

Predictive Control Algorithm for Pneumatic Positioning Cyber-Physical Systems Using Standard ON/OFF Valves

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Abstract. *Precise positioning of pneumatic linear actuators is challenging due to nonlinear pneumatic dynamics and the discrete nature of standard ON/OFF valves. This paper presents a low-cost positioning approach in which an ESP32 controller uses an empirically identified pulse-duration–displacement model to estimate the initial valve actuation pulse, followed by position-feedback corrections. Experimental validation at 2.5 bar using identical sets of 50 target positions yielded mean absolute endpoint errors of 3.44 mm for the Hafner configuration and 1.50 mm for the Pneumax configuration.*

Keywords. Pneumatic Positioning, ON/OFF Valves, Linear Regression, ESP32, Cyber-Physical Systems

1 Introduction

In the field of industrial automation, pneumatic linear actuators are widely implemented due to their ability to provide high power-to-weight ratios, fast response, and relatively low cost, making them suitable for a broad range of industrial applications (Tootchi & Chaibakhsh, 2025; Xavier et al., 2022). However, their application in precise positioning tasks is significantly complicated by the inherent compressibility of air and nonlinear flow dynamics, which introduce nonlinear, delayed, and state-dependent responses in the system (Qi, Bone, & Zhang, 2019; Xavier et al., 2022). These effects, combined with friction and uncertain load conditions, make accurate trajectory tracking and positioning a challenging control problem (Tootchi & Chaibakhsh, 2025). High-accuracy pneumatic positioning is therefore commonly addressed using proportional or servo valves capable of continuous flow modulation and fine control of the pneumatic actuation process (Šitum & Čorić, 2022; Zhang et al., 2022).

In cost-sensitive industrial applications, such as the development of an automated bow testing machine, the cost and implementation complexity of proportional valves may represent a significant disadvantage. Consequently, standard 5/3-way discrete ON/OFF valves provide an attractive alternative. These valves are used

in digital fluid power systems but are inherently constrained by their discrete switching nature and lack of continuous control authority (Gao et al., 2023). Their operation is characterized by switching delays, finite response times, and the delivery of compressed air through discrete valve states rather than continuously adjustable flow, which can affect positioning performance (Gao et al., 2023). These characteristics make precise endpoint positioning with conventional ON/OFF actuation challenging.

To address such limitations, research has investigated control strategies that account for the nonlinear and hybrid behaviour of pneumatic systems. In particular, model-based and predictive control approaches have demonstrated the potential to improve positioning performance when discrete pneumatic actuation is used (Qi, Bone, & Zhang, 2019; Tootchi & Chaibakhsh, 2025). These approaches incorporate information about system behaviour into the control process to reduce the influence of pneumatic nonlinearities, valve dynamics, and disturbances.

In this context, this paper investigates a computationally lightweight positioning approach for a pneumatic linear actuator controlled by standard ON/OFF valves. The proposed cyber-physical system combines an ESP32-based controller with an empirically identified pulse-duration–displacement model and position-feedback corrections. Separate models are identified for both directions of motion and for the tested valve configurations. The approach is experimentally evaluated under controlled operating conditions with emphasis on calibration-model behaviour and endpoint positioning accuracy.

2 Related Work

The control of pneumatic positioning systems has been investigated using several control architectures. One common approach relies on servo-pneumatic systems equipped with proportional or servo valves. These systems provide continuous airflow regulation and are therefore suitable for applications requiring smooth motion and accurate positioning (Gao et al., 2023;

Mandali & Dong, 2022). Their use, however, is generally associated with higher component cost and increased implementation complexity compared with conventional discrete pneumatic hardware (Sciatti et al., 2024).

An alternative research direction uses discrete ON/OFF valves as part of digital fluid power systems. In such systems, high-frequency switching techniques such as Pulse Width Modulation (PWM) can be used to approximate continuous airflow regulation (De Carvalho et al., 2023). The achievable performance nevertheless depends on valve characteristics including hysteresis, finite switching times, and nonlinear dynamic behaviour (Gao et al., 2023; Li et al., 2023). These non-idealities constrain the useful switching frequency and can introduce deviations between the commanded and resulting pneumatic response.

More advanced control strategies have also been investigated to compensate for nonlinearities and uncertainties in pneumatic systems, including sliding mode control, feedback linearization, and model-based approaches (Duong et al., 2023; Xavier, Fleming, & Yong, 2022). Sliding mode control can provide robustness against parameter variations and external disturbances, although its implementation requires appropriate system modelling and controller tuning (Xavier, Fleming, & Yong, 2022). Model-based approaches may additionally require detailed knowledge of the pneumatic process, increasing modelling and computational requirements for embedded implementations.

These studies demonstrate that improved pneumatic positioning can be achieved either by increasing the capabilities of the pneumatic hardware or by introducing more sophisticated control strategies. For low-cost embedded applications using conventional industrial ON/OFF valves, however, there remains motivation for control methods that require only limited model complexity while explicitly accounting for discrete valve actuation.

The approach investigated in this paper uses an empirically identified pulse-duration–displacement relationship rather than a detailed thermodynamic model or continuous-flow approximation. Separate models are identified for both directions of motion and for the tested valve configurations. The model provides the pulse-duration estimate, while position feedback is used to evaluate the remaining displacement error and perform corrective movements. This structure is intended to maintain low computational complexity while adapting the pulse calculation to the characteristics of the tested pneumatic configuration.

3 Materials and Methods

This section describes the experimental setup, actuator force analysis, embedded control architecture, calibration procedure, pulse-duration–displacement model, and feedback-based positioning method.

3.1 Hardware Architecture

To emphasize the cost-effectiveness of the design, the cyber-physical system was constructed entirely using standard, off-the-shelf industrial parts. The primary actuator driving the mechanical guide is a standard double-acting pneumatic cylinder manufactured by Hafner (type HIF 80/800), featuring a piston diameter of 80 mm and a piston rod diameter of 25 mm.

The central control unit of the system is an ESP32 microcontroller, selected for its 32-bit architecture and hardware timers. However, because the ESP32 operates at a 3.3 V logic level and cannot directly drive the power-hungry 24 V DC industrial solenoid valves, an intermediary power switching interface is required. For this purpose, a dual N-channel MOSFET switching module (utilizing AOD4184A transistors) was integrated. This module safely handles the higher current demands and acts as a robust voltage-level translator between the microcontroller and the pneumatic hardware.

Through this switching module, the ESP32 discrete digital outputs govern the airflow and directional control via standard 5/3-way solenoid valves with closed center positions (such as the Hafner MH 531 121 or Pneumax alternatives). Finally, real-time positional feedback is captured and transmitted back to the microcontroller via a high-resolution (0.005 mm) optical linear encoder.

3.2 Actuator Force Analysis

For a double-acting pneumatic cylinder, the extension and retraction forces depend on the applied pressure and the corresponding effective piston areas. The practical actuator forces are estimated as

$$F_{\text{push}} = p \cdot A_{\text{push}} \cdot \eta \quad (1)$$

$$F_{\text{pull}} = p \cdot (A_{\text{push}} - A_{\text{rod}}) \cdot \eta \quad (2)$$

where p is the supply pressure, A_{push} is the full piston area, A_{rod} is the piston-rod cross-sectional area, and η is a practical force correction coefficient. According to the cylinder manufacturer's guidance, approximately 5% of the theoretical cylinder force may be deducted as a rule-of-thumb estimate of frictional losses (Hafner-Pneumatik Krämer GmbH & Co. KG, 2024). Therefore, $\eta = 0.95$ was adopted in this study. This coefficient was not identified experimentally and is used only for estimating the practical actuator force; it does not represent a dynamic model of the pneumatic system.

The parameters of the experimental testbed used for the force calculation are summarized in Table 1.

Table 1. Main testbed parameters used for the actuator force calculation.

Parameter	Symbol	Value
Cylinder bore diameter	D	80 mm
Piston-rod diameter	d_{rod}	25 mm
Nominal cylinder stroke	–	800 mm
Usable experimental stroke	–	≈ 610 mm
Supply pressure	p	2.5 bar
Piston area	A_{push}	5026.5 mm^2
Piston-rod area	A_{rod}	490.9 mm^2
Force correction coefficient	η	0.95
Estimated extension force	F_{push}	1193.8 N
Estimated retraction force	F_{pull}	1077.2 N

At the experimental supply pressure of 2.5 bar, the estimated practical extension and retraction forces are therefore approximately 1194 N and 1077 N, respectively. The difference results from the reduced effective piston area during retraction and provides additional motivation for identifying separate pulse-duration–displacement models for the two directions of motion.

3.3 Software Architecture and Model-Based Pulse Calculation

The custom control software, implemented in C++ on the ESP32, utilizes an asynchronous state machine to manage the operational flow without blocking primary background processes. The positioning method uses an empirically identified pulse-duration–displacement relationship to estimate the required valve actuation. The software execution is divided into two primary phases: an automated calibration sequence and the active positioning calculation.

Auto-Calibration Sequence

When calibration is initiated, the cylinder repeatedly returns to a predefined home position and dispatches test pulses of varying durations, as illustrated in Fig. 1. After each pulse, the resulting traveled distance is recorded using the linear encoder.

In the experimental calibration procedure, pulse durations from 40 to 520 ms were evaluated in 40 ms increments. Each pulse duration was repeated five times, resulting in 65 displacement measurements for each direction of motion and each tested valve configuration.

Once the calibration dataset is collected, the method of least squares is applied to establish a linear regression model relating the pulse duration t to the traveled distance d :

$$d = k \cdot t + q \quad (3)$$

where k represents the experimentally identified displacement gain and q represents the model offset. Separate models are identified for forward and

backward motion because the pneumatic actuator exhibits direction-dependent behaviour resulting from the different effective piston areas and other direction-dependent pneumatic and mechanical effects.

The calibration is intended as a commissioning or re-identification procedure rather than as a step required before every positioning command. After successful identification, the model parameters are stored in the Non-Volatile Storage (NVS) of the ESP32 and can be reused while the pneumatic and mechanical configuration remains unchanged. Recalibration may therefore be performed when relevant system parameters change, for example after replacing the valve, modifying the operating pressure, or changing the mechanical configuration.

The calibration procedure must be executed within predefined actuator limits. In the present experiments, calibration pulses were restricted to the 40–520 ms range and the cylinder was referenced to a predefined home position before subsequent test pulses. These constraints reduce the risk of excessive actuator travel during system identification. In practical deployment, the admissible calibration range should be selected according to the physical stroke and safety constraints of the specific machine and supplemented by appropriate hardware or software interlocks.

Linear Model Evaluation

Equation 3 is not intended to estimate the internal position of the valve spool or to represent the complete pneumatic dynamics. Instead, it provides a first-order empirical relationship between the commanded valve pulse duration and the resulting piston displacement under a fixed pneumatic and mechanical configuration. Its purpose is to provide a computationally lightweight estimate of the pulse duration required for a requested displacement.

The suitability of the linear approximation was evaluated using the coefficient of determination (R^2), the root mean square error (RMSE), and an analysis of the regression residuals. For each calibration measurement, the residual was calculated as

$$e_i = d_i - \hat{d}_i, \quad (4)$$

where d_i is the measured displacement and $\hat{d}_i$ is the displacement predicted by the fitted linear model.

Residual normality was assessed using the Shapiro–Wilk test at a significance level of $\alpha = 0.05$. This analysis was used as a diagnostic of whether the remaining approximation error could reasonably be described as normally distributed measurement variability. A rejection of residual normality was not treated as sufficient evidence to discard the linear model, since systematic pneumatic and mechanical effects may remain outside the first-order approximation. The linear model is therefore used as a lightweight pulse-duration estimator, while position feedback is used to evaluate the

remaining displacement and perform subsequent corrective movements when required.

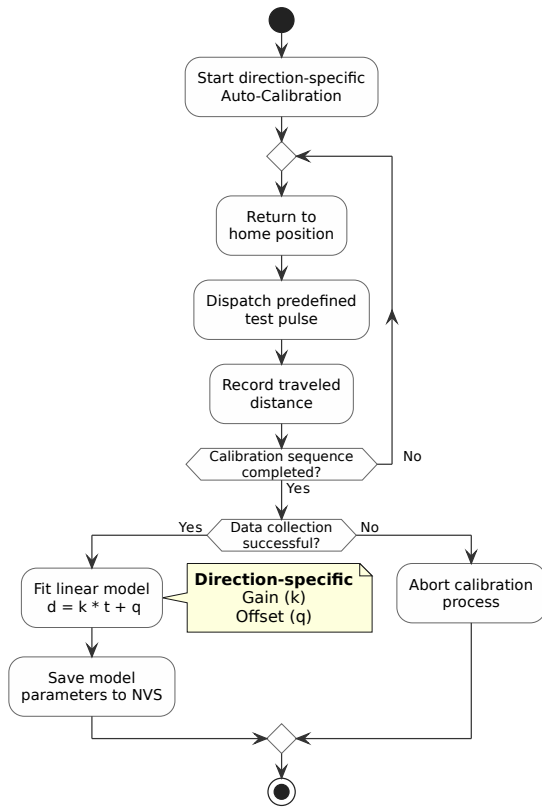


Figure 1. Auto-calibration workflow for direction-specific identification of the pulse-duration-displacement model.

Active Positioning and Pulse Calculation

During active positioning, the controller determines the required displacement from the current piston position and the requested target position. The corresponding forward or backward calibration model is selected according to the direction of motion. Using the inverse of the identified regression model in Equation 3, the required base pulse duration (t_{base}) is calculated as

$$t_{base} = \frac{d - q}{k}, \quad (5)$$

where d is the required displacement and k and q are the parameters of the corresponding directional calibration model.

The complete logical execution of the pulse calculation is illustrated in Fig. 2. The control sequence consists of the following steps:

1. **Target and Model Validation:** The system receives the target position, determines the required displacement, and verifies the validity of the corresponding regression model. If the stored model is invalid, pulse calculation is aborted and recalibration is required.

2. **Pulse Calculation and Heuristic Adjustment:**

If the model is valid, t_{base} is calculated using Equation 5. A fixed pulse-duration factor of 0.95 is subsequently applied:

$$t_{final} = 0.95 \cdot t_{base}. \quad (6)$$

The factor was selected heuristically during controller development to reduce the commanded pulse duration and decrease the likelihood of target overshoot. It was not determined through formal parameter optimization. Furthermore, this pulse-duration factor is independent of the force correction coefficient $\eta = 0.95$ used in the actuator force analysis.

3. **Pulse-Duration Constraint Filtering:** Before execution, t_{final} is evaluated against the configured pulse-duration limits. The lower pulse-duration limit was set to 38 ms for the Hafner configuration and 25 ms for the Pneumax configuration. Pulse requests at or below the corresponding limit are not executed. These values represent controller configuration parameters used in the experiments and should not be interpreted as universal physical switching thresholds of the valves.

For both configurations, the maximum commanded pulse duration was limited to 1100 ms. Pulse requests exceeding this value are saturated at the upper limit.

4. **Execution and Feedback Correction:** If the calculated pulse satisfies the execution conditions, the corresponding ON/OFF valve is actuated for the commanded duration. After the pulse, a stabilization interval is applied before the piston position is evaluated using the linear encoder. The remaining displacement error is then used to determine whether an additional corrective movement is required.

The calibration data used to identify the linear models covered pulse durations from 40 to 520 ms. Therefore, pulse-duration estimates above 520 ms represent an extrapolation of the fitted first-order model. For longer movements, the resulting position is re-evaluated through feedback and any remaining displacement error is handled by subsequent corrective movements.

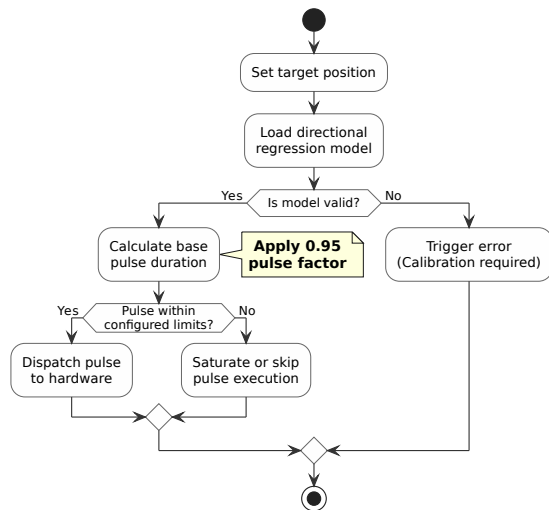


Figure 2. Pulse-duration calculation and execution workflow including the heuristic pulse factor and configured pulse-duration limits.

4 Results

This section presents the experimental results obtained for the two tested ON/OFF valve configurations. The evaluation is divided into calibration-model performance, residual analysis, and endpoint positioning validation.

4.1 Calibration Results

The calibration procedure produced separate pulse-duration–displacement models for both directions of motion and for both tested valve configurations. Each model was identified from 65 displacement measurements covering pulse durations from 40 to 520 ms.

The identified first-order models are summarized in Table 2, while the corresponding model parameters and goodness-of-fit metrics are reported in Table 3.

All four models achieved high coefficients of determination over the evaluated calibration range. The identified displacement gains also differed substantially between the two valve configurations. For example, the forward gain was approximately 0.4333 mm/ms for the Hafner configuration and 0.2017 mm/ms for the Pneumax configuration. These differences support the use of configuration-specific calibration rather than a single fixed pulse-duration model.

Table 2. Identified first-order pulse-duration–displacement models.

Configuration	Direction	Identified model
Hafner	FWD	$d = 0.4333t - 8.3791$
Hafner	BWD	$d = 0.4001t - 5.8931$
Pneumax	FWD	$d = 0.2017t - 5.5962$
Pneumax	BWD	$d = 0.1693t - 1.8552$

Table 3. Parameters and goodness-of-fit metrics of the identified linear calibration models.

Config.	Dir.	k	q	R^2	RMSE [mm]
Hafner	FWD	0.4333	-8.3791	0.9985	2.509
Hafner	BWD	0.4001	-5.8931	0.9975	2.980
Pneumax	FWD	0.2017	-5.5962	0.9970	1.655
Pneumax	BWD	0.1693	-1.8552	0.9943	1.913

4.2 Residual Analysis

The residuals of the four calibration models were analysed using the Shapiro–Wilk test at a significance level of $\alpha = 0.05$. The results are summarized in Table 4.

Table 4. Shapiro–Wilk test results for the calibration-model residuals.

Configuration	Direction	p -value
Hafner	FWD	0.093
Hafner	BWD	< 0.001
Pneumax	FWD	0.060
Pneumax	BWD	0.004

Residual normality was not rejected for the Hafner forward and Pneumax forward models. In contrast, normality was rejected for both backward models. Thus, although the first-order model captures the dominant pulse-duration–displacement relationship, the remaining approximation error cannot in all cases be described as normally distributed measurement variability.

The remaining residual structure may include pneumatic and mechanical effects that are not explicitly represented by the linear model, such as transient pressure behaviour, friction, valve dynamics, or state-dependent actuator response. The residual analysis alone does not allow the individual contribution of these effects to be identified. A higher-order or piecewise model could potentially reduce systematic approximation errors; however, the present implementation retains the linear model because of its low computational complexity and its use together with subsequent position-feedback corrections.

4.3 Positioning Validation

Fig. 3 compares the distributions of absolute endpoint positioning errors for the two tested valve configura-

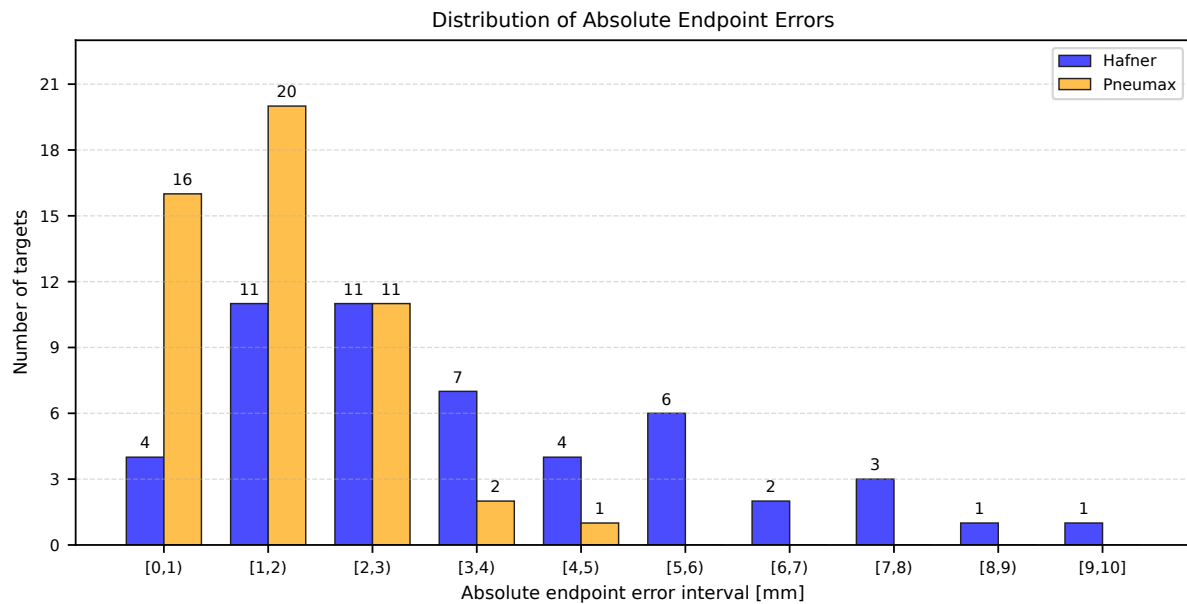


Figure 3. Comparison of the absolute endpoint-positioning error distributions for the Hafner and Pneumax valve configurations over the identical 50-target validation sequence.

tions.

The final positioning performance was evaluated using the same deterministic sequence of 50 target positions for both valve configurations. The experiments were performed using the same pneumatic cylinder, mechanical arrangement, position encoder, operating pressure of 2.5 bar, stabilization logic, and pulse-duration factor of 0.95. The target generator was reset to the same seed before each validation run, resulting in an identical target sequence for both configurations. The configured lower pulse-duration limits were 38 ms for the Hafner configuration and 25 ms for the Pneumax configuration.

The resulting endpoint-positioning metrics are summarized in Table 5.

Table 5. Endpoint positioning results for the identical 50-target validation sequence.

Metric	Hafner	Pneumax
Number of targets	50	50
MAE [mm]	3.441	1.495
SD of $ e $ [mm]	2.262	0.929
Maximum $ e $ [mm]	9.350	4.200

Under the evaluated experimental conditions, the Pneumax configuration produced lower endpoint positioning errors than the Hafner configuration. Its mean absolute error was approximately 56.5% lower. Because both configurations were evaluated using the identical sequence of target positions, a direct target-by-target comparison was also possible. The Pneumax configuration produced the lower absolute endpoint error for 38 of the 50 targets, whereas the Hafner configuration produced the lower error for 12 targets.

The two configurations also differed in the number of commanded movements required during the validation procedure. The Hafner configuration required approximately 1.08 commanded movements per target on average, whereas the Pneumax configuration required approximately 2.16. This indicates that the lower endpoint error obtained with the Pneumax configuration was accompanied by a greater number of corrective movements.

The observed performance difference should not be attributed solely to the configured lower pulse-duration limits. The two valve configurations also exhibited substantially different pulse-duration gains, residual behaviour, and short-pulse responses. The results therefore characterize the complete tested valve-controller configurations rather than isolating a single physical cause of the positioning difference.

The calibration models were identified using pulse durations up to 520 ms, whereas the positioning controller allowed commanded pulse durations up to 1100 ms. Pulse-duration estimates above the calibration range therefore represent an extrapolation of the fitted first-order models. In such cases, the position-feedback correction procedure remains an essential part of the complete positioning method.

5 Future Work

Future work will include validation using additional target sequences, operating pressures, and loading conditions. Further development will investigate adaptive pressure control, where a higher supply pressure could be used for rapid motion over larger distances and a lower pressure near the target for finer position-

ing. Pressure feedback from both cylinder chambers, velocity-aware pulse termination, and online adaptation of the pulse-duration factor will also be investigated to reduce positioning time and the number of corrective movements.

In addition, automatic model re-identification and over-the-air (OTA) firmware updates will be implemented to enable remote deployment of control algorithm improvements, calibration updates, and maintenance fixes without physical access to the system, thereby reducing downtime and simplifying lifecycle management of field-deployed cyber-physical systems (Kubaščík et al., 2024).

6 Conclusion

This study experimentally evaluated a lightweight positioning approach for a pneumatic linear actuator controlled by standard discrete ON/OFF valves. The method combines configuration- and direction-specific pulse-duration–displacement models with position-feedback corrections and was implemented on an ESP32-based controller.

The calibration experiments showed that a first-order linear model provides a close approximation of the dominant pulse-duration–displacement relationship over the evaluated 40–520 ms calibration range. The coefficients of determination exceeded 0.994 for all four identified models. Residual analysis, however, showed that the remaining errors were not normally distributed in all cases, indicating that the linear model does not capture all pneumatic and mechanical effects. The model should therefore be interpreted as a computationally lightweight pulse-duration estimator rather than as a complete physical model of the pneumatic system.

Using an identical sequence of 50 target positions at an operating pressure of 2.5 bar, the Hafner configuration achieved a mean absolute endpoint error of 3.441 mm, whereas the Pneumax configuration achieved 1.495 mm. The corresponding maximum absolute errors were 9.350 mm and 4.200 mm, respectively. Under the evaluated experimental conditions, the Pneumax configuration therefore provided lower endpoint positioning errors, although it also required a greater number of commanded corrective movements.

The observed differences should not be attributed solely to the configured lower pulse-duration limits, since the tested configurations also exhibited different pulse-duration gains, residual behaviour, and short-pulse responses. Furthermore, the results are specific to the tested valve specimens and experimental configuration and should not be interpreted as a general comparison of all Hafner and Pneumax valves.

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