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Development and Evaluation of an HMI-Based Remote Laboratory Arm Robot for Control System Learning

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ABSTRACT

A Human–Machine Interface (HMI)-based remote laboratory arm robot was developed to provide an accessible, internet-based solution for learning control systems in vocational education. The system integrates an Arduino-based robotic arm, ESP8266, ESP32-CAM, MQTT communication, and an Android HMI application, and was developed using Cennamo's 5D Spiral model (Define, Design, Demonstrate, Develop, Deliver). Product validation involved expert review, black-box testing, latency and speed measurements, and quasi-experimental testing with 315 vocational students from five schools using a nonequivalent pretest–posttest control-group design. Technical testing revealed that all core functions (start/stop, emergency stop, directional control, speed settings, and video streaming) operated reliably, with average communication latencies of 44.2 ms (Wi-Fi) and 85 ms (GSM), indicating stable real-time performance. Expert validation placed functionality, usability, portability, and interface quality in the "highly valid" category (>88%). Learning outcome analysis demonstrated that students in the experimental classes achieved higher N-Gain scores (0.31–0.60; moderate to high) than those in the control classes (0.14–0.18; low), with statistically significant differences between pre-test and post-test scores ($p < 0.05$). Student response data also indicated high levels of satisfaction and perceived usability. These findings confirm that the HMI-based remote laboratory arm robot is technically robust, pedagogically feasible, and effective in enhancing control system competencies in vocational education.

INTRODUCTION

The advancement of digital technologies in the era of Industry 4.0 has fundamentally transformed how control systems, automation, and robotics are operated and learned across various industrial sectors [1], [2], [3]. The integration of the Internet of Things (IoT), Human–Machine Interfaces (HMI), and real-time communication networks has created new demands for technical competencies, particularly for personnel capable of operating, monitoring, and troubleshooting remotely connected control devices [4]. In vocational education, especially in Electrical Installation Engineering and industrial automation programs. these competency demands have grown stronger alongside the increasing use of robotic manipulators, distributed control systems, and cloud-based technologies in modern production environments [5]. Consequently, students in Indonesian vocational schools must gain learning experiences that reflect contemporary industrial conditions, including skills to operate IoT-based control systems through responsive and flexible HMI platforms.

However, fulfilling the needs of IoT-based and robotics-based control practicums continues to face substantial structural barriers. Most vocational schools in Indonesia have limited practical facilities, including control modules, robotic arms, industrial HMIs, and supporting network devices. Equipment such as industrial PLCs, commercial HMI panels, and robotic manipulators are relatively expensive and typically require dedicated laboratory environments, making it challenging for many schools to provide adequate practical resources for all learners. Moreover, hands-on learning activities in vocational schools remain heavily dependent on students' physical presence in the laboratory, thereby restricting opportunities for remote control practice, real-time monitoring, and IoT-based simulation. These limitations contribute to the low attainment of essential competencies, particularly in IoT-based control systems, sensor–actuator integration, and HMI implementation within automation workflows.

Meanwhile, research on remote laboratories has expanded significantly over the past decade. Numerous studies have introduced remote laboratory systems for various applications, including robotic control using gesture-based interfaces and digital twins, web-based control platforms, teleoperation of mobile robots, and IoT-based PLC simulations. These studies demonstrate that remote laboratories can effectively enhance flexibility, accessibility, and efficiency in practical learning. Nonetheless, most existing research focuses on university

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environments, employs large-scale servers or high-end devices, or prioritises simulation capabilities over authentic control of physical equipment. In addition, a number of studies have produced only technical prototypes without integrating them into the pedagogical context of vocational education, which has distinct characteristics in terms of student readiness, curriculum requirements, and facility constraints [6], [7].

From a technological standpoint, several studies have employed MQTT as an efficient IoT communication protocol; however, its implementation in robot-arm-based learning for vocational schools remains extremely limited [8], [9]. MQTT is recognised for its advantages in lightweight data transmission, publish–subscribe mechanisms, and low latency [8]. Yet, most existing implementations are confined to smart-home systems, environmental monitoring, or simple IoT applications. Very few studies have combined robotic arms, Android-based HMIs, MQTT communication, and remote video streaming into a single, integrated system explicitly designed to address the instructional demands of vocational control-system learning.

This situation reveals a substantial research gap. First, there is a lack of integrated remote laboratory systems that combine a robotic arm with an Android-based HMI application that students can operate in real time. Second, no research has systematically examined the pedagogical feasibility, functional performance, communication latency, and learning effectiveness of such media in the context of Indonesian vocational schools. Third, most existing studies assess only the technical performance of remote systems, without evaluating their direct impact on students' learning outcomes in IoT-based control competencies. Fourth, no comprehensive media-development model has yet been applied that emphasises iterative cycles grounded in the real needs of vocational institutions.

At the same time, the *Merdeka Curriculum* emphasises project-based learning, problem-solving, and the integration of advanced technologies into vocational instruction. In the learning outcomes specified for Phase F of the Electrical Installation Engineering program, students are required to master the operation of IoT-based control mechanisms, understand device communication architectures, and practise sensor–actuator programming techniques in industry-aligned contexts [7], [10]. Therefore, learning media capable of authentically simulating industrial environments through remote operation of a robotic arm via HMI constitutes a strategic solution for bridging the gap between theoretical knowledge and practical application.

Addressing these issues, the present study offers a solution that integrates a robotic arm as the primary hands-on object, an Android-based Human–Machine Interface as the control medium, and MQTT as the main communication protocol to ensure fast, stable, and low-cost responses. This system not only provides real-time control experiences over the internet but also incorporates ESP32-CAM video streaming as visual feedback, enabling students to monitor robotic movement remotely in a manner analogous to industrial operations. Such integration of multiple components remains underexplored, particularly within the development of practical learning media tailored to the vocational domain.

Based on theoretical analysis and empirical needs, this study presents several key novelties: (1) the development of a fully integrated robotic-arm-based remote laboratory system combining MQTT communication, video streaming, and an Android HMI, designed specifically for vocational education; (2) the application of the Spiral 5D development model to produce media that is technically, pedagogically, and functionally validated rather than a mere technical prototype; (3) comprehensive testing involving expert validation, black-box testing, communication-latency analysis, robotic-performance evaluation, and a quasi-experimental assessment of learning effectiveness, ensuring that the system links directly to students' achievement; and (4) the creation of complete instructional materials (modules, worksheets, and applications) supporting project-based learning aligned with the Merdeka Curriculum and Industry 4.0 requirements.

Accordingly, this study is grounded on a strong theoretical and practical foundation. Theoretically, the media development draws upon constructivist learning principles, remote laboratory theory, layered IoT architectures, and HMI design principles for engineering education. Practically, the research addresses the industrial equipment gaps in vocational schools and the pressing need for authentic, flexible, and affordable practical experiences.

Aligned with the research gap and the demands of vocational education, this study aims to: (1) develop an HMI-based remote laboratory system using a robotic arm that meets the learning needs of vocational control-system instruction; (2) evaluate its technical, pedagogical, and functional feasibility through expert validation and performance testing; and (3) analyse its effectiveness in enhancing students' learning outcomes through a quasi-experimental design.

This research is expected to contribute to innovation in IoT-based practical learning in vocational schools, expand access to modern control laboratories, and foster a learning ecosystem that is adaptive to advancements in future industrial automation technologies.

METHOD

This study uses a Research and Development (R&D) approach by adopting Cennamo's 5D Spiral model, which consists of five iterative stages: Define, Design, Demonstrate, Develop, and Deliver [11]. This model was chosen because of its adaptive nature, which allows the development of learning media to be carried out repeatedly and in a targeted manner, in accordance with user needs and based on continuous evaluation results. Figure 1 below illustrates the complete flow of the development of a remote laboratory arm robot media-based on a human-machine interface, from the initial stages to the outputs produced in each phase.

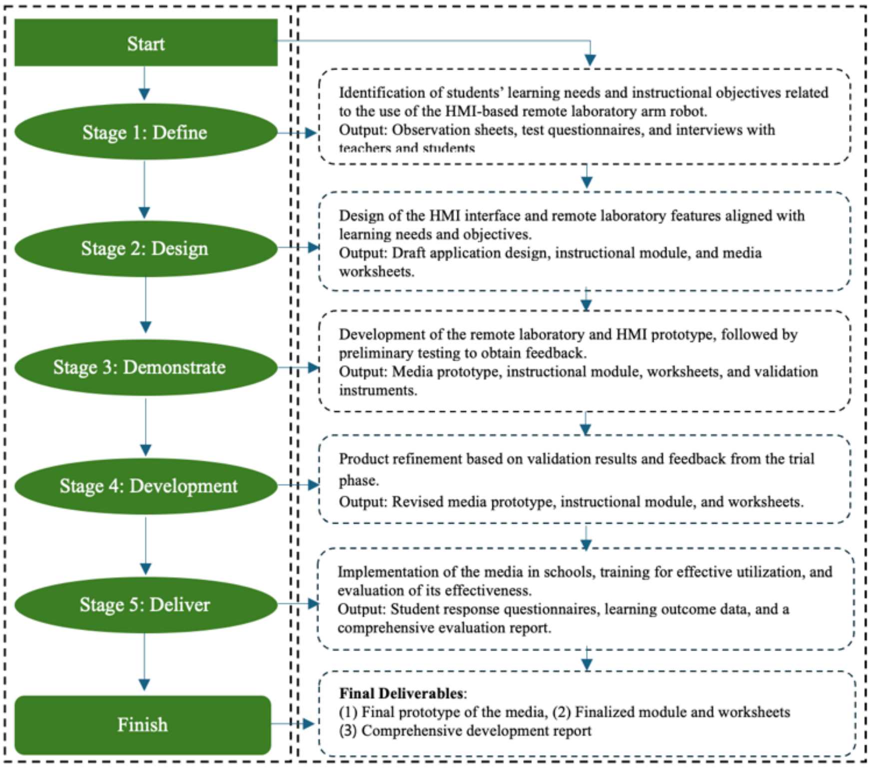


Figure 1. Flow Diagram of Research Phase

Product Testing Design

Product testing in this study was conducted in two sequential phases: limited testing and extensive testing. The limited testing phase was conducted at SMK Muhammadiyah 1 Malang and SMK Semen Gresik, involving 60 students. This phase aimed to evaluate the initial functionality of the developed media and to gather direct feedback from both teachers and students regarding its technical performance and pedagogical relevance.

Participant

The study involved a total of 315 students from five vocational high schools in Malang City, East Java, specifically SMK Muhammadiyah 1 Malang, SMK Semen Gresik, SMKN 8 Malang, SMKS Turen, and SMKN 1 Singosari. The sample was selected using a cluster random sampling technique, ensuring representation from five sub-district clusters within the city. The research employed a quasi-experimental design with a nonequivalent pretest–posttest control group model, in which the experimental group received instruction utilizing the HMI-based remote laboratory arm robot media, while the control group followed conventional instructional methods without the intervention. Pre-tests and post-tests were administered to measure the effect of the media on improving students' learning outcomes in control system competencies.

Data Collection Techniques and Instruments

This study employed a quantitative approach and collected qualitative data through various instruments. For quantitative data, a test instrument comprising pre- and post-tests was used to measure the effectiveness of the remote laboratory arm robot media, based on the human-machine interface, in improving the competence of vocational high school students majoring in Electrical Installation Engineering (EIT). The tests were administered in two stages: pre-test (before treatment) and post-test (after treatment), with the aim of comparing student learning outcomes and identifying improvements in competency following media use.

In addition to test instruments, expert validation questionnaires were given to media and material experts to assess the technical and pedagogical quality of the media. Student response questionnaires were used to assess perceptions of the media's usability, interface appearance, portability, and functionality. For qualitative data, observations and interviews were conducted with students and teachers to explore user needs and the context of media implementation. Additionally, technical testing was conducted using black-box testing to ensure that all system control functions and interfaces operate properly according to the design, without directly examining the program code.

The test instrument grid was developed to ensure that each question aligns with the learning outcome indicators for the Internet of Things (IoT)-based control system material, in accordance with the five-layer IoT architecture used in media development. Details of the indicators, descriptors, and number of questions for each sub-variable are presented in Table 1 below.

Table 1. Test Instrument

Variable	Sub-Variable	Indicator	Description	Number of Items	No. of Items
Control System	IoT	Perception Layer	Arduino, ESP8266, Servo, DC motor, Arduino IDE, ESP32CAM, L298N, Thinkercad	2	1
		Network Layer	communication networks such as 3G, 4G, 5G, Wi-Fi	1	2
		Middleware layer	IoT communication protocols such as HTTP, MQTT, CoAP, AMQP	8	30
		Application layer	HMI design in the form of an Android application using APP Inventor software	11	38
		Business Layer	Impact of remote laboratories	2	49-50
Total				50	

Source: Data constructed by researcher (2025)

Data Analysis

The data analysis techniques in this study are divided into two main parts, namely validation analysis and effectiveness analysis. Validation analysis is used to assess the suitability of the media based on expert evaluation, while effectiveness analysis aims to evaluate improvements in student learning outcomes before and after the use of the media. Details of the techniques used and explanations of the categorisation of each analysis are presented in Table 2 below.

Table 2. Data Analysis Techniques

Type of Analysis	Techniques Used	Description
Validation Analysis	Likert Scale → Percentage Conversion	Category: Highly Valid (≥81.25%), Valid (62.5–81.24%), Less Valid (43.75–62.49%), Not Valid (<43.75%)
Effectiveness Analysis	Normality and homogeneity tests	Prerequisites for further tests
	T-test (α = 0.05)	Measuring the difference in pre-test and post-test results between the experimental and control groups
	N-Gain calculation	Gain categories: Low (<0.30), Moderate (0.30–0.69), High (≥0.70)

Source: Data constructed by the researcher (2025)

RESULTS

Define: Needs Analysis

The define stage began with literature review, observation, and interviews with vocational teachers from the Electrical Installation Engineering (EIT) program at two partner vocational schools. The findings revealed a gap between the learning outcomes of the IoT-based control system in the Merdeka Curriculum and the limited practical facilities available at the schools. Teachers reported that practical devices such as PLCs, industrial HMIs, and IoT modules are expensive and hard to obtain. Additionally, students struggle to understand IoT concepts due to the lack of interactive, contextual, and project-based learning materials. Based on this analysis, the need to develop a remote laboratory system using an Android-based HMI and the MQTT protocol was identified. This system enables remote, real-time learning of control systems at a lower cost.

Design: System Design

During the design phase, the system was developed through the design of hardware and software components, including Arduino Uno, ESP8266, ESP32-CAM, DC motors and servos, and L298N motor drivers. The control interface was designed using Android-based MIT App Inventor. The design focuses on three main aspects: the robotic system (mechanical and electrical), MQTT-based communication architecture, and an intuitive user interface (UI/UX). Additionally, learning modules and worksheets were developed to integrate project-based activities for IoT control system topics. The design was validated by two subject matter experts and two media experts using a 4-point Likert scale questionnaire. Illustrations of media development during the design phase are presented in Figures 2 to 4, including initial design drafts, media diagrams, and application interfaces.

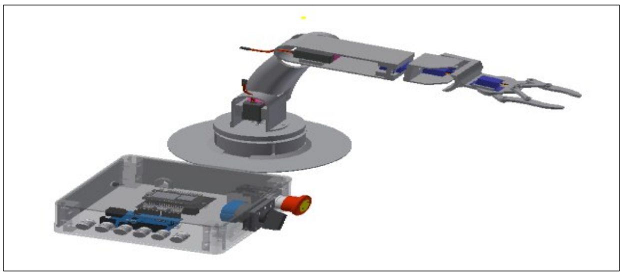


Figure 2. Draft Media Design

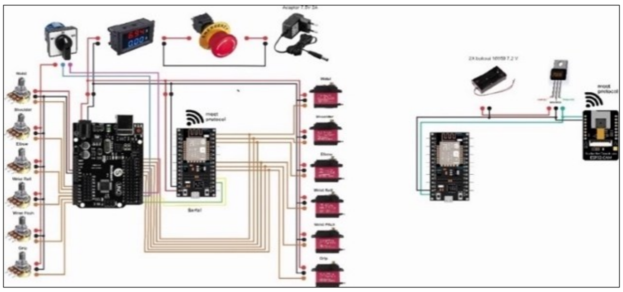


Figure 3. Draft Media Learning Schema

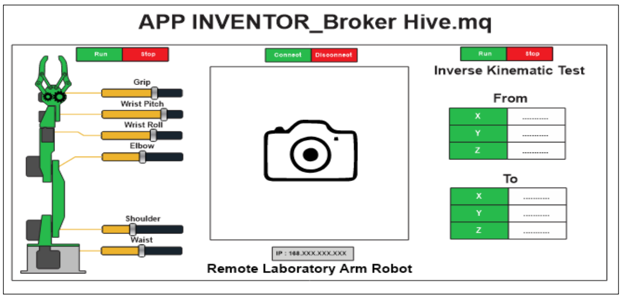


Figure 4. Draft Media Application Design

Meanwhile, the results of the physical and digital implementation of the media, including the Android application and learning documents, are shown in Figures 5 to 7.

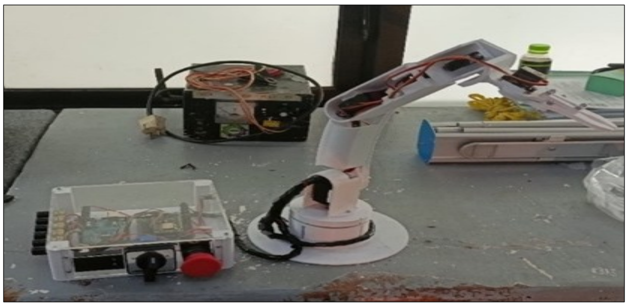


Figure 5. Draft of Remote Laboratory Arm Robot Learning Media Based on Human Machine Interface

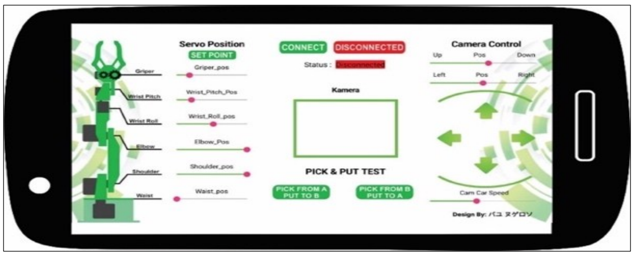
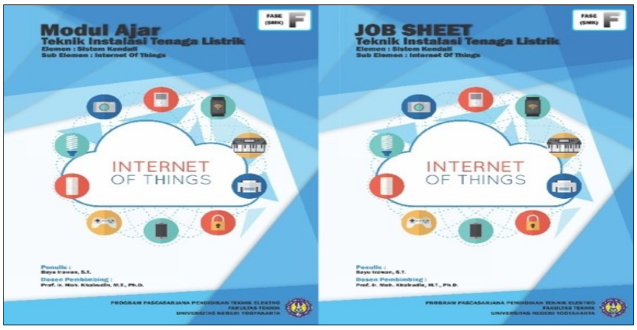


Figure 6. Draft Application Interface



FASE (SMK) F

Modul Ajar
Teknik Instalasi Tenaga Listrik
Elemen : Sistem Kendali
Sub Elemen : Internet Of Things

INTERNET OF THINGS

FASE (SMK) F

JOB SHEET
Teknik Instalasi Tenaga Listrik
Elemen : Sistem Kendali
Sub Elemen : Internet Of Things

INTERNET OF THINGS

Figure 7. Draft Module Cover and Worksheet Media

Demonstrate: Media Functionality Testing

The Remote Laboratory Arm Robot prototype was tested on a limited basis at SMK Muhammadiyah 1 Malang, involving 15 students as initial users. This functional test covered several key aspects, including system performance, actuator speed, functional validity, and suitability of content and media. The black box testing results showed that all main features, such as the start button, stop button, emergency button, direction navigation, speed adjustment, and streaming camera, functioned as designed, as detailed below.

System Performance Testing

Performance testing was conducted to evaluate the system's responsiveness under different network conditions. In latency testing, communication between user commands and robot responses showed an average latency of 44.2 ms via Wi-Fi and 85 ms via GSM network. These values indicate that the system has sufficiently stable real-time communication and is suitable for remote control learning needs.

To support the system's real-time responsiveness to commands, communication between the user and the robot was developed using the Message Queuing Telemetry Transport (MQTT) protocol. This protocol is designed for lightweight and efficient communication in IoT-based systems and is well-suited for remote control with bandwidth limitations. The MQTT architecture in Figure 8, which was implemented, enables fast two-way data exchange through publish and subscribe modes.

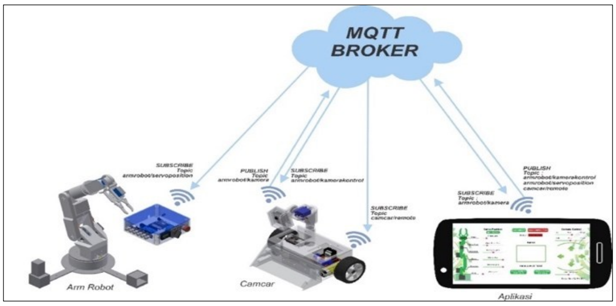


Figure 8. MQTT Architecture in the Media Remote Laboratory Arm Robot

This architecture illustrates the communication flow between the user interface, the MQTT broker, and the microcontroller-based robot module. Commands sent through the application are forwarded to the MQTT broker, where they are received by the microcontroller to execute specific functions, such as actuator movement or emergency button activation. This model enables direct connectivity between the human interface and the machine, with low latency and reliable real-time data transmission. As part of the system performance testing, MQTT communication latency measurements were conducted using the HiveMQ WebSocket Client platform. This test included observations across various connection modes (Wi-Fi and GSM), both in publish and subscribe modes, to determine the extent of delay between command transmission and system response. Detailed latency test results are presented in Appendix 1.

Mobile Robot Speed Testing

Performance evaluation was also conducted on the speed and responsiveness of the mobile robot unit when moving over a certain distance. This test aims to measure the influence of the connection medium (Wi-Fi and GSM) and communication mode (publish and subscribe) on the travel time and actual speed of the robot's movement. The theoretical calculation speed of the robot was obtained using the linear speed formula, based on a wheel diameter of 6.5 cm and a rotational speed of 174 RPM, resulting in an estimated speed of 0.59 meters per second.

The test results are presented in Table 5, which includes download and upload speed data for each mode, as well as the robot's travel time over 1.2 metres. Actual performance is compared with the theoretically calculated speed in Table 4 to obtain absolute error and relative error values.

Table 4. Results of the Mobile Robot's Movement Speed Test

Test No.	Mode	Wi-Fi Speed (Mbps)		GSM Speed (Mbps)	
		D	U	D	U
1	Publish	25.6	13.7	-	-
	Subscribe	24.3	21.5	-	-
2	Publish	-	-	27.7	36.1
	Subscribe	-	-	39	29.6
3	Publish	7.22	32.3	-	-
	Subscribe	-	-	39	29.6
4	Publish	-	-	21.6	34.6
	Subscribe	24.3	21.5	-	-

Source: Data constructed by the researcher (2025)

The mobile robot speed test in Table 4 shows that, in publish mode using Wi-Fi, the download speed reached 25.6 Mbps and the upload speed was 13.7 Mbps, with a travel time of 3.6–3.9 seconds, resulting in a relative error of up to 48%. Conversely, the second test in publish mode using GSM yielded better performance, with a travel time of 2.3–2.7 seconds and a relative error as low as 12%. This performance variation suggests that while GSM generally exhibits higher latency, signal quality and bandwidth stability during testing significantly influence the robot's response speed.

Table 5. Results of Mobile Robot Movement Speed Testing

Test No.	Distance (Meters)	Time (Seconds)	Actual Speed (metres/second)	Calculated Speed (metres/second)	Absolute Error	Relative Error
1	1.2	3.8	0.32	0.59	0.28	47
	1.2	3.6	0.33	0.59	0.26	44
	1.2	2.8	0.43	0.59	0.16	28
	1.2	3.9	0.31	0.59	0.28	48
	1.2	3.7	0.32	0.59	0.27	45
	1.2	3.2	0.38	0.59	0.22	37
2	1.2	2.3	0.52	0.59	0.07	12
	1.2	2.5	0.48	0.59	0.11	19
	1.2	2.7	0.44	0.59	0.15	25
	1.2	2.4	0.50	0.59	0.09	16
	1.2	2.6	0.46	0.59	0.13	22
	1.2	2.3	0.52	0.59	0.07	12
3	1.2	2.4	0.50	0.59	0.09	16
	1.2	2.6	0.46	0.59	0.13	22
	1.2	2.7	0.44	0.59	0.15	25
	1.2	2.4	0.50	0.59	0.09	16
	1.2	2.5	0.48	0.59	0.11	19
	1.2	2.8	0.43	0.59	0.16	28
4	1.2	2.9	0.41	0.59	0.18	30
	1.2	2.8	0.43	0.59	0.16	28
	1.2	3	0.40	0.59	0.19	32
	1.2	3.1	0.39	0.59	0.21	35
	1.2	2.7	0.44	0.59	0.15	25
	1.2	2.8	0.43	0.59	0.16	28
		Average Error			0.16	27

Source: Data constructed by the researcher (2025)

Table 5 describes that the overall average relative error of 27% indicates a significant gap between theoretical and actual speeds. One of the primary causes of this deviation is the robot's total weight, which reaches 637 grams, resulting in greater inertia and requiring more time for acceleration and deceleration. High inertia hinders the motor's ability to respond quickly to commands, especially under suboptimal network signal conditions.

To reduce this error rate, recommended solutions include using DC motors with greater torque, which can overcome inertia more efficiently and enable the robot to respond to commands more quickly and accurately. In addition, optimisation of the control system and mechanical design is also necessary to achieve motion performance that is more in line with theoretical specifications under various network conditions and operating modes.

System Functionality Testing (Functional Testing – Black Box)

The testing was conducted using a black box testing approach, which focuses on verifying control functions and safety without reviewing internal code. All main features were successfully tested, including the start button, stop button, emergency stop button, direction navigation, speed settings, and streaming camera, and all functioned as designed without malfunctions. The emergency stop button response was recorded under 1 second, indicating a quick response to emergency scenarios.

Content Validation by Subject Matter Experts

Content validation was conducted by two experts in IoT systems, with experience in automation control and remote technology. The assessment focused on three main aspects: (1) core system functions, such as robot arm control, video streaming, and emergency buttons; (2) system relevance to industry needs, particularly in the fields of automation and remote control; and (3) operational reliability in various usage scenarios.

The validation results show the following average scores: core system function scored 76 out of 84 points, relevance to industry needs scored 33.5 out of 36 points, and operational reliability scored 36.5 out of 40 points. Based on the percentage of suitability relative to the maximum score, all aspects fall into the Highly Valid category. This confirms that the Remote Laboratory Arm Robot learning media has high content validity, both in terms of technical functionality and relevance to the demands of the automation technology-based industry. The visualisation of the validation results can be seen in Figure 9.

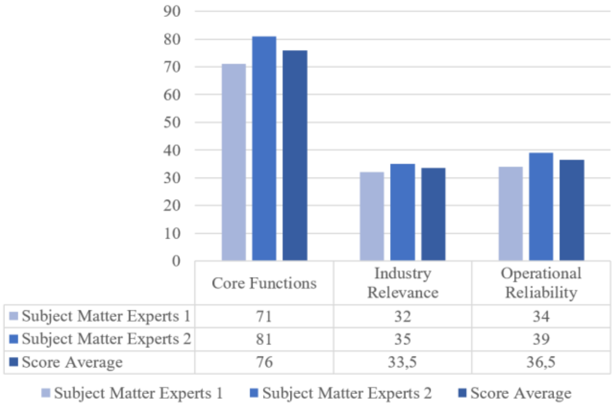
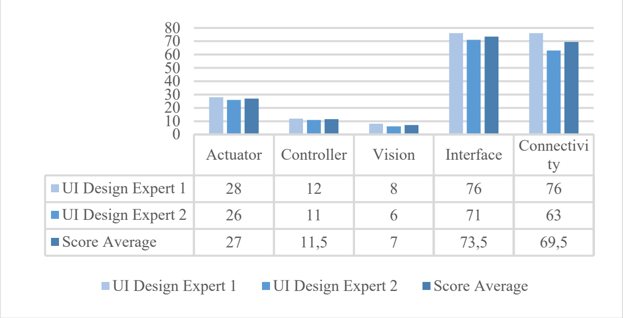


Figure 9. Results of Material Validation Testing

Media Validation by UI Design Experts

Technical validation of the media was conducted by two experts in UI/UX and network connectivity, focusing on five main aspects: (1) actuators, (2) controllers, (3) vision systems, (4) interfaces, and (5) connectivity. The interface system was developed using the MIT App Inventor platform and tested for design, accessibility, and user interface functionality. The technical validation results yielded the following feasibility scores: actuator, 27 out of 30 points; controller, 11.5 out of 12 points; vision, 7 out of 8 points; interface, 73.5 out of 76 points; and connectivity, 69.5 out of 72 points. The feasibility percentage for all aspects ranges from 88% to 97%, and the overall result is categorised as Highly Valid. These results indicate that the Remote Laboratory Arm Robot learning media has high quality in terms of actuator control, visualisation accuracy, user interface design, and internet connection stability required for distance learning. This technical validation is visualised in Figure 10.



	Actuator	Controller	Vision	Interface	Connectivity
UI Design Expert 1	28	12	8	76	76
UI Design Expert 2	26	11	6	71	63
Score Average	27	11,5	7	73,5	69,5

Figure 10. Validation Test Results of the Media

Develop: Product Improvement

Feedback from the demonstration phase was used to refine the media. Some improvements include reconfiguring the MQTT broker to improve connection speed, adding connection status indicators to the HMI, and optimising the integration of ESP32-CAM for more stable video display. The learning module was also updated with the addition of technical instructions and reinforcement of reflective elements in project activities. This stage ensures that all learning components have been developed to their fullest potential to achieve the desired educational objectives and enhance students' learning experience in the field of control systems. The results of the develop stage are shown in Figure 11.

Figure 11. Media Remote Laboratory Based on Human Machine Interface

Deliver: Testing the Scope and Effectiveness of the Media

A comprehensive analysis of system performance was conducted by comparing data from the five classes involved in the study. Descriptively, there was a significant improvement in the final results compared to the initial values, particularly in the experimental classes that received the implementation of the remote laboratory arm robot media based on a human-machine interface (HMI).

In the experimental classes, all five schools demonstrated score improvements, with the highest increase occurring at SMKN 8 Malang, where the average score rose from 43.10 in the pre-test to 75.20 in the post-test. This substantial gain positioned SMKN 8 Malang in the high N-Gain category. SMKN 2 Malang also showed notable improvement, with scores increasing from 45.60 to 67.90. SMK Muhammadiyah 1 Malang experienced an increase from 50.45 to 65.29, while SMKS Semen Gresik rose from 42.00 to 62.71. SMKN 1 Malang followed closely, with scores improving from 48.20 to 64.50.

Conversely, the control classes across the five schools also experienced score increases, but these were relatively smaller. For example, the control class at SMK Muhammadiyah 1 Malang improved only from 45.16 to 51.35, and at SMKS Semen Gresik from 44.10 to 50.80, indicating that natural learning progression occurred but without the substantial boost provided by the intervention.

To ensure the validity of the statistical analysis, normality and homogeneity tests were conducted using the Shapiro–Wilk and Levene tests, both of which confirmed that the data were normally distributed and homogeneous ($p > 0.05$). The homogeneity test (Levene) revealed that the variance between groups was homogeneous, with p-values of 0.694 for the pre-test and 0.792 for the post-test.

The paired sample t-test further demonstrated statistically significant differences ($p < 0.05$) between pre-test and post-test scores in all experimental classes, confirming that the use of remote laboratory arm robot media had a positive effect on improving student learning outcomes. For example, in the experimental class at SMKN 8 Malang, the mean difference reached 32.10 points with a t-value of -9.012 ($p = 0.000$), indicating a highly significant improvement. Similarly, at SMKN 2 Malang, the difference was 22.30 points with a t-value of -7.415 ($p = 0.000$). Even in schools with lower pre-test baselines, such as SMKS Semen Gresik, the gain remained meaningful, with an increase of 20.71 points ($p = 0.001$).

Although the control classes also showed statistically significant improvements, the differences were much smaller. For instance, at SMK Muhammadiyah 1 Malang, the average gain was only 6.19 points ($p = 0.003$), reinforcing the finding that the intervention produced a stronger and more consistent effect compared to regular instruction. The effectiveness of the media was also measured using N-Gain scores, which reflect the relative improvement from the pre-test to the post-test. The detailed results are presented in Table 6.

Table 6. N-Gain Scores and Their Categories

School	Class	Pre-Test	Post-Test	N-Gain	Category
SMK Muhammadiyah 1 Malang	Experimental	50.45	65.29	0.31	Moderate
	Control	45.16	51.35	0.14	Low
SMKS Semen Gresik	Experimental	42.00	62.71	0.36	Moderate
	Control	44.10	50.80	0.15	Low
SMKN 8 Malang	Experimental	43.10	75.20	0.60	High
	Control	46.50	52.10	0.16	Low
SMKN 2 Malang	Experimental	45.60	67.90	0.45	Moderate
	Control	47.00	53.30	0.18	Low
SMKN 1 Malang	Experimental	48.20	64.50	0.35	Moderate
	Control	46.80	52.00	0.15	Low

Source: Data constructed by the researcher (2025)

The N-Gain data clearly illustrate that the experimental classes achieved moderate to high gains, with the highest effectiveness at SMKN 8 Malang (0.60). Meanwhile, the control classes consistently remained in the low category, reinforcing that the improvement in learning outcomes was largely attributed to the implementation of the HMI-based remote laboratory arm robot system. As illustrated in Figure 12, the bar chart visually reinforces this trend: experimental classes consistently outperform their control counterparts, with a distinct gap in learning gains between the two groups. This pattern provides strong evidence of the system's effectiveness in enhancing students' mastery of control system concepts.

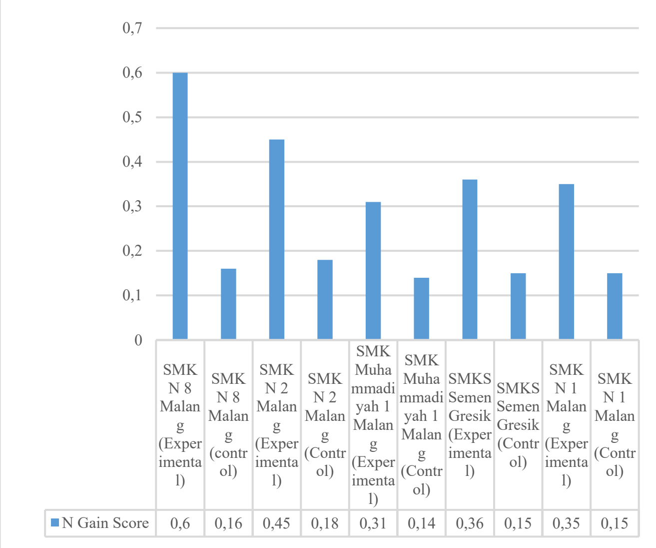


Figure 13. N-Gain Effectiveness Test

Overall, the findings strongly indicate that the integration of innovative learning media not only enhanced students' test performance but also demonstrated consistent effectiveness across diverse learning contexts. The most substantial improvements were observed in schools that optimally utilized the technology, highlighting its potential to significantly strengthen students' conceptual understanding and practical skills.

Beyond the quantitative outcomes, students' perceptions of the media also reflected a high level of satisfaction. Results from the distributed questionnaire revealed that all evaluated aspects achieved scores ranging from 76% to 80%, placing them in the "highly valid" category. Specifically, the substance/content aspect scored 80%, instructional design scored 76%, functionality scored 77%, portability scored 78%, usability scored 79%, and layout scored 78%. These findings affirm that the HMI-based remote laboratory arm robot media is appropriate, effective, and well-suited for enhancing the learning process of control systems in vocational high schools, as illustrated in Figure 14.

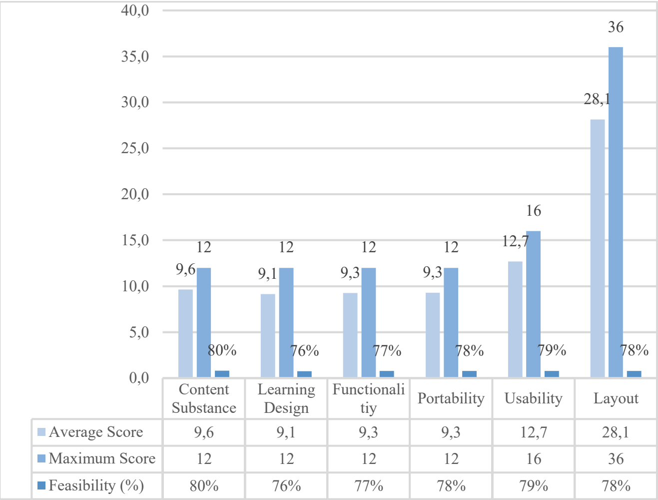


Figure 14. Functionality Graph Based on User Responses

As a follow-up to the validation results and expert input, several product revisions were made to further optimise the system. Some of the improvements included adding estimated operation duration information to the job sheet, compiling more detailed operational steps while still allowing room for student independence, and developing operational guidelines in video format to facilitate independent understanding. These revisions aim to ensure that the system is not only technically feasible but also capable of operating optimally in various contexts of vocational education based on automation technology.

Discussion

Media Functionality: Functionality, Portability, Usability, Layout, and Latency

Based on the Human-Machine Interface (HMI), showed excellent performance in various technical and pedagogical aspects. The evaluation of this remote laboratory arm robot covered five main dimensions: functionality, portability, usability, layout, and latency, all of which support the effectiveness of this medium as a practice-based learning tool in vocational high schools.

In terms of functionality, black box testing results confirm that all main features of the system operate optimally, including start, stop, direction control, emergency buttons, speed control, and camera access for visual monitoring. These findings align with the concept of effective educational media design, which integrates technical and instructional needs into a reliable, unified system [1], [12], [13]. The success of the testing demonstrates that the system can replicate conventional laboratory experiences in a remote format without compromising the quality of student interaction with practical objects.

Portability is another key advantage of this medium. All devices are designed in a compact and portable practical box, enabling flexible use in classrooms, laboratories, or at home. This addresses the challenge of limited access to physical laboratories, which has long been a major obstacle in technical and robotics education at vocational schools. With this portable design, teachers can integrate practical sessions at any time and from anywhere, thereby increasing the intensity of student engagement in project-based learning.

In terms of usability, this media received very good ratings from users. Based on the survey results, student satisfaction reached a score of 80.2%, indicating that the media is intuitive, easy to use, and not confusing. This aspect is important because positive user experiences directly contribute to learning motivation and achievement [14]. The Android-based interface was designed considering user-centred design principles, enabling students of various ability levels to interact with the system quickly without requiring intensive training [15], [16], [17]. Furthermore, the simple yet functional layout of the interface is another added value. The HMI interface is designed to be compatible with various versions of Android devices, minimising technical barriers that users may encounter. This design aligns with digital ergonomics principles that emphasise visual simplicity, clear icons, and logical navigation [18], [19]. The simplicity of the layout not only enhances user comfort but also reduces the potential for operational errors that could disrupt the learning process [20].

The final aspect, latency, indicates the technical performance that supports real-time remote control practices. The test results recorded an average latency of 44.2 ms when using a Wi-Fi connection and 85 ms via a GSM network. These values are low and align with the response speed standards set by the International Association for Autonomous Vehicles and Mobility for remote-based robotic operations [21], [22]. Recent studies have investigated latency in remote robotic control and teleoperation systems. Bray et al. (2024) examined network latency across various scenarios, finding average round-trip latencies of 6.6 ms for local networks, 58.4 ms for Wi-Fi, and 115.4 ms for cellular connections [23]. In medical applications, Legeza et al. (2021) demonstrated successful remote endovascular interventions, with network latencies below 400 ms providing acceptable operator control [22]. Black et al. (2024) evaluated a mixed reality teleguidance system, reporting communication latencies of 40 ± 10 ms over 5G networks. They also measured human response times to position and force changes [24]. For remote driving, Yu and Lee (2022) achieved video streaming latencies under 50 ms using UDP protocol, emphasizing the importance of low latency for effective control [25]. These studies collectively highlight the critical role of low latency in ensuring responsive and efficient remote robotic operations across various applications. This response speed is crucial to ensure that student-robot interactions occur without significant delays, thereby maintaining a natural and effective learning experience.

These findings indicate that the Android HMI-based remote laboratory media and MQTT communication protocol, integrated with the robot arm, are not only technically superior but also possess high pedagogical value. Recent research highlights the integration of Industry 4.0 technologies in engineering education, particularly through the use of remote laboratories. Guerrero-Osuna et al. (2025) developed a remote lab with a robotic arm controlled via FPGA-Based Motor Control, emphasizing the importance of IR4.0 in curriculum design [12]. This technological integration aligns with the direction of modern vocational education development, which emphasizes blended learning and the utilisation of Industry 4.0 technologies in education [26], [27], [28]. These approaches align with the Industry 4.0 paradigm, which emphasizes advanced Human-Machine Interfaces (HMIs) as discussed by Setiyawami et al. (2019). Their work presents a flexible HMI architecture supporting adaptable applications, including real-time motor control and digital twins of robotic arms [3]. These studies collectively demonstrate the pedagogical value and technical superiority of integrating remote laboratories, IoT, and HMIs in modern vocational education. Furthermore, this medium has the potential to address the gap in access to conventional laboratories, expand practical learning opportunities, and enhance students' readiness to face the challenges of an increasingly digitalised workplace.

The comprehensive testing results also support previous research findings on the effectiveness of virtual laboratory-based and distance learning media. These technologies offer advantages such as flexible learning, enhanced visualization, and reduced resource constraints [29]. Virtual laboratories have proven effective in addressing the gap between school equipment and industry standards, especially in areas like micro power generation [30]. Furthermore, cloud- and IoT-integrated remote laboratories for FPGA-based motor control have demonstrated high student satisfaction and alignment with the principles of Education 4.0. Sekaran and Hildas (2023), Rodríguez-Sánchez et al. (2024), Aswardi et al. (2023), and Vilalta-Perdomo et al. (2022) emphasize that such experiences are crucial for preparing vocational graduates who are ready to adapt to the developments of Industry 4.0 technology. [10], [12], [31], [32], [33]. These findings collectively support the implementation of virtual and remote laboratory-based media in vocational education, contributing to improved learning outcomes and addressing challenges in practical skill development. Thus, the implementation of remote laboratory-based media is not only relevant to the technical needs of robotics education but also makes a tangible contribution to improving the quality of education at vocational schools in Indonesia.

Overall, the performance of this media indicates technological readiness for wider adoption in the vocational education ecosystem. The optimal combination of functionality, portability, usability, layout, and latency makes this media an innovative solution that can support effective, efficient, and industry-aligned remote practical learning.

Media Viability: Content, Substance, and Instructional Design

The feasibility of the Android HMI-based remote laboratory arm robot learning media using the MQTT protocol can be assessed from two main dimensions: content substance and learning design. A thorough analysis of these two dimensions reveals that the developed media is not only relevant in terms of content but also pedagogically effective, thereby addressing the practical learning needs of Vocational High Schools, particularly the Electrical Installation Technology (EIT) programme.

In terms of content substance, the media content fully aligns with the learning outcomes of Phase F in the Merdeka Curriculum, which has been implemented since 2021. These learning outcomes emphasize mastery of skills in mechanical and electromechanical control systems based on cutting-edge technology, such as the Industrial Internet of Things, including PLC, smart relays, smart homes, and the Internet of Things (IoT) [31], [34], [35], [36]. Recent research demonstrates the integration of robot arm technology with the MQTT protocol for enhanced learning and communication in automation. Yang et al. (2024) [37] Propose a pedagogical framework utilizing mixed reality and robot arms for experiential, active learning in robotics education. Velinov et al . (2024) [38] present a telepresence solution using MQTT for virtual tours, enabling remote control of robots in museums and galleries. Diddeniya et al. (2022) [39] describe an MQTT-based office assistant robot system for navigation and person identification in isolated environments. Lin et al. (2023) [40] introduce a synchronized control system for robotic arms using virtual reality, IMU sensing, and MQTT communication. The integration of robot arm technology with the MQTT communication protocol provides a more contextual learning experience as it closely mirrors real-world scenarios in modern automation industries. This approach directly addresses the gap between the competencies required by the business and industrial world (DUDI) and the skills of vocational school graduates, which have been deemed suboptimal, as reflected in the Indonesian Central Statistics Agency's data (2025) regarding the high rate of open unemployment among vocational school graduates.

Additionally, the media content is designed to support project-based learning, where students can integrate theoretical concepts with practical operations of remote control systems. With this method, students not only learn concepts but also gain practical experience that sharpens their psychomotor skills while enhancing their conceptual understanding [41].

The learning design dimensions also demonstrate high quality, as the media was developed using the 5D Spiral model (Define, Design, Demonstrate, Develop, Deliver), which is iterative and feedback-based. The development process begins with the Define stage, which analyzes real-world needs, followed by the Design stage, which focuses on interface simplicity and alignment with the vocational school learning context. The resulting prototype is then tested in the Demonstrate phase and refined based on feedback from teachers and students in the Develop phase, until it is finally ready for optimal use in the Deliver phase. This iterative approach aligns with the principles of effective learning media development that prioritise adaptation to user needs [11], [42], [43].

The media interface design is simple and intuitive, making it easy to operate even for students with limited technological skills. This simplicity does not reduce the complexity of the material but rather enhances the user experience (user experience) as students can focus more on learning the content rather than learning how to use the system. The user-centred design principle applied supports inclusivity of use and ensures the media can be used at various levels of student competence.

The results of validation by subject matter experts and media experts confirm that this media is suitable for use as a practical learning aid. In terms of content, it is considered accurate, relevant to the curriculum, and in line with industry standards. In terms of media, the interface design, layout, and system integration are considered to support ease of operation and learning effectiveness. Teachers involved in the validation process also assessed that this media is flexible for use in both face-to-face learning in laboratories and distance learning, thus supporting various learning models such as blended learning.

The active involvement of teachers and students in the development process also provided additional advantages in the form of increased ownership and adoption of the media. Teachers felt more confident in integrating the media into their learning activities, while students were more motivated because they felt that the media used was appropriate to their learning needs and context. These findings are in line with the research by [44]Achuthan et al. (2021) show that remote laboratory-based media can significantly improve student engagement, motivation, and learning outcomes.

Overall, this media is not only technically feasible but also adaptable to pedagogical needs. The relevance of the material to learning outcomes and industry needs ensures that learning is contextual and applicable. Meanwhile, the iterative, user-experience-based, and flexible learning design allows this media to be used in various learning scenarios, including face-to-face, distance, and project-based learning. The combination of these two dimensions positions this media as an educational innovation capable of bridging the gap between the world of education and the world of industry, while supporting the transformation of vocational education towards a more modern, adaptive, and competency-based education ecosystem for the 21st century.

Effectiveness of Remote Laboratory Arm Robot Media Using MQTT-Based Human-Machine Interface on Learning

The effectiveness of the media, in terms of content and learning design, indicates that this medium has great potential as an innovative and practical learning tool in vocational schools. The content aligns with industry needs, ensuring that students acquire skills that meet workplace demands and thereby enhance graduates' competitiveness. The integration of an IoT-based control system with a robot arm provides contextual, practical experience aligned with the competencies required in the Industry 4.0 and 5.0 era, including an understanding of automation, data communication, and MQTT protocol-based control [45], [46], [47].

From a learning design perspective, an adaptive and user-centred approach enhances student motivation and engagement. This platform facilitates project-based learning, where students not only learn theory but also conduct remote control experiments, analyse results, and solve problems collaboratively. This process aligns with the constructivist learning approach, which emphasises active and contextual learning, thereby fostering deeper mastery of competencies [48], [49].

Additionally, the implementation of modern technologies such as Android HMI and the MQTT protocol introduces students to technologies widely used in the manufacturing, energy, and modern automation industries. This experience transforms the media from merely a learning tool into a bridge between the educational and industrial worlds, which have often been separated [50] (Jacobs et al., 2022). Teachers can also utilise this media to expand learning scenarios, including distance learning, blended learning, and inter-school collaboration.

The success of this media development also confirms that the iterative and feedback-based Spiral 5D approach is an effective model for vocational learning innovation in the digital age [40], [51], [52]. This flexible development process allows for continuous improvement and adaptation to user needs, ensuring that the resulting product is truly relevant, efficient, and sustainable.

Overall, this remote laboratory arm robot-based learning media is not only a solution to overcome the limitations of practical infrastructure in vocational schools but also a strategic tool to equip students with 21st-century skills, such as technological literacy, problem-solving abilities, and collaboration. This opens up opportunities to adopt similar models in other vocational fields, thereby enabling the transformation of vocational education towards a more adaptive and industry-oriented system on a broader scale.

CONCLUSION

The results of the study indicate that the human-machine interface-based remote laboratory arm robot media demonstrates excellent functionality in various technical aspects. Validation by experts showed scores above 88% for functionality, portability, usability, and layout, while latency test results showed an average delay time of 44.2 to 85 milliseconds, indicating that the system has a fast response and is suitable for use in distance learning. The interface design developed was also assessed as responsive and compatible with various Android devices. In terms of content and media design, validation by subject matter and media experts showed a suitability score above 90%, indicating that this media is highly suitable for use as a learning tool. The media content has also been adapted to the learning outcomes of the Electrical Installation Technology (EIT) vocational programme and the needs of the industry, thereby bridging the gap between theory and practice effectively. Furthermore, the effectiveness of the media in improving student learning outcomes was demonstrated through N-Gain analysis, where the average N-Gain value in the experimental class reached 0.36 (moderate category), significantly higher than that of the control class, which achieved only 0.14 (low category). Additionally, the results of the paired sample t-test showed a statistically significant difference between pre-test and post-test scores in the experimental class, indicating that the use of this media is effective in improving students' learning outcomes in automation-based control system learning at vocational high schools.

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Moh. Khairudin

Penulis merupakan peneliti dan dosen di Departemen Teknik Elektro Universitas Negeri Yogyakarta yang berfokus pada robotika, kontrol sistem, dan pembelajaran berbasis teknologi untuk pendidikan vokasi.

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APPENDICES

Table 3. Remote Laboratory Arm Robot Latency Test Results

No..	Mode	Wi-Fi Speed (Mbps)		GSM Speed (Mbps)		Latency (ms)	Average Latency (ms)
		D	U	D	U		
1	Publish	87.3	84.4	-	-	32	36.2
						26.5	
						39.5	
						36.5	
						36.5	
						38.5	
	Subscribe	11.5	14.2	-	-	43	
						44	
						40.5	
						35.5	
						21.5	
						40	
2	Publish	11.5	14.2	-	-	32.5	32.7
						23	
						32.5	
						29	
						42.5	
						36.5	
	Subscribe	87.3	84.4	-	-	35	
						37	
						42	
						41	
						35	
						34	
3	Publish	-	-	36.5	1.76	74	43.7
						32	
						44	
						46	
						32.5	
						33.5	
	Subscribe	11.7	13.8	-	-	32	
						30	
						43.5	
						36.5	
						31	
						33	
4	Publish	11.7	13.8	-	-	40.5	40.7
						37.5	
						44.5	
						34.5	
						38	
						49	
	Subscribe	-	-	36.5	1.76	45	
						41.5	
						34	
						45.5	
						46.5	
						42	
5	Publish	-	-	11.7	4.5	51	49.3
						39.5	
						52.5	
						50.5	
						51	
						51	
	Subscribe	4.04	11.9	-	-	51	
						51	

No..	Mode	Wi-Fi Speed (Mbps)		GSM Speed (Mbps)		Latency (ms)	Average Latency (ms)
		D	U	D	U		
						50.5	
						51	
						50.5	
						51	
6	Publish	8.28	11.9	-	-	55.5	58.4
						62.5	
						50.5	
						85.5	
						48	
						48.5	
	Subscribe	-	-	11.7	4.5	70	
						148.5	
						75.5	
						62	
						60	
						37.5	
7	Publish	-	-	16.8	0.5	39.5	45.6
						37.5	
						50.5	
						58.5	
						44.5	
						43	
	Subscribe	-	-	12.9	0.32	45	
						66.5	
						49.5	
						70	
						68.5	
						51.5	
8	Publish	-	-	12.9	0.32	72.5	47.1
						32.5	
						45.5	
						48	
						46	
						38	
	Subscribe	-	-	16.8	0.5	54	
						52	
						44.5	
						35	
						45.5	
						43.5	

Source: Data constructed by the researcher (2025)