International Journal of Multidisciplinary and Innovative Research

ISSN(print): 3050-6883, ISSN(online): 3050-6891

Volume 03 Issue 06 June 2026

DOI: 10.58806/ijmir.2026.v3i6n05

Page No: 466-477

Design and Implementation of An Intelligent Pneumatic Automation System with Integrated Industrial Safety and Monitoring Functions: A Review Paper

T. M. S. A. Hossain[1], M. A. Emran, I. Hosen, R. Mia[2]

[1]Department of Automobile Engineering (AE), World University of Bangladesh (WUB), Dhaka-1230, Bangladesh

[2]Department of Mechanical Engineering (ME), World University of Bangladesh (WUB), Dhaka-1230, Bangladesh

ABSTRACT

Pneumatic systems are widely used in industrial automation due to their simplicity, robustness, and cost-effectiveness. However, conventional pneumatic systems lack intelligent monitoring, predictive maintenance capability, and integrated safety intelligence. With the advancement of Industry 4.0 technologies, significant research has been conducted on integrating IoT, PLC-based control, artificial intelligence (AI), and sensor networks into pneumatic systems. This review paper presents a comprehensive analysis of intelligent pneumatic automation systems with integrated industrial safety and monitoring functions. The study synthesizes recent research on condition monitoring, anomaly detection, system control, and predictive maintenance. It also highlights system architectures, enabling technologies, challenges, and future research directions for smart pneumatic automation systems.

ARTICLE DETAILS

Published On:
13 June 2026

KEYWORDS: Pneumatic system, Industrial automation, PLC, IoT, Condition monitoring, Predictive maintenance, Smart manufacturing, Industrial safety, AI-based diagnostics

Available on:
https://ijmir.com

1. INTRODUCTION

Pneumatic systems are extensively used in manufacturing industries due to their fast response, simple design, and low operational cost. They convert compressed air energy into mechanical motion and are widely applied in actuation, clamping, packaging, and assembly operations. Despite their advantages, traditional pneumatic systems operate in a largely non-intelligent manner, lacking real-time monitoring, predictive diagnostics, and automated safety integration. This leads to inefficiencies, unexpected downtime, and increased maintenance costs.

The emergence of Industry 4.0 has introduced smart manufacturing systems that integrate IoT, artificial intelligence, and industrial communication protocols. These advancements enable pneumatic systems to evolve into intelligent cyber-physical systems capable of self-monitoring, fault detection, and adaptive control.

This paper reviews recent developments in intelligent pneumatic automation systems with a focus on safety integration and monitoring technologies.

2. LITERATURE REVIEW

2.1 Pneumatic Monitoring and Data-Driven Systems

Kovacs and Ko [1] demonstrated a real-world data-based monitoring approach for pneumatic actuators, emphasizing the importance of accurate data acquisition and analysis in evaluating actuator performance and reliability. Their study focused on collecting operational data from pneumatic systems under practical working conditions to identify variations in actuator behavior, detect performance degradation, and improve maintenance planning. The research highlighted that continuous monitoring can significantly enhance system efficiency, reduce unexpected failures, and support predictive maintenance strategies in industrial automation systems. Furthermore, their work showed that integrating sensors and data acquisition techniques enables more precise assessment of actuator health and operational stability.

Similarly, Alyami et al. [6] proposed a microcontroller-based monitoring system designed for real-time condition tracking of pneumatic actuators. Their system utilized embedded microcontrollers, sensors, and communication modules to continuously monitor important operational parameters such as pressure, displacement, temperature, and actuator response time. The proposed method provided a cost-effective and efficient solution for industrial monitoring applications by enabling real-time data processing

and fault detection. In addition, the study demonstrated that microcontroller-based systems can improve automation reliability, support early fault diagnosis, and facilitate remote monitoring capabilities. Their research contributed to the development of smart monitoring systems suitable for modern industrial environments and Industry 4.0 applications.

2.2 AI-Based Condition Monitoring and Fault Detection

Mallia et al. [2] presented a comprehensive systematic review of anomaly detection techniques used in compressed air systems, highlighting the growing importance of intelligent monitoring methods in industrial automation. Their review analyzed various conventional and advanced approaches for detecting faults, leakages, pressure fluctuations, and abnormal operating conditions in pneumatic systems. The study compared data-driven, statistical, and machine learning-based techniques, emphasizing their effectiveness in improving system reliability and energy efficiency. Furthermore, the authors discussed the challenges associated with real-time monitoring, sensor integration, and fault classification, while identifying future research directions for the development of more robust and adaptive anomaly detection frameworks in compressed air applications.

Similarly, Tiboni and Remino [3] applied artificial intelligence (AI)-based methods for condition monitoring of pneumatic drive systems. Their work focused on utilizing machine learning algorithms and intelligent diagnostic models to analyze actuator behavior and detect early signs of system degradation or malfunction. The study demonstrated that AI-based monitoring approaches can effectively process large volumes of operational data, recognize hidden patterns, and provide accurate fault prediction capabilities. Their findings indicated that integrating AI techniques into pneumatic systems can enhance maintenance efficiency, reduce downtime, and improve the overall operational reliability of industrial automation processes.

In addition, Francalanza et al. [20] further demonstrated the application of AI-driven anomaly detection techniques to improve predictive maintenance accuracy in pneumatic and industrial systems. Their research employed advanced data analytics and intelligent learning models to identify abnormal operating conditions before critical failures occur. The proposed methods enabled continuous monitoring and automated fault diagnosis by analyzing sensor-generated data in real time. The study showed that AI-driven anomaly detection significantly improves maintenance decision-making, minimizes unexpected equipment failures, and reduces maintenance costs. Moreover, their work emphasized the role of predictive analytics and smart monitoring technologies in supporting Industry 4.0-based maintenance strategies and enhancing industrial system sustainability.

2.3 Modeling and Control of Pneumatic Systems

Ramezani and Baghestan [5] developed nonlinear observer-based control strategies for pneumatic servo systems to enhance control performance, system stability, and tracking accuracy. Their research addressed the inherent nonlinear characteristics of pneumatic actuators, such as air compressibility, friction effects, pressure variations, and parameter uncertainties, which often make precise control difficult. By employing observer-based control techniques, the proposed method was able to estimate unmeasured system states and compensate for disturbances in real time. The study demonstrated that nonlinear observers improve the dynamic response and robustness of pneumatic servo systems while reducing steady-state errors and sensitivity to external disturbances. Their work contributed significantly to the advancement of intelligent control methods for high-performance pneumatic automation applications.

Similarly, Emhemed et al. [4,17] focused on non-parametric modeling and system identification techniques for intelligent pneumatic actuators with the aim of improving system accuracy, adaptability, and operational stability. Their research investigated data-driven modeling approaches that do not rely heavily on predefined mathematical models, making them more suitable for complex nonlinear pneumatic systems. By utilizing experimental input-output data, the proposed identification methods effectively captured actuator dynamics and system behavior under varying operating conditions. The study demonstrated that non-parametric techniques can provide more flexible and accurate representations of pneumatic actuator performance compared to traditional parametric models. Furthermore, their work improved the precision of actuator control, enhanced stability during operation, and supported the development of intelligent pneumatic systems capable of adaptive and efficient real-time performance in industrial automation environments.

2.4 PLC-Based Industrial Automation

Rios et al. [18] and Ashshidiqi et al. [12] highlighted the implementation of PLC-based automation systems utilizing the IEC 61131-3 programming standard and Modbus communication protocols for industrial control applications. Their studies emphasized the importance of standardized programming environments in improving system interoperability, scalability, and maintenance efficiency within industrial automation systems. By adopting IEC 61131-3 standards, the proposed systems supported multiple programming languages such as Ladder Diagram (LD), Function Block Diagram (FBD), and Structured Text (ST), enabling flexible and reliable controller development for complex industrial processes.

Furthermore, the researchers demonstrated the integration of Modbus communication protocols to facilitate efficient data exchange between programmable logic controllers (PLCs), sensors, actuators, and supervisory systems. The use of Modbus communication enhanced system connectivity, simplified device integration, and enabled real-time monitoring and control of industrial operations.

Their work showed that PLC-based automation systems provide high reliability, deterministic control, and stable performance in harsh industrial environments where precise timing and dependable operation are critical. In addition, these systems contribute to improved operational efficiency, fault diagnosis, and process automation, making them highly suitable for modern smart manufacturing and Industry 4.0 applications.

2.5 IoT and Smart Manufacturing Integration

Li and Kara [16] discussed the application of wireless sensor networks (WSNs) in manufacturing monitoring systems, emphasizing their role in enhancing industrial automation, data acquisition, and real-time process supervision. Their study highlighted how wireless sensing technologies enable efficient communication between distributed sensors, machines, and monitoring platforms without the limitations of wired infrastructure. The researchers demonstrated that WSNs can significantly improve manufacturing flexibility, reduce installation costs, and support continuous monitoring of machine conditions, environmental parameters, and production performance. Furthermore, their work emphasized the importance of wireless communication in enabling predictive maintenance, fault detection, and intelligent decision-making within modern smart manufacturing environments.

Similarly, Hendrawati et al. [13] developed an IoT-enabled real-time PLC monitoring system designed to improve industrial process visibility and remote supervisory capabilities. Their proposed system integrated programmable logic controllers (PLCs) with Internet of Things (IoT) technologies to enable continuous data transmission, remote monitoring, and real-time system analysis through network-based platforms. The study demonstrated that IoT integration enhances operational efficiency by allowing operators to monitor industrial equipment and control processes from remote locations. In addition, the system supported rapid fault identification, reduced maintenance response time, and improved overall production reliability. Their research contributed to the advancement of smart industrial monitoring systems aligned with Industry 4.0 concepts.

Furthermore, Quernheim et al. [19] emphasized the importance of IoT integration for developing resource-efficient manufacturing systems. Their work focused on the use of interconnected devices, intelligent sensors, and cloud-based communication technologies to optimize industrial resource utilization, energy consumption, and production efficiency. The researchers highlighted that IoT-based manufacturing systems enable real-time data collection and analysis, facilitating adaptive process control and intelligent production management. Their findings demonstrated that IoT integration can improve system sustainability, minimize operational waste, and enhance overall manufacturing productivity. Moreover, the study underscored the significance of digital transformation and smart connectivity in achieving efficient, flexible, and sustainable industrial operations in modern manufacturing environments.

2.6 Safety and Security in Industrial Systems

Al Farooq et al. [8] investigated programmable logic controller (PLC) safety and fault detection mechanisms using data provenance techniques to improve the reliability and security of industrial automation systems. Their research focused on tracking the origin, flow, and modification of operational data within PLC-controlled environments to identify abnormal activities, system faults, and potential cyber-physical threats. By utilizing data provenance methods, the proposed approach enabled detailed monitoring of control processes and enhanced the traceability of system events. The study demonstrated that provenance-based fault detection can effectively identify unauthorized changes, operational inconsistencies, and malfunction conditions in industrial control systems. Furthermore, their work emphasized the importance of secure data management and transparent monitoring in maintaining safe and dependable industrial operations, particularly in critical automation infrastructures.

Similarly, Celik et al. [9] proposed Internet of Things (IoT)-based safety frameworks designed to ensure secure, reliable, and resilient industrial automation systems. Their research addressed the growing challenges associated with integrating IoT technologies into industrial environments, including cybersecurity risks, communication vulnerabilities, and system reliability concerns. The proposed framework incorporated secure communication protocols, intelligent monitoring mechanisms, and risk management strategies to protect industrial devices and automation networks from potential failures and cyberattacks. The study highlighted that IoT-enabled safety architectures can significantly improve real-time monitoring, fault detection, and system responsiveness while maintaining operational security and reliability. In addition, their work emphasized the critical role of secure IoT integration in supporting Industry 4.0 applications, smart manufacturing systems, and next-generation industrial automation technologies.

2.7 Energy Efficiency in Compressed Air Systems

Abela et al. [11,15] analyzed the performance of compressed air systems and emphasized the importance of energy optimization strategies for achieving industrial sustainability and operational efficiency. Their research focused on evaluating energy consumption patterns, system losses, pressure regulation, and overall performance characteristics of industrial compressed air networks. The studies identified that compressed air systems often experience significant energy wastage due to leakages, inefficient pressure management, improper system design, and inadequate maintenance practices. By conducting performance assessments and energy audits, the researchers demonstrated that optimized operational strategies can substantially reduce energy consumption and improve system reliability.

Furthermore, the authors highlighted various energy optimization techniques, including intelligent pressure control, leakage detection, efficient compressor operation, and real-time monitoring of system parameters. Their work showed that implementing advanced monitoring and control mechanisms can improve energy efficiency while reducing operational costs and environmental impact. In addition, the studies emphasized that sustainable compressed air system management plays a crucial role in supporting modern industrial sustainability goals, reducing carbon emissions, and enhancing resource utilization efficiency. Their findings contributed significantly to the development of energy-aware industrial automation systems aligned with Industry 4.0 and sustainable manufacturing initiatives.

3. SYSTEM ARCHITECTURE OF INTELLIGENT PNEUMATIC SYSTEMS

An intelligent pneumatic automation system typically consists of five major subsystems: (i) pneumatic subsystem, (ii) control subsystem, (iii) sensor network subsystem, (iv) communication subsystem, and (v) safety subsystem. The integration of these subsystems enables real-time monitoring, predictive maintenance, industrial safety, and Industry 4.0 compatibility [11], [13], [19].

3.1 Pneumatic Subsystem

The pneumatic subsystem is one of the core components of the automation system, responsible for generating, conditioning, controlling, and utilizing compressed air to perform mechanical operations. It converts compressed air energy into linear motion through pneumatic actuators and ensures reliable and efficient system operation [15].

Air Compressor Unit: The air compressor unit is responsible for generating compressed air required for the operation of the pneumatic system. It converts electrical energy into pneumatic energy by compressing atmospheric air and storing it at a specified pressure level. The compressor supplies continuous airflow to the system, ensuring stable operation of pneumatic actuators and control devices. Proper compressor selection is important to maintain sufficient pressure, airflow capacity, and energy efficiency for industrial automation applications [15], [11].

Air Preparation Unit (FRL: Filter, Regulator, Lubricator): The air preparation unit, commonly known as the FRL unit, is used to improve the quality and stability of compressed air before it enters the pneumatic system [15]. 1. The Filter removes dust particles, moisture, and contaminants from the compressed air to prevent damage to pneumatic components. 2. The Regulator controls and maintains a constant air pressure suitable for system operation, ensuring stable actuator performance. 3. The Lubricator introduces a controlled amount of lubricant into the airflow to reduce friction and wear in moving pneumatic components. The FRL unit enhances system reliability, improves component lifespan, and ensures efficient operation of pneumatic devices [15].

Directional Control Valves: Directional control valves regulate the flow path and direction of compressed air within the pneumatic system. These valves control the movement of pneumatic actuators by directing compressed air to different ports of cylinders. Depending on the control signal, the valves can start, stop, or reverse actuator motion. Directional control valves play a critical role in automation sequencing, process control, and motion synchronization in industrial applications [5], [14].

Double-Acting Cylinders: Double-acting cylinders are pneumatic actuators that use compressed air to produce linear motion in both forward and reverse directions. Unlike single-acting cylinders, they utilize air pressure on both sides of the piston, providing greater control, higher force output, and improved operational efficiency. These cylinders are widely used in industrial automation systems for pushing, pulling, lifting, clamping, and positioning operations. Their bidirectional operation enables precise and reliable movement control in automated manufacturing processes [4], [17].

3.2 Control Subsystem

The control subsystem is the central part of the automation setup that manages system operations, coordinates pneumatic actuator movements, processes sensor signals, and enables communication between hardware components. It ensures accurate sequencing, reliable control, and real-time monitoring of industrial processes [18].

Programmable Logic Controller (PLC): The Programmable Logic Controller (PLC) is the primary industrial controller used to automate and control the operation of the pneumatic system. It receives input signals from sensors and switches, processes control logic according to programmed instructions, and generates output signals to actuators, relays, and solenoid valves. PLCs are widely used in industrial automation because of their reliability, robustness, fast response time, and ability to operate continuously in harsh industrial environments [18], [12], [14]. They support deterministic control, making them highly suitable for sequential operations, process automation, and safety-critical industrial applications.

Microcontroller Unit (Arduino/ESP32 for IoT Integration): Microcontrollers such as Arduino and ESP32 provide additional monitoring, communication, and IoT integration capabilities. These devices collect real-time sensor data, process monitoring information, and transmit operational parameters to cloud platforms, dashboards, and remote monitoring applications [13], [11]. The ESP32 offers built-in Wi-Fi and Bluetooth communication features, making it highly suitable for wireless industrial monitoring systems. Their integration enhances system flexibility, enables remote supervision, supports predictive maintenance, and contributes to Industry 4.0-based smart automation applications [16], [19].

Relay and Solenoid Valve Drivers: Relay modules and solenoid valve drivers serve as interface circuits between the control system and industrial devices. Since PLCs and microcontrollers typically operate with low-voltage control signals, relay and driver circuits are required to safely control higher-voltage pneumatic valves, motors, and actuators [12], [18]. Relays provide electrical isolation and protect control devices from excessive current or voltage fluctuations, thereby improving operational safety and reliability.

3.3 Sensor Network Subsystem

The sensor network forms a critical layer of the automation system by providing real-time data acquisition, system feedback, and condition monitoring capabilities. It enables continuous observation of pneumatic subsystem performance, supports closed-loop control, and enhances fault detection and predictive maintenance [1], [2], [3].

Pressure Sensors: Pressure sensors measure air pressure within different sections of the pneumatic system, such as compressor output lines, FRL units, and actuator chambers. Accurate pressure measurement is essential for maintaining stable operating conditions and detecting leaks, blockages, or abnormal load conditions [1], [6].

Flow Sensors: Flow sensors monitor the rate of compressed air flowing through pipelines and components. They help evaluate system efficiency, detect air leakage, and ensure proper air consumption by pneumatic actuators. Flow data is also valuable for energy optimization and system performance analysis [2], [15].

Proximity Sensors: Proximity sensors are used to detect the position of moving components, such as piston positions in double-acting cylinders or the presence of objects in automated processes. These sensors provide digital feedback for sequence control, safety interlocking, and position verification [14], [18].

Vibration Sensors for Condition Monitoring: Vibration sensors monitor the mechanical health of compressors, actuators, and rotating components. They detect abnormal vibration patterns associated with wear, misalignment, imbalance, or impending mechanical failure. Continuous vibration analysis supports predictive maintenance and improves operational reliability [3], [20].

3.4 Communication Subsystem

The communication subsystem provides the infrastructure for data exchange, system coordination, and remote monitoring. It ensures seamless connectivity between sensors, controllers, actuators, and supervisory platforms [16], [19].

Industrial Ethernet: Industrial Ethernet is a high-speed communication network used to connect PLCs, sensors, controllers, and industrial devices. It supports low-latency and deterministic communication required for time-critical automation applications [18].

MQTT/HTTP IoT Protocols: MQTT and HTTP are widely used IoT communication protocols that facilitate data exchange between industrial systems and cloud-based platforms. MQTT is particularly suitable for real-time industrial monitoring because of its lightweight publish-subscribe architecture, while HTTP is commonly used for web-based dashboards and data visualization applications [11], [13], [16].

SCADA Integration System: The Supervisory Control and Data Acquisition (SCADA) system is a centralized platform for monitoring, controlling, and analyzing industrial processes in real time. It collects operational data from PLCs, sensors, and communication networks, presenting information through graphical interfaces for operators. SCADA integration improves process visibility, alarm management, historical data analysis, and fault response capability [13], [18].

3.5 Safety Subsystem

The safety subsystem protects equipment, operators, and industrial processes from abnormal operating conditions and unexpected failures. It ensures safe shutdown, prevents equipment damage, and provides early warning mechanisms for fault conditions [8], [9].

Emergency Stop Circuit: The emergency stop (E-stop) circuit is a fundamental safety mechanism that allows immediate shutdown of the system during hazardous conditions. Implemented using normally closed switches in a fail-safe configuration, it disconnects power to actuators and control devices when activated, ensuring personnel and equipment safety [8].

Overpressure Protection Valves: Overpressure protection valves automatically release compressed air when system pressure exceeds a predefined threshold. These valves protect cylinders, hoses, and compressors from excessive pressure buildup and prevent hazardous failures caused by regulator malfunctions or pressure surges [15].

Fault Detection and Alarm Indicators: Fault detection and alarm systems continuously monitor parameters such as pressure, flow, actuator position, vibration, and sensor signals. When abnormal conditions are detected, alarms are generated through LEDs, buzzers, HMI panels, or SCADA interfaces. This enables rapid operator response, reduces downtime, and improves overall operational safety [2], [8], [20].

The integration of pneumatic components, intelligent control systems, sensor networks, industrial communication technologies, and safety mechanisms creates a robust cyber-physical automation platform capable of supporting predictive maintenance, remote monitoring, and Industry 4.0 manufacturing objectives [11], [13], [19].

4. DESIGN AND IMPLEMENTATION METHODOLOGY

4.1 Requirement Analysis

System requirements define the essential performance, operational, and safety criteria that the automation system must satisfy to ensure reliable and efficient functioning under real industrial conditions. These requirements typically include load capacity, actuation speed, energy efficiency, safety constraints, and environmental considerations [14], [15], [18]. Load capacity refers to the maximum force or mechanical load that pneumatic actuators, particularly double-acting cylinders, must handle without performance degradation. Proper sizing of cylinders, compressors, and valves is essential to ensure that the system can consistently deliver the required force for industrial tasks such as pushing, lifting, clamping, and positioning operations [4], [5], [17]. Insufficient load capacity may lead to incomplete actuation, slow response, and reduced operational reliability.

Actuation speed defines how quickly the system can complete a motion cycle, including cylinder extension and retraction. It depends on airflow rate, valve response characteristics, pneumatic line design, and control logic implementation [5], [14]. High actuation speed is particularly important in automated manufacturing environments where production throughput is directly related to cycle time. Energy efficiency is a critical design requirement because compressed air generation represents one of the largest energy costs in industrial facilities. Efficient system design aims to reduce air leakage, optimize compressor operation, and minimize pressure losses throughout the pneumatic network [15]. Intelligent monitoring, pressure regulation, and predictive maintenance strategies contribute significantly to improved energy performance and sustainability [2], [20].

Safety constraints ensure that the system operates within predefined safe limits to protect both personnel and equipment. These constraints include emergency stop mechanisms, overpressure protection devices, fault detection systems, and fail-safe control architectures [8], [9]. Compliance with industrial automation standards is essential for preventing accidents and maintaining safe operation under abnormal conditions. Environmental considerations address factors such as temperature, humidity, dust, vibration, and industrial noise. Pneumatic components must be selected to withstand harsh operating environments while maintaining long-term reliability and performance [6], [14]. Furthermore, minimizing air leakage and reducing compressor noise contribute to environmentally sustainable manufacturing practices [15].

4.2 Pneumatic Circuit Design

ISO 1219 symbols are widely used in the design and documentation of pneumatic control circuits, providing a standardized graphical language for representing system components and operational functions [14]. These symbols improve communication among engineers and simplify system analysis, implementation, troubleshooting, and maintenance. In actuator control circuit design, ISO pneumatic symbols are used to represent components such as double-acting cylinders, directional control valves, flow control valves, check valves, and FRL units [4], [17]. Standardized symbols allow engineers to focus on system functionality and control logic rather than physical component appearance.

For valve configurations, ISO standards provide symbolic representations for different valve types, including 2/2, 3/2, 5/2, and 5/3 directional control valves. These symbols also identify actuation methods such as solenoid, pneumatic, mechanical, or manual control [5], [14]. Such representations are essential for designing sequential automation systems and analyzing compressed air flow paths. In air distribution systems, ISO symbols are used to document compressors, air preparation units, pipelines, regulators, and safety devices. This facilitates visualization of airflow routing, pressure regulation points, and protection mechanisms such as relief valves [15]. Standardized circuit diagrams also support simulation studies and maintenance planning activities.

Overall, the application of ISO 1219 pneumatic symbols improves design consistency, reduces ambiguity in technical documentation, and supports efficient implementation of industrial pneumatic automation systems [14].

4.3 Control Logic Development

PLC ladder logic remains one of the most widely used programming approaches in industrial automation because of its simplicity, reliability, and similarity to traditional relay-based control systems [18]. In intelligent pneumatic automation systems, ladder logic is used to implement sequential actuator control, safety interlocking, and fault management functions.

Sequential actuator control is achieved through ladder logic routines that execute operations according to predefined process sequences. Each operational step is triggered by input signals from sensors, timers, or position switches [12], [18]. For pneumatic systems, this typically involves coordinated extension and retraction of double-acting cylinders to ensure smooth and deterministic process execution.

Safety interlocking is implemented to prevent unsafe operating conditions and conflicting actuator movements. Ladder logic conditions ensure that actuators are activated only when predefined safety and process requirements have been satisfied [8], [18]. For example, cylinder movement may be inhibited unless sufficient pressure is available or unless another actuator has completed its cycle. Such interlocks significantly improve operational safety and protect mechanical equipment from damage.

Fault handling and emergency shutdown functions are integrated directly into the PLC program. The controller continuously monitors sensor signals and system status parameters to detect abnormalities such as overpressure conditions, sensor failures, actuator malfunctions, or communication interruptions [8], [9]. When faults are detected, the PLC initiates alarms and executes

controlled shutdown procedures or emergency stop sequences depending on fault severity. These mechanisms ensure safe system operation while minimizing equipment damage and production losses.

4.4 Sensor Integration

Sensors are deployed throughout the intelligent pneumatic automation system to provide continuous feedback on critical operating parameters. Real-time sensor data supports closed-loop control, predictive maintenance, fault detection, and system optimization [1], [2], [3].

Pressure Sensors: Pressure sensors measure compressed air pressure at critical locations including compressor outlets, FRL units, pipelines, and actuator chambers. Accurate pressure monitoring ensures stable operation and facilitates early detection of leaks, blockages, and abnormal load conditions [1], [6]. Pressure data is also used for process control and energy optimization.

Flow Sensors: Flow sensors monitor compressed air consumption and airflow distribution throughout the pneumatic network. These sensors provide valuable information regarding system efficiency and help identify leakage, valve malfunction, or excessive air demand [2], [15]. Flow monitoring also supports energy management initiatives by identifying opportunities for reducing compressed air waste.

Vibration Sensors: Vibration sensors are installed on compressors, valves, and mechanical assemblies to evaluate equipment health. Variations in vibration signatures often indicate wear, imbalance, misalignment, or impending mechanical failure [3], [20]. Continuous vibration monitoring forms a key component of predictive maintenance programs and improves system reliability.

Actuator Position Sensors: Actuator position sensors provide real-time feedback regarding cylinder extension and retraction positions. These sensors verify correct motion execution and support sequence control, synchronization, and safety interlocking functions [14], [18]. Position monitoring ensures accurate process control and reduces the risk of operational errors.

4.5 IoT Integration

IoT technologies play a crucial role in modern intelligent automation systems by enabling connectivity between field devices, controllers, cloud platforms, and supervisory applications [11], [13], [19]. Through IoT integration, traditional pneumatic systems evolve into smart cyber-physical systems capable of advanced monitoring, analytics, and predictive maintenance.

Cloud-based monitoring allows operational data including pressure, flow rate, vibration levels, and actuator status to be transmitted continuously to remote servers using communication protocols such as MQTT and HTTP [11], [13]. Engineers and operators can access this information through web dashboards or mobile applications, enabling real-time performance monitoring regardless of physical location.

Remote diagnostics capabilities allow maintenance personnel to evaluate machine performance and investigate faults without being physically present at the installation site [13], [19]. Historical and real-time sensor data can be analyzed to identify abnormal behavior, reducing troubleshooting time and improving maintenance responsiveness. IoT-enabled predictive maintenance systems combine cloud connectivity with artificial intelligence and machine learning techniques to forecast equipment degradation and potential failures [2], [3], [20]. By identifying deterioration trends before failures occur, maintenance activities can be scheduled proactively, reducing downtime, and extending equipment service life.

Overall, IoT integration transforms conventional PLC-based pneumatic automation systems into intelligent, connected, and data-driven platforms capable of supporting Industry 4.0 objectives, smart manufacturing initiatives, and sustainable industrial operations [11], [13], [19].

5. INDUSTRIAL SAFETY INTEGRATION

Safety is a critical component of intelligent pneumatic systems because these systems operate under pressurized air conditions and involve fast-moving mechanical actuators that can pose risks to both personnel and equipment if not properly controlled [8], [14], [18]. In modern automation environments, safety is not treated as a separate layer but is integrated into the overall system architecture, combining hardware protection mechanisms with intelligent software-based monitoring and control strategies [9], [13].

At the hardware level, safety is ensured through components such as emergency stop circuits, overpressure relief valves, and fail-safe directional control valves. These elements are designed to bring the system to a safe state during abnormal conditions such as pressure surges, power failures, actuator faults, or communication failures [8], [15]. Protective devices prevent excessive force buildup in actuators and help avoid structural damage or hazardous motion.

At the control level, Programmable Logic Controllers (PLCs) implement safety interlocking and emergency shutdown logic using ladder programming techniques [18]. This ensures that unsafe operating conditions, including conflicting actuator commands, sensor failures, or abnormal pressure levels, are detected and handled immediately. The control system can automatically stop operations or transition to a predefined safe state whenever faults are identified [8], [14]. In intelligent pneumatic systems, safety is further enhanced through real-time monitoring and data-driven diagnostics. Sensors continuously track parameters such as pressure, flow rate, vibration, and actuator position, enabling early detection of abnormal behavior and equipment degradation [1], [2], [3]. When

combined with IoT-enabled monitoring platforms and cloud-based analytics, these systems support predictive safety measures by identifying potential failures before they escalate into critical incidents [11], [13], [20].

Overall, safety in intelligent pneumatic systems is achieved through a combination of mechanical safeguards, robust control logic, continuous monitoring, and cybersecurity mechanisms, ensuring reliable and secure operation in industrial environments [8], [9], [18].

5.1 Emergency Shutdown System

The emergency shutdown system ensures immediate system shutdown during abnormal operating conditions by continuously monitoring system parameters and triggering a fail-safe response whenever unsafe situations are detected [8], [18]. In industrial automation systems, this functionality is typically implemented through emergency stop (E-stop) circuits integrated with PLC-based safety logic. The emergency stop mechanism overrides all normal operational commands and immediately disconnects outputs associated with actuators, solenoid valves, and compressors [14], [18].

When abnormal conditions such as overpressure, actuator malfunction, sensor failure, electrical faults, or communication interruptions occur, the control system rapidly de-energizes critical outputs and forces the system into a safe operating state [8]. This prevents further equipment damage and minimizes the risk of injury to personnel. The shutdown process is designed to be deterministic and hardware-prioritized, ensuring that safety functions remain operational even in the event of software failures or communication delays. Consequently, the system automatically defaults to a safe condition during controller failures or network disruptions. Such immediate response capability is essential for maintaining equipment integrity and operational safety in industrial pneumatic environments [8], [18].

5.2 Overpressure Protection

Overpressure protection is a fundamental safety requirement in pneumatic systems due to the potentially hazardous effects of excessive compressed air pressure [15].

Relief valves serve as primary protection devices by automatically releasing compressed air whenever system pressure exceeds a predefined safety threshold [15]. This prevents mechanical damage to pneumatic components such as cylinders, hoses, fittings, seals, and compressors.

Pressure buildup may occur because of compressor malfunction, regulator failure, valve blockage, or sudden changes in process demand. If left uncontrolled, excessive pressure can result in component failure, production interruptions, and safety hazards for operators [15].

When the pressure exceeds the configured limit, the relief valve opens automatically and safely discharges excess compressed air. After the pressure returns to the normal operating range, the valve closes without requiring manual intervention, thereby restoring normal system operation [15].

The incorporation of overpressure protection devices significantly enhances equipment reliability, operational stability, and compliance with industrial safety standards [14], [15].

5.3 Fault Detection System

The fault detection system provides real-time monitoring and diagnostic capabilities for identifying abnormal operating conditions within pneumatic and industrial automation systems [2], [3], [20]. By continuously analyzing data collected from pressure sensors, flow sensors, vibration sensors, and actuator position sensors, the control system can identify faults at an early stage and initiate corrective actions [1], [2].

Air leakage is typically detected through unexpected pressure reductions or abnormal increases in airflow demand. Such deviations often indicate leakage within pneumatic pipelines, fittings, valves, or actuator chambers, resulting in reduced efficiency and increased energy consumption [2], [15]. Valve malfunctions are identified by comparing commanded control actions with actual system responses. For example, if a directional control valve receives an activation signal but the corresponding actuator movement does not occur, the system can infer valve sticking, blockage, or solenoid driver failure [5], [20].

Sensor failures are detected through consistency checks, signal validation algorithms, and operational limit monitoring. Sensors that produce constant readings, erratic behavior, communication loss, or physically impossible measurements are automatically flagged as faulty devices [1], [3]. The integration of fault detection mechanisms with predictive maintenance algorithms allows maintenance personnel to address developing problems before they result in critical failures, thereby reducing downtime and improving overall system reliability [2], [3], [20].

5.4 Cyber-Physical Security

Cyber-physical security ensures secure communication and data exchange between PLCs, sensors, IoT devices, cloud platforms, and supervisory control systems [8], [9]. The increasing integration of industrial automation systems with IoT technologies has significantly expanded the attack surface of modern manufacturing environments. Consequently, cybersecurity has become a critical component of intelligent pneumatic automation architectures [11], [13].

Secure communication mechanisms typically include Transport Layer Security (TLS), Secure Socket Layer (SSL), encrypted MQTT communication, user authentication, and role-based access control [9], [13]. These technologies ensure that only authorized devices and users can access, modify, or transmit operational data. Industrial gateway devices are frequently employed to isolate operational technology (OT) networks from external information technology (IT) networks. Such segmentation reduces exposure to cyberattacks while maintaining secure connectivity for cloud-based monitoring and analytics applications [11], [19].

Al Farooq et al. [8] emphasized the importance of detecting safety and security faults in PLC-controlled industrial systems through data provenance techniques. Similarly, Celik et al. [9] demonstrated that automated safety and security analysis frameworks can effectively identify vulnerabilities in interconnected IoT environments. Without adequate cybersecurity protections, industrial systems remain vulnerable to unauthorized access, malicious control commands, data manipulation, ransomware attacks, and service disruptions [8], [9]. Therefore, implementing secure communication architectures, authentication mechanisms, and continuous cybersecurity monitoring is essential for ensuring safe, reliable, and resilient industrial automation operations. The convergence of industrial safety and cybersecurity within a unified cyber-physical security framework represents a key requirement for future Industry 4.0-enabled pneumatic automation systems [9], [11], [19].

6. MONITORING AND PREDICTIVE MAINTENANCE

The integration of intelligent monitoring technologies, Industrial Internet of Things (IIoT) platforms, and artificial intelligence (AI)-based analytics has significantly improved the reliability, efficiency, and maintainability of modern pneumatic automation systems. Real-time monitoring and predictive maintenance enable early fault detection, optimize system performance, reduce operational costs, and support data-driven decision-making in Industry 4.0 environments [2], [3], [11], [13], [19].

6.1 Real-Time Monitoring

Continuous monitoring of pressure, flow rate, cycle time, and energy consumption is essential for maintaining optimal performance, efficiency, and reliability in pneumatic and industrial automation systems [1], [6], [11]. Real-time monitoring provides continuous visibility into system behavior and supports both operational control and long-term performance assessment.

Pressure Monitoring: Pressure monitoring ensures that pneumatic systems operate within safe and efficient pressure ranges. Pressure sensors installed at compressor outlets, FRL units, distribution pipelines, and actuator chambers continuously measure operating pressure and provide feedback to control systems [1], [6]. Deviations from expected pressure values may indicate leakage, regulator malfunction, compressor degradation, or flow restrictions. Maintaining stable pressure is essential for consistent actuator performance, process stability, and equipment protection [15].

Flow Rate Monitoring: Flow rate monitoring tracks the amount of compressed air consumed throughout the pneumatic network. Since compressed air generation is energy-intensive, monitoring airflow helps identify inefficiencies, leakage, and excessive air demand [15]. Flow data also supports optimization of compressor operation and assists in evaluating overall pneumatic system efficiency [2], [20].

Cycle Time Monitoring: Cycle time monitoring measures the duration of actuator operations, including extension and retraction cycles. This parameter directly influences manufacturing productivity and process efficiency [14], [18]. Variations in cycle time may indicate valve sticking, mechanical wear, insufficient air pressure, actuator degradation, or control system inefficiencies. Continuous monitoring enables rapid identification of performance deterioration before it affects production output.

Energy Consumption Monitoring: Energy consumption monitoring evaluates electrical and pneumatic energy utilization throughout the automation system, particularly compressor power demand and compressed air consumption [15]. Energy monitoring data enables operators to identify inefficiencies, optimize compressor loading conditions, and reduce operational expenses. Furthermore, energy management contributes to sustainability objectives by minimizing unnecessary energy waste and improving resource utilization [19].

Overall, continuous monitoring of pressure, flow rate, cycle time, and energy consumption provides the foundation for predictive maintenance, operational optimization, fault diagnosis, and intelligent decision-making in modern industrial automation systems [11], [13], [19].

6.2 Predictive Maintenance Techniques

Predictive maintenance represents one of the most significant advancements in intelligent pneumatic automation systems. Unlike traditional preventive maintenance approaches, predictive maintenance relies on continuous data collection, condition monitoring, and advanced analytics to forecast equipment failures before they occur [2], [3].

AI-based predictive models analyze vibration signals, pressure trends, flow characteristics, and historical operational data to identify hidden patterns associated with component degradation and impending failures [2], [20]. These models employ machine learning algorithms capable of recognizing subtle anomalies that may not be detectable through conventional threshold-based monitoring methods.

Vibration-Based Fault Prediction: Vibration analysis is widely used for assessing the mechanical condition of compressors, pneumatic actuators, bearings, and rotating equipment [3]. Machine learning algorithms analyze vibration frequency spectra, amplitude variations, and waveform characteristics to identify faults such as: 1. Bearing wear 2. Shaft misalignment 3. Mechanical imbalance 4. Structural looseness 5. Actuator degradation

Research by Tiboni and Remino [3] demonstrated that AI-driven vibration analysis can effectively predict equipment failures and improve maintenance planning accuracy.

Pressure Trend Analysis: Pressure trend analysis provides valuable insight into pneumatic system health and operational stability. AI algorithms continuously evaluate pressure variations and compare them with established baseline operating conditions [1], [2]. Abnormal pressure behavior may indicate: 1. Air leakage 2. Regulator malfunction 3. Valve obstruction 4. Compressor inefficiency 5. Pneumatic line blockage

By detecting these abnormalities at an early stage, maintenance personnel can intervene before significant performance degradation occurs [20].

Historical Data Analytics: Historical operational data forms the foundation of predictive maintenance systems. Long-term records collected from sensors, PLCs, and IoT platforms are used to train machine learning models capable of forecasting future failures [2], [13]. These datasets typically include: 1. Pressure measurements 2. Flow rate data 3. Energy consumption records 4. Actuator cycle counts 5. Vibration signatures 6. Maintenance history

Through continuous learning and model refinement, AI systems improve prediction accuracy and provide increasingly reliable maintenance recommendations [20].

AI-Based Decision Support: Advanced predictive maintenance platforms integrate AI analytics with IoT infrastructure and cloud computing technologies [11], [13]. Such systems automatically generate maintenance alerts, estimate remaining useful life (RUL) of components, and recommend optimal maintenance schedules.

The integration of AI-based decision support enables organizations to transition from reactive maintenance strategies toward condition-based and predictive maintenance approaches, significantly reducing unexpected equipment failures and production interruptions [2], [3], [20].

Overall, predictive maintenance technologies improve equipment reliability, reduce maintenance costs, enhance operational safety, and support sustainable industrial operations [2], [3], [20].

6.3 Benefits of Intelligent Monitoring and Predictive Maintenance

The implementation of intelligent monitoring and predictive maintenance technologies provides substantial operational, economic, and maintenance-related benefits for industrial pneumatic systems [2], [11], [19].

Reduced Downtime: One of the most significant advantages is the reduction of unplanned downtime. Continuous monitoring and AI-based fault detection enable early identification of abnormal conditions such as pressure loss, air leakage, actuator malfunction, and valve degradation [2], [3]. By detecting faults before they escalate into critical failures, maintenance activities can be scheduled proactively, minimizing production interruptions, and improving system availability [20].

Improved Operational Efficiency: Operational efficiency is enhanced through optimized control of pneumatic processes and intelligent resource management. Real-time sensor feedback enables precise regulation of pressure, airflow, and actuator motion [11], [13].

IoT-enabled monitoring systems provide visibility into process performance, allowing operators to optimize production parameters and eliminate inefficiencies. Consequently, organizations benefit from: 1. Faster cycle times 2. Improved process synchronization 3. Reduced energy consumption 4. Higher production throughput. These improvements contribute directly to increased manufacturing productivity and competitiveness [15], [19].

Extended Equipment Lifespan: Intelligent monitoring systems help extend equipment lifespan by maintaining optimal operating conditions and preventing excessive mechanical stress [3], [15]. Proper pressure regulation, effective air preparation, and early fault detection reduce wear on critical components such as: 1. Compressors 2. Pneumatic cylinders 3. Directional control valves 4. Solenoid drivers 5. Sensors. Predictive maintenance strategies ensure that maintenance interventions occur before catastrophic failures develop, reducing component damage and extending service life [2], [20].

Reduced Maintenance Costs: Predictive maintenance minimizes unnecessary routine maintenance while preventing costly emergency repairs [2], [3]. Maintenance resources can be allocated more effectively based on actual equipment condition rather than fixed maintenance schedules. This approach reduces: 1. Spare parts consumption 2. Labor costs 3. Equipment replacement expenses 4. Production losses due to unexpected failures.

As a result, organizations achieve significant long-term cost savings while maintaining high levels of operational reliability [20].

Enhanced Safety and Reliability: Continuous monitoring improves safety by detecting abnormal operating conditions before hazardous situations arise [8], [9]. Early identification of pressure abnormalities, mechanical degradation, and control system faults enables timely corrective actions, reducing risks to both equipment and personnel.

The combination of predictive maintenance, intelligent diagnostics, and safety monitoring contributes to highly reliable and resilient industrial automation systems capable of supporting Industry 4.0 objectives [11], [13], [19]. In summary, intelligent monitoring and predictive maintenance technologies provide a comprehensive framework for improving productivity, reliability, sustainability, and safety in modern pneumatic automation systems [2], [3], [11], [13], [20].

7. DISCUSSION

The reviewed literature demonstrates a clear and progressive transition from conventional pneumatic control systems toward intelligent cyber-physical systems that integrate sensing, computation, communication, and control within a unified architecture. Traditional pneumatic systems, which primarily rely on fixed logic control and manual monitoring, are increasingly being replaced by smart systems capable of real-time data acquisition, adaptive decision-making, and remote supervision.

The integration of artificial intelligence (AI), Internet of Things (IoT), and programmable logic controller (PLC) technologies has significantly improved system performance, safety, and reliability. AI enables predictive analytics and fault detection through data-driven modeling, IoT facilitates seamless connectivity and cloud-based monitoring, while PLCs ensure deterministic and robust control of industrial processes. Together, these technologies create an interconnected framework that enhances operational efficiency, reduces downtime, and supports predictive maintenance strategies in modern industrial environments. However, despite these advancements, several challenges still exist. The implementation of intelligent pneumatic systems often involves high initial costs due to advanced sensors, communication infrastructure, and computing resources. System complexity also increases as multiple technologies must be integrated and properly synchronized. Interoperability between different devices, protocols, and vendors remains a critical issue, particularly in heterogeneous industrial environments. Additionally, data reliability can be affected by sensor inaccuracies, network latency, and communication failures, which may impact the performance of AI-based decision-making systems.

Overall, while intelligent pneumatic and cyber-physical systems offer substantial benefits, addressing these challenges is essential for achieving scalable, cost-effective, and robust industrial automation solutions.

8. CONCLUSION

Intelligent pneumatic automation systems represent a significant advancement in modern industrial automation by combining traditional pneumatic control with advanced digital technologies. These systems integrate programmable logic controllers (PLCs), Internet of Things (IoT) connectivity, artificial intelligence (AI)-based diagnostics, and industrial safety mechanisms into a unified and coordinated framework, enabling more adaptive, efficient, and reliable operation. The integration of PLCs ensures robust and deterministic control of pneumatic actuators and sequencing operations, while IoT connectivity enables real-time data acquisition, remote monitoring, and cloud-based system supervision. AI-based diagnostic techniques further enhance system capability by enabling predictive maintenance, fault detection, and performance optimization through the analysis of sensor data such as pressure, flow, vibration, and cycle time. In addition, industrial safety systems, including emergency shutdown circuits, relief valves, and fault detection mechanisms, ensure safe operation under both normal and abnormal conditions.

Together, these technologies significantly improve operational efficiency by reducing cycle times, optimizing energy consumption, and minimizing unplanned downtime. They also enhance system reliability through continuous monitoring and early fault detection, while improving overall safety by enabling rapid response to abnormal conditions.

As Industry 4.0 continues to evolve, further advancements in digitalization, machine learning, edge computing, and industrial communication protocols are expected to accelerate the adoption of intelligent pneumatic systems. These developments will support the creation of more autonomous, interconnected, and self-optimizing industrial environments, making smart pneumatic automation a key component of future manufacturing systems.

REFERENCES

1) Kovacs, T., & Ko, A. (2020). Monitoring pneumatic actuators' behavior using real-world data set. SN Computer Science.
2) Mallia, J., Francalanza, E., Xuereb, P., & Refalo, P. (2023). Intelligent approaches for anomaly detection in compressed air systems: A systematic review. Machines.
3) Tiboni, M., & Remino, C. (2024). Condition monitoring of pneumatic drive systems using AI methods. Sensors.
4) Emhemed, A. A. A., Mamat, R., & Faudzi, A. A. M. (2015). Non-parametric identification techniques for intelligent pneumatic actuator. Journal Teknologi.
5) Ramezani, S., & Baghestan, K. (2019). Observer-based nonlinear control of pneumatic servo systems. IMechE Part E.
6) Alyami, M., Grosvenor, R. I., & Prickett, P. W. (2009). A microcontroller-based approach to monitoring pneumatic actuators. International Journal of Production Research.
7) Hoang, S., et al. (2024). Error detection using pneumatic logic. arXiv.

8) Al Farooq, A., et al. (2019). Detecting safety and security faults in PLC systems with data provenance. arXiv.
9) Celik, Z. B., McDaniel, P., & Tan, G. (2018). Soteria: Automated IoT safety and security analysis. arXiv.
10) Saleem, Y., et al. (2017). IoT-aided smart grid systems: survey. arXiv.
11) Abela, K., et al. (2024). IIoT framework for industrial pneumatic systems. Procedia CIRP.
12) Ashshidiqi, H., et al. (2024). Data acquisition of pneumatic vane motor using Modbus RTU and PLC. JITEL.
13) Hendrawati, D., et al. (2025). IoT-enabled real-time PLC monitoring system for industrial automation. JAETS.
14) Luna Pérez, H. A., et al. (2026). Mechanical-pneumatic systems with PLC control based on IEC standards. Tesla Revista Científica.
15) Abela, K., et al. (2020). Compressed air system performance and energy optimization. Procedia CIRP.
16) Li, W., & Kara, S. (2017). Wireless sensor networks and IoT in manufacturing monitoring. Procedia CIRP.
17) Emhemed, A. A. A., et al. (2014). Intelligent pneumatic actuator modeling and identification. Journal of Control & Automation.
18) Rios, R., et al. (2021). PLC-based industrial automation systems using IEC 61131-3 standards. Engineering Proceedings.
19) Quernheim, N., et al. (2022). IoT platform integration for resource-efficient manufacturing. Procedia CIRP.
20) Francalanza, E., et al. (2023). AI-based anomaly detection in compressed air systems. MDPI Machines.
21) T. M. S. A. Hossain, M. Hasanuzzaman. (2026). Characterization of Nanostructure Sedimentary Clay Material of Netrokona District . International Journal of Multidisciplinary and Innovative Research, 3(5), 410-415.
22) Hossain, T. M. S. A., M. A. Matin, M. A. Hakim, and M. F. Islam. "Fabrication and Characterization of NiO-doped BaTiO 3 for Multilayer Ceramic Capacitor." In 2018 10th International Conference on Electrical and Computer Engineering (ICECE), pp. 77-80. IEEE, 2018.
23) Hossain, T. M. S. A., M. A. Matin, M. A. Hakim, and M. F. Islam. "Characterization of Available Sedimentary Clay of Hobiganj District." (2019).
24) Hossain, Tarazul, and Muhammand Hasanuzzam. "Characterization and Beneficiation of Available Sedimentary Clay Collected from Netrokona District for Industrial Application." (2023).
25) Hossain, Tarazul Mulk Syed Anzam. "Synthesis and structure-property characterization of BaTiO3/xNio nanocomposite ceramics." (2015).