Preserving Central Sulawesi Megaliths via Virtual Reality and Photogrammetry

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Abstract

This research addresses the challenge of limited physical access to the significant megalithic cultural heritage sites in Central Sulawesi, which are geographically dispersed across the Bada, Napu, and Behoa valleys. Conventional media, such as 2D photos and videos, fail to convey the spatial and monumental scale of these artifacts. This study develops an immersive Virtual Reality (VR) application as an alternative cultural preservation and information accessibility medium. The methodology employs a multimedia development pipeline, beginning with photogrammetric data acquisition using drones to create high-fidelity 3D models of megalithic artifacts. These models are then optimized through retopology and texture baking to ensure smooth performance on standalone VR devices like the Meta Quest 3. Quantitative performance analysis shows that the optimization process successfully reduced the polygon count by over 99% (from an average of 1.5 million to approximately 12,000 polygons per artifact). This massive geometry reduction resulted in significant computational efficiency, with statistical tests indicating a statistically significant increase in the average frame rate from an unstable 28.69 FPS to a highly stable 72.28 FPS ($t(118.8) = 18.94$, $p < 0.001$). Furthermore, user experience evaluation indicates high visual fidelity and comfort, proving the application to be an effective and inclusive digital preservation medium for cultural heritage.

Keywords *— Virtual Reality, Cultural Heritage, Photogrammetry, 3D Model, Blender, Megalith, Central Sulawesi*

1. INTRODUCTION

The development of digital technology has opened new opportunities in education and cultural preservation, one of which is Virtual Reality (VR) [1]. VR is capable of providing an immersive experience as if the user were physically present in a virtual environment, which fundamentally emphasizes 'the value of being there' in a learning process. Warsito et al. assert that virtual technologies, such as 360-degree panoramas, allow users to experience the real environment without physical limitations, enabling students to focus on learning in a more enjoyable way [16]. A systematic review indicates the significant advantage of Head-Mounted Display (HMD)-based Immersive Virtual Reality (I-VR) over 2D media in topics requiring high-level spatial visualization [1]. However, its effectiveness depends on the design and user familiarity, where the 'novelty effect' can become a cognitive load during initial use [1].

Consistent with these findings, research in AR/VR in education has indeed shown exponential growth, underscoring the relevance and great potential of this technology [3]. In Central Sulawesi, there is a wealth of megalithic culture centered in the Bada, Napu, and Behoa Valleys, which are prehistoric remains of archaeological, historical, and cultural value [4]. However, limited geographical access to these sites poses a challenge for education and preservation. This condition contributes to the fading of collective memory, a challenge quantitatively confirmed where public awareness of similar megalithic heritage remains low, despite the high demand for digital solutions [5].

Conventional learning media such as photos and videos have proven unable to adequately convey the monumental scale and spatial context of artifacts. Studies show that VR experiences can improve architectural feature recognition capabilities by up to 62% compared to 2D images [6]. This confirms the need for 3D-based digital approaches, such as photogrammetry or Building Information Modeling (BIM), for cultural heritage to present a more authentic spatial representation [7].

The gap between the great potential of megalithic sites and the limitations of access underpins this research. Extensive systematic reviews have confirmed that 3D virtual reconstruction in VR is an effective approach for the dissemination of cultural heritage [8]. By integrating photogrammetry for 3D reconstruction and optimizing it for standalone VR devices [4], this research aims to develop an alternative learning medium. A proven workflow, encompassing retopology and simplification processes [9][10], enables high-polygon 3D models to be optimized into lightweight low-polygon models, capable of running smoothly on standalone VR devices [11]. Although VR adoption faces constraints such as investment requirements and technical expertise [2], this application is positioned as a complementary solution that addresses accessibility challenges with a more immersive and informative experience. This approach is supported by the findings of Imansyah and Widiastuti, who concluded that immersive technology can provide new interaction experiences effective for overcoming physical constraints in delivering learning materials that are difficult or require specialized equipment [15].

2. RESEARCH METHOD

The research methodology employs a multimedia development pipeline, specifically adapted for Virtual Reality application development. This framework encompasses three main stages: pre-production, production, and post-production.

2.1. Pre-production

This stage involves a literature review to collect data regarding VR technology, photogrammetry, and the archaeological context of megalithic sites. The process began with analyzing the main problem, namely the limited physical access to Central Sulawesi megalithic sites, and formulating the need for alternative learning media based on immersive technology. Visual data was collected in the field using photogrammetry methods with a DJI drone and RealityCapture software to produce raw 3D models. The drone photo results of the Tadulako statue are shown in Figure 1.

Figure 1. Drone Photo of Tadulako Statue

2.2. Production

This stage focuses on product development. Visual Data Collection: Photo data of megalithic artifacts (Palindo, Tinoe, Loga statues, and several Kalambas) were collected in the Bada, Napu, and Behoa Valleys using a drone. Photogrammetry techniques were applied by ensuring a minimum photo overlap of 80% (front) and 70% (side) to produce accurate 3D reconstructions. The point cloud display of the Palindo statue is shown in Figure 2.

Figure 2. Point Cloud of the Tadulako Statue

The photos were processed into high-poly 3D models. These models were then optimized through retopology and texture baking processes to produce low-poly models that are lightweight yet visually detailed. To illustrate the modeling technique from photogrammetry to cleanup, a diagram was designed as shown in Figure 3.

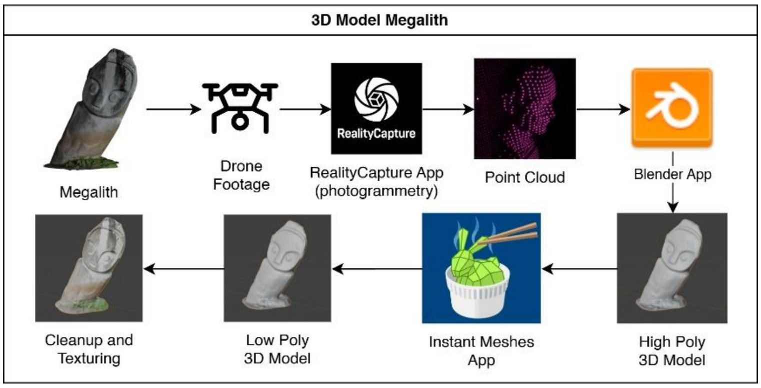


Figure 3. Modelling Technique

The visual data processing began by importing the raw photogrammetry model into Blender software. In the initial stage, spatial orientation correction was performed to align the model's axis with the world axis, along with the cleaning of noise or irrelevant geometric artifacts using vertex isolation and inverse selection techniques. This process is shown in Figure 4.

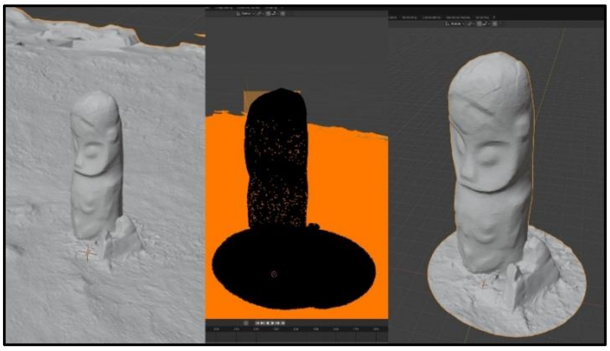
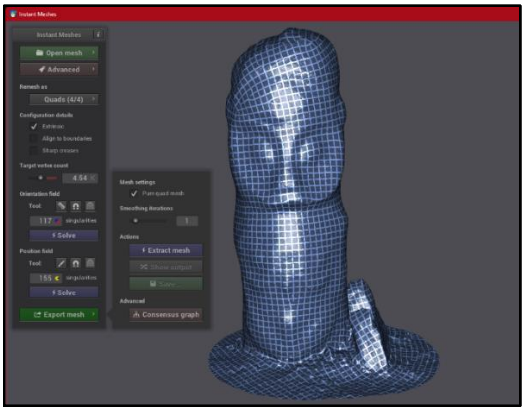


Figure 4. 3D Model Correction Process

Given that the raw model possessed a random triangulated mesh topology and a massive polygon count (millions of faces), an automatic retopology process was performed using algorithms available in the Instant Meshes software. The target parameter was set in the range of 8,000 to 15,000 vertices to produce a quad-dominant topology that is efficient while maintaining the object's main silhouette. The workflow from raw model to new topology is shown in the asset processing flowchart. The Retopology process is shown in Figure 5.



Remesh as Quads (4/4)
✓ Extrinsic
Target vertex count 4.54 K
117 singularities
155 singularities
✓ Pure quad mesh
Smoothing iterations 1

Figure 5. Retopology Process via Instant Meshes

To address the loss of surface detail due to drastic polygon reduction, the High-to-Low Poly Baking method was applied. This process transfers geometric detail information from the original model (high-poly) into texture maps which are then applied to the retopologized model (low-poly).

Two main types of texture maps were produced in this process:

1. Diffuse/Albedo Map: Captures object surface color information based on the original photogrammetry data.
2. Normal Map: Stores depth and surface direction information (surface normals) to simulate rock relief details, cracks, and weathering without increasing geometric load.

The baking process was carried out using the Cycles rendering engine with configurations optimized for time efficiency, limiting Max Samples to 8 and Total Light Paths Bounces to 2. To ensure detail projection was captured perfectly without artifacts, the Selected to Active feature was activated with an Extrusion value of 0.1 m. The baking results, in the form of Diffuse Map (for color) and Normal Map (for relief detail), proved capable of displaying visuals almost identical to the high-poly model despite having 98% lower geometric complexity. The comparison of low-poly and high-poly appearances is shown in Figure 6.

Figure 6. Comparison of Low-Poly and High-Poly Appearance

Asset integration into the virtual environment was performed using the Unity 6 game engine based on the OpenXR standard to ensure cross-platform compatibility. The interaction architecture was built upon the XR Interaction Toolkit framework, which handles HMD (Head-Mounted Display) position tracking and controller input.

The optimized megalith assets were imported along with PBR (Physically Based Rendering) materials arranged using the Diffuse Map on the Base Map channel and the Normal Map on the Normal channel. This setting allows for realistic lighting simulation on the statue surfaces when running in real-time on the Meta Quest 3 device. Visual validation within the engine showed that surface details were maintained even when running on a mobile VR platform. Comparison of model details with Normal Map is shown in Figure 7 and Figure 8.

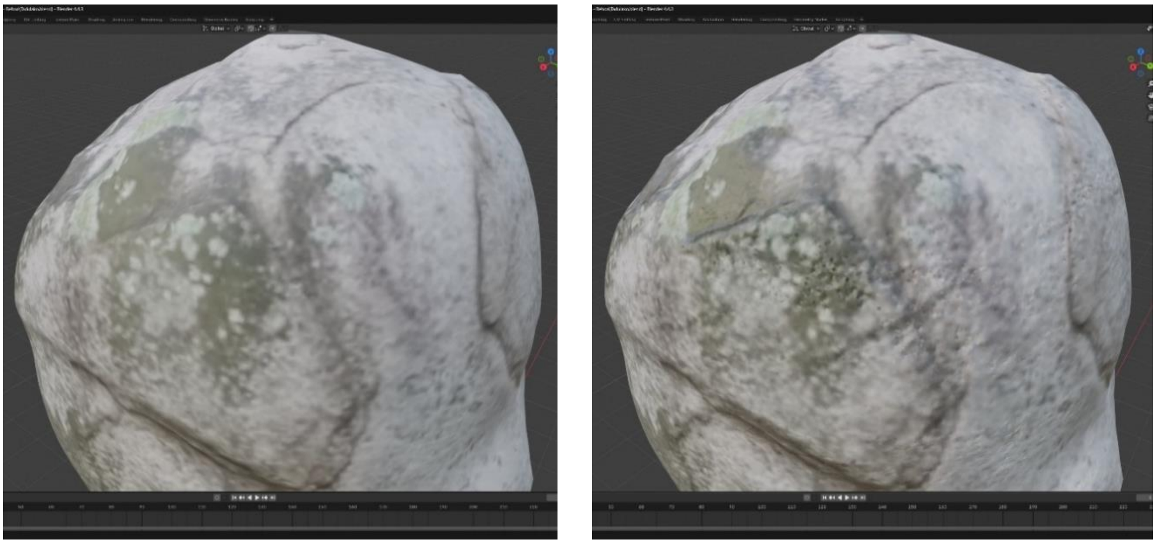


Figure 7. 3D Model without Normal Map and with Normal Map

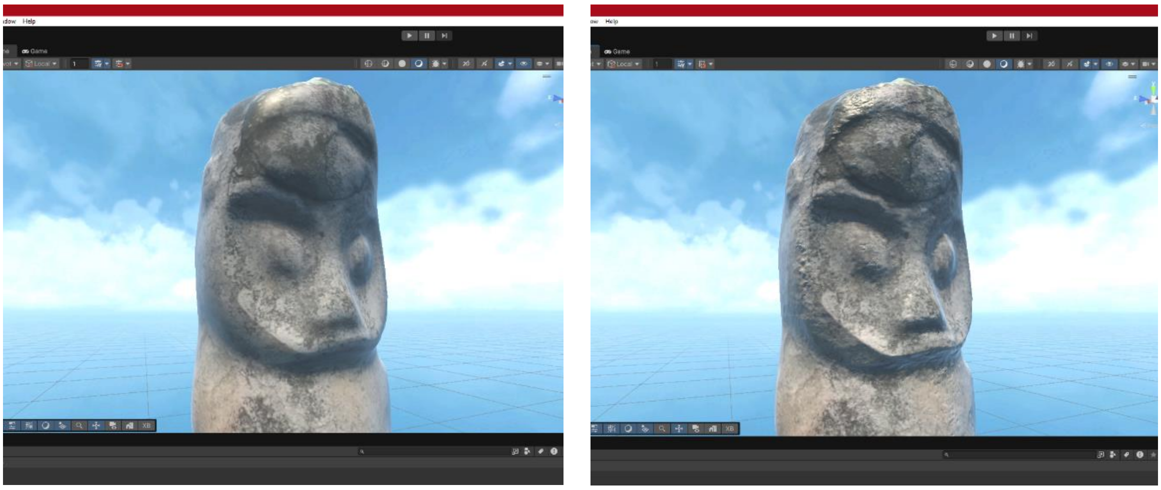


Figure 8. 3D Model without Normal Map and with Normal Map in Unity

This development process employs the Agile Scrum framework to ensure flexibility and measurable progress. To model the functional interactions between the user and the VR application, a use case diagram was designed, as shown in Figure 9.

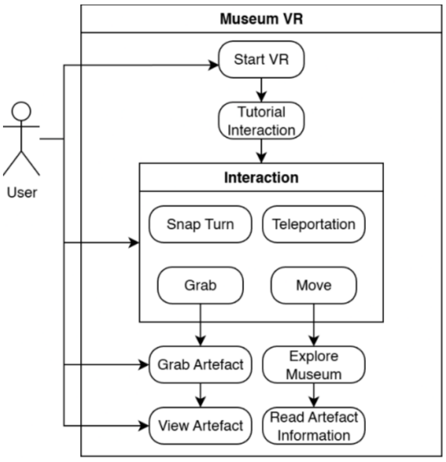


Figure 9. VR Application Use Case Diagram

The project was divided into several iterations or sprints, each lasting 1-2 weeks, with the objective of delivering a functional component of the application at the end of each sprint. Testing was conducted during each iteration to ensure functionality and quality. Functional testing verified that each feature operated as expected, while technical testing evaluated aspects of user comfort (cybersickness) and initial learning effectiveness.

The results from the testing phase were analyzed to assess whether the feature objectives had been met. If deficiencies or areas for improvement were identified, the cycle returned to the design or implementation stage. Features meeting the criteria and research objectives were considered complete and integrated into the product. Once all priority features were implemented, tested, and evaluated, the VR application was compiled into a final product version ready for user testing. Research documentation was then compiled into a scientific article.

The development flow is illustrated in Figure 10.

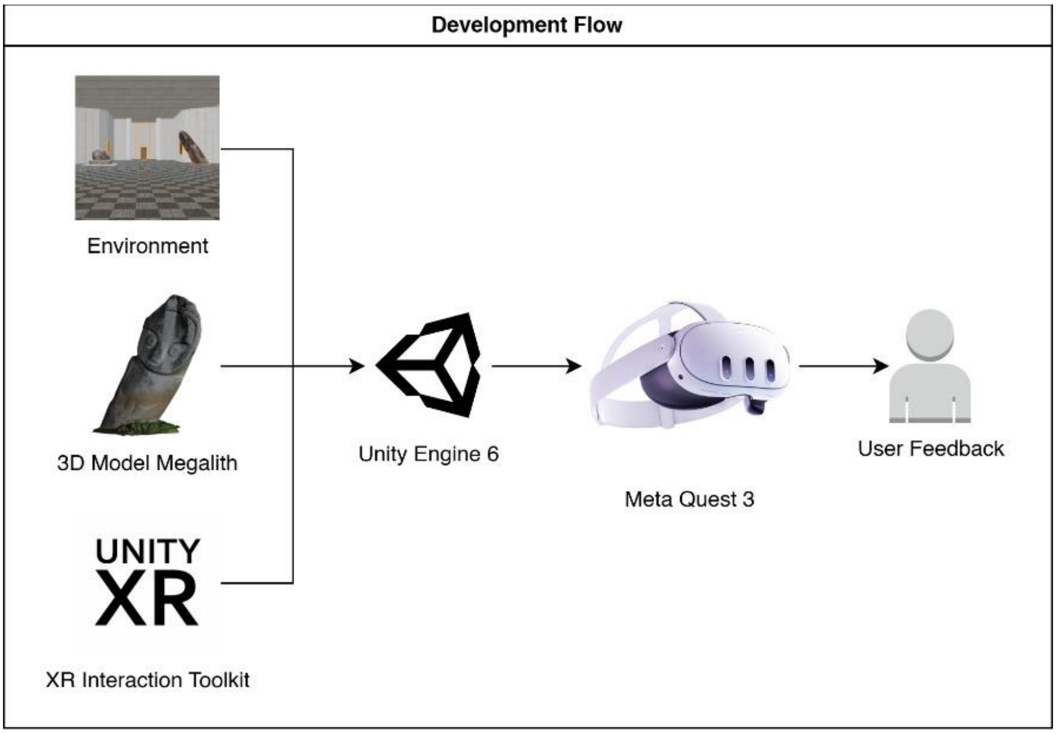


Figure 10. Development Flow

2.3. Post-production

This final stage focuses on evaluating the effectiveness of the application as a learning medium. The main activity is user testing involving respondents. This procedure includes administering a pre-test questionnaire to measure initial knowledge, a VR application usage session, and concluding with a post-test questionnaire to measure knowledge improvement and user experience. The collected data was then analyzed to draw research conclusions.

The research flow is illustrated in Figure 11.

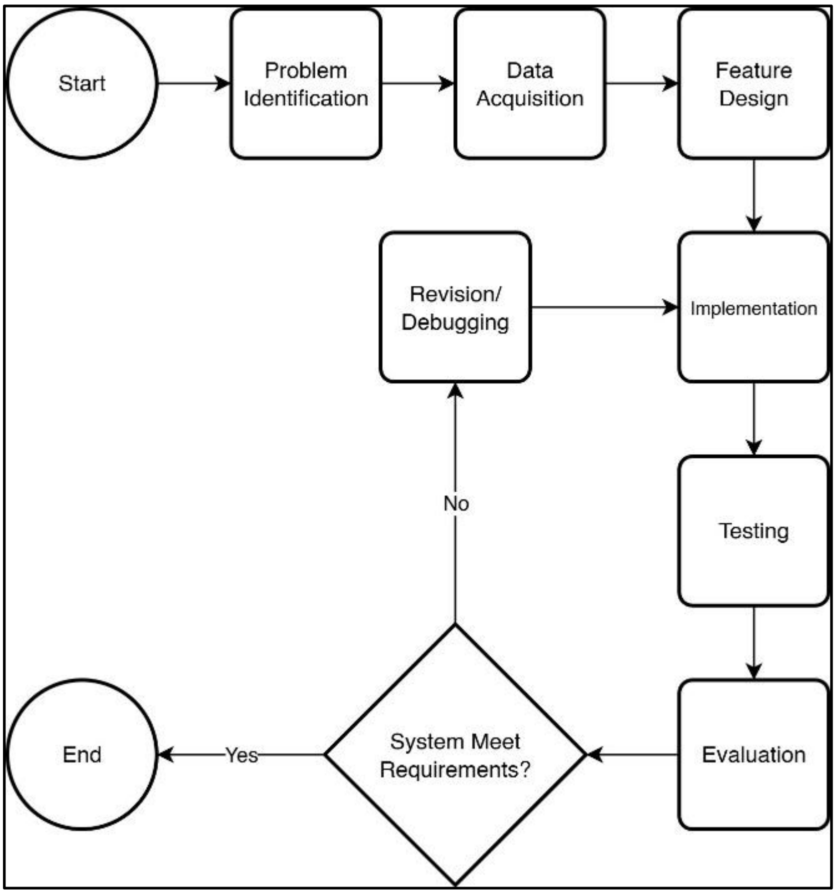
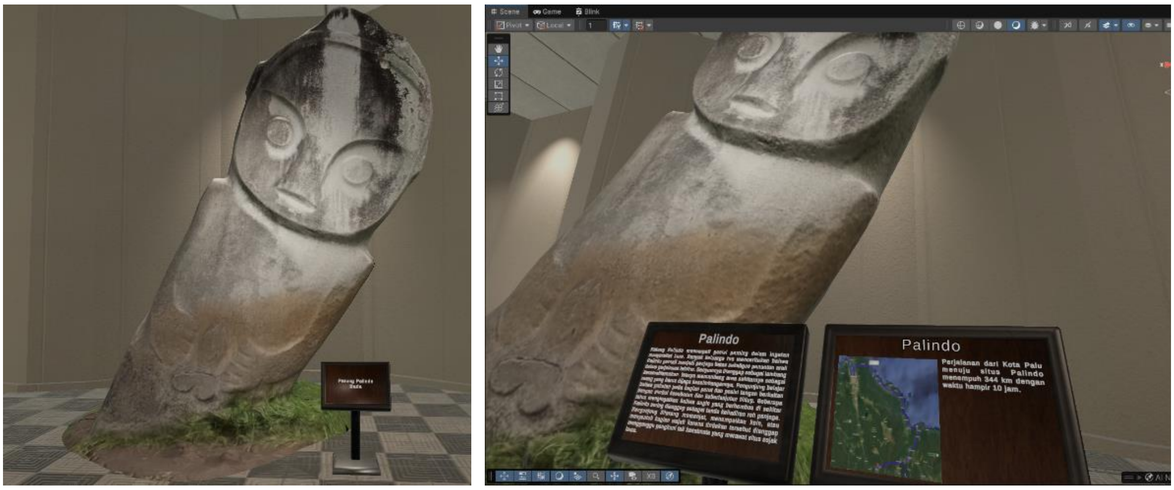


Figure 11. Research Flow

Data from respondents were utilized for further development of the application. Information regarding each statue was supplemented with history, statue symbolism, location, and distance from the nearest city. Developments in features and the megalith statue area are shown with an infographic of the Palindo statue in Figure 12.



Perjalanan dari Kota Palu menuju situs Palindo menempuh 344 km dengan waktu hampir 10 jam.

Figure 12. Infographic of the Palindo statue

3. RESEARCH RESULTS AND DISCUSSION

This section presents the results from two main aspects: the application's technical performance and the evaluation of learning effectiveness.

3.1. Application Architecture and Technical Implementation

This VR application was developed using the Unity 6 game engine. Core VR functionalities, including controls, display, and interaction, were implemented using the XR Interaction Toolkit package. The main virtual environment was designed as a museum-style room modeled in Blender. The Unity view is shown in Figure 13.

Figure 13. Virtual Reality Initial View

Eight optimized photogrammetry megalith models were imported into this museum environment. These artifacts represent the three main valleys: Palindo, Tinoe, and Loga (Bada Valley); Mpolenda, Watatau, and Watunongko Kalamba (Napu Valley); and Tadulako and Monkey Statue (Behoa Valley). Each model is equipped with an informative signboard. One of the artifact displays in VR is shown in Figure 14.

Figure 14. Palindo Megalith in Virtual Reality

To ensure an intuitive user experience, an interactive tutorial session was implemented at the beginning. This tutorial teaches basic mechanisms such as movement, teleportation, incremental camera rotation (snap turn 45 degrees), and grab interactions to hold miniature versions of the megaliths. A screenshot of the tutorial view is shown in Figure 15.

Figure 15. Virtual Reality Interactive Tutorial

3.2. Technical Performance Results

The main challenge in running photogrammetry models on standalone VR devices is the extremely high geometric complexity. Therefore, the optimization process is a crucial step. To quantitatively validate the effectiveness of the proposed workflow, a comparative performance analysis (A/B testing) was conducted on the Meta Quest 3 hardware using the Meta Quest Developer Hub (MQDH) profiling tool.

The testing scenario involved rendering eight identical megalithic statues within a single Unity scene to simulate a high-load rendering environment. The evaluation was divided into two distinct conditions:

1. Scenario A (High-Poly): Using raw photogrammetry models without optimization.
2. Scenario B (Low-Poly): Using optimized models (retopologized) with baked Normal Maps.

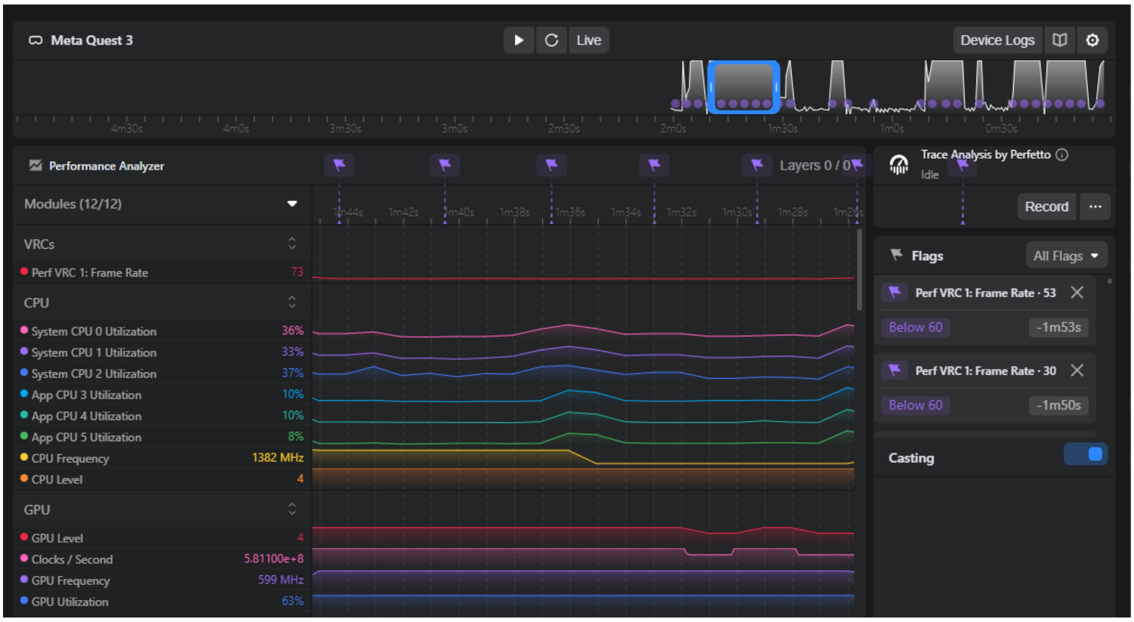
The profiling results revealed a critical performance disparity between the two scenarios. In Scenario A, the standalone device experienced severe computational bottlenecks. As visualized in Figure 16, the application struggled to run, averaging only 10 Frames Per Second (FPS). This low frame rate was caused by the massive geometric load, forcing the GPU Utilization to peak at 96%. Additionally, the System CPU utilization reached approximately 83%, while the App CPU utilization hovered around 65%. Such performance renders the application unplayable and would immediately trigger motion sickness (cybersickness) due to high visual latency.

Perf VRC 1: Frame Rate 10
System CPU 0 Utilization 83%
System CPU 1 Utilization 82%
System CPU 2 Utilization 87%
App CPU 3 Utilization 65%
App CPU 4 Utilization 63%
App CPU 5 Utilization 60%
CPU Frequency 1382 MHz
CPU Level 4
GPU Level 4
Clocks / Second 5.44961e+8
GPU Frequency 545 MHz
GPU Utilization 96%

Perf VRC 1: Frame Rate · 30
Below 60 -1m56s
Perf VRC 1: Frame Rate · 10
Below 60 -1m53s
Perf VRC 1: Frame Rate · 11
Casting

Figure 16. Performance profiling of Scenario A (High-Poly)

In contrast, Scenario B demonstrated the significant impact of the optimization process. The application successfully maintained a stable frame rate of 73 FPS, which meets the recommended refresh rate standard for a comfortable VR experience on Meta Quest 3. The computational load was drastically reduced, with App CPU utilization dropping to approximately 10% and System CPU stabilizing at around 36%. GPU utilization also decreased to a manageable 63%, providing sufficient headroom for other interactive elements.



Perf VRC 1: Frame Rate 73
System CPU 0 Utilization 36%
System CPU 1 Utilization 33%
System CPU 2 Utilization 37%
App CPU 3 Utilization 10%
App CPU 4 Utilization 10%
App CPU 5 Utilization 8%
CPU Frequency 1382 MHz
CPU Level 4
GPU Level 4
Clocks / Second 5.81100e+8
GPU Frequency 599 MHz
GPU Utilization 63%

Perf VRC 1: Frame Rate · 53
Below 60 -1m53s
Perf VRC 1: Frame Rate · 30
Below 60 -1m50s
Casting

Figure 17. Performance profiling of Scenario B (Low-Poly)

A summary of the performance metrics comparison is presented in Table 1.

Table 1. Comparison of High Poly and Low Poly Models

Attribute	Scenario A	Scenario B
Polygon Count	2,098,577	27,949
File Size	236 MB	3.92 MB
Meta Quest 3 Frame Rate	~10 FPS	>72 FPS (+630% Increase)
App CPU Usage	~65%	-10% (~55% Efficiency)
System CPU Usage	~83%	~36% (-47% Efficiency)
GPU Utilization	96%	63% (-33% Efficiency)

$$((2.098.577 - 27.949)/2.098.577) * 100 = 98{,}66\ldots\%) \qquad (1)$$

Data in Table 1 shows the success of the optimization process, with a polygon reduction reaching 98.7%. This drastic decrease had a direct impact on application performance, where the frame rate increased from below 30 FPS (which can cause motion sickness) to stable above 72 FPS, complying with the minimum standards for a comfortable VR experience on the Meta Quest 3 device. The model comparison is shown in Figure 18.

To statistically validate this performance gain, an Independent Sample t-test (Welch's t-test) was conducted on the real-time frame rate logs extracted from the Meta Quest Developer Hub over 2 minutes duration. The test results confirmed that the average frame rate of the optimized Low-Poly scenario (M = 72.28,SD = 2.25) was significantly higher and more stable compared to the unoptimized High-Poly scenario (M = 28.69,SD = 24.91). This difference was statistically significant ($t(118.8) = 18.94, p < 0.001$) proving that the optimization pipeline effectively resolves the computational bottleneck on standalone VR devices.

Figure 18. Comparison of High Poly and Low Poly Models

It is important to note that aggressive polygon reduction inherently removes fine geometric details from the model surface. To address this loss of detail, this study applied the texture baking technique [4]. This process projects and "bakes" surface details from the high-poly model into a series of texture maps which are then applied to the low-poly model. Specifically, the normal map is used to simulate complex surface details like carvings and cracks without increasing polygon count, while other texture maps such as specular, normal, and height maps help replicate material properties and surface relief. Thus, the optimized low-poly model is capable of maintaining very high visual fidelity, close to the original model, but with significantly lower computational costs. High detail retention is shown in Figure 19.

Figure 19. Comparison of High Poly and Low Poly Model Details

The leap in performance from 10 FPS to 73 FPS confirms that polygon count is the primary determinant of rendering performance on mobile VR architecture. The retopology process successfully reduced the polygon count by over 99% (from ~1.4 million to ~12,000 polygons per artifact), while the texture baking technique preserved the high-frequency details (such as rock textures and cracks) into the Normal Maps. This result validates that the implemented pipeline effectively balances visual fidelity with computational efficiency, making the digital preservation of Central Sulawesi megaliths accessible on consumer-grade standalone VR devices.

3.3. User Evaluation Results

User evaluation was conducted with 31 respondents (N=31) to measure the quality of user experience (qualitative). User experience quality was measured using a questionnaire with a Likert scale (1 = Strongly Disagree, 5 = Strongly Agree) and open-ended questions. The average results of key statements based on data from 31 respondents are presented in Table 2.

Table 2. User Experience Questionnaire Results (N=31)

Question	Average Score
The VR application helps understand the scale and original size of megalith artifacts.	4.45
The VR experience is more informative compared to just seeing 2D photos or videos.	4.68
I feel as if I am truly at the megalith site location (immersive).	4.39
Navigation and interaction within the VR application are easy to use.	4.45
After using this application, my interest in megalithic cultural heritage increased.	4.45

Average scores above 4.3 in all aspects indicate that the majority of respondents rated the VR application very positively. The highest response appeared in the statement that VR is more informative compared to 2D media (4.68), confirming the superiority of immersive experiences in the context of spatial learning.

In general, users assessed that this application helps understand artifact size and provides an experience as if being at the actual location. Navigation and interaction were rated as intuitive, while the increase in interest towards megalithic culture was also significant. User interaction is shown in Figure 20.

Figure 20. Central Sulawesi Megalith Virtual Reality Respondents

In terms of comfort, 65% of respondents reported experiencing mild physical discomfort such as dizziness or nausea at the beginning of use, while the other 35% did not experience these symptoms. Complaints generally occurred during rapid rotation movements, indicating the need for further optimization in motion control and motion smoothing aspects.

Analysis of open-ended answers showed that the most appreciated features were the ability to interact directly with artifacts (grab/inspect) and the ability to view details and scale up close without having to visit the original site. Some suggestions for improvement include adding narration or interactive information panels, improving camera stability, and refining the initial tutorial to be more easily understood by new users.

3.4. Discussion

Findings from this study demonstrate that the integration of photogrammetry and aggressive 3D asset optimization is a highly effective solution for the digital preservation of cultural heritage on standalone virtual reality platforms. The statistically significant increase in frame rate stability ($t = 18.94$, $p < 0.001$) confirms the initial hypothesis that raw photogrammetry models cause severe computational bottlenecks, and that targeted optimization successfully mitigates this issue. These technical results align with the premise that while Immersive VR (I-VR) is superior for spatial visualization [1], it requires strict performance management to be viable on mobile architectures.

From a technical perspective, the success of the 3D model optimization is the primary factor enabling a comfortable and immersive user experience. By reducing the polygon count by over 99% (from an average of 1.5 million to approximately 12,000 polygons per artifact) and preserving high-frequency visual details through normal map texture baking, the application runs smoothly at an average of 72.28 FPS on the Meta Quest 3. This workflow effectively resolves the hardware limitations that typically hinder high-fidelity photogrammetry in VR, as outlined by Bolognesi & Manfredi [4]. Maintaining a stable frame rate above 72 FPS is critical, as it minimizes visual latency, prevents cybersickness, and allows users to comfortably explore the artifacts.

Furthermore, the high score on the statement "my interest in cultural heritage increased" (score 4.4) indicates that this application functions not only as a knowledge transfer tool but also as a medium capable of evoking emotional engagement and cultural appreciation. This aligns with the findings of Haber et al. [13], which link the level of enjoyment in VR with long-term knowledge retention.

Nevertheless, this study has several limitations. The relatively small sample size of respondents and the testing scope limited to a single session cannot yet measure the impact on long-term knowledge retention. Additionally, the "novelty effect" explained by Hamilton et al. [1] likely still plays a role in the high initial user engagement scores.

4. CONCLUSION

Based on the results and discussion, several conclusions can be drawn as follows:

1. An immersive Virtual Reality application was successfully developed as an alternative digital preservation medium for Central Sulawesi megalith sites, presenting authentic and highly detailed artifact representations on standalone VR headsets.

2. The integration of photogrammetry workflows with aggressive 3D model optimization (retopology and texture baking) proved highly effective. This method successfully reduced the geometric complexity of the raw assets by over 99% while maintaining essential visual fidelity through normal mapping.
3. User evaluation showed a statistically significant increase in knowledge after using the VR application, proving its effectiveness as a learning tool.
4. This application successfully addresses the challenge of limited physical access to megalith sites, providing a practical solution for education and cultural preservation in the digital era.

5. SUGGESTED

For future development, it is suggested to add more artifacts and sites from the three valleys to provide a more comprehensive overview. Additionally, interactive features such as folklore-based narration and artifact function simulations can be integrated to enrich the learning experience. Longitudinal studies could also be conducted to measure long-term knowledge retention.

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