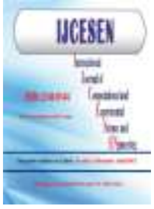
International Journal of Computational and Experimental Science and ENgineering
(IJCESEN)

Vol. 10-No.4 (2024) pp. 4383-4392
http://www.ijcesen.com



ISSN: 2149-9144

Research Article

A Comparative Analysis of Effective Control Methods For Pneumatic Servo Actuators

Uscan Uskaner[1], Mehmet Erkan Kütük[2]*, Sadettin Kapucu[3]

[1]Gaziantep University, Engineering Faculty, Mechanical Engineering Department, 27310, Gaziantep-Turkiye
Email: mekutuk@gantep.edu.tr - **ORCID:** 0000-0002-3001-2788

[2]Gaziantep University, Engineering Faculty, Mechanical Engineering Department, 27310, Gaziantep-Turkiye
* **Corresponding Author Email:** uscan.uskaner@gmail.com - **ORCID:** 0009-0008-6438-5735

[3]Gaziantep University, Engineering Faculty, Mechanical Engineering Department, 27310, Gaziantep-Turkiye
Email: kapucu@gantep.edu.tr - **ORCID:** 0000-0002-7061-9672

Article Info:

DOI: 10.22399/ijcesen.663
Received : 25 October 2024
Accepted : 22 December 2024

Keywords

Pneumatic
Control Strategies
Position Control
Servo Actuator
Multi-Physics Simulation

Abstract:

The compressibility of air and the uncertainties present in real-world applications make pneumatic cylinders inherently nonlinear and challenging to control. These characteristics demand sophisticated control strategies to achieve accurate and reliable performance. This study compares four control strategies PID, SMC, PID_PWM, and SMC_PWM to determine their effectiveness for pneumatic servo actuators under industrial conditions. The research involved a thorough analysis of the system's mathematical model, which has been then simulated to replicate its dynamic behavior accurately. Each control strategy's performance has rigorously been tested in this simulation environment. An experimental setup has been constructed to validate these findings, allowing for real-world performance evaluation and comparison against the simulation results. Using the TOPSIS method for evaluation, the SMC control strategy has stood out as the most effective, with an average score of 0.9, demonstrating superior practicality and adherence to the predefined criteria. However, the other strategies also performed notably well, each offering distinct advantages depending on specific application scenarios. Given the observed position-dependent responses and varying error rates, the study suggests further exploration of hybrid control strategies to optimize overall system performance. Additionally, future research should focus on refining the parameters of similar control systems, validating these in simulation environments, and conducting comparative analyses with other advanced control methods to extend the study's depth.

1. Introduction

Pneumatic power, a versatile and widely used technology in industrial applications, offers several advantages over other power sources. Its simplicity, feasibility and ability to generate substantial forces in compact spaces make it a compelling choice for numerous applications. Compared to hydraulic systems, pneumatic power is cleaner, requires less maintenance and is more economical for many tasks. Additionally, its resistance to electromagnetic interference and reduced susceptibility to temperature variations enhance its reliability and adaptability.

However, pneumatic power is not without challenges. The compressibility of air introduces nonlinear behaviour that complicates control efforts. Leakage, a common issue in pressurized gas systems, can lead to energy losses and control uncertainties. Furthermore, the production and transmission of compressed air involve significant energy consumption, resulting in higher operating costs compared to electrical and hydraulic systems. Despite these limitations, pneumatic actuators remain essential components in various industries, including aerospace, packaging, robotics and textiles. They are particularly well-suited for applications requiring linear motion, such as those involving Cartesian coordinate systems. However, the nonlinear dynamics of pneumatic actuators necessitate the development of advanced control strategies to achieve precise position control and rapid responses, especially in demanding robotic applications.

The control of pneumatic systems, particularly the challenges posed by friction and the nonlinear dynamics of pneumatic cylinders due to air compressibility, has been a subject of extensive research since the 1990s. Numerous studies have explored various control strategies and modelling techniques to address these complexities.

Early researches focused on overcoming the nonlinear control problem through traditional methods such as PID control. However, the inherent nonlinearities of pneumatic systems, coupled with varying pressures and masses necessitated approaches that are more sophisticated. Pandian et al. introduced sliding mode control (SMC) as a potential solution, demonstrating its effectiveness in handling these challenges [1].

Subsequent studies explored other control techniques and modelling approaches. Van Varseveld and Bone proposed a hybrid approach combining PID control with pulse width modulation (PWM) to address nonlinearity and friction [2]. Andrighetto et al. conducted a comparative analysis of different controllers, including P, PI, PID and SPC-100 highlighting the trade-offs between performance and complexity [3].

Research that is more recent has delved deeper into the underlying dynamics of pneumatic systems. Bone and Ning investigated the impact of reference wave frequency, mass and linear versus nonlinear SMC on actuator movement [4]. Ali et al. provided a comprehensive overview of pneumatic actuator modelling and control, emphasizing the role of SMC and other modern techniques like fuzzy logic and adaptive control [5].

Friction, a significant source of nonlinearity in pneumatic systems, has been a focal point of several studies. Ismalia et al. explored friction modelling and compensation using artificial intelligence, demonstrating its effectiveness in improving position control [6]. Tran and Yanada investigated the dynamic friction behaviour of pneumatic actuators, using the LuGre model to characterize friction characteristics [7].

As research has progressed, there has been a growing emphasis on developing more accurate and robust control models. Saravanakumar et al. reviewed recent studies on position control, highlighting the importance of considering friction effects, air compressibility and mass flow conditions [8]. Mansour et al. experimentally evaluated a fuzzy logic-based control system for pneumatic positioning, demonstrating its effectiveness in achieving accurate control [9].

More advanced control techniques have also been explored. Ramezani and Baghestan proposed a nonlinear precise servo control method based on observer models, combining sliding mode control with output prediction [10]. Jamian et al. conducted a comparative analysis of various control algorithms, including P, PI, PD, PID, SMC and adaptive control highlighting the strengths and weaknesses of each approach [11].

In recent years, there has been a focus on improving existing control techniques. Azahar et al. enhanced SMC algorithms by integrating fuzzy logic and self-tuning modifications [12]. Dağdelen and Sarıgeçili estimated friction parameters using simple experimental methods [13]. Gyeviki et al. conducted experimental studies on a double-acting piston, demonstrating the effectiveness of SMC in controlling its movement [14].

In conclusion, the field of pneumatic system control has made significant advancements in recent years. While traditional methods like PID control have been widely used, more sophisticated techniques such as SMC, fuzzy logic, and adaptive control have emerged as promising solutions. The ongoing research efforts to address the challenges of friction, nonlinear dynamics and modelling are essential for improving the performance and reliability of pneumatic systems in various applications.

This study delves into the intricacies of pneumatic actuator control with a particular emphasis on position control, control algorithms, and the mechanical properties of actuators. To facilitate the widespread adoption of pneumatic actuators in repetitive and industrial applications, a comprehensive understanding of the underlying physics of these systems is imperative. Existing research suggest that PID and SMC algorithms offer both simplicity and effectiveness for controlling pneumatic actuators and their performance can be further enhanced through the integration of additional control techniques.

The study primarily focuses on PID and SMC control models, augmented with PWM to improve position control accuracy. A dedicated test setup has been constructed, comprising a piston, a linear scale, control valves, a pressure source, a rail-slider mechanism for mass adjustment, an Arduino-based control board, and other essential electronic and mechanical components. Evaluations have been conducted at specific positions, including zero, maximum length reference and during continuous movement within the piston's operational range. The effectiveness of proposed control strategies has been assessed based on accuracy, speed, overshoot, and oscillations presence.

The experimental setup utilizes a compressor to supply a constant pressure of 2 bar to a pneumatic cylinder with specific dimensions: a piston diameter of 40 mm, a rod diameter of 16 mm, and a stroke length of 300 mm. This configuration is designed to linearly move a predetermined mass. Measurements have been collected from this setup and the real-world data have been used to evaluate the performance of different control strategies. Additionally, a simulation model has been developed based on the experimental results, incorporating certain assumptions to ensure a high degree of similarity between the two platforms.

All proposed control strategies have been tested on both the experimental and simulation platforms. The TOPSIS method has been employed to rank the performance of these strategies, considering at least two possible control design scenarios. The procedures outlined in this study provide valuable insights into the design of effective pneumatic position controllers.

2. Modelling and Controlling of Pneumatic Systems

Pneumatic cylinders are structures that consist of one or two pressure chambers and move according to the pressure forces generated within these chambers. Before controlling a system, it is essential to understand and recognize its physical structure. The pneumatic power control model is difficult to control and critical for position control. To better understand this control model and the parameters that ensure the effectiveness of control strategies, the mathematical model of the system is a useful tool. These cylinders have two pressure chambers and work done by actuators is provided by the difference in areas, flow rates, and pressure values. The equation of motion for this type of cylinder and mass configuration has been given in equation 1.

$$M\ddot{x} + B\dot{x} + F_s = (P_1A_1 - P_2A_2) \qquad (1)$$

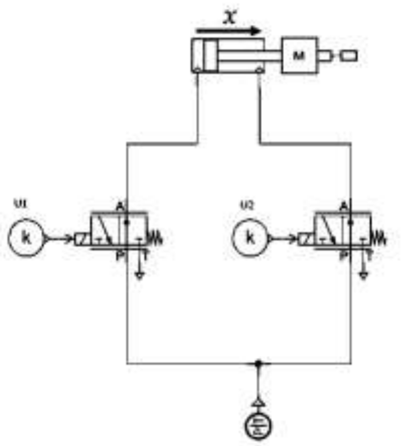


Figure 1. *An example of a pneumatic circuit diagram with a double-acting cylinder.*

State variables are position, velocity, and pressures. State equations can be derived as in equation 2 by the flow rate expression in the controlled volume bounded by the internal volume on the left side of the piston, along with the pressure, temperature, density expressions, and discharge coefficients.

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \end{bmatrix} = \begin{bmatrix} x_2 \\ v \\ \frac{\gamma}{x_{10}-x_1}\left[x_2x_3 + \left(\frac{R\,T}{A_1}\frac{C_d}{\sqrt{T}}\,\alpha\right)C_{m_1}x_3(u)\right] \\ \frac{\gamma}{x_{20}-x_1}\left[x_2x_4 + \left(\frac{R\,T}{A_2}\frac{C_d}{\sqrt{T}}\,\alpha\right)C_{m_2}x_4(u)\right] \end{bmatrix} \quad (2)$$

First two state equations that describe the mechanical system are linear ($\dot{x}_1\ and\ \dot{x}_2$). The other two state equations ($\dot{x}_3\ and\ \dot{x}_4$) are nonlinear and unstable due to the compressible nature of the air.

In many applications, mechanical friction is mathematically expressed as F_R in equation 3 with the stick (F_{stick}), Stribeck velocity effect($F_{stribeck}$), that is about a speed threshold, Coulomb ($F_{coulomb}$) and viscous friction effects ($F_{viscous}$).

$$F_R = sgn(\dot{x})F_c\left[1 + \left(\frac{F_{st}}{F_c} - 1\right)e^{-\left(\left|\frac{\dot{x}}{\dot{x}_s}\right|\right)^{\delta}}\right] + B\dot{x} \qquad (3)$$

For the control of a double-acting pneumatic cylinder using a model with two identical 3/2 on-off valves, it is necessary to adopt algorithms that can perform binary control. The system can be controlled by two basic signals denoted as (u_1, u_2) as illustrated in Fig. 1. Due to the compressibility of air, the effect of mass inertia, and stick-slip friction such a sharp control model will not be feasible. Therefore, the definition of a dead zone is necessary. By accepting values that are within a "Δ" amount less than and greater than the reference value oscillations around the reference can be prevented. The signal model that will trigger the signals becomes as:

$$f(x,u) = \begin{cases} u_1 = 1 \quad and \quad u_2 = 0 & , x < x_{ref} + \Delta \\ u_1 = 0 \quad and \quad u_2 = 0 & , x_{ref} - \Delta \le x \le x_{ref} + \Delta \\ u_1 = 0 \quad and \quad u_2 = 1 & , x_{ref} - \Delta < x \end{cases} \qquad (4)$$

The mathematical model in equation 2 is quite complex to model and solve. To address this, standard PID and Sliding Mode Control (SMC) are proposed for their applicability and Pulse Width Modulation (PWM) can be applied to improve the control models.

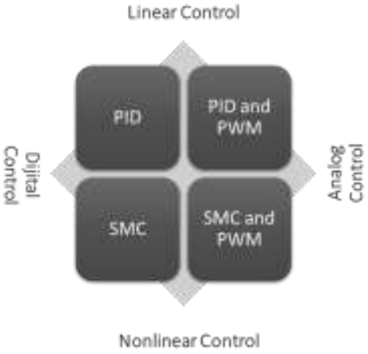


Figure 2. *Control models method and characteristic evaluation cartesian plane.*

In the evaluation of pneumatic position control strategies, two main axes can be considered as shown in Fig. 2; control method and control characteristic. From the perspective of the control method, strategies can be classified as digital or analog. Digital control strategies include PID and SMC methods, where control signals are generated through numerical computations and implemented by digital controllers. Analog control strategies, on the other hand, involve PWM to convert control signals into analog signals and are implemented by analog controllers, including PWM-supported PID (PID_PWM) and PWM-supported SMC (SMC_PWM) methods.

Regarding control characteristics, strategies can be divided into linear and nonlinear. Linear control strategies include PID and PWM_PID methods that generate a linear control signal based on the error signal, while nonlinear control strategies include SMC and PWM_SMC methods that generate control signals based on the nonlinear characteristics of system dynamics. In the general Cartesian plane, digital and linear control strategy PID is placed upper left quadrant, analog and linear control strategy PID_PWM is placed upper right quadrant, digital and nonlinear SMC is placed lower left quadrant and analog and nonlinear SMC_PWM is placed in the lower right quadrant as shown as Fig. 2. Visualization on Fig. 2 also clarifies determination of control strategies and provide better vision to discuss control strategies' advantages and disadvantages. Fig. 3 shows examples of control structure I simulations. In each model controller block has a different type of control approach used as a block and all approaches are described below.

2.1 PID Control Algorithm

The PID Control Algorithm is the most common control approach for many applications. Fig. 4 shows a block diagram for the PID control strategy with a dead band block to have two signals for two identical control valves.

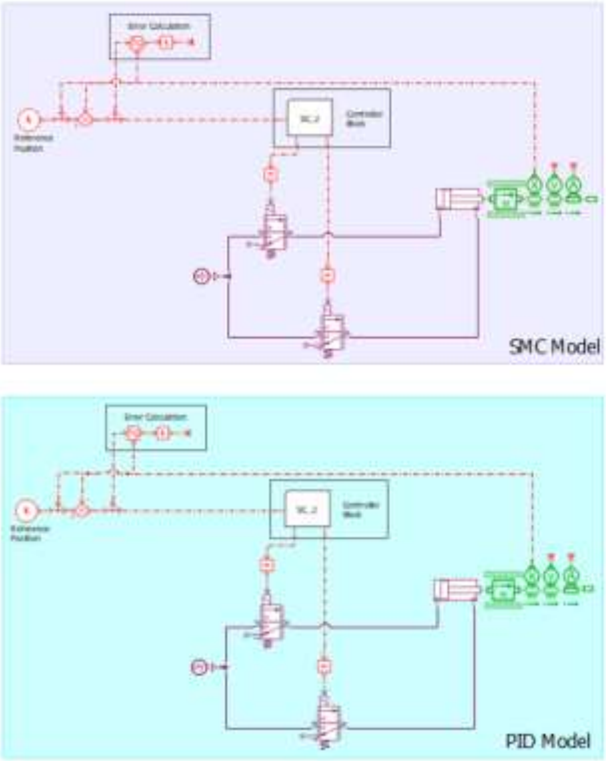


Figure 3. *Simulation models with different control strategies in same structure.*

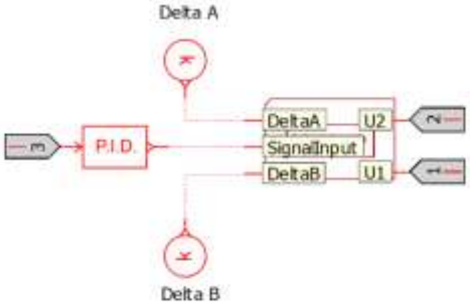


Figure 4. *PID and dead zone definition control block.*

The feedback signal fed by port number 3 is stated as u and the output from "PID Block" is stated as U* given equation 5 shows the mathematical model of the PID control block.

$$U^* = Kp.u + Ki\int_{t_{tstart}}^{t} u.dt + Kd.\frac{du}{dt} \qquad (5)$$

2.2 SMC Control Algorithm

Linearization simplifies system analysis in engineering by approximating the system's response with acceptable errors. As Khalil mentioned according to Lyapunov, this is possible around an equilibrium point where energy dissipates [15]. In control, a linear differential equation based on the system's error is used, representing a line, plane, or space. SMC reduces error by bringing it and its derivative close to the origin along a sliding surface. For pneumatic cylinder position control, the error and its derivative are multiplied by "K_p" and "K_v" respectively, and their sum is fed into a dead zone block. The sliding surface described in equation 6 and the controller block with SMC model shown in Fig. 5.

$$S_s = Kp.e + Kv.\frac{de}{dt} = K_p e + K_v \dot{e} \qquad (6)$$

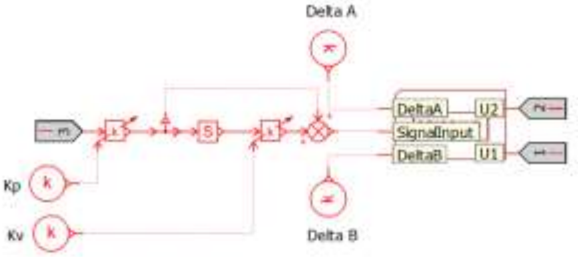


Figure 5. *SMC and dead zone definition control block.*

2.3 PID_PWM Control Algorithm

Almost every natural system has analog input-output characteristics, requiring a transition between analog and digital formats for effective control. This challenge arises in systems like pneumatic cylinder positioning, where digital signals from on-off valves must mimic analog behavior. PWM achieves this by integrating digital signal frequency and duty cycle, producing an analog-like output. For nonlinear systems, PID control can still be applied, but PWM adapts the digital signal into an analog form, based on the error-to-reference ratio. The error, less than "1" when the piston is behind or ahead of the reference, adjusts the PWM duty cycle. Additionally, operating frequency, tied to system components, plays a critical role. By integrating PWM with PID, analog control precision and system performance can be improved across various references. he described control model's block diagram is given in Fig. 6 and the error percentage calculation is given in equation 7.

$$\left|\frac{Error}{Reference}\right| = \left|\frac{Reference - Real\ Position}{Reference} \leq 1\right| \qquad (7)$$

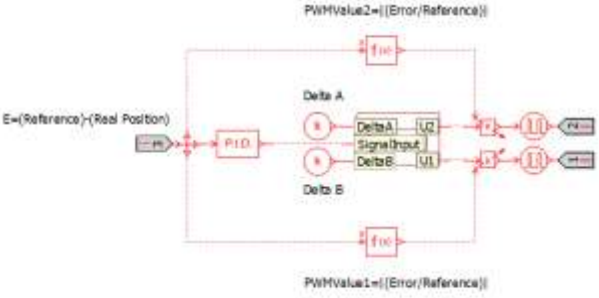


Figure 6. *PWM-Supported PID control and dead zone definition control block.*

2.4 SMC_PWM Control Algorithm

The application of SMC for nonlinear systems has been enhanced with PWM to improve accuracy, stability, and control efficiency. While valve actuation decisions are still based on SMC, the PWM signal determines the valve's triggering time using the error ratio. In the model shown in Fig. 7, control starts with the error input, and the SMC signal is used to evaluate the dead zone, defining the valves' open/closed status. The PWM widths, based on the error ratio, set the valve open time according to system frequency, allowing direct control of the flow rate to move the mass.

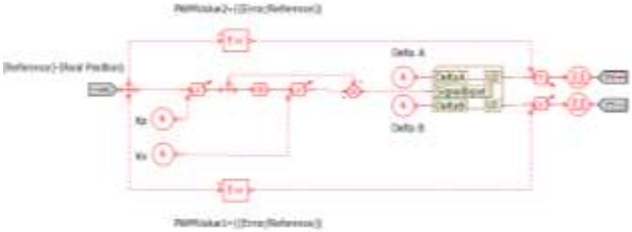


Figure 7. *PWM-Supported SMC and dead zone definition control block.*

2.5 Comparison Criteria for Control Algorithms

For the pneumatic cylinder system, which includes linear motion, friction-affected mass, pneumatic valves, and control models, performance evaluation is based on key criteria. The primary criterion is response time, targeted to be under 2 seconds, with piston speeds ranging from 50 to 200 mm/s. An acceptable error is up to 0.5 mm. Oscillations and overshoots are also considered, with no oscillations preferred, and overshoots limited to 1% of the reference value. The criteria are as follows:

1. Response time under 2 seconds,
2. Steady-state error up to 0.5 mm,
3. No oscillations, with overshoot not exceeding 1%.

These criteria will be used to rank control methods, with weights assigned based on two scenarios:

- **Safety prioritized**: 40% for steady-state error (mm), 15% for steady-state error (%), 10% for settling time, and 35% for overshoot.
- **Speed prioritized**: 40% for steady-state error (mm), 15% for steady-state error (%), 40% for settling time, and 5% for overshoot.

The methods will be ranked using the TOPSIS method [16], a multi-criteria decision-making approach that ranks alternatives based on their proximity to an ideal solution. This structured process ensures objective evaluation and selection of the best control method based on the defined criteria.

3. Simulation Studies and Parameter Impacts

AMESim (Advanced Modeling Environment for performing Simulations) is a powerful software used for simulating fluid power systems, particularly pneumatic components. Bideaux and Scavarda developed a comprehensive pneumatic library for AMESim, which includes basic elements and advanced models, enabling the simulation of various pneumatic systems [17]. Studies like Li et al. and Wang et al. highlighted its use in designing complex systems, such as an ultrahigh internal pressure booster cylinder and an Intelligent Air Transfer System [18, 19]. AMESim has also been applied to control system design, as demonstrated by Li et al. in their work on a pneumatic manipulator, showing the software's versatility in modeling and optimizing pneumatic systems for improved performance across industrial applications [20].

In industrial design, initial assumptions and simulations are essential for evaluating approaches before final designs. 1-D simulation programs like AMESim, based on Modelica, help compare models to real test setups, providing high accuracy in a short time. The program uses pneumatic, linear 1D mechanical, and control libraries, employing iteration techniques for real-time simulations. For pneumatic cylinder position control, the system must be divided into units for efficient simulation and design. Table 1 shows thesimulation parameters of the pneumatic and mechanical model designed by AMEsim.

Table 1. *Pneumatic and Mechanical Model Simulation Parameters*

Parameters	**Value**
Piston Diameter	40 mm
Piston Rod Diameter	16 mm
Piston Stroke Length	300 mm
Valve 1 Nominal Orifice Area	3.2 mm²
Valve 1 Cv	0.18
Moving Mass	7.34 kg
Estimated Viscous Friction	80 N/(m/s)
Estimated Stick-Slip Friction	65 N
Estimated Coulomb Friction	60 N
Pressure Source	2 bar
Piston Tilt Angle	0°

All control strategies have been tried and fine tunning has been done regarding the following considerations:

- No overshoot.
- Reaching a steady-state within 1.5 seconds.
- Steady-state error of less than 0.5 mm.

For all control strategies fine-tuned control parameters are given in Fig. 8.

Name	Title	Value	Unit	Default	Minimum	Maximum
SMC_PWM						
Kp_PWM	Kp_PWM	0.065	-	0.065	0	5
Kv_PWM	Kv_PWM	0.012	-	0.012	0	5
SMC						
Kp	Kp	0.065	-	0.065	0	5
Kv	Kv	0.02	-	0.02	0	5
PID_PWM						
Derivative_PWM	Derivative_PWM	0.01	-	0.01	0	5
Integral_PWM	Integral_PWM	0.001	-	0.001	0	5
Proportion_PWM	Proportion_PWM	0.08	-	0.08	0	5
PID						
Derivative	Derivative	0.01	-	0.01	0	5
Integral	Integral	0.001	-	0.001	0	5
Proportion	Proportion	0.085	-	0.085	0	5
Delta	Delta	0.5	mm	0.5	0	1
Frequency	Frequency	50	Hz	50	0	50
M	Mass	7.5	kg	7.5	1	15
P	P	2	bar	2	1.2	8
Ref_Position	Ref_Position	150	mm	150	0	300
ViscousFrictionCoefficient	ViscousFrictionC...	80	N/(m/s)	80	0	250

Figure 8. *Adjusted parameters for the simulation model with simultaneous operation of different control strategies.*

After all models have been tuned and tried some of the system parameters have been tested in a range of given in Fig. 8. Results and impact of system parameters can be abstracted as below respectively:

a. **Effect of Pressure**: Increasing supply pressure boosts system speed, but pressures above 4 bars lead to overshoot, even when parameters are adjusted.

b. **Effect of Mass**: Heavier masses increase inertia, leading to higher steady-state errors. Lighter masses cause errors behind the reference, while heavier ones result in errors beyond the reference.

c. **Effect of Viscous Friction**: Higher friction forces slow the system but cause smaller steady-state errors compared to other parameters. Increased friction also causes positioning above the reference due to asymmetry in the cylinder.

d. **Effect of Frequency**: Frequencies above 10 Hz do not affect system performance because the valves cannot respond. Frequencies below 5 Hz prevent the system from reaching the reference in 5 seconds, with the optimal range being 10-15 Hz.

e. **Effect of Valves**: Valve flow rate significantly affects control. A smaller valve (3.2 mm² orifice) maintained stability, while a larger valve (10.2 mm² orifice) caused erratic behavior under the same control settings.

4. Experimental Setup and Results

To ensure a realistic comparison of control strategies, the study emphasizes the need for an experimental setup using industrial products, as simulations and mathematical models often involve assumptions and linearization that may lead to discrepancies with real-world results. The experimental setup includes a piston, linear position measurement ruler, two 3/2 valves, a slider with measurable mass, pneumatic pressure transducers, a compressed air regulator, a compressor, and a sturdy construction to handle oscillations. Control and measurement are handled using an Arduino Giga R1 with a dual relay board and 24 VDC power supply. The components are shown in Fig. 9, they also have been listed in Table 2. For all control strategies, 100 mm, 150 mm and 200 mm references have been tested at 2 bar pressure and with 0.5 mm position tolerance. All experiments started with a fully closed position and movement applied just in the positive direction, which is piston to rod direction. Position control tests showed that steady-state conditions are reached within 2 to 5 seconds, with each test lasting 5 seconds. The experimental setup uses Arduino, and the code is written in the Arduino IDE to support user data input and create .csv files via USB for each control method. The process begins when a USB drive is inserted, prompting for reference values, tolerance, and control parameters (K_p, K_i, K_d, or K_p and K_d). A "homing" algorithm then sets the initial cylinder position, and the system runs for 5 seconds after receiving the "start" command, operating the valves according to the control method.

Table 2. *Components used in setup*

Product	Specification
Pneumatic Cylinder	40 mm piston diameter, 16 mm rod diameter, and 300 mm stroke length DNC40-300 pneumatic cylinder.
Linear Measurement Scale	OPKON RTL-300, 50 KOhm potentiometer scale.
Valves	WAIRCOM ULCSV/R 02400B 3/2 Valve 1/8”, Pmax 10 bar, 24VDC, up to 15Hz 3.2 mm² (Cv=0.18)
Control Board	ARDUINO GIGA R1, 16-bit ADC, 3.3 V, STM32H747XI 32-bit microcontroller, 480 MHz
Power Supply	Phoenix Contact STEP-PS/ 1AC/24DC/4.2 (220VAC-24VDC)
Moving Mass	A chamber to add a mass is attached, Double rail and carriage (HGW25CC) linear bearing and rail mechanism.

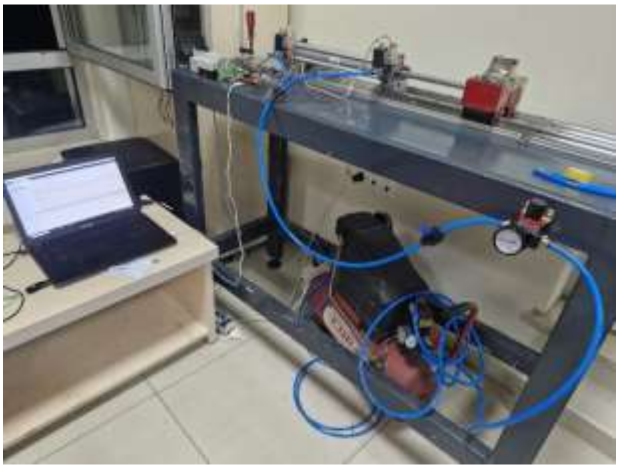


Figure 9. *The experimental setup.*

Experiments have been conducted for different references 100, 150, and 200 mm respectively, results have given in Table 3-5, respectively.

4.1 Comparison of Experimental and Simulation Results

Steady-State error results for different references and control methods applied in experimental studies have been presented. These results reflect the actual behaviour of the pneumatic cylinder system and its control system, while also providing insights into the validation of the simulation model. Using the 1-D simulation model in AMESim, the experimental parameters have been tested. Through trial and error, the viscous damping coefficient generating friction force has been estimated at 65 N/(m/s), and Coulomb friction has been estimated at 75 N. The ratio of Coulomb friction to stiction force has been determined to be 0.95. After identifying these friction values in the simulation, the system's response to various strategies has been compared with the experimental results using gain coefficients from the experimental method. Despite no radical differences between experimental and simulation results, discrepancies in the speed of mass, particularly in Fig. 10, suggest that the friction estimations need further refinement. For instance, oscillations in the simulation for 150 mm and in experimental results for 100 mm highlight issues with model validation.

Table 3. *Evaluation of control methods according to control criteria for a 100 mm reference.*

Control Method	Steady State Value (mm)	Steady State Error (%)	Settling Time (s)	Overshoot (%)
SMC	99.82	+0.18	1.391	0.84
PID	100.77	-0.8	1.129	1.9
SMC_ PWM	100.9	-0.5	1.053	1.84
PID_ PWM	99.64	+0.37	0.901	1.47

Table 4. *Evaluation of control methods according to control criteria for a 150 mm reference.*

Control Method	Steady State Value (mm)	Steady State Error (%)	Settling Time (s)	Overshoot (%)
SMC	149.811	-0.13	1.012	0.58
PID	150.179	+0.12	1.113	2.214
SMC_ PWM	149.357	-0.57	1.473	1.37
PID_ PWM	150.23	-0.15	1.092	0.99

Table 5. *Evaluation of control methods according to control criteria for a 200 mm reference.*

Control Method	Steady State Value (mm)	Steady State Error (%)	Settling Time (s)	Overshoot (%)
SMC	199.574	+0.21	1.488	0.34
PID	198.506	+0.75	1.218	0.1
SMC_ PWM	199.164	+0.42	1.349	0.41
PID_ PWM	200.267	-0.14	1.485	1.77

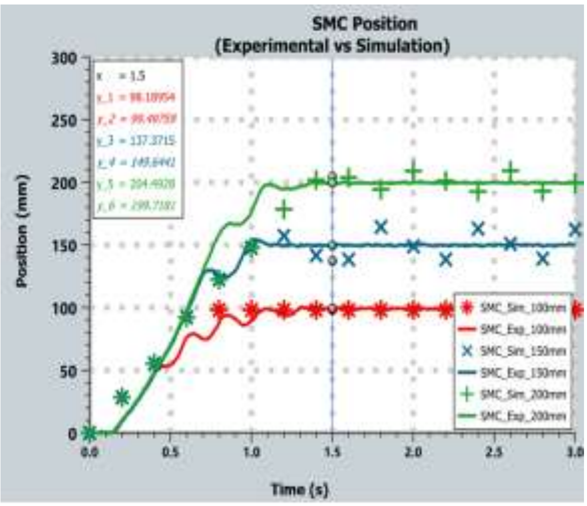


Figure 10. *SMC Model experimental and simulation study comparison.*

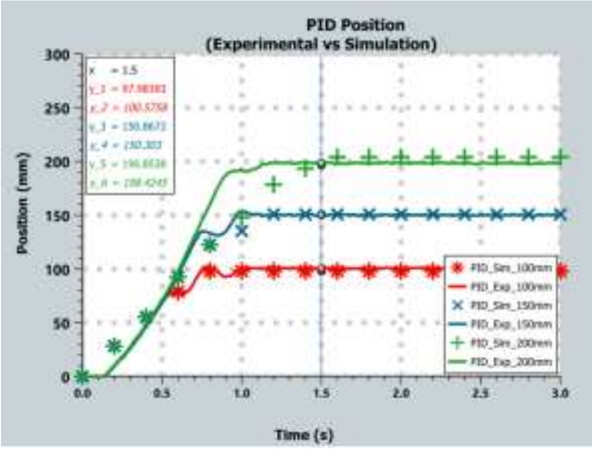


Figure 11. *PID Model experimental and simulation study comparison.*

In Fig. 11, the speed discrepancy is less apparent, but the differences in SSE for other references remain significant. Nonetheless, the graph trends between the two models are close, implying that the control parameters may not hold the same validity across both simulation and experimental planes. Friction characteristics, chamber pressure monitoring, and other control/measurement systems are recommended for future experiments to improve validation.

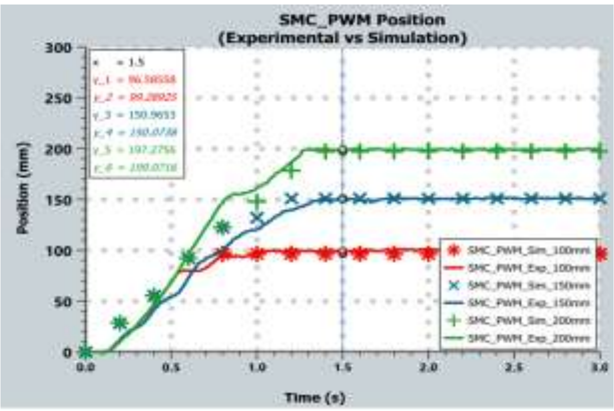


Figure 12. *SMC_PWM Model experimental and simulation study comparison.*

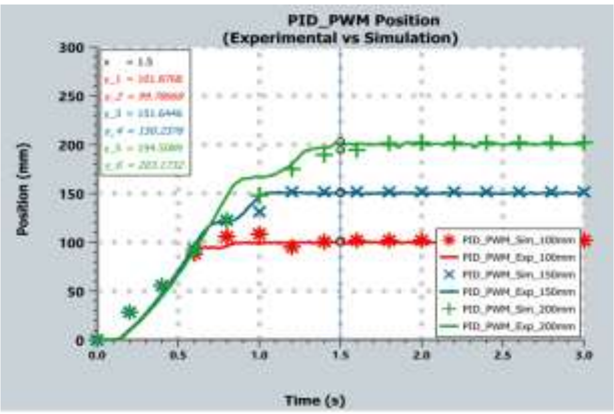


Figure 13. *PID_PWM Model experimental and simulation study comparison.*

Figures 12 and 13 underline the importance of frequency as a control parameter for SMC_PWM and PID_PWM models. Both system and control frequencies need to be specified clearly. While the overall similarity between experimental and simulation results is high, differences in actual values affect reliability. In conclusion, a thorough comparison of the discrepancies between these methods, particularly in terms of friction estimations, is crucial for developing a validated virtual model.

5. Conclusion

This study evaluates control strategies for the position control of a pneumatic cylinder, focusing on both performance and comparative effectiveness. Using the TOPSIS method, each strategy has been scored for safety and speed across different position references, with results detailed in Tables 6 and 7. The Sliding Mode Control (SMC) model consistently outperformed other methods, particularly under safety prioritization, where its lack of overshoot proved advantageous. In speed-prioritized scenarios, SMC also excelled, with PID_PWM emerging as a strong alternative, although SMC_PWM and PID underperformed in both cases.

Table 6. *TOPSIS Score table for Safety Prioritization for experimental data.*

Control Method	**100 mm**	**150 mm**	**200 mm**	**Average**
SMC	93	98	86	92.3
PID	15	83	67	55
SMC_PWM	15	58	52	41.67
PID_PWM	67	26	48	47

Table 7. *TOPSIS Score table for Speed Prioritization for experimental data.*

Control Method	**100 mm**	**150 mm**	**200 mm**	**Average**
SMC	74	98	83	85
PID	23	89	17	43
SMC_PWM	24	05	54	27.67
PID_PWM	76	89	83	82.67

The SMC model consistently outperformed other strategies, especially in the safety scenario, where its lack of overshoot played a significant role. While other models varied in performance across references, overshoot negatively impacted their scores under the safety criteria. In the speed-prioritized scenario, the SMC model again excelled, with the PID_PWM strategy following closely behind, indicating both strategies' effectiveness for speed. However, SMC_PWM and PID performed poorly in both cases.

The findings suggest that while the SMC strategy is the most effective overall, a hybrid approach could provide greater versatility for high-precision industrial applications. Hybrid control strategies, such as those incorporating fuzzy logic, may offer improvements in accuracy and repeatability.

The research involved both experimental and theoretical analysis of four control methods. A 1-D simulation model was developed to guide the experimental design, and the TOPSIS method, with weighted criteria, was used for evaluation. The experimental setup validated the simulation model, though differences arose due to system uncertainties. Despite these, the convergence of results underscores the robustness of the SMC strategy.

The study highlights the potential for new approaches to pneumatic position control, particularly through modern and hybrid control methods. It also emphasizes the role of friction force feedback in optimizing pneumatic systems. Future research could explore the development of control strategies that bridge position and force control, particularly for nonlinear systems. The experimental setup developed serves as a useful prototype for moderate-speed, moderate-force applications, offering a foundation for future exploration.

References

[1] Pandian, S. R., Hayakawa, Y., Kanazawa, Y., Kamoyama, Y., & Kawamura, S. (1997). Practical design of a sliding mode controller for pneumatic actuators. *Journal of Dynamic Systems Measurement and Control*, *119*(4), 666–674. https://doi.org/10.1115/1.2802376

[2] Van Varseveld, R., & Bone, G. (1997). Accurate position control of a pneumatic actuator using on/off solenoid valves. *IEEE/ASME Transactions on Mechatronics*, *2*(3), 195–204. https://doi.org/10.1109/3516.622972

[3] Andrighetto, P. L., Valdiero, A. C., & Vincensi, C. N. (2004). *Experimental Comparisons of The Control Solutions For Pneumatic Servo Actuators*. https://www.abcm.org.br/symposium-series/SSM_Vol1/Section_II_Control_Systems/SSM_II_29.pdf

[4] Bone, G. M., & Ning, S. (2007). Experimental comparison of position tracking control algorithms for pneumatic cylinder actuators. *IEEE/ASME Transactions on Mechatronics*, *12*(5), 557–561. https://doi.org/10.1109/tmech.2007.905718

[5] Ali, H. I., Noor, S. B. B. M., Bashi, S. M., & Marhaban, M. H. (2009). A review of Pneumatic Actuators (Modeling and Control). *Australian Journal of Basic and Applied Sciences*, *3*(2), 440–454.

[6] Ismaila, T., Akmeliawati, R., & Salami, M. J. E. (2011). Artificial intelligent based friction modelling and compensation in motion control system. In *InTech eBooks*. https://doi.org/10.5772/23432

[7] Tran, X. B., & Yanada, H. (2013). Dynamic friction behaviors of pneumatic cylinders. *Intelligent Control and Automation*, *04*(02), 180–190. https://doi.org/10.4236/ica.2013.42022

[8] Saravanakumar, D., Mohan,B., & Muthuramalingam, T. (2017). A review on recent research trends in servo pneumatic positioning systems. *Precision Engineering*, *49*, 481–492. https://doi.org/10.1016/j.precisioneng.2017.01.014

[9] Mansour, A., Hashim, W., & Muhammad, A. (2018). Design and implementation of a pneumatic servo system using conventional direction control valve. *Iraqi Journal of Computer Communication Control and System Engineering*, 1–11. https://doi.org/10.33103/uot.ijccce.18.3.1

[10] Ramezani, S., & Baghestan, K. (2018). Observer-based nonlinear precise control of pneumatic servo systems. *Proceedings of the Institution of Mechanical Engineers Part E Journal of Process Mechanical Engineering*, *233*(2), 165–176. https://doi.org/10.1177/0954408918756906

[11] Jamian, S., Salim, S. N. S., Kamarudin, M. N., Zainon, M., Mohamed, M. S. S., Abdullah, L., & Hanafiah, M. a. M. (2020). Review on controller design in pneumatic actuator drive system. *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, *18*(1), 332. https://doi.org/10.12928/telkomnika.v18i1.12626

[12] Azahar, M. I. P., Irawan, A., & Ismail, R. R. (2021). Self-tuning hybrid fuzzy sliding surface control for pneumatic servo system positioning. *Control Engineering Practice*, *113*, 104838. https://doi.org/10.1016/j.conengprac.2021.104838

[13] Dağdelen, M., & Sarigeçili, M. İ. (2020). Doğrusal pnömatik silindirlerin sürtünme parametrelerinin tahmini. *Mühendislik Bilimleri Ve Tasarım Dergisi*, *8*(2), 397–406. https://doi.org/10.21923/jesd.569339

[14] Gyeviki, J., Sárosi, J., Endr, T., Dy, Forgács, E., & Toman, P. (2010). LabVIEW based position control for a pneumatic cylinder, *Annals*, 25-32.

[15] Khalil, H. K. (2014). Nonlinear control. *Pearson.*

[16] Madanchian, M., & Taherdoost, H. (2023). A comprehensive guide to the TOPSIS method for multi-criteria decision making. *Sustainable Social Development*, *1*(1). https://doi.org/10.54517/ssd.v1i1.2220

[17] Bideaux, E., & Scavarda, S. (1998). *A Pneumatic Library for AMESim* (Vol. 15939). American Society of Mechanical Engineers. https://doi.org/10.1115/imece1998-0489

[18] Li, G., Xv, Y., Zhou, B., Xie, K., & Hua, W. (2018). *Structure of an ultrahigh internal pressure compound cylinder and its simulation by AMESim*. https://api.semanticscholar.org/CorpusID:139550506

[19] Wang, B., Wang, Y., Gao, L., Cao, H., Song, Q., & Shuang, F. (2014). *Pneumatic design for Intelligent Air Transfer System based on AMESim*. https://api.semanticscholar.org/CorpusID:13993135

[20] Li, J., Su, H., Liang, P., & Gao, X. (2017). The control system design and simulation analysis of pneumatic manipulator based on AMESim. *2017 IEEE International Conference on Unmanned Systems (ICUS)*. https://doi.org/10.1109/icus.2017.8278362