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3D Gaussian Splatting for Modern Architectural Heritage: Integrating UAV-Based Data Acquisition and Advanced Photorealistic 3D Techniques

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Abstract. 3D Gaussian Splatting (3DGS) is an advanced 3D representation method that enhances point clouds by incorporating spectral image content, enabling high-fidelity heritage documentation. A 3DGS visualization presents these enriched Gaussians, ensuring high geometric accuracy, detailed texture representation, and efficient spatial reconstruction, thereby enhancing both precision and efficiency in digital heritage preservation. This paper applies 3DGS to modern architectural heritage, combining UAV-based data acquisition with advanced rendering techniques. Using the Delft University of Technology Aula and Library buildings as case study, the research establishes a workflow for efficient heritage documentation and visualization.

Submission Type. Model

BoK Concepts. Foundations for Data Modelling Storage and Exploitation, Graphic representation techniques, Unmanned Aerial Systems (UAS)

Keywords. 3D gaussian splatting (3DGS), modern architectural heritage, UAV-based data acquisition, 3D visualization, virtual reality (VR)

1 Introduction

Recently, 3D Gaussian Splatting (3DGS), as a cutting-edge 3D photorealistic representation and 3D interactive visualization technology, has garnered significant attention in fields such as computer vision, buildings (Cai et al., 2024), and gaming due to its high precision, low processing time, and excellent visualization results. Since the publication of the first paper in August 2023 (Kerbl et al., 2023), the number of publications on 3DGS has surged. As of January 20, 2025, 216 papers have been published in the Web of Science (WoS). Current applications of 3DGS include, but are not limited to, image segmentation and recognition (Lan et al., 2024; Pham et al., 2024), digital modelling of urban environments (Mohamad et al., 2024), and real-time rendering in gaming engines (Mirocha, 2024), achieving remarkable outcomes. The demonstrated technical reliability and feasibility of 3DGS in these domains suggest its potential for applications in modern heritage.

Evaluation criteria used by Docomomo International [1] define modern architectural heritage as buildings constructed in the interwar and postwar period of the 20th century that hold historical, cultural, or artistic value (Kahrovic Handzic & Dimitrijevic, 2024). Their preservation and research require an approach that integrates their unique historical context and technological characteristics (Kaptan et al., 2023; Pottgiesser & Quist, 2023). The demonstrated technical reliability and feasibility of 3DGS in various fields suggests its potential for applications in modern heritage documentation and conservation. The motivation behind this study is to explore the application of representation of 3DGS in the context of modern architectural heritage, leveraging its capabilities for high-fidelity visualization, real-time rendering, and immersive interaction in digital heritage preservation.

[1] DOCOMOMO (Documentation and Conservation of buildings, sites, and neighborhoods of the Modern Movement) is an international organization dedicated to the documentation and conservation of modern movement architecture.

1.1 3DGS and Modern Architectural Heritage

3DGS originates from high-quality 3D rendering and addresses the challenges of sparse point clouds by filling gaps and smoothing transitions (Kerbl et al., 2023). It leverages the smoothness of Gaussian functions and the sparsity of point cloud data to achieve more efficient data processing and rendering results (Chen et al., 2024). The core principle of 3DGS is based on Gaussian kernel functions, where each sample point is approximated as a 3D Gaussian distribution (Fei et al., 2024). This is combined with colour and opacity to construct differentiable volumetric rendering. Accelerated by graphics processing unit (GPU) parallel computing, 3DGS significantly enhances efficiency while maintaining rendering quality, seamlessly filling gaps and details in point clouds (Dalal et al., 2024).

3DGS employs a new method based on 3D Gaussians or "splats." These splats are essentially 3D ellipsoids that can be rotated and stretched in any spatial direction to effectively capture the brilliance and appearance of scenes. Compared to Neural Radiance Fields (NeRF), which reconstructs scenes by querying a continuous volumetric function along sampled rays, 3DGS represents scenes through explicit Gaussian distributions that are directly optimized for rendering. NeRF samples discrete points along each camera ray, requiring extensive neural network computations to infer density and color at each location. In contrast, 3DGS replaces these discrete samples with smoothly blended Gaussians, which enables more efficient rendering and higher real-time performance (Fig. 1).

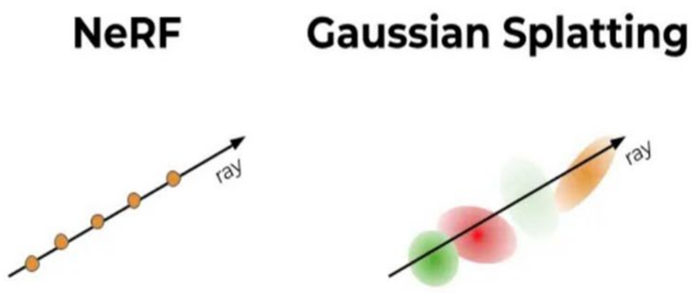


Figure 1. Conceptual sketch of Neural Radiance Fields (NeRF) and 3DGS (Tosi et al., 2024).

3DGS, initially developed for efficient 3D point cloud rendering, has recently been introduced into the field of cultural heritage preservation and research (Basso et al., 2024; Dahaghin et al., 2024; Shende, 2024). However, its application in architectural heritage preservation remains largely unexplored, with limited discussion on the role and viable paradigms of 3DGS in this domain. This paper expands on previous studies by investigating how image-based 3DGS can enhance interactive heritage experiences, bridging the gap between visualization and user engagement while establishing its potential as a tool for architectural heritage conservation.

1.2 Modern Architectural Heritage and the Application of Digital Technologies

The digitization of modern architectural heritage encompasses documentation, modelling, and visualization, typically using the following methods:

(a) Structure from Motion (SfM): High-resolution photography captures architectural details, and SfM reconstructs precise 3D models by analysing the motion and overlap between multiple images, resulting in a 3D point cloud with RGB information for detailed documentation and spatial analysis. (Al Khalil, 2020).

(b) Building Information Modelling (BIM) and Heritage Building Information Modelling (HBIM): These methods digitize building information through manual modelling or “Scan to HBIM” techniques, integrating historical, structural, and material information to support comprehensive analysis and management (Selim & Ahmed, 2018; Vali Yousefi, 2020).

(c) Laser Scanning and Point Cloud Modelling: Laser scanning or structured light scanning generates high-precision point cloud data without RGB, suitable for recording and reconstructing complex surfaces (Kościuk, 2012; van Oosterom et al., 2022).

(d) UAV-Based Remote Sensing: Unmanned Aerial Vehicle (UAVs) enable efficient aerial data acquisition, especially over large or inaccessible areas. Combined with SfM, UAV data support terrain modelling and building facade documentation(Chetverikov et al., 2024).

UAV technology has become a transformative tool for 3D reconstruction, offering diverse applications in urban planning (Lyu et al., 2024), heritage research

(Chetverikov et al., 2024), infrastructure monitoring (Aela et al., 2024), and emergency response (Bashir et al., 2024). By integrating UAV-based low-altitude aerial photography and 3DGS for optimized rendering, this approach enables rapid data collection over extensive areas while producing highly efficient, interactive visualizations. UAV imagery provides high-resolution input, and 3DGS enhances these models with real-time rendering capabilities that require minimal hardware resources This approach provides a more immersive experience for the preservation and study of modern heritage buildings.

1.3 Research Objectives

As discussed above, although 3DGS is a relatively recent technology, it has already achieved a level of technical maturity suitable for exploratory applications in modern architectural heritage. However, research specifically applying this technology to modern heritage buildings remains scarce. The objective of this study is to establish a workflow that leverages 3DGS for the documentation, rendering, and visualization of modern architectural heritage. Additionally, this study aims to evaluate the advantages and limitations of this approach in comparison to other digital documentation methods. Similarly, the integration of UAV-derived imagery with 3DGS remains underexplored.

2 Related Work

In addition to 3DGS, two other widely used and related techniques for 3D reconstruction in modern architectural heritage documentation are SfM and Neural Radiance Fields (NeRF), Comparisons of 3DGS, SfM and NeRF in Cultural Heritage Applications are given in Table 1.

- **SfM :** SfM excels at generating detailed and accurate 3D models by analysing the motion and overlap between multiple images, reconstructing spatial geometry without requiring prior camera calibration (Jiang et al., 2020). Its adaptability allows for the documentation of objects across a wide range of scales, from small artifacts to expansive landscapes and large architectural structures. SfM-derived models are measurable and scalable, making the method invaluable for heritage recording and analysis. However, SfM struggles with reflective and transparent surfaces, often leading to data voids or artifacts. While these issues can be mitigated through manual post-processing or the integration of complementary scanning techniques, such interventions are labour-intensive and time-consuming, highlighting a significant limitation of the method.
- **NeRF:** NeRF and 3DGS share similarities in their lack of reliance on traditional mesh structures, which often leads to confusion when distinguishing between the two. NeRF excels in capturing complex lighting conditions, reflections, and transparency effects, significantly enhancing visual realism. This makes it particularly well-suited for applications requiring detailed visual representations of environments, such as skies, horizons, and intricate indoor elements like ceilings (Croce et al., 2024). However, NeRF's major drawback lies in its computational inefficiency (Condorelli & Luigini, 2024). The method requires extensive training and produces slow rendering speeds, with low Frames Per Second (FPS) during visualization, making it unsuitable for real-time interaction or VR applications.
- **3DGS:** In contrast to NeRF and SfM, 3DGS strikes a balance between performance and efficiency. It supports real-time rendering on lower-specification hardware while handling complex lighting and dynamic scenes, making it particularly well-suited for heritage environments. While NeRF surpasses 3DGS in rendering intricate lighting effects and perspective changes, its computational demands limit its practicality. SfM, on the other hand, offers higher geometric precision and is a well-established workflow for heritage documentation. However, it faces challenges with reflective or transparent surfaces and often requires manual intervention for accurate results. A potential future trend is the integration of SfM and 3D Gaussian Splatting, where SfM is utilized to establish a geometrically accurate framework, while Gaussian Splatting enhances visual fidelity. This hybrid approach can effectively balance metric precision and high-quality visualization, making it particularly valuable for heritage documentation and interactive applications.

Table 1. Comparison of 3DGS, SfM and NeRF in Cultural Heritage Applications.

Feature	3DGS (Gaussian Splatting)	SfM	NeRF (Neural Radiance Fields)
Hardware Requirements	Low	Moderate	High
Real-time Interaction	Yes	No	No
Lighting and Transparency Handling	Handles complex lighting and dynamic scenes	Challenges with reflective and transparent surfaces	Excellent, dynamic lighting and reflections
Detail and Accuracy	High	Moderate	High
Ease of Application	Emerging, good for real-time use	Mature and widely adopted	Experimental, advanced applications
Strengths	Low hardware requirements, real-time VR support	Scalability, cost-effectiveness, adaptability	Photorealistic rendering, perspective changes
Limitations	Less mature than traditional methods, may lack precision in some cases	Sensitive to lighting, computationally intensive, requires high-quality images	High computational demands, not suitable for real-time or VR applications

3 Methods

This study establishes an efficient and cost-effective data visualization framework for modern architectural heritage using publicly accessible hardware and open-source or widely available software, primarily involving data collection using drones and cameras, data processing through Postshot, and rendering 3DGS to create visualizations that facilitate the dissemination of modern architectural heritage. The specific process is as follows (Fig. 2):

3.1 Data Acquisition

The UAV used for this project is the DJI Mini 2, equipped with a 1/2.3-inch CMOS sensor capable of capturing 12MP effective pixels. This UAV is lightweight, efficient, and ideal for heritage data acquisition.

(a) Capture Date and Duration: The total flight time was approximately 2 hours, divided into multiple 20-minute sessions to allow for battery replacements and to ensure comprehensive coverage of the site.

(b) Camera Angles and Positions: High and low-altitude passes were conducted to capture both broad architectural structures and detailed elements such as façades and ornamentations. Images were taken with a 60-80% overlap rate to ensure photogrammetric reconstruction in Postshot.

In addition to UAV images, high-resolution ground photographs were taken using a DSLR camera to capture intricate details of the site, such as textures, sculptures, and inscriptions.

3.2 Data Processing

Drone and ground images are imported into Postshot (Jawset Postshot) for preprocessing, where the software utilizes Structure from Motion (SfM) to align the images, calculate camera poses, and generate a sparse point cloud.

3.3 3DGS Ellipsoid Generation

The optimized point cloud is converted into anisotropic Gaussian ellipsoids to enhance rendering efficiency. Each point carries position, colour, opacity, and Gaussian attributes instead of being converted into a polygonal mesh. Parameters such as colour, opacity, and size are adjusted based on loss calculations between rendered and original images, ensuring high-quality output.

The optimization of the 3DGS point cloud involves several key steps: denoising to remove outlier points and artifacts for improved model clarity, color and transparency refinement through global color correction to balance brightness and contrast, and center size adjustment based on point cloud density to ensure smooth rendering while preserving details.

3.4 The Interactive Use of 3DGS

3DGS has the potential to further enhance rendering efficiency, realism, and interactivity in architectural heritage visualization. Its compatibility with immersive platforms such as VR, AR and international heritage platforms like DOCOMOMO could facilitate broader

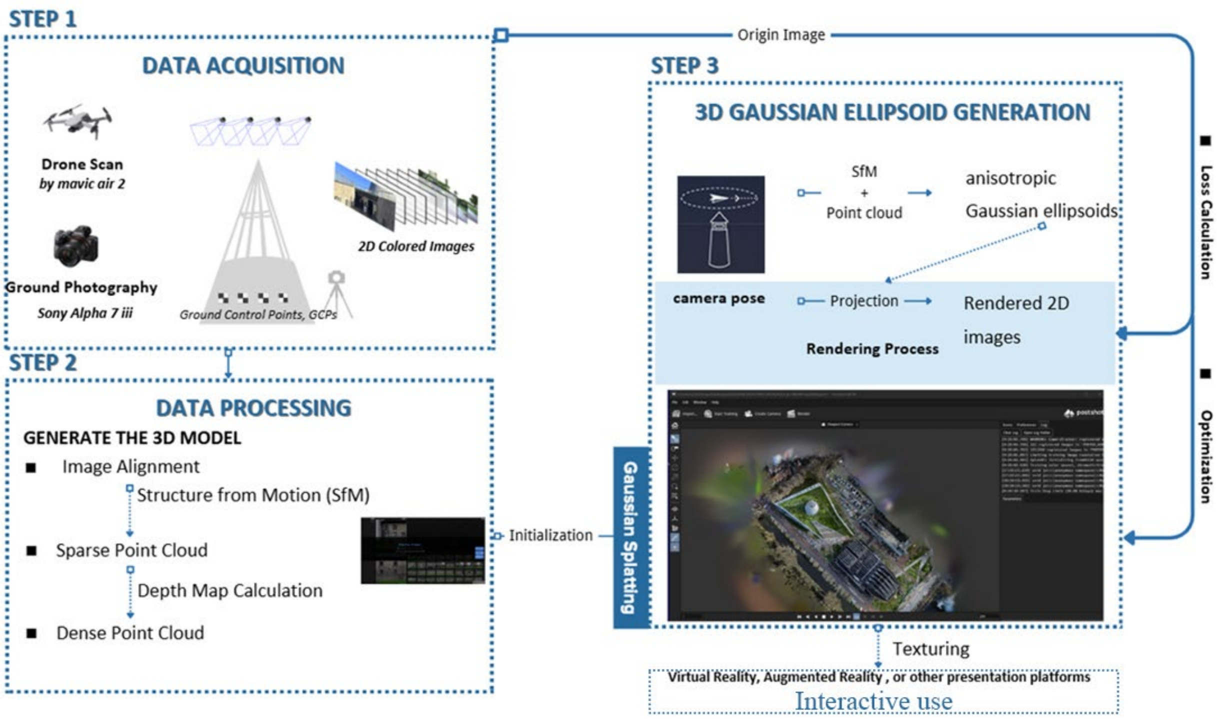


Figure 2. The overview of 3D visualisation workflow (by the author).

accessibility and engagement with modern architectural heritage.

3.5 Data and Software Availability

All data used in this study were collected using publicly available hardware and open-source tools. The complete dataset—including the processed 3D Gaussian Splatting point cloud (.ply) and the Unity-based VR environment—has been deposited on the Open Science Framework (OSF). The dataset is openly available under the CC-BY 4.0 license and includes structured documentation to support reproduction of the visualization workflow. All materials can be accessed at: https://doi.org/10.17605/OSF.IO/P3CW7 (accessed on 22 April 2025).

4 Case Study: Aula and Library

To achieve the above objectives, this study focuses on two modern architectural heritage buildings in Delft, the Netherlands: Delft University of Technology Library and the Aula Conference Center (Fig. 3). These buildings are exemplary of modern architectural design and hold significant cultural and historical value, meeting the fundamental characteristics of modern architectural heritage. Each modern building represents notable differences in materials, structures, and functionality, thus providing diverse case studies for digitizing modern heritage architecture.

Figure 3. Aula in the UAV's detection screen.

5 Results and discussions

5.1 Rendering Results and Efficiency

The final visualization (Fig. 4) achieved a high degree of realism, accurately representing the geometric structures, material textures, and intricate details of modern architectural heritage. 3DGS ensures smooth transitions in lighting and perspective, delivering an immersive and photorealistic experience. Fine details, such as façade textures, structural patterns, and decorative designs, were preserved with exceptional clarity. Furthermore, the rendered models exhibited smooth real-time interactivity, supporting dynamic adjustments in lighting and camera perspectives, making them highly versatile for immersive applications.

The rendering process demonstrated impressive computational performance. For medium-complexity architectural models, the average rendering time per frame was approximately 20-25 milliseconds, enabling real-time frame rates of 40-50 FPS on standard GPU hardware. The full dataset, including loss calculation (used to minimize errors between the reconstructed model and the input images) and optimization, required about 2 hours to render. The 3DGS technique eliminates the need for high-polygon models while maintaining visual fidelity, thereby reducing computational loads. Adaptive density control further concentrates resources on regions requiring higher detail, optimizing the overall rendering process.

3DGS-rendered models achieve a high level of detail comparable to traditional photogrammetric mesh models.

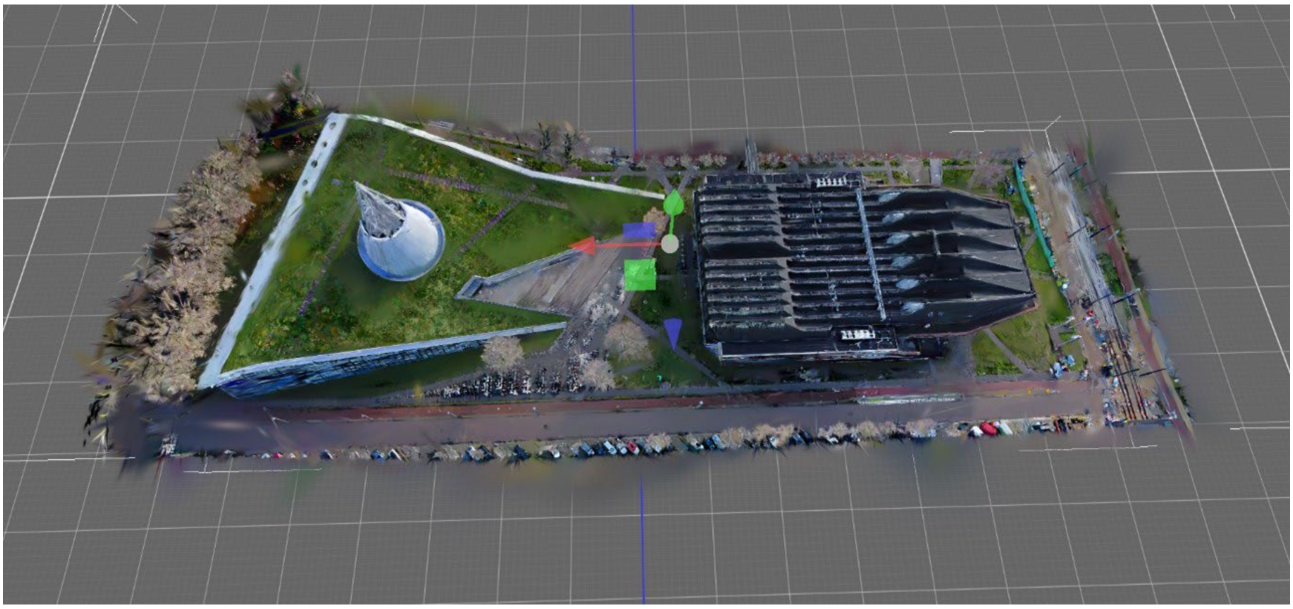
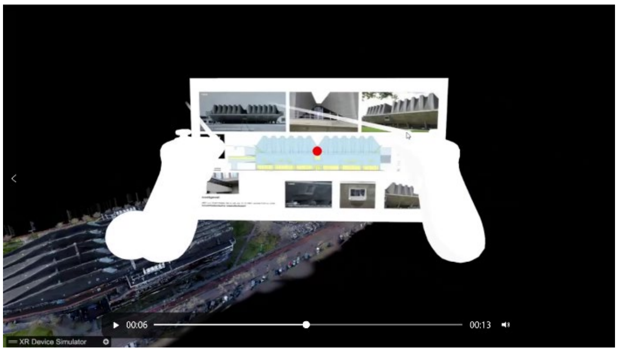


Figure 4. The result of 3DGS.

Fine details such as textures, subtle lighting variations, and intricate architectural features are effectively captured and rendered. In addition, 3DGS distinguishes itself by offering superior real-time performance, enabling interactive visualization and dynamic scene rendering without significant hardware demands (Qiu et al., 2024). Compared to mesh-based methods, 3DGS reduces hardware requirements (computer) by approximately 50%, making it a more resource-efficient solution. This reduction enables broader accessibility, including applications on web-based platforms and lightweight VR systems, democratizing access to high-quality 3D visualizations.

5.2 Interactive Visualization of 3DGS in VR

The final 3D Gaussian Splatting (3DGS) model, derived from UAV-based photogrammetry, was successfully integrated into an interactive Unity-based virtual environment. Within the VR scene, users can explore the photorealistic heritage model in real-time, with smooth rendering and continuous camera control. To enhance spatial understanding and user engagement, a series of interactive hotspots were embedded into the 3DGS environment. These hotspots correspond to historically or architecturally significant elements within the model, and when triggered—via gaze or proximity—display contextual information such as textual annotations and image overlays. This integration enabled not only immersive visualization of high-resolution spatial data but also supported layered information delivery through spatially anchored interactions, offering a hybrid experience between physical realism and interpretive storytelling.



5.3 Advantages of the Workflow

Through the trail with the modern architectural buildings in Delft, the advantages of the proposed workflow are identified:

(a) UAV Integration: The aerial images captured with UAVs, particularly lightweight drones, serve as powerful tools for documenting medium-scale architectural heritage, enabling efficient data acquisition from multiple perspectives. They are cost-efficient, easy to operate, and subject to minimal regulatory restrictions in most jurisdictions. UAVs can capture images from various heights, angles, lighting conditions, and weather scenarios, providing comprehensive coverage of architectural structures. By integrating Images captured by UAV into the generation of heritage datasets, this workflow combines detailed data acquisition with operational flexibility and cost-effectiveness, making it accessible for a wide range of applications.

(b) 3DGS: 3DGS offers unique advantages over SfM and NeRF. Beyond being compatible with smartphone-captured images, 3DGS supports direct loading and visualization on web platforms and Virtual Reality (VR) devices (Kim & Lee, 2024; Schiavo, 2024). Its computational efficiency significantly reduces hardware requirements, making it highly suitable for real-time applications, like digital twins (Do et al., 2024). Compared to SfM and NeRF, 3DGS achieves higher frame rates, enabling dynamic and immersive visualization of architectural heritage in virtual environments. This efficiency enhances accessibility and scalability for diverse modern architectural heritage projects.

5.3 Limitations

The limitations of this workflow primarily revolve around its focus on visualization rather than detailed modelling. While GS enables efficient and visually compelling point cloud visualization, it lacks the capability to produce comprehensive and structured digital representations. To achieve fully detailed models with semantic and structural information, this workflow must be integrated with frameworks such as Building Information Modelling (BIM) or Heritage Building Information Modelling (HBIM). These frameworks allow for the inclusion of critical metadata, such as material properties, construction methods, and historical context, which are essential for in-depth heritage analysis and conservation planning.

Another notable limitation is the rendering time. Although 3DGS incorporates optimization techniques that enhance computational efficiency, the rendering process for large datasets remains computationally intensive, particularly during the optimization phase. This can present challenges for real-time or large-scale applications, where processing delays may hinder timely visualization and analysis (Kerbl et al., 2024). Further algorithmic improvements or advancements in computational hardware are necessary to mitigate these issues and ensure the workflow's practicality for a broader range of scenarios.

Finally, the accuracy of this workflow is inherently limited by the quality of the input data, which is primarily derived from UAV and camera imagery. While adequate for visualization purposes, the precision of 3DGS-generated models cannot yet match the accuracy of static scanning devices such as LiDAR or high-resolution terrestrial scanners (LiDAR and high-resolution scanners are capable of capturing sub-millimeter geometric detail, whereas 3DGS results are often dependent on the quality of the input data) (Jiang et al., 2024). These devices offer superior detail and geometric accuracy, particularly for capturing intricate architectural features and complex spatial relationships. Addressing these limitations will require integrating complementary data acquisition methods and refining processing algorithms to improve the fidelity of 3DGS-rendered models, especially for applications that demand high levels of precision.

6 Conclusion

This study validates the effectiveness and cost-efficiency of using 3DGS based on UAV imagery for initial point cloud visualization, particularly for large heritage sites with limited computational resources. By relying on accessible UAV technology and 3DGS, the proposed workflow eliminates the need for expensive static scanning devices, making it a practical and economical solution for researchers and institutions with constrained budgets.

The scalability of the workflow further enhances its utility, as it can be applied to a wide range of modern architectural heritage sites, from small monuments to expansive architectural complexes. This flexibility ensures that researchers working in resource-limited environments can still document and visualize heritage sites effectively. Despite its strengths, future research should address some limitations to further improve the workflow’s practicality and precision, like integrating 3DGS with BIM or HBIM frameworks could enable more comprehensive digital representations, combining geometric, historical, and material data for in-depth analysis, restoration planning, and management.

In conclusion, this study demonstrates the potential of a 3DGS-based workflow as a cost-effective, scalable, and efficient method for modern architectural heritage representation. It provides a robust solution for resourceconstrained environments while supporting cutting-edge visualization technologies. With further refinement and integration, this approach could become a cornerstone for digitally enhanced heritage preservation and dissemination, enabling broader accessibility and deeper engagement with modern architectural heritage worldwide.

Declaration of Generative AI in writing

The author[s] declare[s] that [I/they] have [not] used Generative AI tools in the preparation of this manuscript. Specifically, the AI tools were utilized for [describe the specific purpose, e.g., "language editing, improving grammar, and sentence structure,"] but not for generating scientific content, research data, or substantive conclusions. All intellectual and creative work, including the analysis and interpretation of data, is original and has been conducted by the author[s] without AI assistance.

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