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Design and Manufacturing of a Control System for a Pneumatic Robotic Arm for Training Purposes

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ABSTRACT

This study focuses on designing and manufacturing a new control system for an industrial pneumatic robotic arm, specifically to meet the practical training needs of students in the field of mechatronics. The primary objective of this research is to build an "open" control system, allowing learners to freely connect input and output signals to program the robotic arm according to specific operational requirements. This design enhances students' autonomy and understanding of control systems. It supports flexible and easy adjustments to the robot's operation, helping students gain a stronger grasp of robotic arm control and operation in a real industrial setting. The research methodology consists of three main steps. First, the study applies a programmable logic controller (PLC) as the system's foundation. The PLC was chosen for its flexibility and practical relevance, making it easier for students to engage with industrial applications. Second, the study explores the structure of the pneumatic drive system, control factors, and necessary conditions for stable operation in the robotic arm's pneumatic system. Finally, the research identifies the essential actuators and piston position sensors to ensure effective operation of the robotic arm. The findings demonstrate that the new control system, developed using PLC technology, can flexibly meet practical training requirements and holds great potential for application in technical education. This system not only fulfills basic control needs but also provides extended functionality, allowing students to easily modify the system to practice programming skills for controlling pneumatic robotic arms. As a result, it lays a solid foundation for training in the field of mechatronics.

Keywords: Open control system, Programmable Logic Controller, Pneumatic robotic arm, Pneumatic drive system, Programming skills, Position sensors, Technical education.

1. INTRODUCTION

Pneumatic robotic arms are widely used in various industries, particularly in the plastics industry, due to their advantages such as high speed, operational precision, and durability in harsh or hazardous environments where human presence is undesirable. However, most industrial pneumatic robotic arms from major manufacturers are designed with built-in controllers or integrated into automated production systems, making it challenging to intervene or adjust them for specific applications, such as in plastic molding production lines. This design limitation can restrict companies' ability to adapt and improve their production processes to meet specialized requirements.

In today's diverse production landscape, with various scales and types of manufacturing, the ability to flexibly adjust and program pneumatic robotic arms is essential. Operators must have a solid understanding of automated control to be able to program and adjust the robotic arm according to the specific production needs of each business. This need calls for an open control system that allows operators to customize the robotic arm's functions without being limited by the manufacturer's fixed design.

Therefore, this research focuses on designing a new control system for pneumatic robotic arms, capable of meeting the production requirements of factories, allowing users to adjust control parameters as needed, and flexibly reprogram the robot's operations. This control system is intended not only for production but also for educational and training purposes, enabling students and technicians to practice programming and controlling the robotic arm in a hands-on laboratory environment. Although there have been some studies on the application of microcontrollers and microprocessors in pneumatic robotic arms, this research emphasizes developing a highly applicable control system for training purposes, while also meeting diverse production requirements.

In the context of Industry 4.0, pneumatic robotic systems are increasingly integrated with intelligent sensors, distributed control, and reconfigurable architectures. Recent studies [2], [13] emphasize that training platforms must allow learners to access low-level I/O, modify control logic, and integrate external modules to meet modern automation requirements. However, most commercial pneumatic robotic arms remain closed systems, limiting the ability to customize control algorithms for educational purposes. Therefore, developing an *open PLC-based training platform* addresses a significant gap by enabling flexible signal wiring, user-defined operating modes, and real-time experimentation with industrial hardware

2. NOVELTY AND CONTRIBUTION

This study introduces a fully open and reconfigurable PLC-based control framework for a pneumatic robotic arm, specifically designed to support educational and training activities in mechatronics. Unlike conventional industrial pneumatic manipulators equipped with fixed and closed control units, the proposed system exposes all essential input/output (I/O) terminals, allowing learners to freely wire sensors, configure actuators, and modify the control sequence according to specific training objectives.

Compared with previous PLC-controlled pneumatic robotic arms reported in the literature [10], [11], the proposed system offers several key advancements:

- Open-access I/O architecture: all digital inputs and outputs are fully available through terminal blocks, enabling rewiring and complete accessibility for experimentation.
- Multiple configurable operating modes, allowing students to construct and test different control flows and task-oriented sequences.
- A modular PLC structure that supports future expansion with additional modules, sensors, or smart pneumatic components.
- A training-oriented design that bridges industrial pneumatic structures with student-friendly programmability and hands-on learning.

In addition, the proposed system provides a significant improvement compared with existing PLC training platforms commonly used in educational institutions. Most current training kits adopt fixed and non-expandable I/O configurations, limiting the ability to integrate additional input modules for tasks such as product feeding or detection, as well as output modules for advanced functions like sorting or classifying products. These limitations restrict learners from developing complete industrial automation scenarios that require flexible signal integration. In contrast, the open and expandable architecture of our system enables seamless incorporation of extra sensors, actuators, conveyors, or end-of-line sorting mechanisms, supporting a wide spectrum of real-world applications.

Recent developments in Industry 4.0 highlight the growing adoption of cyber-physical pneumatic systems, data-driven maintenance strategies, and smart actuator integration. Pneumatic robotic arms are increasingly expected to operate in flexible, adaptive production environments, requiring adjustable and transparent control architectures [13]. Moreover, several studies from 2020–2024 emphasize the importance of open PLC-based learning platforms that allow students to practice ladder logic, I/O mapping, fault handling, and sequential control under realistic industrial conditions [2]. These trends reinforce the necessity for training systems that are modular, expandable, and fully reconfigurable—requirements that are directly addressed by the design proposed in this study.

Overall, the contributions of this work enhance hands-on learning, promote algorithmic thinking, and provide a versatile and scalable platform aligned with modern mechatronics curricula and Industry 4.0 educational objectives.

3. DESCRIPTION OF THE PNEUMATIC ROBOTIC ARM

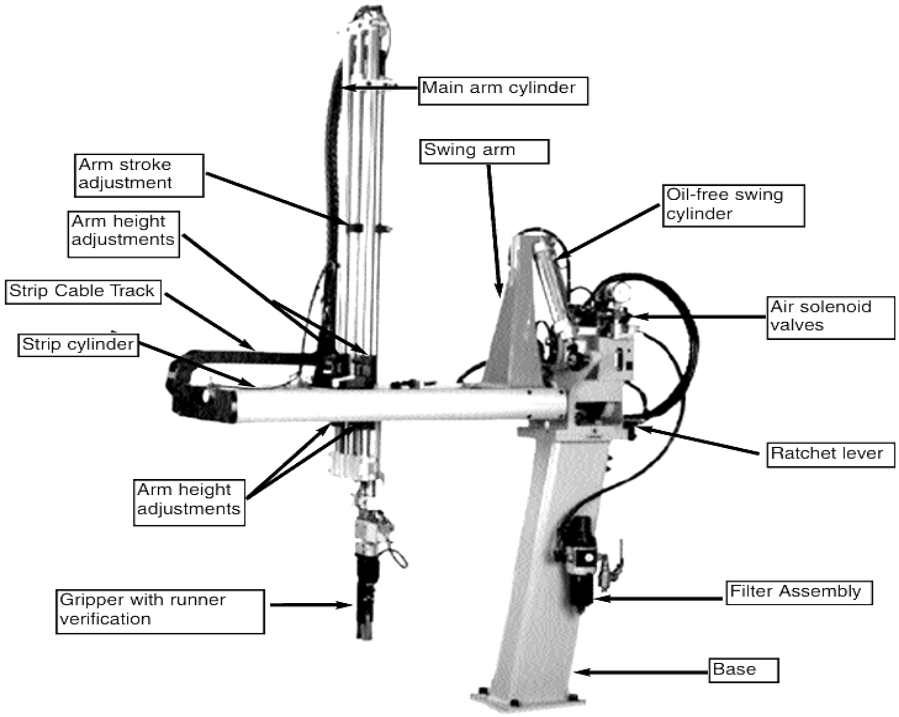


Figure 1. Functions of Pneumatic Robotic Arm Components

3.1 Functions of Pneumatic Robotic Arm Components (Figure 1)

- Main Arm Cylinder: The main cylinder of the arm, providing the primary force and movement to control the up-and-down or vertical motion of the robotic arm.
- Swing Arm: The swing arm allows the robotic arm to rotate or move horizontally, enhancing its reach to various positions.
- Oil-free Swing Cylinder: A swing cylinder that operates without oil, controlling the arm's rotational movement without the need for lubrication, making it suitable for clean environments.
- Air Solenoid Valves: Pneumatic solenoid valves that control the flow of air into the cylinders, thereby regulating the movements of the robotic arm.
- Ratchet Lever: A ratchet lever typically used to lock or adjust the position of the robotic arm.
- Filter Assembly: The air filter assembly removes impurities from the air before it enters the system, protecting the cylinders and valves from damage caused by dust and debris.
- Base: The base of the robotic arm, providing stability to the entire system and anchoring other components on the platform.
- Gripper with Runner Verification: The robotic arm gripper with runner verification functionality, which grips and inspects the item to ensure the product or runner (excess material in plastic molding) is handled correctly.
- Strip Cylinder: The strip cylinder assists in separating parts or pushing items away from the gripper.
- Strip Cable Track: The cable track for the strip cylinder, which secures electrical and pneumatic cables neatly and prevents tangling.
- Arm Stroke Adjustment: Allows for adjustment of the arm's stroke, enabling changes to the arm's range of motion to meet various requirements.

3.2 Basic Specifications of the Pneumatic Robotic Arm

The dimensions and structural specifications of the robotic arm are shown in Figure 2 and Table 1..

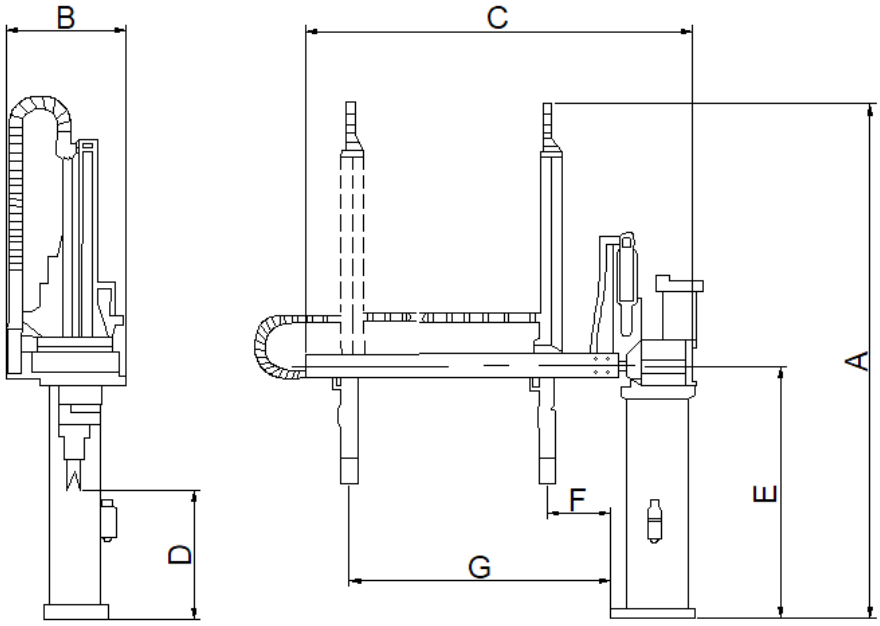


Figure 2. The dimensions of the robotic arm.

Dimensions (mm)	
A - Height	1300
B - Width	290
C - Length	720
D - Clamp Center	120
E - Distance from Axis Center to Base	557
F - Moving Distance	50-430mm
Weight (kg):	
No Load	37kg
With Load	39kg
Performance Characteristics:	
Arm Rotation Angle	45-90°
Clamp Rotation Angle	90°
Minimum Cycle Time	3.2s
Physical Characteristics:	
Air Consumption	0.5kg
Working Air Pressur	11.6MPa
(220V / 1 phase, 50-60 Hz)	2.5W

Table 1. The structural specifications of the robotic arm

3.3 Pneumatic System Circuit

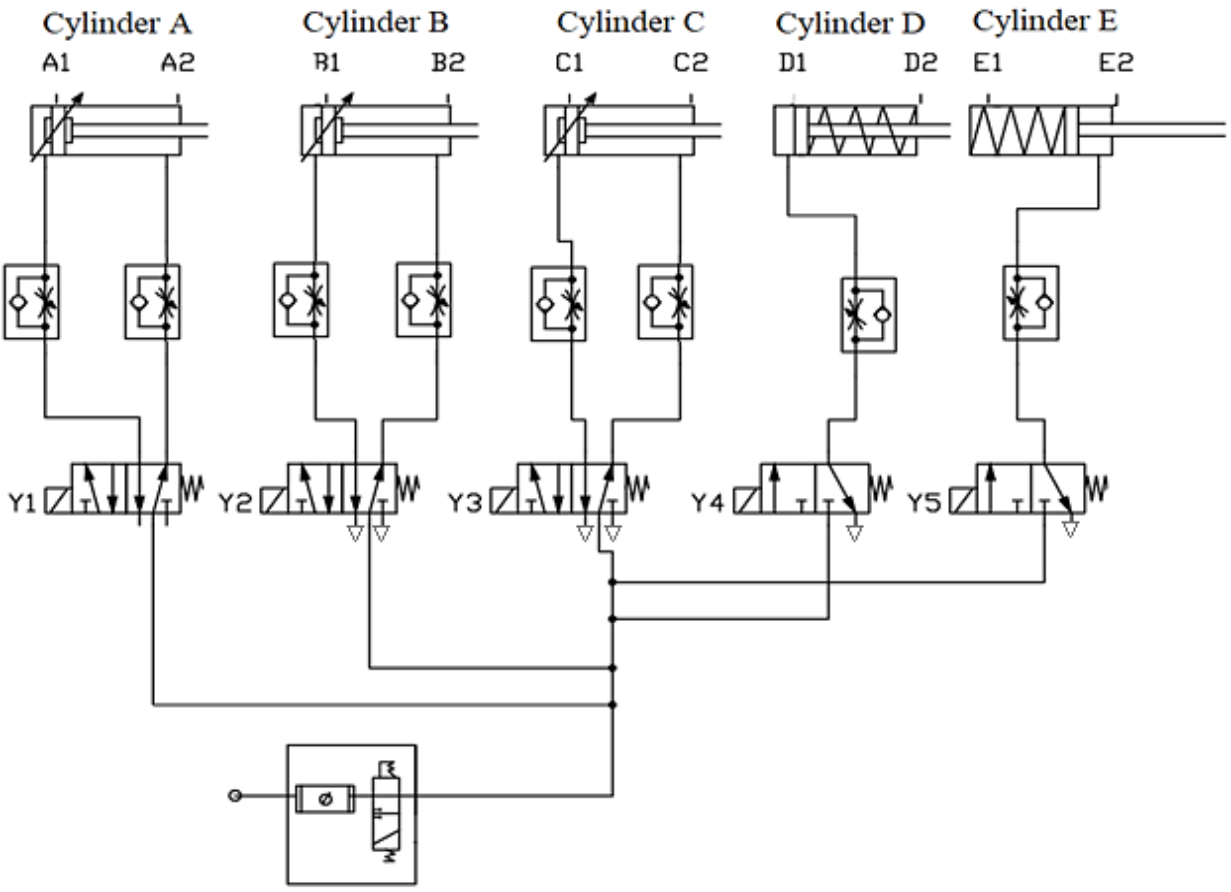


Figure 3. Pneumatic circuit of the Robotic Arm

The above image (Figure 3) is a diagram of the pneumatic system. The pneumatic robotic arm uses pneumatic energy in the form of pressure and airflow to generate movement. This pneumatic energy is supplied by an air compressor available in the factory. The air pressure is regulated by a pressure control valve, ensuring that the pneumatic pressure supplied to the robotic arm remains constant. The forward and backward movements of the piston are controlled by pneumatic distribution valves operated by a 24 VDC electric control system

4. DESIGN OF CONTROL SYSTEM USING PLC

The objective is to design a flexible robotic arm control system that allows for easy program modification and parameter adjustments. One of the programs (operating modes) is shown in Figure 4.

The operating procedure of the pneumatic robotic arm begins with checking the start power. If the power is correct, cylinder E is activated, and the robotic arm moves to its initial position. Once the robotic arm is confirmed to be in its starting position, the program is initiated. Next, the sensor detects the presence of the workpiece; if the workpiece is identified at the correct location, it is moved to the designated position, and cylinder C begins operating. At this stage, a temporary stop sensor is activated, and if all conditions are met, cylinder D performs a clamping action while cylinder C moves backward. Following this, cylinder A rotates, and cylinder B moves forward to continue the process. Once completed, cylinder A rotates again to return the workpiece to its initial position along with cylinder C. If the sensor confirms reactivation, the cylinders return to their original positions; otherwise, the process stops. Finally, cylinder E locks to complete the cycle, and the robotic arm returns to its starting state, ready for the next cycle. This diagram describes an automatic sequential control process for the pneumatic robotic arm, with precise steps of inspection and control to ensure efficient and safe operation in an industrial environment.

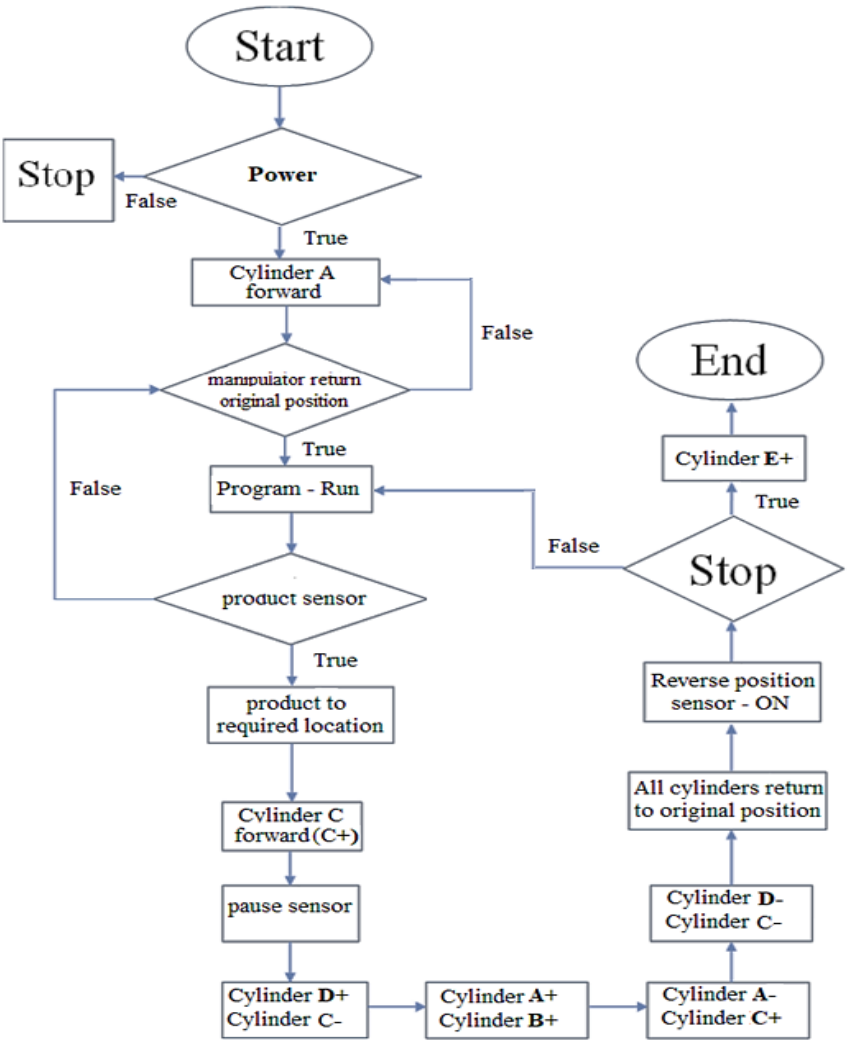


Figure 4. Flowchart Representing the Operation of the Robotic Arm

A stroke-step diagram in Figure 5 illustrates the pneumatic robotic arm's operation.

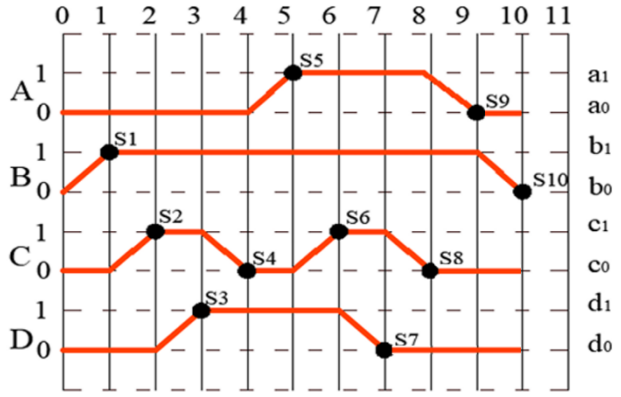


Figure 5. STROKE-STEP Diagram Representing One Operating Cycle

The control system using a PLC is widely trusted in machinery and production lines due to its many advantages: high stability, excellent noise resistance, and various options for system expansion, such as adding additional modules. For these reasons, in this study, we also chose Mitsubishi's PLC for the pneumatic robotic arm control system (Figure 6).

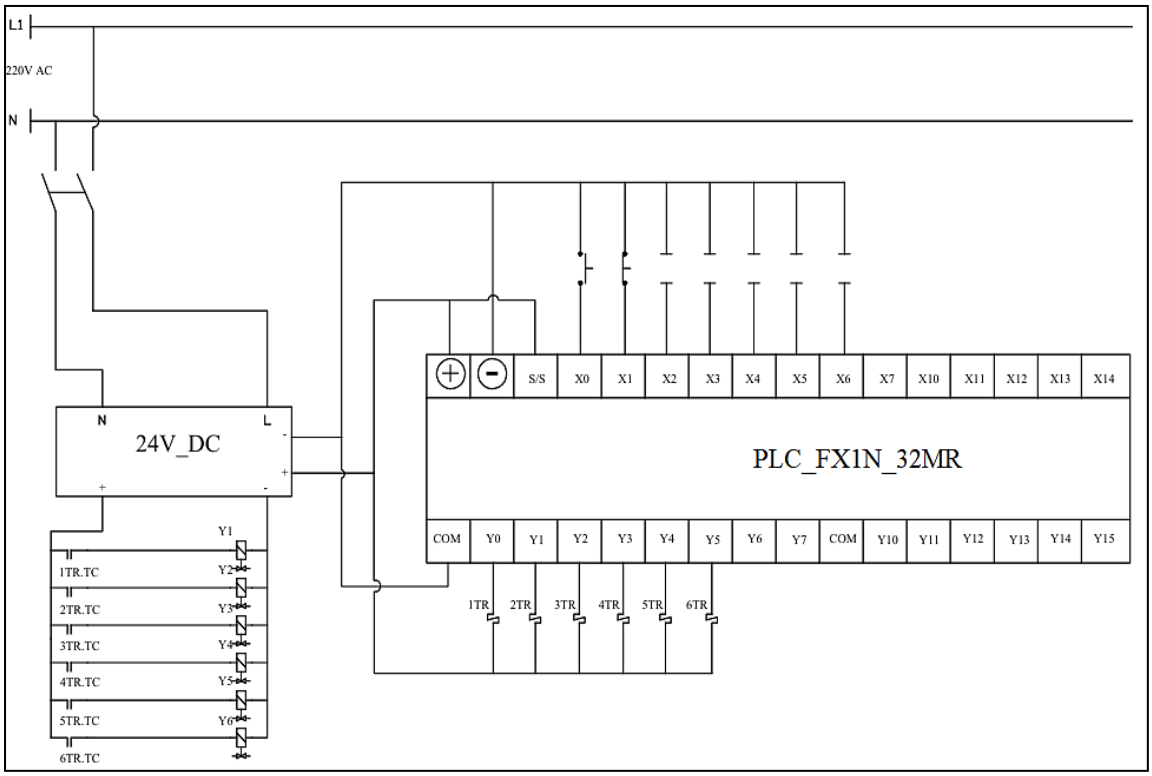


Figure 6. Electrical System Diagram for PLC Connection

5. RESULTS OF CONTROL SYSTEM MANUFACTURING

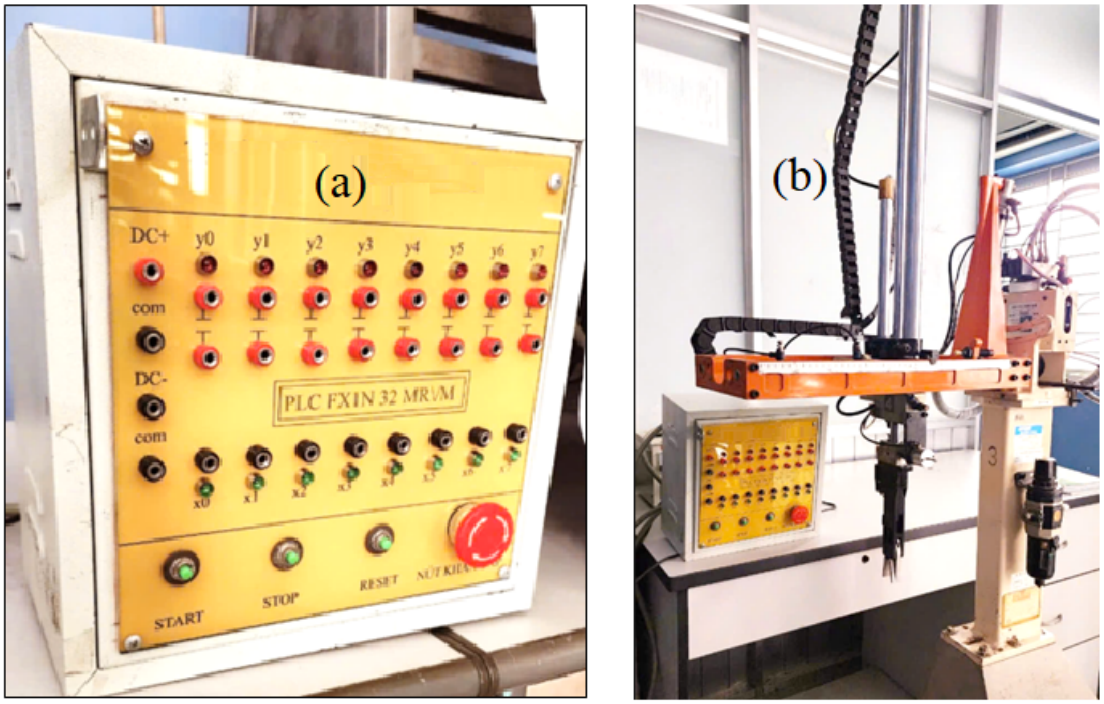


Figure 7. (a) Control system using the FX1N_32MR PLC, (b) Pneumatic robotic arm with controller in trial operation

The research team has completed the trial manufacturing of a control system using the FX1N_32MR PLC for a pneumatic robotic arm intended for training purposes (Figure 7), and the trial operation has yielded positive results. Since the system is designed for educational use, the control system was developed with an "open" connection for input signals (from the robotic arm's sensors) and output signals to control the arm's movements through 5/2 and 3/2 distribution valves. Learners programming the robotic arm need to clearly understand these input and output signal addresses and connect them to the controller, providing a foundation for developing control algorithms and programming the robotic arm.

Each different operating mode of the robotic arm corresponds to a different control program. Within the scope of this research, the author proposes four operating modes for the robotic arm, corresponding to four modes as shown in Table 2. Each mode is associated with a specific control program that learners will implement.

MODE 1	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6
Arm descend	Arm descend	Arm descend	Arm descend	Arm descend	Arm descend
Strip forward	Strip backward	Grip on	Grip on	Grip on	Strip backward
Grip on	Grip on	Strip backward	Strip forward	Strip backward	Grip on
Strip backward	Strip forward	Arm retract	Arm retract	Arm retract	Strip forward
Arm retract	Arm retract	Swing outward	Swing outward	Swing outward	Grip off
Swing outward	Swing outward	Second arm descent	Arm second descend	Arm second descend	Arm retract
Second arm descent	Arm second descent	Grip off	Grip off	Grip off	
Grip off	Grip off	Second arm retract	Arm second retract	Arm second retract	
Second arm retract	Second arm retract	Swing inward	Swing inward	Swing inward	
Swing in	Swing in	Strip forward	Strip backward	Strip forward	

Table 2. Operating Mode of the Robotic Arm

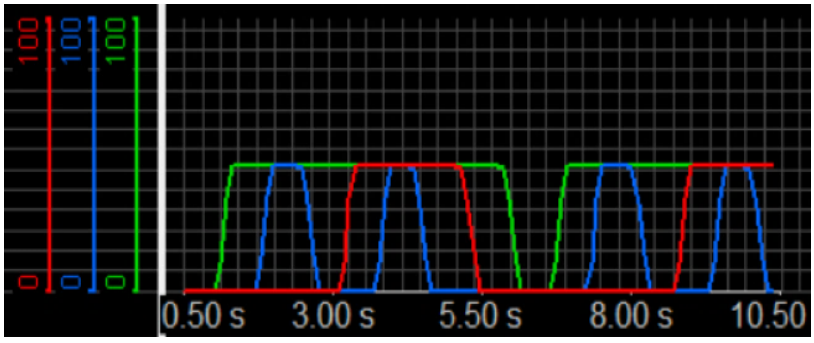


Figure 8. Experimental results of the stable operation with MODE 1

To evaluate the stability and repeatability of the proposed control system, each operating mode was tested over 50 continuous cycles under identical air pressure (6 bar). The piston stroke, cycle time, and end-stroke damping behavior were monitored using inductive position sensors and a digital time logger. Variations in cycle time remained within ±0.12 s for Mode 1 and ±0.15 s for other modes, demonstrating good repeatability for training purposes. Figure 8 illustrates the recorded motion profiles of the cylinders under Mode 1. The curves in the graph represent the motion of the main cylinders of the pneumatic robotic arm. The stable operating parameters of the pneumatic robotic arm corresponding to the MODES are displayed in Table 3.

MODE	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Operating Pressure	6 bar	6 bar	6 bar	6 bar	6 bar	6 bar
Cycle Time (s)	5.3	5.6	5.2	5.9	5.8	4.9

Table 3. Experimental result of the stable operation with the modes

The results demonstrate that the open PLC architecture provides high flexibility for both educational and industrial scenarios. This aligns with current trends in modular robotic systems, where reconfigurability and user-driven programming are essential. The ability to modify operating modes easily reflects the shift from rigid automation towards adaptable, operator-centric pneumatic systems. In future work, integrating smart flow sensors or IoT modules could further enhance compatibility with Industry 4.0 teaching labs

It is expected to continue further research to determine the optimal operating mode of the pneumatic robot arm by finding better damping solutions for the rapid piston movement at the end of its stroke, while also studying the ratio between speed and air consumption. This will help improve the energy efficiency of similar systems in the industry.

6. CONCLUSION

In this study, an open-access control system based on the FX1N_32MR PLC was successfully designed and implemented for a pneumatic robotic arm intended for training in automation and mechatronics. The open architecture enables full accessibility to input and output signals, allowing learners to wire sensors, operate 5/2 and 3/2 pneumatic valves, and program control sequences directly on industrial hardware. This provides a highly practical environment for understanding pneumatic actuation and developing real-world PLC control algorithms.

Six operating modes were developed to demonstrate the flexibility of the system, and the results of trial operation confirmed stable and repeatable performance. This versatility allows students to practice programming, troubleshooting, and system adjustment, while also enabling easy addition of new operating modes as required—an advantage compared to conventional closed controllers.

Overall, the system effectively bridges theoretical learning and industrial practice, offering a robust foundation for educational applications in pneumatic automation. Its reconfigurable design supports diverse instructional scenarios and aligns with modern Industry 4.0 training needs. Future improvements may include integrating smart sensors, advanced monitoring, product identification or IoT connectivity to further enhance functionality and enrich the learning experience.

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