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Implementation of augmented reality in an application to recognize traditional Papuan musical instruments as a medium for cultural preservation

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ABSTRACT

Traditional musical instruments of Papua represent a rich cultural heritage that faces a decline in public awareness due to limited access and physical preservation challenges. Most instruments are stored exclusively in cultural houses (*Sanggar*) or museums, isolating them from the younger generation who are deeply engaged with modern mobile technologies. This study aimed to develop and evaluate an Augmented Reality (AR)-based cultural preservation medium that improves public access to information on Papuan traditional musical instruments, specifically the Tifa, Tifa Titir, and Gong from the Fakfak region. The novelty of this study lies in its localized integration of three-dimensional visualization, authentic instrument sounds, and contextual cultural information into a mobile AR application designed for indigenous musical heritage preservation. Using a structured Waterfall development approach, cultural data were collected from local cultural custodians and transformed into interactive digital content. The application projects realistic 3D assets, plays authentic instrument sounds, and displays textual cultural information upon scanning unique physical markers. Black-box testing validated that all system features, including marker tracking, audio triggers, and page navigation, functioned successfully across various Android hardware environments. User satisfaction evaluations yielded an overall cumulative usability index of **90.35%**, classifying the application as highly effective and user-friendly. This digital intervention bridges the gap between historical preservation and modern education, providing an accessible, interactive, and community-oriented model for cultural digitization and learning.

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Introduction

In the current era of globalization, the rapid development of information and communication technology has transformed smartphones into an inseparable part of human life. While these mobile computing devices dominate daily activities, their usage presents a dual implication; on one hand, they risk shifting the younger generation's interest away from traditional culture, but on the other hand, they offer a powerful, user-friendly platform for cultural preservation (Diego Wisnu & Adelaide

Gracegefa, 2025; Rizky Febriansyah, 2025). Traditional musical instruments embody a unique cultural identity for every region across Indonesia and function as cultural knowledge carriers that transmit historical, artistic, and ceremonial values across generations (Solihin, Iskandar Mulyana, et al., 2022). However, the reality in the field indicates a critical research problem characterized by a severe decline in public awareness and a lack of accessibility to these cultural artifacts(Apolos Buttu et al., 2024; B. Beribe, 2023). In the context of Papua, particularly in the Fakfak Regency, traditional musical instruments such as the Tifa, Tifa Titir, and Gong are becoming increasingly rare and isolated. Access to these instruments is highly exclusive, as they are mostly preserved only within specific cultural houses (Sanggar), such as Sanggar Wakiong in Wurkendik and Sanggar Mbaham Matta in Lusiperi, or displayed exclusively during rare traditional ceremonies(Arridha et al., 2025; Aziz et al., 2024). Consequently, a large portion of the general public, including the native Papuan youth, remain unfamiliar with the physical forms, historical background, and authentic sounds of their own cultural heritage(Solihin, Mulyana, et al., 2022).

To address this preservation barrier, this study uses mobile-based interactive media as a cultural preservation strategy rather than merely as a technical application development project. Rather than allowing digital technology to marginalize ancestral heritage, this research proposes integrating physical cultural documentation with modern software engineering (Alvendri et al., 2023; Christoper Redja & Carudin, 2025). The development process entails capturing the authentic values of Fakfak's traditional instruments through direct field observations and expert interviews, and subsequently synthesizing this data into an interactive mobile application. By adopting the systematic Waterfall development methodology, the technical execution focuses on building a marker-based tracking system that overlays high-fidelity digital replicas onto the real-world environment (Frialdo, 2022; Roy et al., 2024). This framework bridges the gap between historical preservation and modern digital education, providing a scalable strategy to revitalize fading cultural legacies. However, the value of this approach is not limited to visualizing objects; it also supports multimodal cultural learning by combining object recognition, three-dimensional representation, authentic sound, and contextual information in a single accessible platform.

Although several studies have applied Augmented Reality to cultural heritage and traditional musical instrument learning, important research gaps remain. Previous applications have generally emphasized technical visualization or object recognition, while fewer studies have integrated local cultural validation, authentic sound, three-dimensional representation, and contextual ethnomusicological information within one mobile preservation medium. In addition, limited attention has been given to Papuan traditional instruments from the Fakfak region, particularly the Tifa, Tifa Titir, and Gong, which are rarely accessible outside cultural houses or ceremonial events (Firdaus et al., 2022, 2023). Furthermore, the objective extends to supplying a highly accessible educational tool that delivers real-time auditory experiences and textual history without requiring users to physically visit isolated Sanggars or museums, thereby embedding cultural learning into a highly popular contemporary platform(Arseniev-Koehler & Foster, 2022; Marhamah et al., 2025) Therefore, this study addresses a specific gap in localized AR-based cultural preservation media by developing an application that combines cultural authenticity, accessibility, and interactive learning for indigenous Papuan musical heritage.

Theoretical studies examined in this research establish a robust foundation for building the interactive system. Augmented Reality is defined as a technology that seamlessly integrates two-dimensional or three-dimensional virtual objects into a real-world environment and projects them in real-time, establishing a distinct interactive experience known as Mixed Reality(C.G. et al., 2023; Walker et al., 2023). Unlike Virtual Reality which immerses a user entirely inside a simulated world, AR superimposes digital assets directly onto the user's existing surroundings (Bretos et al., 2024). From an educational and cultural preservation perspective, AR is relevant because it allows users to experience cultural objects through visual, auditory, and textual interaction rather than through passive reading alone. This multimodal interaction can strengthen attention, support contextual understanding, and make rare cultural artifacts more accessible to users who cannot directly observe the original objects. To recognize and anchor these virtual objects, the system relies on Marker-Based Tracking, a proven method that uses the device camera to detect distinct visual patterns, surface points, or image

targets(Al-Khowarizmi et al., 2021; Harahap et al., 2024). In this study, marker-based tracking is positioned not only as a technical mechanism, but also as a practical strategy to provide stable object recognition for educational use on commonly available Android smartphones. The development architecture incorporates specialized software suites, including Blender 3D for non-destructive mesh modeling, texturing, and realistic material scaling, alongside Unity 3D as the primary cross-platform engine(Chai & Li, 2022; Rahmat & Noviyanti, 2021). Image recognition stability is achieved via the Vuforia Software Development Kit (SDK), which manages target databases and cloud-synchronized tracking variables to ensure consistent real-time rendering on mobile hardware(Simon, 2023).

The primary research objective is to design, build, and implement an interactive Android-based application for recognizing traditional Papuan musical instruments by utilizing Augmented Reality (AR) technology. Specifically, the study aims to create stable visual tracking mechanisms capable of projecting accurate three-dimensional (3D) models of the Tifa, Tifa Titir, and Gong (Firdaus et al., 2022, 2023). Furthermore, the objective extends to supplying a highly accessible educational tool that delivers real-time auditory experiences and textual history without requiring users to physically visit isolated Sanggars or museums, thereby embedding cultural learning into a highly popular contemporary platform (Arseniev-Koehler & Foster, 2022; Marhamah et al., 2025). The novelty of this study lies in the development of a localized AR preservation model that integrates expert-informed cultural content, realistic 3D visualization, authentic audio, and interactive mobile access for traditional Papuan musical instruments from Fakfak. The expectations of the results and benefits of this research point toward a significant positive impact on both cultural conservation and digital education. Systematically, the finalized AR application is expected to achieve reliable functional performance, delivering successful black-box testing marks across various Android devices regarding marker detection, audio triggers, and interface navigation(Cahyono & Saputra, 2023; Zen et al., 2024). Empirically, user satisfaction evaluations anticipate a highly favorable response, aiming to surpass standard criteria for usability and effectively increase public engagement(Vlachogianni & Tselios, 2022). The ultimate benefit of this digital intervention lies in its capacity to serve as a sustainable, electronic information media that democratizes cultural knowledge, protects endangered heritage from external misappropriation, and successfully fosters a renewed sense of cultural pride among the younger generation.

Method

The development of the Augmented Reality (AR) application for introducing traditional Papuan musical instruments was systematically executed using the Waterfall software development life cycle framework. The choice of the Waterfall method is highly appropriate for educational multimedia development, as its linear and sequential structure ensures that each development phase is fully verified before moving to the next, thereby minimizing logic conflicts and software defects. This method was selected because the application requirements, cultural objects, main features, and target users had been clearly identified at the beginning of the study, making a sequential development model suitable for controlling the flow from analysis, design, implementation, testing, and evaluation. Compared with Agile and Prototype models, which are more appropriate for projects with rapidly changing requirements and repeated user-driven iterations, the Waterfall model provided stronger documentation control and stage-by-stage validation. In comparison with the Multimedia Development Life Cycle (MDLC), which emphasizes multimedia production stages, Waterfall was considered more appropriate for this study because the research required not only media design but also systematic software validation through functional testing and user evaluation. To guarantee theoretical and methodological rigor, the selection of this software engineering framework is firmly grounded in established computing literature, particularly drawing upon the architectural guidelines for interactive multimedia assets adapted by Pressman (2022) for interactive platforms and the contemporary framework of marker-based mobile spatial tracking synthesized by Pratama (2023).

The empirical data required to construct this digital repository was obtained through a multi-channeled data collection strategy deployed directly in the Fakfak Regency, Papua Barat. The initial phase involved extensive field observations and rigorous field studies at two primary cultural centers, namely Sanggar Wakiong in Wurkendik village and Sanggar Mbaham Matta in Lusiperi village. To

complement these visual observations, structured face-to-face interviews were conducted with key cultural custodians, specifically Mr. Fredi Warpopor as the head of Sanggar Mbaham Matta and Mrs. Yuliana Manggaprouw as the leader of Sanggar Wakiong. The cultural experts were selected purposively based on several criteria: they were recognized leaders or custodians of local cultural studios, had direct experience in preserving and presenting Papuan traditional musical instruments, possessed knowledge of the historical and ceremonial functions of the instruments, and were able to verify the visual form, sound characteristics, and cultural descriptions used in the application. These qualitative interactions provided critical information regarding the historical context, exact geometry, and functional roles of the Tifa, Tifa Titir, and Gong. Authentic audio recordings of each instrument were captured on-site to serve as the application's native sound samples. Finally, an exhaustive literature review was conducted to cross-reference the field data with accredited informatics journals and historical publications concerning Papuan ethnomusicology (Sugiyono, 2021).

The development procedure followed a strict chronological pipeline consisting of five interrelated stages. The process initiated with the Requirements Analysis phase, where all qualitative data, user specifications, and target hardware capacities were synthesized to establish the system boundary, focusing specifically on three indigenous instruments from Fakfak. At this stage, the main functional requirements were defined, including marker scanning, 3D object visualization, instrument sound playback, cultural information display, menu navigation, and Android device compatibility. This was immediately followed by the System Design stage, which mapped out the logical flow of the software. During this phase, Figma was utilized to build collaborative user interface prototypes, while visual modeling assets including system flowcharts, use case diagrams, and activity diagrams were drafted to illustrate the behavioral interactions between the user and the mobile environment.

The third chronological stage was System Implementation, where the theoretical designs were converted into functional source code and interactive assets. High-fidelity 3D modeling, texturing, and non-destructive material mapping of the physical instruments were executed inside Blender 3D, creating realistic digital replicas of the Tifa, Titir, and Gong. These 3D assets, along with the physical marker targets, were then imported into the Unity 3D cross-platform game engine, which served as the primary development environment. The internal application logic, scene transitions, and audio triggers were scripted using JavaScript within an integrated development environment. Computer vision tracking capabilities were integrated by embedding the Vuforia Software Development Kit (SDK) into Unity, which enabled the mobile device's camera to process, identify, and align virtual objects onto the physical marker targets in real time(Dewi & Sahrina, 2021). The use of physical markers was intended to support stable object anchoring and consistent recognition during the initial implementation stage, while also enabling the application to run on commonly available Android smartphones without requiring advanced depth-sensing hardware.

To verify the software's integrity, the final stages focused on strict measurement, testing, and evaluation protocols before deployment. System testing was measured and executed using Black-Box Testing methods, which focused entirely on the functional requirements of the software without examining internal code structures. A structured test matrix was applied to systematically evaluate core operational units, including the successful initialization of the AR camera scene, the tracking stability of the image targets, the programmatic rendering of the 3D meshes, and the correct delivery of contextual information and audio files upon user command. The black-box testing indicators included main menu initialization, AR camera activation, Tifa marker recognition, Tifa Titir marker recognition, Gong marker recognition, 3D object rendering accuracy, instrument audio playback, cultural information display, back-navigation function, and application stability during repeated use. Any functional failures or interface anomalies discovered during this testing phase were pushed back into an evaluation loop for code optimization and maintenance. In addition to functional validation, the testing protocol also considered device compatibility and basic operational performance, including the responsiveness of marker detection and the smoothness of object rendering, to ensure that the application could be used effectively on Android devices with different hardware capacities.

The final evaluation of the application's overall success was measured through user satisfaction testing using Likert Scale questionnaires distributed to a target group of twenty respondents comprising local students and community members. Respondents were selected to represent potential

users of the application, particularly individuals who were relevant to cultural learning and community-based preservation. To strengthen the interpretation of usability results, respondent characteristics were documented, including age group, gender, educational level, community role, familiarity with Papuan traditional musical instruments, and previous experience with AR-based applications. The questionnaire evaluated ten unique usability metrics, including ease of use, interface comprehension, asset fidelity, and cultural delivery values. These metrics covered interface accessibility, AR camera responsiveness, clarity of 3D models, marker tracking stability, audio synchronization, clarity of cultural information, operational stability, application efficiency, relevance as a preservation medium, and overall satisfaction. The data obtained from the respondents was converted into numerical weights ranging from one for strongly disagree to five for strongly agree. These scores were then calculated using a standard percentage index formula where the total empirical score was divided by the maximum potential score and multiplied by one hundred. The final percentage was interpreted against a standardized five-tier interval scale to classify user acceptance, ranging from highly negative at zero percent to highly satisfactory and effective at eighty to one hundred percent, thereby providing a quantifiable measure of the research benefits.

Results and Discussions

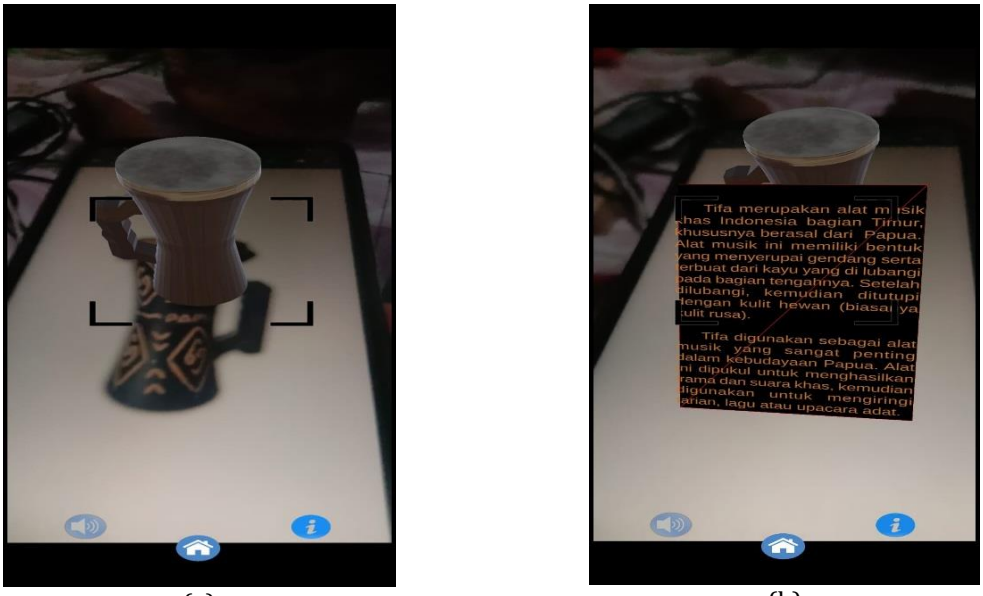
The development phase successfully culminated in a fully operational Android-based Augmented Reality application titled *Aplikasi Pengenalan Alat Musik Tradisional Papua*. The software system structures user interactions into three main features consisting of the primary camera tracking interface, an informational repository detailing cultural backgrounds, and an application guide. These features were designed to support not only object recognition but also public access to cultural information through the integration of 3D visualization, authentic sound, and concise historical descriptions. The operational essence of the application relies heavily on the technical harmony between the custom image targets and the real-time processing capability of the Vuforia SDK engine. To establish an optimal tracking foundation, three distinct markers were developed into physical printouts representing the Tifa, Tifa Titir, and Gong. Based on the feature point analysis conducted within the Vuforia Developer Portal, these markers achieved a maximum rating of five stars, signifying a rich density of high-contrast edge structures and unique geometric trackable points. This excellent score is visually supported by the explicit feature maps generated during the deployment phase, where the software identifies sharp intersecting contrast boundaries to anchor virtual objects without shaking or drifting. The use of physical markers therefore provided stable recognition and reliable object anchoring; however, it also introduced practical limitations because users must prepare printed markers, position them within the camera view, and scan them under adequate lighting conditions. This condition may reduce flexibility for spontaneous use, although it remains suitable for classroom demonstrations, community exhibitions, and guided cultural learning activities.

Table 1 Black-Box Functional Validation Results

Test Case ID	System Function Evaluated	Expected Outcome	Status
TC-01	Main Menu Initialization	Render Main UI	Success
TC-02	AR Camera Scene Activation	Camera Stream Active	Success
TC-03	Tifa Marker Tracking	Render 3D Tifa Asset	Success
TC-04	Tifa Titir Marker Tracking	Render 3D Titir Asset	Success
TC-05	Gong Marker Tracking	Render 3D Gong Asset	Success
TC-06	Instrument Audio Initialization	Play Audio Loop	Success
TC-07	Cultural Information Display	Display correct instrument description	Success
TC-08	Audio Synchronization	Play the sound corresponding to the selected instrument	Success
TC-09	UI Back Navigation	Return to Main Menu	Success

TC-10	Repeated Use Stability	Application remains stable during repeated scanning and navigation	Success

To verify that the application satisfies all operational criteria, rigorous structural verification was carried out via black-box testing methods. This evaluation isolates the functional inputs and outputs of the mobile platform to guarantee that the internal application logic performs without system crashes or interface overlaps across modern Android runtime environments. The systematic outcomes of these diagnostic tests are compiled in Table 1. The structural data presented in Table 1 proves that all ten fundamental test cases achieved an absolute success rate, validating that the software triggers its functions accurately when interacting with the physical environment. Specifically, the tracking engines for the Tifa, Tifa Titir, and Gong markers operated efficiently, successfully instantiating the virtual prefabs exactly over the detected visual planes. The expanded validation indicators also confirmed that the application displayed the correct cultural information, played the appropriate instrument audio, supported navigation back to the main menu, and remained stable during repeated scanning activities. These indicators are important because the application's usefulness depends not only on marker detection but also on the consistency of cultural content delivery and interaction flow.



(a) (b)

Figure 1. The 3D model of the Tifa Instrument

The graphical rendering execution and user interface behaviors are documented in Figure 1. Part (a) of Figure 1 illustrates the optimized low-poly mesh structure of the Tifa instrument engineered inside Blender, which maintains an efficient polygon count to prevent frame-rate drops on mid-range smartphones while preserving organic wood and leather textures. Part (b) of Figure 1 displays the final runtime application view, showcasing how the 3D model overlays perfectly on the physical paper target alongside the integrated user interface components, which deliver real-time historical text and interactive audio playback buttons. From a performance perspective, the use of optimized low-poly assets was intended to reduce rendering burden and maintain smooth interaction on commonly available Android devices. Nevertheless, this study did not yet include instrumentation-based benchmarking for frame rate per second, CPU load, detailed memory consumption, rendering latency, or marker detection distance. Therefore, the current performance evidence should be interpreted as functional and user-perceived operational stability, while more detailed technical profiling is recommended for subsequent development.

Table 2 Quantitative Usability Metrics via Likert Scale Evaluation

No.	Usability and System Quality Criteria Assessed	Score Index (%)
1.	Ease of navigation and user interface accessibility	91.5%
2.	Responsiveness of the AR camera initializing phase	89.0%
3.	Visual clarity and aesthetic value of the 3D models	87.5%
4.	Stability of the marker-based tracking loop	88.5%
5.	Accuracy and synchronization of the instrument audio	93.0%
6.	Clarity of historical information text delivery	90.5%
7.	System operational stability without execution crashes	92.0%
8.	Application efficiency regarding memory and hardware	86.5%
9.	Relevance of the application as a preservation medium	94.0%
10.	Overall satisfaction and recommendation willingness	91.0%
Average Cumulative System Usability Index		90.35%

Following the functional black-box verification, the system underwent an empirical evaluation to measure user acceptance and usability using a ten-point Likert scale questionnaire distributed among twenty active respondents, including local Papuan students and cultural representatives from *Sanggar Wakiong* and *Sanggar Mbaham Matta*. The respondent group represented potential users of the application, particularly individuals involved in cultural learning, community activities, and local heritage preservation. However, detailed demographic variables such as age, gender, educational level, and prior experience with AR technology should be reported more explicitly in future evaluations because these characteristics may influence perceived usability and acceptance. The empirical data gathered from this human-computer interaction study is comprehensively detailed in Table 2. The statistical insights from Table 2 indicate that the application secured an outstanding average cumulative system usability index of 90.35%. The highest approval score reached 94.0% for the relevance of the application as a sustainable cultural preservation medium, reflecting that the target community highly values this digital migration. Furthermore, audio accuracy and UI navigation scores both exceeded 91%, indicating that the interactive features are highly intuitive for non-technical users. The relatively lower score for application efficiency regarding memory and hardware, although still within a positive category, suggests that technical optimization remains necessary, especially for devices with limited specifications.

The relevance of these results directly answers the core research problems stated in the introduction, specifically concerning the severe lack of public access to rare indigenous instruments in the Fakfak Regency. By interpreting the high user satisfaction metrics alongside the error-free functional black-box logs, the discussion confirms that marker-based AR acts as an efficient bridge to democratize exclusive cultural assets. In comparison to conventional passive learning media such as printed text or basic two-dimensional photographs, this interactive mobile application introduces an immersive layer of mixed reality that can increase user engagement by allowing learners to observe instrument forms, listen to authentic sounds, and read cultural explanations within the same interaction space. This finding is consistent with previous AR-based learning and cultural heritage studies, which suggest that interactive visualization can strengthen user attention and make abstract or rarely encountered cultural objects easier to understand. However, this study extends earlier work by focusing specifically on traditional Papuan musical instruments from Fakfak and by combining visual, auditory, and contextual cultural information verified through local cultural sources. The system successfully bypasses geographic and logistical barriers, allowing students to inspect the minute carvings of the Tifa Titir and listen to the resonance of the Gong directly through personal mobile devices without needing to access rare museum storage or isolated cultural centers. Consequently, this digital solution establishes a scalable, verified framework for preserving endangered indigenous knowledge, transforming mobile smartphones into active tools for cultural protection and cross-generational learning.

The contribution of the application to public access is reflected in its ability to convert cultural information that was previously tied to physical locations into portable digital learning content. Users do not have to visit Sanggar Wakiong, Sanggar Mbaham Matta, museums, or ceremonial events to obtain introductory knowledge about the Tifa, Tifa Titir, and Gong. Through the Android platform, the application enables broader audiences, especially students and young users, to access visual representations, sound samples, and cultural narratives using devices that are already familiar in daily life. This strengthens the practical role of AR as a bridge between local cultural custodians and wider public learning.

Despite these benefits, several limitations must be considered. First, the use of physical markers supports stable tracking but may reduce user comfort when markers are unavailable, damaged, poorly printed, or scanned in low-light environments. Second, the evaluation emphasized functional success and user satisfaction, while detailed technical benchmarks such as FPS, CPU usage, memory profiling, rendering latency, and marker detection range were not yet measured using dedicated profiling tools. Third, the relatively small respondent group limits the generalizability of the usability findings. Therefore, future testing should involve larger and more diverse respondents, compare different device specifications, and include objective AR performance indicators to strengthen the technical and educational validity of the application.

Conclusions

This research has successfully demonstrated the design, systematic development, and empirical deployment of an interactive Android-based Augmented Reality application dedicated to the preservation and recognition of traditional Papuan musical instruments from the Fakfak Regency. In line with the research objective, the application was developed to recognize and introduce the Tifa, Tifa Titir, and Gong through interactive three-dimensional visualization, authentic audio playback, and contextual cultural information. By integrating the structural linear workflows of the Waterfall software development methodology, the technical execution seamlessly synchronized 3D instrument models with the cross-platform rendering capabilities of the Unity engine and the computer vision tracking loops of the Vuforia SDK. Comprehensive evaluation through rigorous functional black-box testing validated that the software platform functioned successfully across the main interactive components, achieving complete validation across all critical interactive components, including real-time image target recognition, dynamic scene transitions, and synchronized authentic audio playback. Furthermore, quantitative human-computer interaction studies utilizing a standardized Likert scale model yielded a cumulative system usability index of 90.35%, indicating a highly satisfactory user acceptance rate among local students, community members, and cultural custodians from *Sanggar Wakiong* and *Sanggar Mbaham Matta*.

The core contribution of this digital intervention lies in its capability to improve public access to information on rare indigenous musical instruments such as the Tifa, Tifa Titir, and Gong. By migrating traditional physical heritage into an immersive mobile mixed-reality environment, this application effectively democratizes rare ethnomusicological knowledge, bypassing geographical barriers and transforming everyday smartphones into active instruments for cultural learning and preservation. Scientifically, this study contributes a localized AR-based cultural preservation model that integrates expert-informed cultural content, visual representation, audio experience, and mobile accessibility. Practically, the application provides an educational medium that can be used by students, communities, and cultural institutions to introduce Papuan musical heritage beyond the limited space of cultural houses or ceremonial events. Based on these substantial outcomes, future research paths should aim to broaden the operational scope of the platform by incorporating a wider array of indigenous Papuan instruments from diverse tribal regions, optimizing markerless tracking capabilities to eliminate physical printout dependencies, and implementing cloud-based content delivery networks to guarantee continuous software sustainability and scalability across broader educational ecosystems. Further studies should also evaluate learning outcomes, cultural awareness, long-term user engagement, technical performance indicators such as FPS, memory usage, CPU usage, and marker detection range, and test the application with larger and more diverse respondent groups to enhance its effectiveness, scalability, and educational impact.

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