

Integrating Terrestrial Laser Scanning and 3D Gaussian Splatting for Heritage Building Documentation and Monitoring

Deni Suwardhi^{1,3}, Lea Kristi Agustina², Wahyunan Andika³, Ratri Widyastuti¹, Widiatmoko Azis Fadilah⁴, Arnadi Murtiyoso⁴, Fabio Remondino⁵

¹ Spatial System and Cadastral Research Group, Institut Teknologi Bandung (ITB), Indonesia - (deni.suwardhi, ratri)@itb.ac.id

² Geodesy & Geomatic Eng. Doctoral Programmes, Institut Teknologi Bandung (ITB), Indonesia - 35120008@mahasiswa.itb.ac.id

³ PT Inovasi Mandiri Pratama, Spatial Information Company, Indonesia - wahyunan.andika@inovamap.com

⁴ Université de Strasbourg, CNRS, INSA Strasbourg, ICube Laboratory UMR 7357,

Photogrammetry and Geomatics Group, 67000, Strasbourg, France - (widiatmoko-azis.fadilah, arnadi.murtiyoso)@insa-strasbourg.fr

⁵ 3D Optical Metrology (3DOM) Unit, Bruno Kessler Foundation (FBK), Trento, Italy - remondino@fbk.eu

Keywords: Heritage 3D Documentation, Laser Scanning, 3D Gaussian Splatting, HBIM, Co-registration, Immersive Visualization.

Abstract

Accurate and reliable 3D documentation is important for the conservation and long-term monitoring of heritage buildings, where both metric precision and visual interpretability are required. This paper presents a co-registered hybrid 3D information model for heritage buildings, integrating Terrestrial Laser Scanning (TLS), Historic Building Information Modelling (HBIM), and 3D Gaussian Splatting (3DGS). The approach is demonstrated through a case study of Aula Timur ITB, a nationally protected heritage building in Indonesia. TLS data serve as the geometric backbone of the framework, providing survey-grade spatial reference. An HBIM model is generated from the TLS point clouds and structured using the Industry Foundation Classes (IFC) standard, ensuring that semantic building components are co-registered with the metric geometry. In parallel, a photorealistic 3DGS representation is generated from image-based reconstruction and rigidly aligned to the same TLS reference frame. Rather than producing a single fused geometry, the proposed integration results in a multi-layer representation in which metric, semantic, and radiance-field-based models coexist within a shared spatial reference. Quantitative alignment metrics, including transformation residuals, and cloud-to-cloud distance analysis, are used to assess geometric consistency between TLS and 3DGS. The integrated model is deployed in an immersive VR/MR environment to support intuitive navigation and visual inspection tasks. The results demonstrate that anchoring 3DGS to survey-grade geometry enables photorealistic real-time visualization while preserving spatial reliability, making the approach suitable for heritage documentation and monitoring scenarios. The proposed workflow highlights the complementary roles of metric surveying, information modelling, and emerging radiance-field representations in heritage-oriented 3D information systems.

1. Introduction

1.1 Background

Accurate and detailed three-dimensional (3D) documentation is important for the preservation and monitoring of heritage buildings, particularly in tropical regions where high humidity, intense rainfall, and biological weathering accelerate material degradation. Reliable geometric and visual data are therefore crucial to support condition assessment, change detection, and long-term conservation planning (Agustinova, 2022; Alya et al., 2023).

Terrestrial Laser Scanning (TLS) is widely used in heritage documentation due to its ability to provide highly accurate and metrically consistent 3D geometry, supporting shape analysis, dimensional measurement, and geometric change monitoring. However, TLS data are limited in their ability to represent fine visual details and surface appearance in a photorealistic manner, which constrains their use for visual inspection and material assessment. To address this limitation, TLS is commonly combined with image-based photogrammetric models or textures (Murtiyoso et al., 2023). In contrast, recent radiance-field-based approaches such as 3D Gaussian Splatting (3DGS) enable highly realistic representations of color, lighting, and surface appearance and support real-time rendering (Kerbl et al., 2023). Nevertheless, as 3DGS primarily targets visual rendering, it does not explicitly encode survey-grade geometric

accuracy, limiting its standalone applicability for metric analysis and quantitative monitoring.

Beyond accurate geometry and visual realism, effective heritage management requires information systems that integrate geometric data with semantic, historical, and maintenance-related information. Historic Building Information Modelling (HBIM), based on object-oriented representations and the Industry Foundation Classes (IFC) standard, provides a structured framework for managing such information. When integrated with Geographic Information Systems (GIS) and immersive visualization technologies such as Virtual Reality (VR) and Mixed Reality (MR), HBIM-based systems enable intuitive exploration, inspection, and communication of heritage data, extending 3D models from static documentation toward interactive analysis and decision support (Barazzetti and Banfi, 2017; Banfi, 2021).

This paper proposes an integrated framework that combines hybrid 3D representations derived from TLS and 3DGS with an HBIM-GIS approach and immersive visualization to support heritage building documentation, management, and monitoring. The proposed integration aims to preserve survey-grade geometric accuracy while enhancing visual interpretability for inspection and condition assessment.

The framework is demonstrated through a case study of the Aula Timur Building at Institut Teknologi Bandung (ITB), one

of Indonesia's oldest academic buildings and a designated national cultural heritage asset. Completed in 1919 and designed by Dutch architect Henri Maclaine Pont, the building represents an early example of Indies architecture adapted to tropical conditions. Its historical significance and continued use provide a compelling context for evaluating the proposed workflow and its potential extension toward a decision-oriented heritage digital twin system. Figure 1 presents the Aula Timur building, the case study selected for this research, including both exterior and interior elements.



Figure 1. The Aula Timur heritage building at ITB campus.

1.2 Related Work

Research on 3D documentation for cultural heritage has progressively evolved from single-sensor recording toward integrated, multi-source approaches that aim to balance geometric accuracy, visual completeness, and long-term usability for conservation and management. Best-practice frameworks emphasize the importance of carefully designed acquisition strategies, multi-sensor integration, and traceable quality control to ensure that 3D products support not only visualization but also condition assessment and conservation-oriented decision-making (Remondino and Campana, 2014).

Several studies have demonstrated the relevance of integrated approaches for heritage documentation. The Digital 3D Borobudur project showed how combining multiple surveying and modeling techniques can effectively support large and complex heritage sites, particularly for long-term monitoring and preservation (Suwardhi et al., 2015). Image-based approaches, including close-range UAV photogrammetry, have proven capable of generating detailed 3D reconstructions of heritage buildings, while also revealing challenges related to dense image matching stability, geometric consistency, and acquisition design, especially for complex architectural structures (Murtiyoso and Grussenmeyer, 2017).

To address these limitations, multi-scale and multi-sensor strategies have been increasingly adopted. Murtiyoso et al. (2018) demonstrated that integrating data from different sensors and levels of detail is essential for documenting heritage complexes in urban environments, where both individual buildings and their spatial context must be represented. Beyond documentation, 3D data have been progressively embedded within spatial information systems to support heritage management and decision-making, shifting from static models toward operational, GIS-oriented frameworks (Suwardhi et al., 2016; Suwardhi et al., 2022).

Meanwhile, recent advances in real-time neural and explicit scene representations have introduced new opportunities for interactive 3D visualization. 3D Gaussian Splatting (3DGS) has emerged as an efficient explicit radiance-field representation capable of real-time, high-quality rendering, making it attractive for interactive inspection and immersive applications (Kerbl et

al., 2023). However, visual realism does not necessarily guarantee geometric reliability, and recent studies have shown that image-based evaluation metrics may poorly correlate with geometric accuracy when compared to LiDAR-based references (Xiong et al., 2024). To mitigate these limitations, hybrid approaches integrating active sensor data have been proposed. For example, LI-GS incorporates LiDAR information into Gaussian splatting frameworks, demonstrating improved geometric accuracy and stability through image–LiDAR supervision (Jiang et al., 2025).

Recent heritage-oriented studies have further explored neural rendering approaches. Balloni et al. (2024) compared neural rendering methods, including NeRF and Gaussian Splatting, for complex heritage sites, highlighting trade-offs between visual quality and practical applicability. In heritage-focused photogrammetric research, Mazzacca et al. (2023) demonstrated neural radiance field–based heritage reconstruction with an emphasis on camera network recovery, metric consistency, and quantitative evaluation against reference data.

From a visualization and interaction perspective, immersive visualization has gained increasing attention for heritage exploration and communication. VR-based studies emphasize the role of interactive navigation and user experience in enhancing spatial understanding and public engagement (Tribhuvan and Binnaser, 2024). However, most existing works address either reconstruction accuracy or immersive visualization in isolation. This study addresses this gap by integrating georeferenced TLS, UAV LiDAR-derived 3D basemaps, and 3D Gaussian Splatting within a unified spatial framework, while explicitly evaluating their performance for immersive navigation in heritage environments.

Overall, the existing literature indicates a clear progression from accurate but visually limited 3D documentation toward hybrid representations that combine metric robustness, photorealistic visualization, and system-level integration. Nevertheless, a remaining gap lies in the seamless integration of multi-sensor heritage documentation, emerging Gaussian splatting-based visual representations, and structured spatial information systems that support immersive interaction and decision-making. Addressing this gap is particularly relevant for heritage monitoring scenarios, where accurate geometry, reliable visual assessment, and operational usability must coexist within a single, coherent framework.

2. Methodology

The proposed methodology is structured into two main components. The first component focuses on the co-registration and assessment of multi-source 3D datasets, including TLS point clouds and image-based reconstructions used for 3DGS. The second component addresses the construction of a heritage information system and its immersive visualization, integrating semantic building models, metric geometry, and photorealistic representations within a unified spatial framework. The overall workflow is illustrated in Figure 2.

2.1 Co-registration of TLS and Image-based Datasets

The first part of the methodology focuses on integrating heterogeneous 3D datasets within a common, metrically consistent spatial reference. A hierarchical alignment strategy is adopted, in which a UAV LiDAR-derived 3D basemap provides the global geodetic framework, while terrestrial and

image-based datasets are subsequently aligned within this reference system.

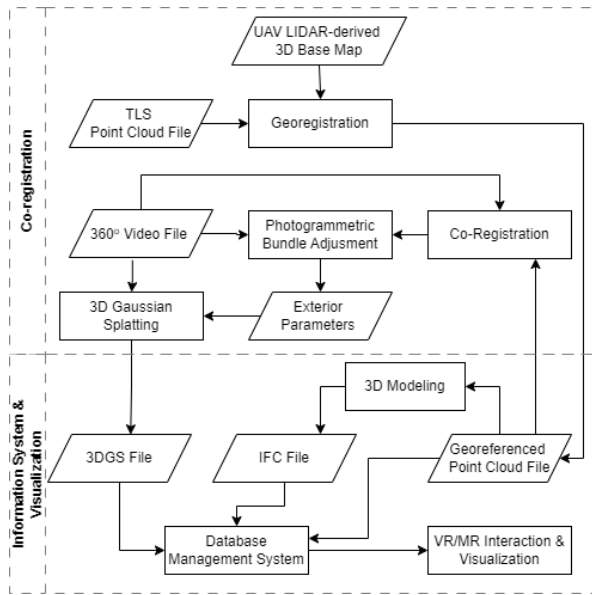


Figure 2. Workflow of the proposed co-registered 3D heritage information model integrating TLS-based geometry, HBIM semantics, and 3DGS for photorealistic visualization and immersive interaction.

The 3D basemap was generated from UAV-based LiDAR data acquired using a DJI Zenmuse L2 sensor mounted on a multi-rotor platform. Owing to its homogeneous coverage and consistent global positioning, the UAV LiDAR dataset serves as the absolute spatial reference for the study area and subsequent multi-layer integration. The dataset exhibits RMS check point errors of 0.071 m and 0.086 m in the horizontal components (X and Y), and 0.207 m in height (Z), which are sufficient for TLS georeferencing and multi-layer integration. The observed accuracy is partly influenced by the use of RTK GNSS-measured check points, which typically introduce larger uncertainties in the vertical component.

Terrestrial laser scanning data were acquired using a Leica BLK360 scanner. The BLK360 is a compact time-of-flight TLS system suitable for architectural environments. According to Jung et al. (2024), it provides point accuracy on the order of 6 mm at 10 m and 8 mm at 20 m, making it appropriate as a survey-grade geometric reference for heritage documentation and co-registration tasks. In this study, TLS data were used as the survey-grade geometric backbone for integrating image-based and neural rendering representations.

The TLS point cloud was first georeferenced to the UAV LiDAR basemap using a rigid 3D similarity transformation, establishing the TLS data in a global coordinate system. Prior to integration, the TLS point cloud was pre-processed through noise filtering and resolution downsampling to balance geometric detail and computational efficiency while preserving key structural features required for reliable alignment.

Image-based data were acquired using 360° video capture with a GoPro MAX camera, ensuring comprehensive visual coverage of interior and exterior spaces. The video sequences were converted into 1,095 equirectangular image frames and processed using a photogrammetric bundle adjustment to

estimate camera orientations and generate an image-based reconstruction in a local coordinate system. Co-registration to the TLS reference frame was achieved by integrating manually identified 3D control points into the bundle adjustment. These control points were extracted from the georeferenced TLS point cloud and constrained the adjustment, ensuring a metrically traceable alignment between the image-based reconstruction and the TLS geometry. Figure 3 illustrates the UAV LiDAR flight trajectories over the ITB campus, showing the spatial coverage and acquisition geometry used to generate the 3D basemap, as well as the spatial distribution of 360° video camera positions around the Aula Timur building.

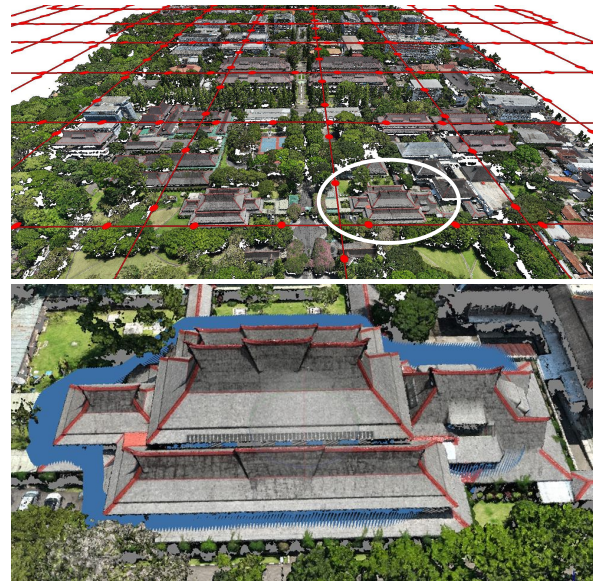


Figure 3. UAV LiDAR trajectories (top) and 360° camera positions at the Aula Timur building (bottom).

Following co-registration, the aligned image-based reconstruction is used to generate a 3DGS representation. The 3DGS representation was generated following the standard formulation proposed by Kerbl et al. (2023). The implementation builds upon recent open-source developments in Gaussian Splatting, including the gsplat library by Ye et al. (2024), and was realized using the high-performance LichtFeld Studio C++/CUDA framework. The resulting 3DGS model inherits the same spatial reference as the TLS point cloud through the established transformation parameters. Rather than producing a single fused geometry, the workflow maintains the TLS point cloud and the 3DGS representation as distinct but spatially aligned layers within a shared reference system. This strategy preserves the metric reliability of the survey data while enabling visually expressive and real-time rendering through the radiance-field-based representation.

To support scalable visualization and platform-independent access, the georeferenced TLS point cloud and the co-registered 3DGS model are converted into streamable formats and deployed through a cloud-based spatial data service. This enables efficient data streaming and consistent spatial alignment across web-based and immersive visualization environments without duplicating large datasets.

Co-registration quality is evaluated using complementary quantitative metrics. TLS georeferencing to the 3D basemap is assessed through residual errors at similarity transformation control points and cloud-to-cloud distance analysis. For the

3DGS model, accuracy is evaluated using bundle adjustment residuals at control points, complemented by cloud-to-cloud distance analysis between TLS and 3DGS. Together, these metrics provide an objective assessment of spatial consistency between metric and image-based representations, supporting reliable visualization and inspection tasks.

2.2 Information System and Immersive Visualization

The second part of the methodology focuses on the development of an information-oriented representation of the heritage building and its integration into an immersive visualization environment. HBIM is generated directly from the georeferenced LiDAR point cloud, ensuring inherent spatial consistency between semantic building components and metrically reliable geometry.

Due to the geometric complexity and non-standard architectural forms typical of heritage buildings, fully automated modelling approaches are often insufficient. Therefore, a manual solid modelling strategy based on point cloud tracing is adopted to ensure that architectural elements accurately reflect the as-built condition. The resulting model is structured according to the IFC standard, enabling the organization of building components into semantically meaningful entities enriched with heritage-related attributes such as material information and conservation data.

Rather than merging all representations into a single geometric model, the methodology adopts a multi-layer approach in which the IFC-based HBIM model, the TLS point cloud, and the 3DGS representation are maintained as distinct but spatially aligned data layers. This design choice reflects the complementary roles of each representation: LiDAR point clouds provide metric reliability for spatial measurements, HBIM supports structured semantic interaction, and 3DGS enables photorealistic visualization for intuitive inspection.

These co-registered data layers are managed within a heritage information system that preserves spatial references and logical links between metric, semantic, and visual representations. For visualization, the integrated datasets are accessed through both web-based and immersive environments. In immersive Virtual Reality (VR) and Mixed Reality (MR) applications, users can explore the heritage building, switch between metric, semantic, and photorealistic layers, and perform inspection tasks within a consistent spatial framework. Visual exploration relies primarily on the 3DGS representation, semantic queries are supported by the IFC-based HBIM model, and spatial measurements are grounded in the LiDAR point cloud.

The proposed framework is designed to support repeated data acquisition and long-term monitoring. Subsequent TLS surveys can be registered to the same spatial reference to enable quantitative assessment of geometric changes, while updated image-based acquisitions can be used to regenerate co-registered 3DGS representations. This separation between metric analysis and visual inspection allows coherent assessment of both structural changes and surface appearance over time within a single heritage information system.

To operationalize the proposed multi-layer and co-registered heritage information model, a modular software architecture is implemented to support data management, streaming, and user interaction across multiple platforms. The architecture is designed to preserve the separation between metric, semantic,

and photorealistic data layers while ensuring consistent spatial referencing and interoperability between system components.

As illustrated in Figure 4, the architecture follows a distributed design in which data management, visualization services, and user interaction are decoupled. Semantic and heritage-related information is managed within a heritage information system, which maintains logical links between IFC-based HBIM elements and externally stored 3D datasets. Metric geometry from LiDAR point clouds and photorealistic 3DGS representations are streamed through a dedicated 3D data service, enabling efficient level-of-detail handling and multi-client access.

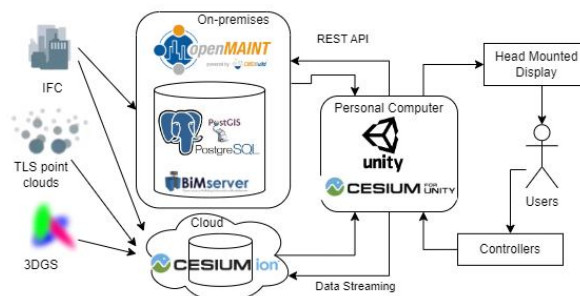


Figure 4. Software architecture of the proposed heritage information system integrating LiDAR point clouds, IFC-based HBIM, and 3DGS for immersive visualization.

User interaction is supported through web-based and immersive applications that access the same co-registered datasets. Immersive visualization environments enable intuitive navigation and inspection by combining photorealistic rendering, semantic querying, and metric measurement within a unified spatial reference. This architecture ensures that visual realism, semantic richness, and metric reliability can be jointly exploited without conflating their respective data representations.

3. Results

This section presents the results obtained from the proposed co-registered hybrid 3D heritage information model. The results are organized to reflect the main objectives of the study, namely the quality of TLS-3DGS integration, the consistency of the multi-layer representation, and the performance of the integrated model in immersive visualization.

3.1 Georeferencing and Co-registration Accuracy

3.1.1 Georeferencing of TLS to the UAV LiDAR-derived 3D Basemap

The first evaluation examines the georeferencing of the TLS point cloud to the UAV LiDAR-derived 3D basemap, characterized by centimeter to decimeter-level absolute accuracy (Section 2.1), which provides a geodetically referenced, large-scale spatial framework for the study area. The TLS dataset, initially defined in a local scanner coordinate system, was transformed into the basemap coordinate system using a 3D similarity transformation. The transformation parameters were estimated from stable architectural features identifiable in both the TLS and UAV LiDAR datasets, allowing the TLS point cloud to inherit the absolute positioning and orientation of the airborne LiDAR basemap while preserving its local geometric consistency.

Georeferencing accuracy was evaluated using transformation residuals, explicitly separated into horizontal (XY) and vertical (Z) components. The results indicate RMS residuals of approximately 11.1 cm in the horizontal (XY) direction and 0.95 cm in height (Z), with maximum residuals of 14.1 cm (XY) and 1.30 cm (Z).

In addition, a cloud-to-cloud distance analysis was conducted to examine the spatial distribution of residual discrepancies (Figure 5). Most surface deviations remain below approximately 15 cm, with larger localized differences mainly observed along roof edges, vegetation, and occluded areas. The absence of systematic distortion patterns confirms a stable and reliable alignment between the TLS point cloud and the UAV LiDAR basemap.

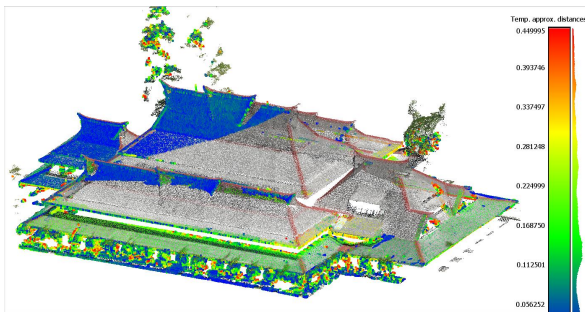


Figure 5. Cloud to Cloud Distance between TLS and UAV LiDAR point clouds.

3.1.2 Co-registration between TLS and 3DGS

After georeferencing the TLS data to the UAV LiDAR basemap, the image-based reconstruction used for 3DGS was co-registered to the TLS coordinate system, ensuring consistency between survey-grade geometry and photorealistic representation. Co-registration quality was first assessed using residual errors at the TLS-derived control points employed during bundle adjustment. The results yield an RMS residual of approximately 12.5 cm, with a maximum residual of 18.7 cm, after joint adjustment of interior and exterior image observations. The absence of systematic residual patterns confirms that the image-based reconstruction is consistently anchored to the TLS geometry. The resulting exterior orientation parameters were subsequently used for 3DGS generation.



Figure 6. Cloud to Cloud Distance between TLS and 3DGS.

To further evaluate geometric consistency, a cloud-to-cloud distance analysis was performed between the TLS point cloud and a point set sampled from the 3DGS-derived geometry. The analysis yields a mean spatial deviation of 15.2 cm, with 88% of points falling within a predefined tolerance threshold (Figure 6). This confirms that the spatial correspondence between the two

representations is consistent, without requiring geometric fusion or deformation of either dataset.

Overall, the results demonstrate a robust two-stage spatial alignment strategy. First, the TLS point cloud is reliably georeferenced to the UAV LiDAR-derived 3D basemap, ensuring global spatial consistency. Second, the 3DGS representation is co-registered to the TLS data, enabling photorealistic visualization to coexist with survey-grade geometry within a shared spatial reference. By maintaining TLS, 3DGS, and the 3D basemap as distinct but co-registered layers, the proposed approach preserves metric traceability while supporting visually expressive real-time inspection, making it well suited for heritage documentation and monitoring applications.

3.2 Multi-layer Representation and Information Consistency

The co-registered model maintains three complementary representations: TLS point clouds for metric geometry, HBIM/IFC models for semantic information, and 3DGS for photorealistic visualization. Consistency across these layers is evaluated in terms of spatial correspondence and information coverage. The HBIM model derived from the TLS point cloud represents key architectural components of the building, including walls, columns, and roof structures, with high spatial consistency relative to the TLS geometry. All IFC elements remain correctly aligned with the corresponding TLS data within the accuracy limits of the survey-grade reference, enabling reliable spatial queries and inspection tasks.

The 3DGS representation, while not intended for metric analysis, provides continuous photorealistic coverage of both interior and exterior surfaces. Visual inspection, supported by the quantitative co-registration results presented in Section 3.1, confirms that major architectural features and surface details are spatially consistent with the TLS and HBIM layers. This consistency allows seamless switching between metric, semantic, and photorealistic views within the integrated environment, without introducing spatial ambiguity between representations.

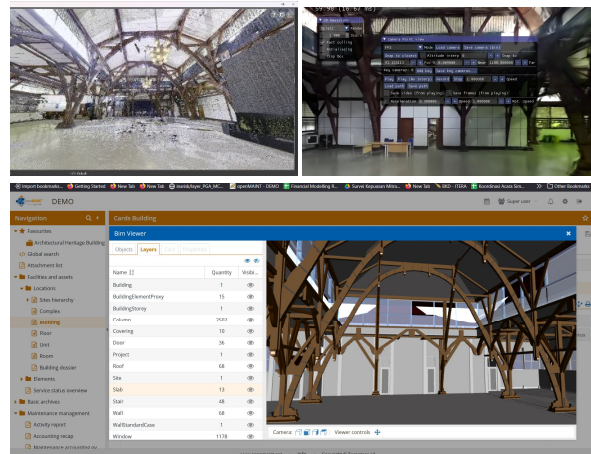


Figure 7. Integration of the Point Cloud, 3DGS and IFC-based geometric model within the OpenMAINT environment.

Figure 7 illustrates the integrated model within the OpenMAINT environment, demonstrating how heritage data can be stored, managed, and visualized within a unified

information system. Several Custom Pages were developed to extend OpenMAINT's capabilities for advanced 3D visualization and immersive interaction. A CesiumJS-embedded page enables simultaneous visualization of multiple datasets, including IFC models (structural and interior components), CityGML data (landscape context), and 3DGS reconstructions (photorealistic façades), allowing metric, semantic, and visual information to coexist coherently within a unified digital workspace.

3.3 Performance of Immersive Visualization

The performance of immersive visualization was evaluated by comparing point cloud, IFC, and 3DGS representations using rendering-related metrics relevant to real-time navigation, including frame rate, frame time stability, GPU pressure, and memory usage. The results indicate that 3DGS and point cloud representations achieve consistently high rendering performance, maintaining frame times of approximately 6–8 ms (corresponding to 120–180 FPS) during navigation. Among the three, 3DGS shows the most stable frame-rate behavior, with minimal frame-time fluctuation and no significant performance spikes. Point cloud rendering remains largely interactive, although occasional frame-rate drops are observed during navigation. Figure 8 illustrates the frame-time behavior observed during immersive navigation for the three representations.

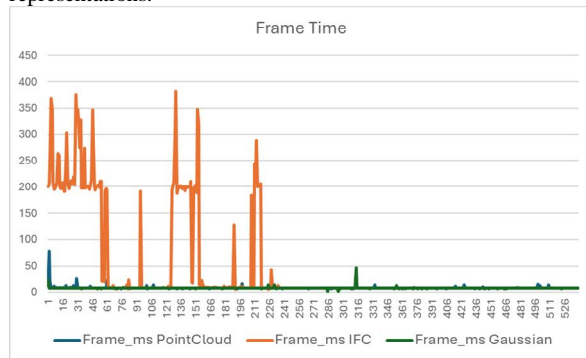


Figure 8. Frame-time comparison of point cloud, IFC, and 3DGS representations during immersive navigation. The results highlight the stable real-time performance of 3DGS, moderate variability in point cloud rendering, and severe performance degradation for IFC models.

In contrast, IFC models exhibit substantially lower and unstable rendering performance, with frame times frequently exceeding 180 ms and resulting in non-interactive frame rates. This behavior is further reflected in cumulative rendering time and GPU pressure metrics, where IFC shows highly fluctuating GPU loads, indicating rendering bottlenecks caused by complex mesh geometry and draw-call overhead. Memory usage analysis shows that 3DGS maintains the most stable and efficient memory footprint, while IFC requires a high initial memory allocation and point cloud rendering exhibits a gradual increase in memory usage over time.

Overall, these results demonstrate that 3DGS provides the most suitable representation for immersive visual navigation, combining high frame-rate stability, efficient GPU utilization, and stable memory usage. Point cloud representations remain usable for immersive navigation with moderate limitations, whereas IFC models require significant optimization to support interactive immersive visualization.

3.4 Implications for Monitoring Applications

The repeatability of the workflow enables its application to multi-epoch data acquisition scenarios. By registering repeated TLS surveys to the same reference framework, geometric changes can be quantitatively assessed using point-based distance metrics. In parallel, updated image data can be used to regenerate 3DGS models anchored to the same coordinate system, enabling qualitative assessment of surface appearance changes over time.

While only a single acquisition epoch is analysed in this study, the results demonstrate the feasibility of extending the proposed approach to long-term monitoring applications, where metric deformation analysis and visual inspection can be combined within a consistent spatial and information framework.

4. Discussion

This section discusses the implications of the results obtained from the proposed co-registered hybrid 3D heritage information model. The discussion focuses on the integration strategy between TLS and 3DGS, the role of the multi-layer representation for heritage documentation and monitoring, performance considerations for immersive visualization, and the limitations of the current approach.

4.1 Integration Strategy between TLS and 3DGS

The results demonstrate that the proposed integration strategy based on co-registration, rather than geometric fusion, provides a robust and conceptually sound solution for combining metric and photorealistic representations. By using TLS as the geometric reference frame, the workflow preserves survey-grade metric reliability while enabling the use of 3DGS for real-time photorealistic visualization.

The reported transformation residuals and depth consistency metrics indicate that the 3DGS representation can be reliably anchored to the TLS geometry, even though it does not constitute a metrically accurate surface model. This confirms that 3DGS is best interpreted as a radiance-field-based visualization layer, complementary to, but not replacing, metric point clouds or HBIM geometry. The absence of geometric fusion avoids ambiguity in metric interpretation and simplifies data management, while still allowing joint navigation and inspection of all representations within a shared spatial reference.

4.2 Value of Multi-layer Representation for Heritage Information Systems

The co-registered multi-layer representation highlights the complementary roles of TLS, HBIM, and 3DGS in heritage documentation and monitoring. In this study, TLS provided a stable geometric reference suitable for measurement and change detection, HBIM structured this geometry into semantically meaningful building components enriched with conservation-related attributes, and 3DGS contributed photorealistic visualization of surface appearance and lighting conditions.

The results indicate that maintaining these representations as distinct but spatially aligned layers is beneficial for heritage-oriented applications, where different users may prioritize metric reliability, semantic clarity, or visual realism. This approach avoids enforcing a single representation paradigm and

instead supports flexible workflows tailored to heterogeneous documentation and inspection needs.

Within immersive visualization environments, the photorealistic rendering enabled by 3DGS enhanced perceptual understanding of architectural details and surface conditions during virtual inspection. However, interaction with structured information, such as querying attributes or recording conservation observations, relied on the IFC-based HBIM model, while metric measurements remained grounded in the TLS point cloud. This separation of roles proved essential for maintaining both usability and analytical reliability.

Precise co-registration between the three layers therefore emerges as a critical enabler, allowing seamless transitions between visual, semantic, and metric perspectives within a shared spatial reference. Through this multi-layer and co-registered strategy, the proposed heritage information system supports realistic visual exploration, semantically meaningful interaction, and traceable metric analysis within a single integrated environment.

4.3 Implications for Monitoring and Repeated Surveys

Although the present study focuses on a single acquisition epoch, the repeatability of the workflow has important implications for long-term monitoring. The use of TLS as a stable reference enables quantitative assessment of geometric changes through repeated surveys, while the regeneration of co-registered 3DGS models from updated image data allows qualitative comparison of surface appearance over time. This separation between metric change detection and visual inspection aligns well with conservation practice, where structural deformation and surface deterioration are often assessed using different criteria. The proposed approach therefore provides a practical framework for integrating quantitative and qualitative monitoring within a consistent spatial and information context, without requiring continuous real-time data streams.

4.4 Performance and Usability in Immersive Environments

The reported performance indicators demonstrate that the proposed integration is compatible with immersive VR/MR visualization on current hardware. The ability to render large TLS datasets alongside dense 3DGS representations at interactive frame rates supports intuitive exploration and inspection tasks that are difficult to perform using conventional desktop-based visualization alone. Beyond rendering performance, the immersive setup enables direct user interaction with the co-registered heritage model, allowing natural head-tracked navigation and close-range visual inspection of architectural elements. As illustrated in Figure 9, users can explore the photorealistic 3DGS representation using a head-mounted VR display, while a synchronized large-screen visualization provides a shared view of the model. This configuration supports both individual immersive exploration and collaborative inspection scenarios, enhancing usability for heritage analysis and interpretation.

Nevertheless, rendering performance remains sensitive to model complexity, particularly to the number of Gaussian primitives and the resolution of the TLS point cloud. These observations highlight the need for careful data decimation and level-of-detail strategies when deploying multi-layer 3D models in immersive environments, especially for large-scale or multi-building heritage sites.

Recent studies have emphasized the potential of Gaussian Splatting as a visually rich representation for immersive building visualization. Gao et al. (2025), for instance, demonstrate that 3DGS enables photorealistic building models that support visual interpretation and semantic description, evaluated through image–text consistency metrics rather than user-centered interaction. While their work confirms the effectiveness of 3DGS as a visual representation, it does not address how such models support interactive visual navigation. The present study complements these findings by explicitly evaluating navigation performance and usability in immersive environments, thereby linking visual realism with user-centered spatial interaction.

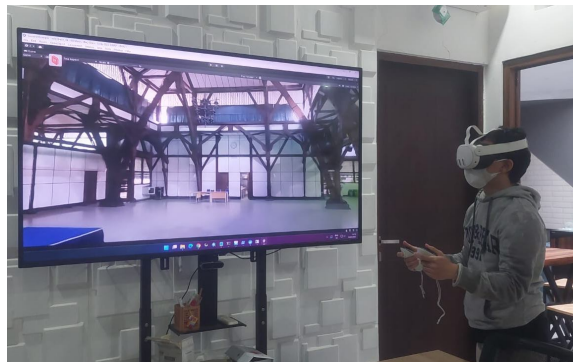


Figure 9. User interacting with the heritage model in a VR/MR.

4.5 Limitations and Future Work

Several limitations of the proposed approach should be acknowledged. First, TLS and image-based data for 3DGS were not acquired simultaneously, which may introduce differences in illumination and surface appearance, potentially leading to minor visual inconsistencies between metric geometry and photorealistic representations. Second, the current system implementation still exhibits limitations in software customization and integration. In particular, fully bidirectional communication between the spatial database and the immersive visualization environment has not yet been achieved. As a result, spatial edits or updates performed at the database level cannot be immediately reflected in the VR/MR interface, restricting real-time interactive workflows. Third, the present study does not include a formal user evaluation to quantitatively assess usability or task performance in immersive environments, and the evaluation is therefore limited to technical metrics and qualitative observations.

Future work will focus on integrating synchronized LiDAR-imaging acquisition systems to improve geometric and radiometric consistency, enhancing real-time database–visualization interoperability, and conducting controlled user studies. Extending the workflow to multi-epoch datasets and larger heritage complexes will further support its application for long-term heritage monitoring and management.

5. Conclusions

This paper has presented a co-registered hybrid 3D heritage information model that integrates Terrestrial Laser Scanning, Historic Building Information Modelling, and 3D Gaussian Splatting within a unified spatial framework for heritage documentation, inspection, and monitoring. By adopting TLS as the geometric reference and maintaining photorealistic and

semantic representations as distinct but spatially aligned layers, the proposed approach avoids geometric ambiguity while enabling realistic real-time visualization and structured information management. The results demonstrate that 3DGS, when rigidly anchored to survey-grade geometry, can effectively complement metric and semantic models by providing real-time photorealistic visualization without compromising spatial reliability.

The study further highlights the value of a multi-layer integration strategy for heritage applications, where different representational paradigms address complementary needs. Quantitative alignment metrics and performance evaluations confirm the feasibility of deploying the integrated model in immersive VR/MR environments, supporting intuitive exploration and visual inspection tasks. Although the current work focuses on a single acquisition epoch, the repeatable nature of the workflow provides a foundation for future monitoring scenarios that combine quantitative geometric analysis and qualitative visual assessment.

Acknowledgements

This research was funded by the Foundation for Research and Industrial Affiliation Institut Teknologi of Bandung (LAPI-ITB), through the International Collaborative Research Program 2024, under contract number 8404/IT1.B07.1/TA.00/2024.

References

- Agustinova, D., 2022: Strategi pelestarian benda cagar budaya melalui digitalisasi. *ISTORIA: Jurnal Pendidikan dan Ilmu Sejarah*, 18(2).
- Alya, J.S., Adhari, M.A.R., Rahadian, E.Y., 2023: Upaya pelestarian bangunan cagar budaya melalui pendekatan implementasi metode Heritage-BIM: Studi kasus Au Bon Marché, Braga Bandung. *Proceedings / Journal of Architecture and Planning* (in Indonesian).
- Balloni, E., Ceka, D., Pierdicca, R., Paolanti, M., Mancini, A., & Zingaretti, P., 2024: Comparative assessment of neural rendering methods for the 3D reconstruction of complex heritage sites in the inner areas of the Marche region – Italy. *Digital Applications in Archaeology and Cultural Heritage*, 35, e00371.
- Banfi, F., 2021: The Evolution of Interactivity, Immersion and Interoperability in HBIM: Digital Model Uses, VR and AR for Built Cultural Heritage. *ISPRS International Journal of Geo-Information*, 10(10), 685.
- Barazzetti, L., & Banfi, F., 2017: Historic BIM for Mobile VR/AR Applications. *Proc. Mixed Reality and Gamification for Cultural Heritage*, Springer, Cham, pp. 271-290.
- Gao, Y., Zhang, X., Liu, H., Chen, Z., Wang, J., 2025: Digital buildings analysis: 3D modeling, GIS integration, and visual descriptions using Gaussian splatting, ChatGPT/DeepSeek, and Google Maps Platform. *arXiv preprint*, arXiv:2502.05769.
- Jiang, C., Gao, R., Shao, K., Wang, Y., Xiong, R., Zhang, Y., 2025: LI-GS: Gaussian splatting with LiDAR incorporated for accurate large-scale reconstruction. *IEEE Robotics and Automation Letters*, 10(2), 1864–1871.
- Jung, J., Lee, J., Kim, S., & Hong, S., 2024: Accuracy analysis of opening detection using terrestrial laser scanning data. *Remote Sensing*, 16(4), 759.
- Kerbl, B., Kopanas, G., Leimkühler, T., Drettakis, G., 2023: 3D Gaussian splatting for real-time radiance field rendering. *ACM Transactions on Graphics*, 42(4), Article 139.
- Mazzacca, G., Karami, A., Rigon, S., Farella, E. M., Trybala, P., & Remondino, F., 2023: NeRF for heritage 3D reconstruction. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLVIII-M-2-2023, 1051–1058.
- Murtiyoso, A., Grussenmeyer, P., 2017: Documentation of heritage buildings using close-range UAV images: Dense matching issues, comparison, and case studies. *The Photogrammetric Record*, 32(159), 206–229.
- Murtiyoso, A., Grussenmeyer, P., Suwardhi, D., Awalludin, R., 2018: Multi-scale and multi-sensor 3D documentation of heritage complexes in urban areas. *ISPRS International Journal of Geo-Information*, 7(12), 483.
- Remondino, F., Campana, S. (eds.), 2014: *3D recording and modelling in archaeology and cultural heritage: Theory and best practices*. Archaeopress, BAR International Series 2598, Oxford.
- Suwardhi, D., Menna, F., Remondino, F., Hanke, K., Akmalia, R., 2015: Digital 3D Borobudur – integration of 3D surveying and modeling techniques. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XL-5/W7, 417–423.
- Suwardhi, D., Trisyanti, S.W., Ainiyah, N., Fajri, M.N., Hanan, H., Virtriana, R., Edmarani, A.A., 2016: 3D surveying, modeling and geo-information system of the new campus of ITB-Indonesia. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLII-2/W2, 97–105.
- Suwardhi, D., Trisyanti, S.W., Virtriana, R., Syamsu, A.A., Jannati, S., Halim, R.S., 2022: Heritage smart city mapping, planning and land administration (HESTYA). *ISPRS International Journal of Geo-Information*, 11(2), 107.
- Tribhuvan, A. P., & Binnaser, A. A., 2024: Exploring the digital heritage of Ajanta Caves through VR technology. *Digital Applications in Archaeology and Cultural Heritage*, 35, e00381.
- Xiong, B., Zheng, N., Liu, J., Li, Z., 2024: GauU-Scene V2: Assessing the reliability of image-based metrics with expansive LiDAR image dataset using 3DGS and NeRF. *arXiv preprint*, arXiv:2404.04880.
- Ye, V., Li, R., Kerr, J., Turkulainen, M., Yi, B., Pan, Z., Seiskari, O., Ye, J., Hu, J., Tancik, M., & Kanazawa, A., 2024: gsplat: An open-source library for Gaussian Splatting. *arXiv preprint*, arXiv:2409.06765.