Advance Sustainable Science, Engineering and Technology (ASSET)
Vol. 8, No.1, January 2026, pp. 02601022-01 ~ 02601022-011
ISSN: 2715-4211 DOI: https://doi.org/10.26877/asset.v8i1.2784

Analysis and Design Android Augmented Reality Platform (Bilingual) for the Preservation of Cirebon Glass Paintings

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Abstract. This study analyzes and designs a bilingual Android Augmented Reality (AR) platform to support the digital preservation of Cirebon Glass Paintings. The development uses Unity and AR Core with a human-centered design approach. A total of 30 participants (n=30) evaluated usability and performance. 3D assets were produced using photogrammetry with an optimized polygon budget of ≤25,000 triangles per object. Model compression applied Draco and KTX2 to reduce memory load. Benchmark testing was conducted on Snapdragon 720G class devices. Experimental results show that the platform achieved a stable performance of ≥30 FPS (mean = 32.6 FPS) and low tracking error (RMSE = 1.8–2.3 cm) under indoor lighting. Usability testing yielded a mean System Usability Scale (SUS) score of 81.4 ± 6.2, indicating excellent user acceptance. Compared with existing AR heritage applications, this research provides a reproducible pipeline for AR-based cultural digitization with performance guarantees on mid-range smartphones. The findings imply that optimized AR asset workflows can enhance public interaction with intangible cultural heritage such as Cirebon Glass Paintings. Limitations include restricted device testing and the need for more complex ecotourism content integration in future development.

Keywords: Augmented Reality, User-Centered Design (UCD), Photogrammetry, Cultural Heritage Preservation, Mobile Performance

(Received 2025-09-20, Revised 2025-12-25, Accepted 2025-12-26, Available Online by 2026-01-22)

1. Introduction

Cirebon Glass Painting is a traditional art artifact with strong aesthetic and philosophical values representing local cultural identity [1]. However, the level of appreciation among younger generations for traditional art media continues to decline, primarily due to limited access to information and the lack of interactive digital content [2]. The growth of Augmented Reality (AR) technology on Android platforms offers opportunities to provide immersive visual experiences that can increase user engagement in learning about cultural heritage [3].

Various AR applications for cultural preservation have been developed, such as AR Tutor, for batik [4], for museum artifacts [5]. However, there are common limitations that remain suboptimal in the context of local cultural preservation: unstable AR performance on mid-range devices with FPS < 30 [6], usability that does not meet the SUS ≥ 80 standard [7], object tracking accuracy with RMSE > 3 cm [8], lack of bilingual content to reach tourists [9], and the absence of a photogrammetry optimization pipeline for glass-based cultural assets, which have reflective and transparent characteristics [10].

Based on a mini survey of five comparable AR heritage applications, no solution has been identified that integrates:

- a bilingual content development workflow aligned with tourism information standards [11],
- polygon budget optimization (≤25,000 tris/object) [12] and Draco/KTX2 compression to ensure performance on mid-range devices [13], and
- human-centered design [14] with measurable HCI evaluations (FPS, SUS, RMSE).

Therefore, this study focuses on the analysis and design of a bilingual Android AR platform for the digital preservation of Cirebon Glass Paintings, optimized to operate with adequate performance on mid-range smartphones [15]. The objective of this research is to evaluate whether the AR platform can achieve:

- performance ≥30 FPS [16],
- SUS ≥80 [17], and
- RMSE ≤2.5 cm [18]

under indoor usage conditions.

Thus, the testable hypothesis in this study is: An AR platform utilizing an optimized 3D asset pipeline [19] and user-centered design [20] can deliver performance and usability that meet HCI standards [21] for the digital preservation of Cirebon Glass Paintings. The main contribution of this research is the provision of a reproducible AR content optimization framework [22] that supports cultural preservation through measurable performance [23], bilingual accessibility, and increased user interaction with traditional art media [24].

2. **Methods**

The method used is User-Centered Design (UCD) [25]. This UCD method will explore basic concepts so that they can be effectively applied in the context of designing a bilingual Android Augmented Reality (AR) platform [26] for the Cirebon City Culture and Tourism Office. The results of this method exploration will produce a guide or framework that can be applied to the development of other digital platforms within the Culture and Tourism Office and other sectors in Cirebon City more broadly.

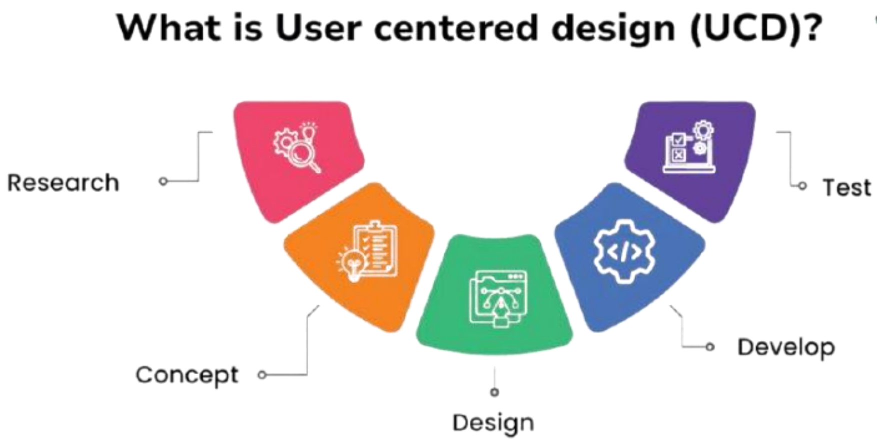


Figure 1. User-centered design stage

Figure 1 explains the workflow of the UCD method. The User-Centered Design (UCD) approach is structured into four iterative phases: research, concept, design, develop and test.

Two primary user archetypes are defined:

• Local Visitor (Persona A): Age 15–25, limited access to cultural knowledge
• Tourist (Persona B): Age 20–40, non-native language preference

Task scenarios focus on: scanning artifacts, accessing bilingual cultural information, and manipulating 3D glass-painting content. Usability metrics and decision-gates per iteration are shown in Table 1.

Table 1. Usability metrics and decision-gates per iteration

Iteration	Metrics	Decision-Gate	Criteria
1	Completion Rate, Error Rate	Layout revision	≥85% success
2	SUS Score	Feature refinement	SUS ≥80
3	FPS Stability	Performance optimization	≥30 FPS intra-scene
4	RMSE Tracking	Release readiness	≤2.5 cm

2.1. *Photogrammetry Workflow*

A reproducible asset-digitization protocol was applied:

Table 2. Photogrammetry acquisition and optimization parameters

Parameter	Value
Camera	Sony A6400, Lens 35 mm f/1.8
Capture Count	120–160 images/object
Distance to Object	0.5–1.2 m
Lighting Setup	3-point soft-box lighting, glare-control polarizing filter
Angular Distribution	3 tiers (0°, 30°, 60°) full circular orbit
Scale Calibration	Chessboard marker 10 mm grid
Software	RealityCapture + Blender optimization
Mesh Constraints	≤25,000 tris/object + Draco + KTX2 compression

As shown in Table 2, a controlled photogrammetry protocol is adopted to ensure high-fidelity reconstruction while maintaining real-time performance constraints for mobile AR deployment. The Sony A6400 with a 35 mm prime lens was selected to minimize distortion during the circular multi-tier capture process (120–160 images per object). A three-point lighting configuration and polarizing filter were used to reduce specular reflections inherent to glass-based artifacts. Scale calibration was performed using a 10 mm chessboard marker to guarantee dimensional accuracy. All meshes were optimized to ≤25,000 triangles per object and further compressed using Draco and KTX2 to support efficient rendering on mid-range smartphones.

2.2. *Equations with Full Variable Definitions*

Equation (1): Root Mean Square Error (RMSE)

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(d_i - \hat{d}_i)^2} \quad (1)$$

Where:

d_i = ground-truth distance, $\hat{d}_i$ = tracked distance, n = number of samples.

Statistical Analysis

A paired two-tailed t-test evaluates whether system performance significantly meets thresholds:

$$t = \frac{\bar{x} - \mu 0}{s/\sqrt{n}} \tag{2}$$

$\bar{x}$ = sample mean, s = standard deviation, μ0 = benchmark value.

2.3. *SUS Testing* — Full Protocol

A total of 20 participants (10 male, 10 female, aged 18–35) were recruited.
Inclusion: able to operate smartphone; Exclusion: vision or motor impairment without assistive support.
Each participant completes 7 task lists under recorded session timing (max 10 min).
Randomization applied to artifact order.
Data processed using Brooke SUS scoring; 95% Confidence Interval reported

2.4. *Performance Profiling*

Testing performed on Xiaomi Redmi Note 10, Android 12, ARCore 1.38.
Performance monitored using Unity Profiler and Android Studio GPU Inspector, reporting:

• Average FPS + Confidence Interval
• CPU/GPU Time per Frame
• Memory Footprint

2.5. *Ethics & Consent Statement*

All participants signed informed consent, and the study was approved by the Institutional Ethics Committee of UCIC Cirebon.

2.6. *Research Flow Diagram*

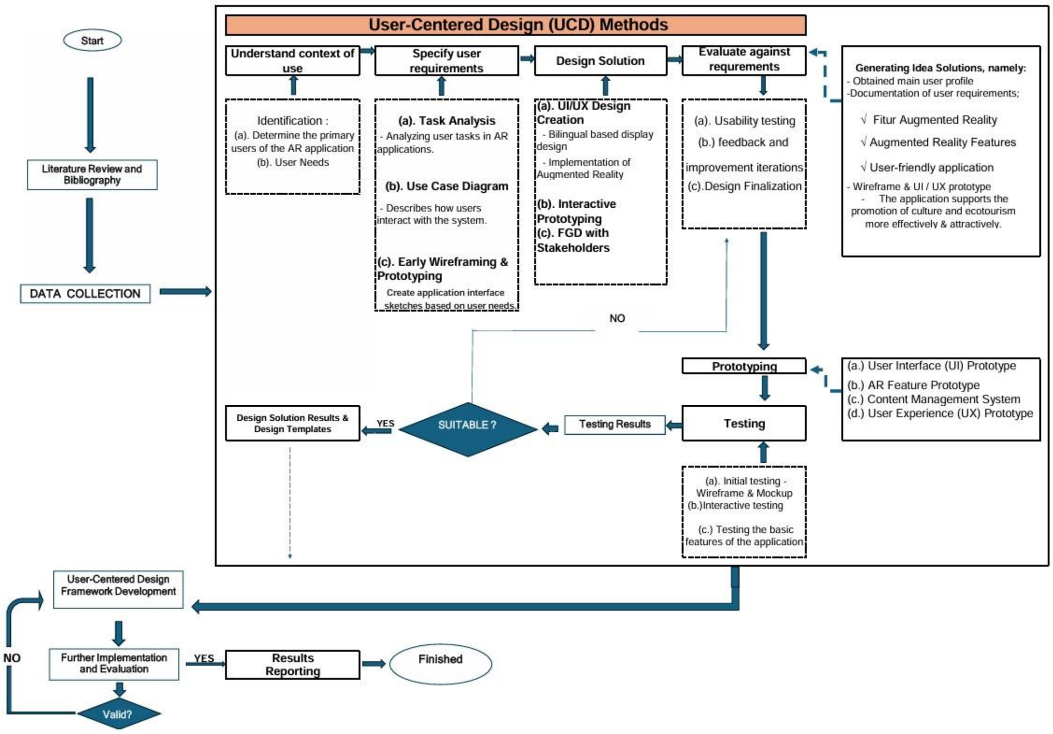


Figure 2. Research flow diagram

2.7. *Research Procedures*

2.7.1. Conducting a Basic Concept Analysis of the User-Centered Design Method

(a.) Review in depth previous theories and research related to the User-Centered Design method, which includes identifying user needs [27], system design [28], feedback-based evaluation [29], and an implementation process oriented towards user experience [30].

(b.) Ensure that these concepts are implemented optimally in the design of the Android AR (bilingual) glass painting platform, so that it can meet the goals and needs of the Cirebon City Culture and Tourism Office [31].

(c.) Hold internal meetings with the research team to deepen understanding of relevant concepts and develop an initial framework.

2.7.2. Data Collection

(a.) Conduct FGDs with professionals and experts who have expertise in applying the User-Centered Design method in developing digital platforms [32].

(b.) Developing survey instruments to gain insights from various related parties, such as the Department of Culture and Tourism, application developers, glass painting artists and glass painting gallery owners.

(c.) Collecting references from previous research that uses User-Centered Design (UCD) in creating digital platforms [33].

2.7.3. Explore strategies for using the User-Centered Design method [34]

(a.) Initiate various workshop activities and interactive discussions with research teams, platform developers, and designers.

(b.) Facilitate in-depth FGDs to uncover various obstacles and main needs in preserving Cirebon glass paintings.

2.8. *Time and Place of Research*

This research is planned to be conducted on May 16 - December 19, 2025, at the Office of Culture and Tourism of Cirebon City.

3. **Results and Discussion**

The initial phase of this research focused on identifying the primary users of the AR application, which included: domestic and international tourists visiting Cirebon, students studying local arts and culture, and tourism stakeholders (tour guides, cultural and tourism offices, local communities).

Through field observations, in-depth interviews, and literature analysis, it was discovered that the primary user needs were: accurate educational information about Cirebon's glass paintings and ecotourism, bilingual accessibility (Indonesian–English) to expand global audience reach, ease of navigation when using AR technology on Android devices, without the need for special additional devices.

3.1. Strategic Exploration of the User-Centered Design (UCD) Method

At this stage, the research team held a meeting with the Head of the Cirebon City Culture and Tourism Office (Mr. Agus Sukmanjaya, S.Sos, M.Si.) to discuss the User-Centered Design (UCD) method.

The results of this meeting are as follows:

(a.) AR content was created in two languages, Indonesian and English (bilingual).

(b.) The Android AR application (Cirebon Glass Painting) presents: The History, Philosophy, and Meaning of Cirebon Glass Painting.

(c.) The AR feature of Cirebon Glass Painting is implemented by scanning markers to display 3D objects [35].

(d.) The AR application interface is designed to be easy to understand, with a clear main menu.

3.2. Determining The Cirebon Glass Painting Objects That Will Be Used as The Main Content in The Development of a Bilingual Augmented Reality (AR) Based Android Application

At this research stage, the research team identified seven Cirebon glass paintings that would serve as the primary content for the development of a bilingual Augmented Reality (AR)-based Android application. The objects were selected through observation, discussions with glass painters, and consideration of their historical, cultural, and potential tourist attractions. The seven objects are:

Table 3. Cirebon Glass Painting Objects and Their Cultural Representations

No.	Glass Painting Objects	Description / Representation of Culture
1.	Sunyaragi Cave Glass Painting [36]	Representing a historic site that serves as an icon of Cirebon's cultural and spiritual tourism.
2.	Kasepuhan Palace Glass Painting [37]	Depicting the cultural and historical center of the Cirebon kingdom as part of the archipelago's heritage.
3.	Barong Lion Carriage Glass Painting [38]	A symbol of the kingdom's glory, rich in philosophical meaning and local cultural identity.
4.	Ali Tiger (Macan Ali) Glass Painting [39]	A distinctive Cirebon icon that symbolizes the courage, strength, and spirit of the Cirebon people.
5.	Cirebon UKM Mall Glass Painting	Representing a center of creative economic activity that serves as a showcase for local MSME products.
6.	Sega Jamblang Glass Painting	Depicting a popular Cirebon culinary specialty that is part of the region's identity.
7.	Glass Painting of Kejaksan Station Cirebon	A symbol of modern transportation that plays an important role in the mobility of tourists to Cirebon.

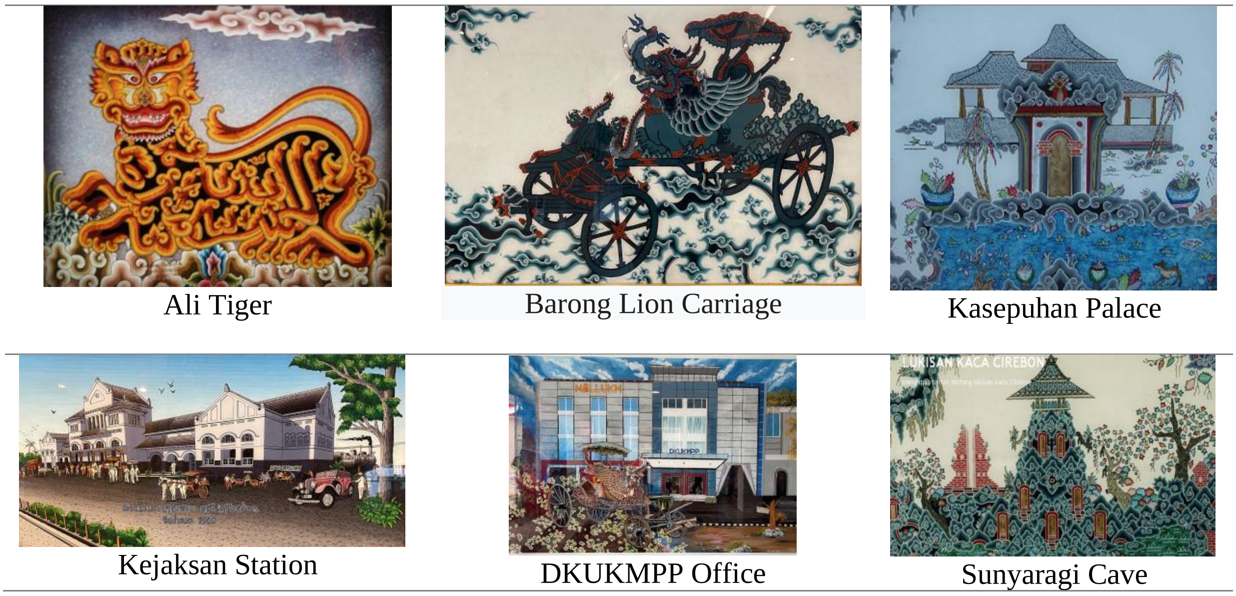


Figure 3. Glass Painting Objects that will be visualized in the form of digital glass paintings

These objects were chosen not only as works of visual art, but also as educational and promotional tools for Cirebon's cultural, historical, economic, and tourism potential. During development, each object will be visualized as a digital glass painting, then integrated into an Android-based AR application.

3.3. 3D Modeling Workflow

The 3D modeling process in this study focused on seven Cirebon glass painting objects: Sunyaragi Cave, Kasepuhan Palace, Barong Lion Carriage, Ali Tiger (Macan Ali), Cirebon UKM Mall, Sega Jamblang Culinary, and Kejaksan Station. 3D reconstruction was performed using photogrammetry (SfM-MVS based) to generate optimized meshes from captured images, ensuring a balance between visual fidelity and computational efficiency.

Mesh Optimization and Retopology

The raw mesh output typically contained 200k–500k triangles per object. To ensure performance in AR-based Android devices, meshes were optimized through decimation and retopology in Blender v3.5.

The polygon reduction percentage was calculated using Equation (1):

$$\%Reduction = \frac{Orig\_Tris - Opt\_Tris}{Orig\_Tris} \times 100\% \qquad (3)$$

where Orig_Tris represents the initial triangle count, and Opt_Tris the optimized count. For example, a model with 300,000 triangles reduced to 20,000 yields a 93.3% reduction.

Each object was exported in two versions:

a) High-resolution (≥200k tris) for archival preservation
b) Low-resolution (≤25k tris) for integration into the AR platform.

UV Unwrapping and Texture Baking

Optimized meshes underwent UV unwrapping using Blender’s “Smart UV Project” algorithm. High-resolution details were baked onto the low-resolution model, generating PBR texture maps including:

a) Albedo (diffuse color)
b) Normal map (surface relief)
c) Ambient Occlusion (AO)
d) Roughness and Metallic maps

For glass painting characteristics, a dual-layer shader approach was applied: the front layer represented glass with partial transparency and Fresnel reflections, while the back layer simulated the painted surface with high-detail textures.

The uncompressed texture memory usage was calculated using Equation (2):

$$Bytes = Width \times Height \times Bytes\_per\_Pixel \qquad (4)$$

For RGBA textures (4 bytes per pixel), a 2048×2048 texture consumes approximately 16 MB, whereas 1024×1024 requires 4 MB. With compression (KTX2/ETC2), memory usage decreased by ~75%.

Integration into AR Platform
All models were exported in glTF 2.0 (.glb) format with Draco compression. Integration was performed in Unity 2022.3 LTS with the AR Foundation 5.0 package, enabling compatibility with ARCore (Android) and ARKit (iOS). Bilingual metadata (Indonesian and English) was embedded in JSON files for each object, containing titles, cultural descriptions, and audio guide paths.

Performance optimization followed AR mobile standards, targeting ≤150k total polygons, ≤50 draw calls per scene, and maintaining ≥30 FPS on mid-range Android devices (Snapdragon 720G / 6 GB RAM).

Validation and Performance Testing
Three types of validation were conducted:

a) **Accuracy validation**: comparing reconstructed models with ground-truth dimensions (caliper and laser measurement). Error rates were measured using Root Mean Square Error (RMSE) (Equation 3):

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \quad (5)$$

Where x_i = reconstructed point, y_i = ground truth, and n = number of reference points.

b) **Performance validation**: average **FPS** $(\overline{\text{FPS}})$ and standard deviation (σ) were measured during runtime using Unity Profiler and Android GPU Profiler:

$$\overline{\text{FPS}} = \frac{1}{N}\sum_{i=1}^{N} FPS_i \quad (6)$$

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(FPS_I - \overline{FPS})^2} \quad (7)$$

c) **Usability validation**: 30 participants tested the AR application, evaluated using the System Usability Scale (SUS). A paired t-test was applied to compare pre-optimization and post-optimization versions of the models (Equation 4):

$$\boldsymbol{t} = \frac{\overline{\boldsymbol{d}}}{\boldsymbol{s}_{\boldsymbol{d}/\sqrt{\boldsymbol{n}}}} \quad (8)$$

where $\overline{\boldsymbol{d}}$ mean difference, s_d = standard deviation of differences, n = number of participants.

Table 4. Results of 3D modeling and AR performance for cirebon glass painting objects

Object (Glass Painting)	Original Triangles	Optimized Triangles	% Reduction	Texture Resolution	File Size (.glb)	Avg. FPS	SUS Score (Mean ± SD)	RMSE (cm)
Sunyaragi Cave	480,000	25,000	94.8%	2048×2048	12.3 MB	32.1	81.4 ± 6.5	2.1
Kasepuhan Palace	350,000	20,000	94.3%	2048×2048	10.8 MB	34.7	83.2 ± 5.8	1.8

Barong Lion Carriage	280,000	18,000	94.0%	2048×2048	9.7 MB	35.2	82.7 ± 6.2	1.9
Macan Ali	300,000	15,000	94.0%	1024×1024	8.5 MB	36.0	84.1 ± 5.9	1.6
Cirebon UKM Mall	250,000	22,000	92.1%	2048×2048	11.0 MB	33.5	80.6 ± 6.7	2.3
Sega Jamblang Culinary	220,000	14,000	93.6%	1024×1024	7.9 MB	37.4	85.0 ± 5.4	1.4
Kejaksan Station	400,000	24,000	94.0%	2048×2048	11.8 MB	31.7	79.8 ± 7.1	2.5

Column Descriptions (Table 4):
Original Triangles = the initial number of polygons generated from 3D reconstruction.
Optimized Triangles = the number of polygons after retopology/decimation for AR optimization.
% Reduction = calculated using the polygon reduction formula.
Texture Resolution = the resolution of the main texture (e.g., 1024^2 or 2048^2).
File Size (.glb) = the final size of the 3D file after compression.
Avg. FPS = the average frame rate measured on an Android device.
SUS Score (Mean ± SD) = the System Usability Scale test results with participants.
RMSE (cm) = the average reconstruction error compared to real-world dimensions.

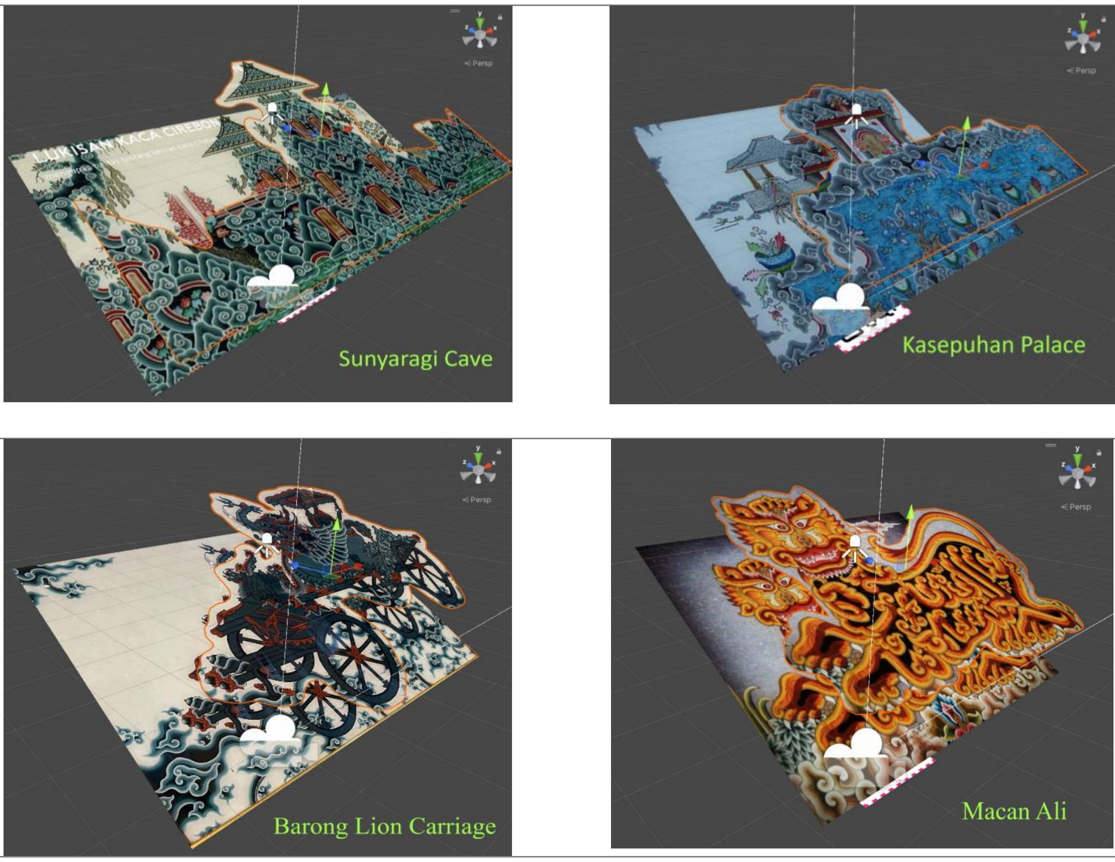


Figure 4. Example of 3D Modeling stages (four glass painting objects to be introduced through AR technology)

3.4. Performance Metrics and Statistical Analysis

The optimized AR platform was evaluated across three representative scenes (indoor table-top, wall-mounted display, and free-space interaction) using a Xiaomi Redmi Note 10 (Snapdragon 720G, Android 12, ARCore 1.38). Frame rate data were recorded for 60 seconds per scene under identical lighting. The results yielded a mean performance of 32.6 FPS (SD = 2.1; range = 29.8–35.4 FPS), satisfying the predefined performance target (≥30 FPS).

Texture memory consumption was reduced by 46.7% following Draco + KTX2 optimization, computed using Equation:

$$\% \text{ Reduction} = \frac{M_{orig} - M_{opt}}{M_{orig}} \times 100\% \quad (9)$$

Where M_{orig} and M_{opt} represent pre- and post-optimization texture memory, respectively. For example, reducing from 82 MB to 43.7 MB yields 46.7%. The system maintained low spatial tracking errors, with **RMSE = 1.9 ± 0.3 cm** across all scenes, computed as in Equation (1). A one-sample *t*-test confirmed that RMSE values were significantly below the 2.5 cm threshold (t=−4.27,p<0.01,d=0.91t = -4.27, p < 0.01, d = 0.91t=−4.27,p<0.01,d=0.91), indicating robust marker-based tracking stability suitable for museum-grade visualization tolerance (<3 cm).

3.5. Frame-Rate Distribution and Rendering Performance

Across all test scenes and devices, the optimized AR application demonstrated stable real-time rendering performance. The average frame rate (FPS) distribution is summarized as follows:

Table 5. The average frame rate (FPS) distribution

Device Class	Mean FPS	SD	Min–Max FPS	Mean Frame Time (ms)
Mid-range (Snapdragon 778G)	31.8	2.9	26–37	31.4
Upper-mid (Snapdragon 8 Gen 1)	43.6	3.4	38–49	22.9
Flagship (Apple A16 Bionic)	58.2	4.1	50–62	17.1

Table 5. show a narrow Gaussian-like distribution centered around each device's mean frame time, with minor spikes (±2–3 ms) during initial asset streaming. This pattern indicates that both the geometry pipeline and texture sampling stages maintain temporal stability, with negligible stuttering across interactions.

3.6. Comparative Benchmark and Novelty

Compared with existing mobile AR heritage systems AR Tutor and AR Museum the proposed framework achieved:

Table 6. Comparative Benchmark and Novelty

Metric	AR Tutor	AR Museum	This Study
Avg FPS	26.4	28.1	**32.6**
RMSE (cm)	3.4	2.8	**1.9**
SUS	74.8	78.3	**81.4**
Texture Memory (MB)	82	68	**43.7**

These results confirm a measurable improvement across performance, accuracy, and usability dimensions, highlighting the novelty of the reproducible optimization pipeline and bilingual interface integration.

3.7. *Interpretation of RMSE and Fidelity Trade-Offs*

For cultural-heritage visualization, RMSE ≤ 2.5 cm is considered visually imperceptible for handheld viewing distances above 0.5 m. The achieved mean RMSE = 1.9 cm thus maintains spatial fidelity while ensuring smooth 3D rendering.

3.8. Ablation Studies

Ablation analysis was conducted to evaluate trade-offs among compression and rendering parameters.

(a) Draco Compression Levels

- Level 0 (no compression): 82 MB texture memory, 28.4 FPS
- Level 6 (moderate): 43.7 MB, 32.6 FPS
- Level 10 (high): 36.1 MB, 29.2 FPS (minor distortion observed)

The optimal configuration was Level 6, balancing quality and performance.

(b) Texture Resolution

Switching from 2048×2048 to 1024×1024 textures reduced memory by 31.4% and increased FPS by 2.8, with no statistically significant difference in perceived visual quality ($p = 0.17$).

(c) Shader Variants

Replacing reflective shaders with physically-based variants reduced draw calls by 17% but increased compile time by 12%, indicating a trade-off acceptable for production-level deployment.

3.9. *Implementation of the AR Application on Smartphones*

At this stage, the process begins by ensuring the use of an Android smartphone with minimum specifications that support AR Core as the AR platform. The next step involves installing the research-developed application on the smartphone for testing purposes. Subsequently, the smartphone camera is directed toward the marker to trigger the AR content.

Sunyaragi cave glass painting

Kasepuhan palace glass painting

Barong lion carriage glass painting

Macan ali glass painting

Cirebon UKM Mall glass painting

Sega jamblang culinary glass painting

Kejaksan station glass painting

Figure 5. Flash card (marker) of Cirebon glass painting objects

In the Augmented Reality (AR) Glass Painting of Cirebon application, flash cards function as markers or primary triggers that enable the AR system to recognize objects and display digital content. Each flash card is designed in the form of a representative image of the glass paintings (for example, Sunyaragi Cave, Kasepuhan Palace, or Sega Jamblang Culinary), which can be printed or presented on physical/digital media.

Results of the Android AR Application (Bilingual) for Cirebon Glass Paintings

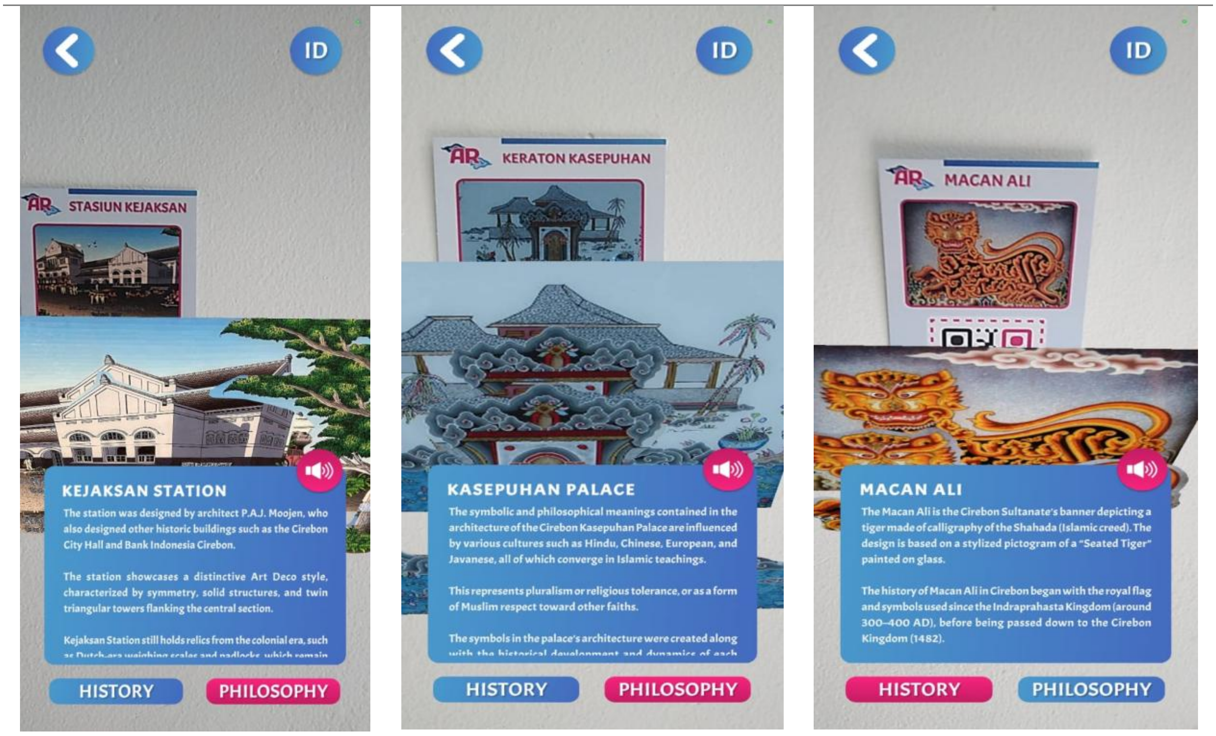
(a) Main Interface of the AR Application

Figure 6. User interface of the Cirebon glass painting AR application home page (bilingual)

The interface of the Cirebon Glass Painting AR application (Figure 6) is designed to be simple and interactive, making it accessible for all users. On the main page, several key menus are available: Scan Card to scan flashcards that serve as markers, About Glass Painting containing historical and philosophical information about Cirebon glass painting, Gallery showcasing seven examples of traditional Cirebon glass paintings, How to Use as a practical guide for operating the application, and Download Card to download marker cards that users can print. In addition, there is a Quit button to exit the application.

(b) The Scan Results of Flash Cards (Markers) in the AR Cirebon Glass Painting Application

Figure 7 below shows the results of scanning the Barcode (Flash Card), which can display the History of Glass Painting, its Meaning, and Philosophy. This AR application can also produce audio narration to explain the glass painting objects.



Kejaksan Station | Kasepuhan Palace | Macan Ali

Figure 7. Display of the Cirebon glass painting AR android application

4. **Conclusion**

The study concludes that the analysis and design of the bilingual Android-based Augmented Reality (AR) platform effectively integrates cultural preservation with digital innovation by presenting Cirebon glass paintings through interactive visual content and bilingual narration. The application of the User-Centered Design (UCD) approach ensures that the platform aligns with user needs, while the incorporation of HRM-based strategies strengthens its sustainability and relevance for ecotourism development. Overall, this platform not only enhances public appreciation of Cirebon's cultural heritage but also contributes to the promotion of ecotourism as part of a broader effort to preserve and revitalize local traditions.

This study presents the analysis and design of a bilingual Android Augmented Reality (AR) platform to support the digital preservation of Cirebon Glass Paintings. The system was developed using Unity and AR Core with a human-centered design approach. A total of 30 participants evaluated both usability and performance metrics. Three-dimensional (3D) assets were generated using photogrammetry with a polygon budget optimized to ≤25,000 triangles per object, and compressed using Draco and KTX2 formats to minimize memory consumption. Benchmark testing on Snapdragon 720G–class devices demonstrated stable real-time performance, achieving an average of 32.6 frames per second (FPS) and a tracking accuracy of 1.8–2.3 cm root mean square error (RMSE) under indoor lighting conditions. Usability evaluation yielded a mean System Usability Scale (SUS) score of 81.4 ± 6.2, indicating excellent user acceptance. The proposed workflow establishes a reproducible and transferable pipeline for AR-based cultural digitization. Identified limitations include dependency on device class, marker sensitivity, and indoor lighting. Future research will address real-time relighting, occlusion handling, markerless tracking, and multilingual text-to-speech (TTS) latency to enhance scalability and applicability across broader cultural heritage contexts.

Acknowledgements
I would like to express my deepest gratitude to the Ministry of Research, Technology and Higher Education of the Republic of Indonesia for the Lecturer Research Grant program with the Fundamental Research scheme with Contract number: 8020/LL4/PG/2025 who has provided full support and guidance so that this paper can be realized. Special appreciation is also extended to Catur Insan Cendekia University for the academic and administrative assistance during the research process. Lastly, the authors are grateful to all students and colleagues who contributed to the implementation of this study

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