Design and implementation of an IoT-based PLC-HMI trainer for pneumatic control system education

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ABSTRACT

Industrial automation education requires practical learning media that integrate control systems, visualization, and physical processes. However, many pneumatic training systems used in laboratories still operate as standalone devices and lack system integration and remote monitoring capability. This study presents the design and implementation of an internet of things (IoT)-based programmable logic controller (PLC) and human–machine interface (HMI) trainer for pneumatic control education. The proposed platform integrates PLC control, HMI visualization, pneumatic actuators, and IoT monitoring within a unified learning environment. A modular PLC software architecture was developed to support multiple pneumatic learning scenarios using a single control program. Functional testing was conducted to verify system reliability, actuator operation, and communication performance. An educational evaluation using pre-test and post-test assessments was also performed. The results show that the developed trainer operates according to the intended design specifications and improves student understanding. The average student score increased from 62 in the pre-test to 84 in the post-test, representing an improvement of approximately 35.5% in learning performance. These results demonstrate that the proposed PLC–HMI–IoT trainer effectively supports practical learning in pneumatic automation education.

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1. INTRODUCTION

Industrial automation has become a fundamental component of modern manufacturing systems, where programmable logic controllers (PLCs) and human-machine interfaces (HMIs) are widely used for process control and monitoring [1], [2]. Among various actuation technologies, pneumatic control systems are commonly employed in automation due to their simplicity, safety, and cost-effectiveness, making them an essential topic in engineering education, particularly in electrical engineering and mechatronics programs [3]. In educational laboratories, pneumatic trainers are typically used to introduce basic concepts of actuator control, sensor integration, and PLC-based sequential logic [4]. However, most available trainers still operate in isolation with limited capabilities for system integration and real-time monitoring. Consequently, students often face difficulties in understanding the interaction between control devices, communication systems, and data visualization platforms, which are increasingly important in modern automation systems [5]. This limitation creates a pedagogical gap, where students learn isolated control concepts without understanding integrated automation architectures commonly implemented in Industry 4.0 environments.

The rapid advancement of internet of things (IoT) technology has significantly influenced industrial automation by enabling remote monitoring, data acquisition, and system connectivity [6]. The integration of IoT with PLC and HMI systems allows process variables and system status to be accessed remotely, thereby enhancing system flexibility and transparency. In the educational context, IoT-based trainer kits can provide a richer learning experience, including remote observation, learning process analysis, and a better understanding of automation architecture and communication protocols [7].

Although interest in IoT-based automation continues to grow, research specifically addressing the development of an IoT-integrated PLC-HMI trainer kit for pneumatic system education remains limited. Most previous studies have focused on software simulations or industrial scale implementations, which are not fully aligned with the needs of educational laboratories in terms of cost, complexity, and direct interaction with real hardware. Furthermore, many existing educational trainer systems employ separate control programs for different learning scenarios, resulting in increased software complexity and reduced learning continuity. In addition, IoT integration in most previous works is primarily oriented toward industrial monitoring purposes, rather than being explicitly designed to support structured learning processes, scenario-based experimentation, and educational evaluation [8], [9]. Overall, previous works tend to emphasize either industrial deployment or simulation-based approaches, with limited attention to integrated, hardware-based educational trainers that combine PLC, HMI, pneumatic systems, and IoT within a structured pedagogical framework. Therefore, there is a need for an educational trainer that integrates pneumatic components, PLC–HMI control, and structured IoT-based monitoring within a learning-oriented design. To the best of the authors' knowledge, no prior study has comprehensively developed and validated an IoT-integrated PLC–HMI pneumatic trainer specifically designed with modular control architecture and educational-oriented IoT monitoring for structured laboratory learning. This paper contributes to three main aspects, namely the development of a low-cost IoT-integrated PLC–HMI pneumatic trainer kit based on real hardware implementation, the introduction of a modular single-program PLC architecture supporting multiple learning scenarios through HMI selection, and the implementation of educational-oriented IoT monitoring designed not only for visualization but also for learning supervision and assessment.

The proposed system is also aligned with the research scope of telecommunication, electronics, control, and computing systems. The integration of PLC control (control engineering), HMI visualization (embedded computing interface), and IoT communication (telecommunication networks) represents a multidisciplinary automation architecture. Therefore, the developed trainer not only supports pneumatic control education but also introduces students to integrated cyber-physical systems commonly implemented in modern industrial automation environments.

This study presents the design and implementation of an IoT-based PLC and HMI trainer kit for pneumatic control system education. The proposed system integrates a Haiwell PLC and HMI with pneumatic actuators and IoT communication to support practical learning and remote monitoring. The trainer kit is designed to facilitate basic learning scenarios, including manual and automatic control, sensor-based interlocking, and real-time system visualization. Functional testing and educational evaluation are conducted to demonstrate the feasibility and effectiveness of the trainer kit as a learning tool for automation and mechatronics courses.

Compared to previously developed PLC trainer kits and IoT-based automation trainers [1] , [5], [6], the proposed system offers several distinctive contributions. First, most existing educational trainers either focus on PLC–pneumatic control without IoT integration or implement IoT primarily for industrial-style monitoring purposes. In contrast, the proposed trainer integrates PLC, HMI, pneumatic hardware, and IoT within a structured educational architecture specifically designed for progressive laboratory learning rather than industrial deployment. Second, unlike many previous trainer systems that require separate PLC programs for different learning scenarios, this work introduces a single modular PLC control program capable of executing multiple pneumatic scenarios through HMI-based scenario selection. This unified architecture fundamentally reduces software redundancy, enhances program readability, and supports structured pedagogical progression. Third, IoT integration in this work is not only intended for visualization but also explicitly designed to support learning assessment and laboratory supervision. Selected variables such as actuator status and cycle counts are transmitted for remote monitoring to enhance instructional transparency. Therefore, the main novelty of this research lies not merely in system integration, but in the pedagogically structured modular control architecture combined with educational-oriented IoT monitoring, specifically tailored for pneumatic control education.

2. RESEARCH METHOD

This study employed a development and validation approach to design, implementation, and evaluation of an IoT-integrated PLC–HMI pneumatic trainer for educational applications. The research was conducted systematically to ensure technical reliability, reproducibility, and pedagogical relevance. The methodological framework integrates engineering design procedures with instructional considerations to support structured laboratory learning.

The research process began with requirement analysis and system specification, where educational needs, laboratory constraints, and functional objectives were identified. Based on these specifications, the hardware and software architectures were designed, including the selection of PLC, HMI, pneumatic components, and IoT communication modules. The system was then implemented and integrated to enable coordinated operation between control hardware, visualization interfaces, and remote monitoring features.

Following implementation, functional testing was conducted to evaluate system performance, reliability, and communication stability. Subsequently, an educational evaluation was performed to assess the effectiveness of the trainer kit in supporting learning outcomes in pneumatic control and automation courses. By combining technical validation with pedagogical assessment, this methodological approach ensures that the proposed trainer is not only operationally feasible but also educationally meaningful.

2.1. Educational system architecture

The block diagram of the proposed trainer kit educational system is designed to support structured learning in pneumatic control through direct interaction with real hardware and a comprehensive understanding of system integration. In automation education, system architecture plays a crucial role as a bridge between theoretical concepts and practical implementation by clearly defining the functions and data flows among system components [10]. The proposed architecture adopts a layered educational framework, which is commonly used in automation learning systems to simplify system comprehension and support modular learning [11]. This approach enables learners to study each subsystem independently while understanding their interconnections within the overall control system. The layered architecture was deliberately selected to enhance pedagogical clarity, simplify troubleshooting processes, and allow scalable expansion of additional learning modules without modifying the entire system structure.

The pneumatic system represents the physical process of the system, consisting of pneumatic cylinders, solenoid valves, a compressed air supply unit, and cylinder position sensors. This layer enables learners to directly observe actuator behavior in response to control signals, which is essential for understanding the relationship between electrical control and mechanical motion in pneumatic systems [12]. The use of real pneumatic components has been shown to enhance learning outcomes compared to simulation-only approaches [13].

The control system consists of a PLC that serves as the main processing unit. The PLC receives input signals from sensors and executes control logic to generate output signals that drive the solenoid valves. In educational environments, PLC-based control architectures are widely used because they represent industrial practice while remaining suitable for laboratory-scale learning [14]. Through this system, learners can study sequential control, interlock logic, and system behavior analysis across various operating modes.

The HMI provides a local interaction and visualization medium for the system status. The HMI displays real-time information such as actuator positions, sensor statuses, and operating modes, enabling learners to correlate the PLC program logic with system responses. The integration of HMI in educational trainers has been shown to enhance students' understanding of system monitoring concepts and human–machine interaction [15].

The IoT extends the functionality of the trainer kit by enabling selected system data to be transmitted to a remote monitoring platform. Unlike industrial IoT implementations that focus on performance optimization, the IoT integration in this trainer is specifically designed for educational purposes, emphasizing data visibility and support for learning evaluation [16]. Remote monitoring allows instructors to observe laboratory activities and provides students with additional insights into system behavior without requiring constant direct interaction with the physical device.

In the proposed architecture, data flow follows a structured closed-loop control mechanism. Sensor signals from the pneumatic layer are transmitted to the PLC input modules, where the ladder logic program processes the signals according to the selected operating scenario. The PLC then generates output commands to actuate the solenoid valves, resulting in mechanical motion of the cylinders. Simultaneously, operational variables such as actuator status, cycle counters, and operating modes are transmitted to the HMI for real-time visualization. Selected data variables are further forwarded to the IoT platform through a defined communication interface, enabling remote observation and logging. This structured data flow ensures synchronization between physical processes, control logic execution, user interaction, and remote monitoring, thereby reflecting a simplified but realistic industrial automation architecture suitable for laboratory implementation.

Communication between the PLC and HMI is established using an industrial communication protocol to ensure reliable real-time data exchange. Meanwhile, IoT data transmission utilizes a lightweight communication mechanism suitable for laboratory-scale monitoring, ensuring low latency and stable connectivity during practical sessions.

The integration of these subsystems results in a modular educational system architecture that supports fundamental learning objectives in pneumatic control, PLC programming, HMI design, and IoT concept introduction. The proposed architecture emphasizes clarity of structure, ease of learning, and educational relevance, without prioritizing industrial system complexity, as illustrated in Figure 1.

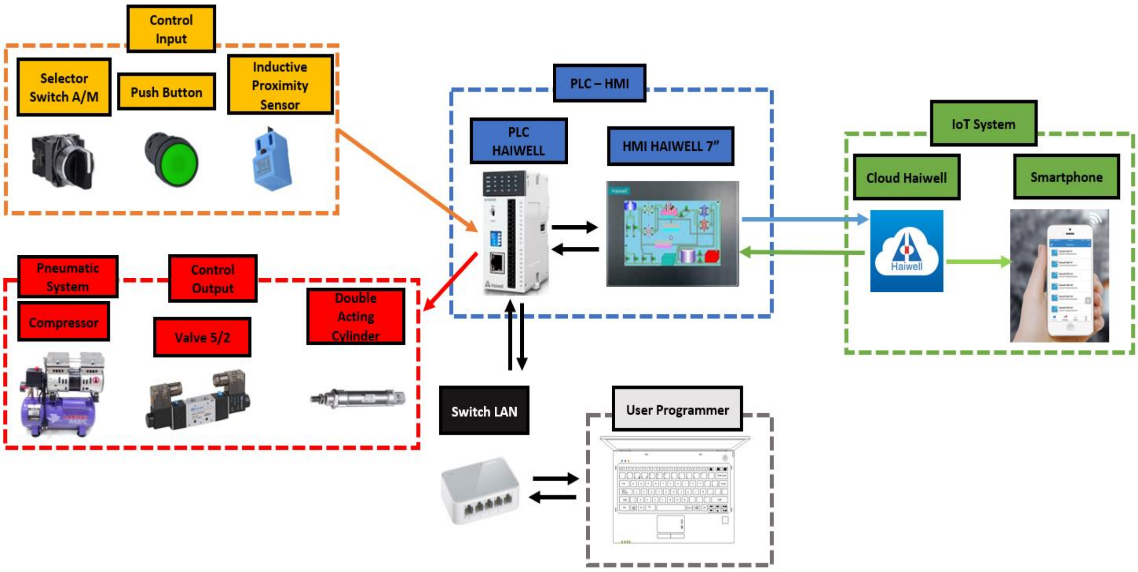

Figure 1. Architecture of the educational trainer system

2.2. Hardware design

The hardware design of the proposed trainer kit is developed to support learning activities in pneumatic control, PLC programming, and understanding of system integration. The selection of hardware components places greater emphasis on educational suitability, modularity, safety aspects, and ease of use, rather than on the performance requirements of large-scale industrial systems. Such design considerations are commonly applied in automation trainer systems to achieve optimal learning outcomes [17], as illustrated in Figure 2.

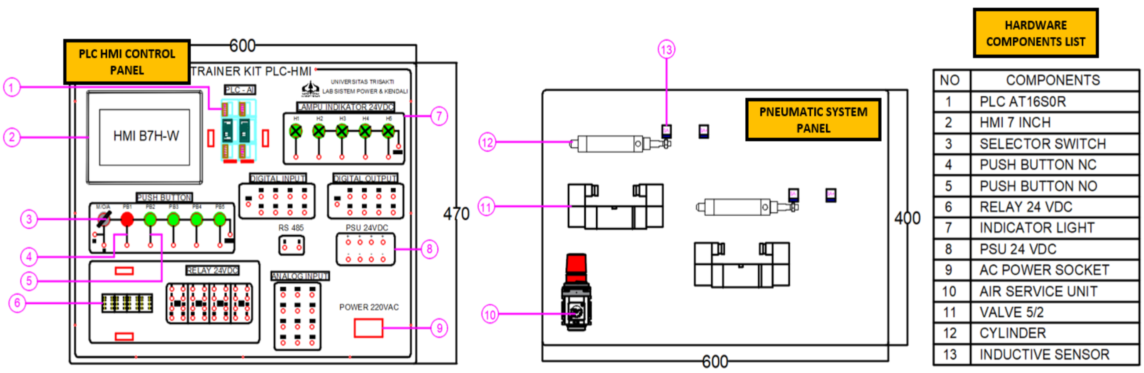

Figure 2. Educational system design of the trainer kit

The main component of the trainer kit is the Haiwell AT16S0R PLC, which functions as the central control unit. This PLC is equipped with a sufficient number of digital input and output channels to support basic pneumatic control experiments, such as sequential control and sensor-based interlocking. PLC-based hardware platforms are widely used in educational laboratories because they can represent real control systems while remaining easy for students to learn. The Haiwell PLC was selected due to its integrated Ethernet communication capability, cost-effectiveness compared to mainstream industrial PLC brands, and suitability for educational laboratory deployment. While premium industrial PLC brands such as Siemens or Omron offer advanced features, their higher cost and complexity are not necessary for basic pneumatic control education. The selected model provides sufficient digital input/output (I/O) capacity and communication support for laboratory-scale experiments without requiring additional expansion modules. This selection also reduces the overall system cost compared to high-end industrial PLC platforms, making the trainer more feasible for educational institutions with limited laboratory budgets. The PLC operates at 24 volts direct current (VDC) with a digital input and relay output configuration, which is commonly used in laboratory-scale automation systems. The PLC provides 8 digital input channels and 8 relay output channels, which are sufficient to implement multiple pneumatic learning scenarios, including sequential control, sensor interlocking, and mode switching, without requiring additional expansion modules.

A 7-inch Haiwell HMI is integrated to provide local visualization and interaction with the system. Through the HMI, users can monitor system conditions, such as sensor status and actuator positions, as well as operate the trainer in both manual and automatic modes. The use of HMI in educational trainers has been proven to enhance students' understanding of system monitoring concepts and control interfaces [18]. The 7-inch touchscreen size was selected to provide adequate visualization space for actuator indicators, ladder status feedback, and operating mode selection while maintaining affordability and compact panel integration.

The pneumatic subsystem consists of pneumatic cylinders, solenoid valves, an air supply unit, and position sensors. Double-acting cylinders are used to demonstrate two-way motion control, while the solenoid valves are directly controlled by PLC output signals. Inductive proximity sensors are installed to detect the actuator status and provide feedback to the PLC. Inductive proximity sensors were selected due to their non-contact operation, durability, and fast response time compared to mechanical limit switches. In educational environments, this reduces mechanical wear and minimizes maintenance while ensuring reliable repetitive experimentation. The sensors operate at 24 VDC with a negative-positive-negative (NPN) output configuration compatible with the PLC digital input module.

The use of real pneumatic components allows students to observe the physical response of the system directly, which is essential for learning the principles of pneumatic control [19]. To support IoT-based monitoring in an educational context, the trainer kit is equipped with communication interface modules, such as Ethernet or wireless fidelity (Wi-Fi), connected to the PLC. These modules enable the transmission of selected system variables to an IoT platform for remote observation. In educational applications, the communication module is more focused on system visualization and learning assessment rather than performance optimization [20]. The communication between the PLC and IoT module utilizes a lightweight protocol suitable for laboratory implementation, ensuring stable data transmission with minimal configuration complexity.

The input components consist of push buttons for start operations and a selector switch to choose between manual and automatic modes, with additional relay control included for voltage switching when direct current (DC) to alternating current (AC) conversion is required. Indicator lights are also added as output components to provide visual feedback on system performance. Electrical protection mechanisms were incorporated, including circuit breakers and relay isolation modules, to prevent overcurrent and protect control circuits from unintended voltage exposure. An emergency stop function was also implemented to enhance operational safety during laboratory sessions.

All hardware components are mounted on the trainer panel using terminal sockets and connectors that are clearly labeled to ensure safety and ease of operation. This design approach is recommended for educational trainers as it promotes flexibility and hands-on learning [21]. The PLC and HMI input/output addresses are presented in Tables 1 and 2. The detailed hardware configuration and I/O addressing tables allow other researchers and educators to replicate the proposed trainer system in similar laboratory environments.

Table 1. PLC I/O address

Input	Address	Output	Address
Sensor SA-	X0	Solenoid A+	Y1
Sensor SA+	X1	Solenoid A-	Y0
Sensor SB-	X2	Solenoid B+	Y2
Sensor SB+	X3	Solenoid B-	Y3
Auto	X4		
Manual	X5		
Pb stop	X6		
Pb start	X7		

Table 2. HMI I/O address

Input	Address	Output	Address
Auto	M1	Manual Solenoid A	M4
Manual	M2	Manual Solenoid B	M5
Pb stop	M0		
Pb start	M3		

2.3. Software design

The software design of the proposed trainer system integrates PLC control, HMI visualization, and IoT-based monitoring to support pneumatic automation learning. The software architecture is developed to coordinate actuator control, system monitoring, and user interaction within an integrated control environment. The control program is implemented using the Haiwell Happy PLC programming software with the ladder diagram (LD) programming language. The PLC logic is structured into several functional sections responsible for input signal processing, operating mode selection, sequential control execution, actuator command generation, and safety interlocking. This structured organization allows multiple pneumatic training scenarios to be implemented within a single PLC program while maintaining program readability and facilitating troubleshooting during laboratory activities. The HMI is developed using the Haiwell Cloud HMI configuration software. Through the HMI interface, users can observe system conditions in real time, including sensor states, actuator positions, and the active operating mode. In addition to visualization functions, the interface also enables users to perform control operations such as starting or stopping the system, selecting manual or automatic operation modes, and activating specific actuators during training exercises. This interactive visualization helps students understand the relationship between PLC control logic and the resulting physical movement of pneumatic actuators. To extend system functionality, IoT communication is implemented through the Ethernet interface integrated in the Haiwell PLC. Selected operational parameters, such as actuator status, are transmitted to an IoT monitoring platform. The transmitted data can be accessed through the Haiwell Link application dashboard, allowing remote observation of system operation during laboratory sessions. The integration of PLC control, HMI visualization, and IoT monitoring forms a unified software framework that supports both system operation and educational activities in pneumatic automation training, as illustrated in Figure 3.

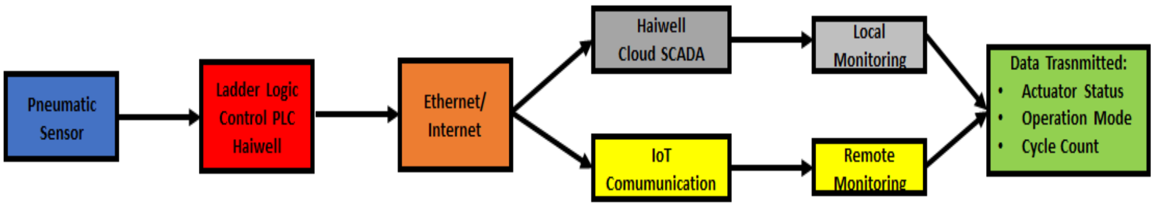

Figure 3. Software architecture of the PLC–HMI–IoT integrated pneumatic trainer system

The IoT communication architecture follows a client–server data transmission model. The Haiwell PLC transmits selected operational variables to the Haiwell Cloud platform through Ethernet communication using a lightweight industrial communication protocol supported by the PLC firmware. The transmitted variables include actuator status, operating mode, and cycle count. These data are visualized on the Haiwell Link dashboard, allowing instructors to remotely observe system activity during laboratory sessions.

From an educational perspective, IoT integration allows instructors to monitor student activities, analyze system operation logs, and evaluate learning progress without direct supervision of each workstation. This capability supports data-driven learning assessment and introduces students to the concept of connected industrial systems commonly implemented in modern Industry 4.0 environments.

2.4. Functional testing

Functional testing was conducted to verify the operational performance of the developed PLC–HMI–IoT pneumatic trainer system. The purpose of this testing stage was to ensure that all control functions, actuator operations, and monitoring features operated correctly under different operating conditions. To ensure reproducibility of the experiment, each test scenario was repeated ten times under identical operating conditions. The measured parameters include actuator response time, sequence execution delay, HMI display latency, and IoT communication delay. The measurements were obtained using system time logging and manual observation of actuator movement synchronized with PLC execution cycles. The average value of each parameter was calculated to evaluate system stability and operational consistency. The overall functional testing procedure is illustrated in Figure 4. The testing process begins by activating input devices such as push buttons and sensors to verify that the PLC correctly receives and processes the input signals. The PLC program then executes the corresponding control logic to operate the pneumatic actuators according to the predefined sequence. During the testing process, the system status and actuator positions are monitored through the HMI interface to confirm that the visualization accurately reflects the real operating conditions of the system. In addition, system operation data are transmitted through the PLC Ethernet interface to the IoT monitoring platform, enabling remote observation of the trainer system during laboratory activities. Each test scenario was repeated several times to ensure the reliability of the system. The response time between command activation and actuator movement was recorded, and the communication performance between the PLC and the IoT monitoring platform was observed to evaluate data transmission stability and communication delay. The testing results were analyzed to determine whether the system operated according to the intended design specifications. Successful operation was indicated by correct actuator sequencing, accurate HMI visualization, stable IoT data transmission, and consistent system response during repeated trials.

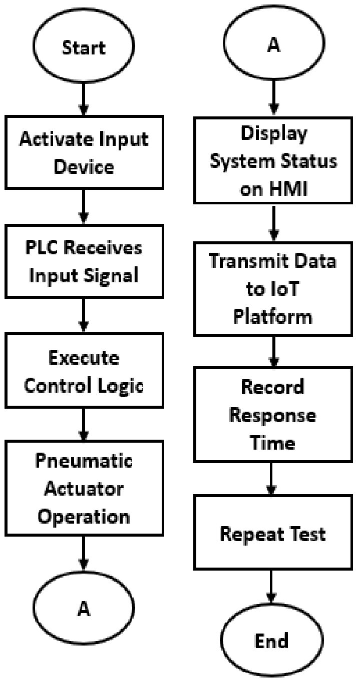

Figure 4. Functional testing procedure of the PLC–HMI–IoT pneumatic trainer system

2.5. Educational evaluation

The educational effectiveness of the developed PLC–HMI–IoT pneumatic trainer was evaluated through a questionnaire distributed to undergraduate students who participated in the laboratory learning session. A total of 30 students were involved in the evaluation process. The questionnaire was designed using a five-point Likert scale consisting of strongly disagree, disagree, neutral, agree, and strongly agree. The evaluation focused on students' perceptions of the trainer system in terms of learning effectiveness, ease of operation, visualization clarity, and understanding of pneumatic automation concepts. The results of the student evaluation are presented in Figure 5. The majority of students expressed positive responses toward the developed trainer system. Approximately 47% of students strongly agreed that the trainer effectively supports learning activities, while 33% agreed with the statement. A smaller portion of students (13%) provided neutral responses, and only a small percentage indicated disagreement. These results indicate that the integration of PLC control, HMI visualization, and IoT monitoring provides a supportive learning environment that helps students better understand the relationship between control logic, system monitoring, and pneumatic actuator operation.

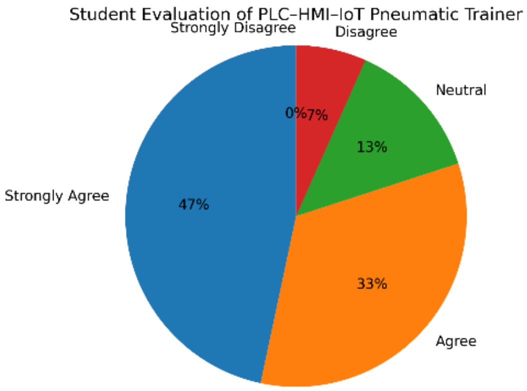

Figure 5. Student evaluation results of the developed pneumatic trainer system

2.6. Pneumatic learning scenario

The implementation of the pneumatic learning scenarios is designed to support step-by-step learning objectives using a modular PLC program. Instead of creating separate programs for each practical exercise, all scenarios are integrated into a single control structure, with scenario selection performed through the HMI interface. This approach reduces software complexity while maintaining learning flexibility in an educational context. Operational testing of the system was conducted on the IoT-based PLC–HMI trainer for two-cylinder pneumatic control, based on the timing diagrams shown in Figure 6. The PLC functions as the main controller executing the ladder program to manage the sequence of movements of cylinders A and B, while the HMI is used as the interface for selecting manual and automatic modes as well as monitoring actuator status in real-time. In manual mode, the system was tested using the movement scenarios A+A+ and A+A–B+B– as shown in Figures 6(a) and (b). Subsequently, in automatic mode, testing was carried out based on the sequential orders A+B+B–A–, A+B+(B–A–), and B+A+B–A– as shown in Figures 6(c) to (e). All input/output statuses and cylinder movement sequences are displayed on the HMI and transmitted through the IoT platform for remote monitoring.

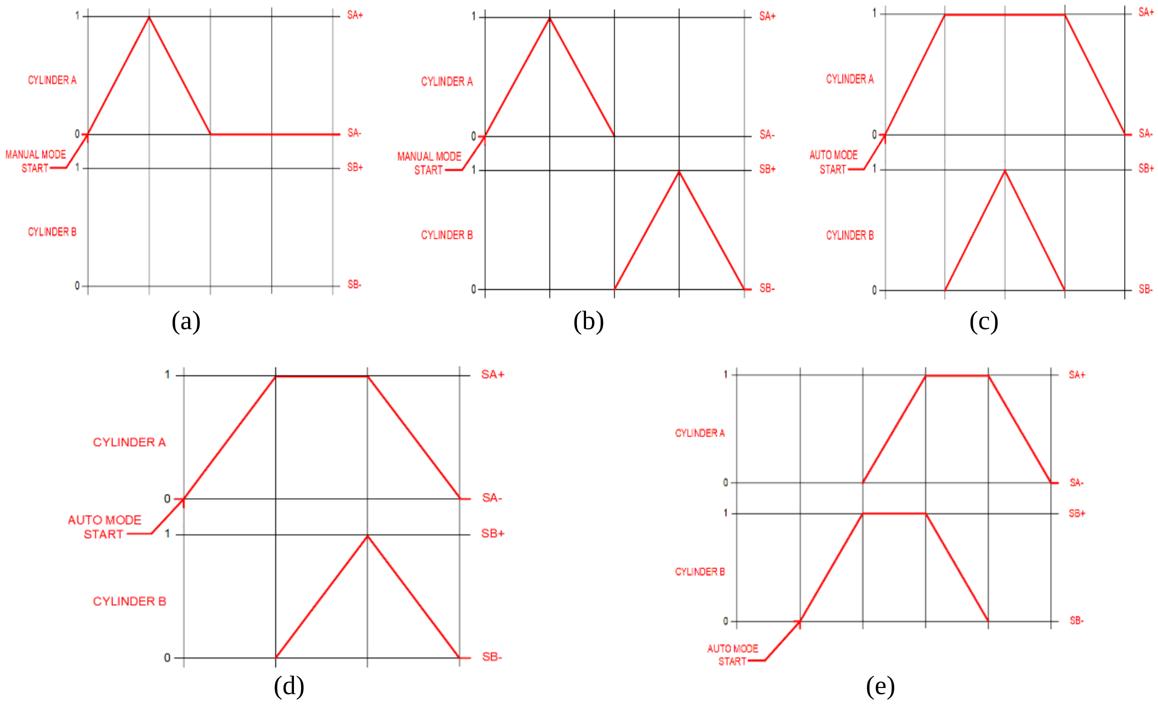

Figure 6. Pneumatic cylinder movement scenarios in manual and automatic modes: (a) A+A-, (b) A+A-B+B-, (c) A+B+B-A-, (d) A+B+(B-A-), (e) B+A+B-A-

To evaluate the system performance and support learning of pneumatic control based on PLC, HMI, and IoT, several cylinder movement scenarios were developed, referring to the timing diagrams in Figure 7. Each scenario is designed to represent manual and automatic modes with different learning focuses, ranging from mastering basic control to understanding sequential logic and system integration. These scenarios are summarized in Table 3.

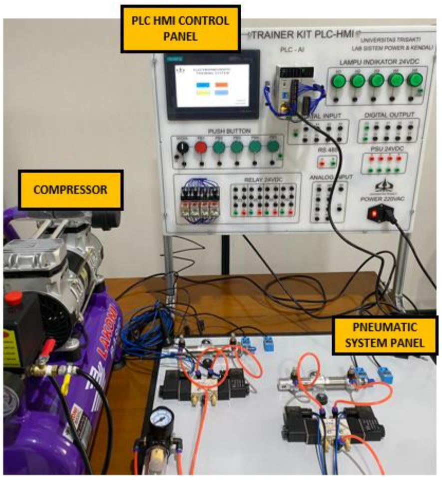

Figure 7. Hardware implementation

Table 3. Pneumatic cylinder movement scenarios

Scenario	Mode	Cylinder motion sequence	Learning focus
a	Manual	A+A-	Basic actuator control and PLC I/O understanding
b	Manual	A+A-B+B-	Manual sequencing of multi cylinder system
c	Automatic	A+B+B-A-	Sequential logic in automatic control
d	Automatic	A+B+(B-A-)	Interlocking and motion synchronization
e	Automatic	B+A+B-A-	Flexible sequencing and PLC programming

3. RESULTS AND DISCUSSION

This section presents the implementation results and performance evaluation of the developed IoT-based PLC and HMI trainer designed for pneumatic control system learning. The developed system integrates the PLC control unit, HMI visualization interface, and pneumatic training panel, enabling real-time system monitoring, actuator control, and data communication through the IoT interface. Experimental testing was conducted to evaluate the functionality, reliability, and operational performance of the proposed trainer system. The testing results were analyzed to verify the correct execution of pneumatic control sequences, system responsiveness, and communication performance. In addition, the effectiveness of the trainer as a practical learning medium for industrial automation and mechatronics education is evaluated through student-based learning assessments. The obtained results are further discussed by relating them to previous studies and existing training systems in order to highlight the contribution of the proposed trainer in improving hands-on learning experiences and the integration of PLC-based control systems with IoT technologies.

3.1. Hardware implementation

The hardware design of the proposed trainer kit was developed to support learning activities in pneumatic control, PLC programming, and understanding of system integration. The selection of hardware components emphasizes educational suitability, modularity, safety aspects, and ease of use, rather than the performance requirements of large-scale industrial systems. Such design considerations are commonly applied in automation trainer systems to achieve optimal learning outcomes [22].

The main component of the trainer kit is the Haiwell PLC, which functions as the central control unit. This PLC is equipped with a sufficient number of digital input and output channels to support basic pneumatic control experiments, such as sequential control and sensor-based interlocking. PLC-based hardware platforms are widely used in educational laboratories because they can represent real control systems while remaining easy for students to learn [23].

A Haiwell HMI is integrated to provide local visualization and interaction with the system. Through the HMI, students can monitor system conditions, such as sensor status and actuator positions, and operate the trainer in both manual and automatic modes. The use of HMI in educational trainers has been proven to enhance students' understanding of system monitoring concepts and control interfaces [24].

The pneumatic subsystem consists of pneumatic cylinders, solenoid valves, an air supply unit, and position sensors. Double-acting cylinders are used to demonstrate two-way motion control, while the solenoid valves are directly controlled by PLC output signals. Position sensors are installed to detect the actuator status and provide feedback to the PLC. The use of real pneumatic components allows students to directly observe the physical response of the system, which is essential for learning the principles of pneumatic control [25].

To support IoT-based monitoring in an educational context, the trainer kit is equipped with communication interface modules, such as Ethernet or Wi-Fi, connected to the PLC. These modules enable the transmission of selected system variables to an IoT platform for remote observation. In educational applications, the communication module is more focused on system visualization and learning assessment rather than performance optimization [26].

All hardware components are mounted on the trainer panel using clearly labeled terminals and connectors to ensure safety and ease of operation. The modular layout allows reconfiguration of components according to the practical exercise objectives. This design approach is recommended for educational trainers as it promotes flexibility and hands-on learning [27]. All installed components are shown in Figure 7.

3.2. PLC and HMI software implementation

The software design of the proposed trainer kit is developed to support step-by-step learning in PLC programming, HMI operation, and understanding of pneumatic control principles. The software architecture emphasizes simplicity, modularity, and clarity to suit the educational environment. Educational control systems generally adopt structured software design to facilitate gradual learning and experimental activities.

The PLC software is developed using the LD approach, which is widely used in engineering education due to its intuitive representation of relay logic and sequential control. The PLC program is divided into several functional blocks, including input processing, sequential control logic, actuator control, and safety interlocks. Modular PLC programming has been shown to enhance students' understanding of control logic as well as their ability to analyze system faults [28]. Two main operating modes are implemented in the PLC program, namely manual mode and automatic mode. In manual mode, students can directly control the pneumatic actuators through commands from the HMI to understand the relationship between control signals and the physical movement of actuators. In automatic mode, the system executes predefined work sequences based on sensor feedback, allowing students to learn sequential control and interlock mechanisms. The implementation of these two operating modes is a common pedagogical strategy used in automation trainer systems.

A key educational innovation in this study is the implementation of a single modular PLC control program capable of handling multiple pneumatic learning scenarios. In conventional trainer systems, each experiment typically requires a separate PLC program, which increases programming redundancy and disrupts learning continuity. By contrast, the proposed unified control structure allows scenario switching via HMI without rewriting the PLC program. This approach provides several concrete educational advantages: (i) students can analyze logic variations within one structured program, (ii) debugging and fault analysis become more systematic, (iii) learning progression from manual to automatic mode becomes continuous, and (iv) reduced cognitive load compared to multi-program approaches.

This modular programming strategy enhances conceptual clarity and supports higher-order understanding of control system architecture. A representative example of the PLC program is presented to illustrate the control logic of the proposed system in Figure 8. The HMI software is designed to provide clear system condition visualization and user interaction. The HMI interface displays real-time information such as sensor status, actuator positions, and the system operating mode. In addition, control buttons for start, stop, and mode selection are provided, along with an alarm display. Visualization through the HMI interface can enhance students' understanding of system behavior and support interactive learning. A representative HMI interface is presented to illustrate the monitoring and control functions implemented in the proposed system in Figure 9.

In addition to control and visualization functions, the software design also integrates basic data communication functionality to support IoT-based monitoring in an educational context. Certain system variables, such as cycle count and actuator status, are transmitted to an external monitoring platform. This feature enables instructors and students to observe the system remotely and supports learning assessment. The IoT-based monitoring interface of the proposed system is illustrated in Figure 10. In educational applications, the IoT functionality is more focused on visualization and monitoring rather than real-time control optimization.

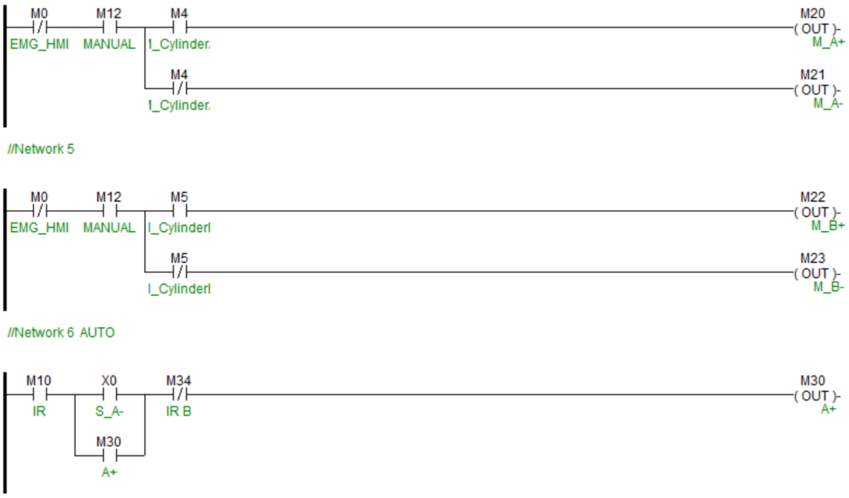

Figure 8. Representative example PLC control logic of the proposed system

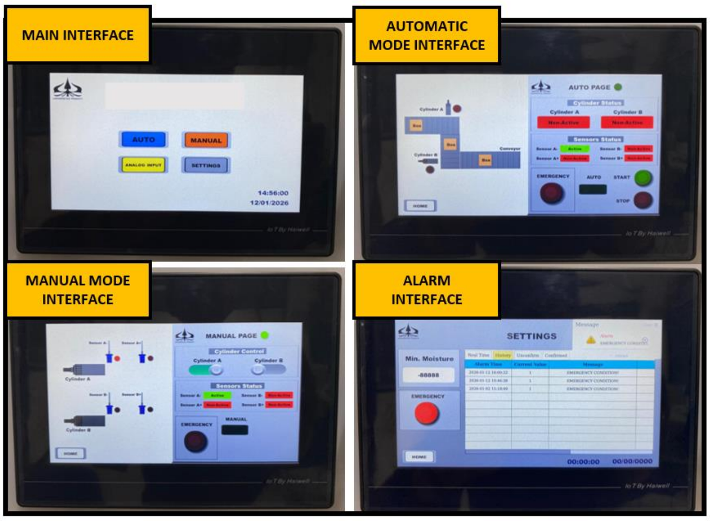

Figure 9. Representative HMI Interface of the proposed system

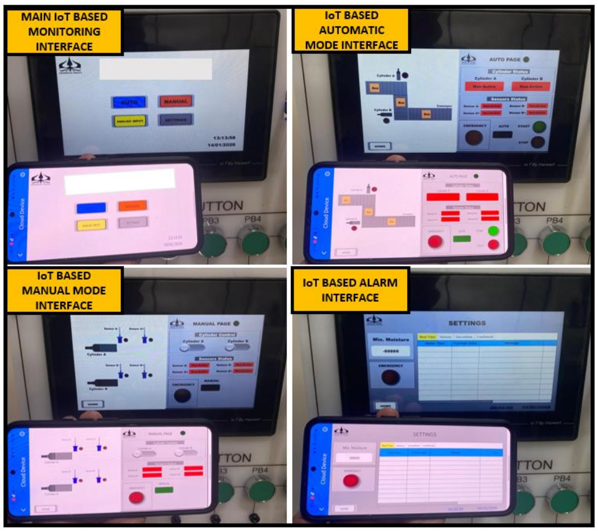

Figure 10. IoT-Based monitoring interface of the proposed system

The learning module design is aligned with the implementation of the trainer software. The practical activities are organized into sequential modules, starting with basic input–output testing, followed by manual control exercises, and ending with automatic sequential control. Each module is equipped with clear learning objectives, procedures, and evaluation criteria. Structured learning modules integrated with trainer software have been proven effective in automation education.

3.3. Testing and evaluation results

Testing and evaluation were conducted to verify the operational performance of the developed PLC–HMI trainer integrated with IoT monitoring. The testing process focused on validating the main system functions, including manual actuator control, automatic pneumatic sequencing, HMI-based system monitoring, and IoT communication capability. The summary of the functional testing results is presented in Table 4.

The results presented in Table 4 indicate that all tested functions operated according to the intended design specifications. The manual control mode allowed users to activate pneumatic actuators through push button commands with an average response time of approximately 0.35 seconds. The automatic sequence operation executed the predefined PLC ladder logic with a sequence delay of about 0.40 seconds. In addition, the HMI interface displayed actuator status and system conditions in real time with a display delay of around 0.25 seconds. The IoT monitoring function also operated correctly, where system parameters were transmitted to the monitoring dashboard with an average communication delay of approximately 0.85 seconds. The response time obtained in this experiment is within the acceptable range for educational pneumatic training systems, indicating that the developed trainer is capable of providing real-time control interaction for laboratory learning. These results demonstrate that the developed trainer system provides stable control performance and reliable communication during laboratory operation.

Table 4. Functional testing summary

Test item	Description	Trials	Measured parameter	Result
Manual control	Actuators operated through push button commands	10	Average response time: 0.35 s	Successful
Automatic Sequence	Pneumatic sequence executed according to PLC program	10	Sequence execution delay: 0.40 s	Successful
HMI interaction	System status and actuator conditions displayed correctly on HMI	10	Display refresh delay: 0.25 s	Successful
IoT-based Monitoring	System parameters successfully transmitted to IoT dashboard	10	Communication delay: 0.85 s	Successful

3.4. Educational evaluation result

The effectiveness of the developed pneumatic trainer system was further evaluated through pre-test and post-test assessments conducted during laboratory learning sessions. The pre-test was administered before students interacted with the IoT-integrated PLC-HMI pneumatic trainer in order to measure their initial understanding of pneumatic control concepts. After completing the learning activities using the developed trainer system, students were given a post-test covering similar topics related to pneumatic automation and PLC-based control systems. The comparison of the average scores is presented in Figure 11.

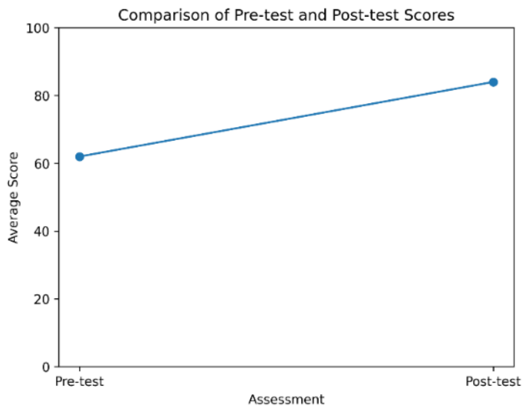

Figure 11. Comparison of pre-test and post-test score

The results indicate a significant improvement in student understanding after the implementation of the developed trainer system. The average pre-test score was 62, while the post-test score increased to 84, representing an improvement of approximately 35.5% in the average learning score. This improvement indicates that the integration of PLC control, HMI visualization, and IoT monitoring can effectively support practical learning in pneumatic automation training. Compared with conventional pneumatic trainers that operate without system integration and remote monitoring, the proposed PLC–HMI–IoT trainer provides a more comprehensive learning environment. Students are able to simultaneously observe actuator motion, PLC logic execution, HMI visualization, and IoT data transmission. This integrated observation capability reduces troubleshooting time and improves conceptual understanding of system interactions.

3.5. Comparison with related works

To explicitly address the novelty positioning of this study, a structured comparison with recent PLC and IoT-based educational trainers is provided in Table 5. The comparison emphasizes differences in system architecture, modular control design, educational evaluation approach, and IoT functionality orientation. The comparison presented in Table 5 highlights the main differences between the proposed trainer system and previous PLC-based educational trainers. Unlike earlier studies that focused primarily on PLC programming or standalone pneumatic systems, the proposed system integrates PLC control, HMI visualization, real pneumatic components, and IoT monitoring within a unified learning platform. This integration enables students to understand the interaction between control logic, physical processes, and network-based monitoring, which is essential for modern industrial automation education.

Table 5. Comparative analysis of the proposoed trainer and releted works

Reference	Hardware scope	IoT feature	Modular software	Educational evaluation	Cost orientation	Learning outcome focus
[1]	PLC-based trainer	Basic monitoring	Independent PLC program for each learning module	Limited	Medium	PLC operation
[5]	Pneumatic PLC	No IoT	Non-modular	Practical testing	Low	Sequential logic
[6]	General PLC	No IoT	Limited modularity	Reported	Medium	PLC programming
Proposed work	PLC + HMI + Real pneumatic + IoT	Educational oriented remote monitoring	Single modular PLC program for multiple scenarios	Functional + qualitative educational evaluation	Laboratory-scaled	Integrated automation understanding

4. CONCLUSION

This study presented the design and implementation of an IoT-based PLC and HMI trainer for pneumatic control system education. The developed trainer integrates PLC control, HMI visualization, real pneumatic actuators, and IoT-based monitoring within a single laboratory learning platform. Functional testing results confirmed that all system components operated according to the intended design, including actuator control, sequential operation, HMI visualization, and IoT communication, demonstrating stable performance during repeated operation scenarios. The educational evaluation results indicated a significant improvement in student learning outcomes. The average pre-test score increased from 62 to 84 after students used the developed trainer, representing an improvement of approximately 35.5% in learning performance. These results demonstrate that the integration of PLC control, HMI visualization, and IoT monitoring can effectively support practical learning in pneumatic automation education. Overall, the proposed trainer provides an integrated and flexible learning platform for laboratory-based education in industrial automation and mechatronics courses. Future work may focus on expanding the trainer capabilities by incorporating additional automation modules, sensor networks, and more advanced control strategies to further support Industry 4.0-oriented education.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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