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Design and Implementation of Marker-Based Augmented Reality to Enhance Public Awareness in Waste

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ABSTRACT

Waste problem in Indonesia remains a complex issue for the community due to a low level of understanding and awareness about waste management and its impacts. On this research, we will aims to raise awareness and educate ranging from children, teenagers, to adults, about waste management using an Augmented Reality-based application that employs System Development Life Cycle method and evaluates the performance of Marker-Based Augmented Reality. Performance evaluation was conducted by testing the response time of marker recognition based on estimated distance and angle under normal and dim light intensity, as well as in outdoor lighting conditions. High-contrast visual markers with simple geometries were deliberately selected to maximize tracking stability. The test results showed that the system was able to recognize markers with an average response time of 0.31–0.93 seconds, which excellently meets the standard real-time AR response benchmark of under 1.0 second. Based on user assessment results through questionnaires distributed to 30 respondents and evaluated using the System Usability Scale method, the application received a perfect rating. Furthermore, preliminary pre-test and post-test evaluations indicated a significant improvement in users' comprehension when compared to conventional text-based educational methods, making it suitable for use as an interactive educational medium.

I. INTRODUCTION

Issue about waste remains a complex problem in Indonesia, primarily because public understanding of the impacts caused by waste is still low. This is reinforced by data showing that the amount of waste generated each year increases along with population growth. The performance report for Indonesia's waste management in 2025 indicated that only 25% of the total waste generated was managed [1]. This situation is further exacerbated by the government's limited funds to provide proper and standard-compliant waste disposal. In addition, the rising standard of living among the community, which is not accompanied by adequate knowledge about waste management, as well as low public awareness in maintaining cleanliness, makes waste problems increasingly complicated [2]. Improperly managed waste can cause health, economic, and social problems alongside environmental issues. Addressing this requires a shared perception among all stakeholders, including the government, society, businesses, and industries. This can be effectively achieved through continuous education, providing the public with information about current waste issues and actionable steps to mitigate them [3].

Information and communication technology on this era was offers innovative solutions to strengthen public education, particularly in waste management. One such technology is Augmented Reality (AR), which integrates the real world with the virtual world using devices such as smartphones, laptops, or PCs equipped with webcams. Instead of replacing reality, AR overlays 2D or 3D virtual objects into the real world in real-time [4]. AR has been successfully applied as an educational and informational tool across various fields. In tourism, AR applications provide foreign tourists with real-time data like exchange rates and locations [5]. In healthcare, AR has been used to introduce pharmacognosy laboratory equipment [6]. Specifically in environmental education, an interactive AR game called Eco Guardians was developed and evaluated for its effectiveness in teaching waste management [7]. From these cases, AR-based learning media have great potential to create more interactive educational experiences to provide education about the waste crisis [8].

A crucial element in AR technology is the marker, which functions as the initial trigger point where the virtual object appears. Currently, there are two primary tracking types used in AR development: Marker-Based Tracking and Markerless Tracking [9]. Marker-Based Tracking recognizes predefined patterns on physical markers to display virtual objects [10], whereas Markerless Tracking displays virtual objects without relying on physical markers, typically by detecting flat surfaces like tables or floors [11], [12]. Both methods have distinct advantages. Marker-Based Tracking boasts a high success rate and stability, which is positively influenced by its performance under low lighting and specific scanning distances [13]. Conversely, Markerless Tracking offers the convenience of not requiring additional printed objects to detect 3D spaces [12]

Several previous studies have evaluated these tracking types, compared Marker and Markerless methods for 3D digits 0-9, finding that the Markerless method has a lower minimum detection distance but a relatively high maximum distance [14]. However, this study did not examine light intensity or marker reading angles. Some research was utilized Marker-Based Tracking for information on Lampung tapis cloth history, yielding satisfactory results regarding marker detection and user satisfaction [15]. Additionally, AR application for introducing Hudoq masks was tested detection angles, distances, and light intensity using Marker-Based Tracking, successfully visualizing the 3D models [16]. Despite these efforts, these prior studies did not specifically measure the system's response time during marker reading. Based on this literature review, a comprehensive evaluation of marker reading response time using Marker-Based Tracking accounting for distance, angle, and light intensity factors has not been fully explored. This gap forms the technical focus of this research.

To ensure the developed AR application functions properly and meets user needs, a structured development process is essential. We identified software commonly used in augmented reality application development. One such software is Unity 3D [17]. Therefore, the SDLC method was used as a basic framework because it encompasses several sequential stages: planning, analysis, design, implementation, testing, and system maintenance, which ensures a smooth, reliable, and well documented application development process.

Given the urgency of waste management issues in the community and the testing gaps in prior literature, this study was designed with a multidimensional objective encompassing both technical development and empirical evaluation. Fundamentally, this study aims to design, build, and implement an interactive Augmented Reality (AR)-based educational application as an innovative learning tool on waste management, inclusively targeting various demographic groups, from children and adolescents to adults. The entire software engineering process for developing this application was systematically implemented using the System Development Life Cycle (SDLC) framework to ensure a structured approach from requirements analysis through maintenance.

Furthermore, to ensure the reliability and stability of visual object tracking across various real-world use cases, this study conducted a rigorous system performance evaluation. The technical evaluation focused on testing marker-based AR tracking response-time metrics, measured from fluctuations in physical environmental parameters. This testing included variations in the estimated camera viewing distance, changes in viewing angle, and a range of lighting intensities under both normal and dim conditions. In addition to validating these computational technical parameters, this study also set a crucial goal of comprehensively measuring end-user acceptance and interaction using System Usability Scale method[18]. This was done to evaluate the operational feasibility, educational effectiveness, and usability of the developed application when operated directly by users.

II. METHOD

On this study, we used Software Development Life Cycle (SDLC) with the waterfall model as a method to solve this problem. Waterfall model is a system development model that applies a sequential flow, so one stage must be completed before moving on to the next stage. This method has several advantages, one of which is the ease in the system design process, because each stage must be completed step by step, ensuring that the research process is not disrupted. Stages in SDLC method with the waterfall model include Planning, Analysis, Design, Implementation, Testing, and System Maintenance.

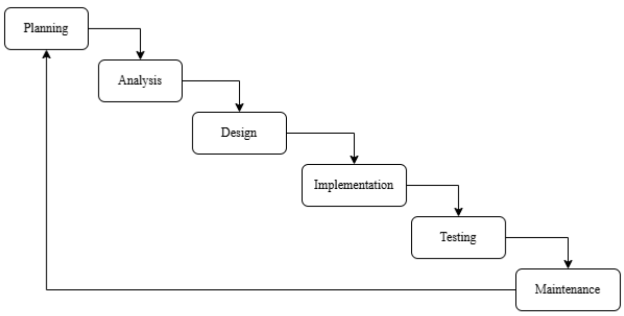

Figure 1. SDLC Waterfall Model Method

A. Planning

The planning stage is carried out by conducting a study based on observations of literature review. This is done to get an overview of the waste conditions in Indonesia so that the author can tailor the necessary education for the community. The reason the author created this application is to increase public awareness and participation through education that is enjoyable, engaging, and requires minimal literacy, making it easier to understand how to manage waste. At this stage, the author also determines the creation date, selects the software to be used, and assigns tasks during the development process.

B. Analysis

The analysis stage is a stage carried out systematically to determine system requirements based on data and information obtained in the previous stage so that the application can function according to the research objectives. To determine user needs and the system overview to be developed, the author analyses data obtained from observations and literature studies. The analysis process is carried out by studying how the delivery of educational waste management information needs to be established so that the application can be used properly by users or the public. System requirements are analysed by grouping them into functional and non-functional requirements. Functional requirements are analysed to determine the main features that the system must provide, while non-functional requirements are analysed to determine system qualities such as ease of use, application performance, and device compatibility.

C. Design

On design phase, we focuses on creating the user interface design. The user interface design will be tailored to an educational theme and will be easy to use. The author also creates a use case diagram to illustrate the interactions between users and the system's main features. In addition, the marker design is also created at this stage. All of these system designs are based on references obtained from the analysis stage, which discusses the system requirements specifications. The results of this design stage are then implemented in the next stage.

D. Implementation

We integrates all the system design results into the application development process. The implementation is carried out using Unity software as the game engine and Vuforia SDK to support Augmented Reality. The author also develops application features, user interface, marker design, and button settings for menu navigation. All application interactions are developed in accordance with the use case diagram created in the previous stage.

E. Testing

The testing phase is carried out to ensure that all features, including the material feature, quiz feature, and AR camera feature, function and run properly according to the design. This testing is conducted with several users by having them use the application directly and fill out questionnaires to obtain validation and feedback regarding the ease of use and feasibility of the application. At this stage, the author also evaluates the performance of Marker-Based Augmented Reality. The performance evaluation was conducted by testing the response time and speed of reading markers based on estimated distances and angles under normal and dim lighting conditions. Distance estimates were obtained based on the size and position of markers detected by the camera, thereby providing the relative distance between the camera and the marker. Angles were detected using a gyroscope sensor, while light intensity was measured using the light sensor installed in this application. Although the application is equipped with distance and angle estimation features, this study only used these values as testing parameters, whereas the analysis focused on measuring the system's response time in detecting markers.

F. Maintenance

Final stage in the SDLC method is maintenance. At this stage, the author carries out system maintenance, including updating or adding features if necessary. System maintenance also includes making fixes when users encounter bugs while using the system. Maintenance is carried out based on feedback from users who have tried using this application.

III. Result and Discussion

Results on this research was linear to method we used is SDLC, detailed explanation of the steps carried out as follows:

A. Planning

Based on the observations and literature study conducted, the author obtained an overview that waste management in Indonesia still faces various problems, such as low public awareness and a lack of understanding of waste sorting. Based on the conducted study, the educational materials available are still mostly presented in a predominantly text-based form, making them less engaging and less easily understood in conveying information to the public. Therefore, the author sets out to develop an interactive, visual, and easy-to-understand educational waste management application. The author chooses Augmented Reality as the technology to present the material in a more engaging way, which is expected to enhance users' understanding of proper waste management methods.

The system development plan is compiled by including the determination of software requirements, namely Unity as the game engine, Vuforia as the supporting Augmented Reality technology, Visual Studio for writing program code in C#, and other supporting devices. In addition, the division of tasks during the development process is also arranged so that each stage can be carried out systematically. The results of this planning stage serve as a basis for the author to carry out the next stages, so that application development can be conducted in an orderly manner in accordance with the research objectives, namely to raise awareness and provide education to users or the public, ranging from children, teenagers, to adults, regarding waste management through an Augmented Reality-based application.

B. Analysis

Based on the analysis through observation and literature study, it shows that the public still lacks awareness regarding the understanding of types of waste and proper waste management, so an educational medium that is easy to understand, interactive, and engaging is needed. Therefore, an application will be developed to present educational materials on waste management, which will provide Augmented Reality to display three-dimensional objects of waste types and waste management animations. This presentation aims to minimize text so that the material can be more easily understood by users. In addition, simple interaction features are needed so that the application can be used by people of all ages. The analysis also results in the specifications for the system's functional and non-functional requirements, including the following:

TABLE I
FUNCTIONAL REQUIREMENTS

No	Functional Requirements	Description
1	Home Page	The system displays the 'GO' screen
2	Main Menu	The system displays the main menu consisting of the Home button, AR Camera, Question Menu, Introduction to Waste Material Menu (Organic, Inorganic and B3)
3	Menu of introduction to Waste Material	The system displays explanations about the status of waste in Indonesia and the consequences that may occur. In addition, it provides explanations about waste management, namely by sorting or separating it according to its type.
4	Organic Waste Material Menu	The system displays an explanation of the material about the definition and how to sort organic waste.
5	Inorganic Waste Material Menu	The system displays material explanations about the definition and how to sort inorganic waste.
6	B3 Waste Material Menu	The system displays material explanations about the definition and how to sort hazardous and toxic waste.
7	Augmented Reality Camera	The system activates the camera to display marker-based AR objects. In addition, there are interactive features within it.
8	3D Object	The system displays 3D objects representing different types of waste and animations of how to manage them.
9	Questions/Quiz Menu	The system provides evaluation questions to measure the user's understanding.

Following 9 functional requirement, this research was designs and implements educational and evaluation features in the form of questions or quizzes to measure user understanding. Results of this analysis will be used as a reference in designing the system so that the developed application aligns with the research objectives.

C. Design

At this stage, we obtained results regarding the system architecture that explains the relationship between users and the application. Users interact with the application through Android devices, while the system uses a camera to detect markers in order to display Augmented Reality objects in real-time. In addition to the system architecture, the author also designed a use case diagram that serves to illustrate the interaction between users and the main features of the application. The design stage also includes the user interface design, which is created according to an educational and simple theme, so it can be used comfortably by users. The menu layout is arranged clearly to facilitate user navigation.

1. Use Case Diagram: A use case diagram is created to illustrate the interaction between users and the main features of the application.

Figure 2. Use Case Diagram

Based on the use case diagram in Figure 2, the user starts the interaction by pressing the Go button. Next, the user can access the features for recognizing waste, including organic, inorganic, and B3 waste, where each category provides material explanations and instructions on how to sort waste. Additionally, the application offers a quiz evaluation feature to test the user's understanding and an Augmented Reality feature that uses the camera to detect markers so that AR objects can be displayed. Meanwhile, the exit feature is used to end the application usage.

2. User Interface: User interface is designed to match the education theme and is predominantly green. Before being implemented in Unity, it was designed as a prototype in Figma to test interactions.

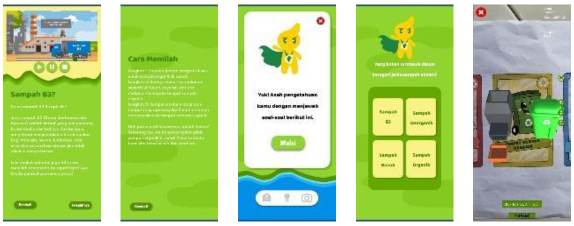

Figure 3. User Interface

3. Marker Design: The markers used correspond to the type of trash bin. Once the marker is detected, a waste management animation object will appear. Otherwise we target a marker as 5 star rate on Vuforia database. This was called because tracking reliability was rock solid and zero wobble on 5 star rating.

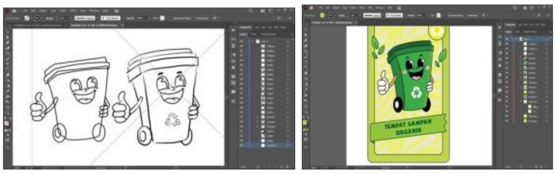

Figure 4. Marker Design

D. Implementation

At the implementation stage, we implements all designs and concepts that were planned in the previous stage into Unity 3D, resulting in an augmented reality-based waste management educational application. There was 5 star rating system was used in Vuforia, In addition, the author also writes scripts for creating a gyroscope, a light sensor, response time speed, and distance estimation measurement.

TABLE III
INTEREST POINT MARKER

Marker Interest Point	Marker Name	Explanation
	Green Marker (5 star marker score)	The green marker is an image of an organic trash bin, which means it is used to detect how to manage organic waste collection.
	Blue Marker (5 star marker score)	The blue marker is an image of a non-organic trash bin, which means it is used to detect how to manage the collection of non-organic waste.
	Red Marker (5 star marker score)	The red marker is an image of a B3 trash bin, which means it is used to detect how to manage a collection of B3 waste.

On the AR camera display, it is equipped with interactive features for virtual objects, such as presenting information on waste management based on detected markers, object display settings (zoom and rotation), animation playback, and refreshing the object display without having to exit the application.

E. Testing

At this stage, we conducted a performance evaluation of Marker-Based Augmented Reality by measuring marker reading response time as a function of estimated distances and angles under normal and low-light conditions. The testing criteria are as follows:

- Daytime testing location: house terrace.
- Night time testing location: bedroom.
- Normal lighting ranges from 200-300 lux.
- Normal lighting ranges from 100-150 lux inside the room with one indirect light source, namely, light coming from another room.
- Light intensity measuring device: a light sensor installed in the application.
- Measurement of response time speed using system time logging.
- Respond time target : < 1s
- Test device: OPPO A74 smartphone.
- Number of markers: 3
- Marker size: 10 × 6.5 cm

1. *Testing Results of Response Time Detection on the Green Marker during Daytime*: This test was conducted outdoors during the daytime with a light intensity of 200-300 lux.

TABLE IV
RESPONSE TIME DETECTION ON GREEN MARKERS DURING THE DAY

Parameters	0° Angle	30° Angle	60° Angle	90° Angle
Distance of 10 cm	-	0,45 s	0,31 s	0,41 s
Distance of 20 cm	-	0,31 s	0,31 s	0,31 s
Distance of 30 cm	-	0,35 s	0,31 s	0,31 s
Distance of 40 cm	-	0,45 s	0,35 s	0,31 s
Distance of 50 cm	-	0,45 s	0,35 s	0,31 s

From the test results above, it was found that the system is unable to recognize markers at a 0° angle from any distance. The system can recognize markers well within the 30°-90° angle range. Therefore, the average response time for the system to recognize and display the object on the green marker is 0.35 seconds.

2. Results of Response Time Detection Testing on the Blue Marker during Daytime: This test was conducted outdoors during the daytime with a light intensity of 200-300 lux.

TABLE V
RESPONSE TIME DETECTION ON BLUE MARKERS DURING THE DAY

Parameters	0° Angle	30° Angle	60° Angle	90° Angle
Distance of 10 cm	-	0,33 s	0,31 s	0,38 s
Distance of 20 cm	-	0,31 s	0,31 s	0,31 s
Distance of 30 cm	-	0,31 s	0,21 s	0,33 s
Distance of 40 cm	-	0,35 s	0,35 s	0,25 s
Distance of 50 cm	-	-	0,31 s	0,31 s

From the test results above, it was found that the system is unable to recognize markers at a 0° angle from any distance. The system can recognize markers well within the 60°-90° angle range. Therefore, the average response time for the system to recognize and display the object on the blue marker is 0.31 seconds.

3. Results of Response Time Detection Testing on the Red Marker during Daytime: This test was conducted outdoors during the day with a light intensity of 200-300 lux.

TABLE VI
TESTING RESPONSE TIME DETECTION ON RED MARKERS DURING THE DAY

Parameters	0° Angle	30° Angle	60° Angle	90° Angle
Distance of 10 cm	-	0,35 s	0,33 s	0,41 s
Distance of 20 cm	-	0,33 s	0,31 s	0,31 s
Distance of 30 cm	-	0,41 s	0,35 s	0,31 s
Distance of 40 cm	-	0,45 s	0,36 s	0,31 s
Distance of 50 cm	-	0,71 s	0,35 s	0,33 s

From the test results above, it was found that the system cannot recognize the marker at a 0° angle from any distance. The system can recognize the marker well within the angle range of 30°-90°. Therefore, the average response time for the system to recognize and display the object on the red marker is 0.37 seconds.

1. Results of Response Time Speed Detection Testing on the Green Marker at Night: This test was conducted at night indoors with a light intensity of 100-150 lux.

TABLE VII
TESTING RESPONSE TIME DETECTION ON GREEN MARKERS AT NIGHT

Parameters	0° Angle	30° Angle	60° Angle	90° Angle
Distance of 10 cm	-	0,41 s	0,41 s	0,41 s
Distance of 20 cm	-	0,45 s	0,41 s	0,41 s
Distance of 30 cm	-	1,21 s	0,68 s	0,68 s
Distance of 40 cm	-	-	-	1,74 s
Distance of 50 cm	-	-	-	-

From the test results above, it was found that the system could not recognize the marker at a 0° angle from any distance. The system was able to recognize the marker within an angle range of 30°-90°, although at certain distances and angles, the marker was not detected. Therefore, the average response time for the system to recognize and display the object on the green marker is 0.67 seconds.

2. Results of Response Time Speed Detection Testing on the Blue Marker at Night: This test was conducted at night indoors with a light intensity of 100-150 lux.

TABLE VIII
TESTING RESPONSE TIME DETECTION ON BLUE MARKERS AT NIGHT

Parameters	0° Angle	30° Angle	60° Angle	90° Angle
Distance of 10 cm	-	0,41 s	0,41 s	0,84 s
Distance of 20 cm	-	0,5 s	0,41 s	0,38 s
Distance of 30 cm	-	0,55 s	0,68 s	0,41 s
Distance of 40 cm	-	-	4,53 s	0,66 s
Distance of 50 cm	-	-	-	-

From the test results above, it was found that the system could not recognize the marker at a 0° angle from any distance. The system recognized the marker within a 30 °- 90 ° angle range, though at certain distances and angles the marker was not detected. Therefore, the average response time for the system to recognize and display the object on the blue marker is 0.93 seconds.

3. Results of Response Time Speed Detection Testing on the Red Marker at Night: This test was conducted at night indoors with a light intensity of 100-150 lux.

TABLE IX
TESTING RESPONSE TIME DETECTION ON RED MARKERS AT NIGHT

Parameters	0° Angle	30° Angle	60° Angle	90° Angle
Distance of 10 cm	-	0,41 s	0,41 s	0,41 s
Distance of 20 cm	-	0,41 s	0,38 s	0,41 s
Distance of 30 cm	-	0,45 s	0,41 s	0,41 s
Distance of 40 cm	-	0,84 s	1,82 s	1,61 s
Distance of 50 cm	-	-	-	-

From the test results above, it was found that the system is unable to recognize the marker at a 0° angle from any distance. The system can recognize the marker at an angle range of 30°-90°, although at certain distances and angles, the marker is not detected. Thus, the average response time for the system to recognize and display the object on the red marker is 0.69 s.

The next testing phase involved testing the application on several users to obtain validation and feedback regarding the feasibility of the application by filling out questionnaires. The questionnaires were distributed to 20 respondents with 10 statements provided. Criteria for SUS method was serve in Table X.

TABLE X
SELECTION CRITERIA

Value	Answer
5	Sangat Setuju
4	Setuju
3	Netral
2	Tidak Setuju
1	Sangat Tidak Setuju

Respondents were asked two types of questions: positive and negative. The questions are asked based on the SUS method of delivery, and then the results of the respondents will be calculated one by one. The following are the questions asked to respondents shown on Table XI.

TABLE XI
SELECTION CRITERIA

No	Positive	No	Negative
1	Saya berpikir akan sering menggunakan aplikasi edukasi sampah ini.	2	Saya merasa aplikasi ini terlalu rumit untuk digunakan.
3	Saya merasa aplikasi ini mudah digunakan.	4	Saya pikir saya membutuhkan bantuan dari orang teknis/ahli untuk dapat menggunakan aplikasi ini.
5	Saya merasa fitur-fitur dalam aplikasi ini (AR, Kuis, Navigasi) berjalan dengan baik	6	Saya merasa ada banyak hal yang tidak konsisten (inkonsistensi) dalam aplikasi ini.
7	Saya yakin kebanyakan orang akan dapat belajar menggunakan aplikasi ini dengan sangat cepat.	8	Saya merasa aplikasi ini sangat merepotkan untuk digunakan.
9	Saya merasa sangat percaya diri saat menggunakan aplikasi ini.	10	Saya harus belajar banyak hal terlebih dahulu sebelum bisa menggunakan aplikasi ini.

Answers to these questions are categorized as positive and negative for a reason. In SUS method, each positive question is subtracted by 1 from the score, while for negative questions, the score is subtracted from the maximum score; in this case, 5 is used as the maximum score. The results for each respondent, converted into SUS values. R was called for Respondent and S was call for Score. Results of converted score can be seen in Table XII.

TABLE XII
CONVERTED SUS VALUES

R	S	R	S	R	S	R	S
1	**36**	6	**33**	11	**29**	16	**30**
2	**31**	7	**30**	12	**32**	17	**30**
3	**30**	8	**29**	13	**29**	18	**27**
4	**27**	9	**33**	14	**29**	19	**27**
5	**30**	10	**31**	15	**27**	20	**32**

After obtaining the SUS conversion value, the next step is to multiply it by 2.5 to normalize the data. Normalized data refers to the entire data set, not just a subset. This is necessary to determine the average value for the application being developed. Result of normalized data was shown in Table XIII and in this section N is used to explain about Normalized value.

TABLE XIII
NORMALIZED VALUES

R	N	R	N	R	N	R	N
1	**90**	6	**82.5**	11	**72.5**	16	**75**
2	**77.5**	7	**75**	12	**80**	17	**75**
3	**75**	8	**72.5**	13	**72.5**	18	**67.5**
4	**67.5**	9	**82.5**	14	**72.5**	19	**67.5**
5	**75**	10	**77.5**	15	**67.5**	20	**80**
N Totals						**1505**	

After got the normalized data, we searched for its average value. We used this formula used to find the average value:

$$Mean = \frac{\Sigma N}{\Sigma R}$$

From that formula, the results are then obtained score:

$$\frac{1505}{20} = 75,25$$

The average values obtained were then classified into the interpretation range of the SUS method. This interpretation has 11 classes as shown in Table XIV.

TABLE XIV
SELECTION CRITERIA

SUS Score Range	Grade Percentile	Range
84.1–100	A+	96–100
80.8–84	A	90–95
78.9–80.7	A−	85–89
77.2–78.8	B+	80–84
74.1–77.1	B	70–79
72.6–74	B−	65–69
71.1–72.5	C+	60–64
65–71	C	41–59
62.7–64.9	C−	35–40
51.7–62.6	D	15–34
0–51.7	F	0–14

Based on Table XIV, the value obtained in the test was 75.25, which falls in class B (70-79), indicating that this application was acceptable.

F. Maintenance

During system maintenance, the author added a video pause action to the "Kembali" and "Selanjutnya" buttons in the video explanation menu. This addition was made based on direct feedback from several users who had responded to the application and aimed to improve user experience. The video would only pause when the pause button was pressed, but it would continue playing when moving to another page without pressing the pause button. This was a concern for us because this crucial issue could disrupt user focus and required immediate remediation.

After the fix, which involved setting a trigger action to pause the video, users complained that they disliked having to restart a video they had already watched. Ultimately, we decided to pause the video so users could resume the video when they moved to another page.

IV. CONCLUSION AND SUGGESTION

Based on the research conducted, an Augmented Reality-based waste management educational application was successfully developed using the System Development Life Cycle (SDLC) method. This application can display Augmented Reality objects based on detected markers and includes evaluation features such as quizzes.

The initial performance target required a marker detection time of <1 second, and marker detection test results showed an average response time of 0.31–0.93 seconds. This was influenced by marker characteristics and factors such as distance, angle, and light intensity. On average, markers could be easily detected at a 90° angle, with a maximum distance of 50 cm, in daytime conditions with a light level of 200–300 lux. In nighttime conditions with a light range of 100–150 lux, markers could be easily detected at a 90° angle, with a maximum distance of 40 cm. No markers could be detected at 0°, either during the day or at night. Furthermore, the user experience evaluation conducted using the System Usability Scale showed that this application received an average score of 75.25 (a B grade). This leads to the conclusion that the developed application is suitable for use as an interactive application for waste management education.

However, the performance evaluation was limited to 20 respondents, which remains a limitation in the testing. Therefore, future research could focus on increasing the number of respondents, broadening the testing scope, and expanding to other platforms to assess the system's performance in marker detection.

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