RECENT J. (2026), 80:088-096
https://doi.org/10.31926/RECENT.2026.80.088

# Implementation of a Pneumatic Actuation System to Improve Reliability and Reduce Maintenance Costs in an Assembly Line

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**Abstract**
The continuous optimization of manufacturing processes is essential for improving equipment reliability, reducing maintenance costs, and increasing production efficiency in modern automated assembly systems. This paper presents the design and implementation of a pneumatic actuation system intended to improve the functionality of an automated workstation affected by recurrent maintenance interventions. The proposed solution consists of replacing a mechanically demanding operation with a pneumatically actuated mechanism that provides controlled, repeatable, and reliable movement throughout the assembly cycle. The research includes the selection of the pneumatic cylinder, the design and simulation of the pneumatic circuit, the implementation methodology, and the technical selection of the required components. The results demonstrate that the pneumatic solution improves process stability, reduces mechanical stress on the equipment, minimizes maintenance interventions, and contributes to higher operational reliability. The proposed approach represents a practical and cost-effective engineering solution that can be adapted to various automated manufacturing systems.

**Keywords**
industrial automation, maintenance optimization, manufacturing systems, assembly workstation, pneumatics

## 1. Introduction

Manufacturing companies continuously seek engineering solutions capable of increasing equipment reliability while simultaneously reducing production costs and unplanned downtime. As production systems become increasingly automated [1, 2], the reliability of individual workstations has a direct impact on overall manufacturing performance, product quality, and maintenance expenditures. Repeated equipment failures often originate from mechanical components subjected to continuous cyclic loading. Besides increasing maintenance costs, these failures interrupt production flow, decrease equipment availability, and reduce process efficiency. Consequently, improving workstation design has become an effective strategy for increasing manufacturing reliability rather than relying solely on corrective maintenance activities. Among the available industrial automation technologies [3], pneumatic systems [4] remain one of the most widely adopted solutions because of their simple construction, rapid response, high operational reliability, low maintenance requirements, and relatively low implementation costs. Their ability to generate controlled linear motion [5] makes pneumatic actuators particularly suitable for repetitive industrial operations such as positioning, clamping, pressing, lifting, and component transfer.

This paper proposes the implementation of a pneumatic actuation system designed to improve the operation of an automated assembly workstation experiencing repetitive maintenance-related issues. The research focuses on the engineering design process, including the selection of the pneumatic actuator, circuit development, simulation, component selection, and workstation integration. The proposed solution aims to simplify the mechanical operation, improve movement repeatability, reduce maintenance interventions, and increase overall production reliability. The study demonstrates how a relatively simple pneumatic automation solution can significantly improve workstation performance while reducing long-term operating costs.

# 2. Materials and Methods

## 2.1. Pneumatic Actuation Systems

Pneumatic actuation systems are widely employed in industrial automation due to their reliability, simplicity, and cost-effectiveness. They convert the energy stored in compressed air into linear or rotary mechanical motion, allowing automated execution of repetitive manufacturing operations with high repeatability and minimal maintenance requirements. Compared with hydraulic or fully electric actuation systems, pneumatic solutions [4] offer several operational advantages, including lower installation costs, fast response times, clean operation, and a reduced number of moving mechanical components. Since compressed air is commonly available in manufacturing environments, pneumatic equipment can usually be integrated into existing production lines without major infrastructure modifications.

Pneumatic actuators are particularly suitable for applications requiring repetitive linear motion, positioning, clamping, pressing, lifting, or transferring components between workstations. Their robust construction enables continuous operation under demanding industrial conditions while maintaining consistent performance over extended operating periods. The operating principle of a pneumatic actuator is based on pressure differences generated by compressed air inside a sealed cylinder. When compressed air enters one chamber of the cylinder, the pressure acting on the piston surface generates a force that produces linear displacement. The piston rod transfers this movement to the mechanical element connected to the workstation.

## 2.2. Selection of the Pneumatic Cylinder

Selecting an appropriate pneumatic cylinder requires evaluating both the functional requirements of the workstation and the mechanical characteristics of the intended movement. The actuator must generate sufficient force while ensuring stable, accurate, and repeatable operation throughout the production cycle.

Several technical criteria were considered during the selection process: required linear stroke; generated pushing and pulling force; operating pressure range; piston diameter; mounting configuration; overall dimensions; operating speed; compatibility with the available pneumatic infrastructure; expected service life. A double-acting pneumatic cylinder was selected because it provides controlled movement in both extension and retraction directions. Unlike single-acting cylinders, which rely on a spring return mechanism, double-acting cylinders use compressed air on both sides of the piston. This configuration ensures improved positioning accuracy, higher operational stability, and greater control of the actuator during repetitive industrial cycles. The actuator dimensions were selected according to the available installation space and the required displacement of the mechanical assembly (Figure1, Figure 2 and Figure 3). The chosen stroke length guarantees complete movement while avoiding unnecessary piston travel, thereby reducing cycle time and compressed-air consumption.

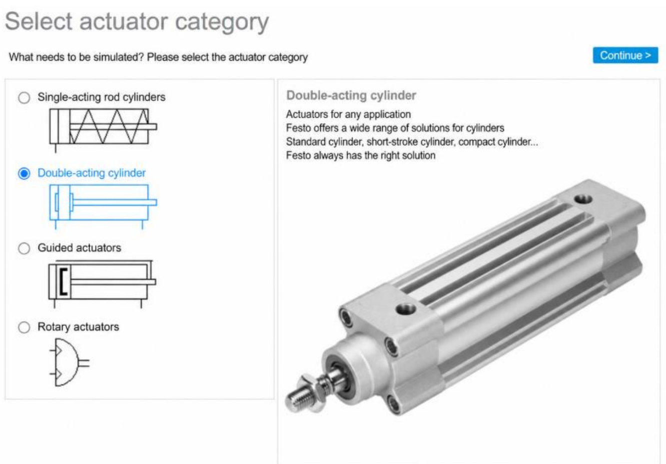


Fig. 1. Actuator category [8]

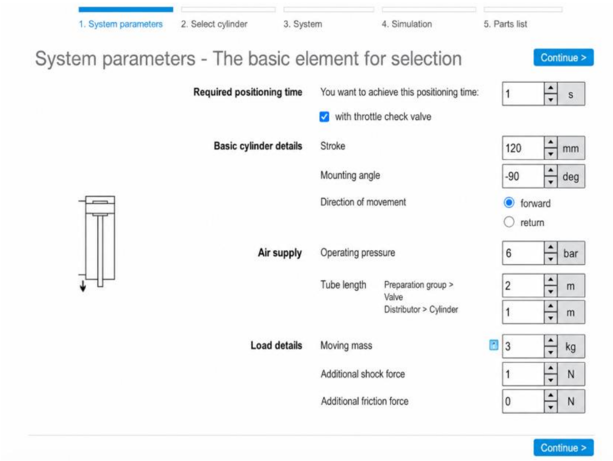


Fig. 2. Basic element for selection [8]

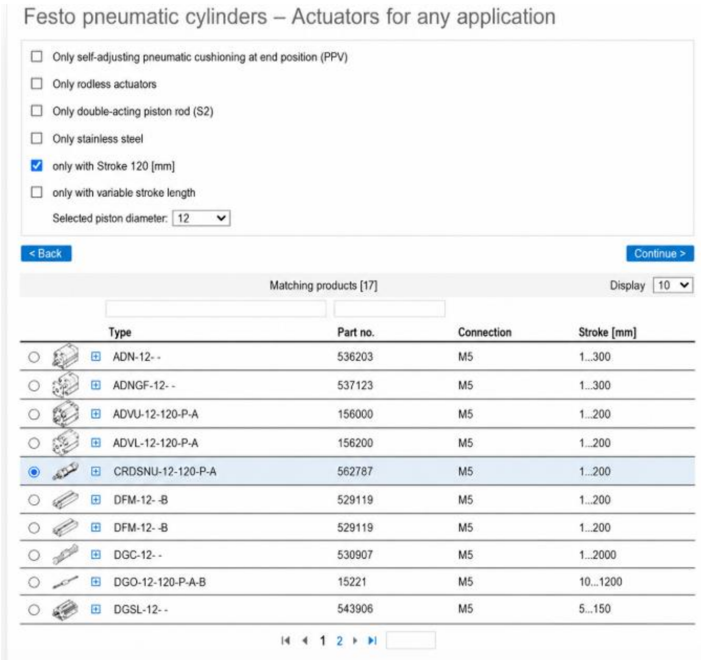


Fig. 3. Pneumatic cylinders [8]

To improve operational reliability, the actuator incorporates integrated cushioning near both end positions. These cushions reduce impact forces at the end of each stroke, minimizing mechanical shocks transmitted to the workstation structure and extending the service life of both the actuator and the connected mechanical components. Furthermore, the selected actuator allows the integration of magnetic position sensors, enabling future implementation of process monitoring and automated position verification. Such capability facilitates predictive maintenance strategies and supports the transition toward more intelligent manufacturing systems [6, 7].

### 2.3. Pneumatic Circuit Design

After selecting the actuator, a pneumatic circuit was designed to ensure safe, stable, and repeatable operation of the workstation. The circuit distributes compressed air from the main supply to the actuator while controlling both movement direction and operating speed.

The designed pneumatic system consists of the following main components: compressed air supply; air preparation unit (filter, pressure regulator, and lubricator where required); directional control valve; double-acting pneumatic cylinder; pneumatic tubing and fittings; flow-control valves for speed adjustment; exhaust silencers.

The directional control valve alternately supplies compressed air to each cylinder chamber, allowing controlled extension and retraction of the piston rod. Flow-control valves regulate the airflow rate, enabling precise adjustment of actuator speed according to process requirements. The entire pneumatic circuit was designed with emphasis on operational simplicity, ease of maintenance, and long-term reliability while minimizing unnecessary pressure losses and energy consumption.

## 3. Pneumatic Circuit Simulation and Experimental Validation

### 3.1. Pneumatic Circuit Design and Simulation

Prior to physical implementation, the proposed pneumatic system was validated through simulation in order to evaluate its operational behavior under different working conditions. The simulation phase allowed verification of the actuator sequence, control logic, positioning accuracy, and pressure-dependent operation before constructing the experimental setup.

The pneumatic circuit was designed to satisfy several functional requirements identified during the workstation analysis. The primary objectives included bidirectional actuator control, adjustable extension and retraction speeds, automatic sequencing based on piston position, temporary holding of the actuator in the extended position, and pressure-based operational safety. These design requirements ensured that the proposed system would provide both reliable operation and sufficient flexibility for industrial applications.

To achieve these objectives, the circuit incorporated a double-acting pneumatic cylinder controlled by a 5/2 directional control valve, flow-control valves for speed adjustment, end-of-stroke limit valves, a pneumatic timer, and a pressure control valve. Each component was selected to perform a specific function within the automation sequence while maintaining a simple and reliable circuit architecture.

The complete pneumatic circuit was developed and simulated using FluidSIM [8], an engineering software package widely employed for the design, analysis, and validation of pneumatic and electro-pneumatic systems. The simulation environment enabled observation of piston displacement, timing characteristics, pressure conditions, and actuator response throughout the operating cycle before experimental implementation.

### 3.2. Simulation Scenarios

Several operating scenarios were investigated to verify the robustness of the proposed pneumatic solution. The first simulation evaluated the nominal operating conditions. The pressure control valve was adjusted to 6 bar, corresponding to the required operating pressure of the system. Under these conditions, the actuator completed its entire forward stroke before remaining in the extended position for a predefined time interval controlled by the pneumatic timer. This delay simulated the execution time required for the workstation operation before initiating the return movement. The simulation confirmed stable actuator movement and correct sequencing throughout the complete operating cycle.

A second simulation examined the influence of insufficient supply pressure. When the available pressure dropped below the established threshold of 6 bar, the pressure valve prevented completion of the forward stroke and immediately initiated actuator retraction. This safety mechanism eliminates incomplete operating cycles and prevents improper workstation operation under inadequate pneumatic conditions. Such behavior contributes to increased process reliability while reducing the probability of component damage caused by insufficient actuation force.

An additional simulation investigated the influence of airflow regulation on actuator motion. By adjusting the flow-control valve, the extension speed of the pneumatic cylinder could be accurately controlled without affecting the rapid return movement. A slower extension resulted in smoother positioning of the mechanical assembly and reduced dynamic loading of the moving components. Consequently, the system achieved greater positioning accuracy while simultaneously decreasing mechanical shocks transmitted to the workstation structure.

The final simulation combined all operating conditions. The supply pressure remained fixed at 6 bar, while the flow-control valve was adjusted to approximately 60% of its maximum opening. Under these conditions, the actuator completed a 120 mm stroke while generating an actuation force of approximately 30 N, which satisfied the functional requirements established during workstation design. The corresponding motion diagram confirmed continuous, stable, and repeatable actuator behavior throughout the complete operating sequence.

The complete circuit was developed and validated using the FluidSIM [8] simulation environment before its practical implementation. The system is based on a double-acting pneumatic cylinder controlled by a 5/2 double-pilot directional valve. This configuration enables controlled extension and retraction of the actuator while maintaining stable operation throughout the production cycle. A manually actuated 3/2 valve was incorporated to initiate the operating sequence, allowing the system to be activated only after operator input.

To ensure accurate positioning of the actuator, two 3/2 limit valves were installed at the end positions of the cylinder stroke. These valves detect the completion of the forward and return movements and generate the pneumatic control signals required for the next stage of the operating sequence. The extension velocity of the actuator is adjusted by means of a flow-control valve, allowing smooth positioning during the working stroke. In addition, a quick exhaust valve was incorporated into the circuit to accelerate the evacuation of compressed air during the return movement. This solution decreases the overall cycle time while maintaining stable actuator control.

A pneumatic timer was integrated into the control circuit to maintain the actuator in the forward position for a predetermined period. This delay allows the technological operation to be completed before the cylinder automatically returns to its initial position.

To improve operational safety, the pneumatic system also includes a pressure valve adjusted to 6 bar. If the supply pressure falls below the preset value, the control logic prevents completion of the forward stroke and immediately commands actuator retraction. Consequently, the workstation cannot operate under inadequate pressure conditions, preventing incomplete operating cycles and reducing the risk of equipment malfunction. The pneumatic control logic incorporates a shuttle (OR) valve that combines the pneumatic signals received from the pressure control system and the timing circuit. This configuration ensures correct synchronization between actuator movement, pressure monitoring, and timing functions throughout the complete operating sequence.

The proposed circuit combines simple architecture with reliable operation, providing accurate actuator positioning, repeatable movement, reduced mechanical stress, and improved maintenance performance (Figure 4). Furthermore, all selected components are standardized industrial pneumatic elements, facilitating installation, servicing, and future system upgrades.

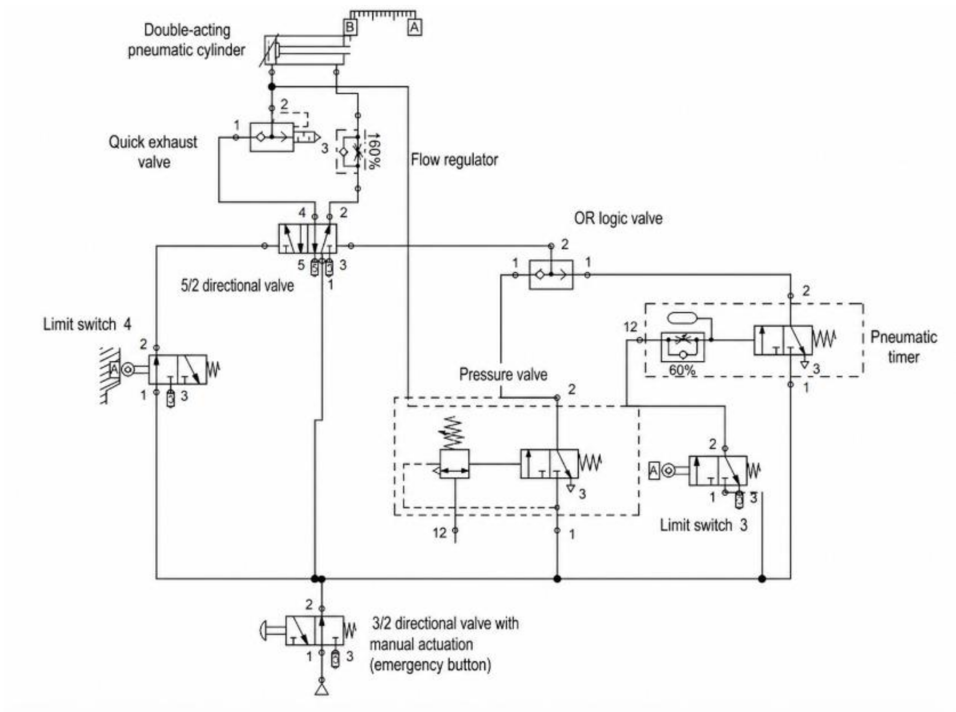


Fig. 4. Simulation diagram [9]

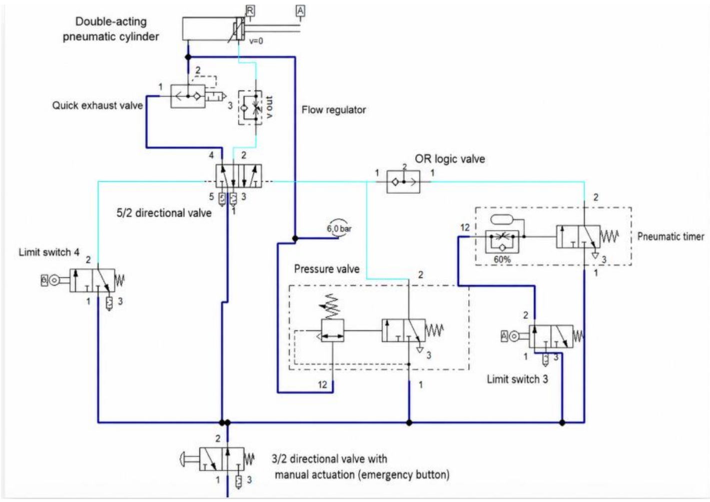


Fig. 5. Simulation diagram [9]

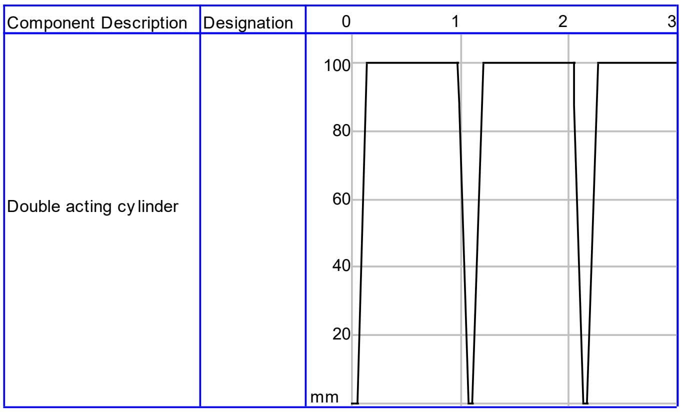


Fig. 6. Circuit cyclogram [9]

### 3.3. Experimental Validation

Following the simulation stage, the pneumatic circuit was assembled and experimentally validated using laboratory pneumatic equipment. The objective of the experimental implementation was to verify whether the behavior observed during simulation could be reproduced under real operating conditions.

The experimental results demonstrated excellent agreement with the simulation model. Once compressed air was supplied to the system, the actuator advanced smoothly toward the working position and remained fully extended for approximately six seconds, corresponding to the duration required for the technological operation. After completion of the holding period, the cylinder retracted rapidly to its initial position, preparing the workstation for the next production cycle. The extension velocity was adjusted using the flow-control valve, allowing precise positioning while maintaining fast cycle completion.

The validation confirmed that the proposed pneumatic circuit provides stable actuator motion, accurate positioning, reliable pressure-dependent operation, and consistent repeatability. These characteristics demonstrate the suitability of the designed system for integration into automated manufacturing workstations where precision, operational reliability, and reduced maintenance requirements are essential.

## 4. System Implementation and Component Selection

### 4.1. System Integration

Following the successful validation of the pneumatic circuit through simulation, the next stage consisted of integrating the proposed solution into the workstation design. The implementation focused on replacing the existing actuation mechanism with a pneumatic system capable of performing the required movement in a controlled, repeatable, and reliable manner.

During the implementation phase, particular attention was given to preserving the existing workstation architecture while minimizing structural modifications. This approach reduces installation time, lowers implementation costs, and allows future maintenance activities to be performed without affecting adjacent equipment. The proposed configuration was therefore designed as a modular solution that can be integrated into similar automated workstations with only minor adjustments.

The pneumatic actuator was positioned to ensure that the generated linear motion was aligned with the direction of the technological operation. Proper alignment minimizes lateral forces acting on the piston rod, reducing mechanical wear and improving the overall service life of the actuator. To guarantee safe operation, all pneumatic components were installed in locations that facilitate inspection, maintenance, and replacement whenever necessary. Pneumatic tubing was routed to minimize pressure losses while avoiding excessive bending or mechanical interference with moving workstation elements.

### 4.2. Selection of Pneumatic Components

The selection of pneumatic components represents one of the most important stages in the development of an automated actuation system. Each component must satisfy the functional requirements while ensuring long-term reliability and compatibility with the overall pneumatic installation [10].

The proposed system includes a double-acting pneumatic cylinder, a 5/2 directional control valve, an air preparation unit, flow-control valves, pneumatic tubing and fittings, a pressure gauge, a pneumatic timer, and end-position sensors. The cylinder was selected according to the required stroke, available installation space, operating pressure, and actuation force. A double-acting cylinder was chosen to provide controlled motion during both extension and retraction.

The 5/2 valve controls the airflow between the two-cylinder chambers, while the flow-control valves regulate piston speed and ensure smooth motion during the working stroke. The air preparation unit supplies clean air at the required pressure, reducing contamination and component wear. Flexible tubing and standardized fittings were used to simplify installation and maintenance. Their modular design allows individual components to be replaced without dismantling the entire pneumatic circuit.

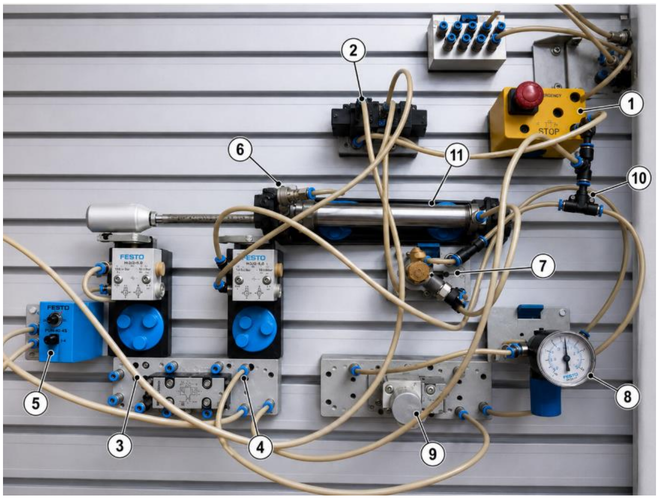


Fig. 7. Pneumatic system

### 4.3. Implementation Considerations

The proposed pneumatic solution was designed according to several engineering principles intended to improve long-term operational performance. First, the number of mechanical components subjected to repetitive loading was minimized. Reducing the complexity of the mechanical transmission decreases the probability of wear-related failures and simplifies maintenance procedures. Second, the modular architecture of the pneumatic system allows individual components to be replaced independently, reducing equipment downtime during maintenance activities.

Finally, the proposed solution provides opportunities for future upgrades through the integration of proximity sensors, pressure monitoring devices, or programmable logic controllers (PLCs). Such additions would enable real-time monitoring of actuator performance and facilitate predictive maintenance strategies consistent with Industry 4.0 manufacturing concepts.

Table 1. Main Components of the Pneumatic Circuit and Their Functions [10, 11]

| Component | Pneumatic Component | Description / Function in the Circuit |
|---|---|---|
| 1 | 3/2 Safety Directional Control Valve (Emergency Push Button) | Normally open directional control valve used as the main safety device of the pneumatic circuit. It interrupts the air supply in the event of an emergency or system malfunction. |
| 2 | 5/2 Double-Pilot Directional Control Valve | Controls cylinder extension and retraction by directing compressed air between the two actuator chambers. Pilot ports 12 and 14 determine the switching position. |
| 3, 4 | 3/2 Directional Control Valves (End-of-Stroke Limit Valves) | Detect the fully retracted and fully extended actuator positions and generate the pneumatic signals required for sequence control. |
| 5 | Normally Closed Pneumatic Timer with Counter | Introduces a 6 s delay, maintaining the cylinder in the extended position until the technological operation is completed. |
| 6 | Flow Control Valve | Regulates the exhaust airflow during cylinder extension, ensuring controlled actuator speed and smooth positioning while permitting free flow in the opposite direction. |
| 7 | Quick Exhaust Valve with Silencer | Enables direct air evacuation during cylinder retraction, thereby increasing the return speed and reducing the overall cycle time. |
| 8 | Pressure Gauge | Measures the pneumatic pressure at the cylinder inlet, allowing continuous monitoring of the operating pressure supplied to the actuator. |
| 9 | Pressure Control (Sequence) Valve | Prevents actuator extension when the supply pressure is below the required threshold, ensuring pressure-dependent operation. |
| 10 | T-Connection (Pneumatic Tee Junction) | Functions as a pneumatic OR logic element, providing an output signal whenever at least one of the input ports is pressurized. |
| 11 | Double-Acting Pneumatic Cylinder | Main actuator of the system. The double-acting configuration provides independent control of both extension and retraction movements, allowing precise regulation of actuator position and speed throughout the operating cycle. |

## 5. Results and Discussion

The implementation of the proposed pneumatic actuation system improved the operational stability and reliability of the automated workstation. Both simulation and experimental testing confirmed that the system meets the required functional conditions and provides a consistent operating cycle.

A major improvement was the increase in process repeatability. The pneumatic cylinder performed uniform extension and retraction movements during successive cycles, ensuring stable positioning and reducing process variability. The controlled actuator motion also limited impact forces and mechanical loads, thereby reducing wear on the workstation components.

The redesigned system simplified the mechanical architecture by replacing complex movements with standard pneumatic components. This reduced the number of elements exposed to continuous wear and facilitated maintenance, troubleshooting, and component replacement. Flow-control and pressure-regulation devices ensured smooth motion and prevented operation under insufficient pressure conditions.

The proposed solution also supports future digitalization initiatives. By integrating magnetic sensors, pressure sensors, or programmable logic controllers (PLCs), the pneumatic workstation can be transformed into an intelligent manufacturing module capable of monitoring actuator position, cycle duration, and operating conditions in real time. Such capabilities provide the foundation for predictive maintenance strategies and continuous process optimization. Overall, the obtained results demonstrate that relatively simple engineering modifications can generate substantial improvements in workstation reliability, maintenance efficiency, and production stability. Instead of increasing system complexity, the proposed solution simplifies the mechanical architecture while maintaining the required functionality, making it suitable for implementation in various automated manufacturing environments.

Overall, the results show that a relatively simple pneumatic solution can improve workstation reliability, process stability, and maintenance efficiency without increasing system complexity.

## 6. Conclusions

This study presented the design, simulation, and implementation of a pneumatic actuation system for an automated assembly workstation. The objective was to improve operational reliability, reduce mechanical wear, and simplify the workstation structure while maintaining the required process functionality.

The development process included actuator sizing, pneumatic circuit design, component selection, simulation, and three-dimensional modelling. Virtual validation confirmed the technical feasibility of the solution and helped identify potential design issues before implementation.

Experimental testing demonstrated stable, repeatable, and controlled actuator operation. The modular pneumatic architecture simplified maintenance procedures, reduced intervention time, and improved equipment availability.

The proposed solution demonstrates that low-cost pneumatic automation can effectively improve the performance of industrial workstations. Future research may focus on sensor integration, real-time data acquisition, and predictive maintenance algorithms to support Industry 4.0 applications.

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