Asia-Pacific Journal of Information Technology and Multimedia 14(2) 2025: 513 – 524
https://doi.org/10.17576/apjitm-2025-1402-11

Markerless Augmented Reality Application for Interactive Exploration of Melaka's Historical Sites

Eksplorasi Tapak Bersejarah Melaka Secara Interaktif Menggunakan Augmented Reality Tanpa Penanda

Nur Arieza Aziera Izzaty Sulaimana [1], Shafina Abd Karim Ishigaki [2], Fatin Aliah Yahya [2], Che Ku Nuraini Che Ku Mohd [2], Faaizah Shahbodin [2], Nurhafiyah Hazwani Haris Fazillah [3],*

[1]Department of Media Interactive, Fakulti Teknologi Maklumat dan Komunikasi, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal Melaka, Malaysia

[2] Pervasive Computing and Educational Technology, Center for Advanced Computing Technology (C-ACT), Fakulti Teknologi Maklumat dan Komunikasi, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal Melaka, Malaysia

[3] UTM VicubeLab, Faculty of Computing, Universiti Teknologi Malaysia, Skudai, 81310 Johor Bahru, Johor, Malaysia

**Corresponding author: shafina@utem.edu.my*

Received 11 March 2025
Accepted 10 September 2025, Available online 15 December 2025

ABSTRACT

This study aims to identify the technical requirements, develop, and evaluate a markerless augmented reality (AR) application to enhance the exploration of historical sites in Melaka, Malaysia. Utilizing markerless AR technology, the application enables seamless interaction through detailed three-dimensional (3D) models of iconic landmarks without requiring physical markers. Developed using Blender to create accurate 3D models and Unity with the AR Foundation toolkit for AR integration, the application features seven significant sites, including A Famosa, Christ Church, and the Stadthuys, each accompanied by descriptive narratives and audio guides. Designed for Android mobile devices, it leverages AR Foundation's multi-platform capabilities to ensure broad compatibility. Usability and user acceptance were evaluated using the System Usability Scale (SUS) and the Perceived Ease of Use (PEOU) dimension of the Technology Acceptance Model (TAM). A total of 30 users and 3 experts participated in the evaluation, yielding a SUS score of 74.91% (Grade B) and TAM mean scores above 4.0 across all items, indicating strong usability and positive reception. The findings demonstrate the potential of markerless AR in heritage contexts, offering a user-friendly and educational tool for both tourists and local communities. By integrating immersive technology, historical content, and validated usability testing, this study contributes to cultural preservation and provides a scalable model for interactive heritage experiences in the digital era.

Keywords**:** Markerless Augmented Reality; AR Foundation; Culture heritage preservation; Melaka Historical Sites; Location-based AR; Mobile AR applications; Unity; System Usability Scale; Technology Acceptance Model

INTRODUCTION

Augmented Reality (AR) enhances the user's perception of reality by overlaying digital elements onto physical surroundings (Benassi et al. 2020). Positioned within the Reality-Virtuality (RV) continuum in Figure 1, AR intersects with technologies like Extended Reality (XR), Mixed Reality (MR), and Virtual Reality (VR) (Pan 2021). A key feature of AR is its ability to detect and recognize feature points, enabling virtual elements to seamlessly integrate with real-world environments (Syed et al. 2023). Markerless AR, which operates without physical markers, has gained popularity for its flexibility and applicability in outdoor scenarios (Minaee et al. 2022).

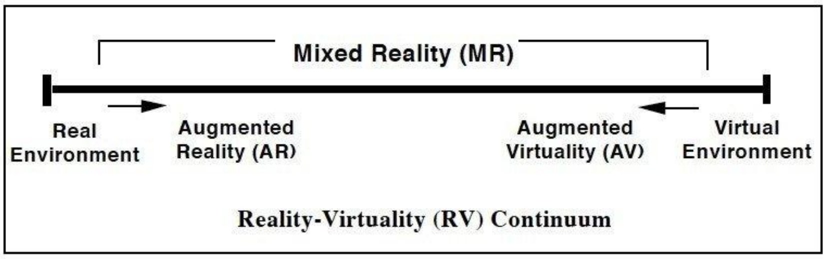

FIGURE 1. RV Continuum

Melaka, a UNESCO World Heritage Site, is celebrated for its historical monuments and cultural richness (Tom Fleming 2021). Preserving and promoting Melaka's historical sites is essential for maintaining its identity and attracting tourists (Jamaludin et al. 2021). However, these sites face challenges from ageing, weathering, and human interference, which treaten their preservation (Abdul Aziz et al. 2023). Conventional approaches, such as static displays and guided tours, often fail to fully engage modern, tech-savy visitors (Telfer and Hashimoto 2024).

AR has emerged as a powerful tool for preserving cultural heritage and enhancing tourism. Yet, many AR heritage applications rely on marker-based systems, which require physical triggers and limit usability in outdoor environments (Allcca-Alarcón et al. 2023). While markerless AR offers greater accessibility and a more seamless experience, it presents technical challenges such as mapping accuracy under varying lighting, occlusion, and feature similarity (Scargill et al. 2023). The lack of innovative and engaging ways to depict cultural assets exacerbates the problem of outdated historical sites, resulting in a lack of interest and involvement among tourists (Ibiş and Çakici Alp 2024). Moreover, most existing heritage AR studies have focused on well-known global sites, with limited research on Malaysian contexts, particularly Melaka. Few have combined markerless AR with formal usability and user acceptance evaluations, leaving a gap in understanding its effectiveness for cultural heritage engagement.

This study addresses these gaps by designing, developing, and evaluating a markerless AR mobile application for the interactive exploration of Melaka's historical sites. The application features accurate three-dimensional (3D) reconstructions of seven iconic landmarks—such as A Famosa, Christ Church, and the Stadthuys—paired with descriptive narratives and audio guides. Developed using Unity with the AR Foundation toolkit and Blender for 3D modelling, the application is designed for Android mobile devices to ensure accessibility. Usability and user acceptance are assessed through the System Usability Scale (SUS) and the Perceived Ease of Use (PEOU) dimension of the Technology Acceptance Model (TAM). By integrating immersive technology, historical storytelling, and validated evaluation, this research not only contributes to cultural heritage preservation but also provides a scalable framework for interactive heritage experiences in similar contexts.

The aims of this study are to: (i) identify the technical requirements for a markerless AR mobile application for cultural heritage exploration, (ii) develop an AR application featuring interactive 3D models of seven Melaka heritage sites, and (iii) evaluate its effectiveness in enhancing user engagement and understanding of Melaka's history.

BACKGROUND STUDY

Augmented Reality (AR) has been widely adopted across fields such as education, gaming, and tourism, offering real-time integration of computer-generated content into the physical environment Itoh et al. (2022). Unlike pre-rendered scenes in films, AR requires active user engagement and real-time scene composition, merging what the user sees with what is happening in their surroundings. Technological advancements in mobile computing, sensor accuracy, and AR algorithms have expanded the potential for AR in outdoor applications, including cultural heritage contexts.

AR tracking techniques generally fall into two categories: marker-based and markerless. Marker-based AR uses fiducial markers or predefined images for object placement, allowing accurate pose estimation without relying on environmental features (Huang et al. 2023). This approach is effective in controlled settings but can suffer from reduced stability under varying lighting or marker occlusion. Markerless AR, also known as location-based or environment-based AR (Koumpouros 2024), uses environmental features and device sensors (gyroscopes, accelerometers, GPS) for tracking and placement. It eliminates the need for physical markers, enabling greater flexibility in outdoor scenarios (Minaee et al. 2022). However, markerless AR is sensitive to environmental factors such as lighting variation, occlusion, and feature similarity, which can affect tracking accuracy (Scargill et al., 2023).

A comparison by Asmara and Fabroyir (2023) outlines key differences between the two approaches based on four key features: tracking method, SDK usage, stability, and hardware support, which are displayed in Table 1. Table 1 shows that Markerless AR utilizes localization technology and gyroscopes to track and place virtual objects within a real-world environment, while marker-based AR relies on fiducial markers or specific picture descriptors. For SDK usage, markerless AR often requires fewer SDKs, relying on advanced frameworks like ARCore, ARKit, or occasionally Vuforia. In contrast, marker-based AR typically depends on specialized SDKs such as Vuforia and ARToolkit.

In terms of stability, markerless AR generally offers a more robust and flexible experience across different environments. Marker-based AR, however, is stable under ideal conditions but may face issues with light variations and marker occlusion. Meanwhile, for hardware support, markerless AR is widely supported on modern mobile devices equipped with advanced sensors like gyroscopes and accelerometers. In contrast, marker-based AR enjoys broader hardware support, extending to various devices, including AR glasses and dedicated AR hardware.

TABLE 1. Comparison Between Markerless AR and Marker-Based AR

Features	Markerless AR	Marker-based AR
Tracking Method	Localization technology and gyroscopes are used to compute relative positions.	Tracks objects using fiducial markers and picture descriptors.
SDK Usage	Often uses frameworks such as ARCore, ARKit, and Vuforia.	Commonly uses SDKs like Vuforia, ARToolkit
Stability	More stable, suitable for a variety of mobile applications.	Stable, but can encounter issues with light variations and marker occlusion.
Hardware Support	Widely supported on modern mobile devices.	Supported on various devices, including AR glasses and dedicated AR hardware

Despite its advantages, markerless AR presents development challenges. Sonia (2024) identifies three common issues: (1) reliance on flat, textured surfaces for object placement, limiting applicability in certain environments; (2) high power consumption, which can deter prolonged use; and (3) performance variations across devices due to hardware differences. Addressing these challenges requires careful optimization of models, textures, and AR tracking algorithms to balance visual fidelity and performance.

In line with the growing interest in integrating AR into heritage and tourism, several applications have been developed to enhance user interaction with historical sites. One such example is a research paper that was conducted by implementing Mobile Augmented Reality (MAR) experiences in large-scale environments by integrating OPEN-V-SLAM with Unity AR Foundation (Torresani et al. 2021). By utilizing sparse reconstructions produced during a preliminary phase, this markerless system minimizes tracking drift and allows for wider localization than conventional marker-based or GNSS/INS-dependent AR techniques. Using dense point clouds and ground truth data, the visual map created by surveying an area is then scaled and aligned for precise AR placement. OPEN-V-SLAM receives live camera data while in use and uses it to maintain accurate AR alignment by returning corrected poses. The system demonstrated its potential to improve cultural heritage experiences without the constraints of current AR frameworks by reducing drift by 51% and successfully superimposing historical content in both controlled indoor settings and real-world heritage sites in Trento and Fiavè. Similar principles of optimizing spatial alignment and interaction in immersive environments have been explored in prior mixed reality telepresence and collaborative interface research (Ishigaki et al., 2022; Ishigaki et al., 2023), which inform the design considerations for markerless AR applications in cultural heritage contexts.

FIGURE 2. MAR experiences in large-scale environments (Torresani et al. 2021)

Another noteworthy example of the reconstruction of cultural heritage in AR's application is the Digital preservation and reconstruction of old cultural elements in AR (Shih et al. 2020). This research explored the use of AR and VR for the digital preservation and promotion of cultural heritage in Lukang, Taiwan. By employing photogrammetry to create 3D models of historical elements and urban fabric, the study enabled interactive situated learning experiences, allowing users to virtually explore and compare cultural contexts. The applications Augment and Sketchfab were utilized on smartphone platforms, making these digital preservation efforts accessible and efficient. The research aimed to enhance cultural sustainability by documenting and recontextualizing heritage, even in cases of demolition or natural disasters, thereby fostering a deeper understanding and appreciation of local identity and history.

FIGURE 3. Digital preservation and reconstruction of old cultural elements in AR (Shih et al. 2020)

Despite facing technical challenges during validation, the study successfully demonstrated the potential of AR/VR in creating immersive and educational experiences for cultural heritage preservation. These examples highlight AR's potential for enriching heritage tourism but also reveal common limitations: dependence on marker-based tracking or indoor environments, lack of scalability to outdoor contexts, and minimal attention to structured usability evaluation. Therefore, this study addresses these gaps by designing, developing, and evaluating a markerless AR mobile application for Melaka's historical sites. The application integrates accurate 3D models, descriptive narratives, and audio guides to enhance both engagement and accessibility. Unlike prior work that focused primarily on technical optimization, this study emphasizes content-driven user experiences validated through empirical usability testing. The outcome contributes not only to cultural preservation efforts but also provides a scalable model for interactive heritage engagement in similar outdoor contexts.

METHODOLOGY

This section outlines the approach taken to achieve the study's first two aims: (i) identifying the technical requirements for a markerless AR mobile application for cultural heritage exploration, and (ii) developing the application featuring interactive 3D models of seven Melaka heritage sites. The process covers key components including tracking implementation, 3D model creation, texture mapping, animation, and user interface (UI) design. The goal is to create an immersive and interactive AR experience that showcases the historical sites of Melaka, thereby enhancing user engagement and learning.

TRACKING TECHNIQUE

In markerless augmented reality, accurate tracking of real-world features is crucial for seamlessly integrating virtual objects into the user's environment. The tracking process ensures that the digital content remains aligned with the user's surroundings, enhancing the immersive experience (Scargill et al. 2021). Figure 4 illustrates the development process of Markerless AR, which ensures precise placement and realistic representation of AR content, particularly for historical sites in Melaka. The process begins with the AR Scene, where a 3D map of

Melaka serves as the focal point, with pick-point locations marking historical sites for user exploration.

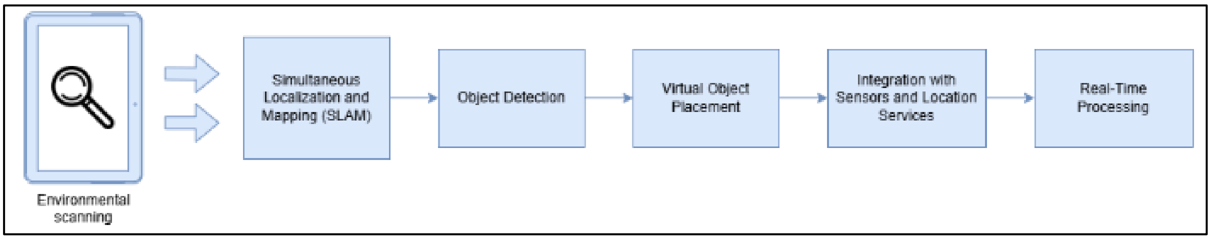

FIGURE 4. Process of Developing Markerless AR

When a pick-point is selected, the system initiates tracking and registration methods. It detects and tracks features in the environment using the device's camera, providing reference points for determining the camera's position and orientation (Ahmadyan et al. 2020). The 3D model of the historical site is then registered to these features, ensuring precise alignment in the user's view. Once registered, the system renders the AR content in real-time, dynamically overlaying the digital representation onto the camera feed. The AR application also provides educational content, such as site descriptions and narration, enhancing the immersive learning experience.

USER INTERFACE (UI)

Next, designing UI is an important part of creating a successful and entertaining markerless AR application (Ghazwani and Smith 2020). A user-friendly UI allows users to interact with the program straightforwardly and efficiently, improving their overall experience and engagement with the content. Figure 5 depicts the expected UI design for the AR application. The main page serves as the entry point for users, while the settings panel allows for adjustments to background sound and sound effects volume. After users select the "Start Exploring" button, they are directed to a second page with two options: the "Virtual Exploration" button, which leads to the AR scene (depicted in the 4th and 5th UI screens), and the "Melaka Tourist Hotspot" button, which takes users to an infographic explaining ten popular tourist hotspots in Melaka (represented in the 6th and 7th UI screens).

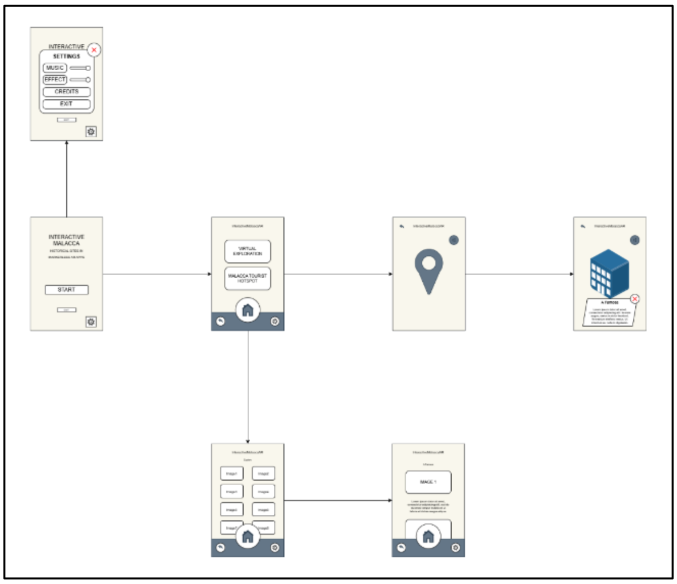

FIGURE 5. Wireframe of UI for the AR Application

CREATION OF 3D MODEL

The development of 3D models for the markerless AR application involves three key processes: designing, texture mapping, and animation. These steps ensure historical accuracy and enhance the immersive experience of exploring Melaka’s heritage sites. The design phase begins with research on historical records, architectural blueprints, and visual references to ensure model authenticity. Initial sketches establish the design concept before transitioning to 3D modeling software such as Blender. The modeling process starts with basic structures and is refined to include intricate architectural details. Optimization techniques are applied to balance visual quality and performance, ensuring smooth integration into the AR environment.

Once the model structure is complete, texture mapping is applied to enhance realism. High-quality textures are generated or sourced to replicate historical materials and surfaces. Using UV mapping techniques, these textures are aligned and scaled for consistency. Adjustments are made to correct distortions and refining properties such as roughness, reflectivity, and color. The final textured models, illustrated in Figure 6, showcase enhanced visual fidelity, improving the AR experience.

FIGURE 6. The 3D models of the Melaka maps

Animation enhances the interactivity of the AR application by simulating movement and dynamic behaviors (Teplá et al. 2022). Keyframe animation techniques define motion sequences, while interpolation ensures smooth transitions between frames. The animated models are then integrated into the AR system and tested for seamless playback and user interaction. Figure 7 illustrates keyframes applied to the 3D model, demonstrating the animation process.

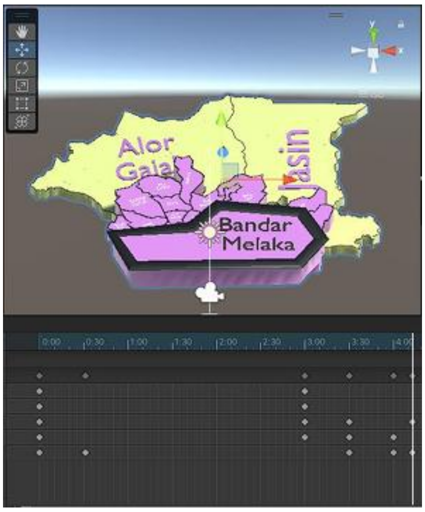

FIGURE 7. Keyframe animation applied to the 3D model

By integrating these processes, the AR application delivers an engaging and realistic exploration of Melaka's historical sites. The combination of optimized modeling, accurate texturing, and dynamic animation enhances the user experience, making cultural heritage more accessible and interactive.

RESULTS

The Markerless Augmented Reality Application for Interactive Exploration of Melaka's Historical Sites successfully integrates augmented reality (AR), an intuitive user interface (UI), and interactive 3D models to provide an immersive experience in exploring historical sites. The application enables users to visualize seven historical buildings in AR without requiring physical markers. Through markerless tracking, users can place virtual models in their surroundings, adjust their positioning, and explore detailed structures of each historical site.

The user interface is designed to be accessible and easy to navigate, allowing seamless interaction with the 3D models. Users can select historical sites, manipulate the models through rotation and zooming, and access additional information about each location. The AR tracking system ensures stable and accurate placement of the 3D models, enhancing user engagement and interaction. Figure 8 illustrates the user interface of the application, including the home page, menu selection, and AR tracking for historical buildings in 3D. The application has been tested across multiple mobile devices, ensuring compatibility and smooth performance across different hardware configurations.

FIGURE 8. User Interface (UI) of the mobile application

To address the final aim of the study—evaluating the application's effectiveness in enhancing user engagement and understanding of Melaka's history—a formal evaluation was conducted using the System Usability Scale (SUS) and the Technology Acceptance Model (TAM). Two types of testing were performed: user testing with 30 participants and expert testing with 3 AR and heritage specialists. Both groups completed structured SUS and TAM questionnaires, while experts also responded to open-ended questions to provide additional feedback.

Table 2 summarizes the results of the SUS-based usability questionnaire. Participants gave high ratings in ease of use (M = 4.47, SD = 0.68) and learning speed (M = 4.60, SD = 0.67), with an overall SUS score of 74.91%, graded B, indicating an acceptable and user-friendly system. While users were generally satisfied, the feedback also suggested opportunities to improve interface clarity and support for independent use.

TABLE 2. Mean and standard deviation for usability questionnaire (user testing)

No	Statements	Mean	SD
1	I would like to use this system frequently.	4.40	0.77
2	The system is straightforward and easy to understand.	3.73	1.05
3	The system was easy to use.	4.47	0.68
4	I can use this system independently without needing technical support.	3.63	1.16
5	Various functions in this system were well integrated.	4.30	0.87
6	The system is consistent and reliable.	3.93	1.01
7	Most people would learn to use this system very quickly.	4.60	0.67
8	The system is easy to manage and user-friendly.	3.87	1.14
9	I felt very confident using the system.	4.33	0.93

Table 3 presents the TAM-based user acceptance data. All five statements scored above 4.0, reflecting a strong agreement with the application's ease of learning, interaction flexibility, and clarity. These results demonstrate the prototype's high level of acceptance and indicate that the interface design and feature integration successfully promote user engagement.

TABLE 3. Mean and standard deviation for user acceptance questionnaire (user testing)

No	**Statements**	**Mean**	**SD**
1	Learning to operate the AR apps would be easy for me.	4.30	0.94
2	It is easy to get the AR apps to do what I want it to do.	4.23	0.92
3	My interaction with the AR apps would be clear and understandable.	4.10	0.93
4	I found that the AR apps were flexible to interact with.	4.23	0.94
5	I found that the AR apps are easy to use.	4.33	0.93

The expert evaluation supported these findings and emphasized the application's potential in cultural education and tourism. Recommendations from experts focused on refining visual design, simplifying the UI layout, and expanding multilingual support for broader accessibility.

CONCLUSION

This study achieved its three aims by (i) identifying the technical requirements for a markerless AR mobile application for cultural heritage exploration, (ii) developing an application featuring high-fidelity 3D reconstructions, historical narratives, and audio guides for seven Melaka heritage sites, and (iii) evaluating its effectiveness in enhancing user engagement and understanding of Melaka's history. By leveraging Blender for model creation and Unity with AR Foundation for AR integration, the application offers an accessible, location-based heritage experience without the need for physical markers.

The evaluation using the System Usability Scale (SUS) and the Perceived Ease of Use (PEOU) dimension of the Technology Acceptance Model (TAM) yielded a SUS score of 74.91% (Grade B) and TAM mean scores above 4.0, confirming strong usability and positive user reception. These results not only validate the application’s effectiveness but also provide empirical evidence supporting the use of markerless AR in cultural heritage contexts.

Theoretical implications include demonstrating how markerless AR can be integrated with user experience frameworks (SUS, TAM) to assess engagement in outdoor heritage settings, contributing to the broader understanding of AR usability in real-world tourism applications. Research implications highlight the importance of combining technical AR development with structured evaluation methods to create scalable models for other heritage sites, particularly in regions with similar environmental and infrastructural conditions. Practical implications suggest that tourism boards, educators, and cultural institutions can adopt and adapt this application to promote heritage education, enrich tourist experiences, and support preservation initiatives.

Future work will focus on enhancing accessibility features, integrating adaptive content based on user profiles, and conducting longitudinal field studies to examine sustained engagement and learning outcomes. By combining technological innovation with heritage preservation, this project provides a foundation for future AR applications that bridge cultural education and tourism in the digital era.

ACKNOWLEDGEMENT

The development of this study was made possible through the support and resources provided by Universiti Teknikal Malaysia Melaka (UTeM). We extend our sincere gratitude to UTeM for its continuous guidance, research facilities, and platform that enabled the successful completion of this project. Special appreciation is also given to our colleagues and faculty members who have contributed valuable insights and support throughout the development process. Their encouragement and constructive feedback have been instrumental in refining the study.

REFERENCES

A. Torresani, S. Rigon, E M Farella, F Menna, and F. Remondino. 2021. “Unveiling Large-Scale Historical Contents with V-Slam and Markerless Mobile Ar Solutions,” 46:761–68. International Society for Photogrammetry and Remote Sensing. https://doi.org/10.5194/isprs-Archives-XLVI-M-1-2021-761-2021.

Adel Ahmadyan, Tingbo Hou, Jianing Wei, Liangkai Zhang, Artsiom Ablavatski, and Matthias Grundmann. 2020. “Instant 3D Object Tracking with Applications in Augmented Reality,” http://arxiv.org/abs/2006.13194.

Akmal Zaki Asmara, and Hadziq Fabroyir. 2023. “Marker vs. Markerless: Usability Insights for Indoor Navigation with Handheld Augmented Reality Systems,” 40–45. https://doi.org/10.1109/ICTS58770.2023.10330861.

Allcca-Alarcón, Luis, Jorge Calagua-Montoya, Orlando Iparraguirre-Villanueva, and Michael Cabanillas-Carbonell. 2023. “Augmented Reality as an Option to Enhance the Tourism Experience - a Review.” *International Journal of Engineering Trends and Technology* 71, no. 4 (April 2023): 190–202. https://doi.org/10.14445/22315381/IJETT-V71I4P217.

Aziz, Abdul, Noor, Nor Atiah Ismail, and Anuar Alias. 2023. “Community Participation in the Importance of Living Heritage Conservation and Its Relationships with the Community-Based Education Model towards Creating a Sustainable Community in

Melaka UNESCO World Heritage Site.” *Sustainability (Switzerland)* 15, no. 3 https://doi.org/10.3390/su15031935.

Benassi, A, A Carboni, S Colantonio, S Coscetti, D Germanese, B Jalil, R Leone, et al. 2020. “Augmented Reality and Intelligent Systems in Industry 4.0.” ARTES 4.0 Webinar. http://si.isti.cnr.it https://hal.science/hal-03018976.

Fleming, Tom. 2021. “Bandaraya Melaka Melaka Tom Fleming / Creative Consultancy Cultural Cities Profile East Asia,”. http://tfconsultancy.co.uk.

Huang, Qiangqiang, Joseph DeGol, Victor Fragoso, Sudipta N Sinha, and John J Leonard. 2023. “Optimizing Fiducial Marker Placement for Improved Visual Localization,” March. http://arxiv.org/abs/2211.01513.

Ibiş, Ali, and Neşe Çakici Alp. 2024. “Augmented Reality and Wearable Technology for Cultural Heritage Preservation.” *Sustainability (Switzerland)* 16, no. 10 (May 2024): 4007. https://doi.org/10.3390/su16104007.

Ishigaki, S. A. K., Ismail, A. W., & Kamruldzaman, M. Q. 2022. MR-MEET: Mixed reality collaborative interface for HMD and handheld users. In 2022 IEEE Global Conference on Computing, Power and Communication Technologies (GlobConPT) (pp. 1-7). IEEE.

Ishigaki, S. A. K., Ismail, A. W., Halim, N. A. A., & Suaib, N. M. 2023. Voice commands with virtual assistant in mixed reality telepresence. In International Conference on Advanced Engineering, Technology and Applications (pp. 148-158). Cham: Springer Nature Switzerland.

Itoh, Yuta, Tobias Langlotz, Jonathan Sutton, and Alexander Plopski. 2022. “Towards Indistinguishable Augmented Reality.” *ACM Computing Surveys* 54, no. 6 (July 2022). https://doi.org/10.1145/3453157.

Jamaludin, I S, T W Seow, S Mat, S Mohamed, and M A Abas. 2021. “Conserving Living Heritage Site in Portuguese Settlement, Melaka World Heritage Site: Issues and Conservation Elements,” Vol. 842. https://doi.org/10.1088/1755-1315/842/1/012056.

Milada Teplá, Pavel Teplý, and Petr Šmejkal. 2022. “Influence of 3D Models and Animations on Students in Natural Subjects.” *International Journal of STEM Education* 9, no. 1 https://doi.org/10.1186/s40594-022-00382-8.

Pan, Yongming. 2021. “VR Reality of the Relationship between Augmented Reality and Virtual Reality in the Context of Virtual Reality,” Vol. 2066. IOP Publishing Ltd. https://doi.org/10.1088/1742-6596/2066/1/012056.

Scargill, Tim, Jiasi Chen, and Maria Gorlatova. 2021. “Here to Stay: Measuring Hologram Stability in Markerless Smartphone Augmented Reality”. http://arxiv.org/abs/2109.14757.

Scargill, Tim, Sangjun Eom, Ying Chen, and Maria Gorlatova. 2023. “Ambient Intelligence for Next-Generation AR”. http://arxiv.org/abs/2303.12968.

Shervin Minaee, Xiaodan Liang, and Shuicheng Yan. 2022. “Modern Augmented Reality: Applications, Trends, and Future Directions”. http://arxiv.org/abs/2202.09450.

Shih, Naai Jung, Hui Xu Chen, Tzu Yu Chen, and Yi Ting Qiu. “Digital Preservation and Reconstruction of Old Cultural Elements in Augmented Reality (AR).” *Sustainability (Switzerland)* 12, no. 21 (2020). https://doi.org/10.3390/su12219262.

Sonia, Schechter. 2024. “The Ultimate Guide to Markerless Augmented Reality.” MarxentLabs, https://www.marxentlabs.com/what-is-markerless-augmented-reality-dead-reckoning/.

Syed, Toqeer Ali, Muhammad Shoaib Siddiqui, Hurria Binte Abdullah, Salman Jan, Abdallah

Namoun, Ali Alzahrani, Adnan Nadeem, and Ahmad B Alkhodre. 2023. “In-Depth Review of Augmented Reality: Tracking Technologies, Development Tools, AR Displays, Collaborative AR, and Security Concerns.” *Sensors* 23, no. 1. https://doi.org/10.3390/s23010146

Telfer, David J, and Atsuko Hashimoto. 2024. “Looking Forward via Historic Travel and Looking Back via Heritage Tourism: An Analysis of Roads, Mobility and Imagination of Place along the Tōkaidō Road in Edo Period, Japan.” *Journal of Tourism History* 16, no. 1 : 1–31. https://doi.org/10.1080/1755182X.2023.2283430.

Yahya Ghazwani, and Shamus Smith. 2020. “Interaction in Augmented Reality: Challenges to Enhance User Experience,” 39–44. Association for Computing Machinery. https://doi.org/10.1145/3385378.3385384.

Yiannis Koumpouros. 2024. “Revealing the True Potential and Prospects of Augmented Reality in Education.” *Smart Learning Environments* 11, no. 1. https://doi.org/10.1186/s40561-023-00288-0.