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DEVELOPING AFFORDABLE WORKFLOW FOR DIGITAL PRESERVATION OF ISLAMIC ARCHITECTURAL HERITAGE THROUGH PHOTOGRAMMETRY AND 3D GAUSSIAN SPLATTING

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Abstract

The rapid dilapidation of Malaysia's Islamic architectural heritage outpaces physical conservation, necessitating an affordable 3D digital documentation workflow requiring minimal manpower. This paper develops a cost-effective workflow through a comparative study of conventional photogrammetry and 3D Gaussian Splatting (3DGS). The methodology utilizes low-specification hardware - a consumer-grade UAV and smartphone, CPU-only processing, and open-source software. Between 150 and 200 video frames of a Masjid Sg. Chinchin roof crown replica were extracted for 3D reconstruction. Quantitative findings reveal that conventional photogrammetry effectively generates editable mesh models but yields low visual accuracy. Conversely, 3DGS produces highly accurate visual models—generating up to 723,566 splats for the UAV input, and is approximately 22% less time-consuming, although it lacks mesh editability. Furthermore, the UAV consistently outperformed the smartphone: while it produced a photogrammetry mesh with approximately 85% fewer vertices, it effectively eliminated visual noise. In the 3DGS workflow, the UAV generated 13% more splats, yielding sharper, more precise visuals. To address individual limitations, it is recommended to adopt a mixed workflow of 3D photogrammetry and 3DGS. By combining photogrammetry's structural editability with the time-efficient, high-fidelity visual accuracy of UAV-driven 3DGS, this integrated approach ensures comprehensive, fast, affordable, and replicable 3D documentation. Future research should integrate CUDA processing for accuracy and develop an interactive 3DGS web database for Malaysia's Islamic architectural heritage.

Keywords: Islamic Heritage, 3D Gaussian Splatting, Photogrammetry, Colmap, Structure from Motion (SfM), SkySplat.

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INTRODUCTION

Preservation and documentation of Islamic architectural heritage is crucial to ensure that the trace of Muslim civilizational history is secured through time. However, the traditional way of preservation and documentation of historical heritage buildings has limitations due to budget, logistics, and scale. And there is a long prioritization queue for heritage buildings in many countries, especially in Malaysia. So, while some heritage buildings are conserved, a large portion of heritage cannot be conserved due to the lack of budget, logistics, and manpower. At the same time, when it comes to digital heritage documentation, the traditional methods of 3D documentation are also sometimes very complex and require high-end technical skills, manpower, extensive on-site presence, and complex logistics. (Sabil et al., 2022; Salleh, 2020). This makes the large-scale documentation of heritage buildings virtually impossible with the limited available resource. As a result, many heritage buildings are dilapidated and demolished before documentation can be done.

This is addressed in this paper by finding an affordable, low-specification 3D documentation workflow, which will utilize low-end, affordable hardware and open-source tools to generate usable digital records of heritage buildings. The output might not be as precise as professional 3D scanning but is at least affordable and accessible to make sure that disintegrating and almost derelict heritage buildings can be documented before they are completely lost into oblivion.

LITERATURE REVIEW

Islamic Heritage Conservation in Malaysia

Since gaining independence, Malaysia has undertaken various conservation initiatives to safeguard its Islamic heritage. Notable projects, such as the restoration of the Sultan Abdul Samad Building in Kuala Lumpur, Masjid Kg Laut in Kelantan, and Batu Surat in Terengganu, stand out for their historical significance in shaping the narrative of Islamic traditions in Tanah Melayu (Suaib et al., 2020). While these efforts have predominantly focused on physical conservation, this review suggests that a digital approach could provide a cost-effective and time-efficient alternative for documenting and preserving the diverse tangible Islamic heritage assets.

Adopting a digital approach does not necessarily nullify the need for physical conservation; rather, it complements the current physical conservation efforts. Due to budget, craftsmanship, and time limitations, the physical conservation approach can only consider a handful of projects each fiscal year. Meanwhile, the digital approach can effectively address this issue, allowing relevant agencies to document and digitize a larger number of Islamic heritage assets with limited resources and budget (Ocón, 2021; Paschalidou et al., 2022).

Dilapidated Heritage and the Need for Rapid Documentation

Each year, the federal government allocates a certain amount in the national budget for heritage conservation works. The scope includes physical acquisition, repair, preservation and adaptive reuse of heritage assets. In 2024, the federal government allocated MYR 80 million for the preservation and conservation of potential heritage sites and buildings recognised by UNESCO (Toyat, 2023). Though MYR 80 million is a significant amount, considering the cost of physical conservation of heritage assets the allocated amount is insufficient. To put the argument into perspective, the conservation cost of a small masjid in Negeri Sembilan, Masjid Lama Kampung Terusan Kuala Pilah, was MYR 4 million (Isa, 2022; Jalil, 2022). As reported by Dr. Isham Shah Hassan, there are around 250 traditional houses and masjids in Negeri Sembilan, which need urgent attention to document and conserve as the Islamic heritage asset of the state (Figure 1). (Isa, 2021; Rahim et al., 2022).

A simple calculation can illustrate that the allocated national budget for heritage conservation is sufficient for less than 8% of the heritage assets of only one state, let alone considering the fact that all 14 states of Malaysia have their own heritage assets, which requires urgent documentation and preservation effort.



Figure 1: Dilapidated masjid in Negeri Sembilan. Masjid Lama Kg. Pelangi (Top Left), Masjid Lama Kampung Parit Istana (Top Right), Masjid Jamek Lama Tanah Data (Bottom Left), Masjid Tua Kampung Tengah (Bottom Right).

Hence, the mismatch between the conservation need and the allocated budget requires the researchers to think of a novel approach for the conservation of national Islamic heritage, which should be highly cost-effective and less time-consuming.

Economic Constraints and the Shift Toward Accessible 3D Documentation

While Malaysia prioritizes the physical conservation of Islamic heritage (Suaib et al., 2020), this approach is fundamentally constrained by severe financial bottlenecks. With a 2024 federal heritage allocation of MYR 80 million (Toyat, 2023) against restoration costs approximating MYR 4 million per traditional masjid (Isa, 2021; Jalil, 2022), it is financially impossible to physically salvage the 250 endangered structures in Negeri Sembilan alone (Isa, 2021; Rahim et al., 2022). This massive deficit dictates a critical shift toward rapid digital documentation (Ocón, 2021; Paschalidou et al., 2022). Yet, conventional 3D scanning methods like LiDAR exacerbate these financial barriers through prohibitive hardware, high maintenance, and specialized manpower demands, rendering large-scale documentation unviable for underfunded authorities (Bramble & Lydon, 2025; Dai et al., 2022; Sabil et al., 2022).

To circumvent these limitations, recent literature emphasizes affordable alternatives like Structure from Motion (SfM), which democratizes 3D reconstruction utilizing standard consumer cameras (Eltner & Sofia, 2020; Murtiyoso & Grussenmeyer, 2017). Concurrently, novel machine learning approaches, notably 3D Gaussian Splatting (3DGS) and Neural Radiance Fields (NeRF), generate highly photorealistic environments using learnable ellipsoids rather than conventional meshes (Kerbl et al., 2023; Stanisheva, 2026). However, the literature reveals a critical paradox: while these techniques eliminate expensive physical scanners, their reliance on high-end, CUDA-enabled graphics cards merely shifts the financial burden from hardware to processing capabilities (Clini et al., 2024). Resolving this requires the strategic integration of open-source freeware, which, despite complicating workflows, is essential for maintaining true cost-effectiveness (Petrovska & Jutzi, 2025). Although employing low-fidelity inputs in 3DGS involves unavoidable trade-offs in geometric accuracy (Jia & He, 2026), continuous platform improvements are mitigating these drawbacks (Yu et al., 2025). Ultimately, in contexts of rapid heritage decay, the paradigm must decisively shift from prioritizing millimeter accuracy toward deploying rapid, hardware-agnostic documentation solutions to prevent irreversible data loss.

Critical Synthesis of Affordable 3D Documentation Workflows

A critical review of the literature reveals a distinct trade-off between geometric precision and operational affordability in heritage documentation. While conventional terrestrial laser scanning (TLS) delivers high accuracy, its prohibitive equipment costs make it largely unfeasible for widespread use in underfunded regions (Dai et al., 2022; Kędzierski et al., 2024). Consequently, recent studies emphasize transitioning towards consumer-grade sensors and open-source pipelines (Petrovska & Jutzi, 2025).

Table 1: Critical Comparison of 3D Documentation Workflows for Heritage Preservation

Documentation Method	Primary Advantage	Critical Limitation	Relevant Studies
Traditional TLS / LiDAR	High geometric accuracy and precision.	Prohibitive hardware, maintenance, and operational costs.	Dai et al. (2022); Kędziorowski et al. (2024)
Photogrammetry (SfM)	Highly accessible and democratized data capture.	Computationally demanding and time-consuming processing.	Murtiyoso & Grussenmeyer (2017); Cruz & Albuerne (2025)
3D Gaussian Splatting (3DGS)	Rapid, photorealistic visual environments.	Relies on expensive GPU/CUDA hardware; lacks editable mesh.	Clini et al. (2024); Stanisheva (2026)
Mobile SLAM & Low-cost Scanners	Real-time tracking and highly mobile.	Lower accuracy and notable noise on large-scale objects.	Gautier et al. (2020)

Table 1 shows from previous studies that low-cost photogrammetry and SfM have proven highly accessible for field data acquisition, though they often demand substantial computational power and long processing times (Cruz & Albuerne, 2025; Gautier et al., 2020). Emerging techniques like 3DGS provide rapid, photorealistic visualizations, but their reliance on high-end, CUDA-enabled graphics cards can undermine true workflow affordability (Clini et al., 2024; Stanisheva, 2026). Additionally, low-cost mobile LiDAR and SLAM tools are viable for rapid damage assessment, despite yielding lower geometric accuracy on larger architectural scales (Kędziorowski et al., 2024). Ultimately, integrating low-fidelity inputs with open-source software—while accepting minor accuracy compromises—offers the most pragmatic pathway for rapidly digitizing endangered heritage before irreversible dilapidation occurs (Cruz & Albuerne, 2025; Jia & He, 2026).

METHODOLOGY

The research develops an affordable 3D documentation workflow by comparing two approaches - photogrammetry-based 3D mesh reconstruction and 3D Gaussian splatting reconstruction. For the study object, a gazebo structure located in front of the KAED building in IIUM Gombak campus is used.



Figure 2: Study object for 3D reconstruction: Gazebo Chinchin- replica of Masjid Sg. Chinchin roof crown at KAED, IIUM.

This gazebo or waqf structure is a reconstruction of the roof structure of Masjid Sungai Chinchin, which is an 80-plus-year-old masjid in the region (Figure 2). The waqf, is selected because of its manageable scale, the structural similarity to a heritage mosque's roof, and suitability for testing low-specification workflow in controlled conditions.

Data Collection

Two types of data input are used- drone videography and smartphone videography. The reason for adopting drone and smartphone as the data input method is because of the availability and affordability of these input devices in recent times. Especially for the drone, a low-spec UAV was used, which can be found in any local market. The specification of the drone and the smartphone is given below.

Hardware, Software, and Frame Sampling Justification

To maintain affordability, data was captured using a basic Android smartphone and DJI Neo drone and processed on a Lenovo laptop with an AMD Ryzen CPU and Vega 8 GPU (no CUDA support) as shown in Table 2. FFmpeg was used to extract video frames. For the photogrammetry pipeline, VisualSFM (Wu, 2011; Wu et al., 2011) and COLMAP (Schönberger & Frahm, 2016) generated point clouds, followed by mesh generation in MeshLab (Cignoni et al., 2008) and Blender. For 3D Gaussian Splatting, the Blender SkySplat add-on (Huang et al., 2025) and Brush App (Brussee, 2025) handled the reconstruction, while SuperSplat enabled viewing and limited modification.

Table 2: Hardware used for the input and processing

		
Lenovo ThinkPad T495s (Processing Device): AMD Ryzen 5 PRO 3500U CPU, Radeon Vega 8 integrated GPU (no CUDA support), 8GB RAM.	DJI Neo (UAV Input): 4K stabilized video camera.	Samsung A34 (Smartphone Input): 48MP OIS main camera (with 4K video support).
Retail Price: MYR 1500	Retail Price: MYR 900	Retail Price: MYR 1200

Frame sampling sizes were justified through empirical trial-and-error to determine the hardware's maximum processing threshold. During the photogrammetry workflow, the software crashed when exceeding 200 frames; thus, exactly 200 frames were extracted for processing. Similarly, for the 3DGS pipeline, the software crashed beyond 152 frames, restricting the extraction to exactly 150 frames. Keeping the frame numbers at these exact minimum levels was a necessary compromise to ensure the workflow's affordability and prevent processing failures.

Process Flow

For the photogrammetry pipeline, the video input was used to extract 200 frames, which were then analysed with VisualSFM to create a sparse reconstruction with .nvm output, and then the sparse reconstruction was used to perform dense reconstruction with .PLY output. The .PLY output was imported into MeshLab for mesh generation and texturing. Once the mesh generation and texturing were done, the mesh was exported to OBJ format, and that OBJ format was then imported into Blender for viewing and modification purposes.

For the 3D Gaussian splatting pipeline, the video input from the drone and phone was imported into the Blender SkySplat add-on, which extracted 150 frames from a 2+ minute video, and then COLMAP was used inside SkySplat for dense reconstruction. From the COLMAP output, the data was imported into Brush software with 15,000 training steps. After the 15,000 training steps were completed, the Gaussian splat output in .PLY format with radiance data was saved and imported into SuperSplat for viewing and modification purposes as illustrated in Figure 3.

Limitations, Validation, and Reproducibility

This study adopts an empirical validation approach; the successful generation of comparative 3D reconstructions serves as a functional proof-of-concept, directly validating the workflow's efficacy. To ensure widespread reproducibility, the methodology strictly relies on accessible open-source freeware without dedicated GPU or CUDA support. However, maximizing affordability introduced processing constraints. Initial 4K inputs caused recurrent system crashes, necessitating a downscale to full HD resolution (1920 x 1280) to maintain stability. By integrating these operational constraints, hardware thresholds, and open-source tools, this methodology establishes a highly replicable blueprint for affordable 3D architectural heritage documentation.

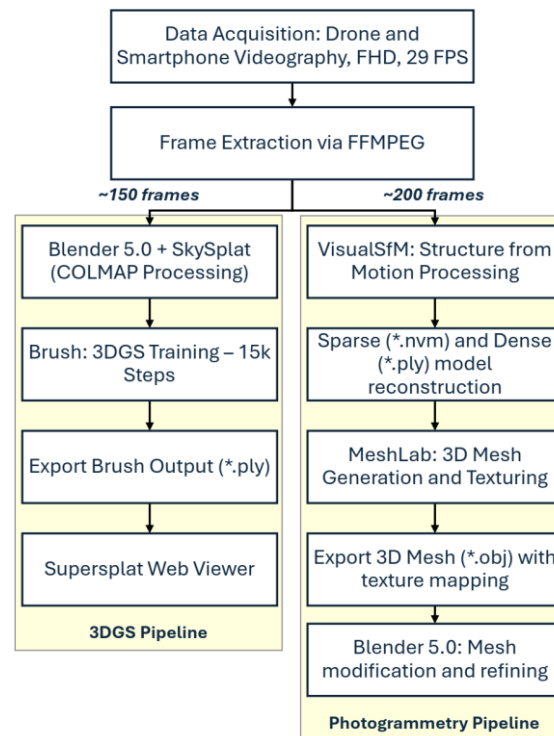


Figure 3: Process flow for different input mode.

FINDINGS

Comparative Analysis of Photogrammetry Outputs

A quantitative comparison of the photogrammetry meshes reveals an inverse relationship between mesh density and geometric accuracy. As detailed in Table 3, the smartphone generated a highly dense mesh (1,818,971 vertices; 3,638,812 faces), whereas the UAV yielded an 85% less dense mesh (270,857 vertices;

540,921 faces). However, higher density did not guarantee better structural representation. As illustrated in Figure 4, the smartphone mesh exhibits severe visual noise and incomplete areas, particularly around the roof. This limitation stems from terrestrial capture constraints; the smartphone could not attain the elevated angles required for complex geometry.

Table 3: Comparison: Drone Vs Smartphone Input in Photogrammetry workflow.

Parameter	Drone Input	Phone Input
Image Matching (VisualSFM)	23,005 matches completed	20,100 matches completed
Processing Time	8,246 seconds	7,289 seconds
Total Processing Time	138.267 minutes	122.567 minutes
Vertices (MeshLab Output)	270,857	1,818,971
Faces (MeshLab Output)	540,921	3,638,812
Mesh quality	More accurate with less noise	Lack of accuracy with more noise and incomplete areas

In contrast, the UAV's stable aerial trajectory captured complete structural data from optimal vantage points. Although the UAV required slightly more processing time (138.27 minutes versus 122.57 minutes), it effectively eliminated structural noise, producing a significantly more accurate, complete, and usable 3D mesh model.



Figure 4: 3D mesh generated in MeshLab; Drone input (Left) and Phone input (Right).

Comparative Analysis of 3DGS Outputs

The 3DGS pipeline produced highly photorealistic environments but revealed distinct performance variances between input devices. To maintain hardware stability, both datasets were downscaled to HD resolution. Despite this uniform baseline, Table 4 demonstrates that the UAV generated 13% more splats

(723,566) than the smartphone (640,418). This higher splat density correlates directly with the UAV's aerial vantage points, allowing the algorithm to map complex upper geometries comprehensively, achieving the sharp, highly accurate representation illustrated in Figure 5.



Figure 15: 3DGS generated in Brush; Drone input (Left) and Phone input (Right).

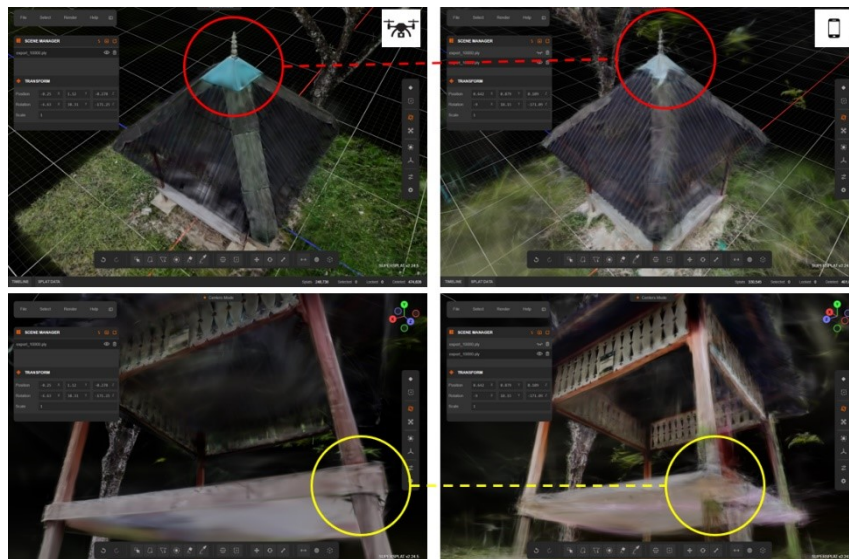


Figure 6: Visual quality of 3DGS; Drone input produced sharper and more accurate output (Left) and Phone input produced lots of floaters or visual noises (Right).

Conversely, the smartphone input suffered from constrained terrestrial angles and a smaller dataset (115 versus 153 frames), producing significant visual noise and geometric "floaters" as seen in Figure 6. Although the smartphone

processed marginally faster and required less memory, it compromised overall visual fidelity. Notably, while initial hypotheses posited that terrestrial capture would better map the gazebo's underside, visual analysis confirmed no significant improvement in under-roof structural detailing, ultimately proving the UAV's superior overall efficacy for 3DGS reconstruction.

Table 4: Comparison: Drone Vs Smartphone Input in 3DGS workflow.

Parameter	Drone Input	Phone Input
Splats	723,566	640,418
Training Steps	9,910	9,005
Steps per Second	1.0	1.1
Training Time	1h 47m 27s	1h 38m 5s
Dataset Train Size	153	115
Bytes in Use	1.07 GB	496.37 MB
Bytes Reserved	2.27 GB	2.20 GB
Output Quality	More precise and visually clear	Less accurate with lots of visual noises

DISCUSSION

Proposed Affordable Digital Preservation Workflow

The findings indicate that relying on a single low-cost 3D scanning method necessitates compromising either structural editability or visual fidelity. To address this limitation, the practical implication of this study is the proposal of a hybridized, dual-pipeline workflow that leverages the distinct strengths of both photogrammetry and 3DGS while remaining strictly within affordable hardware parameters.

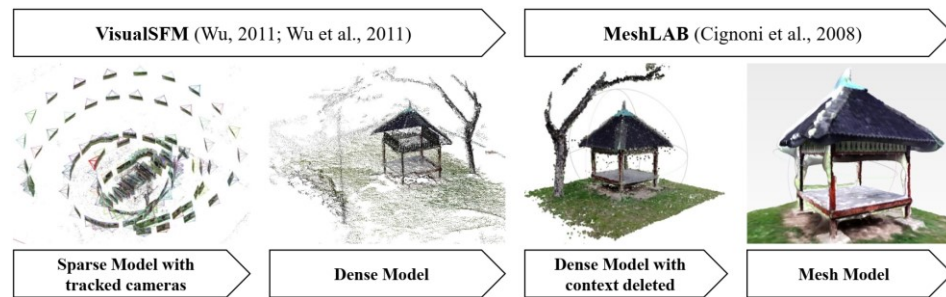


Figure 7: Process-flow for 3D mesh generation with photogrammetry

The first pipeline, illustrated in Figure 7, employs a conventional photogrammetry approach to secure a geometrically workable 3D mesh. UAV-captured videos are processed via FFmpeg to extract exactly 200 HD frames to ensure hardware stability. VisualSFM handles sparse and dense point cloud

reconstruction, followed by mesh generation and texturing in MeshLab using Poisson surface reconstruction. The resulting .obj file provides the essential topological data required for accurate architectural measurements and physical conservation planning.

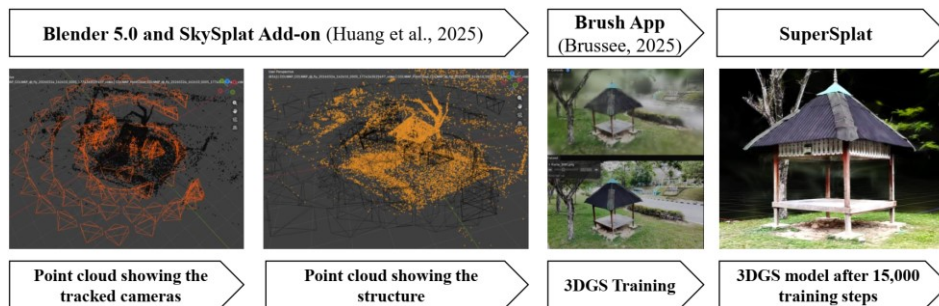


Figure 8: Process-flow for 3D Gaussian Splatting.

Simultaneously, the second pipeline, detailed in Figure 8, utilizes 3DGS to rapidly capture a highly accurate photorealistic environment. Using the Blender SkySplat add-on, exactly 150 frames are extracted and processed through COLMAP. The data is then trained for 15,000 steps in Brush App, outputting a detailed .ply radiance field viewable in SuperSplat. By executing these complementary pipelines in tandem using open-source freeware and CPU-only processing, conservationists can successfully generate both editable structural meshes and high-fidelity visual records with minimal budget, skill, and manpower.

Implications for Heritage Preservation in Malaysia

The critical bottleneck in Malaysian heritage preservation is not merely a lack of funding for physical restoration, but the absence of a scalable strategy to digitally archive endangered structures before irreversible dilapidation occurs (Isa, 2021; Rahim et al., 2022). As established in the literature, attempting to solve this through conventional LiDAR scanning paradoxically replicates the very financial barriers it seeks to bypass, imposing prohibitive hardware and maintenance costs on underfunded regional authorities (Bramble & Lydon, 2025; Dai et al., 2022). This study resolves this dilemma by proving that high-fidelity 3D documentation does not necessitate expensive commercial software licenses or high-end CUDA-enabled processors (Clini et al., 2024; Petrovska & Jutzi, 2025). By successfully executing a hybridized photogrammetry and 3DGS pipeline entirely on consumer-grade sensors and CPU-only freeware, this research provides a direct, empirically tested countermeasure to the national resource deficit. Consequently, the proposed workflow transcends being a mere technological alternative; it

serves as a crucial policy instrument. It empowers Malaysian conservation agencies to urgently pivot from slow, capital-intensive physical restorations toward rapid, democratized digital archiving. This approach bridges the gap between limited federal allocations and the vast number of neglected Islamic architectural assets, establishing a decisive and viable blueprint for a comprehensive national digital heritage repository.

CONCLUSION

This study advances heritage conservation by offering an accessible, dual-pipeline 3D documentation workflow. This approach directly reduces the high costs and logistical challenges of traditional commercial scanning. By successfully combining low-cost photogrammetry and 3D Gaussian Splatting (3DGS) using consumer-grade sensors and open-source freeware, this research provides a practical way to rapidly digitize endangered Islamic architecture. The main contribution of this work is making heritage documentation more democratic. It empowers underfunded regional authorities to digitally save damaged structures before they are lost forever.

However, focusing on maximum affordability brings some limitations. Relying on CPU-only processing and lower image resolutions slightly reduces geometric precision and mesh editability. To improve this, future research should explore using limited CUDA-based processing. This upgrade would increase the accuracy of mesh generation and capture more of the surrounding environment for the 3DGS pipeline. Furthermore, future projects should combine the 3DGS models of various Malaysian Islamic heritage buildings into a single, interactive web platform. By allowing users to click on a map to explore photorealistic 3D models alongside historical data, this collection will eventually grow into a centralized 3D database dedicated to preserving Malaysia's at-risk architectural assets.

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