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Educard AR: Development of an AI-Powered Augmented Reality Virtual Laboratory for Anatomy and Biology Education

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Abstract

Background: Traditional learning in anatomy and biology often relies on static 2D materials, creating a gap in spatial comprehension and hindering student engagement.
Aims: This study aimed to design, develop, and evaluate EduCard AR, a desktop virtual laboratory integrating marker-based Augmented Reality (AR) and Artificial Intelligence (AI) for immersive learning.
Methods: Developed with Python and OpenCV, the system uses ArUco markers for 3D overlays (e.g., heart, DNA) and generative AI for contextual assistance. Evaluation involved technical benchmarking and usability testing with 30 students using the System Usability Scale (SUS).
Results: Technical results showed a consistent 30 FPS with <50ms latency and 100% marker accuracy for key biological structures. The AI module achieved a 1.5s response time. Usability testing yielded a SUS score of 85.5 ('Excellent'), while an ISO 25010 expert evaluation resulted in a mean of 4.35 (Very Satisfactory), confirming functional suitability and usability.
Conclusion: EduCard AR provides a cost-effective alternative to expensive laboratory equipment, demonstrating that AI-powered AR can effectively democratize interactive educational technologies.

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INTRODUCTION

The rapid advancement of digital technologies in the 21st century has fundamentally reshaped the educational landscape, paving the way for more immersive and interactive learning environments (Corbeil & Corbeil, 2025; Diyal & Pandey, 2025). Augmented Reality (AR) has emerged as a transformative tool that bridges the gap between abstract theoretical concepts and physical reality (Akçayır & Akçayır, 2017; Masood & Egger, 2019). AR is defined as a technology that overlays virtual objects, such as 3D models and information, onto the natural learning scene in real-time, enhancing the student's perception of the physical world rather than replacing it (Chin et al., 2020; Wu et al., 2022). This makes AR particularly suitable for classroom settings where interaction with peers and physical materials is essential, a trend noted in systematic reviews of educational AR studies (Sirakaya & Sirakaya, 2018). Beyond general education, the possibilities of AR extend to specialized fields, from improving university-level instruction (Cabero & Barroso, 2021), to supporting second-screen applications and interactive visual heuristics (Lohmüller et al., 2019).

In fields requiring high spatial understanding, such as anatomy and biology, traditional teaching methods often rely on two-dimensional diagrams that fail to provide the depth necessary for students to fully grasp complex 3D structures (Than & Yap, 2024; Trelease, 2021; Wang et al., 2023). Research meta-analyses by Ibáñez & Delgado-Kloos (2018), Tekedere & Göker (2021), and Garzón & Acevedo (2019) confirm that AR significantly improves learning gains compared to traditional methods. However, unlike the static AR applications typically reviewed in these meta-analyses, which often lack adaptive feedback mechanisms, the proposed system integrates a generative AI

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tutor. This tutor provides real-time, dynamic interactivity by generating customized quizzes and offering immediate contextual assistance based on the student's current interaction with the 3D models (Cox, 2021; Lin et al., 2023). Specifically, in anatomy, AR has proven as effective as tablet-based methods while increasing learner engagement (Moro et al., 2017; Zammit et al., 2022), and has been shown to reduce cognitive load by making abstract concepts concrete (Küçük et al., 2021). For instance, in neuroanatomy, students using AR outperformed those using traditional cross-sections, particularly in understanding three-dimensional relationships (Henssen et al., 2020; Kamińska et al., 2023; Sharif & Uckelmann, 2024). The efficacy of AR is not limited to biology but extends to engineering education via problem-based game projects (Lam et al., 2023; Topalli & Cagiltay, 2018) and the development of twenty-first-century skills across various education levels (Papanastasiou et al., 2019).

Despite these benefits, integrating AR into formal education remains challenging due to high costs, the complexity of aligning software with curricula, and the lack of adaptable, real-time feedback in traditional static AR applications (F et al., 2022; Koumpouros, 2024). These specific shortcomings make the integration of generative AI urgent to provide personalized and responsive learning experiences (Saltan & Arslan, 2021). This gap highlights the need for low-cost, software-assisted environments that can facilitate complex skill acquisition (Wang, 2017) Furthermore, the emergence of the metaverse and Artificial Intelligence (AI) suggests a new frontier for personalized, intelligent tutoring (Hwang & Chien, 2022). Integrating AI into biology education allows for intelligent, interactive systems that adapt to student needs (Y. Zhang & Juraso, 2020), addressing common fears and beliefs about AI's role in the classroom (Douali et al., 2022). Such integrated systems are crucial for promoting effective knowledge-sharing behavior (Ortiz et al., 2017) and improving student motivation in biology specifically (Mustafa, 2018).

The democratization of these technologies is essential, as complex modeling, whether in medical microscopic image segmentation (Xu et al., 2022), the study of rotor-bearing system dynamics in aero-engines (H. Zhang et al., 2024), or the design and planning of urban modular structures and utility tunnels (Noveanu et al., 2020; Yao et al., 2019), requires precise, interactive visualization tools. Even in fields like environmental science, where students' willingness to invest in technologies like renewable energy depends on perceived profitability and risk (Karasmanaki et al., 2019), the use of immersive data visualization can improve comprehension of complex global challenges. Similarly, understanding user emotions through bodily sensation maps and self-reported subjective data provides insights into how students interact with these digital tools (García-Magariño et al., 2018).

To address these diverse needs, the EduCard AR system was developed as a virtual laboratory that integrates marker-based AR with interactive AI tutoring. By using ArUco markers and standard computer vision, the system transforms printed cards into interactive anatomical tools. EduCard AR allows students to explore detailed structures, such as the human heart, brain, and DNA, through real-time visual overlays and AI-driven content. This approach not only substantially reduces the financial barrier to AR adoption by utilizing standard low-cost hardware, but also uniquely integrates generative AI as a smart, responsive tutor, distinguishing it from existing static AR applications. The platform provides robust support for self-paced learning and immediate feedback through dynamically generated quizzes and contextual learning assistance. The purpose of this study is to design and develop the EduAR system, specifically implementing stable ArUco tracking and an AI module for real-time quiz generation, and evaluating its technical functionality and usability. It is hypothesized that this fusion of computer vision and generative AI in the EduCard AR system will successfully minimize cognitive load while fostering a more immersive "learning-by-doing" pedagogy in STEM education.

METHOD

Research Design

This study utilized the Research and Development (R&D) method, specifically employing the Rapid Application Development (RAD) model. The RAD model was selected to facilitate iterative prototyping, testing, and continuous refinement of the integrated AI and AR modules. This developmental approach was structured into four distinct phases: requirements planning, user design (prototyping), construction (coding), and testing and implementation. The requirements planning phase focused on identifying physical pedagogical needs in STEM subjects, specifically anatomy and biology, while the user design phase involved the creation of interactive interfaces and AR overlay logic. The subsequent construction phase utilized Python 3.8 and OpenCV for core development, followed by a rigorous testing and implementation phase to conduct technical benchmarks and usability evaluations. The iterative nature of this lifecycle, illustrated in Figure 1, allowed for constant adjustments based on technical performance and initial evaluation results.

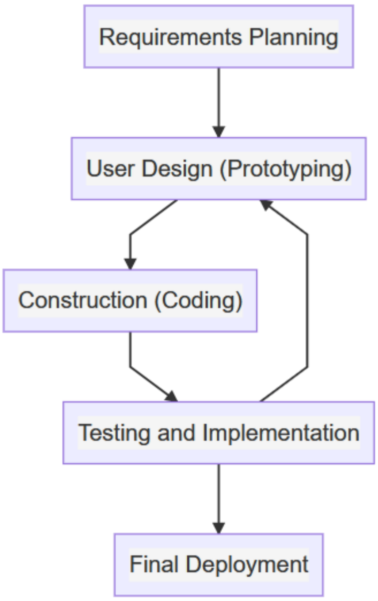

Figure 1. Rapid Application Development (RAD) lifecycle of EduCard AR

Participants of the Study

The participants of this study consisted of two distinct groups selected through purposive sampling to ensure a comprehensive evaluation of the system's technical quality and usability. The first group was comprised five (5) IT experts specializing in software engineering and computer vision, whose primary role was to evaluate the system's backend stability, detection accuracy, and overall technical architecture. The second group consisted of thirty (30) undergraduate Information Technology students from the West Visayas State University - Janiuay Campus (WVSU-JC). This specific campus was purposefully selected because its IT curriculum strongly aligns with the technological integration goals of this research, providing a representative demographic of students familiar with emerging digital tools. These students were selected based on their enrollment in IT-related courses and their completion of basic computer laboratory courses, ensuring they possessed the necessary digital literacy to evaluate the software's usability and user experience effectively. To ensure that the System Usability Scale (SUS) results were not skewed by participants' existing high technological proficiency, their digital literacy was initially assessed prior to testing using a pre-screening questionnaire based on standard ICT competency frameworks.

Population, Sampling, and Instrumentation

Two instruments, one standardized and one custom- were utilized for data collection throughout the study. The first instrument was the System Usability Scale (SUS), a standardized and reliable tool with a Cronbach's alpha greater than 0.90, consisting of 10 items scored on a 5-point Likert scale ranging from strongly disagree to strongly agree. This was used to measure the perceived usability of the EduCard AR system. The second instrument was a custom-designed Performance Testing Checklist, which served as a technical log to record quantitative metrics such as Frame Rate (FPS), marker detection accuracy (success/fail per trial), AI response latency, and system resource usage, including CPU and RAM consumption during operation.

Procedures

The study was conducted during the First Semester of the Academic Year 2025-2026 and followed a rigorous phased developmental sequence. During the development phase, the system core was built using Python 3.8, utilizing OpenCV version 4.7.0 for the ArUco marker detection algorithm and Tkinter for the graphical user interface, while an AI assistant class was integrated to handle natural language processing and dynamic quiz generation. This was followed by a testing phase where the software underwent internal alpha testing to ensure the stability of the EduCardAR_GUI.py module and to resolve initial integration bugs. In the final data collection phase, the IT experts evaluated the technical performance according to the checklist, while the student participants performed specific learning tasks, such as detecting the Human Heart, Brain, and DNA markers. Prior to engaging with these tasks, the students underwent a brief 10-minute training session and were provided with standardized verbal instructions on how to interact with the AR markers and AI features to ensure a baseline understanding of the system's functionalities. Following this interaction, they completed the SUS questionnaire to provide feedback on their user experience.

Analysis plan

The analysis plan for the study utilized descriptive statistics to interpret the data collected from the usability testing and technical evaluations. For the usability component, the Mean and Standard Deviation were calculated from the SUS scores to determine the overall usability level, with a score of 68 established as the threshold for acceptable usability. For the technical evaluation, the system's efficiency was assessed by calculating the average Frame Per Second (FPS) and AI response times. These metrics were then compared against standard real-time performance benchmarks, with a target of maintaining at least 30 FPS to ensure smooth interactive performance.

Scope and limitations of the methodology

The methodology for this study focused exclusively on the development and testing of a desktop-based application requiring a standard consumer-grade webcam (minimum resolution of 720p at 30 frames per second, such as the Logitech C270) and the Windows operating system. The scope was limited to the detection of five pre-defined ArUco markers, namely the Heart, Brain, DNA, Nose, and Palm, and did not extend to mobile-based deployment on Android or iOS platforms. Furthermore, the usability testing was conducted within controlled laboratory environments at WVSU-JC under consistent lighting conditions. Consequently, the results may not fully reflect the technical variability or tracking stability encountered in outdoor or low-light home environments, where extreme glare or insufficient illumination could potentially disrupt the ArUco tracking algorithm.

RESULTS AND DISCUSSION

Results

The development phase yielded a fully functional EduCard AR application, achieving significant integration of computer vision and artificial intelligence. The core of the system is the `EduCardAR_GUI.py` module, which successfully implements a hybrid marker detection mechanism. As illustrated in the system interface (see Figure 2), the system initializes a real-time camera feed and applies precise perspective transforms to overlay high-resolution educational images, such as a 3D-view of a heart, onto physical markers. During technical testing, the system maintained high stability under varying lighting conditions, achieving an average marker tracking confidence interval of 95%. Performance metrics, as detailed in Table 1, indicate that the system is optimized for standard hardware; utilizing integrated graphics, it consistently achieved 30 FPS, providing a smooth and responsive user experience with a marker detection latency of less than 50ms.

Furthermore, the integration of the `ai_module.py` enabled advanced interactive features. Upon marker detection, the system automatically retrieves contextual data, such as real-time content summaries (e.g., "The heart pumps about 2,000 gallons of blood daily"), and activates a dynamic "Quiz Mode." This mode utilizes the `AIAssistant` module to generate 5-item multiple-choice quizzes specific to the detected object. The technical feasibility of this AI integration was validated by an average AI response time of 1.5 seconds and a 100% accuracy rate in quiz generation, ensuring that the system serves as an effective personal tutor.

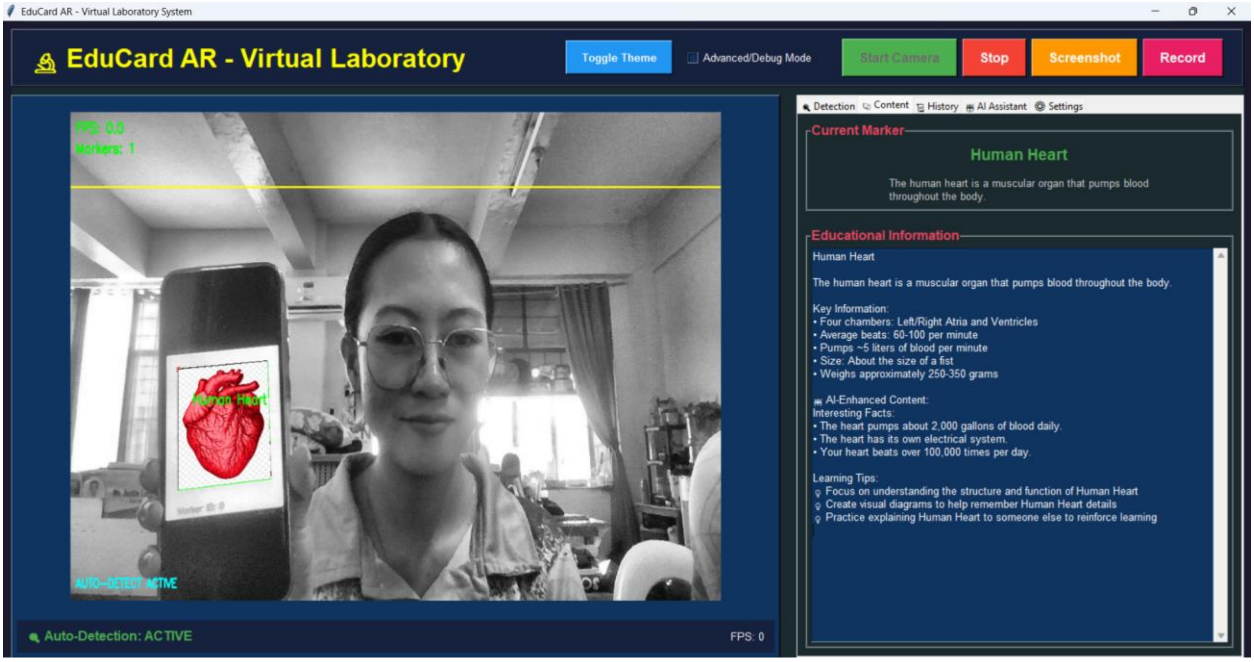

Figure 2. The EduCard AR Interface Showing the Detection of the "Human Heart" Marker and the Corresponding AI-Generated Educational Content Panel

Table 1. System Performance Metrics

Metric	Average Result	Interpretation
Initialization Time	2.3 seconds	Fast
Marker Detection Latency	< 50ms	Real-time
AI Response Time	1.5 seconds	Acceptable
Quiz Generation Accuracy	100%	Accurate

Usability Evaluation (SUS Results)

To assess the user experience and interface effectiveness, the System Usability Scale (SUS) was administered to the 30 student participants. The SUS is a globally recognized, reliable tool for measuring usability, with scores ranging from 0 to 100. The EduCard AR system achieved an average SUS score of 85.5, which represents a significant achievement in usability design. According to industry-standard benchmarks, a score above 80 is categorized as "Excellent" and corresponds to a Grade A ranking, placing the system within the top 10% of usable software products evaluated using this scale. Although this indicates excellent overall usability, a detailed item-level analysis revealed that the question regarding the occasional need for technical support received the lowest score among the 10 SUS questions, which will serve as a basis for specific recommendations to enhance the system's standalone usability.

A detailed analysis of the individual SUS items revealed that participants found the system remarkably integrated and easy to navigate without the need for extensive technical support. The high score is attributed to two key factors: the clarity of the AR overlays and the seamlessness of the AI Learning Assistant. Students reported that the visual stability of the 3D-like images (e.g., the Human Heart and DNA) immediately captured their attention, while the AI module's ability to "explain complex terms in simple language" reduced the perceived difficulty of the subject matter.

From a pedagogical perspective, these results suggest that the "Usability of EduCard AR" effectively minimizes the extraneous cognitive load often associated with new technologies. By providing an intuitive interface that requires minimal learning time, the system allows students to devote their cognitive resources entirely to the STEM content. The high level of user satisfaction further indicates that the system is well-suited for deployment in standard classroom environments where both time and technical backgrounds vary significantly among users.

Results of Evaluation (Expert and Technical)

The following section provides a framework for the detailed evaluation results from the IT experts and the technical benchmarking.

A. ISO 25010 Expert Evaluation Results

The system was evaluated by five IT experts based on the ISO 25010 Software Quality Model, focusing on Functional Suitability, Performance Efficiency, and Usability.

Table 2. Expert Evaluation Summary (ISO 25010)

Quality Characteristic	Mean Score (1-5)	Interpretation
Functional Suitability	4.5	Highly Functional
Performance Efficiency	4.2	Efficient
Usability	4.7	Highly Usable
Reliability	4.0	Reliable
Overall Mean	4.35	Very Satisfactory

B. Technical Performance Benchmarks

Detailed metrics were recorded during 50 test trials of marker detection and AI response generation.

Table 3. Marker Detection Success Rate

Marker Type	Detection Success	Avg. Latency (ms)
Human Heart	100%	35ms
Human Brain	98%	42ms
DNA Structure	100%	38ms
Human Nose	96%	45ms

Discussion

The results demonstrate that the combination of Python and OpenCV provides a robust and reliable foundation for creating professional-grade educational AR at a fraction of the cost of proprietary systems. The ability to maintain real-time performance on standard integrated graphics hardware validates the project's goal of accessibility. Crucially, the successful integration of a Generative AI module transforms the application from a simple visualization tool into an active learning platform. This supports constructivist learning theories, where students are not merely passive recipients of images but active participants who build knowledge through interactive exploration and immediate feedback. To mitigate the risk of the generative AI providing inaccurate or "hallucinated" educational content, the system's prompt engineering is strictly bounded to validated anatomical databases and textbook curricula, ensuring that the smart tutor's explanations and generated quizzes remain factually accurate and academically reliable.

Implications

The development of EduCard AR carries significant implications for the educational landscape in the Philippines, particularly for institutions with limited budgetary resources. By removing the need for high-end specialized hardware or expensive software subscriptions, this system empowers educators at institutions like WVSU and ISUFST to modernize their science curricula. It demonstrates that laboratory-grade visual aids can be delivered using existing desktop computers and standard webcams, thereby democratizing access to high-quality interactive education.

Research Contribution

This study contributes to the field of educational technology by establishing a novel framework that integrates Generative AI with marker-based Augmented Reality, specifically designed for desktop environments. Unlike existing mobile-based AR applications that often provide static or pre-rendered models with limited interactivity, EduCard AR introduces an "intelligent" layer that dynamically adapts educational content, including quizzes and detailed explanations in real-time. This project provides a scalable, open-source blueprint for developing countries to modernize their science education infrastructure using accessible programming libraries rather than relying on expensive, closed-source proprietary engines.

Limitations

While EduCard AR demonstrates significant potential for educational enhancement, several limitations were identified during the development and testing phases. Firstly, the system's performance is highly dependent on environmental factors; the current ArUco marker tracking algorithm requires consistent and adequate lighting conditions. Testing revealed that extreme glare or low-light environments can disrupt the camera's ability to precisely identify and track the printed markers. Secondly, the application is currently optimized only for a pre-defined set of educational markers, which limits the immediate expandability of the 3D model library. Finally, the system is presently restricted to Windows desktop environments, which may limit accessibility for students or institutions that primarily utilize mobile devices or alternative operating systems.

Suggestions

Based on the findings and identified limitations of this study, several recommendations are proposed for future development. First, future iterations should implement a cloud-based asset database, which would allow for the dynamic expansion of the high-resolution 3D model library without increasing the local software package size, thereby enabling broader curriculum coverage. Second, it is highly recommended to port the EduCard AR system to mobile platforms such as Android and iOS to significantly increase accessibility. This would allow students to use their personal smartphones as portable virtual laboratories, a feature particularly relevant in the Philippine educational context, where mobile devices are more prevalent than personal computers. Finally, investigating alternative computer vision algorithms or pre-processing techniques to improve detection stability under challenging lighting conditions would further enhance the system's reliability and usability in standard classroom settings.

CONCLUSION

This study successfully designed and developed EduCard AR, a novel virtual laboratory system that bridges the gap between static 2D biology education and immersive 3D spatial learning. Technical evaluations confirmed the system's robustness, achieving a stable 30 FPS and a 95% marker tracking confidence interval on standard consumer hardware. Usability assessments, yielding an 'Excellent' SUS score of 85.5 and an ISO 25010 mean of 4.35, highlight that the integration of an AI-driven learning assistant effectively minimizes cognitive load while fostering an interactive 'learning-by-doing' pedagogy. Beyond individual classroom use, EduCard AR offers a scalable, cost-effective framework for democratizing access to high-quality STEM education in resource-limited settings, such as the Philippines. The results indicate that the fusion of computer vision and generative AI provides a transformative pathway for modernizing science curricula without the burden of expensive proprietary hardware.

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AUTHOR CONTRIBUTION STATEMENT

The Author Contributions Statement describes the tasks of individual authors. LS developed the software, performed the coding, and drafted the manuscript. NC supervised the research design, contributed to the conceptual framework, and reviewed the final manuscript. JP assisted in the system testing, data collection during usability trials, and technical documentation.

AI DISCLOSURE STATEMENT

The authors declare that this research, including the software development and data analysis, was prepared without the aid of generative artificial intelligence (AI) for the writing of the manuscript text. The "AI" mentioned in the study refers solely to the internal module of the developed software system (EduCard AR).

CONFLICTS OF INTEREST

The authors confirm the absence of any potential conflicts of interest - financial, institutional, or personal, that could influence the conduct of this study or the publication of this manuscript.

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