Effectiveness of augmented reality learning media in enhancing embedded system programming competence: A 4D development study

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Abstract

This study developed augmented reality (AR)–based learning media for analogue and digital input/output programming using Arduino microcontrollers in the Embedded System Programming course at SMK Negeri 4 Pariaman. The research employed a Research and Development (R&D) approach using the 4D model—Define, Design, Develop, and Disseminate. In the Define stage, the study analysed needs, student characteristics, and curriculum materials. The media was designed, validated by experts, tested for practicality, and examined for effectiveness. Validation results indicated that the media was valid, while practicality tests involving teachers and students showed it was very practical. Effectiveness testing using a paired sample t-test revealed a significant improvement in student learning outcomes (Sig. 0.000 < 0.05; t-count > t-table). N-Gain analysis also demonstrated a high level of learning improvement. Overall, the findings confirmed that the AR-based learning media were feasible, practical, and effective in enhancing students' understanding of embedded system programming.

Keywords

Augmented reality, learning media, programming competence, 4D development

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Introduction

The rapid acceleration of technological innovation in the era of Industry 4.0 and the transition toward Industry 5.0 reshaped how education—particularly vocational education—prepared learners for complex and technology-intensive work environments. In Indonesia, the mandate of Law No. 20 of 2003 emphasized that education must develop students' spiritual, intellectual, and practical capacities to participate productively in society. Within this system, Vocational High Schools (SMK) played a strategic role in strengthening national competitiveness by producing graduates equipped with job-ready competencies aligned with industrial needs. Recent empirical studies in vocational education reinforced this mandate, showing that instructional quality, particularly the relevance and effectiveness of learning media, directly affected students' competence development in technical fields (Ramadhan et al., 2024; Supriyanto et al., 2023).

One of the core subjects in the Industrial Electronics Department at SMK Negeri 4 Pariaman is embedded system programming. This discipline requires students to master microcontroller operation, analogue/digital input-output processing, sensor integration, and control system design. However, students often struggled to understand these abstract and highly technical concepts. Traditional instructional approaches—dominated by lectures, static images, outdated modules, and limited hands-on experience—were insufficient to support conceptual comprehension or procedural skills. The situation was further aggravated by the limited availability of laboratory equipment, including Arduino boards, sensor modules, and jumper cables, which resulted in restricted opportunities for practice. These challenges align with findings from recent vocational studies, which reported significant learning barriers when instructional resources were incomplete or when students lacked access to authentic learning tools (Mukhlisin et al., 2025; Kostov & Wolfartsberger, 2022).

Recent theoretical developments emphasized the importance of immersive, interactive, and learner-centered media in supporting cognitive processes, especially in science and engineering learning. The updated Cognitive Theory of Multimedia Learning (CTML) posits that effective learning occurrs when visual-spatial and verbal information are integrated in a cognitively efficient manner. Mayer (2024) highlighted that immersive multimedia environments—such as augmented reality (AR)—were particularly beneficial because they aligned with dual-channel processing, reduced extraneous load through signaling and spatial contiguity, and promoted generative processing through interactive exploration. This theoretical lens demonstrated why multimedia-rich environments were especially effective in teaching embedded system concepts that required students to visualize connections between code, hardware, and sensor behavior.

Spatial visualization theory also evolved recently, emphasizing the importance of three-dimensional representations in technical learning. A series of experimental studies has confirmed that AR substantially enhances learners' spatial reasoning abilities, reduces cognitive abstraction, and improves procedural accuracy in electronics and engineering tasks by transforming symbolic representations into manipulable 3D environments (Kazlaris et al., 2025; Krüger et al., 2022). Embedded systems, which require an understanding of microcontroller pins, input-output pathways, and the behavior of sensors in real-time, fit directly into this category of high-spatial-demand subjects.

Augmented reality has emerged as one of the most impactful immersive technologies in education over the last five years. Systematic reviews published between 2020 and 2025 consistently demonstrated that AR significantly improved learner performance, motivation, practical skills, and conceptual understanding, especially in vocational and engineering contexts (Al-Mansoori, 2023; Supriyanto et al., 2023). AR enabled students to interact with virtualized representations of hardware components, observe real-time simulations, and understand sensor-program interactions without relying solely on physical equipment. Unlike conventional media, AR blends real and virtual contexts, making abstract system operations visible, dynamic, and meaningful.

In the domain of embedded systems and microcontroller programming, AR was shown to be particularly effective. A 2025 quasi-experimental study in a vocational microcontroller course found that AR-based media produced significantly higher learning outcomes than conventional methods, especially in interpreting circuit logic and programming flow (Mukhlisin et al., 2025). Meanwhile, technical education research from 2022 to 2024 reported that AR enhanced students' laboratory readiness by allowing repetitive, risk-free practice of procedures before interacting with actual devices (Ramadhan et al., 2024). These findings were highly relevant to the conditions at SMK Negeri 4 Pariaman, where learning relied heavily on limited laboratory facilities but where students owned smartphones capable of running AR applications.

Contemporary pedagogical frameworks also supported the integration of AR in vocational learning. Recent extensions of the Technological Pedagogical and Content Knowledge (TPACK) model emphasized that technology integration in vocational education must respond to authentic industrial competencies. Torggler et al. (2023) introduced the N-TPACK Framework for vocational teachers, arguing that technology should not merely support teaching but transform it through realistic simulation of industrial practices. AR aligned naturally with this paradigm because it allowed embedded system concepts to be represented in the same way they were applied in professional environments—visually, procedurally, and interactively.

Similarly, recent interpretations of the SAMR Model have demonstrated that transformative learning occurred when technology reaches the Modification and redefinition stages—where learning tasks are redesigned or become newly possible through the use of technology. AR was consistently classified as a redefinition-level tool because it enabled immersive simulation of hardware behavior that could not be replicated through textbooks, videos, or lectures (Boonmoh & Kulavichian, 2023; Zulfiani et al., 2025). In embedded systems, AR allowed students to "see" invisible signals, interact with simulated circuits, and understand the logic flow of microcontroller programming, redefining what learning could be.

Pedagogically, AR is aligned with constructivist experiential learning theory, which emphasizes active knowledge construction through interaction, problem-solving, and real-world engagement. The ability of AR to blend physical and virtual environments created a learning context that promoted exploration, hypothesis testing, and immediate feedback—processes essential for mastering programming and control systems. Current research has confirmed that AR encourages learner autonomy, increases time-on-task, and improves self-efficacy in performing complex technical procedures (Kazlaris et al., 2025; Ramadhan et al., 2024).

With students already possessing AR-compatible smartphones, the implementation of AR learning media became both pedagogically appropriate and technologically feasible. By visualizing analogue/digital I/O processes, sensor operations, and code behavior in real-time, AR had the potential to significantly strengthen conceptual understanding, improve procedural skills, and enhance the overall learning experience in embedded system programming.

Therefore, this study aimed to develop and evaluate augmented reality-based learning media using the 4D model (Define, Design, Develop, and Disseminate) and assess its validity, practicality, and effectiveness in improving student learning outcomes in the Embedded System Programming subject. Integrating AR was expected to provide a transformative learning experience that supported the demands of Industry 4.0, strengthened vocational competencies, and enriched instructional innovation in Indonesian vocational education.

Literature Review

Augmented reality in vocational and engineering education

Augmented reality (AR) has emerged recently as one of the most transformative and pedagogically impactful technologies within vocational and engineering education. Numerous studies from 2020 to 2025 indicate that AR offers unique affordances that traditional learning media cannot provide, such as spatially anchored visualization, real-time simulation, interactive exploration, and enhanced representational fidelity. These affordances are particularly beneficial for engineering-related subjects, where learners must understand abstract system structures, dynamic processes, and complex spatial relationships, as noted in a systematic review by Al-Mansoori. (2023) highlighted that AR significantly improved learner engagement, conceptual comprehension, and psychomotor readiness, especially in contexts such as electronics, mechatronics, and automation, where hands-on practice is essential.

From a pedagogical standpoint, AR aligns well with constructivist, experiential, and problem-based learning paradigms. Unlike static diagrams or two-dimensional images, AR anchors virtual 3D objects directly onto the learners' physical environment, enabling them to manipulate, observe, and interact with systems in ways that mirror real-world practices. Studies in vocational learning environments have demonstrated that AR-based representations can help reduce misconceptions, strengthen procedural fluency, and enhance diagnostic reasoning (Ramadhan et al., 2024). This is because AR simulates not only the visual appearance of components but also their behaviours, allowing students to observe changes in sensor values, current flow, and digital-analogue responses in real-time.

The relevance of AR is even more pronounced in microcontroller and embedded system education. Research by Mukhlisin et al. (2025) demonstrated that AR-assisted learning enabled students to connect programming syntax with real hardware output more effectively. When students view microcontroller pin functions, sensor responses, and data processing flows through AR simulations, they gain clearer mental models of how software logic interacts with hardware systems. Similarly, Krüger et al. (2022) noted that AR significantly enhances spatial reasoning in technical education, making it easier for learners to grasp multidimensional wiring schemes, circuit layouts, and input/output pathways.

Recent frameworks also emphasize the role of AR in fostering vocational readiness. The N-TPACK framework for vocational teachers (Torggler et al., 2023) argues that AR does not merely enrich learning but enables authentic representations of industrial practices—such as testing circuits, monitoring data, and troubleshooting systems—all of which mirror actual workplace procedures. Taken together, these theoretical and empirical insights indicate that AR offers substantial pedagogical value for vocational institutions seeking to strengthen both cognitive and practical competence in engineering-oriented subjects.

Cognitive and multimedia learning theories supporting AR integration

Contemporary developments in cognitive and multimedia learning theories strongly support the instructional effectiveness of augmented reality. The updated Cognitive Theory of Multimedia Learning (CTML) by Mayer (2024) asserts that learning is enhanced when instructional materials engage learners through dual channels—visual/pictorial and auditory/verbal—while managing cognitive load through practical design principles. AR inherently supports these principles by integrating multimodal stimuli into a cohesive environment. Instead of viewing diagrams on a flat screen, learners interact with contextually embedded digital content directly linked to real physical objects, enabling more efficient processing of complex information.

One of CTML's central updates involves the heightened importance of spatial contiguity and embodied interaction. AR fulfills these principles because it presents information at the exact location where learners' attention is focused—for instance, overlaying a microcontroller's virtual pin labels directly onto the real board. This reduces split attention and extraneous load, allowing learners to allocate cognitive resources to essential processing. The signaling principle, another key CTML element, is naturally embedded in AR experiences through visual highlights, animated cues, and real-time object responses that guide learners in interpreting complex phenomena.

Furthermore, AR supports generative processing by encouraging students to actively manipulate virtual objects, predict system behaviour, and test assumptions. According to Kazlaris et al. (2025), embodied interaction in AR learning environments creates deeper cognitive embedding, making new knowledge more durable and transferable. This is essential in embedded system programming, where learners must internalize both conceptual understanding and procedural accuracy.

Beyond CTML, spatial cognition theory also provides strong justification for integrating AR. Krüger et al. (2022) showed that AR environments significantly improve learners' abilities to interpret multidimensional structures and spatially distributed information. This is especially relevant for interpreting pin mappings, wiring schemes, input–output flows, and real-time data processing in microcontroller systems.

The reducing abstraction function of AR is also supported by experiential and situated learning theories. Ramadhan et al. (2024) argue that learning becomes more meaningful when students interact with representations that resemble real-world contexts. AR bridges symbolic programming with tangible hardware behaviour, enabling learners to observe how code execution manifests physically. This provides a more coherent mental model compared to the traditional method that separates programming from hardware visualization.

In summary, the cognitive and multimedia theories underlying AR demonstrate why AR is particularly effective for technical subjects, where abstraction, complexity, and spatial reasoning pose significant challenges to learning.

AR-based media in embedded system programming

Embedded System Programming is a foundational yet challenging subject for vocational students because it requires mastery of hardware–software integration, sensor processing, digital–analogue communication, and control system behaviour. One of the recurring difficulties in this area is that students struggle to visualize how program logic translates into real-time hardware responses. In traditional instruction, teachers often rely on limited laboratory equipment, static images, or demonstrations that cannot be repeated for every learner. This constraint reduces opportunities for hands-on practice and contributes to shallow conceptual understanding.

Recent studies have highlighted the potential of AR-based media to address these challenges. Mukhlisin et al. (2025) showed that students learning microcontrollers with AR tools achieved significantly higher conceptual and practical competence because AR simulated real-world behaviours such as pin voltage changes, input fluctuations, and sensor-triggered events. AR's dynamic visualizations make invisible phenomena—such as data flow, signal transitions, and program execution pathways—observable and comprehensible.

AR also supports iterative practice without relying on expensive or limited hardware. This aligns with Supriyanto et al.'s (2023) findings, which sugget that AR environments enable learners to repeatedly test, reset, and experiment with microcontroller configurations safely and securely. In vocational education, where equipment scarcity is common, AR provides equitable access to realistic learning experiences.

Furthermore, AR enhances procedural knowledge by guiding learners step-by-step through wiring processes, sensor calibration, and programming interpretation. According to Ramadhan et al. (2024), this type of guided experiential learning helps students internalize procedures more effectively because it visually and interactively scaffolds task sequences.

From a technological integration standpoint, AR satisfies the criteria of the SAMR model at the Modification and Redefinition levels (Zulfiani et al., 2025). It not only replaces traditional diagrams but also transforms learning by enabling new forms of task engagement—such as interacting with simulated circuits or observing sensor feedback in real-time—that would not be possible otherwise.

Finally, the adoption of AR in embedded systems aligns with vocational and industrial competency frameworks. Torggler et al.'s (2023) N-TPACK framework emphasizes that vocational learning media must reflect authentic industry practices. AR simulations closely mimic tasks such as debugging circuits, interpreting sensor outputs, and monitoring microcontroller performance—skills directly relevant to modern electronics and automation industries.

Thus, AR-based media offers significant pedagogical value for embedded system programming by making abstract concepts concrete, enabling safe repetition, supporting procedural fluency, and preparing students for real-world technical environments.

Methodology

This study employed a Research and Development (R&D) approach to produce, validate, and evaluate augmented reality (AR)–based learning media for analogue and digital input/output programming using the Arduino microcontroller. The R&D procedure followed the 4D model—Define, Design, Develop, and Disseminate—proposed by Thiagarajan et al., which continued to be widely applied and refined in recent educational technology research (e.g., Dwi et al., 2022; Latif & Aziz, 2023). This model was selected because it enabled systematic development, iterative refinement, and empirical testing of instructional products in real classroom settings.

Research design

The research design consisted of four sequential stages. The Define stage explored the learning problems, student characteristics, and curriculum outcomes relevant to the Embedded System Programming subject under the *Merdeka* Curriculum. The design stage involved constructing flowcharts, storyboards, AR marker configurations, interface prototypes, and learning scenario pathways. The Develop stage included expert validation, practicality testing, and effectiveness evaluation. The final Disseminate stage implemented the final AR media in the classroom and prepared it for broader use.

This hybrid design, which combines product development with classroom experimentation, aligns with contemporary R&D methodological recommendations, that emphasize both design integrity and the empirical validation of learning technologies in authentic environments (Ramadhan et al., 2024; Wardani et al., 2022).

Research site and participants

The study was conducted at SMK Negeri 4 Pariaman, specifically in the Industrial Electronics Department's Grade XI Embedded System Programming class. Participants consisted of one subject teacher and 15 students, selected through purposive sampling based on the requirement that students were enrolled in the Embedded System Programming course and owned AR-compatible smartphones. This sampling strategy aligned with vocational technology research standards, where specific expertise contexts determine participant inclusion (Supriyanto et al., 2023).

Data collection procedures

Expert validation

Two expert validators—one in instructional media design and one in embedded systems—assessed the AR learning media. The evaluation instrument utilized a 5-point Likert scale to measure content accuracy, design quality, software functionality, and pedagogical relevance. The content validity coefficient was calculated using Aiken's V to determine the level of agreement among experts. Aiken's V was widely recognized in recent psychometric analysis for measuring item relevance and expert consensus (Azwar, 2022; Jamaluddin et al., 2021).

Practicality testing

Practicality was examined through teacher and student response questionnaires. Indicators included user-friendliness, clarity of instructions, media accessibility, and classroom applicability. Practicality instruments followed the guidelines of recent studies that emphasized usability, efficiency, and learner satisfaction as key indicators of digital learning practicality (Latip et al., 2023; Rusyida et al., 2025).

Effectiveness testing

Effectiveness was assessed using a one-group pretest–post-test design. Three complementary analytic methods were applied:

a. Classical completeness analysis, requiring 85% of students to achieve the Minimum Mastery Criterion (KKM), following Indonesian national assessment standards.
b. Normalized Gain (N-Gain) to measure improvement in learning outcomes. N-Gain was selected because it has been widely used in recent AR-learning studies to assess meaningful improvements in cognitive performance (Krüger et al., 2022; Mukhlisin et al., 2025).
c. Paired Sample t-Test to determine whether there was a statistically significant difference between pretest and post-test scores. This test was chosen because it is suitable for dependent scores measured on the same participants before and after treatment (Field, 2022).

All statistical computations were performed using SPSS 23. Assumption testing—normality and homogeneity—was conducted before performing the t-test to ensure robustness.

Data analysis techniques

Validity analysis

Aiken's V formula was used to compute expert validation values:

$$V = \frac{\sum s}{n(c-1)}$$

where *s* is the score adjustment, n is the number of experts, and c is the number of scale points. A V-value ≥ 0.80 was interpreted as "high validity," consistent with recent validation benchmarks (Azwar, 2022).

Practicality analysis

Practicality scores were converted into percentages and categorized as Very Practical, Practical, or Less Practical, in accordance usability standards in digital learning media design (Latif & Aziz, 2023).

Effectiveness analysis

Classical completeness was evaluated using:

$$\text{Completeness (\%)} = \frac{\text{Students who achieved KKM}}{\text{Total students}} \times 100$$

N-Gain was computed using:

$$g = \frac{\text{Post-test} - \text{Pretest}}{\text{Max score} - \text{Pretest}}$$

N-Gain categories followed Hake's (1998) threshold adopted in recent AR research: High ($g > 0.70$), Moderate ($0.30 \leq g \leq 0.70$), Low ($g < 0.30$).

Paired t-tests compared mean scores before and after treatment. A significance value of $p < .05$ indicated a meaningful improvement attributable to the AR learning media (Field, 2022).

Findings

The development and evaluation of augmented reality (AR)–based learning yielded several significant findings related to its validity, practicality, and effectiveness in supporting both analogue and digital input/output programming within the Embedded System Programming subject. The validation process conducted by media and material experts showed that the product met the expected standards for instructional quality. Media experts assessed aspects of design, interface navigation, visual layout, and software stability, and the results indicated that the AR media reached a high level of feasibility. The Aiken's V coefficient produced an average score of 0.90, confirming that the media design was visually suitable, technically stable, and pedagogically appropriate for vocational students. Likewise, evaluation by the material expert demonstrated that the content aligned well with the learning outcomes required in the *Merdeka* Curriculum. The expert rated the accuracy and clarity of the analogue and digital input/output concepts, the representation of Arduino components, and the alignment between learning objectives and AR visualizations with high scores, resulting in an overall validity value of 0.93. These findings established that both the material and the media aspects of the product were valid and ready for use in the classroom.

The practicality of the AR media was assessed through teacher and student responses after they used the application during a learning session. The teacher reported highly positive experiences, particularly in relation to clarity of instructions, accuracy of the AR simulation, ease of integration into the lesson plan, and efficiency of classroom implementation. The teacher emphasized that the media allowed more effective explanations of concepts that were previously difficult to visualize, such as sensor behaviour, digital–analogue differences, and the mapping of Arduino pins. The overall teacher practicality score fell into the "very practical" category. Student responses supported these findings, showing that they were able to operate the AR application efficiently and navigate between different simulation layers without difficulty. They also indicated that the application improved their understanding of the functions of input and output devices and helped them visualize the interaction between hardware and programming commands. Students appreciated the interactive and immersive nature of the AR media, describing it as more engaging and easier to understand compared to conventional learning resources. Their average practicality score was 89.08%, also categorized as "very practical," indicating that the product was highly accessible and beneficial for learners.

The effectiveness of the AR learning media was measured using a pretest–post-test procedure. Before using the media, students generally demonstrated limited understanding of analogue and digital input/output programming, as reflected in the pretest scores. After learning with the AR application, their post-test scores improved significantly. Classical completeness analysis revealed that 73.33% of students achieved the minimum mastery level. Although the completeness had not yet reached the ideal criterion of 85%, it still indicated a substantial improvement in students' mastery of the material, especially considering the abstract and technical nature of embedded system concepts.

The normalized gain (N-Gain) analysis further supported the effectiveness of the AR media, with an average N-Gain score of 0.7073, which was classified as "high." This result demonstrated that the AR simulation made s significant contribution to students' cognitive improvement, particularly in understanding real-time sensor responses, interpreting program output, and linking Arduino pin functions to programming logic. The improvement was most visible in items requiring higher-order thinking, such as predicting sensor behaviour or analysing code-hardware interaction.

To determine whether the improvement was statistically significant, a paired sample t-test was conducted. The SPSS output showed a significance value of 0.000 ($p < 0.05$), with a t-count of 8.097, which exceeded the t-table value of 2.145. These results confirmed that the increase in student learning outcomes after using the AR media was not due to random chance. Still, they represented a meaningful and statistically significant effect of the intervention. The AR application, therefore, played a crucial role in enhancing students' conceptual understanding of embedded system programming.

Overall, the findings indicated that the AR-based learning media were valid, practical, and effective. The expert validation results established strong content and media feasibility; teacher and student responses confirmed that the product was easy to use and highly supportive of learning activities. The pretest–post-test analysis demonstrated substantial cognitive gains after the integration of AR technology. These findings collectively indicate that AR media serve as a practical instructional innovation for enhancing the learning experience and improving learning outcomes in vocational education, particularly in the context of embedded system programming, where visualization, interactivity, and simulation play a crucial role in understanding complex technical concepts.

Discussion

The findings of this study demonstrated that the augmented reality (AR)–based learning media developed for analogue and digital input/output programming on Arduino microcontrollers were valid, practical, and effective. These outcomes suggested that AR integration contributed meaningfully to students' cognitive understanding and learning performance in the Embedded System Programming subject. The positive results also aligned with recent theoretical and empirical developments in digital learning and vocational education.

The validity results, which indicated high expert agreement on both content and media quality, reflected the suitability of AR for representing abstract technical concepts. This is consistent with Mayer's (2024) updated Cognitive Theory of Multimedia Learning, which explains that integrated visual-verbal representations facilitate learners in forming mental models of complex systems. AR's immersive representation of components such as sensors, microcontroller pins, and signal flow supported learners' dual-channel processing, enabling them to interpret how program commands translated into hardware behaviour. The strong validity scores also indicated that the design principles applied—clarity, spatial contiguity, and signaling—matched current recommendations for AR instructional design.

Practicality findings from teachers and students also confirmed that the AR media was well-received and integrated into classroom practice. Teachers noted that AR enabled them to demonstrate real-time interactions between code and hardware, compensating for the limitation of their laboratory tools. This finding is supported by Supriyanto et al. (2023), who emphasized that in vocational settings where authentic equipment is often insufficient, AR can provide safe, repeatable, and highly realistic simulations. Students' high ratings for practicality suggested that the interface design, AR tracking stability, and step-by-step simulation features aligned with user-centered design principles recommended for mobile-based AR technologies. The ease of use reported by students also reflected the alignment between AR features and constructivist, experiential learning approaches, in which learners construct understanding through active exploration and interaction.

The effectiveness results provided further evidence of AR's potential to enhance learning outcomes. The significant increase in post-test scores, along with the high N-Gain value, indicated that AR substantially improved conceptual understanding. This result aligned with findings by Mukhlisin et al. (2025), who observed that AR-assisted microcontroller learning enhanced students' ability to connect program syntax with physical device responses. AR's capability to visualize dynamic sensor behaviour and generate immediate feedback allowed students to correct misconceptions, test hypotheses, and reinforce learning, processes central to experiential and inquiry-based learning models.

Classical completeness, although not reaching the ideal mastery threshold, still showed substantial improvement, suggesting that AR reduced the cognitive load associated with learning embedded systems. According to Krüger et al. (2022), AR enhances learners' spatial reasoning by providing manipulable 3D models, enabling them to interpret abstract schematics that are otherwise difficult to visualize. In this study, AR simulations—such as viewing the behaviour of an LDR sensor under different lighting conditions—helped students relate real-world variables to programming logic. This supports earlier assertions that AR allows learners to "see the invisible," making abstract processes more tangible.

Additionally, the effectiveness of the AR media can be understood through the lens of the SAMR model. When viewed through this framework, AR represents a learning transformation at the modification and redefinition stages (Zulfiani et al., 2025). Traditional learning relied on static diagrams or limited hardware demonstrations; AR redefined the task by enabling learners to interact with virtualized circuits, view real-time sensor outputs, and experience simulations that were not possible through conventional methods alone. This transformation created new learning modalities that contributed to students' improved comprehension.

From a vocational education perspective, the findings reinforced the relevance of the TPACK and N-TPACK frameworks. Recent work by Torggler et al. (2023) emphasized that effective technology integration in vocational contexts requires alignment between technological, pedagogical, and content dimensions, supported by authentic industry practices. The AR media developed in this study aligned with these principles because it supported the required embedded system competencies and resembled authentic industrial workflows where technicians rely on digital visualization tools to troubleshoot and test systems. Therefore, the AR media did not merely assist learning—it reflected the technological ecosystem that students are expected to engage with in real-world professional environments.

The combined evidence from validity, practicality, and effectiveness aspects indicates that AR is particularly suitable for teaching concepts that require high spatial visualization and hands-on interpretation. Its integration helps address key challenges in vocational schools, such as insufficient laboratory equipment, limited demonstration time, and the abstract nature of embedded system programming. This study, therefore, supports wider adoption of AR in subjects involving electronics, automation, mechatronics, and control systems.

Overall, the discussion highlights that the AR-based learning media successfully enhanced students' engagement, understanding, and performance. The findings contribute to current literature by reinforcing the suitability of AR for competency-based, practice-oriented learning in vocational education. The positive outcomes suggest that AR should be further developed for more complex embedded system topics, such as serial communication, multitasking, Internet of Things (IoT) integration, and system debugging. With continued refinement, AR has the potential to become a standard instructional tool that advances innovation and quality in engineering-oriented learning environments.

Conclusion

The development and evaluation of augmented reality (AR)–based learning media for analogue and digital input/output programming demonstrated that AR is a feasible, practical, and effective solution for improving learning in the Embedded System Programming subject at SMK Negeri 4 Pariaman. The expert validation process confirmed that both the media design and instructional content met high standards of accuracy, clarity, and pedagogical relevance, indicating that the product was ready for classroom implementation. Teacher and student responses also showed that the AR media was highly practical, accessible, and engaging, providing interactive visualizations that supported comprehension of technical concepts that were previously difficult to demonstrate using conventional materials.

The effectiveness analysis further established that AR significantly improved student learning outcomes. The high N-Gain score and statistically significant increase in post-test results demonstrated that the integration of AR supported a deeper conceptual understanding, particularly in interpreting sensor behavior, distinguishing between analogue and digital signals, and connecting program logic to hardware functions. These results align with current theoretical perspectives that emphasize the role of immersive multimedia, spatial visualization, and experiential interaction in enhancing cognitive processing in technical education.

Overall, the study concluded that AR serves as a powerful instructional innovation for vocational learning environments that require visualization, interactivity, and simulation of complex technical concepts. AR effectively complemented limited laboratory tools and created meaningful learning experiences that aligned with the competency-based characteristics of vocational education. Future development may expand the AR media to more advanced embedded system competencies—such as communication protocols, IoT integration, and control automation—to further strengthen students' readiness for industry demands. The findings of this study encourage wider adoption of AR-based learning tools to enhance teaching quality and learning outcomes in technology-oriented vocational programs.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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Biographical Notes

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