SHM PUBLISHER
SURYA HIJAU MANFAAT

Journal of Soft Computing Exploration

Homepage: https://shmpublisher.com/index.php/joscex

JOSCEX

p-ISSN: 2746-7686
e-ISSN: 2746-0991

.

Comparative study of marker-based and markerless tracking in augmented reality under variable environmental conditions

Mulia Sulistiyono[1], Jaka Wardana Hasyim[2], Bernadhed[3], Febri Liantoni[4], Acihmah Sidauruk[5]
[1,2]Department of Informatics, Amikom Yogyakarta University, Yogyakarta, Indonesia
[3]Department of Information Technology, Amikom Yogyakarta University, Yogyakarta, Indonesia
[4]Department of Informatics and Computer Engineering Education, Universitas Sebelas Maret, Surakata, Indonesia
[5]Department of Information Systems, Amikom Yogyakarta University, Yogyakarta, Indonesia

Article Info

Article history:

Received Dec 2, 2024
Revised Dec 17, 2024
Accepted Dec 20, 2024

Keywords:

Augmented Reality,
Marker-Based Tracking,
Markerless Tracking,
Environmental Factors,
Distance, Angle, and Lighting Indicators

ABSTRACT

Augmented reality (AR) technology integrates virtual content into real environments using two main methods: marker-based and markerless tracking. Marker-based tracking relies on printed markers for object placement, while markerless uses environmental features for flexibility and accuracy. This research aims to evaluate the combined impact of environmental factors-distance, angle, and lighting-on these two methods. The Multimedia Development Life Cycle (MDLC) methodology was applied by testing 72 combinations of indicators: distance (5-120 cm), angle (30°, 45°, 90°), and light color (red, blue, green, yellow) using Xiaomi Note 8 and Google Pixel 4. Results show markerless tracking is superior in all conditions, achieving a 94.4% success rate on both devices. In contrast, marker-based tracking only achieved 72.2% (Xiaomi Note 8) and 77.8% (Google Pixel 4). Markerless tracking was optimally performed from 50 cm away and up close, while marker-based tracking degraded in performance at long distances and red lighting. Markerless tracking proved to be more reliable and consistent, suitable for dynamic and diverse environments, while marker-based methods remained relevant for short distances and controlled lighting. These findings provide guidance for AR developers in choosing a tracking methodology according to application needs.

Corresponding Author:

Mulia Sulistiyono,
Department of Informatics,
Amikom Yogyakarta University,
Jl. Ring Road Utara, Condong Catur, Sleman, 55283, Yogyakarta, Indonesia.
Email: muliasulistiyono@amikom.ac.id
https://doi.org/10.52465/joscex.v5i4.503

1. INTRODUCTION

In this day of highly complex and quick technological progress, the integration of virtual information with the natural environment, or what is popularly called augmented reality (AR) [1], [2], is more widespread. Technically, augmented reality consists of multimedia, 3D modeling, real-time tracking, registration, sensors, and others [3], [4]. The central premise of augmented reality (AR) is to apply computer-generated visual interaction, such as inserting information in the form of text, photos, 3D models, music, movies, etc, into the real environment after being simulated [5]. In this approach, it is possible for both types of information between the actual and virtual worlds to complement each other to bring information enhancements to the real world [6], [7].

More and more research institutes, universities, and companies have investigated augmented reality and published numerous studies that illustrate its potential as a tool for human-computer interaction. With advancements in computer software and hardware, augmented reality has evolved from a laboratory concept into industrial applications, acting as a bridge between the digital and natural worlds [8], [9]. Tracking in augmented reality is a critical component and can be categorized into two main types: marker-based and markerless tracking [10]. Marker-based tracking relies on specific visual markers, such as two-dimensional patterns or black-and-white illustrations with a white background and heavy black borders or lines, which are detected by a camera connected to a computer [11], [12]. However, its performance is affected by environmental factors. For instance, studies have shown that marker-based tracking performs optimally within a range of 15 to 25 cm but is significantly influenced by light intensity, where brighter light enhances marker visibility and ensures accurate tracking [13]. Its effectiveness also decreases when the viewing angle deviates from the ideal position, impacting the stability of AR object placement [14].

On the other hand, markerless tracking does not rely on predefined markers but instead leverages environmental features, such as the device's location, direction, or place, to display 3D objects [15]. This approach offers greater flexibility, as it demonstrates superior accuracy at greater distances, achieving 93% accuracy at up to 150 cm compared to 83.3% for marker-based tracking [16]. Additionally, markerless tracking is more resilient to variations in viewing angle [17] and less dependent on lighting conditions, making it highly adaptable for diverse environments [18]. This research addresses the lack of a holistic evaluation of marker-based and markerless tracking methods considering multiple environmental factors (distance, angle, and lighting color) and hardware variations. By analyzing these variables collectively, this study seeks to determine which tracking method performs more reliably and effectively for AR applications. This research is significant for the continued development of AR technologies as the demand for more robust and adaptive AR systems grows. Industries increasingly require AR solutions capable of functioning seamlessly in dynamic, real-world conditions where lighting, distance, and user perspectives are unpredictable. Understanding the limitations and strengths of marker-based and markerless tracking methods will provide AR developers and stakeholders with valuable insights for designing better AR experiences, optimizing system performance, and selecting appropriate tracking methodologies based on specific use cases. In this study, the performance of marker-based and markerless methods is tested systematically under controlled conditions using a combination of variables-distance, angle, and lighting color-across two devices: Xiaomi Note 8 and Google Pixel 4. This approach enables a comprehensive comparison that addresses gaps in prior research and offers recommendations for future AR applications.

2. METHOD

This research utilizes the Multimedia Development Life Cycle (MDLC) method, which provides a structured approach for developing and testing AR applications. The MDLC method was chosen due to its flexibility and effectiveness in multimedia application development, especially for AR systems, which integrate visual, spatial, and interactive components. By breaking down the development process into stages, MDLC allows systematic testing of marker-based and markerless methods under different environmental conditions. The methodology comprises six stages: concept, design, material collecting, assembly, testing, and distribution. Each stage is outlined below as shown in Figure 1, and its role in the study is explained.

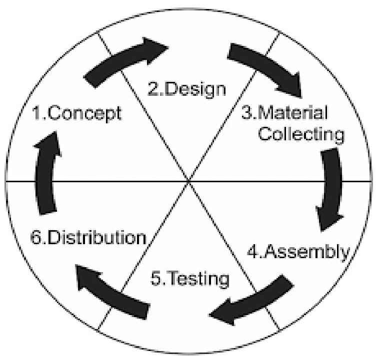

Figure 1. MDLC method [18]

Concept

.

At this stage, the research objectives and relevant research indicators are determined. This research compares marker-based and markerless tracking methods under different environmental conditions (distance, angle, and lighting color) using two smartphone devices (Xiaomi Note 8 and Google Pixel 4). This step serves as the initial stage before designing the creation of augmented reality applications, which aims to determine the purpose of the application through literature study and selection of research objects [19].

In the literature review, it provides a theoretical basis for understanding marker-based and markerless tracking methods. Existing research mainly focuses on one or two indicators, such as distance or lighting intensity [10]–[13]. However, the holistic evaluation of multiple indicators under different hardware specifications has not been explored in detail. This research fills this gap by testing combinations of distance, angle, and lighting conditions as shown in Table 1.

Table 1. Comparison of related research conducted

No	Research	Distance indicator	Angle indicator	Influence of Color Light
1	[16]	Yes	Yes	No
2	[21]	Yes	Yes	No
3	[22]	No	Yes	Yes
4	[23]	Yes	No	No
5	[24]	No	Yes	No
6	[25]	Yes	No	No
7	This Research	Yes	Yes	Yes

The primary objective of this research is to compare the success rates of marker-based and markerless tracking methods while analyzing the impact of environmental factors such as distance, angle, and lighting on augmented reality (AR) tracking performance. Additionally, the study aims to provide valuable insights for selecting the most appropriate tracking methods for developing AR applications.

Design

This stage involves defining the functional requirements and navigation structure of the AR application. There are 3 functional requirements, namely the application must be able to detect and track markers for marker-based AR, display 3D objects using markerless tracking on planar surfaces, and support Android devices (minimum OS: Android 11). On the navigation structure, Figure 2 illustrates the simple navigation structure used in the AR application, which only focuses on testing the successful rendering of 3D objects without a user interface.

Figure 2. Navigation structure

Material Collecting

At this stage, all the required hardware and materials are prepared. This study used the following hardware and software, as shown in Table 2.

Table 2. Research testing tools and materials

Hardware	Spesification
Google Pixel 4	Snapdragon 855, 6GB RAM, 12.2MP Camera, Android 13
Xiaomi note 8	Snapdragon 665, 4GB RAM, 48MP Camera, Android 11
Bardi Smart Lamp	RGBWW, 12W, 110–1300 lumens
Marker	HVS A4 sheets (custom-made low-poly markers)

To ensure consistency in marker-based tracking, the research team designed AR markers using Adobe Illustrator (Figure 3). The markers were optimized for visibility and detection. For both methods, a 3D object (low-poly human model) was created in Blender (Figure 4) to standardize visual outputs for comparison.

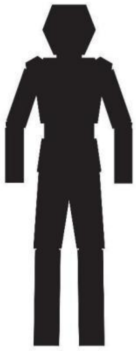

Figure 3. AR marker

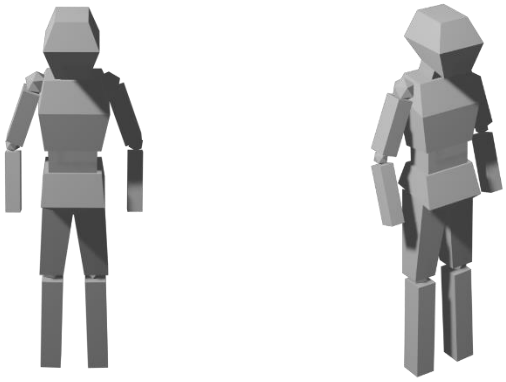

Figure 4. 3D object

Assembly

This stage involves integrating AR markers, 3D objects, and tracking methods into two AR applications (marker-based and markerless). In marker-based tracking, markers are loaded into Unity, and the AR camera is configured to detect and overlay 3D objects on the markers (Figure 5). In markerless tracking, 3D objects are tethered to planar surfaces detected in the real environment using Unity's AR Foundation library (Figure 6). The assembly process ensured that the applications were functional and ready for testing.

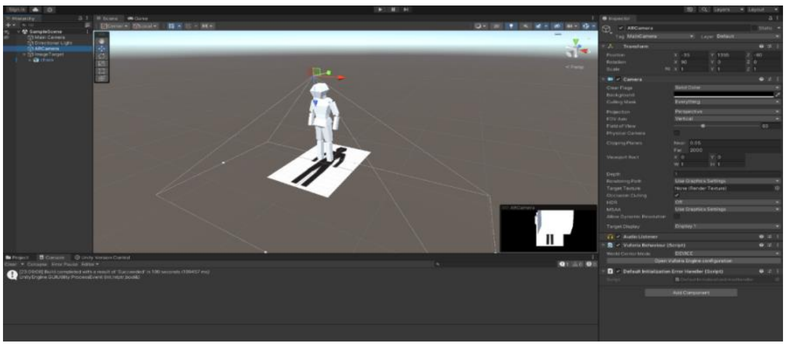

Figure 5. Stages of marker based

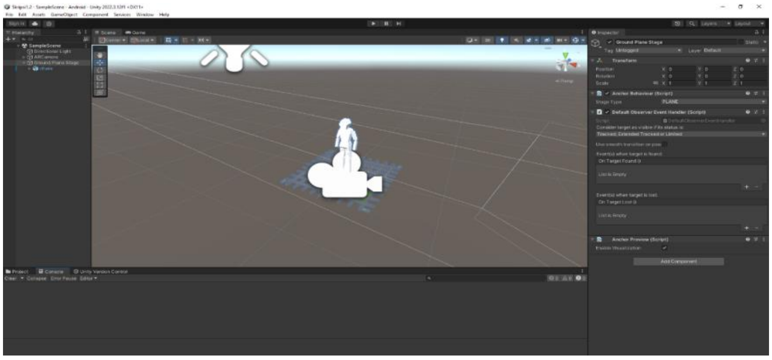

Figure 6. Stages of markerless based

Testing

Testing was the core stage of the methodology, where both AR tracking methods were evaluated under predefined conditions. The study combined the following indicators and sub-indicators, as shown in table 3 below.

Table 3. Research indicators and sub-indicators

Variable Indicator	Sub Indicator	Measurement Scale
distance	5, 15, 30, 50, 80, 120	cm
angel	30, 45, 90	degree (^{0})
light	Red, Blue, Green, Yellow	color

These indicators resulted in 72 test scenarios per device (Table 3). Testing followed 4 procedures, including placing the AR application at each specified distance, adjusting the camera angle (30°, 45°, 90°), changing the lighting conditions using the Bardi Smart Lamp, and recording the success or failure of 3D object rendering (1 = success, 0 = failure). The formula used for calculation is as in formula (1).

$$\chi = \left(\frac{\alpha}{ƀ}\right) x\ 100 \tag{1}$$

Where x is the percentage of success, α is the total number of successful trials, and ƀ is the total number of trials (72). Figures 7 and 8 illustrate the test setup, including device positioning and lighting adjustments. Data was collected systematically for both devices and tracking methods.

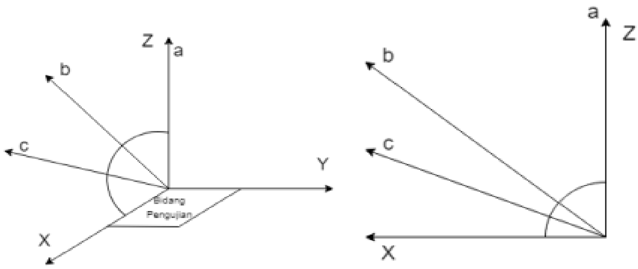

Figure 7. Testing illustration

Figure 8. Implementation of test illustration

Distribution

After testing and evaluation, the AR applications were finalized and stored in APK format for Android distribution. While the distribution stage is not the focus of this research, this step ensures that the applications are preserved for future development and replication.

Differentiation from Previous Studies

Unlike previous studies, this research provides a holistic evaluation of AR tracking methods under multiple environmental conditions (distance, angle, and lighting) using two devices with varying hardware specifications. Previous studies often focused on one or two variables, whereas this study integrates all three factors into a comprehensive analysis.

3. RESULTS AND DISCUSSIONS

The results of this study are organized based on the three leading indicators: distance, angle, and lighting color. Each subsection presents the findings from the comparative evaluation of marker-based and markerless tracking methods on Xiaomi Note 8 and Google Pixel 4 devices as shown in table 4 below.

Table 4. Research results from marker-based and markerless

Description	Total Value	Total Trials	Percentage
Marker Based:			
Xiaomi note 8	52	72	72.2%
Google Pixel 4	56	72	77.8%
Markerless:			
Xiaomi note 8	68	72	94.4%
Google Pixel 4	68	72	94.4%

Xiaomi Note 8 Marker-Based in formula (2), Google Pixel 4 Marker-Based in formula (3), and Xiaomi Note 8 and Google Pixel 4 Without Marker in formula (4).

$$\chi = \frac{52}{72}100 = 72.2\% \quad (2)$$

$$\chi = \frac{56}{72}100 = 77.8\% \quad (3)$$

$$\chi = \frac{68}{72}100 = 92.4\% \quad (4)$$

The results in Table 4 indicate that the markerless method outperforms the marker-based method on the Xiaomi Note 8 and Google Pixel 4. The marker-based evaluations of the Xiaomi Note 8 and Google Pixel 4 yielded 72.2% and 77.8%, respectively as shown in figure 9 below.

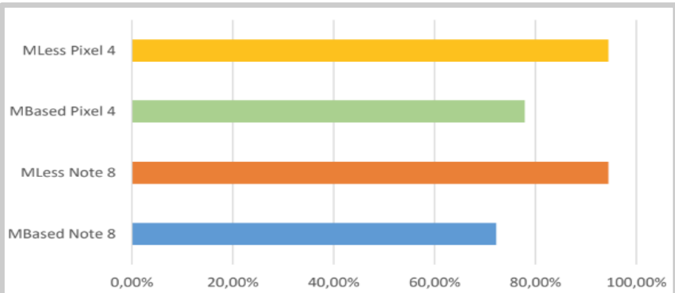

Figure 9. Research results from marker based and markerless

Effect of Distance on AR Tracking Performance

Table 5 and Figure 10 summarize the success rates of marker-based and markerless tracking methods across different distances: 5 cm, 15 cm, 30 cm, 50 cm, 80 cm, and 120 cm. For marker-based tracking, both devices performed well at a distance of 15–50 cm, achieving a 100% success rate. However, performance dropped significantly at 80 cm, with the Xiaomi Note 8 recording a 66.7% success rate and failing at 120 cm, while the Google Pixel 4 managed a 33.3% success rate at this distance. In contrast, markerless tracking achieved consistent success, maintaining a 100% success rate across all distances, including 120 cm, on both devices.

Table 5. Distance indicator research results

Distance (cm)	Xiaomi Note 8 - Marker-Based	Google Pixel 4 - Marker-Based	Markerless (Both Devices)
5	66.7%	66.7%	66.7%
15	100%	100%	100%
30	100%	100%	100%
50	100%	100%	100%
80	66.7%	66.7%	100%
120	0%	33.3%	100%

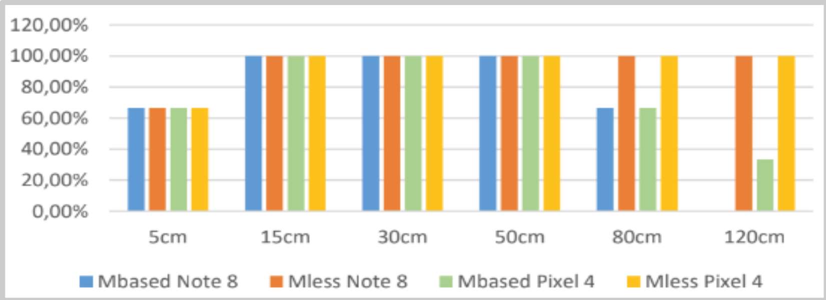

Figure 10. Distance indicator comparison results

The analysis reveals that the superior performance of markerless tracking stems from its ability to detect planar surfaces and anchor objects using environmental features, regardless of distance. In contrast, marker-based tracking relies on the visual detection of markers, which becomes unreliable at longer distances due to decreased marker resolution and camera limitations. The Xiaomi Note 8, with its lower camera sensor quality, exhibited a sharper decline in performance compared to the Google Pixel 4. These findings have important practical implications: markerless tracking proves far more reliable for AR applications requiring long-distance tracking, such as outdoor navigation or large-scale AR, while marker-based tracking remains suitable for applications within close range, such as small product visualization. In conclusion, markerless tracking outperforms marker-based tracking for distances beyond 50 cm, whereas marker-based tracking is effective only up to 50 cm under ideal conditions.

Effect of Angle on AR Tracking Performance

Table 6 and Figure 11 present the results for three angles: 30°, 45°, and 90°. For marker-based tracking, performance declined as the angle increased, with the most significant drop observed at 90°. The Google Pixel 4 performed slightly better than the Xiaomi Note 8, likely due to its superior camera quality and processing power. In contrast, markerless tracking maintained a 100% success rate at angles of 30° and 45° but experienced a slight decrease to 83.3% at 90°.

Table 6. Angle indicator research results

Angle (degrees)	Xiaomi Note 8 - Marker-Based	Google Pixel 4 - Marker-Based	Markerless (Both Devices)
30	70.8%	70.8%	100%
45	79.2%	75%	100%
90	66.7%	83.3%	83.3%

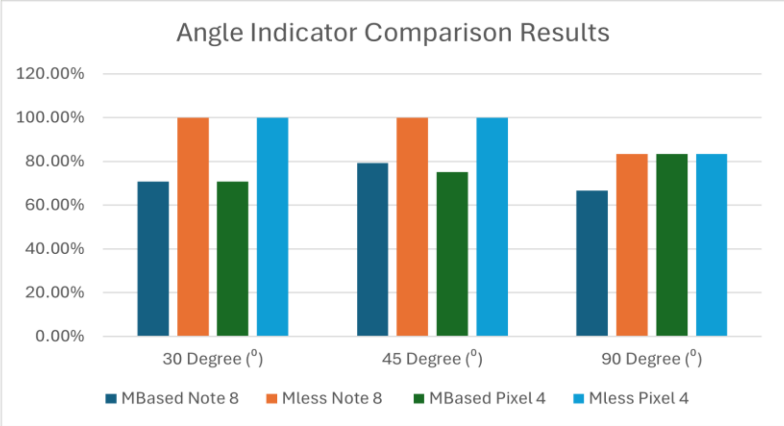

Figure 11. Angle indicator comparison results

The performance drop in marker-based tracking at larger angles can be attributed to the partial obscuration of markers, which reduces the system's ability to detect them accurately. In contrast, markerless tracking is less affected by angle variations as it relies on planar surface detection and spatial recognition. These findings have practical implications: AR systems designed for dynamic or angled interactions, such as AR games or maintenance applications, should prioritize markerless tracking, while marker-based tracking is better suited for scenarios where the marker remains consistently in a frontal position relative to the camera. In conclusion, markerless tracking demonstrates superior resilience to angle variations, whereas marker-based tracking is particularly sensitive to changes in viewing angles, especially at 90°.

Effect of Lighting Color on AR Tracking Performance

Table 7 and Figure 12 illustrate the impact of red, green, blue, and yellow lighting on tracking performance. Marker-based tracking showed a significant drop in performance under red lighting, achieving only 66.7% success on the Xiaomi Note 8 and 72.2% on the Google Pixel 4. In contrast, yellow lighting provided the best results for marker detection. In contrast, markerless tracking demonstrated consistent performance, achieving a 94.4% success rate across all lighting conditions.

Table 7. Color indicator research results

Angle (degrees)	Xiaomi Note 8 - Marker-Based	Google Pixel 4 - Marker-Based	Markerless (Both Devices)
Red	66.7%	72.2%	94.4%
Green	72.2%	77.8%	94.4%
Blue	72.2%	77.8%	94.4%
Yellow	77.8%	83.3%	94.4%

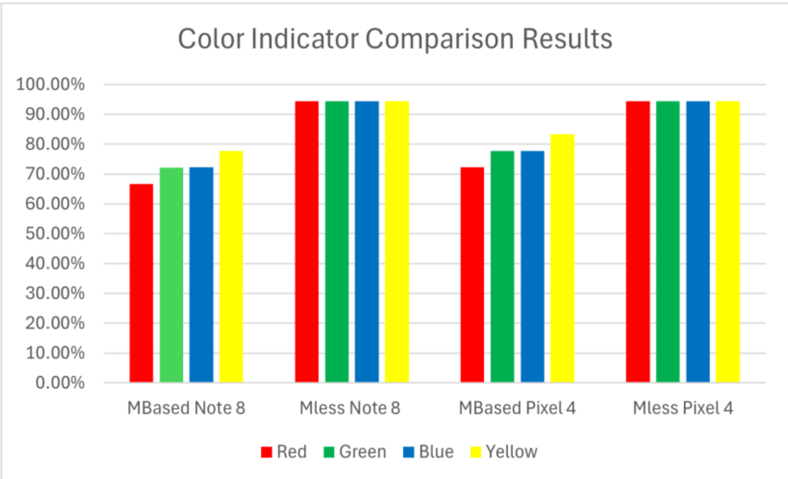

Figure 12. Color indicator comparison results

.

The reduced performance of marker-based tracking under red lighting can be attributed to the longer wavelength of red light, which reduces the contrast between the marker and its background, making detection more challenging. In contrast, green, blue, and yellow lighting provide higher contrast, improving marker visibility and tracking performance. These findings suggest that AR applications relying on marker-based tracking should avoid red lighting and prioritize environments with green, blue, or yellow lighting for optimal results. Markerless tracking, however, remains robust and unaffected across various lighting conditions, making it the ideal choice for AR applications in unpredictable or dynamic environments. In conclusion, while marker-based tracking struggles under red lighting due to reduced marker contrast, markerless tracking consistently performs well regardless of lighting conditions.

General Discussion

This study highlights the strengths and limitations of both marker-based and markerless tracking methods in augmented reality applications. Marker-based tracking proves to be simple and effective at close range, requiring minimal processing power, but its performance is highly sensitive to environmental factors such as distance, viewing angles, and lighting conditions. In contrast, markerless tracking, though more computationally demanding, consistently delivers superior performance across varying environmental conditions, making it particularly suitable for dynamic and large-scale AR applications. The observed differences in tracking accuracy between the Xiaomi Note 8 and Google Pixel 4 further emphasize the significant role of hardware specifications, such as camera resolution and processing power, in determining the overall effectiveness of AR tracking systems.

4. CONCLUSION

The research findings highlight key differences in performance between marker-based and markerless tracking methodologies under identical conditions of distance, angle, and illumination. The results demonstrated that the marker-based method produced varying outcomes depending on the device used, with success rates of 72.2% on the Xiaomi Note 8 and 77.8% on the Google Pixel 4. In contrast, the markerless method consistently outperformed marker-based techniques, achieving identical success rates of 94.4% on both devices. While marker-based systems proved more effective at shorter distances due to their faster object display speed, markerless tracking exhibited superior accuracy and consistency across all tests, regardless of the hardware used. These findings emphasize the reliability and effectiveness of the markerless methodology for augmented reality applications, particularly in dynamic and diverse conditions.

REFERENCES

[1] V. Marrahi-gomez and J. Belda-medina, “The Integration of Augmented Reality (AR) in Education,” no. January, 2023, doi: 10.14738/assrj.912.13689.

[2] T. N. Fitria, “Augmented Reality (AR) and Virtual Reality (VR) Technology in Education : Media of Teaching and Learning : A Review,” vol. 04, no. 01, 2023.

[3] P. A. Rauschnabel, R. Felix, C. Hinsch, H. Shahab, and F. Alt, “Computers in Human Behavior What is XR ? Towards a Framework for Augmented and Virtual Reality,” *Comput. Human Behav.*, vol. 133, no. May 2021, p. 107289, 2022, doi: 10.1016/j.chb.2022.107289.

[4] Y. K. Dwivedi *et al.*, “International Journal of Information Management Metaverse beyond the hype : Multidisciplinary perspectives on emerging challenges , opportunities , and agenda for research , practice and policy,” *Int. J. Inf. Manage.*, vol. 66, no. July, p. 102542, 2022, doi: 10.1016/j.ijinfomgt.2022.102542.

[5] F. Zulfiqar, R. Raza, M. O. Khan, M. Arif, A. Alvi, and T. Alam, “Augmented Reality and Its Applications in Education : A Systematic Survey,” *IEEE Access*, vol. 11, no. January, pp. 143250–143271, 2023, doi: 10.1109/ACCESS.2023.3331218.

[6] Y. Chen, Q. Wang, H. Chen, X. Song, and H. Tang, “An overview of augmented reality technology An overview of augmented reality technology,” 2019, doi: 10.1088/1742-6596/1237/2/022082.

[7] D. Intan, S. Saputra, L. Murjiatiningsih, H. Hermawan, and S. W. Handani, “cARica : Enhancing Travelling Experiences in Wonosobo Through Location-Based Mobile Augmented Reality,” pp. 23–30, 2022.

[8] R. Palmarini, J. Ahmet, R. Roy, and H. Torabmostaedi, “A Systematic Review of Augmented Reality applications in Maintenance,” vol. 49, no. February, pp. 215–228, 2018, doi: 10.1016/j.rcim.2017.06.002.

[9] A. M. Al-ansi, M. Jaboob, A. Garad, and A. Al-ansi, “Social Sciences & Humanities Open Analyzing augmented reality (AR) and virtual reality (VR) recent development in education,” *Soc. Sci. Humanit. Open*, vol. 8, no. 1, p. 100532, 2023, doi: 10.1016/j.ssaho.2023.100532.

[10] G. Koutromanos and G. Kazakou, “Computers & Education : X Reality Augmented reality smart glasses use and acceptance : A literature review,” *Comput. Educ. X Real.*, vol. 2, no. January, p. 100028, 2023, doi: 10.1016/j.cexr.2023.100028.

[11] J. Bacca, S. Baldiris, R. Fabregat, and S. Graf, “Augmented Reality Trends in Education : A Systematic Review of Research and Applications Augmented Reality Trends in Education : A Systematic Review of Research and Applications,” no. January 2016, 2014.

[12] F. A. Maulana and N. L. Azizah, “IMPLEMENTATION OF AUGMENTED REALITY AS A HAIR MODEL VISUALIZATION MEDIA BASED ON ANDROID,” vol. 17, pp. 47–54, 2023.

[13] G. Gunawan, W. Andriani, S. Anandianskha, and M. Indratama, “Implementation Of Marker-Based Tracking Method on Augmented Reality in Multimedia Learning (Case Study of STMIK Tegal),” vol. 5, no. 1, pp. 1–8, 2024.

[14] W. T. Kusuma, A. A. Supianto, H. Tolle, M. Anshori, I. Teknologi, and R. S. Soepraoen, “KEBARUAN FUNGSIONAL

VERTEX MARKER TERHADAP MARKER BASED AUGMENTED REALITY TRACKING FACTORS (JARAK , SUDUT , DAN LUAS PERMUKAAN) FUNCTIONAL TESTING OF VERTEX MARKERS AGAINST MARKER BASED AUGMENTED REALITY TRACKING FACTORS (DISTANCE , ANGLE , AND COVERED SURFACE AREA),” vol. 9, no. 4, 2022, doi: 10.25126/jtiik.202295748.

[15] H. Kato and M. Billinghurst, “Marker Tracking and HMD Calibration for a Video-based Augmented Reality Conferencing System”.

[16] B. Arifitama, A. Syahputra, K. Bayu, and Y. Bintoro, “Analisis Perbandingan Efektifitas Metode Marker dan Markerless Tracking pada Objek Augmented Reality,” vol. 14, no. 1, pp. 1–7, 2022.

[17] Z. Oufqir, A. el Abderrahmani, and K. Satori, “From Marker to Markerless in Augmented Reality,” *Springer*, pp. 599–612, 2020, doi: 10.1007/978-981-15-0947-6_57.

[18] S. Vashisht, “Exploration of Markers in Augmented Reality: Methodologies and Applications,” *2024 Second Int. Conf. Intell. Cyber Phys. Syst. Internet Things*, pp. 1082–1086, 2024, doi: 10.1109/ICoICI62503.2024.10696631.

[19] I. Ahmad, Y. Rahmanto, D. Pratama, and R. I. Borman, “Development of augmented reality application for introducing tangible cultural heritages at the lampung museum using the multimedia development life cycle,” vol. 13, no. 2, pp. 187–194, 2021.

[20] S. Aslamiyah, D. Ananda, A. Pertiwi, and K. Santosa, “Augmented reality development using multimedia development life cycle (MDLC) method in learning media,” pp. 31–38, 2023.

[21] W. Farianto *et al.*, “AUGMENTED REALITY OBJEK BERSEJARAH MUSEUM SOESILO SOEDARMAN MENGGUNAKAN METODE MARKER BASED DAN,” vol. 6, no. 2, pp. 141–153, 2021.

[22] M. I. Arief, Kusrini, and T. Hidayat, “Analysis of Markerless-Based Tracking Methods of Face Tracker Techniques in Detecting Human Face Movements in 2D And 3D Filter Making,” vol. 8, no. 1, pp. 47–56, 2023.

[23] P. Mandarani, R. Yuliani, and A. Syahrani, “PENGARUH SUDUT DAN INTENSITAS CAHAYA TERHADAP KEMUNCULAN OBJEK 3D PADA APLIKASI AUGMENTED REALITY,” *J. Edik Inform.*, vol. 7, no. 1, pp. 73–84, 2020, doi: 10.22202/ei.2020.v7i1.4338.

[24] Y. B. Mulia and E. U. P. B. Bangun, “Analisis Perbandingan Metode Marker dan Markerless Angka 0-9 3D Pada Teknologi Augmented Reality,” *J. Teknol. Dan Sist. Inf. Bisnis*, vol. 5, no. 4, pp. 454–459, 2023, doi: 10.47233/jteksis.v5i4.886.

[25] Y. Gao, “Influence of Virtual Objects ’ Shadows and Lighting Coherence on Distance Perception in Optical See-Through Augmented Reality,” no. July, 2019, doi: 10.1002/jsid.832.

.