Development of a New Virtual Pneumatic Control Simulator for Educational Purposes

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ABSTRACT

In order to generate force, convey power, and regulate motion, pneumatics which uses compressed air to transmit and control energy is essential. Education must change to satisfy industry demands as automation technologies proliferate. However, conventional hands-on pneumatic systems for teaching are frequently costly, logistically difficult, and inaccessible, which prevents students from learning useful skills. This work discusses the design and development of a free virtual pneumatic control simulator in order to address these issues. Students can experiment with control strategies, visualize system reactions, and study pneumatic control concepts in an interactive, software-based environment with the simulator. For simulation, the architecture combines Simscape and MATLAB/Simulink, and real-time interaction and visualization are made possible using a Python/Flask-Bootstrap interface. When compared to traditional techniques, the results show notable gains in students' conceptual understanding and engagement. The potential of virtual labs to democratize engineering education is demonstrated by this platform.

Keywords: Pneumatic, controller design, virtual simulator.

INTRODUCTION

Pneumatic systems use compressed air to transmit energy and control motion, they are used extensively in automation, such as robotic actuation, material handling, and industrial processes. Because of their widespread use in industry, engineering students must learn both theoretical and practical aspects of pneumatic dynamics, actuators, and control algorithms. Despite their significance, hands-on pneumatic educational setups face significant challenges, including high training kit and lab equipment costs, logistical challenges in setup and maintenance, and limited accessibility for remote learners, which exacerbates the gap between theory and practice. Additionally, traditional laboratory experiences frequently do not expose students to nonlinear system behavior, such as valve dynamics, air compressibility, and frictional losses.

In order to facilitate pneumatic teaching, this paper presents the Virtual Pneumatic Control Simulator, a scalable and cost-free system. In contrast to actual labs, the simulator gives students a way to simulate pneumatic systems, change settings, and see how the systems react to various control schemes. By combining interactive visualization and dynamic system modeling, it further connects theory to practice. The simulator offers a Python/Flask-Bootstrap web-based interface for accessibility, a simulation framework for pneumatic actuators based on MATLAB/Simulink and Simscape, and a comparative analysis of open-loop and closed-loop controllers. Student feedback, which shows increased conceptual understanding and engagement, is also used in the paper to support the platform. Compressors, actuators, cylinders, and directional control valves make up pneumatic systems, which transform compressed air into mechanical motion. Physical lab kits have historically been used in educational teaching; however, these setups are expensive and less scalable. Differential equations are commonly used to express actuator displacement mathematically in dynamic modeling of pneumatic systems. While Simscape adds realism by simulating multi-domain physical factors like compressibility and valve delays, MATLAB/Simulink provides a platform for block-based modeling of pneumatic systems.

Both open-loop and closed-loop methods can be used to control pneumatic actuators. Although open-loop systems are straightforward, they can become unstable when disturbed. PID control and state-space approaches are two examples of closed-loop systems that use feedback. Because of its simplicity, PID control is still widely used, yet state-space control provides improved stability and robustness.

The use of web-based or MATLAB-integrated simulation environments has been investigated in a number of research. Although these technologies increase engagement, they frequently lack thorough integration of complex control methods or user-friendly interfaces. Measurable gains in learning outcomes have been shown with interactive platforms. By integrating Simscape's physical realism, real-time parameter adjustment, and integration of numerous control strategies into a web-accessible platform, the simulator described in this work builds on previous research.

BACKGROUND STUDY

Pneumatic Systems in Industrial Automation

Pneumatic systems have been a cornerstone of industrial automation for decades, offering a reliable, safe, and cost-effective means of actuating machines in environments where hydraulic or electrical actuators may be unsuitable. Their use spans diverse domains, including robotic grippers, automated conveyors, and material handling systems. Pneumatic actuators provide clean operation since they do not involve lubricating fluids, making them particularly suited for food processing and pharmaceutical industries. They are also preferred in hazardous environments due to their intrinsic safety when compared to electrical drives [1].

From an educational perspective, pneumatics offers a valuable entry point into fluid power systems and control theory. However, despite their simplicity in concept, pneumatic actuators exhibit nonlinear dynamics caused by air compressibility, valve dead zones, and frictional effects. These nonlinearities make modeling and control design more challenging than in purely mechanical systems [2], [3]. Students must therefore be exposed not only to the mechanical construction of pneumatic circuits but also to dynamic modeling and control strategies that account for such complexities.

Accurate modeling of pneumatic systems has been a subject of continuous research. Traditional approaches rely on Newtonian mechanics and thermodynamic relations to derive governing equations. The force balance of a piston-cylinder assembly, for example, is expressed as:

$$M\ddot{x}(t) + Dx(t) + Cx(\dot{t}) = A.P(t) \qquad (1)$$

where M denotes the piston mass, D the damping coefficient, C the spring constant, A the piston area, and P(t) the air pressure acting on the piston head. Such equations provide the foundation for control-oriented transfer functions [4].

MATLAB/Simulink has become the dominant tool for simulating these models because of its graphical block-based environment that allows easy representation of dynamic systems. Simscape, an extension of MATLAB, offers physics-based components that incorporate compressibility, valve dynamics, and multi-domain interactions. Researchers have highlighted that Simscape-based modeling better captures practical system responses, enabling more accurate testing of control algorithms before deployment [5], [6].

Control Strategies for Pneumatic Systems

Control strategies in pneumatics can be broadly divided into open-loop and closed-loop approaches. Open-loop systems, though simple, are prone to performance degradation under disturbances. They cannot compensate for nonlinearities, resulting in poor accuracy and limited applicability in precision tasks [7].

Closed-loop control introduces feedback, enabling corrective actions that improve stability and accuracy. Among these, the PID controller remains the most widely used due to its intuitive structure and ease of tuning. Nevertheless, PID control in pneumatics often suffers from large overshoots and oscillations unless carefully tuned, as system nonlinearities make classical tuning rules insufficient [8].

Alternative methods include adaptive PID controllers, where gains are adjusted online based on operating conditions [9]. State-space methods have also been employed for pole-placement control, offering superior transient response and robustness [10]. More advanced research explores robust control, model predictive control (MPC), and nonlinear controllers that can explicitly handle valve saturation and compressibility effects [11], [12]. Despite their superior performance, these methods are often mathematically complex, making them less accessible in an educational context.

Virtual Laboratories and Educational Simulators

The growing emphasis on e-learning and remote education has accelerated the adoption of virtual laboratories. Virtual labs allow students to experiment with simulated equipment, reducing dependence on expensive hardware while increasing accessibility. Studies have shown that virtual environments enhance conceptual understanding and engagement compared to traditional lecture-only formats [13].

Several researchers have proposed simulation-based platforms for pneumatics. Montalvo-Lopez et al. [14] developed a training environment using virtual reality for pneumatic circuits. Nasr and Kamel [15] employed MATLAB Web Apps to deliver control experiments online, while Buhl [16] reported positive learning outcomes using virtual control simulators. Pisano and Villani [17] emphasized the importance of interactivity, noting that students learn more effectively when they can manipulate parameters and instantly observe responses.

Despite these advances, many existing simulators suffer from limitations. Some require expensive software licenses or high-performance computing resources, restricting accessibility. Others provide simplified system models that fail to capture nonlinear dynamics, limiting realism. Additionally, integration of advanced control strategies into educational simulators remains limited.

Research Gaps and Motivation for This Work

A clear gap exists between industrial-grade pneumatic control and the resources available to students. While physical labs provide realism, they are costly and difficult to scale for large classes. Existing virtual simulators address cost but often compromise on either realism or user accessibility. Very few tools combine physics-based realism, advanced control strategies, and web-based interactivity in a unified platform.

The Virtual Pneumatic Control Simulator presented in this work addresses these gaps by leveraging MATLAB/Simulink and Simscape for accurate modeling, while integrating a Python/Flask-Bootstrap web interface for universal access. Unlike previous works, the simulator supports both PID and state-space control strategies, offers real-time parameter tuning, and has been validated with student feedback. This combination provides a practical, cost-free, and pedagogically effective tool for pneumatic education, bridging the gap between theoretical instruction and hands-on experience.

METHODOLOGY

The Virtual Pneumatic Control Simulator was developed using a multi-layered architecture that combines a web-based interface, simulation environment, and system modeling.

Newton's laws were used to model the dynamics of the pneumatic actuator, and the transfer function may be written as follows:

$$T(s) = \frac{P(s)}{X(s)} = \frac{A}{(Ms^2 + Ds + C)} \qquad (2)$$

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In this case, A stands for piston area, M for moving component mass, D for damping coefficient, and C for spring constant. The model was enhanced in Simscape for physics-based realism and deployed in Simulink for control analysis. There were two types of simulations created. While closed-loop models incorporated PID controllers and state-space controllers with pole placement for stability optimization, the open-loop model was used as a baseline reference.

HTML/CSS, JavaScript, and Bootstrap were used in the development of the web interface's front end. The MATLAB Engine API was used to combine Python/Flask with MATLAB in the backend. With the use of this interface, one can instantly visualize the responses of the system while adjusting parameters like mass, damping, and air pressure in real time. Rise time, overshoot, settling time, and steady-state error were all evaluated in the performance evaluation. Structured student feedback was used to gauge the success of the education. Fig. 1 shows the pneumatic system model, while Fig. 2 through 5 illustrate open-loop, PID, state-space, and user interface views, respectively.

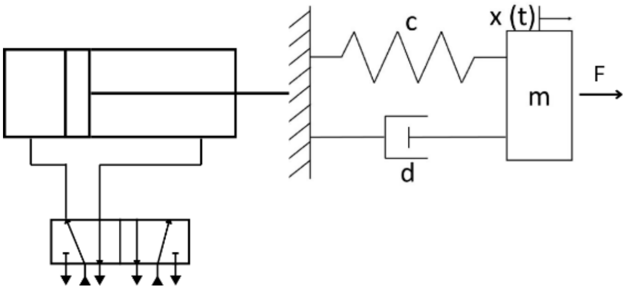

Fig. 1. Pneumatic System

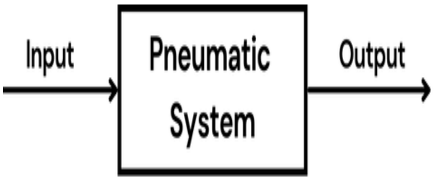

Fig. 2. Open Loop System

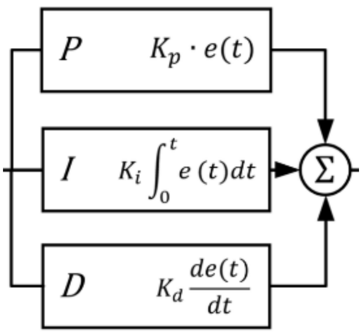

Fig. 3. PID Controller

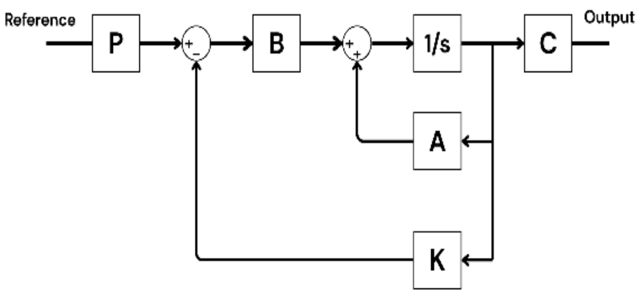

Fig. 4. State-Space (Pole Placement)

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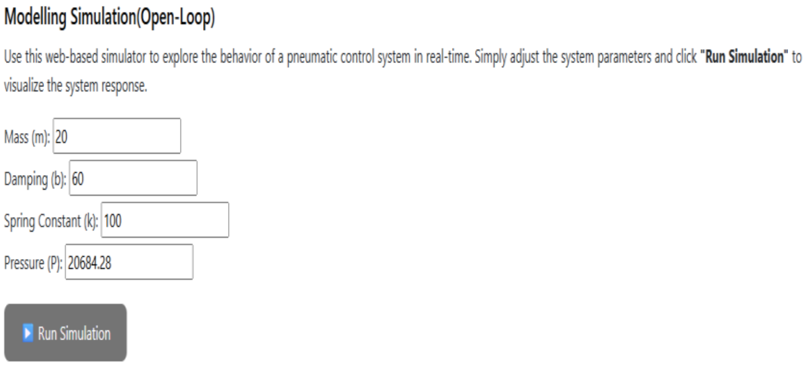

Fig. 5. User Interface for Real Time Simulation

RESULTS AND DISCUSSION

The response of the open-loop system is seen in Fig. 6. The curve displays a settling time of 2.68 seconds and a significant overrun of 8.76%. This demonstrates the intrinsic drawback of open-loop pneumatic systems since there is no feedback, making it impossible to remedy errors when nonlinearities or disturbances arise. In industrial contexts, this kind of behaviour would actually result in poor repeatability, which is why feedback-based control is crucial for pneumatic actuators

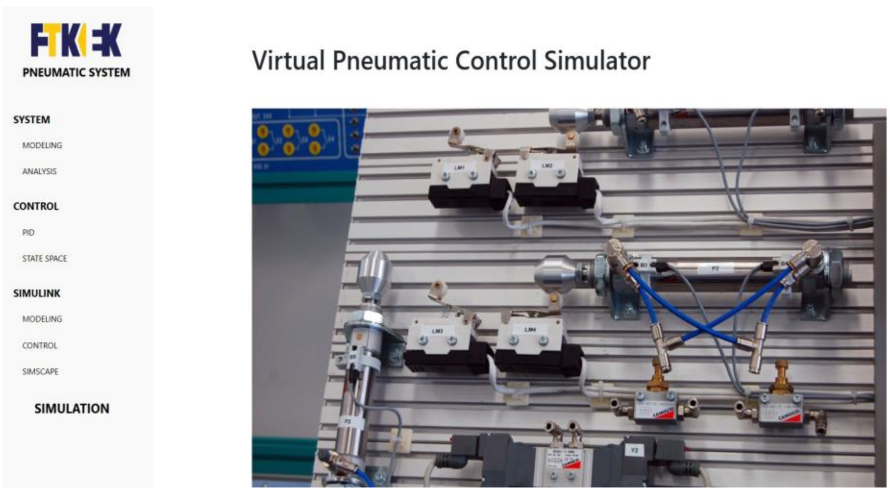

Fig. 6. Virtual Pneumatic Control Simulator

The Simscape simulation with PID control is shown in Fig. 7. The response displays a significant overshoot of 29.05%, despite the PID controller's successful elimination of steady-state error. This is caused by the compressibility of air and valve dynamics that Simscape captures but that are not included in the idealized Simulink model. Although this result shows students that PID controls are effective, they need to be carefully adjusted in pneumatic applications to avoid instability. The modified PID achieves decreased overshoot and increased stability.

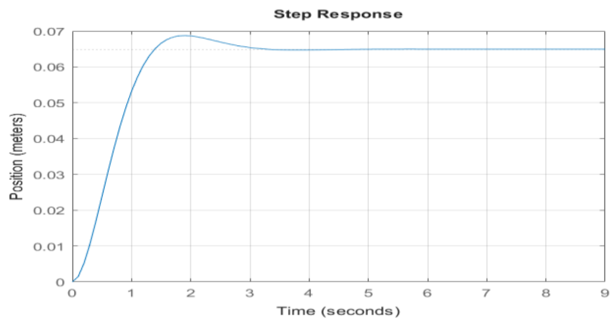

Fig. 7. Result Open-Loop System

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The various PID structures (P, PI, PD, and PID) are contrasted in Table I. Despite producing a quick rise time, the proportional controller (P) had residual steady-state inaccuracy. The PI controller lengthened the settling time while eliminating steady-state error. Although it created a large overrun, the PD controller enhanced transient response. The only controller that achieved balanced performance with 0% steady-state error and good settling characteristics was the complete PID controller. This helps students understand the trade-offs that come with controller design.

Table 1 Comparison Between Each PID

Controller	Rise Time(s)	Settling Time(s)	Overshoot (%)	Steady-State Error
P	0.354	2.43	30.74	0.049
PI	0.336	3.34	26.97	0
PD	0.093	0.85	39.89	0.063
PID	0.367	2.13	0	0

The state-space control response is depicted in Fig. 8. The state-space approach, in contrast to PID, achieved 0% overshoot with faster settling. This demonstrates the benefit of using model-based techniques for pneumatic control, especially when exact pole positioning is required. Students can see that state-space approaches are crucial for sophisticated automation systems because they provide better performance and stability despite their mathematical complexity.

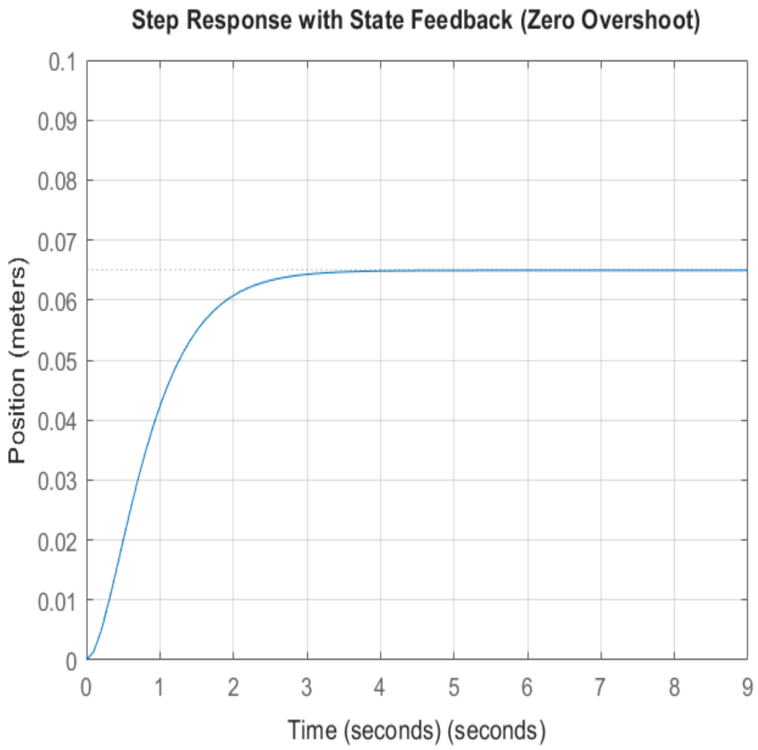

Fig 8. Step Response for State-Space

Simulink and Simscape outputs are contrasted in Fig. 9. The difference is significant: Simscape shows about 10% overshoot because of real-world nonlinearities like friction and valve delay, whereas Simulink recommends an ideal 0% overshoot. This highlights the importance of physics-based simulation and warns students about the perils of depending just on idealized models. The graphic illustrates how instructional simulators can help close the gap between realistic system behavior and simplified theory.

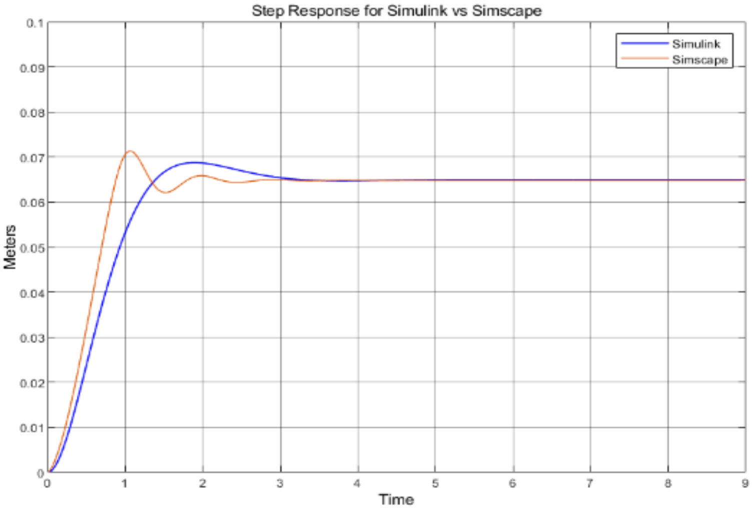

Fig. 9. Step Response Between Simulink and Simscape

Students' comprehension of open-loop versus closed-loop control is seen in Fig. 10. The simulator greatly improved conceptual clarity, according to the average assessment of 4.44/5. Since many students find it difficult to visualize feedback effects while learning solely from textbooks, this result is crucial.

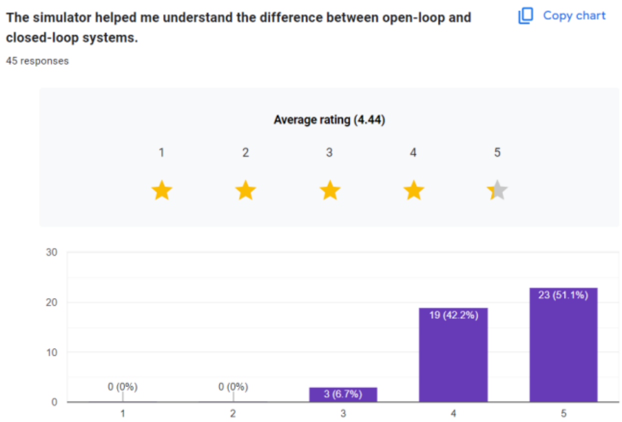

Figure 10. Understanding of Open-Loop vs. Closed-Loop

The efficiency of PID tuning exercises is seen in Fig. 11, which received a score of 4.51/5. Experimenting with various gain levels and seeing the direct effects on system dynamics was beneficial to the students. This is consistent with the ideas of active learning, which hold that experiential learning enhances retention more than passive teaching.

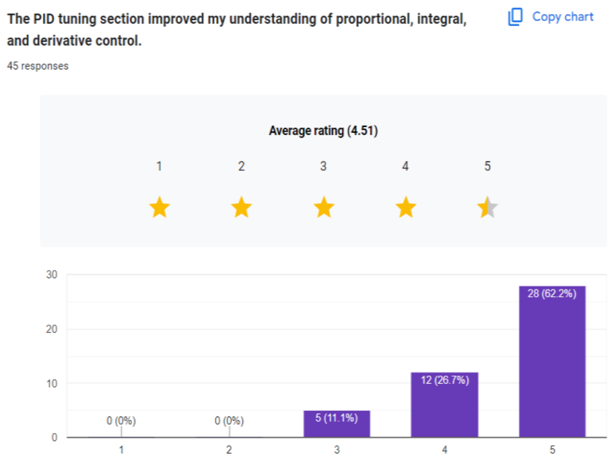

Fig. 11. PID Tuning Educational Effectiveness

The total level of engagement between the simulator and conventional textbook learning is contrasted in Fig. 12. More than 62% of participants gave the simulator a score of 4.47/5, the highest possible. This implies that students are more successfully motivated by the platform's interactive and visual elements, which could result in improved long-term learning outcomes.

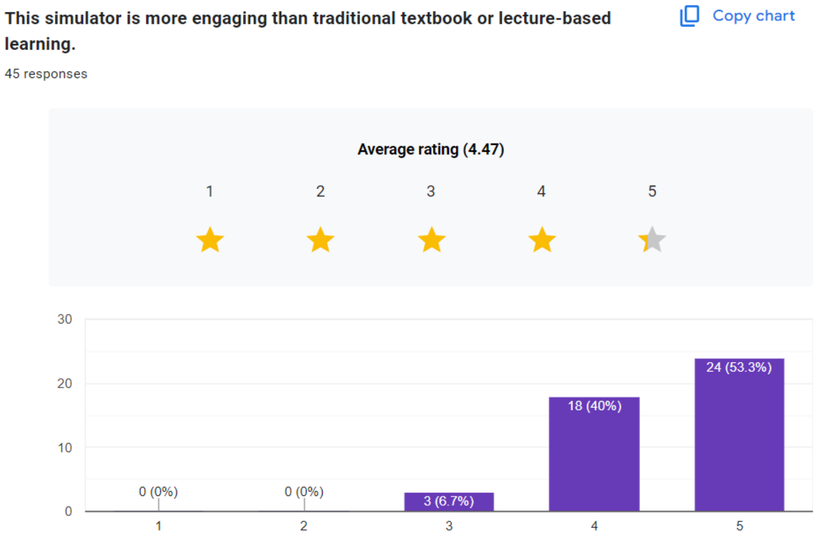

Fig. 12. Engagement Compared to Traditional Learning Methods

CONCLUSION

By overcoming conventional obstacles in pneumatic control training, the new Virtual Pneumatic Control Simulator effectively provides an interactive, cost-free learning environment. Deep experimentation with PID and state-space control algorithms is made possible by the tool's integration of realistic actuator dynamics modeling (via MATLAB/Simulink and Simscape) with an easy-to-use online interface for real-time parameter adjustment and viewing. The extremely positive feedback from 45 engineering students, who indicated notable gains in comprehension of fundamental concepts like system stability and overshoot compensation (4.51/5 rating), validates these skills. The simulator's usability rating of 4.51/5 attests to its capacity to convert theoretical concepts into hands-on learning, democratizing industrial-grade pneumatic education free from hardware limitations.

For suggestion, incorporating collaborative or multi-user functionality could support remote learning and classroom integration. Performance benchmarking on various hardware setups and network conditions would enhance accessibility and reliability for diverse users. Additionally, validation against real pneumatic lab setups or industrial systems could demonstrate fidelity and improve confidence in simulator accuracy.

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