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PNEUMATICS TODAY AND TOMORROW: A REVIEW OF TECHNOLOGY AND DEVELOPMENT TRENDS

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This paper reviews recent innovations and trends in pneumatics, highlighting advances in actuator design, energy efficiency, and intelligent control. Developments in miniature 3D-printed and soft pneumatic actuators offer lightweight, customizable, and safe solutions for robotics and biomedical applications. Proportional and digital pneumatics continue to evolve for Industry 4.0, with reinforcement learning improving controller adaptability. Energy-saving methods-including intermittent air supply, pressure-based cut-off circuits, optimized sizing, and novel throttling-enable up to 71 % efficiency gains and short payback times. Trajectory-based gripping force calculation and product carbon footprint analysis support sustainable practices. Soft robotics contributes with novel actuator designs, data-driven modelling, and nonlinear control strategies. Experimental validations confirm these technologies' practicality and effectiveness. Overall, this review presents pneumatics as a versatile, efficient, and eco-conscious platform for modern automation, integrating IoT, digital twins, and hybrid systems for future-ready fluid power solutions.

Keywords:
pneumatics,
energy efficiency,
soft robotics,
intelligent control,
sustainable automation

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1 Introduction

Pneumatics has long been a cornerstone of industrial automation due to its simplicity, robustness, and cost-effectiveness. Pneumatic systems are widely used in manufacturing, packaging, robotics, and process industries for tasks such as actuation, assembly, gripping, and material handling. Their advantages include simple distribution and transfer of air energy across industrial environments, a favourable power-to-weight ratio, fast response times, and inherent safety in explosive or hygienic settings. Pneumatic systems are also easy to maintain, with cost-effective spare parts and straightforward transformation between linear and rotary motion. Their compliance and softness make them particularly suitable for collaborative and human-safe applications [1], [2].

1.1 State of the art

Compared to hydraulic and electric drives, pneumatic systems offer several distinct advantages that make them highly suitable for a wide range of industrial and commercial applications. Unlike hydraulic systems, which depend on potentially flammable and environmentally hazardous fluids, pneumatic systems operate using compressed air, a clean, abundant, and renewable energy source. This makes them inherently safer, especially in explosive or hygienic environments, and eliminates the risk of toxic leaks or fire hazards. While electric drives are known for their precision and programmability, they are often more complex, sensitive to overloads, and less robust in harsh or vibration-prone settings. Pneumatic systems, by contrast, are mechanically simple, overload-resistant, and capable of continuing operation during brief power outages due to stored compressed air in the system. Modern pneumatic systems are also modular and easy to maintain, making them ideal for both large-scale industrial automation and smaller, mobile, or start-up operations. Their widespread use across industries such as automotive manufacturing, electronics, food and beverage processing, petrochemicals, pharmaceuticals, HVAC, and transportation, particularly in air brake systems, demonstrates their versatility and reliability. Despite lingering misconceptions about noise, leakage, or operational complexity, properly designed pneumatic systems are clean, efficient, and relatively quiet. Their mechanical simplicity allows for quick troubleshooting and reconfiguration, and their compact, lightweight components make them especially advantageous in applications where space and mobility are critical [1], [2].

However, pneumatic systems are not without limitations. The compressibility of air can lead to reduced precision and stick-slip effects, particularly at low speeds. Pressure limitations often necessitate larger components to achieve the same force output as hydraulic or electric systems. Effective air preparation is essential to prevent moisture, oil, and particulate contamination, and the performance of seals and other components can be sensitive to temperature fluctuations. Pneumatic systems are also vulnerable to air leakage, which can reduce efficiency and increase energy costs, especially given the relatively high energy demand of air compression. Additionally, they may be less suitable for applications requiring highly accurate motion or force control, as their speed and position regulation is generally less precise than that of electric drives. Noise from compressors and valves can also be a concern if not properly managed, and the systems may be sensitive to dust and vibration in certain environments [1], [2].

1.2 Industrial pneumatics and recent trends

Every industrial pneumatic system includes essential components such as air generation, pressure control, storage tanks, distribution networks, and end-use devices (Figure 1). Each part must be well-designed to ensure efficiency, stability, and long-term, sustainable operation.

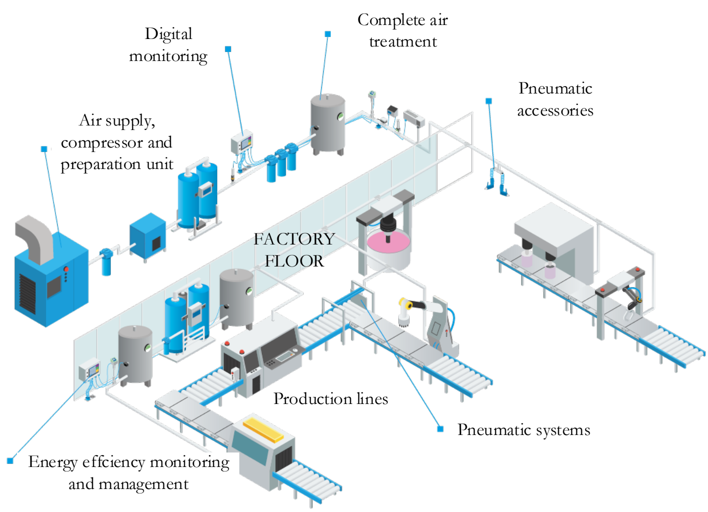

Figure 1: Industrial pneumatics: compressed air chain with main pneumatic subsystems [3].

Recent technological advancements are significantly reshaping the landscape of pneumatic systems. Innovations in actuator design, intelligent control, and energy-saving strategies are helping to overcome long-standing limitations traditionally associated with pneumatics [4]. The integration of these systems with Industry 4.0 technologies, such as the Internet of Things (IoT), digital twins, and machine learning, has opened new possibilities for creating adaptive, efficient, and sustainable automation solutions [5], [6], [7]. Modern pneumatic platforms now support seamless integration with advanced components like multifunctional island valves and flowmeters that are compatible with PLC controllers. These developments enable centralized and streamlined management of multiple pneumatic valves and actuators, while also facilitating real-time data acquisition at the machine level. This data can be used for operational analysis, predictive diagnostics, and performance optimization. Furthermore, the interconnection of pneumatic system data with higher-level IT infrastructures such as ERP (Enterprise Resource Planning), MES (Manufacturing Execution Systems), and other digital platforms enhance transparency and enable more effective decision-making across production environments [8].

This review aims to synthesize these technological developments, highlight emerging trends, and identify opportunities for further research and industrial application in the evolving field of pneumatic automation.

2 Advanced approaches

2.1 Pneumatic actuators

Recent developments in pneumatic actuators have significantly expanded their capabilities, particularly in terms of miniaturization, customization, and integration with soft materials. These advances are enabling new applications in robotics, biomedical devices, and lightweight automation systems.

One of the most promising directions is the use of additive manufacturing to create compact, lightweight pneumatic actuators. Nall and Bhounsule [5] demonstrated a 3D-printed, double-acting linear pneumatic actuator with a power-to-weight ratio comparable to commercial alternatives (Figure 2). Their actuator, weighing only 12 grams, achieved a peak output power of 2 W at 40 psi and was successfully integrated into a hopping robot inspired by the Pixar Luxo lamp. Such actuators offer several advantages such as rapid prototyping and customization, integration of structural and functional components, and low-cost fabrication using hobby-grade printers and therefore are ideal for educational robotics, wearable devices, and exploratory research in soft robotics.

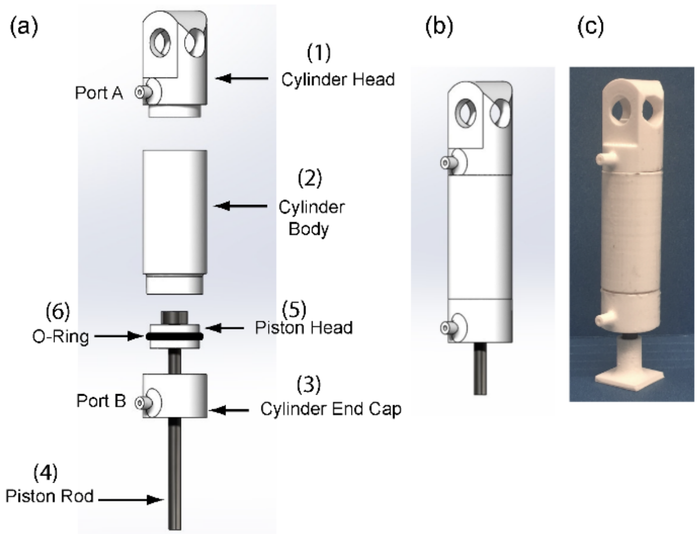

Figure 2: An Overview of the 3D printed actuator: (a) an exploded view, (b) assembled view, and (c) 3d printed and assembled [5].

Soft robotics and biomedical applications have emerged as a key area where pneumatics and pneumatic actuators plays a central role. Soft pneumatic actuators, often made from elastomers or textiles, provide safe and adaptive interaction with humans and unstructured environments (Figure 3) [6].

They are particularly suited for biomedical applications, such as assistive devices and surgical tools. Recent work has focused on functionally graded materials for variable stiffness, antagonistic actuator systems using stereolithography and combustion-powered soft robots for high-thrust applications. These actuators benefit from the inherent compliance of soft materials, enabling complex motions and safe physical interaction. However, challenges remain in modelling their nonlinear behaviour and achieving precise control.

The integration of miniature and soft actuators into robotic systems has led to novel applications such as jumping and hopping robots with high energy efficiency [5] and bioinspired tentacle-like manipulators as well as compact actuators for wearable exoskeletons and prosthetics [6]. These applications highlight the versatility of pneumatic actuation in domains where weight, safety, and adaptability are critical.

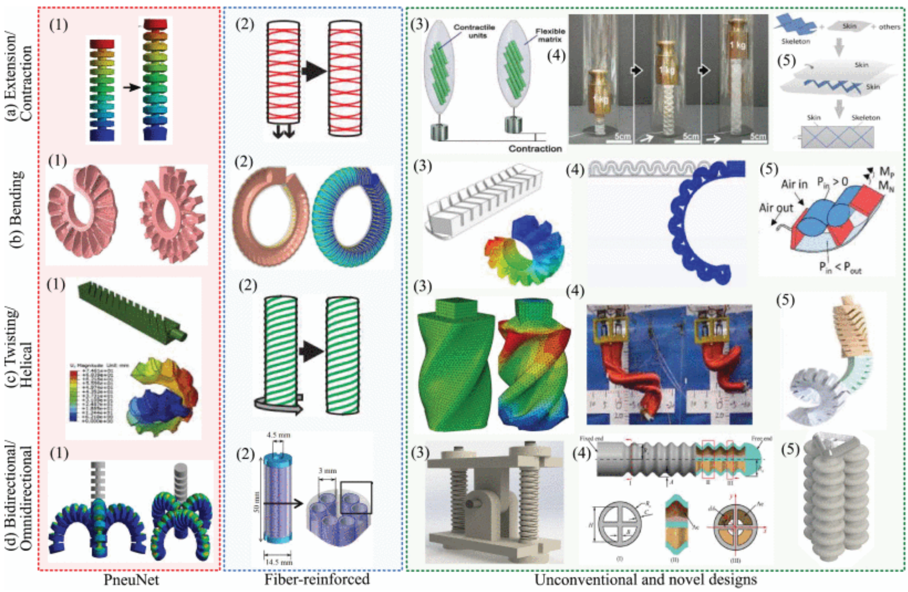

Figure 3: Soft pneumatic actuator designs: (a) Extension and contraction SPAs: (1), (2), (3), (4) and (5). (b) Bending SPAs: (1), (2), (3), (4) and (5). (c) Twisting and helical SPAs: (1), (2), (3), (4) and (5). (d) Bidirectional and Omnidirectional SPAs: (1), (2), (3), (4) and (5) [6].

To address the complexity of soft and miniature actuators, researchers are increasingly turning to data-driven modelling and advanced control strategies. Reinforcement learning and neural networks are being explored to improve adaptability and performance.

2.2 Intelligent control and Industry 4.0 integration

The integration of intelligent control strategies and digital technologies is transforming pneumatic systems into adaptive, efficient, and interconnected components of modern automation. These advancements are driven by the need for higher precision, energy efficiency, and seamless integration with Industry 4.0 frameworks.

2.2.1 Proportional and Digital Pneumatics

Traditional on/off pneumatic control is increasingly being replaced by proportional and digital control systems that offer finer regulation of pressure and flow. Proportional valves, often controlled via analogue or pulse-width modulation (PWM) signals, enable continuous adjustment of actuator force and speed. Recent developments include the use of modulated pulse control for proportional flow regulation, offering high-speed switching (up to 1500 Hz) and compact modular designs [9].

One of the potential alternatives to hydraulic systems presents the pneumatic system designed for dynamic material strength testing, particularly for low-strength materials such as natural fibres (Figure 4). The system uses a pneumatic cylinder to apply cyclic loads, with force controlled via a proportional pressure valve and a PID controller implemented on an Arduino-compatible PLC. A touchscreen interface allows intuitive operation and real-time monitoring. Experimental tests confirm accurate force control up to 11 kN, with reliable performance in low-frequency fatigue testing. The system offers a cost-effective and portable solution for laboratories focused on testing low-strength or natural materials [10].

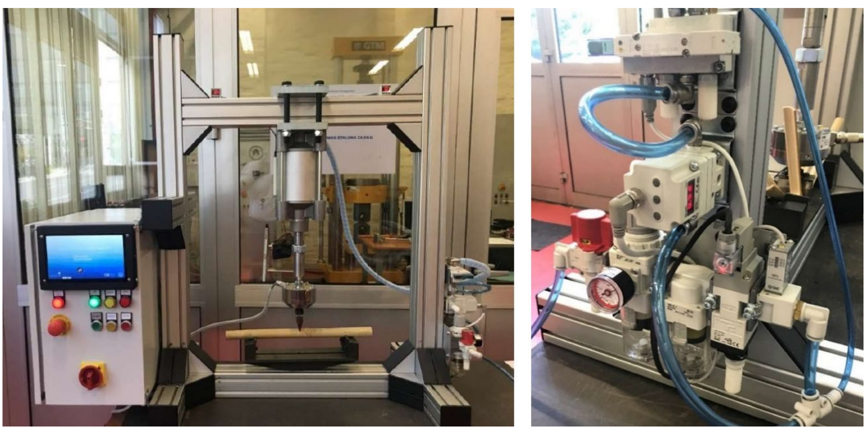

Figure 4: Fatigue testing machine driven by pneumatic system [10].

Digital pneumatics in combination with piezo technology, characterized by the use of binary-controlled microvalves and smart valve terminals, allows for precise and programmable control of pneumatic circuits. These systems are often integrated with embedded sensors and microcontrollers, enabling real-time feedback and diagnostics [11], [12].

2.2.2 Reinforcement learning and Adaptive control

One of the most promising trends in intelligent control is the application of reinforcement learning (RL) and neural networks to pneumatic systems. Allmendinger and Erhard [13] demonstrated a hybrid control approach where a deep deterministic policy gradient (DDPG) agent was trained in a virtual environment to enhance the performance of a conventional PID controller for mass flow regulation (Figure 5). The RL-enhanced controller achieved faster settling times and better adaptability to varying environmental conditions, such as changes in inlet pressure and coil temperature (Figure 6).

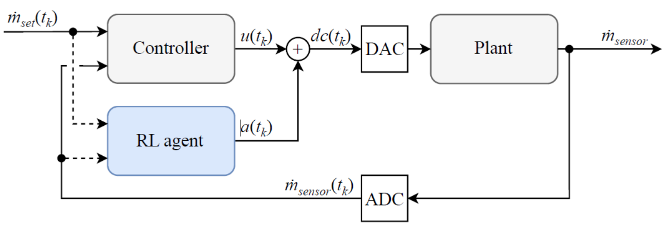

Figure 5: Structure and main components of training model [13].

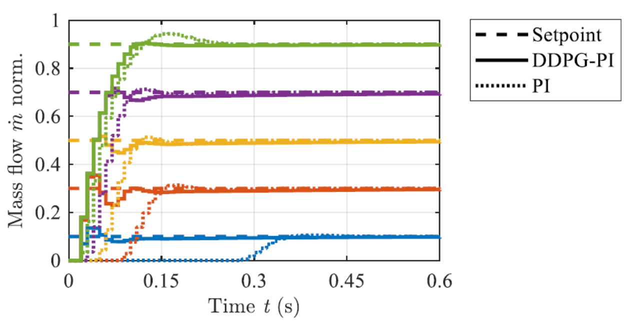

Figure 6: Comparison of the control performance between DDPG-PI and conventional PI controller [13].

This approach highlights the potential of data-driven control to compensate nonlinearities and uncertainties, improve robustness and adaptability and enable self-tuning and predictive behaviour of pneumatic system.

2.3 IoT, Digital twins, and Smart pneumatics

The convergence of pneumatics with the Industrial Internet of Things (IIoT) and digital twin technologies is enabling predictive maintenance, remote monitoring, and system optimization. Smart pneumatic systems are equipped with embedded sensors for pressure, flow, temperature, and position, which feed data into cloud-based analytics platforms with the help of new 5G and 6G technology [14]. Especially 5G and 6G technology is important for modular production systems and distributed control networks [15]. The main players in the pneumatics such as FESTO and SMC proposed and developed Smart pneumatic platforms representing several automations and IIoT layers (intelligent devices with embedded sensors and edge computers; motion and machine control layer with PLC, I/O devices and management and cloud-based analytic layer to perform real-time monitoring an diagnostics, predictive maintenance and energy optimization [16].

Key benefits include:

- Early detection of leaks and component wear
- Optimization of energy consumption
- Real-time performance monitoring and diagnostics

Digital twins, virtual replicas of physical pneumatic systems, allow for simulation, testing, and optimization of control strategies before deployment. This reduces commissioning time and enhances system reliability. Modern pneumatic systems are increasingly being integrated into cyber-physical systems (CPS), where they interact with digital controllers, sensors, and actuators in a closed-loop architecture. Hybrid systems combining pneumatic and electric actuation are also gaining traction, offering the benefits of both technologies in terms of force density, precision, and energy efficiency. These integrations support the broader goals of Industry 4.0, including modular and reconfigurable automation, decentralized control and edge computing, enhanced human-machine collaboration [8], [16], [17], [18], [19].

2.4 Energy efficiency in pneumatic systems

Energy efficiency has become a central concern in pneumatic system design, driven by rising energy costs, sustainability goals, and the need for competitive industrial automation. Traditional pneumatic systems are often criticized for their low energy efficiency, typically ranging between 5 to 20 % [20], [21], [22], [23], [24], [25]. However, recent research has introduced several innovative strategies to significantly reduce air consumption and improve overall system performance. One possible and simple solution presents energy saving circuits (Figure 7). Energy-saving circuits include all the circuits that deviate from standard meter-in or meter-out pneumatic circuits in terms of their structure and whose purpose is to reduce the amount of compressed air supplied to the system [21].

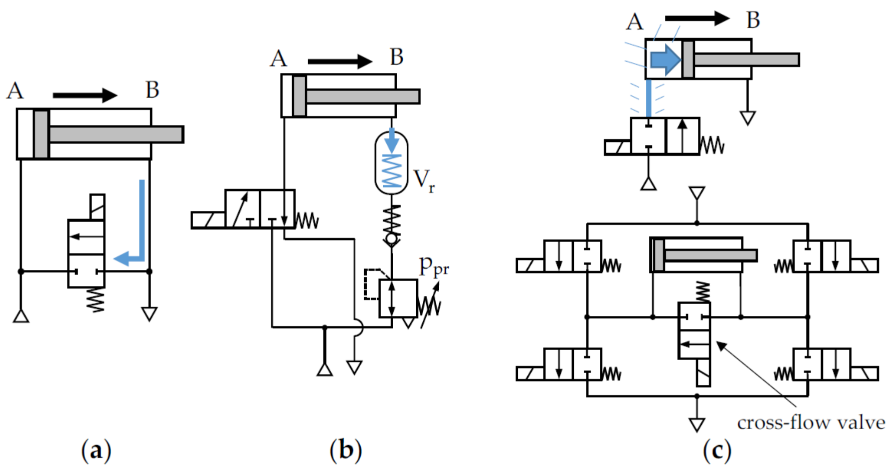

Figure 7: Basic principles of energy-saving circuits: (a) short (cross-flow) circuit; (b) exhaust air storage circuit; and (c) above: cut-off (expansion) principle, below: expansion bridge circuit with an additional cross-flow valve [21].

One of the most effective methods for improving energy efficiency is the use of intermittent air supply. Instead of continuously supplying compressed air throughout the actuator stroke, this method introduces controlled air pulses, allowing the actuator to utilize expansion energy more effectively. Gryboś and Leszczyński [22] demonstrated through exergy analysis that intermittent air supply can reduce exergy consumption by over 60 % compared to conventional systems.

This approach not only minimizes energy losses but also maintains actuator performance. The authors developed a dynamic model and validated it experimentally, showing that actuator speed and force profiles remain within acceptable limits while significantly reducing energy input. Figure 8 illustrates the exergy flow in classical and intermittent air supply systems, highlighting the shift in energy losses from the muffler to the distributed pneumatic line.

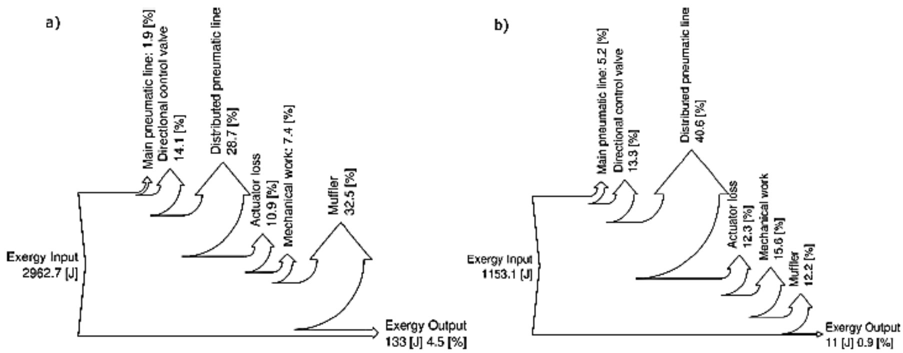

Figure 8: Sankey diagram: (a) exergy flow in classical and (b) intermittent air supply of pneumatic systems [22].

Proper sizing of pneumatic actuators and valves is another critical factor in reducing energy waste. Oversized actuators consume more air than necessary, especially in motion tasks. Doll et al. [7] introduced the Pneumatic Frequency Ratio (PFR) as a design metric to optimize actuator sizing based on stroke length, load, and transition time. Their method ensures that the actuator operates within an efficient dynamic range, avoiding excessive air consumption while maintaining performance.

Additionally, combined throttling strategies, such as adaptive upstream and downstream throttling, have shown promise in experimental studies. Reese et al. [26] developed a novel circuit combining quick exhaust valves and proportional control, achieving substantial air savings without compromising cycle time (Figure 9).

Other strategies, presented in [22] include the use of back pressure regulation and energy recovery systems. By introducing controlled back pressure in the exhaust line, it is possible to recover part of the expansion energy and reduce the net air consumption. These methods are particularly effective in systems with high-frequency actuation or long stroke lengths.

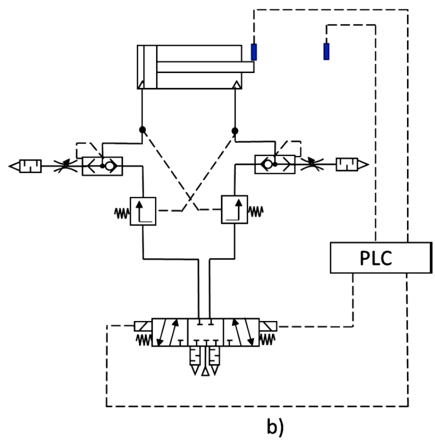

Figure 9: Adaptive upstream throttling configurations: a) original circuit and b) circuit with quick exhaust [26].

Recent trend, which is supported by all major players in the field of pneumatics is focused on reduction of delivery pressure from traditional 6 bar to 4 bar (4-bar factory) [23], [24], [25]. This shift targets significant reductions in energy consumption, operating costs, and CO_2 emissions. Since compressed air generation is a major industrial energy burden, even modest pressure reductions can lead to substantial efficiency gains (for every 1 bar reduction in delivery pressure, an average of 6 to 8 % less specific power is consumed.).

Implementing a 4-bar system requires a phased approach, beginning with an assessment of pressure and flow demands across the facility and detail check of working principles of all pneumatic component under lower 4-bar pressure. Localized control, air storage, and minor component changes often enable existing equipment to operate effectively at lower pressures. Once stability is confirmed at the machine level, the factory-wide supply pressure can be gradually lowered, reducing compressor duty and associated energy use.

This transition also involves redefining design standards to ensure future machinery supports lower pressure operation. Where higher pressure is occasionally needed, local boosters can be used. The 4-bar factory is not only a technical upgrade but a strategic move toward more sustainable and efficient manufacturing [23], [24], [27].

3 Future trends and outlook

The evolution of pneumatic systems is being shaped by a convergence of technological, environmental, and economic drivers. As industries transition toward smarter, more sustainable, and digitally integrated operations, pneumatics is poised to play a renewed role in next-generation automation systems. Here are two typical examples focused on sustainability and eco-conscious design of pneumatic system.

The first approach to sustainability involves quantifying the greenhouse gas emissions associated with pneumatic components. Sprink and Schmitz [28] conducted a cradle-to-gate Product Carbon Footprint (PCF) analysis of various pneumatic actuators and valves. Their study revealed significant variability in emissions depending on material sourcing, manufacturing processes, and data quality. To ensure comparability, the authors emphasized the need for standardized system boundaries, transparent reporting of assumptions and use of primary data where possible. Figure 10 illustrates the system boundary used in their PCF analysis, covering raw material extraction, component manufacturing, and assembly. This framework supports sustainability assessments and digital integration strategies.

The integration of PCF analysis with digital tools such as digital twins and IoT platforms enables real-time monitoring of environmental performance. This supports informed decision-making in design, procurement, and operation. Moreover, manufacturers are increasingly offering low-carbon alternatives, such as components made from recycled materials or produced using renewable energy.

The second potential approach to sustainability is optimizing the gripping force (required holding force) in pneumatic handling systems. Eberhardt et al. [29] proposed a trajectory-specific method for calculating the required holding force of surface (vacuum) grippers (Figure 11).

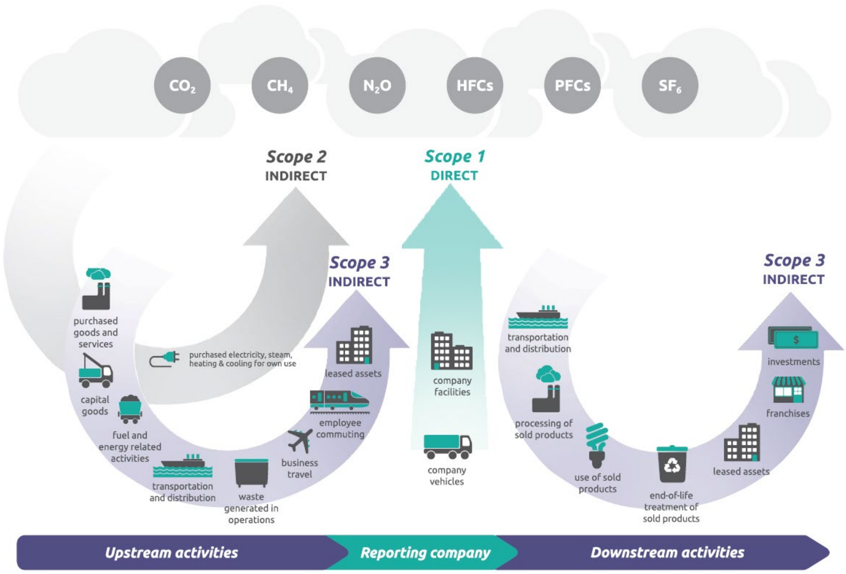

Figure 10: System boundary for cradle-to-gate Product Carbon Footprint (PCF) analysis of pneumatic components [28].

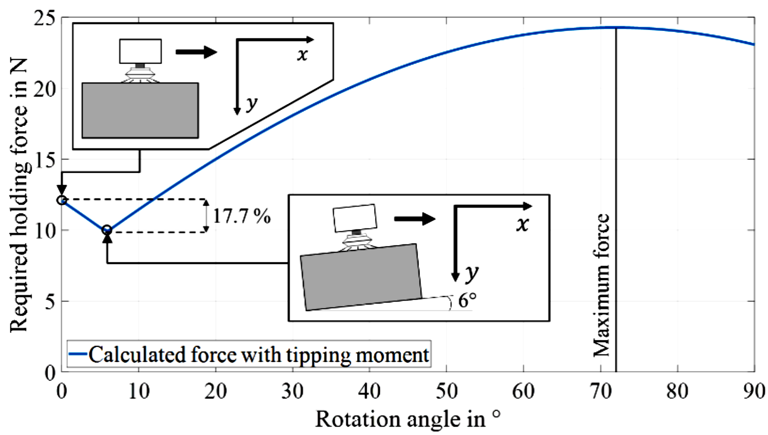

Figure 11: Reduce required holding force through clever alignment of the gripping object [29].

By tailoring the gripping force to the actual dynamic load along the robot path or any other handling device, unnecessary air consumption can be avoided, leading to both energy savings and reduced wear of pneumatic components. This method supports sustainable automation by minimizing overdesign and oversizing of grippers, reducing compressed air usage and extending component lifespan. The major challenge represents the real-time adaptive control of required air supply or control of vacuum pump.

Based on presented advanced approaches from section 2 and some other trends and developments in pneumatics described in [30], [31], [32] we can summarize:

- Miniaturization, supported by soft robotics and microfabrication, is expanding pneumatics into wearable and biomedical fields, with a focus on low-pressure, compact, and safe actuation.
- New strategies have been developed to improve pneumatic system efficiency, such as preventing leaks, using properly sized components, and performing regular maintenance. These also emphasize the role of smart monitoring tools like FLUX flowmeters and IoT-enabled valves in reducing energy waste and enabling predictive maintenance.
- New smart pneumatic grippers that integrate valves, absolute position sensors, and part detection within a compact IO-Link-controlled package are now used in robotics. These units deliver high cycle rates (up to 500 grips/min for RPG), consume up to 90 % less compressed air than conventional systems, and support predictive maintenance through onboard diagnostics.
- The use of airflow sensors, in combination with modular IIoT-enabled systems, 5G technology, enables simple integration and allows real-time monitoring to reduce compressed air waste (saving 10 to 20 % in energy and emissions).
- The use of advanced materials and coatings is significantly improving the durability and performance of pneumatic components.
- Current approaches focus on integrating pneumatics into cyber-physical systems through digital twins, enabling real-time monitoring, simulation, and predictive maintenance. These digital tools enhance performance and align with Industry 4.0 goals.
- Hybrid pneumatic-electric systems are emerging to combine the power density of pneumatics with the precision of electric actuators, particularly in collaborative robots and modular automation.

- Artificial intelligence is advancing pneumatic control through self-optimizing algorithms that adapt in real time, enabling smarter fault detection, autonomous tuning, and efficient system design.
- Sustainability is driving the use of recycled or bio-based materials and circular design principles, supported by growing demands for transparent carbon footprint reporting.

4 Conclusions

This review has outlined the transformative developments shaping modern pneumatic systems. The integration of miniature 3D-printed and soft actuators has extended pneumatics into fields such as robotics, biomedicine, and wearable devices, where lightweight and adaptive actuation is essential. Intelligent control strategies, particularly those based on reinforcement learning and digital pneumatics, are enhancing system adaptability, precision, and efficiency.

Energy efficiency remains a central challenge and opportunity, with approaches such as intermittent air supply, optimized actuator sizing, combined throttling circuits, and reduced operating pressures (e.g., 4-bar systems) demonstrating substantial air and energy savings. These methods not only lower operational costs but also contribute to sustainability goals.

Digitalization is driving the evolution of pneumatics into smart, cyber-physical systems. The integration of IioT sensors, 5G, digital twins, and AI enables predictive maintenance, real-time monitoring, and data-driven optimization. Moreover, sustainability is emerging as a key design driver, exemplified by lifecycle assessments like Product Carbon Footprint (PCF) analysis and innovations in eco-friendly materials and energy-conscious control strategies.

Looking ahead, pneumatic systems are poised to become an essential component of Industry 4.0-characterized by hybrid actuation, smart diagnostics, modular architectures, and environmentally responsible designs. These advancements underscore pneumatics not as a legacy technology, but as a versatile, scalable, and sustainable platform ready to meet the demands of next-generation automation.

Acknowledgments

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