs to address issues such as model compression, streaming loading, GPU memory consumption, frame-rate stability, and browser compatibility. For large archaeological sites and historical districts, partitioned loading, view-frustum culling, LOD strategies, and tile-based organization can be adopted to avoid loading all data at once. OGC 3D Tiles is designed for the streaming transmission of large-scale heterogeneous three-dimensional geospatial data and is suitable for organizing large-scale spatial content such as point clouds, buildings, and photogrammetric outputs. glTF, by contrast, emphasizes the efficient transmission and loading of three-dimensional scenes and models. Although the current format ecosystem for Gaussian Splatting is still developing, its long-term deployment should also draw on the principles of openness, interoperability, and efficient transmission embodied in these standards.

VR/AR deployment can further enhance the immersive potential of Gaussian Splatting. For virtual museums, grotto walkthroughs, site reconstructions, and historical district experiences, head-mounted displays and immersive spaces can provide a stronger sense of presence. However, VR/AR environments impose higher requirements on frame rate, latency, motion-sickness control, and interaction logic. Model size and rendering performance therefore need to be strictly optimized.

Mobile deployment places greater emphasis on lightweight design and accessibility. Smartphones and tablets are the main entry points through which the public encounters digital cultural heritage. However, due to limitations in computing power, memory, network conditions, and screen size, Gaussian Splatting models need to be compressed, simplified, and loaded hierarchically. Mobile applications should also avoid simply presenting users with complex three-dimensional scenes. Instead, they should be combined with guided routes, hotspot annotations, audio interpretation, textual and visual explanations, and search functions, so that users can obtain a clear information structure within the constraints of a limited screen.

6 FUTURE PROSPECTS

The future development of cultural heritage digitization will increasingly shift from the application of individual technologies to the construction of data infrastructures that operate across models, platforms, and institutions. For Gaussian Splatting, the central issue is to improve its connectivity, so that it can be reliably linked with measurement data, semantic data, archival data, and presentation platforms. Only on the basis of unified coordinates, unified identifiers, unified metadata, and unified access management can Gaussian Splatting models be integrated into the long-term workflows of heritage conservation, research, exhibition, and education.

With the development of smartphone photography, UAV imaging, mobile SLAM, and lightweight three-dimensional reconstruction tools, cultural heritage digitization is gradually expanding from a high-threshold task undertaken by a small number of specialized institutions into a multi-level practice involving professional teams, local organizations, and the public. Since Gaussian Splatting relies primarily on image input, it has considerable potential for lightweight data acquisition. This makes it possible for the technique to play a role in the documentation of community heritage, vernacular architecture, intangible cultural heritage spaces, historical districts, disaster-affected sites, and temporary exhibitions. Community residents, bearers of intangible cultural heritage, and local volunteers can contribute spatial memories, lived experiences, and local narratives. Public participation in data acquisition, annotation, and interpretation also has educational value for digital heritage and museum practice.

Cultural heritage conservation is increasingly moving toward preventive conservation. Three-dimensional digitization should therefore support long-term monitoring, change detection, and risk warning. The real-time rendering and image-driven characteristics of Gaussian Splatting give it potential value in multi-temporal heritage documentation. By regularly acquiring images and generating Gaussian Splatting scenes at different time points, researchers can visually present changes in heritage conditions, such as the weathering of building façades, the fading of murals, the exfoliation of stone carvings, changes in vegetation coverage at archaeological sites, the transformation of exhibition spaces, and differences before and after restoration. In the future, the contribution of Gaussian Splatting to preventive conservation can unfold at three levels. The first is condition visualization: multi-temporal scenes can be used to present heritage changes, enabling conservation professionals and the public to understand the development of deterioration and the restoration process more intuitively. The second is change detection: Gaussian Splatting can be combined with point clouds, meshes, image-difference analysis, and sensor data to assist in identifying crack propagation, deformation, surface detachment, and color change. The third is risk communication: immersive scenes can be used to present the impacts of disasters, visitor pressure, and environmental change, helping management authorities, the public, and stakeholders understand the necessity of conservation decisions.

Artificial intelligence and large-scale models will further reshape the application of Gaussian Splatting in cultural heritage digitization. In the future, AI may contribute at three levels. First, it can improve modeling stability by supporting acquisition planning, image selection, camera pose estimation, and the enhancement of low-quality images. Second, it can strengthen semantic capacity by identifying architectural components, artefact parts, deterioration areas, and exhibition-object boundaries, thereby transforming Gaussian scenes into interpretable objects. Third, it can improve communication efficiency by combining Gaussian Splatting with large-model-based guided interpretation, generating differentiated explanations for children, researchers, tourists, and professional users.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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