FUZZY CONTROL STRATEGIES APPLIED TO AN AIR LEVITATION SYSTEM

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ABSTRACT

Pneumatic systems are known for their nonlinear characteristics and susceptibility to disturbances from turbulences in airflow, which make them interesting for validating control strategies in academic studies. This work presents the development and control of a didactic system for vertically positioning a ball via an airflow, a device known as Air Levitation system. The main constructive aspects of the considered low-cost Air Levitation system are described in this paper. Furthermore, three fuzzy control strategies (PD-Fuzzy, Incremental PD-Fuzzy, and PD-Fuzzy+I) were implemented in this system for comparative purposes. The controllers were implemented through the Matlab/Simulink® software along with an Arduino UNO board. Finally, the experimental results of the fuzzy control strategies are presented, and their main differences are highlighted.

KEYWORDS: *Air Levitation System, Fuzzy Control, Intelligent Control, Didactic System*

I. INTRODUCTION

Levitation is the process of suspending an object against gravity using a physical force [1]. In this sense, an Air Levitation system is a device designed to lift an object vertically through a variable airflow [2 - 4]. Such devices are an interesting option as a didactic plant for studying control systems since they present fast nonlinear dynamics, and they are susceptible to disturbances from turbulence and other unexpected events involving airflow characteristics, as well as the physical features of the object to be positioned [5 - 7]. It is important to note that the literature in the area classifies these systems as pneumatic because air is the necessary fluid for moving the object, even though the airflow is not pressurized.

There are papers dealing with Air Levitation systems in the literature. [8] presented the construction and control of a double reverse pneumatic levitation using two fans, in which the action of one fan directly interferes with the control action of the other. Using a decoupler, the authors used decentralized Proportional-Integrative (PI) controllers to control such a system. [9] showed that, besides the classic Proportional-Integral-Derivative (PID) controller, several nonlinear modifications can be implemented to deal with different control needs.

The papers [10 - 12] presented didactic Air Levitation systems to help students visualize and understand theoretical concepts in control engineering using Matlab/Simulink® to control the systems. In [13], the authors developed a ball levitation system and perform a parametric mathematical modelling of it, whose parameters were estimated using a nonlinear least squares method based on experimental data.

A robust control approach using sliding mode was reported in [14], while [15] proposed a robust switched control strategy for Air Levitation systems with minimum sensing. Additional configurations of Air Levitation systems can be found in [16 - 18].

Most cited works consider classic control strategies, such as the PID controller and its variations. However, the Air Levitation system exhibits a nonlinear behaviour, which increases the complexity of the mathematical modelling of the system and, consequently, makes the design of controllers based on the plant model challenging. In order to mitigate these situations, fuzzy control strategies are valid alternatives, given that the design of most of these types of controllers typically relies on expert's knowledge of the plant [19].

In general, promising results have been observed from the application of fuzzy controllers in control systems. For example, in [20], a PD-Fuzzy controller, inspired by the conventional Proportional-Derivative (PD) controller, along with a reinforcement learning method, was used in the simulation of an unstable nonlinear system to enhance the closed-loop dynamic response and eliminate the steady-state error of the system. [21] presented the application of an Incremental PD-Fuzzy to control corrosion in gas pipelines. The authors compared the conventional PI controller and the proposed one, and the results show that the fuzzy controller outperforms its conventional counterpart. Finally, [22] proposed a PD-Fuzzy+I controller for tracking control, which is inspired by a conventional linear PID controller.

The PD-Fuzzy control is used in various applications. For example, it is used to stabilize a Quadcopter in [23], to control a motor-driven inverted pendulum-cart system in [24], and to control the position of an aeropendulum in [25]. [26] used PI-Fuzzy, PD- Fuzzy, and a combination of two independent conventional fuzzy logic controllers for balancing a two-wheel inverted pendulum. [27] presented an incremental fuzzy control strategy for the water membrane evaporator cooling loop of a Mars spacesuit.

Based on the presented considerations, this work proposes the development of an Air Levitation system where a ball is positioned using airflow provided by a fan. Furthermore, this work presents the design of different fuzzy controllers for this system, and the closed-loop system results are compared.

The main contributions of this work can be summarized as follows:

• It presents constructive characteristics of a didactic Air Levitation system, highlighting the low-cost and accessible components, such as structures developed using 3D printers and Arduino control hardware with compatible devices.

• It details the design and implementation of three distinct fuzzy control strategies.

• It compares the performance of the fuzzy control strategies used in this work, namely PD-Fuzzy, Incremental PD-Fuzzy, and PD-Fuzzy+I.

The rest of this paper is organized as follows: Section 2 presents the constructive characteristics of the proposed system; the three fuzzy control strategies used in this work are presented in Section 3; results and discussions are presented in Section 4; the main conclusions are drawn in Section 5.

II. SYSTEM DESCRIPTION

The Air Levitation system consists of a tube positioned vertically with a ball inside. A distance sensor is attached at the upper end of the tube to measure the vertical position of the ball. At the same time, a fan (commonly found in desktop computers) and a base (made with the aid of a 3D printer), which connects the tube to a support structure, are positioned at the lower end of the tube to provide the airflow needed to move the ball inside it, as shown in Figure 1.

In the presented system (see Figure 1), the objective is to control the ball's vertical position by modifying the fan's airflow. For this, an Arduino UNO board was used to receive the signals measured by the distance sensor and send them to the computer. The control strategy is implemented via Matlab/Simulink® software, and the resulting control action is sent to the Arduino UNO board, which sends the corresponding PWM signal to a motor shield driver connected to the fan.

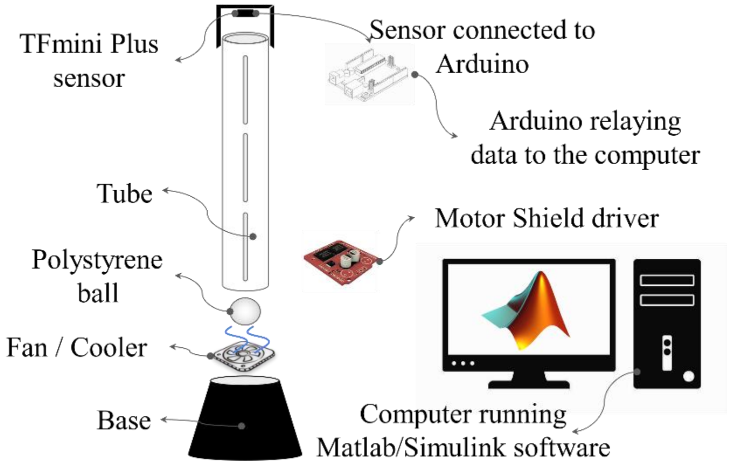

Figure 1. Air Levitation system scheme.

The low-cost Air Levitation system developed in this work and the main characteristics of the structural and electronic components used are shown in Figure 2 and in Table 1, respectively [28].

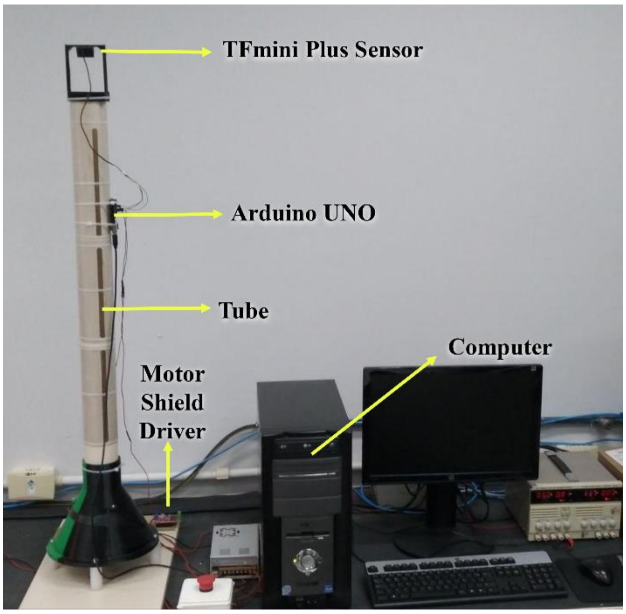

Figure 2. Air Levitation system.

III. Fuzzy Control Strategies

To design the fuzzy control strategies for the Air Levitation system, a closed-loop diagram shown in Figure 3 was considered. The aim was to control the ball in vertical position by modifying the airflow provided by the fan. The design of all fuzzy controllers considered in this work was based on the Mamdani inference method [19], which is commonly used in fuzzy control applications. The Mamdani method allows for creating a set of fuzzy rules that map input variables (in this case, the ball's vertical position and its change in position over time) to an output control action (the PWM signal sent to the fan driver).

Table 1. Characteristics of the main components of the Air Levitation system.

Components	Characteristics
Ball	Weight: 4 g. Diameter: 7 cm.
Tube	Length: 90 cm. Diameter: 7.2 cm.
Arduino UNO	Communication: UART with the sensor and Serial with the computer.
TFmini Plus sensor	Resolution: 1 cm. Range: 0.1 – 5 m.
Motor Shield driver VNH2SP30	Maximum operating current: 30 A. Maximum operating voltage: 16 V. PWM input current: 10 mA.
Fan	Dimension: 12x2.5x12 cm.

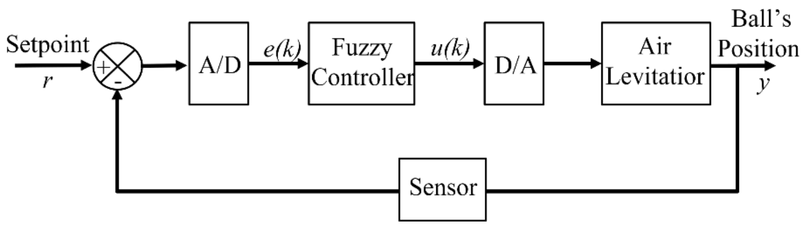

Figure 3. Block diagram of the closed-loop Air Levitation system using a fuzzy controller.

The fuzzy controllers were implemented using Matlab/Simulink® software, and their behaviors were evaluated and compared using different performance indices, as described in Section 4.

This work considered three fuzzy control strategies: PD-Fuzzy, Incremental PD-Fuzzy, and PD-Fuzzy+I. The dynamics of the control action in each strategy are inspired by the typical response of conventional PD, PI, and PID controllers, respectively. The main difference is that the fuzzy design is based on expert's knowledge of the system to be controlled and not on the system's mathematical model, as in conventional strategies. Each strategy is described in the following subsections.

The linguistic variables used in the design of the fuzzy controllers are given in Table 2. The fuzzifications were carried out using the universe of normalized speech for all the linguistic variables. It is worth noting that not all the linguistic variables described in Table 2 were used for all the variables involved in each controller. This was because the selection of linguistic variables for each controller was based on the expert's knowledge of the system and the specific control objective.

Table 2. Linguistic variables used in the design of the fuzzy controllers.

Symbol	Linguistic variable
N	Negative.
NL	Negative Large.
NM	Negative Medium.
NS	Negative Small.
Z	Zero.
PS	Positive Small.
PM	Positive Medium.
PL	Positive Large.
P	Positive.

3.1. PD-Fuzzy Strategy

The PD-Fuzzy control strategy considers a controller with two inputs ($e(k)$ and $\Delta e(k)$) and one output ($u(k)$), as shown in Figure 4. The inputs consist of the error and the variation of the error, calculated using (1) and (2), respectively. In these equations, $SP(k)$ is the setpoint value at the k-th instant; $y(k)$ is the system's output; and dt is the sampling time.

$$e(k) = SP(k) - y(k) \quad (1)$$

$$\Delta e(k) = \frac{e(k) - e(k-1)}{dt} \quad (2)$$

Figure 4. Diagram of the PD-Fuzzy strategy.

The membership functions defined for the error ($e(k)$), for the error variation ($\Delta e(k)$) and for the output ($u(k)$) are shown in Figures 5-7, respectively. The linguistic variables used are described in Table 2.

The PD-Fuzzy structure described in this section generally presents a fast response to input variations. However, an acceptable steady-state error in the system response is expected, due to its similarity with the conventional PD controller [19].

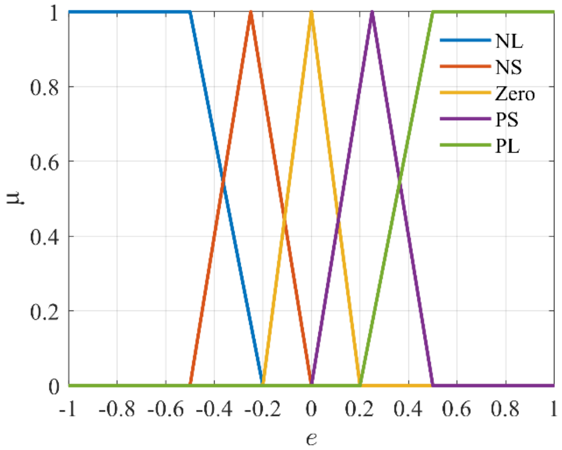

Figure 5. PD-Fuzzy: membership functions for the error variable ($e(k)$).

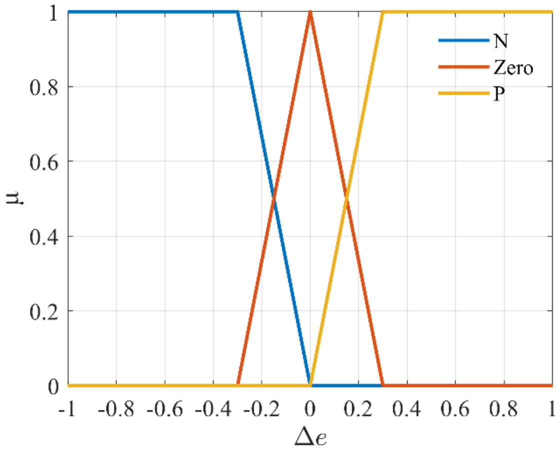

Figure 6. PD-Fuzzy: membership functions for the variation of the error ($\Delta e(k)$).

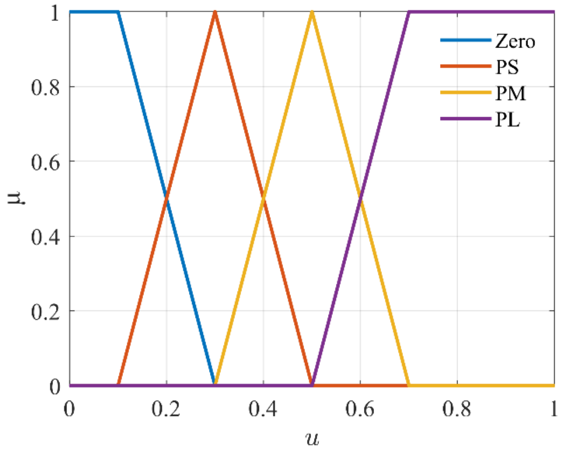

Figure 7. PD-Fuzzy: membership functions for the output ($u(k)$).

From the established base rule, the response surface is shown in Figure 8.

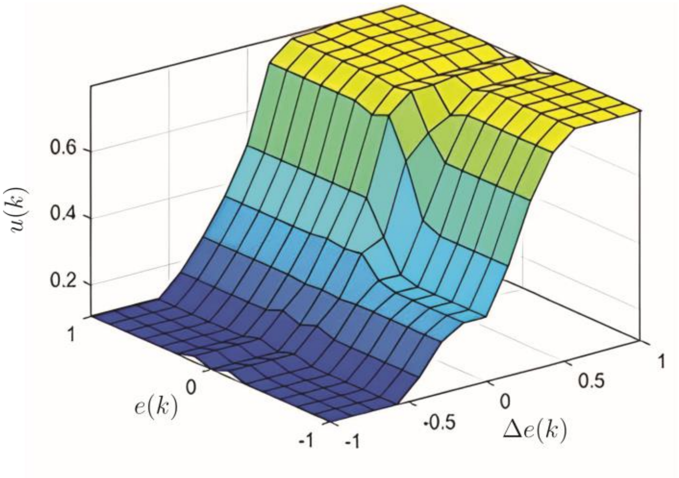

Figure 8. PD-Fuzzy: response surface.

3.2. Incremental PD-Fuzzy Strategy

The Incremental PD-Fuzzy strategy is shown in Figure 9. Its structure is almost the same as that for PD-Fuzzy (Figure 4), with the error ($e(k)$) and the variation of the error ($\Delta e(k)$) as inputs, but its output ($u(k)$) passes through an integrator to generate the resulting control action ($U(k)$).

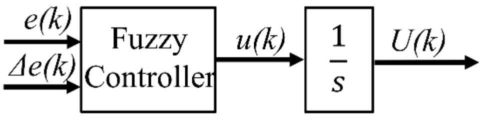

Figure 9. Incremental PD-Fuzzy diagram.

The membership functions for the variables $e(k)$, $\Delta e(k)$, and $u(k)$ are shown in Figures 10-12, respectively, and the linguistic variables used are described in Table 2.

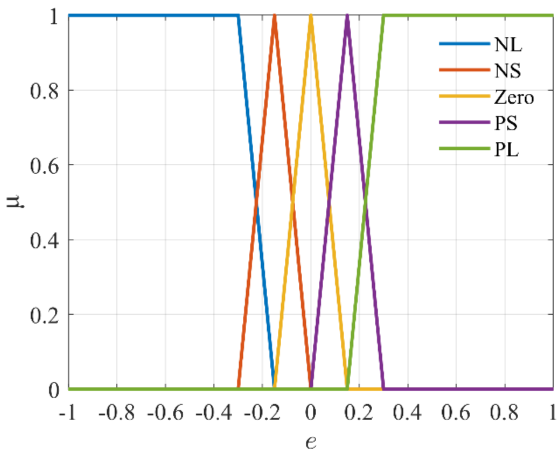

Figure 10. Incremental PD-Fuzzy: membership functions for the error variable ($e(k)$).

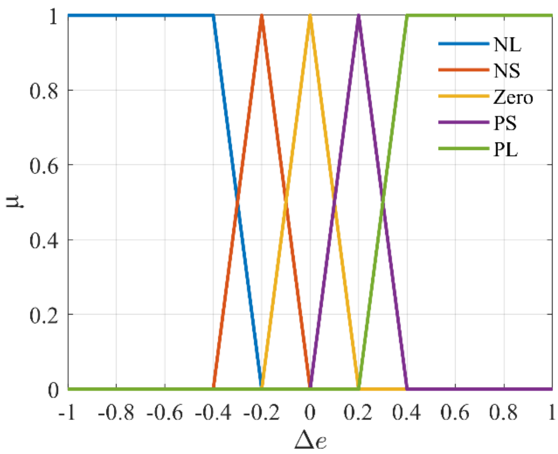

Figure 11. Incremental PD-Fuzzy: membership functions for the variation of the error ($\Delta e(k)$).

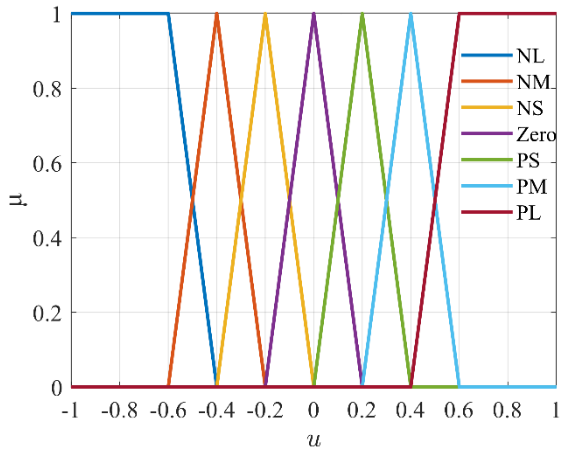

Figure 12. Incremental PD-Fuzzy: membership functions for the output ($u(k)$).

The Incremental PD-Fuzzy controller's response surface is shown in Figure 13.

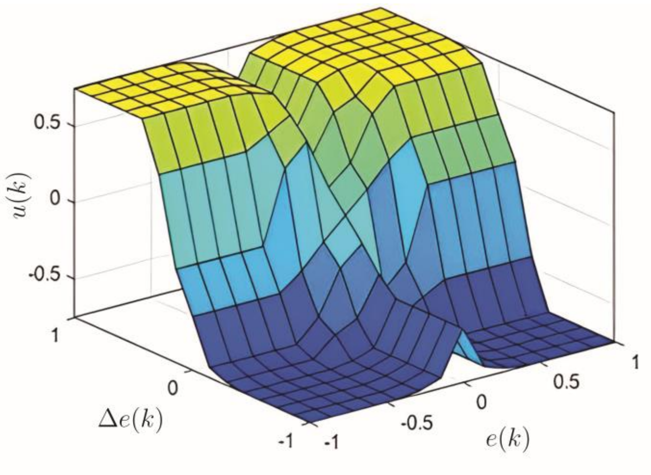

Figure 13. Incremental PD-Fuzzy: response surface.

The incremental structure (Figure 9) presents a significant reduction of the steady-state error, as it is inspired by the typical response of a conventional PI controller [29].

3.3. PD-Fuzzy+I Strategy

The PD-Fuzzy+I strategy is shown in Figure 14. It can be observed that the PD-Fuzzy structure in Figure 4 is preserved, and the error integral ($E(k)$) is added to the controller output ($u(k)$) to generate the control action ($U(k)$). The main reason for directly adding the integral action to the PD-Fuzzy output is to avoid increasing the rule base of the controller by including a third variable, as explained in [19].

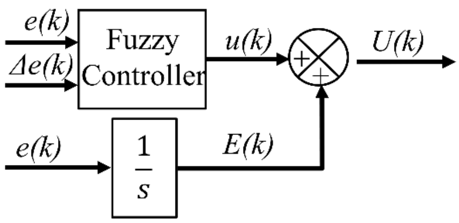

Figure 14. PD-Fuzzy+I diagram.

In the PD-Fuzzy+I strategy used in this work, the same membership functions and rule base as in the PD-Fuzzy were used (Figures. 5-8).

IV. EXPERIMENTAL RESULTS

This section presents the experimental results of implementing each control strategy described in Section 3 in closed loop with the Air Levitation system described in Section 2. During the tests, the system was submitted to step-like references. The objective was to analyse the main differences in the performance of the control strategies, considering indices based on error. The indices considered were the Integral of the Absolute Magnitude of the Error (IAE), the Integral of the Square of the Error (ISE), the Integral of Time Multiplied by the Squared Error (ITSE), and the Integral of Time Multiplied by the Absolute Value of the Error (ITAE), described in equations (3)-(6), respectively.

$$\text{IAE} = \int |e(t)|\, dt \tag{3}$$

$$\text{ISE} = \int e(t)^2\, dt \tag{4}$$

$$\text{ITSE} = \int t \cdot e(t)^2\, dt \tag{5}$$

$$\text{ITAE} = \int t \cdot |e(t)|\, dt \tag{6}$$

Initially, a reference (Setpoint - SP) of 40 cm (height of the ball inside the tube) was defined. The responses of the PD-Fuzzy, Incremental PD-Fuzzy, and PD-Fuzzy+I strategies are shown in Figure 15. In a general analysis of this experiment, it is possible to observe that the three controllers were effective in taking the ball to the desired height (40 cm). However, the Incremental PD-Fuzzy controller took longer to accommodate and caused a high overshoot in relation to the other controllers.

Figure 16 shows the control actions referring to the responses in Figure 15, in the percentage of the PWM signal. It is noticed that the PD-Fuzzy and PD-Fuzzy+I controllers presented similar control actions. However, the PD-Fuzzy+I controller had smaller oscillations from 20 seconds of experiment, which agrees with the indices presented in Table 3.

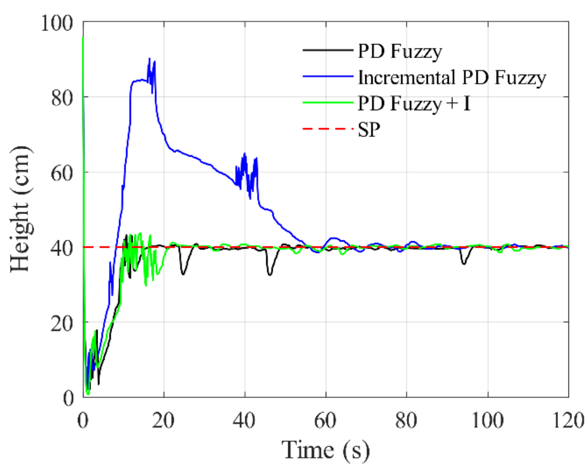

Figure 15. System response with SP of 40 cm.

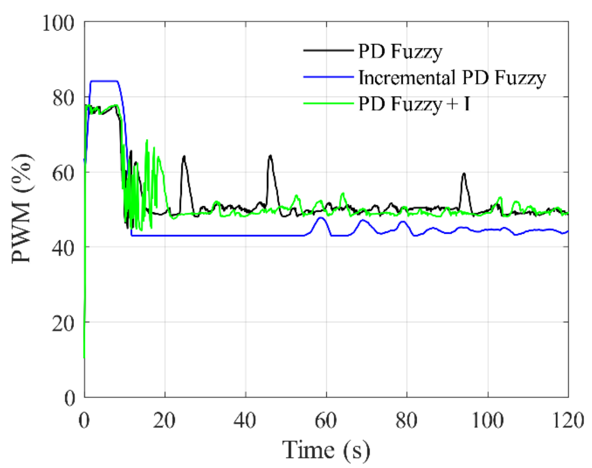

Figure 16. Control action with SP of 40 cm.

In order to test the controllers at another SP level, a desired height of 60 cm was considered. The system's output for this new test with the different controllers are shown in Figure 17, and the respective control actions in Figure 18. As in the previous test, all controllers brought the system's output to the desired reference value. As expected, the Incremental PD-Fuzzy took longer to accommodate and showed a higher overshoot. However, the PD-Fuzzy+I controller kept the system's output around the reference with smaller oscillations than the PD-Fuzzy performance. During the PD-Fuzzy+I experiment, there were two moments after 100 seconds where turbulences in the airflow occurred, as highlighted in red in Figure 17. In these moments, it was required a quick controller action to correct, as shown in the evolution of the control action in Figure 18.

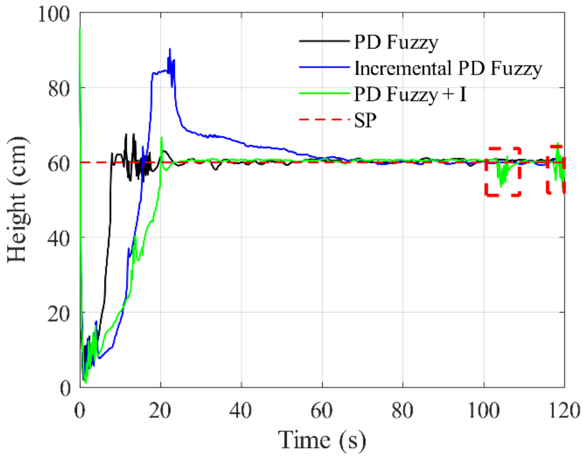

Figure 17. System response with SP of 60 cm.

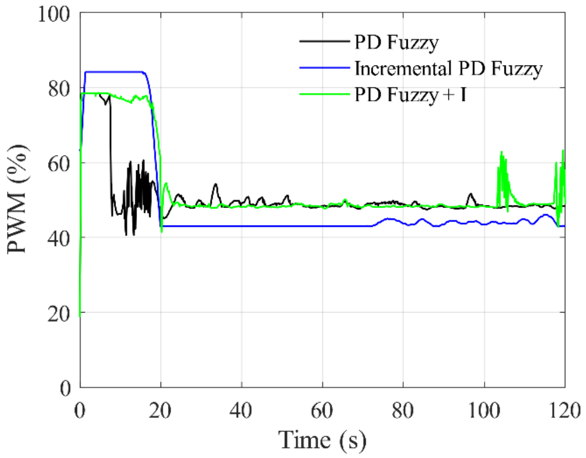

Figure 18. Control action with SP of 60 cm.

Since it was possible to verify that the control actions of the strategies presented adequate responses for the plant under study, the strategies were also tested in two additional experiments with variations in the reference.

In the first variation condition, the SP was initially set at 40 cm, and after 90 seconds, it was changed to 60 cm. The system's output is shown in Figure 19. In this experiment, turbulences occurred in the airflow for all three controllers. The controllers' behavior demonstrates their ability to deal effectively with unpredictable situations. However, the Incremental PD-Fuzzy strategy was the least efficient in terms of speed in bringing the output value to the SP, particularly when considering the high overshoot. Figure 20 displays the control actions carried out by the controllers to position the ball at the desired references.

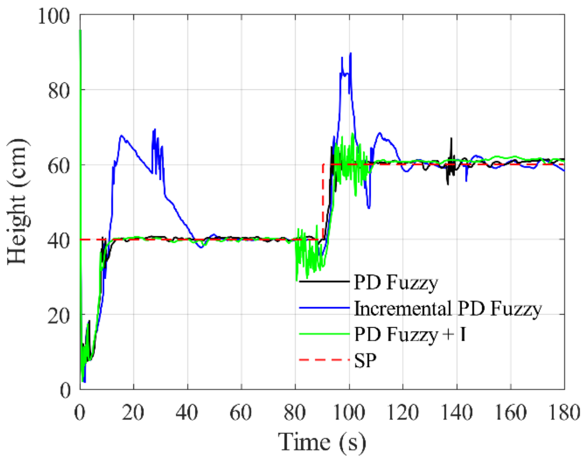

Figure 19. System response with reference variation: 40 cm to 60 cm.

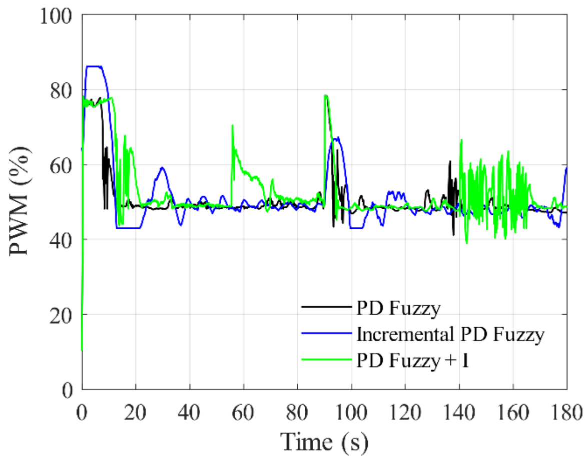

Figure 20. Control action with reference variation: 40 cm to 60 cm.

In a second experiment with reference variation, the SP was initially set at 60 cm, and after 90 seconds, it was changed to 40 cm. The system's output is shown in Figure 21. In this experiment, it can be observed that the PD-Fuzzy+I controller resulted in the lowest steady-state error, despite the occurrence of unexpected turbulence in the airflow and other factors related to distance sensor measurements (e.g., the presence of unexpected peaks). Figure 22 shows the control actions of each controller.

After conducting the four experiments, performance indices based on error were calculated for each control strategy. The performance indices considered were IAE, ISE, ITSE, and ITAE, as described in equations (3)-(6), respectively. It is worth mentioning that the IAE (equation (3)) provides an overview of the error throughout each experiment, while the ISE (equation (4)) emphasizes small errors. The ITSE (equation (5)) emphasizes even small steady-state errors, whereas the ITAE (equation (6)) does not emphasize small values [30]. The results of the indices for each control strategy are presented in Table 3.

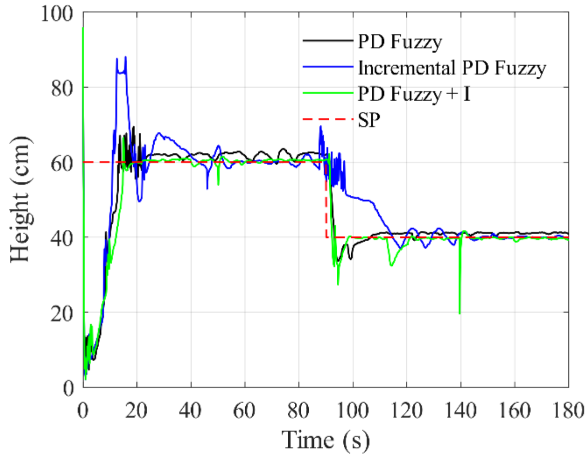

Figure 21. System response with reference variation: 60 cm to 40 cm.

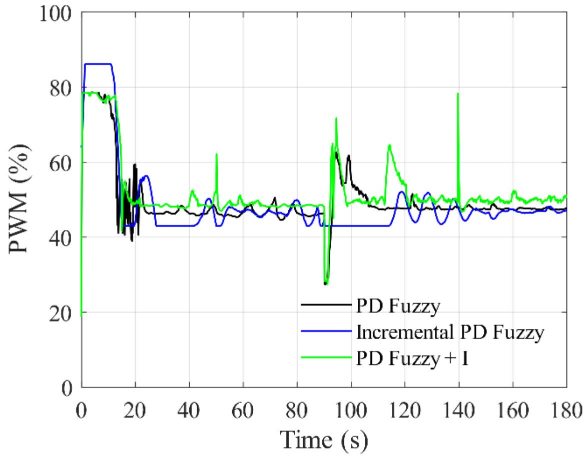

Figure 22. Control action with reference variation: 60 cm to 40 cm.

According to the data presented in Table 3, different characteristics can be observed among the implemented strategies. Regarding the PD-Fuzzy strategy, it presented the best indices (lowest value) for most of the experiments, except for those with SP fixed at 40 cm and two indices (IAE and ITAE) in the variation from 60 cm to 40 cm. On the other hand, the Incremental PD-Fuzzy strategy presented the worst indicators (highest value in the compared metric) in all experiments, mainly due to the high overshoot and slower response compared to the other strategies. Finally, the PD-Fuzzy+I strategy demonstrated a balance between the speed of action and the reduction of the steady-state error, presenting the best indicators in all experiments with SP fixed at 40 cm and in two indices (IAE and ITAE) in the variation from 60 cm to 40 cm.

V. CONCLUSIONS

This paper describes the design and control of an Air Levitation system that uses airflow variation to position a ball. It also evaluates the performance of three fuzzy controller strategies: PD-Fuzzy, Incremental PD-Fuzzy, and PD-Fuzzy+I. Experimental results are presented, where the system's response is analysed for fixed reference values and variations of the reference throughout the experiment.

From the results presented, it was noted that all strategies were able to control the system effectively, that is, they took the controlled variable around the desired reference, with acceptable error values, despite unexpected situations of turbulence in the airflow, which is common to occur in any real systems.

Table 3. Performance indices.

		Setpoint			
		40	**60**	**40/60**	**60/40**
IAE ($\times 10^3$)	**PD-Fuzzy**	0.33	0.40	0.37	0.77
	Incremental PD-Fuzzy	1.22	1.11	0.93	1.01
	PD-Fuzzy+I	0.32	0.78	0.60	0.68
ISE ($\times 10^3$)	**PD-Fuzzy**	7.26	14.98	6.60	21.15
	Incremental PD-Fuzzy	32.96	33.57	16.20	26.04
	PD-Fuzzy+I	6.80	29.23	10.63	22.02
ITSE ($\times 10^3$)	**PD-Fuzzy**	36.18	50.89	99.36	201.83
	Incremental PD-Fuzzy	628.50	389.61	588.47	486.99
	PD-Fuzzy+I	28.70	200.27	196.08	207.18
ITAE ($\times 10^3$)	**PD-Fuzzy**	5.18	5.28	16.59	28.57
	Incremental PD-Fuzzy	31.87	35.51	51.82	42.43
	PD-Fuzzy+I	4.20	10.85	27.39	18.76

The Incremental PD-Fuzzy and PD-Fuzzy+I strategies resulted in a reduction of steady-state error, whereas the PD-Fuzzy showed a fast response with significant oscillations. Although the Incremental PD-Fuzzy reduced the steady-state error, it produced high overshoots.

In general, the results demonstrate that the fuzzy control strategies, categorized as intelligent control, are viable options for controlling systems when mathematical models are not available, and the controller relies on expert's knowledge of the system, as was the case for the implemented strategies.

For future work, it is suggested to evaluate the performance of the controllers using other reference signals, such as sinusoidal inputs, and at SP levels different from those tested in this study.

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