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Advanced Controllers for Level and Temperature Process Applied to Virtual Festo MPS® PA Workstation

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***Abstract*— In this research work, three advanced control algorithms are designed, implemented, and compared to control level and temperature processes in a virtualized Festo Modular Production System of Automatic Processes (MPS® PA) workstation, with an educational focus. A traditional PID control strategy is designed using the lambda tuning technique for each variable, the second controller designed is a fuzzy PD controller with integral action at the output and finally, a Model Predictive Control (MPC) algorithm is designed. These three controllers have as objectives, to minimize the error in steady-state and reduce the sudden actions of control, the three control strategies are compared and the maximum overshoot, error in steady-state and settling time are evaluated as performance indicators, moreover, the actuator performance is analyzed. The design of the Festo MPS® PA virtual workstation is also part of this research work. The gamification of the station allows teaching and learning control techniques under a controlled industrial environment. The designed virtual station has physical and operational characteristics identical to the real station with all its instruments virtualized in 3D using Computer-Aided Design (CAD). The controllers designed for the two variables were implemented in Matlab. The mathematical model of processes is linked to the Unity software through shared memory. The results indicate that the advanced controllers (diffuse and MPC) obtained the best performance, which allows increasing the actuators' lifetime.**

***keywords*——Festo MPS® PA, Fuzzy controller, PID, MPC controller, Unity, virtual laboratory, virtual reality.**

I. Introduction

The gamification of industrial processes has allowed the virtual representation of fully equipped laboratories to improve learning and implementation of advanced controllers for industrial-processes automation [1]. The classical teaching and learning methodology is based on laboratory practices with real equipment. Those laboratories are not efficient when the number of students is high or the available time per student is reduced. In this work, the use of virtual laboratories does not seek to replace real processes, but rather to support the teaching-learning process. It is worth mentioning that in the current lockdown they have become an important supplementary teaching tool [2].

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Regarding the virtualization of industrial processes, stations with training purposes have been presented, such as the gamification of oil processes [3] and the food industry [4].

Virtual laboratories have also been reported for the automation area that include systems of the type: single-input simple-output (SISO) [5]. Unlike these works, no virtualization of the Festo MPS® PA station has been reported on gamification platforms, for this reason, this research paper dedicates a section for the virtualization of the level and temperature processes in the Festo MPS® PA work station.

Currently, industrial processes require controllers that allow the regulation of the optimal operation of the processes and guarantee the correct operation of the actuators. In this context, it is necessary to optimize the classical control techniques and overcome the current limitations through the design of advanced and intelligent controllers.

Within the context of the implementation and performance of controllers in real Festo MPS® PA stations some works have been reported. In [6] implemented a software interface that remotely controls the Festo MPS® PA station. The Operator can see the performance of the system by applying a control technique through a camera placed on the actual station. In [7] simulated a fractional-order controller for the pump in the real Festo MPS® PA station. In that work, only level control was considered. In [8] compared a classical PID control technique with a modern Linear-Quadratic-Regulator (LQR) control technique on the Festo MPS® PA workstation. The authors noted the need for a model-based predictive control (MPC) to improve the results. Finally, in [9] developed an advanced control strategy, based on fuzzy logic, for a Festo mixing and filtering station. In that work, both flow and pressure processes were controlled. However, does not propose predictive control algorithms that apply to both processes of the workstation [9].

In this research work, the comparison of the performance of three control strategies is proposed: a traditional PID based on lambda tuning, a fuzzy PD controller with integral action, and a model-based predictive control strategy. These three strategies are implemented in the Festo MPS® PA virtual station, in real-time. The immersive virtualization of the station is also part of this work, where virtual laboratory practices are carried out remotely to control the level and temperature variables.

II. Festo MPS® PA Workstation Description

The operation of the virtualized Festo MPS® PA workstation is described below. This research work uses the virtual workstation to implementation and comparison of the three control algorithms.

The P&ID Diagram of the workstation used for virtualization is shown in Fig. 1. This workstation allows the user to control

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both level and temperature. The level control of tank B102 works by the control action of pump P101, which pumps the liquid from tank B101 and delivers it to storage tank B102. The temperature of the liquid in tank B101 is controlled by the heater E104 embedded in one of the walls of the tank, this allows heating the contained liquid.

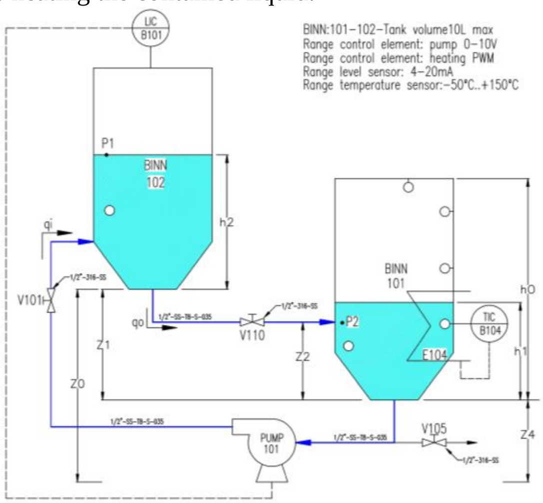

Fig. 1. P&ID diagram Festo MPS® PA workstation.

III. Virtualization Methodology

This section describes the virtualization methodology of the Festo MPS® PA workstation [10].

The virtualization process is comprised of five stages, shown in Fig. 2. The first stage consists of several tasks. First, the individual workstation components such as devices, sensors, actuators, and pipes are 3D modeled using AutoCad software. Afterward, the objects are assembled with wiring, pneumatic connections, and pipes. Subsequently, 3DS Max software produces a file compatible with the Unity gamification platform (with a .fbx extension). Then the virtualized workstation model is exported to Unity, where animations and textures are added.

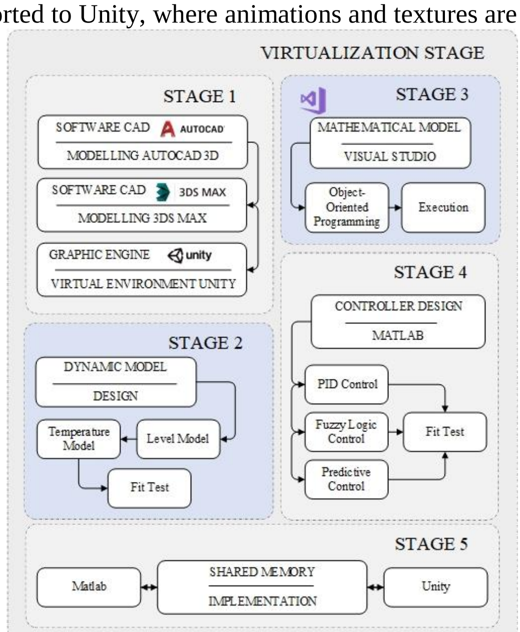

Fig. 2. Virtualization architecture on the Festo MPS® PA workstation.

The second stage consists of designing the mathematical model of the level and temperature processes. This stage is important because it allows representing the real performance of the station dynamics. The mathematical models are shown in detail in Section IV.

In the third stage, the two mathematical models are integrated into Unity. This gamification platform allows entering the dynamics of the process as a code subroutine, using visual studio. In the fourth stage, the control algorithms proposed in this work are implemented in the Matlab software. Finally, in the fifth stage, the bidirectional communication between Matlab and Unity is implemented. The exchange of data between the mathematical models of the processes and the controllers is carried out through shared memories. Additionally, Unity allows tuning the control algorithms from a user interface in the immersive virtual environment.

Fig. 3, shows the virtual station Festo MPS® PA and the real station. A high level of realism can be noticed. The virtualized instrumentation produced in stage 1 is also shown in Fig. 3. The proposed virtualization methodology allows obtaining an immersive 3D workstation that represents in real-time the dynamics of the temperature and level processes.

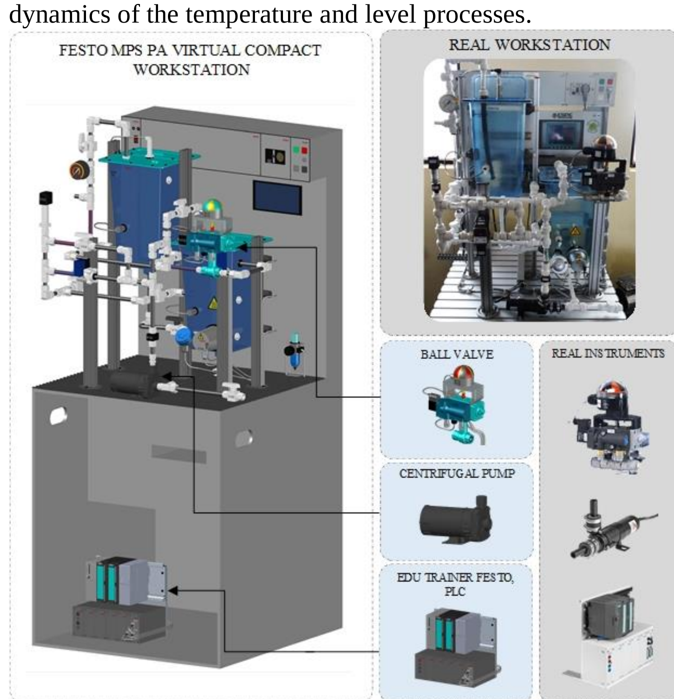

Fig. 3. Virtual and Real versions of the Festo MPS® PA workstation.

IV. Mathematical Model

The mathematical models of the temperature and level processes of the Festo MPS® PA virtual workstation are presented in this section.

A. *Mathematical model of the level process*

The mathematical model of the level station is based on the principle of mass accumulation in (1). The equation relates the input mass flow $\dot{m_{in}}$ minus the output $\dot{m_{out}}$. To define the volume of the tank area in (2), it is necessary to specify the actual dimensions of the tank B102 in Fig. 1. $A(t)$ represents the surface area of the fluid at the height $h(t)$ and $q_i(t), q_o(t)$ are the input and output flow respectively [11].

$$\frac{dm(t)}{dt} = \dot{m_{in}} - \dot{m_{out}} \quad (1)$$

$$\frac{dV(t)}{dt} = \frac{d[A(t)h(t)]}{dt} = q_i(t) - q_0(t) \quad (2)$$

Depending on the height $h(t)$, the volume $V(t)$ is obtained as shown in (3), where A_{base} represents the area of the tank base obtained in (4), with $W_B\ y\ d_B$ as the dimensions of the tank base B102, for this particular case $W_B = d_B$ for being a square flat surface.

The Bernoulli energy balance is applied in (5), this criterion is applied between the point P_1 and P_2 for the two tanks, P_1 and P_2 is the energy per unit volume at that point, Z_1, Z_2 correspond to the height of separation in each tank, g is the gravitational acceleration and v_1, v_2 are the velocity of the liquid at the point P_1, P_2 respectively. The symbol ρ is the density of the water in the two tanks, h_2, h_1 are the height of the liquid in the tank B102 and B101 respectively, as shown in Fig. 1, then (6) is replaced in (5).

$$V(t) = \frac{1}{3}\ h(t)\left(A_{base} + A(t) + \sqrt{A_{base}A(t)}\right) \quad (3)$$

$$A_{base} = W_B d_B \quad (4)$$

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g(Z_1 + h_2) = P_2 + \frac{1}{2}\rho v_2^2 + \rho g(Z_2) \quad (5)$$

$$P_2 = \rho g(h_1 - Z_2) \quad (6)$$

The output q_0 is defined in (7), where h_0 is the height of the tank B101 and r the radius of the pipe. Friction losses R_1 are considered in (8). The pump flow $q_{ip}(t)$ is represented in (9), K_b denotes the gain of the pump in cm^3/s and v_t the voltage applied to the pump. The input $q_i(t)$ in (11) is equal to $q_{ip}(t)$ minus the flow $q_{ih}(t)$ in (10), where Z_0 is the lift height of tank B102 and Z_4 is the lift height of tank B101.

$$q_0 = \pi r^2\sqrt{2g}\sqrt{2h_2 + Z_1 - h_0} \quad (7)$$

$$q_0 = R_1\pi r^2\sqrt{2g}\sqrt{(2h_2 + Z_1 - h_0)} \quad (8)$$

$$q_{ip}(t) = K_b v_t \quad (9)$$

$$q_{ih}(t) = R_1\pi r^2\sqrt{2g}\sqrt{(2h_2 + Z_0 - Z_4 - h_0)} \quad (10)$$

$$q_i = q_{ip}(\mathrm{t}) - q_{ih}(t) \quad (11)$$

The equation resulting from the mathematical model for the level process in the time domain is presented in (12), where W_T is the upper width of the tank and H is the maximum height in tank B102.

$$\dot{h}_2(t) = \frac{6.73\ V - 0.28\ h_2 + 1.43}{\left[\left(\frac{W_T - W_B}{H}\right)^2 {h_2}^2(t) + 2W_B\left(\frac{W_T - W_B}{H}\right)h_2(t) + {W_B}^2\right]} - \frac{R_1\pi r^2\sqrt{2g}\sqrt{2h_2 + Z_1 - h_0}}{\left[\left(\frac{W_T - W_B}{H}\right)^2 {h_2}^2(t) + 2W_B\left(\frac{W_T - W_B}{H}\right)h_2(t) + {W_B}^2\right]} \quad (12)$$

B. Mathematical model of the temperature process

The mathematical model for the temperature process shown in Fig. 1 simulates a tank with a liquid at a temperature $T_T(t)$ isolated from the outside. The tank has an input of cold water at temperature $T_e(t)$ and an output of hot water $T_s(t)$ [12].

Inside the tank, the liquid is heated by the action of $Q(t)$ (actuator E104). Inside the tank it is assumed that the liquid is perfectly mixed, then $T_s(t) = T_T(t)$.

The mathematical model of temperature is based on the principle of conservation of energy, in (13) the equilibrium condition of thermal systems is shown, the administered heat $\frac{dE}{dt}$ is equal to the input energy E_e minus the energy output E_s plus the heat exchange Q.

The heat administered is defined in (14), where m denotes the mass of the liquid in (15), ΔT is the temperature variation, T_e is the input temperature, and T_s is the output temperature. The different variables that interact within the system are given by: C_P the thermal capacity of the liquid, ρ density of the liquid, and V is the volume of the liquid in the tank. The tank has a negligible thermal resistance R due to the optimal insulation of the tank above ambient temperature $T_a(t)$.

$$\frac{dE}{dt} = E_e - E_s + Q \quad (13)$$

$$\frac{d(mC_p\Delta T)}{dt} = \dot{m}_e C_P T_e - \dot{m}_s C_P T_s + Q \quad (14)$$

The equilibrium law in (16) establishes an equality between the mass flow of the output $\frac{dm_e}{dt}$ with the input $\frac{dm_s}{dt}$ and equal to the density ρ times the volumetric flow q that enters the two tanks. In (17), an equality between the output temperature T_s and that of the tank T_T is established, when the mass flow at the input is equal to that at the output.

$$m = \rho V \quad (15)$$

$$\frac{dm_e}{dt} = \frac{dm_s}{dt} = \rho q \quad (16)$$

$$T_s = T_T \quad (17)$$

By substituting (14) and (15) in (17), the result is the mathematical model for the temperature process in the time domain shown in (18), all this when the volume is constant.

$$\rho V C_P \frac{dT_T}{dt} = qC_p[T_e(t) - T_T(t)] + Q(t) \quad (18)$$

V. Design of the Control Algorithms Implemented in the Festo MPS® PA Virtual Station

C. PID controller design

The PID control algorithm is represented in (19). Where, K_P is the proportional gain, E the error, T_i represents the integral time, T_d is the derivative time and M corresponds to the valve position when the error is zero. In this work, the Lambda tuning technique is used with the criterion $\lambda = T$, where λ is the tuning criterion and T is the time constant [13].

$$V = K_P * \left[(E) + \frac{1}{T_i} * \int_0^t (E)dt + T_d * \frac{d(E)}{dt}\right] + M \quad (19)$$

Applying the λ adjustment described above, the parameters $K_P = 6.58$, $T_i = 0.77\ s$, and $T_d = 3.84\ s$ are obtained, which are replaced in (19) for the design of the level controller. For the temperature process of the Festo MPS® PA workstation, the parameters $K_P = 2$, $T_i = 1\ s$, y $T_d = 1\ s$ are obtained and replaced in (19).

D. Fuzzy Control Design

A fuzzy PD controller with integral action is designed in this section. The design of the rules is based on the proposal of Macvicar Whelan [14]. The input variables to the fuzzy controller are the error and the rate of change of the error [15].

In the Fuzzy controller architecture, there are two input variables, the first one is the error $e(k)$ defined as the difference between the desired value SP and the measured value $y(k)$ shown in (20). The second input variable is the rate of change of the error $de(k)$ shown (21), where $e(k-1)$ corresponds to the error in the previous sampled time.

Due to the output range of [-1, 1] in the Fuzzy controller, it is necessary to limit the signal using an integrator and subsequently scale it to obtain a real interval, with a standard signal of voltage 0 to 10 volts in the level process and of 0 to 1,000 watts in temperature process.

$$e(k) = SP - y(k) \quad (20)$$

$$de(k) = e(k) - e(k-1) \quad (21)$$

Seven fuzzy sets are used to represent the input variables, as shown in Fig. 4. All sets are uniformly distributed along the limits [-1, +1] using triangular membership functions, except at the extremes where trapezoidal membership functions are used. The linguistic variables assigned to each input fuzzy set are the following: negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), and positive big (PB). Fig. 4 illustrates those seven fuzzy sets that represent both the error, and the rate of change of the error.

For the output variable, nine fuzzy sets are defined, uniformly distributed along the limits [-1, +1] using triangular membership functions, as can be seen in Fig. 5. The associated linguistic variables are the following: negative big big (NBB), negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), positive big (PB), and positive big big (PBB). Forty-nine control rules with structure IF-AND-THEN are generated, as shown in Table I. Finally, the centroid technique is used as a defuzzification method.

Adding more membership functions can help provide fine control that could reduce jitter, these functions have been subjectively specified from heuristic experience [16].

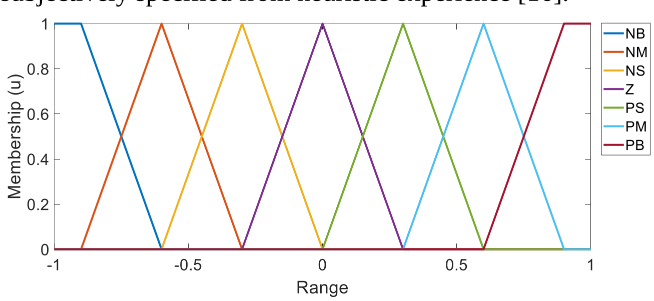

Fig. 4. Input variables membership functions.

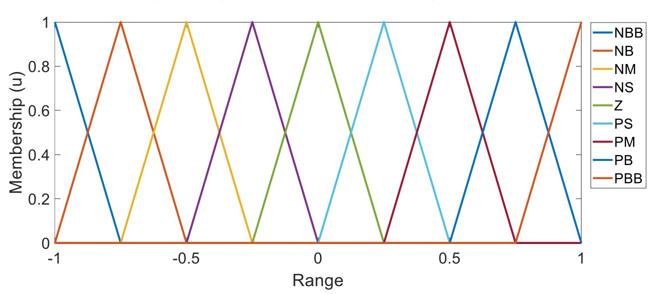

Fig. 5. Output variable membership functions.

TABLE I
FUZZY RULE BASE [14]

e/de	NB	NM	NS	Z	PS	PM	PG
NB	NBB	NBB	NBB	NB	NM	NS	Z
NM	NBB	NBB	NB	NM	NS	Z	PS
NS	NBB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PBB
PM	NS	Z	PS	PM	PB	PBB	PBB
PB	Z	PS	PM	PB	PBB	PBB	PBB

E. Predictive controller design based on MPC model

The structure of the MPC controller includes a prediction model of the workstation, the optimization problem, and the trajectory as shown in Fig. 6 [17].

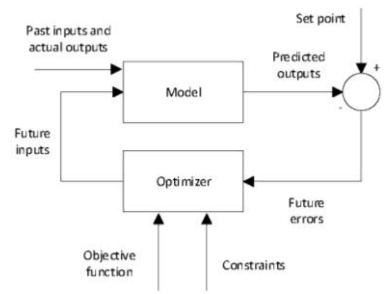

Fig 6. MPC controller structure.

The MPC controller minimizes the steady-state error while reducing the jerky control action for the actuator, considering operating restrictions at settling.

The objective function of the controller minimizes both the error and the control effort. Thus the controlled and manipulated variables are within the established limits [18]. This is defined in (22), where $\hat{y}$ is the output of the prediction model, w the vector of set points and the subtraction between the two is the error, Δu is the minimum change in the action of control for the proper operation of the actuator, λ_1 and λ_2, correspond to the weights associated with the control objectives.

$$Min\ \ J(u) = \sum_{j=1}^{p} \lambda_1 [\hat{y}(t+j|t) - w(t+j)]^2 + \sum_{j=1}^{m} \lambda_2 [\Delta u(t+j-1)]^2 \quad (22)$$

The objective function in (22) is subject to the linear inequality constraints (23) and (24). Equation (23) corresponds to the restriction of the output variable or controlled variable y, that is, level and temperature, which has an operating range between y_{min} y y_{max}. The control action represented by u in (24), is also restricted to levels u_{min} y u_{max}.

$$y_{min} \leq y \leq y_{max} \quad (23)$$

$$u_{min} \leq u \leq u_{max} \quad (24)$$

To obtain $\hat{y}$ a prediction model is required, which is based on state-space (25) and (26). It is composed of three matrices: the state matrix A, the input matrix B, and C the output matrix.

$$\dot{x}(t+1) = Ax(t) + Bu(t) \quad (25)$$

$$y(t) = Cx(t+1) \quad (26)$$

The design parameters used in the design of the MPC controller for the level and temperature processes are shown in Table II. The prediction horizon is defined by p, while the control horizon by m.

TABLE II
PARAMETERS OF THE MPC CONTROLLER

Variable	p	m	λ_1	λ_2	u_{min}	u_{max}	y_{min}	y_{max}
Level	15	2	0.5	0.5	0 [v]	10 [v]	0 [cm]	30 [cm]
Temperature	300	20	0.5	0.5	0 [w]	1000 [w]	25 [ºC]	65 [ºC]

VI. RESULTS

This section shows the performance results of the controllers proposed in Section V for the virtualized workstation Festo MPS® PA.

A. *Operation comparison between the real station and the virtualized station*

To validate the implementation of the virtual station, its realism and functionality are compared to that of the real station. Fig. 7, shows the immersive interface with which the user interacts for the implementation of control algorithms. The user can move the avatar inside the environment and take control or inspection actions with the use of the keyboard.

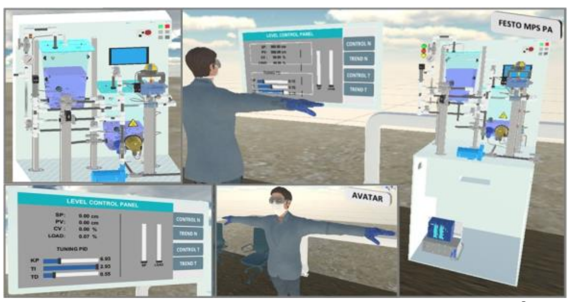

Fig. 7. Avatar interaction with advanced controls on the Festo MPS® PA virtual station.

Fig. 8 and Fig. 9, show the temperature variable, controlled with the fuzzy technique when subjected to set point changes and a disturbance in the simulated real station and the virtual station respectively. When comparing Fig. 8 and Fig. 9 a similar behavior can be observed.

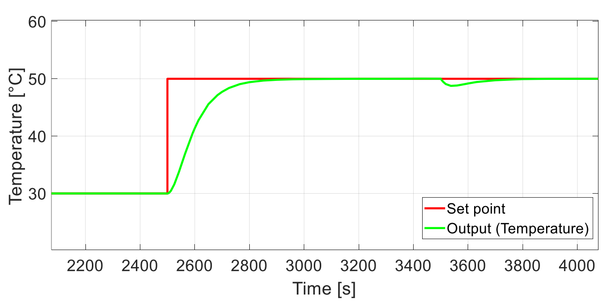

Fig. 8. Response to set point changes and disturbances of the simulated real temperature system using a fuzzy controller.

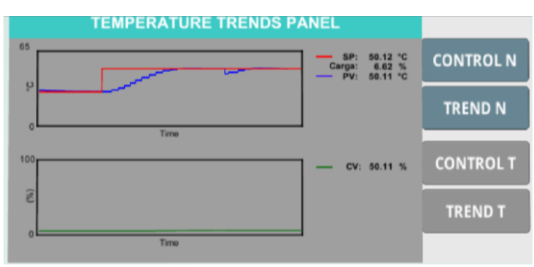

Fig. 9. Response to set point changes and temperature disturbances of the Festo MPS® PA virtual station using the fuzzy technique.

B. *Performance and comparison of the control algorithms proposed for the variable level*

The controllers (PID, Fuzzy, and MPC) designed in Section V for the Festo MPS® PA virtual station were tested in the virtual station level process. In Fig. 10, the performance of the three controllers is shown against a reference change at 400 s, with a disturbance at 900 s. Fig. 10 shows that the MPC controller has a shorter setup time, and also does not have a maximum boost. In all three cases, the steady-state error is zero. In Table III, the performance parameters of the three controllers for the level process are presented.

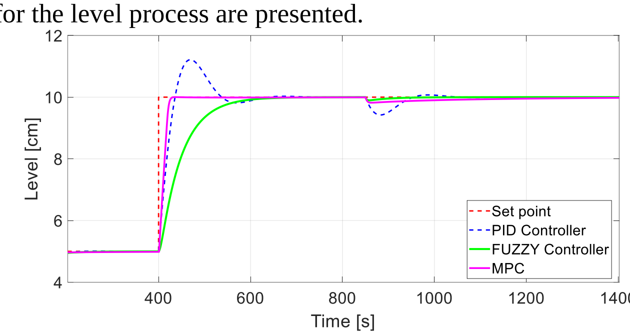

Fig. 10. Comparison between controllers (PID, Fuzzy, MPC) considering the level variable.

TABLE III
CONTROLLER PERFORMANCE PARAMETERS AT THE VARIABLE LEVEL

Parameters	PID	Fuzzy	MPC
Overshoot	17.7%	0%	0%
Settling time	212.2 s	199.2 s	41.8 s
Steady-state error	4×10^{-16} cm	2×10^{-16} cm	4.4×10^{-4} cm

Another parameter of analysis of this work is the control action. Fig. 11 shows the voltage applied to the pump for level control. Both fuzzy controller and MPC produced a quick response. Smoother curves tend to increase the actuator's life.

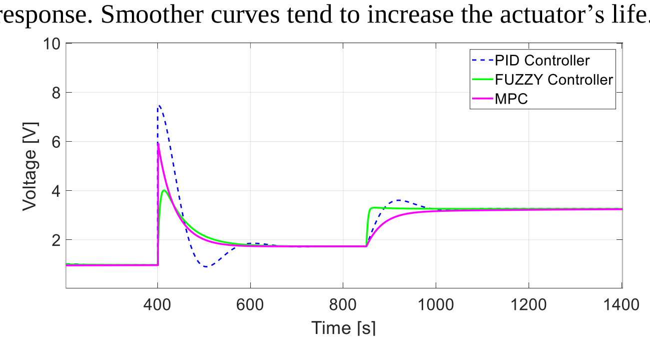

Fig. 11. Comparison between the three controllers (PID, Fuzzy, MPC) considering the voltage at the pump for the variable level.

C. *Performance and comparison of the control algorithms proposed for the temperature variable*

In this section, the controllers (PID, fuzzy, and MPC) designed in Section V are implemented for the virtual station Festo MPS® PA. Temperature changes at 2,500 s and a disturbance at 4,500 s are evaluated, as seen in Fig. 12. When a change in temperature is produced, the MPC controller exhibits shorter settling time, no overshoot, and no steady-state error. However, when a significant disturbance occurs, the three controls present very similar settling times, but the diffuse control has a lower maximum on impulse. Table IV shows the performance parameters of the three controllers for the temperature variable.

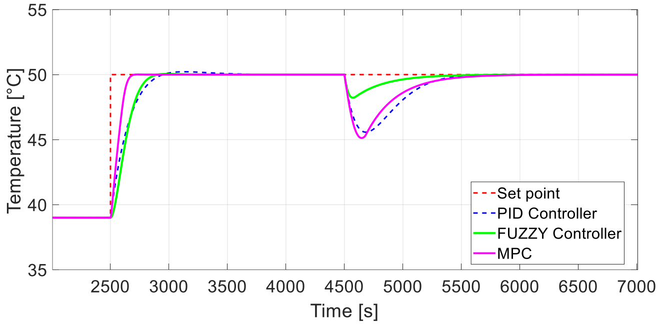

Fig. 12. Comparison between controllers (PID, Fuzzy, MPC) considering the temperature variable.

TABLE IV
CONTROLLER PERFORMANCE PARAMETERS IN THE TEMPERATURE VARIABLE.

Parameters	PID	Fuzzy	MPC
Overshoot	0.982%	0.178%	0.087%
Settling time	903.2 s	807.5 s	585.3 s
Steady-state error	11×10^{-12} °C	11×10^{-12} °C	14×10^{-15} °C

Fig. 13, shows the power supplied to the heater to produce changes in temperature. During the response transient, the fuzzy controller uses less power compared to the other controllers. However, the response of the MPC controller is faster.

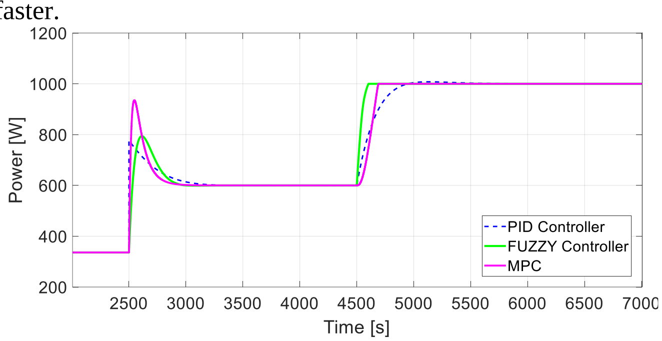

Fig. 13. Comparison between the three controllers (PID, Fuzzy, MPC) considering the power in the heater for the variable temperature.

VII. CONCLUSION

In this research work, three control strategies are evaluated and compared, a PID with Lambda tuning, an advanced control algorithm based on fuzzy logic, and finally an MPC controller. The three control strategies were tested for the control of level and temperature in the designed Festo MPS® PA virtual workstation. The results shown that the best performance was achieved by the MPC control strategy, when subjected to reference changes and disturbances, the analysis parameters are: maximum on impulse, steady-state error, and establishment time. The control actions received by the actuators were also analyzed in order to compare the effect on the useful life. In this context advanced controllers show a smoother response with fewer peaks. This is mainly due to the fact that predictive control is designed with a greater weight to the control target that minimizes the steady-state error.

It is important to note that the immersive virtualization of the Festo MPS® PA station is one of the contributions of this research work. By applying the virtualization methodology, shown in Fig. 2, a station with high similarity to the real station was produced. The virtual station was validated with the real Festo MPS® PA station, the results obtained from the controllers in the virtual station are similar to the real station. The virtual plant will be very useful in the teaching-learning process of professionals in the area of automatic control.

With the results obtained in this work, it is proposed as future work to incorporate optimal operating characteristics of the actuators, to obtain greater efficiency.

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