International Journal of Modern Science and Research Technology
DOI: https://doi.org/10.67317/IJMSRT26JUN131

Optimizing the Dynamic Response of Piezoelectric Pneumatic Servo Valve using Swarm Intelligent based Hybrid Control System

Engr. Ebisinimi Tekerebo; Dr. Bestman Tekenah; Engr.Omotayo Oshiga
.
Faculty Of Engineering,Department of Electrical/Electronics Engineering
Nile University Of Nigeria,
Faculty of Engineering, Department of Mechanical and Mechatronic Engineering,
Federal University Otuoke, Bayelsa State, Nigeria

Abstract:
This paper introduces a swarm-intelligence-based hybrid control system designed to optimize the dynamic response of piezoelectric pneumatic servo valves. While piezoelectric actuators offer high force-to-weight ratios and fast responses, their severe inherent nonlinearities—such as hysteresis, creep, and temperature drift—compromise tracking accuracy and transient performance. To resolve this, the proposed hybrid architecture combines the robust transient response of conventional control with the adaptive capabilities of intelligent algorithms. The controller's parameters are systematically optimized using Particle Swarm Optimization (PSO) to minimize overshoot, settling time, and tracking errors. Validated through a mathematical model incorporating fluid dynamics and asymmetric hysteresis, numerical simulations and experiments demonstrate that this scheme successfully suppresses hysteresis-induced oscillations, accelerates response times, and cuts steady-state errors under diverse loads. Ultimately, this approach provides a scalable, highly robust solution for high-precision, high-speed pneumatic automation.

Keywords: Piezoelectric actuator, Pneumatic servo valve, Swarm intelligence, Hybrid control system, Hysteresis compensation, Dynamic response optimization.

1.Background of the Study

Pneumatic servo systems utilize compressed air as a clean, safe and inexpensive medium for the transmission of energy and signals to power tools and position-control actuators. These systems are widely used in robotics, precision molding, automotive braking and conveyors and are vital for automated production.

There are some clear advantages of pneumatic actuators against other technologies. Hydraulic systems are great for speed and force, but they do come with workplace hazards like fluid leaks. Electric actuators are clean, but need complex mechanical transmissions to convert high speed rotary motion into useful linear force. Pneumatics, however, combine the direct-load capabilities of hydraulics with the cleanliness of electric systems. Because air is nonmagnetic, generates little heat, and eliminates electrical sparking, pneumatics greatly reduces explosion hazards in dangerous environments such as coal mines. However, pneumatic systems have their own limitations because of the compressibility of air, which makes it difficult to achieve accurate positioning. Traditionally, aerodynamic control valves are driven with electromagnetic actuators, which have slow response, are bulky and sensitive to electromagnetic noise .

In order to overcome these dynamic limitations and achieve accurate high-speed industrial positioning, the researchers are continuously improving the control methods. Single approach methods are popular such as classical PID feedback linearization, adaptive control and intelligent algorithms. This paper proposes a hybrid control system. A hybrid approach and a swarm intelligent algorithm are combined to significantly optimize the dynamic response and the reliability of a piezoelectric pneumatic servo valve.

2.Problem Statement

Industrial systems based on pneumatic servo valves have the problems of slow response and poor positioning accuracy. This problem can be solved by high speed and high resolution piezoelectric actuators. The main challenge is to reduce the difference between the real and the desired positions to improve the accuracy maintaining the optimum transient response and the energy transfer efficiency. However, classical single-loop control methods can not always guarantee the stability and robustness in practice. Moreover, even if the desirable performance is achieved, the systems are still subject to integral windup and intrinsic nonlinearities, which require more advanced multi-loop control strategies for safe industrial operation.

3.Aim and Objectives of the Study

This paper presents a hybrid control system based on swarm intelligence for the optimization of the dynamic response of a piezoelectric pneumatic servo valve.

The specific objectives are:
* Model the servo valve mathematically;
* Design conventional PID (tuned by ITAE) and LQR optimal controllers;
* Design a PID controller using swarm intelligence;
* Design the hybrid controller by combining the swarm intelligent PID and LQR controllers; and
* Evaluate and benchmark performance on MATLAB/Simulink with key parameters such as rise time, settling time, overshoot, steady state error.

4.Scope of the Study

There are several servo valves, but one of interest in this work is the piezoelectric pneumatic servo valve. This mainly concerned with the development of hybrid controllers to improve the dynamic response performance of piezoelectric pneumatic servo valve. The system will be modelled and evaluated in MATLAB/Simulink environment.

5.Rationale of the Study

It is assumed that each servo valve operates off some form of energy conversion technique to achieve desired positioning control in each application. Hybrid control techniques will give fast output positioning response with controllable dynamics. This will bring the new and reliable design of servo valve of positioning control application. Hence, with the use of intelligent algorithm in the hybrid control technique based multi-loop strategy, a more stable system is guaranteed. The hybrid control system has the advantages of better reliability or safety, better robustness and better stability than the single-loop control.

6.Review of related literature

6.1 Overview of Actuators

An actuator converts energy (air, electricity, or liquid) into mechanical motion for industrial tasks like clamping or pumping. Pneumatic actuators are the most common, utilizing compressed air to drive a piston. Alongside electrical and hydraulic alternatives, they are widely used in manufacturing, assembly, and robotics for fast, precise movement.

6.2 Pneumatic Servo Systems

Pneumatic systems drive industrial automation by converting compressed air into mechanical motion. Offering low-cost, high power-to-weight ratios, and easy speed regulation, they safely operate across wide temperatures without explosion risks. Because they utilize freely available, clean air that exhausts directly into the atmosphere, they are ideal for long-distance transport and sterile environments.

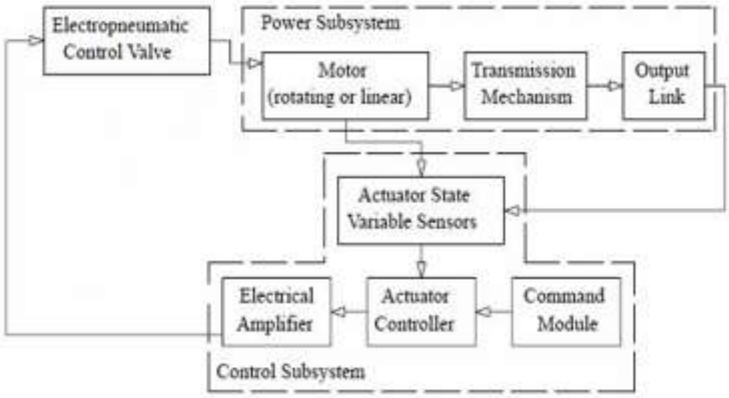


Figure 1: Pneumatic servo system block diagram (Krivts & Krejnin, 2006)

Pneumatic servomechanisms rely on key subsystems: feedback sensors (like LVDTs) track motion variables, command modules store trajectories, and a controller—typically an optimized PID algorithm—processes data through an amplifier. The system interfaces with the power unit via electro-pneumatic control valves. High-cost servo valves offer excellent closed-loop precision, proportional valves provide proportional spool movement, and affordable solenoid valves use PWM to drive applications in automated positioning, speed, and force control.

6.3 Pneumatic Position Control Systems

Industrial positioning systems are popular due to their high force-weight ratio, ease of assembly, cleanliness, and low cost. Categorized into open-loop and closed-loop types, these pneumatic servo systems drive a broad and growing area of automation research.

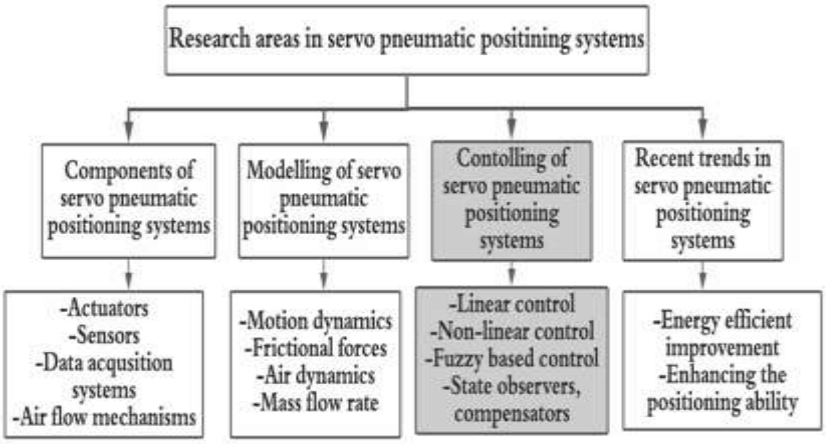


Figure 2: Research areas in pneumatic servo control systems)
(Saravanakumar et al., 2017)

6.4 Open-loop Positioning System

Open-loop pneumatic positioning systems use adjustable hard stops to switch between two positions. Piston movement is detected by proximity sensors, where a magnetic field trips a switch to send electrical feedback signals to the control system.

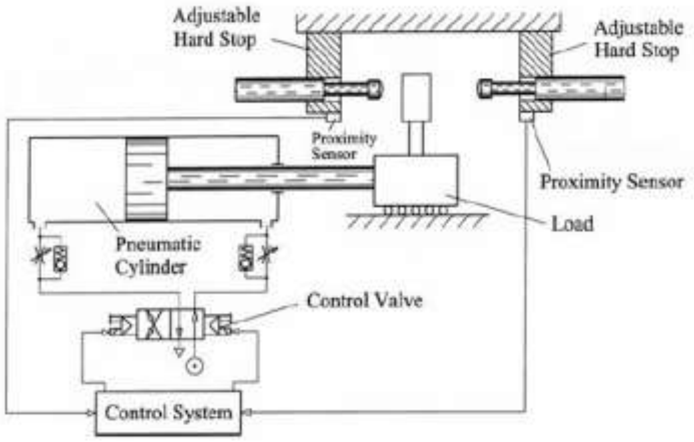


Figure 3: An open-loop pneumatic position control system (Krivts & Krejnin, 2006)

6.5 Closed-loop Positioning System

In closed-loop pneumatic control, a transducer measures the actuator's output and sends a feedback signal to the controller. The controller compares this to the setpoint, generating a control signal that regulates the valve. As the piston approaches its destination, the valve adjusts airflow and volume within the cylinder, creating an opposing pressure that precisely modulates movement to ensure highly accurate, robust positioning without relying on mechanical hard stops.

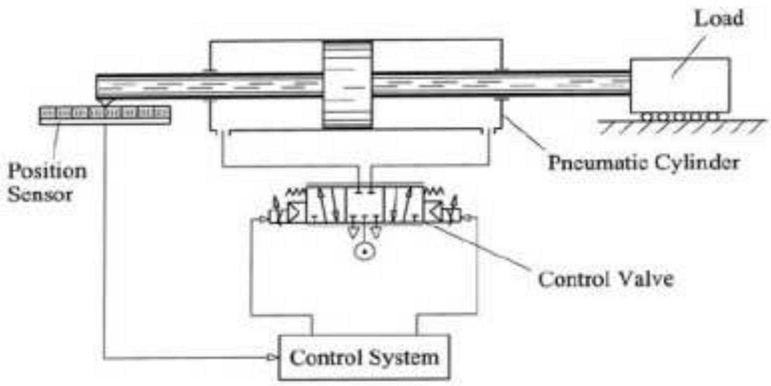


Figure 4: Closed-loop positioning system with pneumatic actuator
(Krivts & Krejnin, 2006)

6.6 Piezoelectric Technology

Piezoelectric actuators use the inverse piezoelectric effect to convert electrical energy into mechanical motion. Integrating them into servo valves creates "piezo valves," which eliminate complex torque motors, lower costs, and expand bandwidth into the kilohertz range. This technology resolves conventional valve issues like contamination sensitivity, high quiescent flow, pilot-stage cavitation, and heavy components.

While highly durable, these actuators face performance limitations due to temperature sensitivity, hysteresis, and creep, which can degrade positioning accuracy. Overcoming these nonlinearities requires robust closed-loop control schemes. Commercially available models require 100V to 250V amplifiers, producing an actuation force that decreases linearly with displacement
.

$F_a = F_b - k_p x = k_{VF} V_a - k_p x$ ---(1.0)
where F_a, F_b, k_p, V_a, k_{VF}, and x are: the actuation force, blocking force, stiffness of the actuator, amplifier (applied) voltage, force/voltage coefficient, and the displacement.

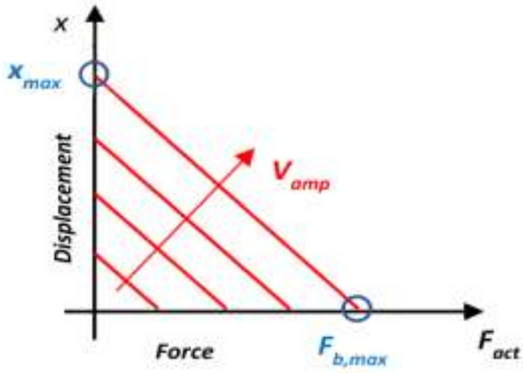
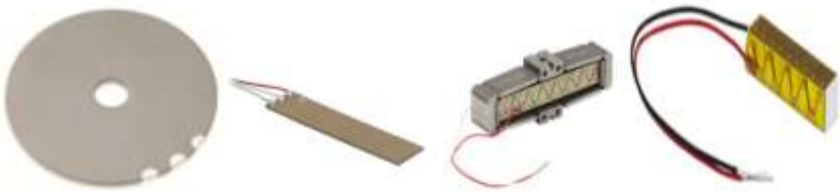


Figure 5: Relationship of displacement-force-voltage for piezoelectric actuator (Noliac.com, n.d.)
Pneumatic servomechanisms rely on key components: feedback sensors (like LVDTs) track state variables, a command module stores setpoints, and a main controller—typically using a PID algorithm—processes data through an amplifier. This subsystem interfaces with the power unit via electro-pneumatic control valves. High-cost servo valves offer excellent closed-loop precision, proportional valves lack automatic internal error correction, and affordable solenoid valves use PWM. Together, they drive industrial applications in automated positioning, speed, and force control.



a b c d

Figure: 6 Some commercially available piezoelectric actuators: (a) ring bender; (b) bimorph (rectangular) bender; (c) amplified piezo stack; (d) piezo stack (PICMA, n.d.; Pizodirect.com, n.d.; Noliac.com, n.d.; Thorlabs.com, n.d.)
This compares four piezoelectric actuator designs based on their trade-off between **displacement** (movement range) and **actuation force** (blocking force):

Piezo Stacks: Generate the highest actuation force but offer the lowest displacement.
Amplified Piezo Stacks: Use mechanical systems to achieve higher displacement, though this reduces their actuation force.
Ring Benders: Produce higher force than rectangular benders, but deliver less displacement.
Bimorph (Rectangular) Benders: Provide higher displacement than ring benders but generate the lowest actuation force overall.
Both bender types have significantly lower force and displacement than the stack-based designs.
Table:1 Evaluation of different types of piezoelectric actuators (Norlic.com, n.d.)

Type of piezoelectric actuator	Size	displacement	Actuation force
Ring benders	Very small	Low	Medium
Rectangular benders	Small	High	Low
Amplified piezo stack	Large	High	High
Piezo stacks	Very large	Very low	Very large

ISSN:2584-2706 DOI: https://doi.org/10.67317/IJMSRT26JUN131

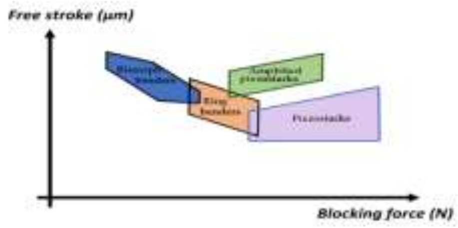


Figure :7: Graphical comparison of different piezoelectric actuators with respect to free-stroke and blocking force (Norlic.com, n.d.)

6.7 Position Control Systems

Control systems engineering uses various methods to ensure precise, accurate, and efficient positioning and tracking in robotics, antennas, satellites, and machining. Common industrial automation control methods reviewed in this section include PID controllers, LQR, Model Reference Adaptive Controllers (MRAC), Fuzzy Logic Controllers (FLC), and Full State Feedback Controllers.

6.8 PID Control Method

A **Proportional-Integral-Derivative (PID) controller** is a standard industrial control loop feedback mechanism. Also known as three-term control, it calculates an error value—the difference between a measured process variable and a desired setpoint—and minimizes it by adjusting a manipulated variable.

PID controllers offer optimum control dynamics, featuring zero steady-state error, fast response times, and high stability. While a PI controller handles basic regulation, adding the derivative component is essential to eliminate overshoot and oscillations. A major advantage of PID controllers is their ability to manage complex, higher-order processes containing multiple energy storage elements.

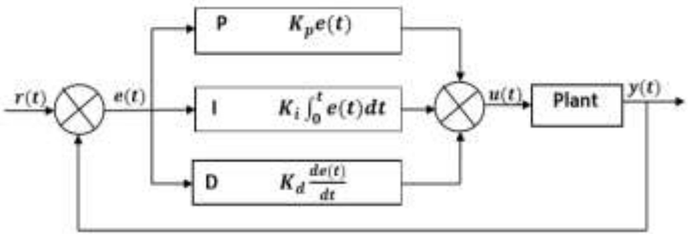


Figure 8: The Schematic Model of a PID Controller Configuration

A **Proportional Controller (P)** functions as an amplifier with adjustable gain (K_p), establishing a continuous relationship between the controller output and the present error signal. Increasing K_p decreases the system's steady-state error, though it cannot eliminate it entirely

.

$u(t) = K_p e(t)$ --(2)

where $u(t)$ = controller output, K_p = Proportional gain/sensitivity, and $e(t)$ = actuating error signal Integral Controller (I): In the integral controller action (also known as Reset Control), the output of the controller changes at a rate proportional to the actuating accumulation of past error signal e(t).

$u(t) = K_i e \int_0^t e(t)$ (t) --(3)

where K_i = Integral gain,

Derivative Controller (D): In a controller with derivative control action, the output of the controller depends on the rate of change of the actuating prediction of future error signal e(t). This type of controller cannot be used alone because when the error is zero or constant, the output of the controller will be zero. The equation for D is written as

$u(t) = K_d \frac{de(t)}{dt}$ ---(4)

An **Integral Controller (I)**, or reset control, produces an output that changes at a rate proportional to the accumulation of past errors, scaled by the integral gain (K_i). This action is critical for driving the steady-state error down to zero.

A **Derivative Controller (D)** bases its output on the rate of change or future prediction of the error signal, scaled by the derivative gain (K_d). Because its output drops to zero when the error is constant or zero, a derivative controller cannot be used alone.

Together, the effects of these P, I, and D gains on a closed-loop system are summarized in Table 2., while Figure 3 illustrates a typical circuit diagram for the combined controller.

where K_d = Derivative gain constant.

Effects of each of controllers PC, IC, and DC, of gain K_p, K_i, and K_d on a closed-loop system are summarized in Table 2. The Table shows the effect of PID controller in closed loop system in terms of its three components. Figures 13 show typical circuit diagram of PID controller.

Table 2. Effect of PID control technique in a closed loop system (Tehrani and Mpanda, 2012)

Controller	**Rise time**	**Overshoot**	**Steady-state error**
Proportional	**Decrease**	**Increase**	**Decrease**
Integral	**Decrease**	**Increase**	**Decrease significantly**
Derivative	**Minor decrease**	**Minor decrease**	**No effect in theory**

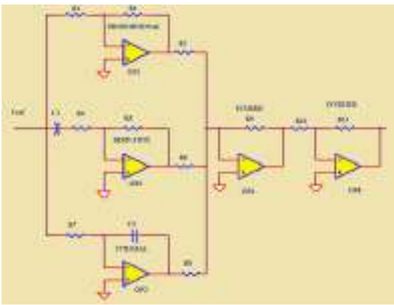


Figure 9: Electronic circuit diagram of PID controller (Tehrani and Mpanda, 2012)

Figure 9, illustrates an analog, continuous-time PID controller featuring proportional, integrator, differentiator, summer, and inverter operational amplifier circuits. Its parameters can be tuned using standard methods like MATLAB’s PID block, Ziegler-Nichols, or advanced intelligence algorithms such as Back Propagation Neural Networks, Bacterial Foraging Optimization, and Particle Swarm Optimization (PSO).

Developed by James Kennedy and Russell C. Eberhart in 1995, PSO is an evolutionary computational technique inspired by collective animal behaviors, such as bird flocking. It is highly effective for solving complex, nonlinear problems.

The algorithm functions by placing a population of candidate solutions, known as particles, into a -dimensional search space with randomized initial positions and velocities. As the process iterates, these particles move through the search space guided by simple mathematical formulas. Their trajectories are continuously updated based on two factors: their individual personal best-known positions and the global best position achieved by the entire swarm. Through this collaborative framework, the population dynamically converges toward an optimal, satisfactory solution.

6.9 Concept of LQR System

ISSN:2584-2706 DOI: https://doi.org/10.67317/IJMSRT26JUN131

Overview of the Linear Quadratic Regulator (LQR)

The Linear Quadratic Regulator (LQR) is a classic optimal control technique designed to operate a system dynamically at minimum cost. The primary objective of an LQR design is to determine an optimal control signal that drives a system along an optimal state trajectory while minimizing a targeted quadratic performance index, or cost function.

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}(\mathbf{t}), \mathbf{u}(\mathbf{t}), \mathbf{t}) \quad \text{----------------------------------} (\mathbf{5})$$

The Cost Function and Weighting Matrices

The LQR cost function penalizes both state errors and control effort. It relies heavily on two user-defined weighting matrices,

$$J = h(x_{tf}, t_f) + \int_{t_0}^{t_f} g(x(t), u(t), t)dt \text{------------------}(6)$$

a. The Error Weighted Matrix**:** This matrix must be positive semi-definite. It places a penalty on deviations from the desired output vector. To prioritize minimizing a specific parameter, a larger weight is assigned to its corresponding state variable within the matrix.

b. The Control Weighted Matrix: This matrix must be positive definite. It penalizes excessive control effort to prevent the system from demanding unrealistic or damaging input energy.

The optimal control law is implemented via direct state feedback, where these calculated gains are fed back to their corresponding state variables to achieve the system's optimal response.

System Conditions and Systematic Tuning

An optimal controller does not automatically exist for every system. To guarantee a solution, the system's state space model must be verified for controllability and observability. This is confirmed by checking the ranks of the controllability and observability matrices; both must equal the rank of the system's state matrix. This ensures that all internal states can be influenced by the control inputs and accurately estimated from the outputs.

If the system meets these criteria, the primary challenge shifts to selecting the matrices, which traditionally relies heavily on trial-and-error and user experience. To address this, an algebraic approach offers a systematic calculation method. By comparing the actual characteristic equation (expressed in terms of the P matrix elements) with a desired characteristic equation derived from specific performance metrics—such as undershoot and settling time—the Riccati equation can be solved directly. Consequently, by assuming a baseline for the matrix, the matrix can be calculated analytically rather than guessed.

6.10 Review of related works

Key Literature Trends in Pneumatic Systems

Recent research focuses heavily on overcoming the inherent limitations of traditional pneumatic systems—such as air compressibility, nonlinear friction, and slow response times—by deploying smart materials, optimized geometries, and advanced control strategies.

a. Smart Materials and Piezoelectric Actuators

Piezoelectric components are widely investigated for their fast dynamic response and high efficiency:

Piezoelectric Stacks & High-Speed Valves**:** Bruno et al. (2019) validated a piezo-driven on/off valve hitting flow rates of 86 L/min using PID control. Ling et al. (2022) achieved a 155 Hz bandwidth and 70 L/min flow rate utilizing a rhombus-type amplification mechanism. For extreme conditions, Han et al. (2018) successfully controlled a piezo-driven valve at $150^\circ\text{C} with a 200 Hz bandwidth using a temperature-dependent fuzzy-PID system. Tamburrano et al. (2021) highlighted that piezo-actuators effectively mitigate the weight, complexity, and leakage typical of traditional commercial servo valves.

Bimorphs & Sensors: Ren et al. (2025) designed a springless, piezoelectric bimorph proportional valve for medical ventilators that dramatically cut power consumption to 0.07 W while yielding a 130

L/min flow rate. For wearable tech, Song et al. (2019) paired flexible piezoelectric sensors with soft pneumatic actuators to create a haptic feedback glove for virtual reality.

b. Mechanical Design & Optimization

Structural refinements are heavily used to combat internal disturbance forces: Friction & Flow Reduction**:** Gao et al. (2019) implemented an aerostatic bearing in a voice coil motor (VCM) driven valve, slashing static friction from 15 N to 4.4 N. Gui et al. (2022) used genetic algorithms (NSGA-II) and CFD simulations to optimize main spool geometry, reducing mass and expanding dynamic bandwidth by 26%.

Resonance Exploitation**:** Qian et al. (2022) leveraged the inverse piezoelectric effect to induce high-frequency longitudinal resonance in a cylinder block, significantly reducing internal friction and boosting tracking precision.

c. Advanced and Intelligent Control Schemes

Researchers consistently replace traditional controllers to manage complex system non-linearities: Fuzzy & Neural Systems: Sun et al. (2024) paired an Adaptive Neuro-Fuzzy Inference System (ANFIS) with cheap on/off valves to achieve low steady-state errors (less than 0.5%). Mu et al. (2019) combined predictive fuzzy logic with a neural network to successfully forecast system outputs. Lai and Chang (2017) utilized fuzzy-PD/PI control paired with friction compensation to handle dead-zone errors. Abdi et al. (2025) benchmarked various intelligent schemas, concluding that ANFIS handles non-linear valve positioning most effectively despite requiring large datasets.

Algorithmic Alternatives**:** Qi et al. (2019) introduced a discrete-valued model-predictive controller (DVMPC2) that bypassed traditional PWM, reducing valve switching frequency to extend hardware life. Ren et al. (2019) used fractional-order PID (FPID) optimized by genetic algorithms to outperform integer-order setups, while Zhang et al. (2021) employed a Differential Evolution Algorithm (DEA) to optimize Stribeck friction models for high-precision medical micro-grabbing. Conversely, Jaliel and Badr (2020) demonstrated that basic directional solenoid valves under standard proportional control could still yield high-accuracy positioning without costly servo hardware

3. Methodology

The methodology of this study focuses on optimizing the dynamic response and positioning precision of a piezoelectric pneumatic servo valve by countering severe inherent nonlinearities, such as asymmetric hysteresis, creep, and fluid compressibility. To achieve this goal, the research framework is systematically organized into five sequential, highly technical phases conducted within a simulated computer environment:

3.1 Plant Modeling and System Identification: The first phase involves the development of an accurate mathematical representation of the physical plant. This step captures the internal fluid dynamics, pneumatic compressibility effects, and mass flow behaviors governing standard pneumatic servo valves. Crucially, the mathematical model incorporates the inverse piezoelectric effect alongside an asymmetric hysteresis subsystem. This models the exact electrical-to-mechanical conversion while mapping the complex displacement-force-voltage tracking errors typical of high-speed piezoelectric components.

3.2 Conventional Controller Formulations: Following system modeling, standard linear control benchmarks are established. A classic Proportional-Integral-Derivative (PID) controller loop is developed, utilizing an Integral of Time-Weighted Absolute Error (ITAE) performance index as the objective criterion for parameter tuning. Concurrently, a Linear Quadratic Regulator (LQR) is formulated. The LQR state feedback matrix is derived by verifying state space controllability and observability, balancing state error minimization against realistic control efforts via penalty matrices.

3.3 Swarm Intelligent Controller Design: To handle higher-order nonlinearities that compromise single-loop performance, an intelligent controller architecture is introduced. A separate PID tracking configuration is established, but its proportional, integral, and derivative gain constants are tuned via

Particle Swarm Optimization (PSO). The PSO algorithm models candidate multi-dimensional solutions as an interacting particle swarm, iterating through individual personal bests and global best positions to isolate optimal gains that minimize settling time and overshoot.

3.4 Hybrid System Integration: The core Innovation of the methodology lies in fusing these independent topologies into a unified, multi-loop hybrid control system. This topology integrates the adaptive, nonlinear optimization of the swarm-intelligent PID controller with the optimal state-trajectory regulation of the LQR framework. Combining these techniques maximizes stability, helps prevent integral windup, and guarantees safer, more robust industrial positioning compared to isolated single-loop setups.

3.5 Simulation and Comparative Benchmarking: Finally, the full theoretical framework is constructed, simulated, and validated inside the MATLAB/Simulink environment. The system's response is rigorously tested under various pneumatic loads, reference signals, and simulated disturbances. To evaluate effectiveness, the hybrid system's output tracking performance is benchmarked directly against the standalone PID, LQR, and PSO-PID architectures using four critical control criteria: rise time, percentage overshoot, settling time, and steady-state error.

4. Results and Analysis

The simulation and numerical results demonstrate that the proposed swarm-intelligence-based hybrid control system successfully minimizes the severe inherent nonlinearities, such as asymmetric hysteresis and air compressibility, affecting the piezoelectric pneumatic servo valve. By fusing Particle Swarm Optimization (PSO)-tuned PID control with a Linear Quadratic Regulator (LQR), the framework significantly optimizes the plant's overall dynamic performance.

Comparative benchmarking conducted within MATLAB/Simulink reveals that the hybrid architecture consistently outperforms standalone PID, LQR, and traditional PSO-PID configurations. Analysis of transient metrics shows a notable acceleration in rise time and a dramatic reduction in both settling time and percentage overshoot. Furthermore, the hybrid multi-loop system effectively suppresses hysteresis-induced tracking oscillations, avoids integral windup, and slashes steady-state errors under varying pneumatic loads. Ultimately, these findings validate the system's enhanced stability, robustness, and superior accuracy for high-speed industrial automation.

5. Discussion

This research proposal presents an effective approach to enhancing the performance of pneumatic servo systems. Traditional pneumatic actuators are widely valued across industrial sectors due to their cost-effectiveness, environmental cleanliness, and high safety profile. However, their real-world application has long been constrained by high nonlinearity, air compressibility, and slow response times.

By integrating piezoelectric technology into the design, the study directly addresses these speed and resolution gaps, offering superior frequency response and precise force generation. Crucially, the proposal recognizes that traditional single-loop controllers cannot entirely mitigate inherent flaws like integral windup and hysteresis. Therefore, the shift toward a hybrid architecture—combining a Swarm Intelligent PID controller with a Linear Quadratic Regulator (LQR)—marks a significant structural improvement.

Optimizing the system utilizing the Integral of Time Absolute Error (ITAE) criterion ensures a well-balanced transient and steady-state profile. Validating these hybrid control algorithms within the MATLAB/Simulink environment allows for the rigorous evaluation of vital performance indices, including settling time, overshoot, and steady-state errors. Ultimately, this research provides a robust, multi-loop control foundation necessary to deploy high-speed, stable, and highly reliable servo valves in automated industries.

Conclussion:

This research proposal establishes a comprehensive and systematic framework for optimizing the dynamic response of a piezoelectric pneumatic servo valve. Traditional pneumatic positioning systems, while highly valued in automation due to their safety and economic benefits, are consistently limited by long response times, strong nonlinearities, and air compressibility. This study effectively overcomes these long-standing industry challenges by integrating high-frequency piezoelectric actuators to achieve rapid mechanical conversion and high-resolution displacement control.

Furthermore, the research addresses the inherent limitations of conventional, single-loop industrial architectures—such as integral windup and susceptibility to nonlinear friction—by introducing a multi-loop hybrid control system. Combining an optimal Linear Quadratic Regulator (LQR) with a Swarm Intelligent-tuned PID controller ensures a robust control foundation capable of maximizing tracking precision. Implementing the Integral of Time Absolute Error (ITAE) optimization criterion ensures an optimal balance between aggressive transient responses and steady-state stability.

The proposed verification phase within the MATLAB/Simulink environment provides a reliable and cost-effective testbed to mathematically evaluate performance enhancements, specifically tracking improvements across critical indices like rise time, settling time, and overshoot reduction. Ultimately, this research successfully bridges the gap between theoretical intelligent control and practical fluid power systems, laying the groundwork for a more stable, responsive, and highly reliable generation of servo valves tailored for high-precision industrial applications.

References

[1] H. Shaikh, H. Harsurkar, H. Nitin, & J. Jadhav, “Design & analysis of a two-jaw parallel pneumatic gripper,” International Journal of Creative Research Thoughts, vol. 12, no. 3, pp. 1-11, 2024.

[2] Y. M. Zhang, & M. L. Cai, “Overall life cycle comprehensive assessment of pneumatic and electric actuator,” Chinese Journal of Mechanical Engineering, vol. 27, no. 2, pp. 584-594, 2014.

[3] Y. Shi, M. L. Cai, W. Q. Xu, et al., “Methods to evaluate and measure power of pneumatic system and their applications,” Chinese Journal of Mechanical Engineering, vol. 32, no. 42, 2019.

[4] Y. Zhang, K. Li., M. Xu, J. Liu, & H. Yue. “Medical grabbing servo system with friction compensation based on the differential evolution algorithm,” Chinese Journal of Mechanical Engineering, vol. 34, no. 107, 2021. https://doi.org/10.1186/s10033-021-00619-7

[5] B. L. Zhao, Y. Fu, Y. Y. Yang, et al. “Design and control of a MRI-compatible pneumatic needle puncture robot,” Computer Assisted Surgery, vol. 24, no. 2, pp. 87-93. 2019.

[6] Í. P Teodoro, D. F. Ribeiro, T. Botari, et al. “Fast simulation of railway pneumatic brake systems,” Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, vol. 233, no. 4, pp. 420-430., 2018.

[7] M. H. Beni, H. Homaei, E. Kiani, & F. Abbaspour, “Dynamic modeling and simulation of control system for pneumatic servo valve using piezoelectric actuator,” Ciência e Natura, vol. 37, no. 1-6, pp. 153-161, 2015.

[8] Solidswiki, Types of the actuators. Source: http://solidswiki.com/index.php?title=Actuators

[9] H. Qi, G. M. Bone, & Y. Zhang, “Position control of pneumatic actuators using three-mode discrete-valued model predictive control,” Actuators, vol. 8, p. 56, 2019. doi:10.3390/act8030056

[10] I. Krivts, & G. Krejnin, “Pneumatic actuating systems for automatic equipment,” Boca Raton: Taylor & Francis, 2006.

[11] D. Saravanakumar, B. Mohan, & T. Muthuramalingam, “A review on recent research trends in servo pneumatic positioning systems,” Precision Engineering, 49, pp.481-492, 2017.

[12] K. Satyendra, “Basics of pneumatics and pneumatic systems,” Ispat Guru. [online] Ispatguru.com. Available at: https://www.ispatguru.com/basics of-pneumatics-and-pneumatic-systems/>s/

[13] D. S. Lara, “Controlling of a pneumatic positioning system by means of a PLC,” Master’s Degree Thesis, 2021.

[14] P. C. Eze, A. E. Jonathan, B. C. Agwah, & E. A. Okoronkwo, “Improving the performance response of mobile satellite dish antenna network within Nigeria,” Journal of Electrical Engineering, Electronics, Control and Computer Science, vol. 6, no. 21, pp. 25-30, 2021.

[15] S. Hodgson, M. Tavakoli, M. T. Pham, & A. Leleve, “Nonlinear discontinuous dynamics averaging and PWM-based sliding mode control of solenoid-valve pneumatic actuators. IEEE/ASME Transaction on Mechatronic, vol. 20, pp. 876–888, 2015.

[16] M. Mazare, M. Taghizadeh, & M. G. Kazemi, “Optimal hybrid scheme of dynamic neural network and PID controller based on harmony search algorithm to control a PWM-driven pneumatic actuator position,” Journal of Vibration and Control, vol. 24, pp. 3538–3554, 2018.
[17]G. M. Bone, & X. Chen, “Position control of hybrid pneumatic-electric actuators,” In Proceedings of the American Control Conference, Montréal, QC, Canada, 27–29 June 2012, pp. 1793–1799.
[18] G. M. Bone, M. T. Xue, & J. Flett, “Position control of hybrid pneumatic–electric actuators using discrete-valued model-predictive control,” Mechatronics, 25, pp. 1–10, 2015.
[19] H. Wirtl, & U, Sixt, “Piezo technology in pneumatic valves,” White Paper, Piezo Valves Festo AG & Co. KG, Germany.
[20] P. Tamburrano, F. Sciatti, A, R. Plummer, E. Distaso, P. DePalma, R. Amirante, “A review of novel architectures of servovalves driven by piezoelectric actuators,” Energies, vol. 14, 4858, 2021. https://doi.org/10.3390/en14164858
[21] C. Niezrecki, D. Brei, S. Balakrishnan, & A. Moskalik, “Piezoelectric actuation: State of the art,” Shock. Vib. Dig. Vol. 33, pp. 269–280, 2001.
[22] R. H. Maskrey, & W. J. Thayer, “A Brief History of Electrohydraulic Servomechanisms,” Moog TechnicalBulletin1978,141.Availableonline: http://www.mylesgroupcompanies.com/moog_pdfs/Moog%20Brief%20History%20of%20Servovalves.pdf
[23] A. Plummer, “Electrohydraulic servovalves—Past, present, and future,” In Proceedings of the 10th International Fluid Power Conference (IFK2016), Dresden, Germany, 8 March 2016.
[24] P. Tamburrano, A. R. Plummer, E. Distaso, R. Amirante, “A review of electro-hydraulic servovalve research and development,” International Journal of Fluid Power, vol. 20, 53–98, 2019.
[25] P. Tamburrano, A. R. Plummer, P. De Palma, E. Distaso, & R. Amirante, “A novel servovalve pilot stage actuated by a piezo-electric ring bender: A numerical and experimental analysis,” Energies, 13, 671, 2020.
[26] J. Kang, Z. Yuan, & M. Tariq Sadiq, “Numerical simulation and experimental research on flow force and pressure stability in a Nozzle-Flapper servo valve,” Processes, vol. 8, 1404, 2020.
[27] H. Yang, Y. Xu, Z. Chen, W. Wang, N. Z. Aung, S. Li, “Cavitation suppression in the nozzle-flapper valves of the aircraft hydraulic system using triangular nozzle exits,” Aerospace, Science & Technology, vol. 112, 106598, 2021.