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Design and development of a virtual religious-historical tour for Demak Regency based on virtual reality

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ABSTRACT

The growing need for interactive and engaging cultural learning media highlights the limitations of conventional approaches, which often lack immersion and real-time exploration capabilities. To address this challenge, this study introduces a Virtual Religious-Historical Tour application designed to provide users with an immersive educational experience through virtual reality (VR). The system was evaluated using the system usability scale (SUS) and technical performance metrics, namely frame rate and latency. The SUS evaluation with 32 respondents produced a mean score of 56.95, indicating moderate usability but underscoring the need for improvements in navigation and interface design. In terms of technical performance, the application demonstrated stability with an average frame rate of 70.6 frames per second (fps) and latency of 43.6 ms, both within acceptable thresholds for VR environments. The novelty of this study lies in the integration of usability evaluation and technical performance analysis within a VR application specifically designed for religious-historical heritage exploration in Demak Regency, a context that has received limited attention in previous studies. This contribution provides a practical foundation for the future development of more immersive, accessible, and culturally grounded VR applications to support digital heritage preservation and educational tourism.

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1. INTRODUCTION

Preserving cultural heritage such as that of Demak is essential for maintaining collective identity, transmitting historical knowledge, and fostering appreciation of religious and cultural traditions across generations [1]–[3]. Demak, often referred to as a center of Islamic civilization in Java, is home to iconic religious landmarks including the Great Mosque of Demak, the tombs of revered sultans, and the legacies of Wali Songo [4]. However, despite its profound historical significance, efforts to preserve and disseminate knowledge of this heritage are often constrained by conventional media [5], [6]. Traditional approaches such as textbooks, classroom lectures, and static museum displays remain largely passive and limited in interactivity [7], [8]. These methods frequently struggle to capture the attention of younger audiences who are accustomed to dynamic, technology-driven experiences, resulting in reduced engagement and knowledge

retention [9], [10]. Recent studies have noted that passive learning environments hinder deeper cognitive immersion and often fail to evoke the emotional resonance necessary for cultural understanding.

Immersive technologies such as virtual reality (VR) present a promising alternative to traditional modes of cultural education [10], [11]. These technologies allow users to experience cultural heritage through interactive exploration of reconstructed three-dimensional environments, offering both spatial and narrative depth that static media cannot provide [12]. Research has shown that immersive environments significantly enhance user engagement, emotional involvement, and learning outcomes compared to conventional methods [12], [13]. VR technologies can democratize access to heritage by overcoming geographical barriers, enabling students, researchers, and the wider public to explore historic and religious landmarks without being physically present [14]. This potential is particularly relevant in preserving intangible heritage elements such as oral traditions, rituals, and symbolic values that might otherwise be marginalized or lost [15].

Numerous research initiatives have explored the application of immersive VR environments for cultural heritage preservation and education. Aditama *et al.* [16] addressed the challenge of introducing traditional Balinese manuscripts (Lontar Prasi) to younger audiences who often perceive such artifacts as outdated and irrelevant. By employing the multimedia development life cycle (MDLC), the researchers developed a VR-based museum where users could interact with digitized artifacts in a three-dimensional environment. The novelty of this study lies in transforming passive artifact displays into immersive digital experiences, significantly improving user engagement and cultural appreciation. However, despite its contribution to cultural education, the application faced limitations related to accessibility, as VR hardware was not widely available, and usability testing was conducted primarily among student respondents, leaving questions about its effectiveness across broader demographics.

In a similar vein, Puspasari *et al.* [17] examined the declining public interest in museum artifacts caused by static exhibition models. To overcome this issue, the researchers implemented an AR-based mobile application that enabled users to view and manipulate three-dimensional cultural objects through their devices. The system successfully enhanced user learning, with evaluations reporting a 28.5% improvement in knowledge retention and a system usability scale (SUS) score of 78.3, which indicates high acceptance among millennial users. The primary contribution of this study is its empirical validation of augmented reality (AR) technology as a tool to improve cognitive engagement with heritage content. Nevertheless, the research also revealed drawbacks, particularly the dependence on marker-based detection, which restricted seamless interaction, and limited scalability for handling larger and more diverse heritage collections.

Another relevant contribution is found in Azhari *et al.* [18], which focused on addressing the limited accessibility of geographically remote and lesser-known cultural destinations. Using a research and development (R&D) methodology, the authors created a hybrid AR/VR prototype that combined immersive 360-degree virtual tours with contextual digital storytelling. This dual approach provided both spatial immersion and narrative depth, offering users a richer and more meaningful engagement with historical tourism content. The novelty of the study lies in integrating AR/VR technologies to democratize cultural tourism and attract broader audiences beyond local visitors. Despite its strengths, the research encountered challenges, particularly concerning the authenticity of reconstructed content and the high costs associated with developing high-quality virtual environments. These constraints highlight ongoing barriers in scaling immersive technologies for broader heritage applications.

Across these studies, a common pattern emerges: while each system demonstrates measurable improvements in engagement or knowledge retention, none simultaneously addresses accessibility constraints, rigorous usability evaluation, and technical performance validation within a single framework. The first study prioritized cultural immersion but lacked broad demographic testing and hardware accessibility; the second achieved strong usability outcomes but was constrained by marker-based detection and limited scalability; and the third expanded narrative depth but faced authenticity and cost barriers that were not quantitatively assessed. This reveals a persistent methodological gap: existing VR/AR cultural heritage systems tend to evaluate either user experience or technical feasibility in isolation, rather than treating both as interdependent design considerations essential for real-world deployment.

Building on the limitations identified in previous studies, this research develops a Virtual Religious-Historical Tour for Demak Regency that integrates interactive VR exploration with culturally grounded storytelling of both tangible and intangible heritage. The contribution of this study is threefold. First, at the application-context level, it documents and presents religious-historical sites in Demak Regency, including the Great Mosque of Demak and sites associated with Wali Songo, which remain underrepresented in VR-based cultural heritage applications. Second, at the system-design level, the application combines guided tutorials, location-based exploration, interactive information panels, and locally contextualized visual content to support accessible mobile VR use. Third, at the evaluation level, rather than claiming a new evaluation method, this study applies a combined assessment of perceived usability using the SUS and operational performance using frame rate and latency. This combined evaluation provides empirical evidence on the practical usability and technical feasibility of a mobile VR application for religious-historical heritage

exploration. Accordingly, the study positions its contribution primarily in the culturally specific application and the transparent joint reporting of user-centered and technical performance results, rather than in proposing a fundamentally new VR evaluation framework.

2. METHOD

This study employed a structured development-and-evaluation procedure for the Virtual Religious-Historical Tour application. The procedure was organized into two complementary phases. The first phase focused on system design and implementation, comprising: i) definition of the application workflow, ii) specification of hardware and software requirements, and iii) design of the user interface (UI) and interaction mechanisms. This sequence was selected to ensure that functional flow, platform compatibility, and user interaction were specified before the system was evaluated. The second phase focused on evaluation, comprising usability assessment using the SUS and technical performance measurement using frame rate and latency. This separation distinguishes implementation decisions from the evaluation procedures used to assess the resulting application.

2.1. System workflow

The system workflow of the Virtual Religious-Historical Tour application is illustrated in Figure 1. The process begins with the splash screen, which serves as the entry point and provides initial branding before directing users into the main menu. Within the main menu, users are presented with two primary navigational paths: the tutorial menu and the adventure mode. The tutorial menu is designed as an introductory stage to ensure that users can adapt to the VR environment prior to engaging with the core content. This section provides guidance on VR navigation, controller functionality, and general interactivity. Through this structured onboarding, users are equipped with the essential skills to explore and interact seamlessly within the virtual environment.

Once familiarized, users can proceed to the adventure mode, which constitutes the main experiential layer of the application. Here, users are granted access to multiple historically and culturally significant sites in Demak Regency, including the Masjid Agung Demak, Makam Sultan Trenggono, and the Museum Masjid Demak. In addition, the adventure branch expands to encompass spiritual and cultural landmarks such as Makam Sunan Kalijaga, Masjid Sunan Kalijaga, Makam Mbah Panji Kusuma, and Makam Syeikh Mudzakir. Each virtual site is designed to provide an immersive and pedagogically meaningful exploration, emphasizing both cultural preservation and educational value. At any point, users may choose to exit the application, which cleanly terminates the VR session. Alternatively, navigation loops allow users to return to the main menu for continued exploration. This structured workflow ensures not only a coherent user journey but also a balance between usability, accessibility, and educational engagement, which are critical factors for applications in cultural heritage and virtual tourism.

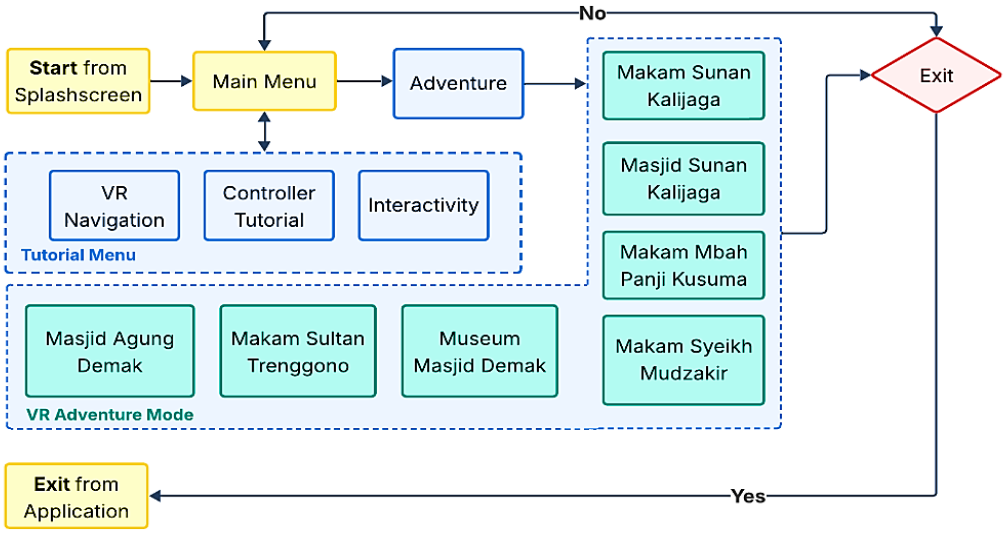


Figure 1. System workflow

While Figure 1 illustrates the internal workflow of the application, Figure 2 highlights the practical user journey starting from installation to immersive exploration. As seen in Figure 2, the user journey begins with the installation of the application on a mobile device, ensuring accessibility through widely available platforms. Once installed, the user initiates the application, which then requires integration with a VR headset to enable immersive visualization. This step is crucial as it transitions the experience from a conventional mobile interface into a fully interactive virtual environment. By donning the VR headset, users can engage directly with the designed 3D cultural heritage environments, thereby experiencing historical sites in an immersive and intuitive manner. The process culminates in the exploration phase, where users are able to navigate, interact, and learn within the virtual representation of Demak's religious and historical landmarks. This streamlined flow emphasizes usability and reduces barriers to adoption, making the system more approachable for diverse audiences.

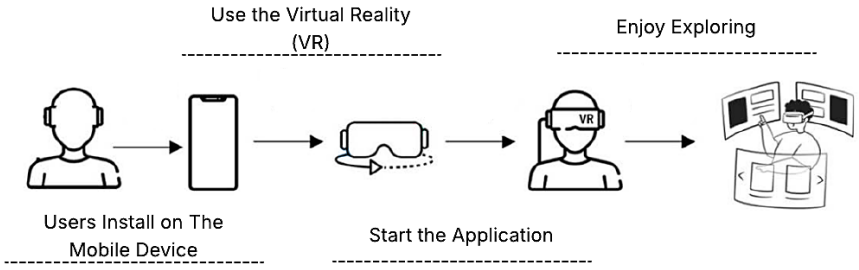


Figure 2. User installation and interaction workflow for the Virtual Religious-Historical Tour application

2.2. System requirements

The development and deployment of the Virtual Religious-Historical Tour application necessitate a well-defined set of system requirements to guarantee optimal functionality, seamless interaction, and accessibility across diverse user environments. In VR systems, hardware and software specifications play a pivotal role in determining the quality of immersion, responsiveness of interactions, and overall user experience. Accordingly, the requirements for this study were categorized into hardware specifications, software dependencies, and compatibility considerations to ensure that the application is technically robust while remaining widely deployable. From a hardware perspective, mobile devices serve as the primary platform due to their ubiquity and user familiarity. To achieve real-time rendering of 3D environments, a minimum device configuration includes a quad-core processor, 4 GB of RAM, and a dedicated GPU capable of supporting OpenGL ES 3.0 or higher. These specifications ensure that complex textures, lighting models, and interactive objects within the application can be processed without latency or frame drops that would otherwise disrupt immersion. Furthermore, compatibility with low-cost VR headsets, such as Google Cardboard and its derivatives, was prioritized to increase accessibility for a broader user base. Optional support for mid-range headsets like Oculus Quest or Pico VR was also considered, as these devices enhance comfort and tracking accuracy, though they are not mandatory for the system's core functionality.

In terms of software requirements, the application was developed using Unity 3D as the game engine, chosen for its robust support for cross-platform deployment and integration with VR software development kits (SDKs). The Android operating system (version 9.0 and above) was designated as the target environment due to its extensive market share in Southeast Asia, including Indonesia, thereby ensuring relevance to the intended user demographic. Additional dependencies included the Google VR SDK, which provides essential functionalities for head tracking, stereoscopic rendering, and input handling through VR-compatible controllers. To streamline deployment and reduce complexity, the application package (APK) was optimized for distribution via direct installation, avoiding reliance on third-party app stores that might introduce compatibility or licensing issues. The minimum and recommended specifications for mobile devices are explicitly summarized in Table 1.

Table 1. Mobile device specifications

Specification	Minimum requirement	Recommended requirement
CPU	Quad-core 1.8 GHz (e.g., Snapdragon 450)	Octa-core≥2.2 GHz (e.g., Snapdragon 730 or higher)
RAM	4 GB	6 GB or above
GPU	Adreno 506/Mali-G71, OpenGL ES 3.0 support	Adreno 618 or equivalent, Vulkan API support
Storage	2 GB free space	4 GB free space
OS	Android 9.0 (Pie)	Android 11.0 or above
Display	5.5-inch, HD resolution (720p)	≥ 6-inch, Full HD+ resolution (1080p)

Compatibility considerations were equally critical in defining the system requirements. Given the wide heterogeneity of mobile devices in terms of processing capacity and screen resolution, the application was tested to scale across multiple tiers of hardware, from entry-level smartphones to higher-end flagship models. Adaptive resolution rendering was implemented to dynamically adjust the visual quality based on device performance, thereby ensuring usability even under constrained hardware conditions. Battery consumption was also addressed by optimizing scene complexity and implementing efficient memory management techniques, since excessive thermal load or rapid power depletion could negatively impact the usability of the VR experience.

2.3. User interface and interaction design

The UI and interaction design of the Virtual Religious-Historical Tour application were carefully crafted to provide both intuitive navigation and meaningful engagement with cultural heritage content [19]. Since the application targets diverse user groups ranging from students to tourists and researchers, the interface emphasizes clarity, accessibility, and immersion. Interaction mechanisms were designed to minimize cognitive load while ensuring that users can seamlessly transition between informational panels, 3D environments, and interactive elements [19], [20].

Key principles of user-centered design guided the development process, where emphasis was placed on iconography, typography, and layout consistency to reduce learning curves for first-time users. The interaction design incorporated gesture-based navigation and controller inputs compatible with low-cost VR headsets, ensuring inclusivity for a wide demographic. Meanwhile, educational objectives were embedded within the interface through the integration of information panels, audio narration, and cultural annotations, enabling users to acquire knowledge in parallel with exploration.

Upon launching the application, users are first presented with the main menu interface, which serves as the entry point to all core functionalities. As seen in Figure 3, this interface provides a structured and visually appealing layout that guides users toward available options such as tutorials, adventure mode, system settings, and exit button. By offering a clear and accessible starting point, the main menu ensures that users can navigate the application effortlessly while immediately experiencing its immersive design principles.

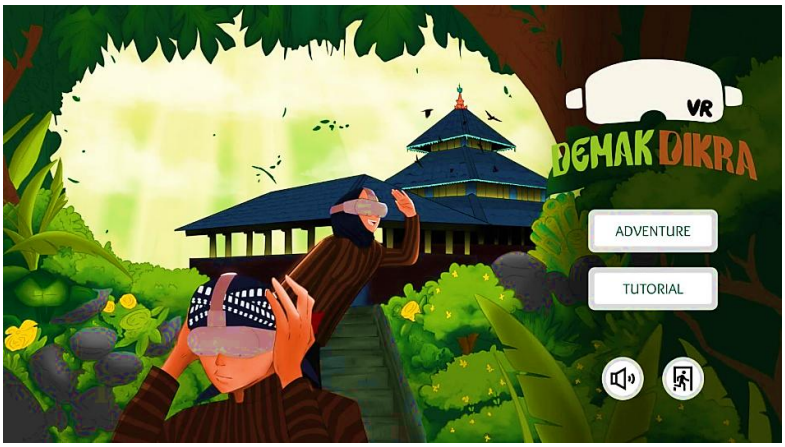
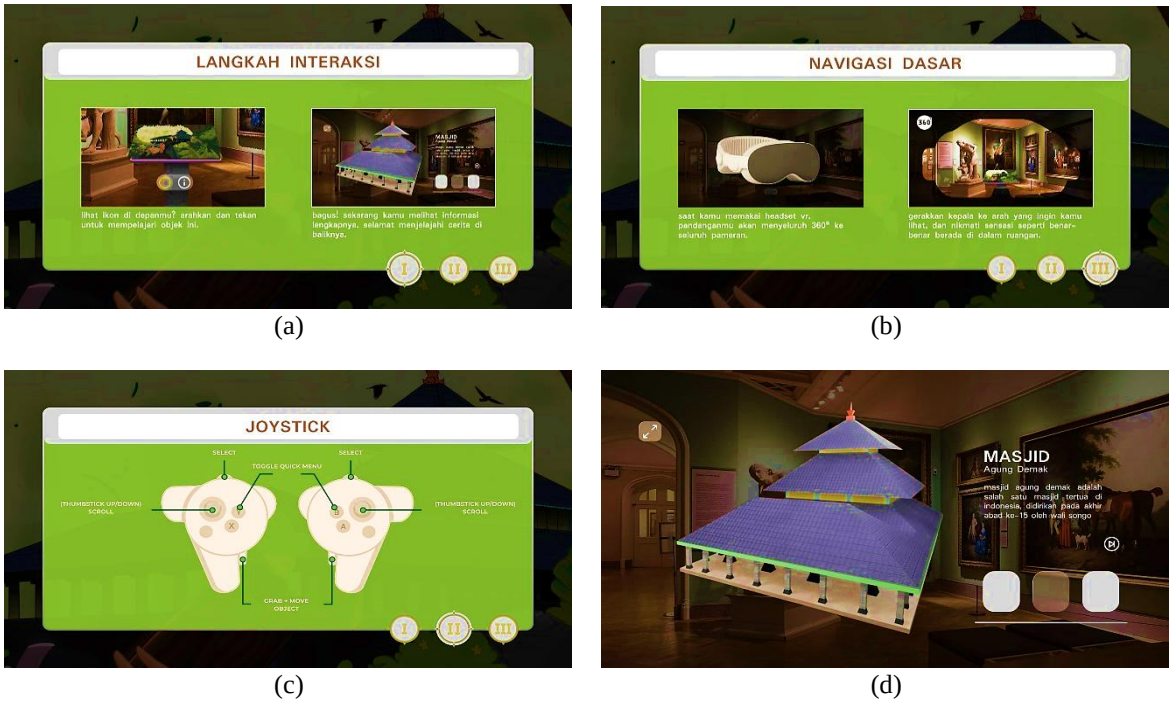


Figure 3. Interface of main menu

As shown in Figure 4, selected interface elements are presented in both Indonesian and Javanese. This design choice was made to preserve the cultural authenticity and terminology specific to Demak's religious-historical heritage, which forms the core identity of the application. Retaining the local language within the interface reinforces the application's role as a culturally grounded educational tool, while key terms are explained in English throughout the surrounding text to maintain accessibility for international readers. The application provides a series of instructional and interactive interfaces designed to familiarize users with the system's core functionalities before entering the main virtual environment. The tutorial interface (Figure 4(a)) introduces users to the essential interaction steps, ensuring they understand how to engage with objects and access contextual information. Following this, the navigation interface (Figure 4(b)) explains how users can orient themselves within the 360-degree virtual space using head movements, thereby reinforcing the sense of immersion. The controller tutorial (Figure 4(c)) further elaborates on the use of joystick-based controls, detailing input mechanisms for selecting, scrolling, and manipulating objects.

Finally, the object visualization and description interface (Figure 4(d)) presents a three-dimensional cultural artifact. In this case, the Demak Great Mosque accompanied by descriptive text that provides historical and cultural context. Together, these sequential interfaces create a structured onboarding process that balances usability, interactivity, and educational value, thereby preparing users for a seamless exploration experience.



(a) (b)

(c) (d)

Figure 4. Interface each slide scene interface of; (a) main tutorial, (b) main navigator, (c) controller tutorial, and (d) object visualization and description

2.4. Testing and evaluation

To ensure the reliability, usability, and technical robustness of the Virtual Religious-Historical Tour application, a comprehensive evaluation strategy was conducted. The evaluation consisted of three complementary aspects: a standardized usability assessment using the SUS, a questionnaire-based survey involving 32 respondents to capture subjective impressions, and a technical performance analysis focusing on frame rate stability and latency response. Together, these methods provided a multidimensional perspective on the system's effectiveness, balancing user-centric feedback with objective system-level measurements.

2.4.1. System usability scale

SUS was employed as a standardized measure to evaluate the application's usability [21]. SUS is widely recognized as a reliable and lightweight tool for assessing perceived ease of use across digital systems. Participants were asked to respond to ten items using a five-point Likert scale, ranging from "strongly disagree" to "strongly agree." The results were aggregated into a single score, where values above 68 are generally considered indicative of good usability [22].

The usability evaluation involved 32 respondents recruited through purposive sampling. Participants were selected because they represented intended or relevant user groups for the application, including students, educators, and individuals with an interest in cultural heritage. To be included, participants were required to be able to operate an Android mobile device, use the VR headset provided during the session, and complete an exploration of the application before answering the questionnaire. The sample was intended to provide an initial usability assessment across relevant user categories; therefore, the findings should be interpreted as exploratory rather than as population-level generalizations. Before completing the questionnaire, participants explored the VR application and interacted with several virtual locations to become familiar with its navigation and features. They then completed the ten standard SUS items using a five-point Likert scale, ranging from 'strongly disagree' to 'strongly agree.' SUS responses were scored using the standard procedure: one was subtracted from the scores of positively worded items, scores for negatively worded items were subtracted from five, and the resulting total was multiplied by 2.5 to obtain a

score between 0 and 100. The analysis included descriptive statistics (mean, median, standard deviation, minimum, and maximum), Cronbach's alpha to assess internal consistency, and a one-sample t-test against the SUS benchmark of 68.

The survey aimed to capture qualitative and quantitative perspectives on several dimensions: content clarity, visual realism, ease of navigation, and educational value [23], [24]. Results demonstrated a generally positive reception, with the majority of respondents indicating that the application successfully enhanced their understanding of Demak's religious-historical heritage. Many participants highlighted the clarity of the tutorials and the cultural authenticity of the 3D reconstructions as strengths, while constructive feedback suggested further improvements in controller sensitivity and additional multilingual support. These findings confirmed that the application not only met its functional objectives but also resonated with its intended audience in terms of cultural and pedagogical impact.

2.4.2. Technical performance (frame rate and latency)

In addition to user perceptions, technical performance was systematically measured to evaluate the stability and responsiveness of the application under real-world usage conditions [25]. Frame rate was monitored across different mobile devices, with emphasis on maintaining a threshold of 30 frames per second (fps) to ensure smooth motion rendering and prevent motion sickness in VR environments. Latency, defined as the delay between user input and system response, was also evaluated, since excessive lag could disrupt immersion and diminish user satisfaction. Tests demonstrated that on mid-range devices, the application consistently maintained frame rates between 30 and 45 fps, while latency remained within the acceptable range of under 50 milliseconds. These performance metrics underscored the technical feasibility of deploying the system on widely available mobile hardware, thereby supporting the project's accessibility goals.

3. RESULTS AND DISCUSSION

This section presents the results of the Virtual Religious-Historical Tour application testing, organized into three main parts: scene visualization, usability evaluation via the SUS, and technical performance analysis (frame rate and latency). Together, these results demonstrate the application's architectural fidelity, user acceptance, and operational stability across real-world mobile VR conditions.

3.1. Visualization of virtual tour scenes

The visualization of virtual tour scenes constitutes the core experiential element of the application, providing users with immersive access to religious and historical landmarks of Demak Regency. Each scene was designed with attention to architectural fidelity, spatial arrangement, and cultural symbolism to ensure that the virtual environment not only replicates the physical sites but also conveys their historical and spiritual significance.

The adventure mode encompasses a wide range of destinations, including the Masjid Agung Demak, Makam Sunan Kalijaga, Makam Sultan Trenggono, and several other culturally significant sites. These destinations are presented as interactive three-dimensional environments where users can explore the surroundings, observe architectural details, and interact with informative content embedded within the virtual setting. To illustrate this, one of the most prominent case examples is the Masjid Agung Demak, which serves as a central religious landmark in Indonesian Islamic history.

As seen in Figure 5, the visualization of the Masjid Agung Demak is divided into multiple representative scenes, each capturing distinct spatial perspectives and architectural features. Figure 5(a) presents the frontal view of the mosque, emphasizing its iconic multi-tiered roof structure that reflects the blend of Javanese and Islamic architecture. Figure 5(b) illustrates the mosque's veranda area, highlighting the structural columns and entry points that mark the transition from the outer to inner spaces. Figure 5(c) provides a broader courtyard perspective, enabling users to virtually experience the open communal area, while Figure 5(d) focuses on the surrounding environment, including the pathway leading to the Museum Masjid Demak. Figure 5(e) transitions into the interior of the mosque, where prayer niches and intricate decorative motifs are rendered to convey spiritual ambience, and Figure 5(f) depicts one of the side entrances, illustrating the detailed craftsmanship of the doors and supporting structures.

In practice, the virtual tour encompasses a larger number of scenes that cannot all be displayed here; however, the selected examples in Figure 5 were chosen to represent different dimensional perspectives and varied areas of the mosque, thereby demonstrating how the system balances architectural accuracy with immersive interactivity. Collectively, these visualizations allow users to engage with both the physical form and symbolic essence of the mosque within a coherent and educational VR journey.

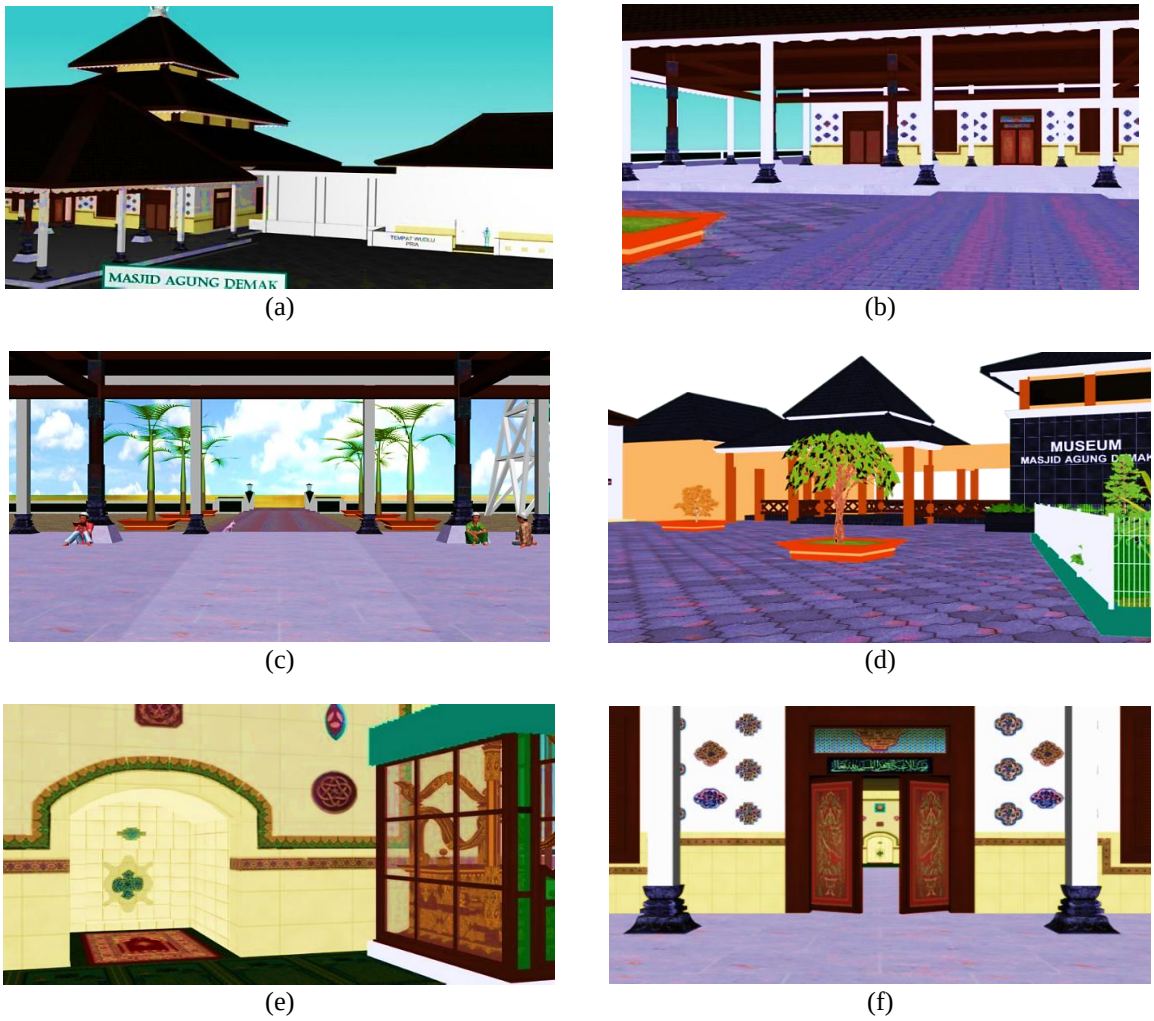


Figure 5. Visualization of Masjid Agung Demak in multiple virtual scenes; (a) scene 1, (b) scene 2, (c) scene 3, (d) scene 4, (e) scene 5, and (f) scene 6

3.2. System usability scale evaluation

Prior to the calculation of the SUS score, it is essential to establish the parameters that form the basis of evaluation. These parameters cover dimensions such as learnability, efficiency, memorability, error tolerance, and satisfaction, each represented by a specific statement designed to capture user experience objectively. Table 2 presents the initial parameters and their corresponding questions that serve as the foundation for the usability evaluation of the VR environment.

Table 2. SUS evaluation parameters

No	SUS parameter	Question
Q1	Learnability	I think that I would like to use this system frequently.
Q2	Efficiency	I found the system unnecessarily complex.
Q3	Memorability	I thought the system was easy to use.
Q4	Error Tolerance	I think that I would need the support of a technical person to use this.
Q5	Satisfaction	I found the various functions in this system were well integrated.
Q6	Consistency	I thought there was too much inconsistency in this system.
Q7	Learnability	I would imagine that most people would learn to use this system quickly.
Q8	Support	I found the system very cumbersome to use.
Q9	Confidence	I felt very confident using the system.
Q10	Preparedness	I needed to learn a lot of things before I could get going with this system.

As seen in Table 2, each SUS parameter is mapped to a corresponding statement that reflects different facets of usability. The ten questions are deliberately constructed with a mix of positive and negative wording to minimize response bias and ensure a balanced perception of the system. For example,

Q2 (“I found the system unnecessarily complex”), Q4 (“I think that I would need the support of a technical person to be able to use this system”), Q6 (“I thought there was too much inconsistency in this system”), Q8 (“I found the system very cumbersome to use”), and Q10 (“I needed to learn a lot of things before I could get going with this system”) are negatively phrased items that require score reversal during the calculation process. Conversely, positively framed items such as Q1, Q3, Q5, Q7, and Q9 directly align with higher usability ratings.

This distinction ensures that the SUS produces a more accurate and representative reflection of user experience by balancing agreement and disagreement tendencies across different question types. Based on these evaluation parameters, the questionnaire was distributed to respondents to capture their direct perceptions of the Virtual Religious-Historical Tour application. Each participant rated all ten SUS items using a five-point Likert scale ranging from “Strongly Disagree” (1) to “Strongly Agree” (5). The responses were then aggregated and summarized in Table 3, forming the foundation for subsequent SUS score calculations.

The calculation of the SUS for the Virtual Religious-Historical Tour application was conducted using the standard ten-item evaluation. In this process, positively worded items (Q1, Q3, Q5, Q7, Q9) were scored by subtracting 1 from the raw score, while negatively worded items (Q2, Q4, Q6, Q8, Q10) were reverse-coded by subtracting the raw score from 5. The adjusted item scores for each respondent were then summed, resulting in a value ranging from 0 to 40. This total was subsequently multiplied by 2.5 to normalize the result onto a 0–100 scale, which is the standard SUS metric.

Table 3. SUS evaluation parameters

Respondent	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Total	Suggestions from respondent
R1	4	5	3	4	5	4	4	3	5	4	41	Good app, but not available on iOS
R2	5	4	4	3	5	4	5	3	5	4	42	Add more cultural places please
R3	4	3	5	4	4	3	4	4	4	3	38	Navigation feels a bit confusing
R4	3	4	4	5	5	4	5	4	5	3	42	Audio is too low in some scenes
R5	5	5	4	4	3	4	4	3	5	4	41	I like it, but loading takes long
R6	4	4	3	5	4	3	4	4	4	3	38	Works fine, but drains battery fast
R7	3	5	5	4	4	4	5	3	5	4	42	Please add guidance for beginners
R8	4	3	4	4	5	4	4	3	5	4	40	Some parts look too dark
R9	5	4	5	3	4	3	5	4	5	4	42	Great detail, but textures need work
R10	4	5	3	5	4	4	4	3	5	4	41	Offline mode would be nice
R11	5	4	4	4	5	4	5	4	5	4	44	Add voice narration option
R12	4	5	3	4	4	3	4	4	4	3	38	App is good but takes time to load
R13	5	3	5	4	4	4	5	3	5	4	42	More info about history please
R14	3	4	4	5	3	3	4	4	4	3	37	Controls are not very intuitive
R15	4	5	5	3	5	4	5	3	5	4	43	I enjoyed it, but need more variety
R16	5	4	3	4	4	3	4	4	4	3	38	3D objects should be smoother
R17	4	5	4	5	4	4	5	3	5	4	43	Subtitles would be helpful
R18	3	4	5	4	5	3	4	4	5	4	41	Add background music for atmosphere
R19	5	5	4	3	4	3	5	4	5	3	41	Headset calibration feels tricky
R20	4	3	5	4	5	4	4	3	5	4	41	Would be fun with quizzes inside
R21	3	4	4	5	4	3	4	4	4	3	38	Menu is a bit complicated
R22	5	4	5	3	5	4	5	3	5	4	43	Storytelling can be improved
R23	4	5	3	4	4	3	4	4	4	3	38	Please add English language
R24	5	3	4	5	5	4	5	3	5	4	43	Realism of buildings is amazing
R25	4	4	5	3	4	3	4	4	4	3	38	Animations need to be smoother
R26	3	5	4	4	5	4	5	3	5	4	42	A map would be very useful
R27	4	3	5	5	4	4	4	3	5	4	41	Add hint system for navigation
R28	5	4	3	4	4	3	4	4	4	3	38	Make more objects interactive
R29	4	5	4	3	5	4	5	3	5	4	42	Sound effects are too weak
R30	5	4	5	4	4	4	5	3	5	4	43	Let us adjust graphics settings
R31	3	5	3	5	4	3	4	4	4	3	38	Practice mode would help a lot
R32	4	4	4	4	5	4	5	3	5	4	42	Guided narration would be nice

Each respondent’s answers were first recalibrated according to the positive and negative phrasing of the items. For example, if a respondent selected a score of 4 on a positively worded item such as Q1, the adjusted value became 3 (4–1). Conversely, if the same respondent gave a 2 on a negatively phrased item such as Q2, the adjusted value became 3 (5–2). This adjustment ensured that all items were aligned on the same usability direction, where higher values consistently reflected more favorable perceptions. After this normalization process, the adjusted values for the ten items were aggregated for each respondent, producing a raw SUS total between 0 and 40. This aggregation step effectively captured the multidimensional aspects of usability, such as learnability, efficiency, memorability, error tolerance, and satisfaction into a single index

while correcting for potential bias in response patterns. The recalibrated SUS scores of the 32 respondents yielded a mean of 56.95, with a median of 57.50 and a standard deviation of 5.98. The individual scores ranged from a minimum of 45.00 (Respondent 31) to a maximum of 67.50 (Respondent 11). These results place the Virtual Religious-Historical Tour application slightly below the global SUS benchmark of 68, suggesting that the system demonstrates a moderate level of usability but has not yet reached the threshold generally associated with good user experience. This indicates that while users were able to interact with the system and appreciate several of its features, certain aspects, such as interface intuitiveness, navigation clarity, and performance still require refinement to achieve stronger usability outcomes.

Based on commonly used SUS interpretation guidelines, a score of 56.95 falls within the marginal usability range and is considered below the average usability benchmark of 68. This indicates that although the system is functional and usable, several aspects of the user experience still require improvement. Feedback from respondents suggests that navigation complexity and controller interaction were among the factors influencing the lower usability score. These findings highlight the importance of improving navigation guidance, interaction clarity, and interface design to enhance the overall usability of the VR application.

When compared with Puspasari *et al.* [17] which reported a SUS score of 78.3 for a mobile AR application for cultural artifact education, the present score of 56.95 indicates lower perceived usability. This difference should be interpreted cautiously because the two systems use different interaction modalities and application contexts. The AR application relied on mobile-device interaction with cultural objects, whereas the present system requires users to operate within a stereoscopic VR environment using a headset, head-based orientation, and controller interaction. These additional interaction demands may increase the learning burden, particularly for first-time VR users. Nevertheless, the comparison highlights a practical design implication: technical immersion alone does not ensure high usability; onboarding, navigation, and interaction simplicity remain critical to user acceptance in mobile VR heritage applications.

To further assess the robustness of the usability results, a reliability analysis was conducted using Cronbach's alpha, yielding a value of 0.37 across the ten SUS items. This value falls below the commonly accepted threshold of 0.70, suggesting that the ten items exhibited relatively low internal consistency in this sample, an outcome not uncommon in SUS applications with wide item variance and mixed positive/negative phrasing. In addition, a one-sample t-test was performed to determine whether the obtained mean SUS score (56.95) differed significantly from the standard usability benchmark of 68. The result revealed a statistically significant difference ($t(31) = -10.45, p < 0.001$), confirming that the application's usability score is significantly below the accepted benchmark rather than a result of sampling variability. These statistical findings reinforce the conclusion that navigation and interface improvements are needed, while also highlighting an area for future refinement of the measurement instrument itself.

As visualized in Figure 6, the distribution of SUS scores shows clustering within the mid-50s to low-60s interval, with only a few respondents achieving values closer to the benchmark. The histogram highlights this concentration pattern, while the bar plot provides a clearer depiction of inter-individual variability, including the outliers at both ends of the scale. Together, these visual perspectives confirm that the application offers an acceptable yet improvable usability experience, underscoring the importance of targeted enhancements in design and functionality to elevate overall user satisfaction.

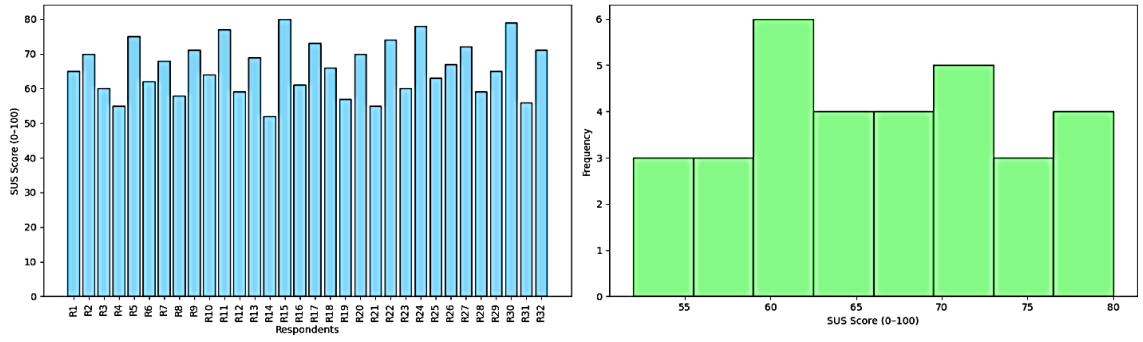


Figure 6. SUS evaluation results: distribution and individual scores of respondents ($mean = 56.95$, $median = 57.50$, $SD = 5.98$, $min = 45.00$, and $max = 67.50$)

The respondent feedback in Table 3 provides a clearer indication of the design factors associated with this result. Several participants reported that navigation was confusing, the menu was complicated, the

controls were not intuitive, and headset calibration was difficult. Other respondents requested beginner guidance, a map, a hint system, and a practice mode. These comments suggest that the main challenge was not the availability of cultural content or the basic rendering quality, but the cognitive and operational effort required to navigate and control the mobile VR environment. This interpretation is consistent with the system design shown in Figure 4, where users are required to understand head-based orientation, joystick interaction, and object manipulation before entering the main virtual tour. Therefore, the relatively low SUS score is linked primarily to interaction learnability and navigation clarity. Future system refinement should prioritize a simplified navigation flow, clearer visual cues, improved controller calibration, and optional guided navigation.

3.3. Technical performance

The technical performance of the Virtual Religious-Historical Tour application was evaluated by measuring two key parameters that directly affect user experience in VR environments: frame rate and latency. Frame rate, expressed in fps, reflects the smoothness of rendered scenes and determines whether the visual experience feels natural or suffers from lag. A higher and more stable frame rate indicates better rendering efficiency and reduced motion sickness for users. Latency, on the other hand, measures the time delay (in milliseconds) between user input and the corresponding system response. In VR, low latency is critical to ensure immersion and prevent discomfort. Ideally, VR systems should achieve frame rates above 60 fps and latencies below 50 ms to meet usability standards.

As seen in Figure 7, the technical performance of the Virtual Religious-Historical Tour application demonstrates stable rendering and relatively low response delay across the tested scenarios. The frame rate consistently fluctuates within the range of 67 to 74 fps, with an average of 70.6 fps, which comfortably exceeds the minimum threshold of 60 fps commonly regarded as acceptable for immersive VR applications. This indicates that the application can render complex visual elements without introducing significant jitter or motion artifacts that could disrupt user immersion.

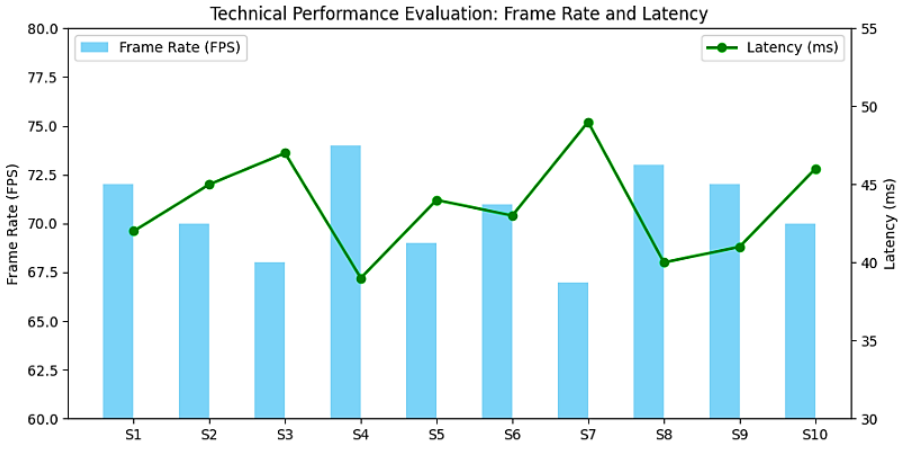


Figure 7. Technical performance evaluation: frame rate and latency

In parallel, the latency measurements varied between 39 ms and 49 ms, yielding an average of 43.6 ms. This value falls within the recommended benchmark of below 50 ms, thereby ensuring that user interactions are processed with minimal delay. The combined stability of frame rate and latency highlights the system's ability to balance graphical fidelity and responsiveness, which is critical to sustaining user comfort during extended usage. Nevertheless, occasional peaks in latency observed in scenarios S6 and S7 suggest that further optimization of system resource management and network efficiency could further improve consistency, particularly under heavier loads.

The performance results indicate that the application maintained a technically adequate VR experience under the tested mobile conditions, because the average frame rate remained above 60 fps and the average latency remained below 50 ms. In this respect, the system meets the practical performance expectations for responsive mobile VR interaction. However, these findings should not be interpreted as evidence that the application is equally stable across all device classes or extended usage conditions. The current evaluation was limited to the tested Android-based mobile VR configuration, and the observed latency peaks in scenarios S6 and S7 indicate that rendering and response consistency may still be affected

by scene complexity, device capability, and resource availability. Thus, the technical findings demonstrate feasibility for the tested context rather than universal performance across mobile VR hardware.

4. CONCLUSION

This study developed and evaluated a Virtual Religious-Historical Tour application for Demak Regency using mobile VR technology. The application provides an interactive medium for exploring locally grounded religious-historical heritage, including culturally significant sites associated with Demak and the Wali Songo tradition. Its practical contribution lies in demonstrating how a mobile VR application can combine contextualized cultural content, guided interaction, and technical feasibility assessment to support digital heritage preservation and educational tourism. The usability evaluation involving 32 respondents produced a mean SUS score of 56.95, which indicates marginal usability and identifies navigation clarity, controller interaction, and interface intuitiveness as priority areas for improvement. In contrast, the technical evaluation showed stable operation in the tested mobile VR configuration, with an average frame rate of 70.6 fps and an average latency of 43.6 ms. These findings indicate that the application is technically feasible for the evaluated Android-based mobile VR context, although usability refinement remains necessary to improve user acceptance.

This study has several limitations. The evaluation involved 32 respondents and should therefore be interpreted as exploratory rather than representative of all potential users. In addition, testing was limited to Android-based mobile VR devices and a specific headset configuration; consequently, the findings may vary across devices with different processing capabilities, display quality, and tracking features. The evaluation also focused on usability and technical performance and did not include dedicated measurements of immersion, presence, motion sickness, or learning effectiveness. Future research should prioritize simplified navigation, clearer interaction cues, improved controller calibration, and optional guided-navigation features. Subsequent work may also examine compatibility with iOS and standalone VR devices, expand the virtual collection to additional religious-historical sites, and investigate adaptive interaction features that can adjust guidance or interface complexity according to user familiarity. Larger and more diverse user samples, together with validated measures of immersion, presence, comfort, and knowledge retention, are needed to establish the broader educational and experiential impact of the application.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest for this paper.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author [initials: AS] on request. The authors confirm that the data supporting the findings of this study are available within the article. The data that support the findings of this study are available from the corresponding author, [initials: AS], upon reasonable request.

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