Implementing 3D Augmented Reality for Increasing Public Outreach of Majapahit Archeological Sites

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Abstract

Cultural heritage sites, such as historical buildings and monuments, hold significant artistic, cultural, and historical value which necessitates preservation. This study explores the integration of 3D modelling and Augmented Reality (AR) technologies to digitally document and promote public engagement with heritage sites. Employing both laser scanning and photogrammetry, the research aims to develop accurate and photorealistic 3D models of key archaeological structures from the Majapahit era located in Trowulan, Indonesia—specifically Bajang Ratu, Wringin Lawang, and Brahu. Laser scanning demonstrates superior geometric accuracy and spatial completeness, producing denser point clouds and more detailed meshes, which are essential for precise documentation, restoration planning, and structural analysis. Photogrammetry, while offering lower geometric resolution, excels in capturing high-quality surface textures, making it more suitable for visual representation, public engagement, and AR applications. The findings highlight the benefits of a hybrid approach that combines laser scanning's spatial precision with photogrammetry's visual realism. This AR experience, when paired with a printed archaeological site map, allows users to interact with the digital reconstructions, enhancing historical understanding and accessibility. Furthermore, this research contributes to digital conservation efforts and innovative historical learning methods for Indonesian cultural heritage.

1. Introduction

Historic assets are tangible assets in which there are values of art, culture, education, history, knowledge and other unique characteristics where in terms of their release, these historic assets are protected by the government, thus they should be maintained and preserved. One way that can be used in managing cultural assets is by recording cultural heritage objects in digital form (Waljiyanto & Chintya, 2020). One form of recording cultural heritage objects is by using 3D modelling. The creation of 3D digital models of cultural monuments is very important for conservation, restoration, and research because it enables more detailed measurements to be conducted as opposed to conventional 2D methods.

In order to obtain 3D data, various kinds of surveys can be carried out. Laser scanning technology can record million-point cloud data of the building in a rapid manner. Yet, laser scanners also generate a lot of data redundancy which is not necessarily of interest. This laser scanner problem usually occurs when documenting complex objects such as heritage buildings (Barsanti et al., 2014). In terms of textural data quality, laser scanners also have their own limitations, even when the device is equipped with a camera (Hassani, 2015).

3D scanning can also be carried out using photogrammetric techniques, either by traditional close-range terrestrial cameras or by UAV (Unmanned Aerial Vehicle). Photogrammetry also has advantages in terms of textural data quality, thus enabling it to generate photo-realistic 3D models. However, processing photogrammetry data with hundreds or thousands of images requires quite a lot of time (Salandra, 2021). Regarding geometric and textural quality, this technique also requires a certain level of skill of data acquisition to produce the best model possible (Murtiyoso et al., 2018).

Once a 3D model is obtained, one solution which can be applied to help democratise the content is the use of Augmented Reality (AR) technology that allows users to interact with three-dimensional (3D) models in real-time (Hikmawan & Sofiani, 2021). With AR, learning history and archaeology can be more interesting, as users can explore sites in digital form with a more immersive and realistic experience.

In this research, photogrammetry and laser scanner data are used in order to create a 3D model which is not only accurate but also interactive. The data will be analysed to determine the best method in creating 3D models which are easily accessible to the public through the AR method. An AR app was developed for the purposes of this research, which when combined with a printed map of the archaeological complex will enable users to interact with the 3D models. The utilization of this technology not only aims to accurately document cultural heritage sites but also to increase the understanding of the public towards cultural heritage (Maté-González et al., 2022). Thus, this research is expected to contribute to historical learning innovation as well as digital conservation of historical sites.

This research is part of Digital Twin of Majapahit Era (DT-MERA) project which focused on documenting Majapahit archaeological sites in Trowulan, Indonesia within the framework of the BOPTN-SAME-PHC (Franco-Indonesian Partenariat Hubert-Curien) "Nusantara" 2023-2025. In history, Majapahit was one of the last great Hindu-Buddhist kingdoms in the Indonesian archipelago between the 13th and 16th centuries and is considered one of the largest and most powerful kingdoms in the history of the region. The Trowulan site in East Java was the capital of this empire, where there are several archaeological remains (Febriyanti et al, 2024). Bajang Ratu, Wringin Lawang and Brahu are the 3 main historical buildings located on the Trowulan site which are relatively well preserved and are thus the subject of this research.

2. Sites Location and Description

This research focused on three cultural heritage buildings, i.e., Brahu, Bajang Ratu, and Wringin Lawang. These three buildings are located on Trowulan District, Mojokerto Regency, Indonesia (Figure 1).

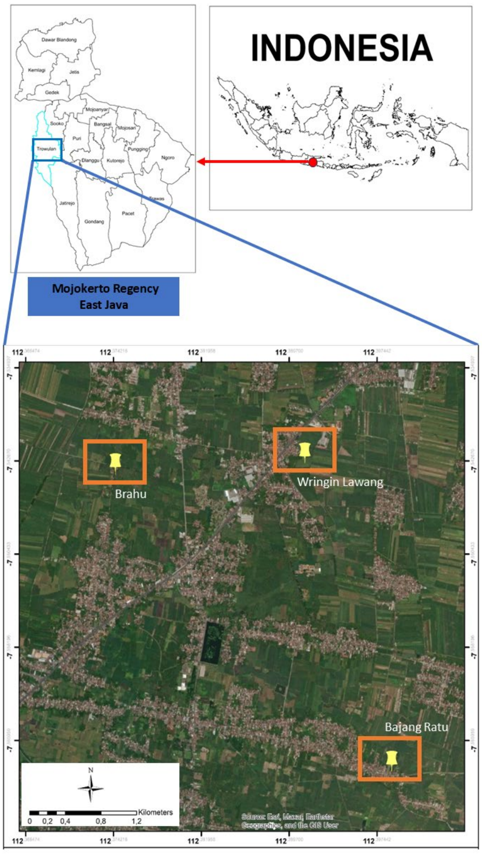

Figure 1. Study Area.

Brahu is older than the other cultural heritage buildings around Trowulan. Built from red bricks, the building was constructed in a Buddhist architecture based on its structure and profile data. The body shape of Brahu is not strictly square but has many angles, blunt and curved. The middle of its body curved inward like a human being’s waists. The curve is emphasized by the brick pattern on the west wall or front wall of the cultural heritage structure (Abadiyah & Pamungkas, 2014). There are no decorations in the form of reliefs or carvings at the foot, body, and roof of Brahu.

Bajang Ratu is a “*paduraksa*” structure, which is a type of a roofed gate. Physically, the entire building is made of red brick, except for the stairs and the lower and upper doorway which are made of andesite. Vertically, this building has 3 parts: foot, body, and roof. It also has wall fences on both sides. Wringin Lawang is a is also made of brick, in the form of a “*bentar*” gate (a roofless gate). Most historians agree that this gate was the entrance to an important building complex in the capital of Majapahit. The structure has no decoration (Arnawa, 1998).

3. Methods

Aerial photogrammetry was employed to acquire both close-range and aerial imagery of the study area. Close-range images were obtained by navigating the imaging platform around the target object, while terrestrial photogrammetry was conducted using a DSLR camera to capture high-resolution details through a short-range methodology. Concurrently, laser scanning data were collected using both Airborne Laser Scanners (ALS) and Terrestrial Laser Scanners (TLS) to facilitate the generation of a three-dimensional (3D) model of the object and its surrounding context.

The photogrammetric dataset was processed using the Structure from Motion (SfM) algorithm to establish image orientation. Following orientation, georeferencing was performed to spatially align the model with real-world coordinates. A point cloud was subsequently generated from the oriented images, producing a dense set of points that served as the foundational geometry for 3D reconstruction. Surface modelling was achieved through Poisson surface reconstruction, resulting in a continuous mesh representation. The final step involved texture mapping, wherein image-based textures were applied to the mesh to accurately reflect the visual characteristics of the original object.

Unlike photogrammetry, laser scanning technology directly generates point clouds from each acquisition station without the need for image matching. Both TLS and ALS were utilized in this study to capture spatial data from ground and aerial perspectives, respectively. ALS provided large-scale topographic coverage, particularly useful for capturing the broader landscape and contextual features surrounding the object. The point clouds obtained from both TLS and ALS were subsequently aligned and merged into a single dataset within a unified coordinate system. Following the construction of the mesh model, georeferencing was applied to accurately position the model in real-world space. Finally, texture mapping was conducted to produce a photorealistic, textured 3D model. For creating the AR application, the process may be divided into two parts: developing the target image with the Vuforia SDK and designing the Augmented Reality application using the Unity game engine. In this study, 3D models created from each data are compared based on its usefulness for augmented reality applications.

The deliverable produced in this study is an orthoimage map of the Trowulan site with AR capabilities. On the map there are markers for the 3 archaeological sites, namely Bajang Ratu, Wringin Lawang, and Brahu. When the user highlights the map using the application on their smartphone, a 3D model of the historic building will concurrently appear. The 3D model can be observed in more detail by moving the cellphone camera back and forth. It is hoped that the map can be used by the Trowulan Museum located on the site and can also be shared with site visitors in the form of a map brochure, to enable an immersive digital means for educational purposes.

4. Results and Discussion

4.1 Analysis of 3D Models

3D models are first visualized in the form of point clouds. Dense point cloud size (number of points) of each technique from each cultural heritage structure is shown in Table 1. Based on the table, the laser scanner is able to collect more points, even up to about 40 times more than that produced by the photogrammetry technique. Build upon the point cloud, 3D models in the form of 3D mesh were constructed. Since laser scanner gave a greater number of points, it can produce a greater number of faces in the mesh (Table 1), which resulted in more detailed structures. Consequently, the 3D model from laser scanner also has a bigger file size than those from photogrammetry.

Figure 2 illustrates a visual comparison of 3D reconstruction results for each sites using both data sources. From the figure, it is evident that the laser scanner yields the most detailed and consistent model geometry, especially in capturing fine architectural features. The photogrammetric model also shows significant detail but suffers from limitations in structural uniformity and surface smoothness compared to the laser-scanned outputs. Overall, this comparison emphasizes that the resolution of point cloud data plays a crucial role in defining the geometric fidelity of the resulting 3D model. The laser scanner provides the most comprehensive and accurate representation of the cultural heritage structure, which is critical for heritage documentation and analysis

	Brahu	**Bajang Ratu**	**Wringin Lawang**
Point cloud size (number of points)			
Photogrammetry	2,473,561	551,884	5,512,765
Laser Scanner	118,291,784	4,560,381	115,261,884
Number of faces in 3D mesh			
Photogrammetry	13,679,619	3,138,763	1,104,089
Laser Scanner	34,412,398	1,016,921	6,518,495
3D model file size			
Photogrammetry	239,527 KB	100,644 KB	39,285 KB
Laser Scanner	815,126 KB	182,000 KB	208,593 KB

Table 1. Comparison of 3D models generated by photogrammetry and laser scanner, in terms of number of points, number of triangles, and 3D model file size.

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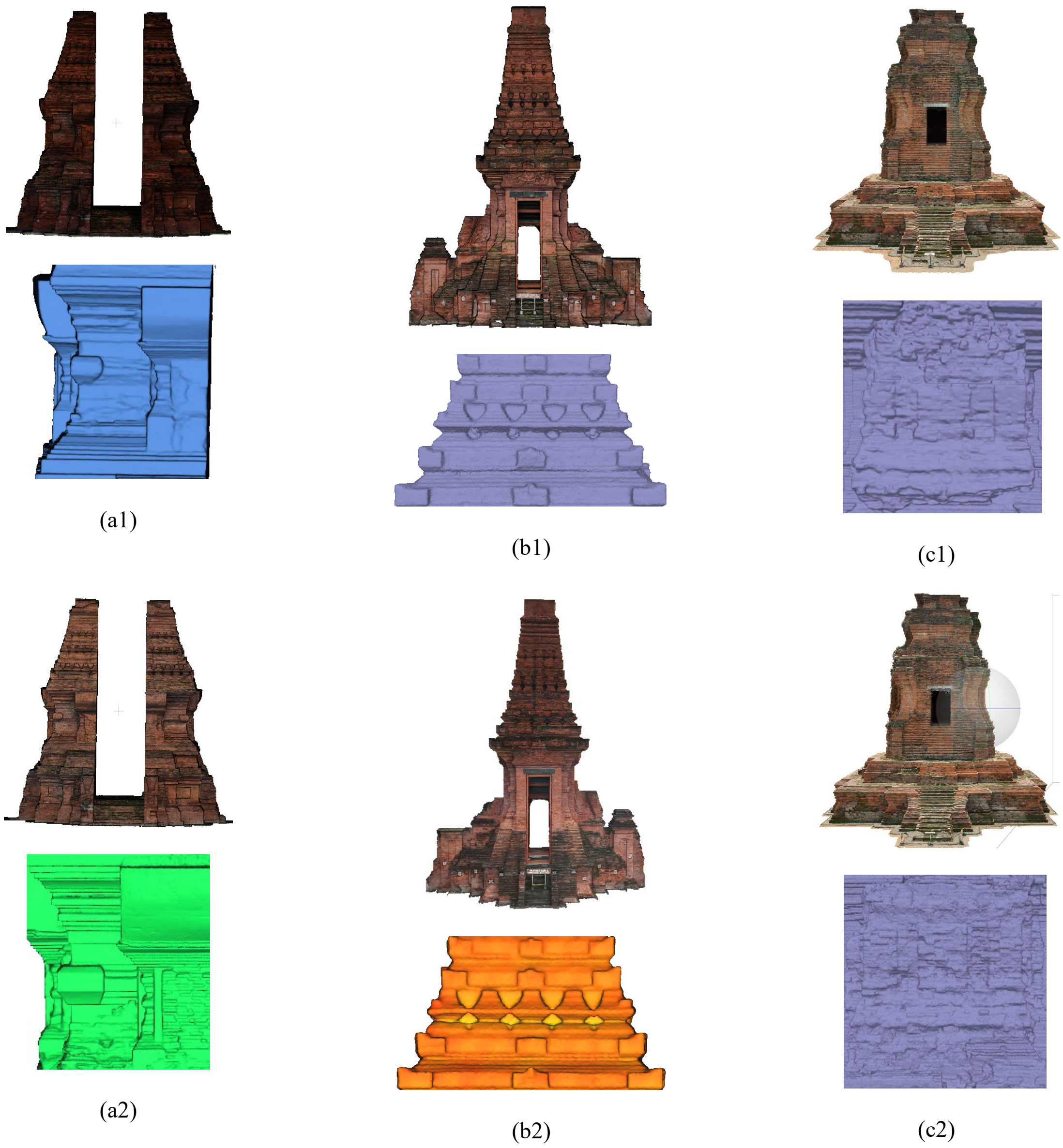
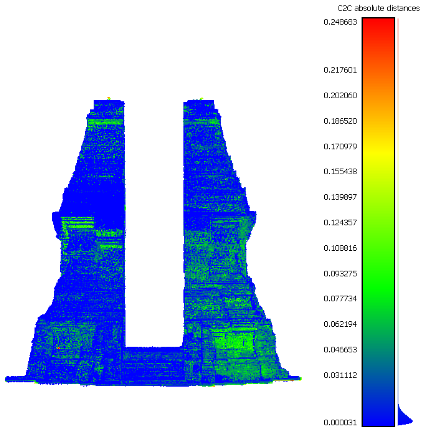
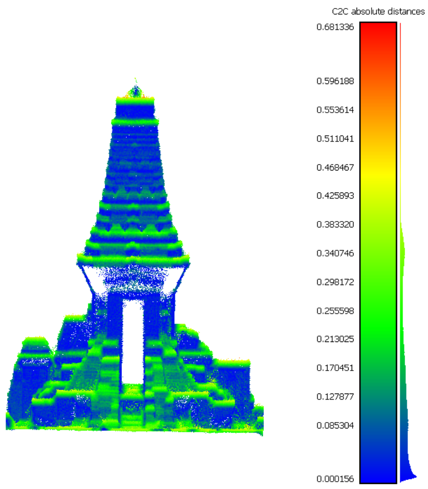


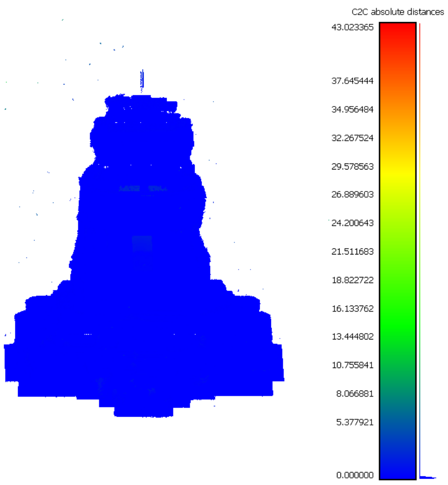
Figure 2. Wringin Lawang (a1) Photogrammetry, (a2) Laser Scanner; Bajang Ratu (b1) Photogrammetry, (b2) Laser Scanner; Brahu (c1) Photogrammetry, (c2) Laser Scanner.



(a)



(b)



(c)

Figure 3. Cloud to Cloud Distance (C2C) from Wringin Lawang (a), Bajang Ratu (b), Brahu (c).

The accuracy and spatial integrity of a 3D reconstruction rely heavily on the quality of point cloud registration. Cloud-to-cloud (C2C) distance analysis is a key metric used to quantify deviations between two aligned point clouds. It provides a visual and numerical understanding of how well data from different sources fit together within the same coordinate system. While absolute numeric values were not computed here, color-coded C2C maps reveal meaningful trends regarding data consistency, registration accuracy, and geometric fidelity for each structure.

For the Wringin Lawang, photogrammetry produced a point cloud with 5.5 million points, whereas Laser Scanner produced over 115 million points. This disparity highlights the significant increase in geometric resolution offered by laser scanning, particularly in occluded or detailed regions. The 3D mesh created from laser scanner data also showed a much higher triangle count (6.5 million vs. 1.1 million in photogrammetry), resulting in a more refined surface model.

A visual analysis of the C2C distance (Figure 3a) demonstrates that the majority of the surface deviations are within the 0.01–0.05-meter range, as indicated by the prevalence of blue and green colouring on the model. The alignment between datasets is generally strong, with only minor misalignments appearing in edge regions, likely due to occlusions or lower texture features. The maximum deviation remains below 0.25 meters, confirming that the overall point cloud registration was successful. These results suggest that while laser scanner adds complexity, it greatly improves spatial consistency and accuracy.

In contrast, Bajang Ratu presented a unique trend. While laser scanner generated approximately 4.5 million points, substantially more than photogrammetry's 551,884 points, the photogrammetric model paradoxically had a higher triangle count (3.1 million vs. 1 million in laser scanner). This indicates an over-meshing of sparse data, possibly introducing noise or surface distortion. Laser scanning data, on the other hand, offers a smoother and more reliable surface, especially for vertical or recessed features.

The C2C map for Bajang Ratu (Figure 3b) shows a broader range of deviations compared to Wringin Lawang. While most points are within a 0.01–0.20-meter range, there are some areas particularly in the upper sections where deviations reach beyond 0.4 meters, represented by yellow and orange zones. This may reflect registration challenges due to the structure's steep and vertically aligned structures. The maximum deviation observed was approximately 0.66 meters, which is significant for precision documentation but acceptable for general visualization and AR use.

Brahu, being the most complex and extensive of the three, benefited most from the integration of laser scanner data. Photogrammetry resulted in a point cloud with 2.4 million points and a mesh with 13.6 million triangles. Laser scanner vastly outperformed this with 118 million points and 34.4 million triangles. This dense spatial data allows for highly accurate modelling of both the structure and its topographic context.

The C2C distance visualization for Brahu (Figure 3c) confirms the high quality of registration. The entire structure appears predominantly blue, indicating near-perfect alignment between the datasets. Although the error extends to 43 meters, these outliers are likely stray points outside the object's boundaries. The actual structure shows deviation well under 5.0 meters, mostly clustering below 0.1 meters. This suggests exceptional precision in both scanning and registration, making the Brahu model a strong candidate for archival and scholarly purposes.

Across all three sites, laser scanner demonstrated consistently superior geometric fidelity and more complete spatial coverage. It mitigated issues commonly found in photogrammetry such as uneven density, alignment errors, and surface voids. While photogrammetry remains efficient for rapid modelling, laser scanner is essential for projects requiring high-precision and scalable data especially for conservation, restoration planning, and spatial analysis.

While spatial accuracy is crucial for documentation, texture quality is equally important for visualization, public outreach, and immersive technologies such as AR. A realistic texture enhances user engagement, facilitates interpretation, and improves the educational value of 3D reconstructions.

Photogrammetry consistently outperforms laser scanner in terms of texture realism. The process of capturing high-resolution images during flight or ground-based imaging enables photogrammetry to reproduce fine surface details, such as material colour, weathering, and architectural ornamentation. For example, the photogrammetric model of Wringin Lawang delivered superior texture clarity despite being geometrically simpler. The visual realism in this case is ideal for public exhibitions or AR-based tourism tools.

In contrast, the textures produced through laser scanner are often limited in resolution and visual fidelity. While TLS systems may include integrated cameras, the resulting images are often lower in quality and resolution. ALS, focused on terrain and surface height data, typically contributes no usable texture data. Therefore, models created using these methods appear visually flatter, with reduced realism in digital platforms.

The texture comparison is also evident in file size differences. For Brahu, the photogrammetric model was 239 MB, whereas the laser scanner model reached 815 MB, almost four times larger, despite delivering lower-quality texture. This suggests that the geometric data in Laser Scanner dominates file size, while photogrammetry delivers more efficient and compact models with higher aesthetic value.

In the case of Bajang Ratu, the photogrammetric model has a file size of 100,644 KB, while the laser scanner model is larger at 182,000 KB. This correction underscores that although the laser scanner model contains more geometric data, the photogrammetric model remains more efficient in encoding visual detail. Despite its smaller size, the photogrammetry-based model maintains superior texture resolution, benefiting from high-quality image capture during data acquisition. This makes it better suited for applications that prioritize visual realism over raw geometric precision, such as mobile AR experiences and virtual reconstructions for public interaction. The increased file size of the laser scanner model reflects its higher point density and mesh complexity, but it does not necessarily translate to better surface appearance, reinforcing the strength of photogrammetry in producing visually compelling and accessible 3D content.

For Brahu, photogrammetric textures offered substantial detail despite the complexity of the structure. In AR demonstrations, the photo-based model responded more effectively, loading quickly and displaying sharp surface textures on mobile devices. This is particularly important for user experience in educational and tourism settings, where users may not be concerned with sub-centimetre geometry but expect lifelike visual representations.

Nevertheless, texture realism in laser scanner can be improved by using hybrid workflows. By mapping high-resolution photogrammetric images onto TLS-based geometry, a model can benefit from both spatial accuracy and visual richness. This approach is recommended for institutions seeking to balance documentation standards with public engagement. Photogrammetry is preferable for applications requiring high visual fidelity, especially for AR deployment. On the other hand, laser scanner excels in delivering complete and accurate geometric representations, essential for scientific, archaeological, and conservation tasks. A hybrid approach could offer the most comprehensive solution, enabling models that are both accurate and visually engaging.

4.2 3D Augmented Reality

Following the generation of 3D models using both photogrammetry and laser scanning techniques, the models were integrated into an Augmented Reality (AR) application to enhance public accessibility and engagement. However, applications created with 3D models from laser scanners are too heavy to load efficiently.

The AR system allows users to visualize the reconstructed cultural heritage structures directly on top of printed or digital maps using mobile devices. The application consists of two main scenes. First, the main page displays the "AR Camera" button to go to the Augmented Reality display and "Quit" to exit the application. Second scene is the AR scene that will display a 3D model of the cultural heritage structure when the marker (Figure 4) is recognized. In the AR scene, there is a "Back" button that functions to return to the main page.

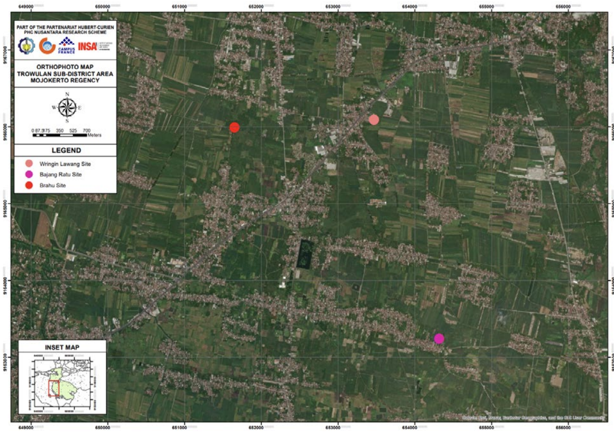


Figure 4. Marker for the application on the printed map.

As shown in Figure 5, the digital models of Bajang Ratu, Wringin Lawang, and Brahu can be interactively explored through a smartphone screen, offering a realistic and immersive experience. This implementation demonstrates the potential of AR as a tool for cultural heritage dissemination, especially in educational and tourism contexts. By overlaying historically accurate 3D reconstructions onto real-world references, users can intuitively learn about the spatial and architectural characteristics of the Majapahit monuments without visiting the physical sites. This approach is expected to contribute to both digital conservation efforts and broader historical learning.

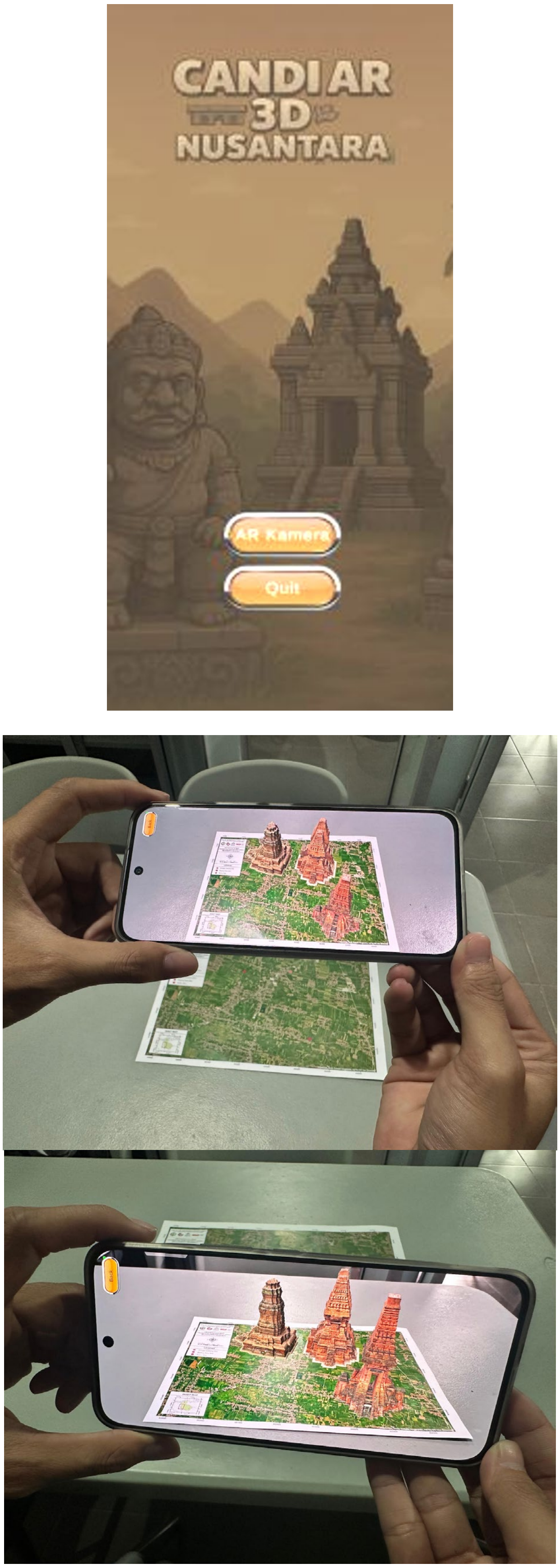


Figure 5. AR visualization of Bajang Ratu, Wringin Lawang, and Brahu using mobile application.

Testing was conducted on the application through three categories of mobile phones based on price range, namely low-end (less than 125 USD), mid-end (125-250 USD), and high-end (more than 250 USD). The parameters tested include FPS (Frame per Second) stability and the functionality of the buttons in the application. The test results showed that all application buttons functioned well on all device categories, indicating optimal application compatibility and responsiveness.

FPS testing shows that high-end devices experience a fairly sharp FPS drop during AR scene open-close transitions, with a minimum FPS of only 17, a variance of 9.0, and an average FPS of 28.9. Mid-end devices record a minimum FPS of 0, a higher variance of 32.9.0, and almost the same average FPS of 28.0. As for low-end devices, the minimum FPS is recorded at 14 with a variance of 16.2 and an average FPS of 25.7, which is still relatively stable although slightly lower. This difference can be influenced by more aggressive power management and thermal throttling on high-end devices, while mid-end and low-end devices tend to optimize performance without strict restrictions. Although there are variations in performance during transitions, all three devices still show playable results and are able to run AR applications well.

5. Conclusions and Perspectives

This study demonstrates the complementary strengths of photogrammetry and laser scanning in the digital documentation of cultural heritage sites. The comparative evaluation of three Majapahit cultural heritage sites, Wringin Lawang, Bajang Ratu, and Brahu shows that laser scanner consistently delivers superior geometric accuracy and spatial completeness. This is especially evident in the cloud-to-cloud distance analyses, where laser scanner results in denser point clouds, more detailed meshes, and tighter registration across complex structures. These characteristics make laser scanning an essential tool for high-precision heritage documentation, restoration planning, and structural analysis.

In contrast, photogrammetry proves highly effective in capturing surface textures and producing visually compelling 3D models. Despite having fewer data points and lower mesh complexity, photogrammetric models offer superior realism in appearance, which is critical for public engagement, virtual exhibitions, and immersive technologies such as AR. The relatively compact file sizes and high-resolution textures make photogrammetry ideal for mobile deployment and educational use, particularly in situations where realism and accessibility are prioritized over exact spatial metrics.

Taken together, the findings suggest that a hybrid approach—leveraging the spatial precision of laser scanning and the visual richness of photogrammetry—offers the most robust solution for cultural heritage digitization. Such integrated workflows not only preserve the physical details of historical structures but also enhance their accessibility to future generations through interactive platforms. As demonstrated in this research, digitizing heritage structures in high detail is not only technically feasible but also essential, especially in disaster-prone regions like Indonesia, where many ancient structures are at ongoing risk of deterioration or destruction.

Using the three sites as case examples, demonstrates the importance of digitizing cultural heritage. Such efforts are crucial in anticipation of unforeseen events that may occur in the future. Indonesia, as a country highly prone to natural disasters, faces a significant risk of damage to the structural integrity of its cultural heritage sites. High-resolution digital documentation can serve as a valuable reference in the event of deterioration or destruction, as it facilitates restoration efforts by providing detailed records of the original structure.

The integration of AR objects with markers on the map is effective, as evidenced by the successful appearance of 3D models when markers are recognized by the camera. Performance tests show the application is stable and playable on low-end to high-end devices.

In this context, digital preservation via the proposed method offers a viable solution to ensure that future generations can continue to observe and study the legacy of their ancestors, even if the physical structures deteriorate or are lost over time.

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