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# Modeling and control of a pneumatic levitator, from the process to plant control

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**Abstract**

This study addresses the modeling, simulation, and control of a pneumatic levitation system to improve its stability and accuracy in regulating the position of a suspended object. A mathematical model is developed based on the laws of fluid mechanics and particle dynamics, which is validated through MATLAB's System Identification tool, allowing the estimation of transfer functions from experimental data.

The system is controlled by implementing a PID controller designed using the root locus method. Various controller configurations were tested on different estimated plants, showing that the best response was achieved using plants identified with normalized data and a 12V step input. The results indicate that the PID controller, after fine-tuning, provides optimal performance in terms of maximum overshoot and settling time.

The study concludes that approximate model identification and the proper selection of controller parameters enable better system stability, facilitating its application in academic and research environments.

**Key words: Automation, Control Systems, Modeling, Pneumatic Levitation**





## Resumen

El presente estudio aborda el modelado, simulación y control de un sistema de levitación neumática con el objetivo de mejorar su estabilidad y precisión en la regulación de la posición de un objeto suspendido, se desarrolla un modelo matemático basado en las leyes de la mecánica de fluidos y la dinámica de partículas, el cual es validado a través de la herramienta System Identification de MATLAB, permitiendo la estimación de funciones de transferencia a partir de datos experimentales. El control del sistema se realiza mediante la implementación de un controlador PID, diseñado con el método del lugar geométrico de las raíces comparando diferentes configuraciones del controlador utilizando con respecto a diferentes plantas estimadas, se observa que la mejor respuesta se obtiene al utilizar plantas identificadas con datos normalizados y una entrada escalón de 12V. Los resultados muestran que el controlador PID ajustado después del diseño proporciona un desempeño óptimo en términos de sobrepaso máximo y tiempo de asentamiento.

El estudio concluye la identificación aproximada del modelo y la correcta elección de los parámetros del controlador que permiten una mejor estabilidad del sistema, facilitando su aplicación en entornos académicos y de investigación.


**Palabras clave: automatización, modelación, levitador neumático, sistemas de control.**

## Introduction

Pneumatic levitation is a physical phenomenon that allows the suspension of an object in the air through controlled airflow. This principle has been applied in various fields of engineering and automation due to its advantages in reducing mechanical friction and component wear (Mosquera *et al.*, 2012). In this context, the development of pneumatic levitators represents an innovative solution for experimentation in control systems, providing a safe and efficient environment for validating advanced control strategies (López & Cadenillas, 2021; Reyes-Orta *et al.*, 2023).

This study addresses the modeling, simulation, and control of a pneumatic levitator designed for the automation and robotics laboratory of a university institution. A fluid dynamics and control theory-based approach is employed to develop a mathematical model that describes the system's behavior. Additionally, a control strategy is implemented to optimize stability and precision in regulating the levitated object's position (González *et al.*, 2004).

Various approaches have been explored in the literature for controlling pneumatic levitation systems. For example, Martínez & Moreta (2025) conducted a comparative study between PID controllers and fuzzy controllers, demonstrating that systems based on fuzzy logic offer advantages in highly nonlinear environments. Additionally, Jernigan *et al.*,

(2008), implemented a remote laboratory based on aerodynamic levitation for teaching fluid dynamics, highlighting the system's applicability in academic and research environments.

## Methods

### General module description

The system consists of a square plastic base with vents that allow airflow toward a direct current motor (a centrifugal fan). This motor is connected to a plastic coupler, which directs the air into a 50 cm acetate tube. Inside the tube, a sphere moves due to the airflow generated by the fan. At the top of the tube, an ultrasonic sensor measures the sphere's position and generates a feedback signal to control its position, as illustrated in Figure 1.

The levitator incorporates an electronic board based on the ESP32 microprocessor (Xtensa Dual-Core 32-bit LX6 with 600 DMIPS), responsible for data acquisition and control operations. Additionally, it includes an L298 H-Bridge module to regulate the fan speed. Finally, the position sensor, located at the top of the tube, is the key component that provides the necessary feedback signal to maintain precise control of the sphere's position. Figure 2 presents the constructed levitator.

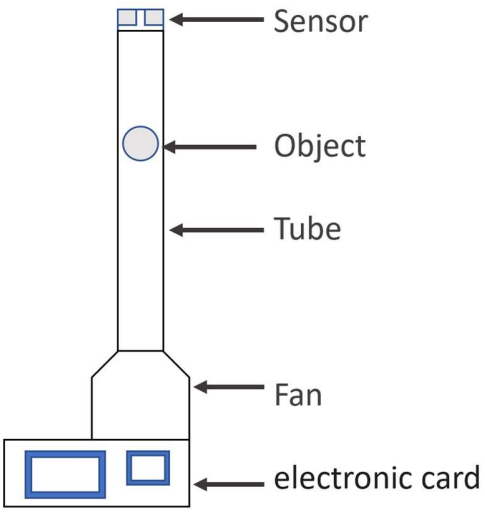



**Figure 1. Pneumatic levitator diagram**



**Figure 2. Constructed pneumatic levitator**




**Obtaining the model of a pneumatic levitator**

The mathematical model of the pneumatic levitator is derived from the application of fundamental laws of fluid mechanics and particle dynamics. Considering Newton's second law for the suspended sphere, Figure 3 illustrates the forces acting on the sphere inside the tube (Jernigan et al., 2008), and the equation of motion is given by:

$$m_b \frac{d^2y}{dt^2} = m_b \frac{dv_b}{dt} = -F_g + F_D \quad (1)$$

Where $m_b$ is the mass of the sphere, $F_g$ is the gravitational force, and $F_D$ is the drag force due to the airflow. These forces are expressed as:

$$F_D = \frac{1}{2} C_D \rho_a A (v_a - v_b)^2 \quad (2)$$

Where $C_D$ is the drag coefficient, $\rho_a$ is the air density, $A$ is the frontal area of the sphere, $v_a$ is the air velocity in the tube, and $v_b$ is the velocity of the sphere.

By combining the previous equations, the differential equation of the system is obtained:

$$m_b \frac{dv_b}{dt} = -m_b g + \frac{1}{2} C_D \rho_a A (v_a - v_b)^2 \quad (3)$$

Similarly, the airflow dynamics inside the tube are modeled by the equation:

$$\frac{dv_a}{dt} = \frac{g(f,y) - v_a}{\tau_a} \quad (4)$$

Where $g(f,y)$ represents the experimental relationship between the fan's operating frequency and the height of the levitated object, and $\tau_a$ is the system's time constant. Finally, by linearizing the model around an equilibrium point and representing it in the Laplace domain, the system's transfer function is obtained:

$$Gp(s) = \frac{K(s+Z)}{(s+P_1)(s+P_2)(s+P_3)} \quad (5)$$

Where $K$ is the system gain, $Z$ is a zero of the system, and $P_1, P_2, P_3$ are the characteristic poles of the system (Jaimes & Arroyave-Giraldo, 2015). Modeled using MATLAB's System Identification toolbox.

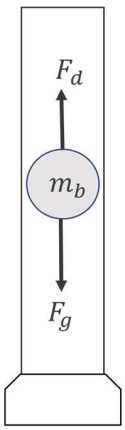



**Figure 3. Forces on the sphere**

**Plant identification from experimental data**

System identification using experimental data is a fundamental process for determining mathematical models that represent the behavior of a physical plant, especially when a predefined model is unavailable or when specific or complete data on the system components are lacking.

In this case, input and output measurements of the pneumatic levitator are collected to fit a dynamic model that describes its response. Based on the experimental data obtained under different operating conditions in response to a step input in open-loop, model-fitting and optimization techniques are used to determine the system's characteristic parameters. This approach allows for the validation of the previously developed theoretical model and enables a more precise adjustment of control strategies.

To analyze the system response, sampling times between 50 and 150 milliseconds were used, resulting in 15 similar data sets, each containing approximately 200 samples. These data were truncated at the settling point due to the presence of a physical limit in the system, to facilitate estimation.Figure 4 presents the plant response for some randomly selected samples.

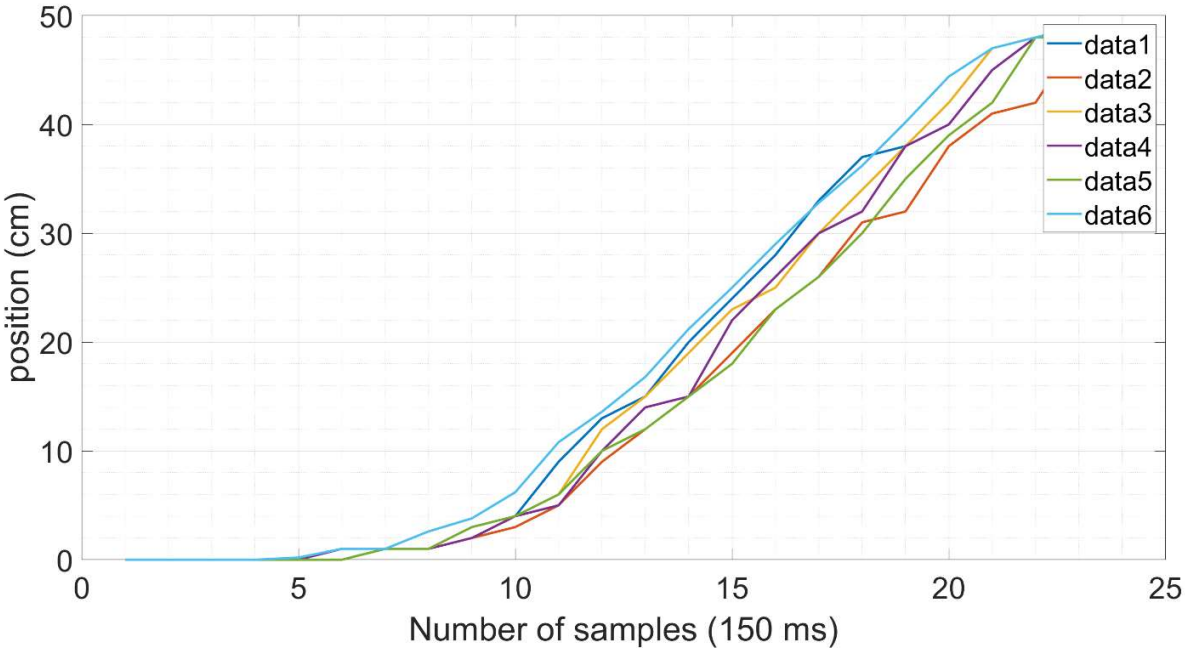



**Figure 4. Data obtained from the plant response to a 12-volt step input.**

For the plant estimation stage, MATLAB's System Identification toolbox is used, in this process, the input signal corresponds to a 12-volt step, while the output is the position of the spherical object inside the acetate tuve, the model estimation is performed by considering the system as a black box, where the internal parameters are unknown, and only the input and output values are available. Figure 5 illustrates the relationship between the experimentally obtained data and the model to be identified. The results obtained for the plant model estimation, considering a sampling time of 150 milliseconds, are shown in Figure 6.

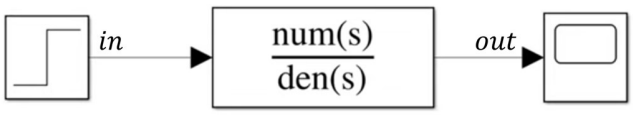



**Figure. 5. Known system data for plant estimation.**

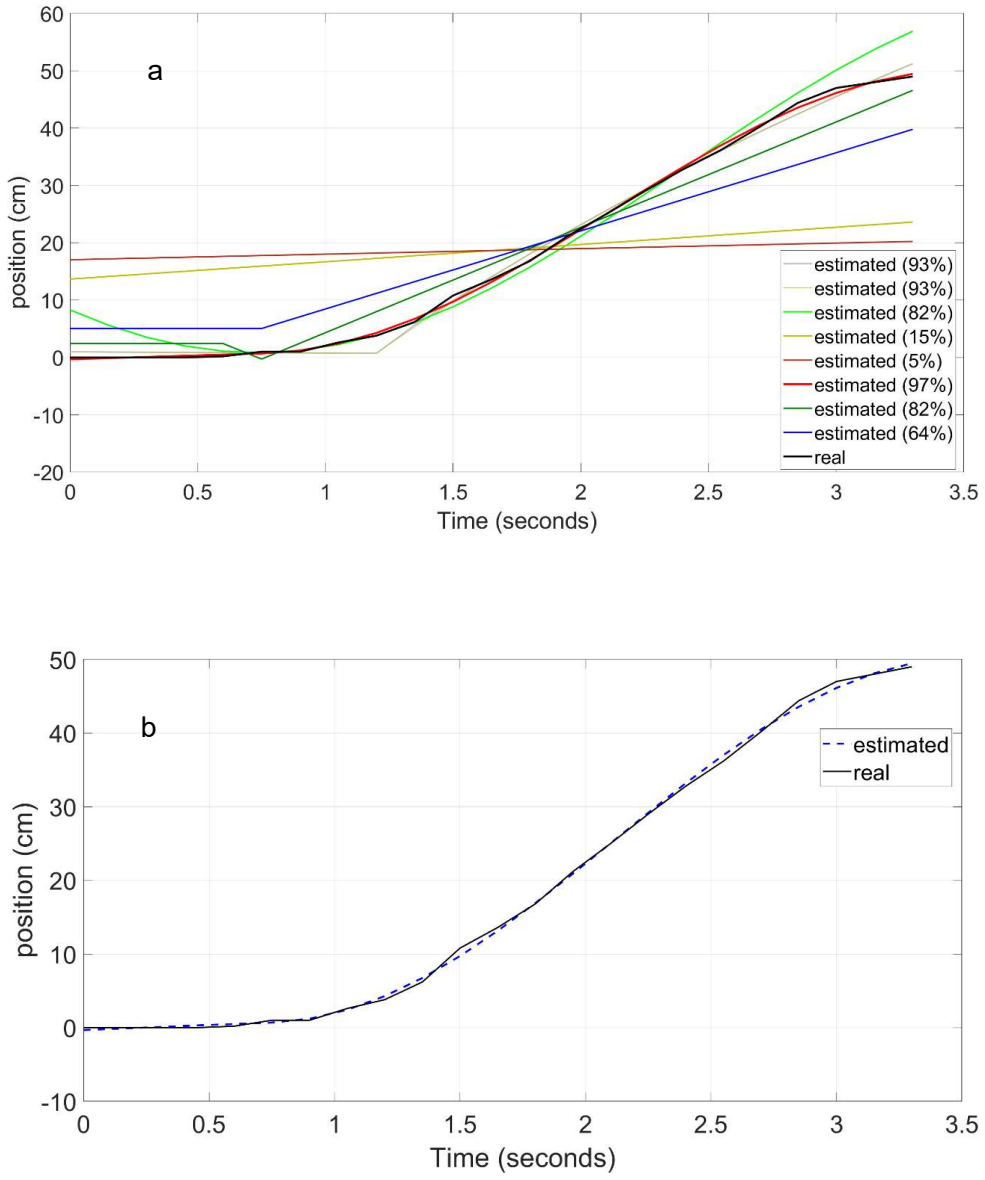



**Figure 6. Plant model estimation. a) Responses obtained in the plant estimation. b) Selected responses in the plant estimation**




In the plant identification process, tests were conducted using both the naturally obtained data from the measurements shown earlier and the normalized data, additionally, a delay of 5 sampling times, equivalent to 0.75 seconds, was introduced, yielding transfer functions and responses that were similar. The best results from each test were selected, and their parameters are shown in the following Table 1.

**Table 1. Estimated transfer functions and their estimation parameters.**

| Estimated transfer functions | Fit estimate |
|---|---|
| Transfer function with natural sensor data and a step input from 0 to 255. $$G1 = \frac{3.798 * e^{-0.75s}}{s^2 + 1.156\,s + 0.5384}$$ | Fit to estimation data: 97.96% (stability enforced)<br>FPE: 0.1976<br>MSE: 0.127 |
| Transfer function with natural sensor data and a step input from 0 to 12 volts. $$G2 = \frac{0.1758 * e^{-0.75s}}{s^2 + 1.114\,s + 0.5483}$$ | Fit to estimation data: 97.94% (stability enforced)<br>FPE: 0.2072<br>MSE: 0.1305 |
| Transfer function with normalized data for both input and output. $$G3 = \frac{0.8788\,e^{-0.75s}}{s^2 + 1.114\,s + 0.5483}$$ | Fit to estimation data: 97.94% (stability enforced)<br>FPE: 7.967e-05<br>MSE: 5.017e-05 |

The model was estimated using MATLAB's TFEST (Transfer Function Estimation) function from time-domain data, where the last plant achieved the best metrics:

Fit to estimation data: 97.94%: This indicates that the model fits the estimation data with an MSE: 5.017e-05: This is the Mean Squared Error (MSE), which measures the average squared difference between the observed values and the values predicted by the model. A low MSE value also indicates a good fit of the model to the data. accuracy of 97.94%. This is a very high value, suggesting that the model is quite accurate.

FPE: 7.967e-05: This is the Final Prediction Error (FPE) value. A low value like this suggests that the model is good in terms of balancing accuracy and complexity.

**Transfer function approximation**

A time delay in the context of process control systems can be defined as the time interval from the application of a control signal to any

observable change in the process variable (Wang *et al.*, 1998). Delays, also known as dead times, are inherent in many physical systems and can complicate the analysis and design of controllers, a system with a delay ($e^{sT}$, where $T$ is the delay time) introduces additional complexity by being nonlinear in the Laplace domain and infinitely dimensional in the time domain, which complicates the use of classical control techniques, such as PID controller tuning and stability analysis.

To make the system more manageable mathematically, a finite-order approximation of the delay is often used. By representing the system with a rational transfer function, manipulation, analysis, and simulation become easier, additionally, techniques such as the root locus or Bode plot can be applied more effectively when the delay is approximated.

However, the delay approximation must consider key aspects such as accuracy in the frequency range of interest, system stability, and computational complexity in some cases, if the digital implementation allows, it may be preferable to work directly with the exact delay rather than an approximation. There are several ways to approximate a delay e^(-sT). In this work, the Padé approximation method is used, which approximates the delay as a rational function (quotient of polynomials in s).

$$e^{-sT} \approx \frac{1+\frac{sT}{2}}{1-\frac{sT}{2}} \tag{5}$$

Using the Padé function in MATLAB with a first-order approximation, the following transfer functions were obtained.

**Table 2. Approximations of the transfer functions estimated with delay.**

| Transfer function with delay | Approximation |
|---|---|
| $G(s) = \frac{3.798 * e^{-0.75s}}{s^2 + 1.156\,s + 0.5384}$ | $G(s) = \frac{-3.798\,s + 10.13}{s^3 + 3.823\,s^2 + 3.621\,s + 1.436}$ |
| $G(s) = \frac{0.1758 \cdot e^{-0.75s}}{s^2 + 1.114s + 0.5483}$ | $G(s) = \frac{-0.1758\,s + 0.4688}{s^3 + 3.781\,s^2 + 3.519\,s + 1.462}$ |
| $G(s) = \frac{0.8788\,e^{-0.75s}}{s^2 + 1.114\,s + 0.5483}$ | $G(s) = \frac{-0.8788\,s + 2.343}{s^3 + 3.781\,s^2 + 3.519\,s + 1.462}$ |

## Results and discussion

### PID controller design and application

Once the estimated and linearized transfer functions were obtained, tests were conducted to design and apply PID controllers. It was observed that the controllers designed with the plants using a 12-volt step input and normalized data provided better results compared to those designed for the plant with a step input of 255, this difference can be attributed to the more consistent linearity and scaling of the normalized signals, which improves the model's ability to capture the real system dynamics. All the designed PID controllers were obtained using the root locus method, considering the same requirements of a maximum overshoot $MP = 15\%$ and a settling time $t_s = 7$ In particular, the controller for the plant identified with normalized data not only met these specifications but also demonstrated greater robustness to setpoint variations and noise, thus validating its applicability in real experimental environments. Finally, the controller constants were determined as $K_p = 1.2748, K_i = 0.3613$, and $K_d = 1.1246$, demonstrating satisfactory performance in controlling the plant, as seen in Figure 7.

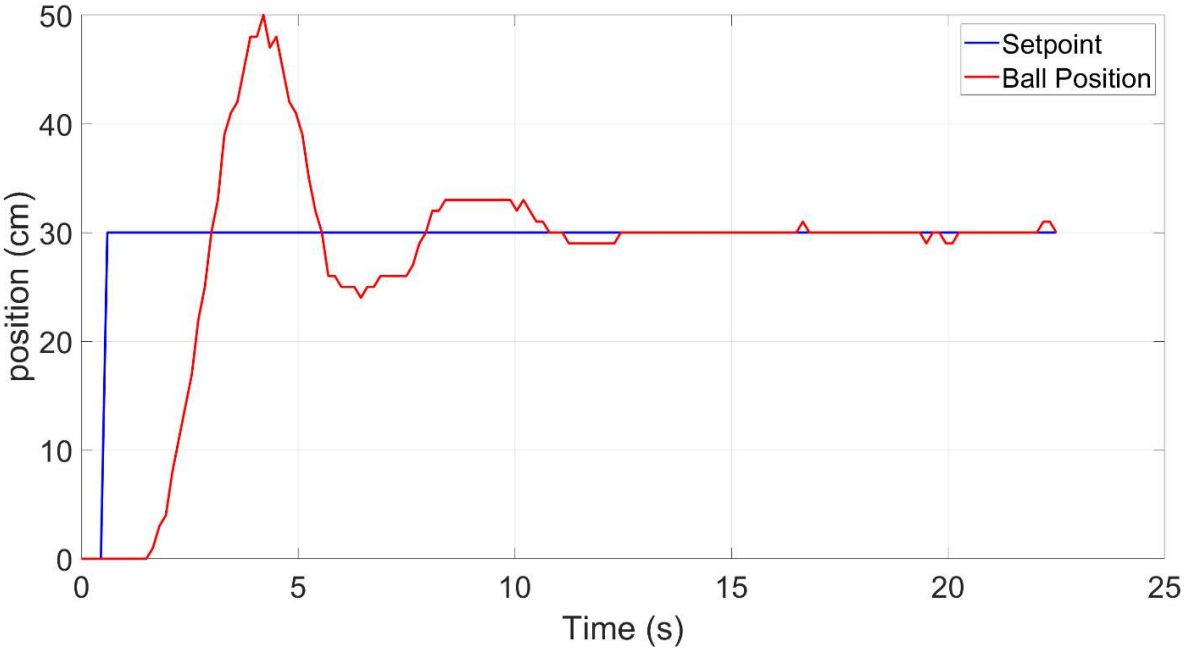



**Figure 7. Response of the levitator with the applied PID controller.**

However, by adjusting the constant values, the controller's performance applied to the physical plant was further improved. Figure 8 shows the controller's performance when assigning different reference values (setpoints) to assess its response under various operational scenarios.

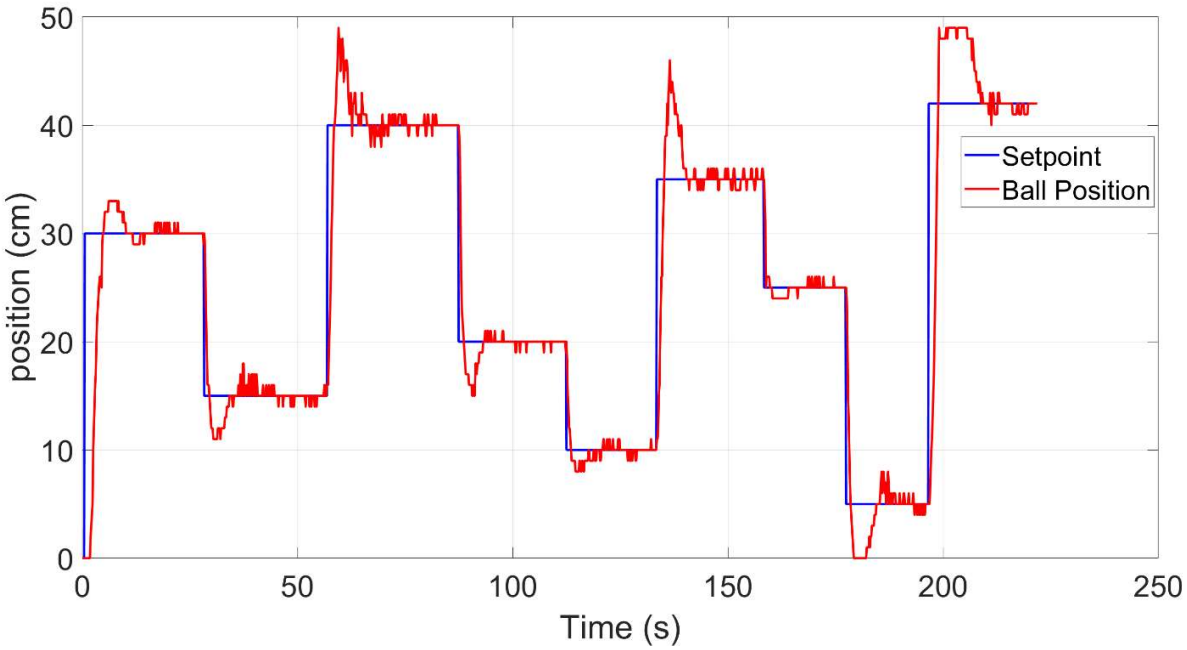



**Figure 8. Controller performance when assigning different reference values (set points).**

In comparison with other studies, such as that of Jaimes & Arroyave-Giraldo (2015), where a PID controller was also implemented on a pneumatic levitation system, similarities can be observed in the design approach, but there are significant differences in the accuracy of the identified model and the final performance of the controller. On the other hand, the work by Hernández Miguel *et al.*, (2015) presents an implementation based on low-cost technologies such as Arduino, in which additional techniques like Wavelet filtering were explored to mitigate noise and improve the robustness of the system, in contrast, the present study demonstrates that proper model identification and accurate PID controller tuning can achieve outstanding performance without the need for complex filters, simplifying its implementation and making it more accessible for academic and educational applications.

## Conclusion

This study addressed the modeling, simulation, and control of a pneumatic levitator, successfully




identifying a mathematical model from experimental data. Using MATLAB's System Identification tool, transfer functions were obtained, which enabled the design of more efficient control strategies.

It was demonstrated that the use of normalized data in the identification process improves the stability and accuracy of the designed controllers. The PID controller designed using the root locus method showed optimal performance when applied to the actual plant with a 12V step input.

Tuning the PID constants further improved the system's response, achieving more precise control of the levitated object's position. This highlights the importance of proper tuning when implementing controllers in physical systems with inherent delays.

Finally, the study reaffirms that correct model identification and proper selection of control parameters are fundamental for designing efficient strategies in pneumatic levitation systems, with potential applications in education, research, and industrial automation.

## Conflict of interests

The authors declare that there is no conflict of interests.

## Acknowledgments

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