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Optimization of compact fuzzy controllers for temperature regulation

Optimización de controladores difusos compactos utilizados para regulación de temperatura

Helbert Eduardo Espitia-Cuchango[1], ***Iván Machón-González***[2], ***Hilario López-García***[3]

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ABSTRACT

This paper presents an optimization of different configurations of a compact fuzzy controller for room-temperature regulation; thus, such configurations are proposed considering the analogy with different discrete linear controllers. The model is characterized by several heat- transfer components. The results demonstrate that the optimization process allows adequate tuning of most of the fuzzy controllers. The initial configuration is suitable for optimization of the controllers; finally, the best result is achieved using the proportional integral derivative in the setting of a compact controller.

Palabras clave:
Control
Sistema difuso
Sistema térmico
Controlador PID

RESUMEN

Este documento muestra la optimización de diferentes configuraciones de un controlador difuso compacto para la regulación de temperatura en una habitación; tales configuraciones se establecen considerando la analogía con diferentes controladores lineales discretos. El modelo se caracteriza por varias componentes de transferencia de calor. Los resultados muestran que el proceso de optimización permite una adecuada sintonía de la mayoría de controladores difusos. Para la optimización de los controladores es de relevancia la configuración inicial, finalmente, el mejor resultado se obtiene con la configuración del controlador compacto de tipo PID.

[1]BSc. in Electronic engineering. Ph.D. In Computer and systems engineering. Current position: Professor at Universidad Distrital Francisco José de Caldas, Bogotá, Colombia. E-mail: heespitiac@udistrital.edu.co

[2]BSc. in Industrial engineering. Ph.D. In Industrial engineering. Current position: Professor at Universidad de Oviedo, Gijón, España. E-mail: machonivan@uniovi.es

[3]BSc. in Industrial engineering. Ph.D. In Industrial engineering. Current position: Professor at Universidad de Oviedo, Gijón, España. E-mail: hilario@uniovi.es

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1. Introduction

By definition, fuzzy logic systems support the connection of the inputs/outputs of a process through linguistic terms [1]. This feature allows the use of fuzzy logic in the development of control systems [2]. Furthermore, fuzzy logic systems allow handling nonlinearities as products among variables, saturations and power functions, which are applied to nonlinear dynamic systems [3].

This paper proposes a fuzzy logic system for controlling a thermal system that regulates the room temperature. The model can be found in [4–6], and the control system seeks to improve the energy efficiency of heating and cooling methods during transient periods. However, energy management is important [4]. Some previous studies have applied fuzzy logic to the control of thermal systems [4, 7], where a fuzzy-proportional integral sum derivative is described. Besides, a nonlinear proposal is proposed based on a fuzzy system of Takagi-Sugeno type, where nonlinearity is included for the discrete-time controller states.

Moreover, an advanced method for the optimization of an F-PID controller was proposed in [6] using genetic algorithms. A similar approach that uses the particle swarm optimization algorithm was proposed in [8]. Finally, in [9], optimization of fuzzy set parameters for a controller was proposed.

Therefore, we establish the controllers starting from a discrete-time linear controller, and then convert them into a compact fuzzy form using fuzzy sets. Also, we perform the optimization of the controller parameters using the plant model. The optimization process occurs through the 'FMINUNC' function of MATLAB®, which implements a quasi-Newton method of the Broyden–Fletcher–Goldfarb–Shanno (BFGS) algorithm, which makes the initial search point suitable [10].

2. System model

From the model used in [4–6], the system is described by a set of differential equations based on energy balances for the heat transfer, the air and the wall of the thermal zone. Figure 1 shows a schematic of the thermal system.

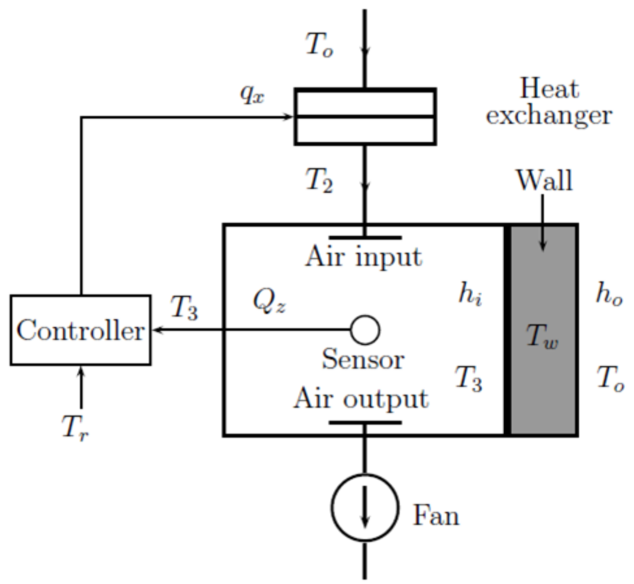
The equations that relate the variables of the model and represent the dynamics of the system are expressed as follows:

$$\rho_x C_x V_x \frac{dT_2}{dt} = \rho_a f C_a (T_o - T_2) + q_x \tag{1}$$

$$\rho_a C_a V_z \frac{dT_3}{dt} = \rho_a f C_a (T_2 - T_3) + h_i A_i (T_w - T_3) + Q_z \tag{2}$$

$$\rho_w C_w V_w \frac{dT_w}{dt} = h_0 A_0 (T_0 - T_w) - h_i A_i (T_w - T_3) \tag{3}$$

Figure 1: Schematic of the thermal system model [4].



In general, the model parameters are defined as follows:

- A: Wall area [m^2].
- C: Specific heat [KJ/Kg°C].
- f: Volumetric flow [m^3/s].
- h: Convection heat transfer coefficient [W/m^{2}K].
- q_x: Heat exchanger input power [W].
- Q_z: Internal thermal load [W].
- R: Thermal resistance [m^2 °C/W].
- T: Temperature [°C].
- V: Volume [m^3].
- ρ: Density [kg/m^3].

The subscripts for the model variables include

- a: Air.
- w: Wall.
- i: Interior of the heating zone.
- o: Exterior of the heating zone.
- z: Heat zone.

3. Fuzzy systems

The fuzzy logic systems support the input–output representation using fuzzy sets and relations (i.e. rules) between the sets. In control systems, they allow establishing different actions to be conducted on the plant [1]. Consequently, various fuzzy systems have been proposed; for example, Mandani proposed rules of the If-Then form, using linguistic terms represented by fuzzy sets at the input and output. Takagi-Sugeno, which uses rules, proposed fuzzy sets in the antecedent and singleton functions in the output, which corresponds to a particular case of the Mandani model, where there is a singleton set (i.e. constant value) [11].

The method of the fuzzy compact controllers proposed in this paper uses fuzzy sets at the input, whereas at the output, the control actions correspond to actuators of a constant type. Consequently, it establishes an initial configuration, which is then improved using optimization algorithms.

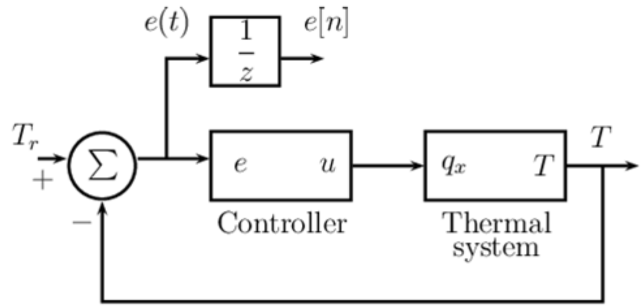
4. Control system

Figure 2 shows a general scheme of the control system. Here, the value of the error is taken to implement the function, that is, the object of optimization.

For the design of compact fuzzy controllers, the linear control strategies are denoted as follows:

- General controller (G).
- Proportional integral control (PI).
- Proportional derivative control (PD).
- Proportional integral derivative control (PID).

Figure 2: Block diagram of the control system.



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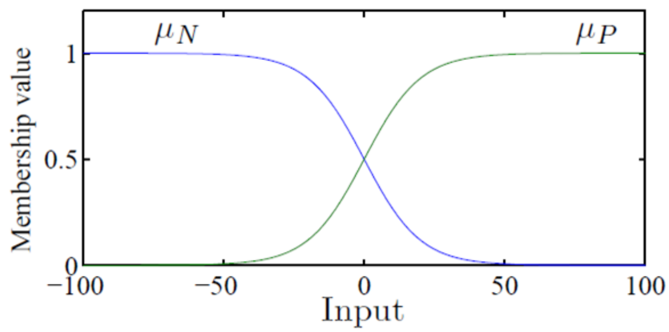
The fuzzy compact controllers are designed using sigmoidal functions, as shown in Figure 3, which represent positive and negative error values. However, the control action is associated with an action value (virtual actuator), that is, activated directly by the membership value produced at the input level.

Figure 3: Fuzzy sets used for each antecedent (input).



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4.1. General controller

Our discrete linear controller comprises a second-order system of the form

$$\frac{U(z)}{E(z)} = \frac{b_2 + b_1 z^{-1} + b_0 z^{-2}}{1 + a_1 z^{-1} + a_0 z^{-2}} \tag{4}$$

Hence, the respective equation in discrete time is expressed as

$$u[n] = -a_1 u[n-1] - a_0 u[n-2] + b_2 e[n] + b_1 e[n-1] + b_0 e[n-2] \tag{5}$$

Figure 4 represents this controller using a block diagram.

Figure 4: Linear controller in discrete time.

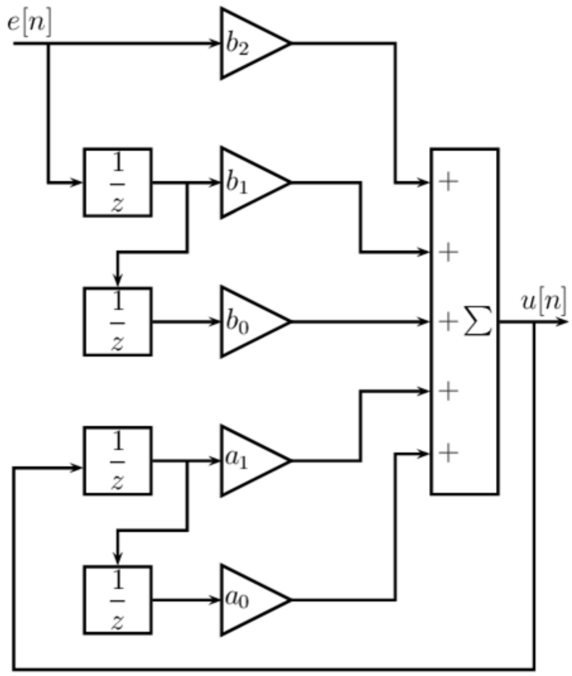

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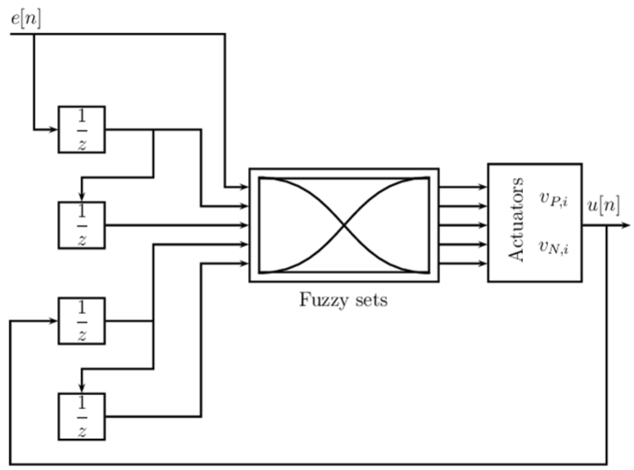
Figure 5 shows the structure of the compact fuzzy controller, where the inputs from the memory elements enter the fuzzy system, where the non-linear relations of the system states are defined. Also, the structure used with the memory elements is similar for the two systems considered (i.e. the linear and fuzzy systems).

Figure 5: Structure of the fuzzy controller.



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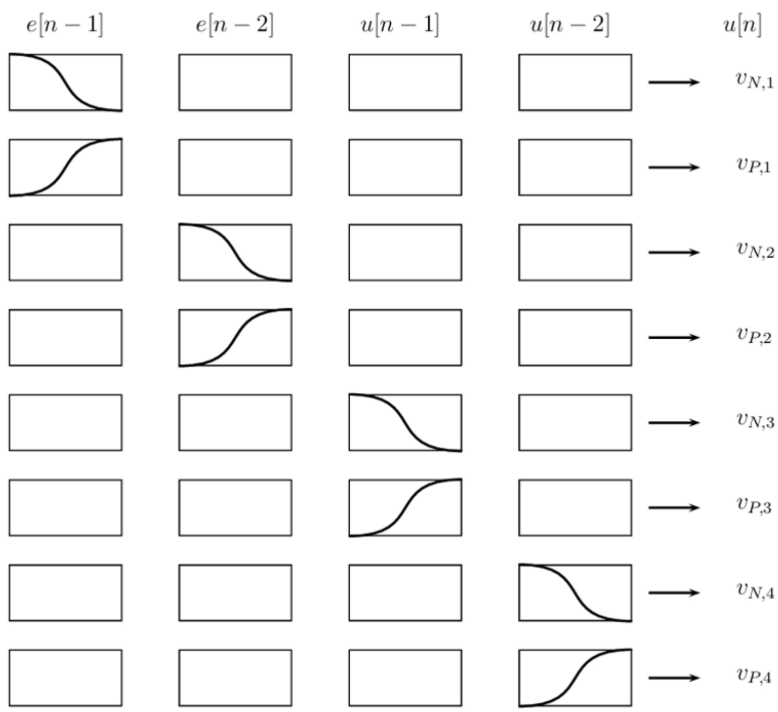
Then, each of the discrete controller variables is modelled using the fuzzy sets shown in Figure 3. Vividly, Figure 6 shows the set of all rules.

Figure 6: Graphical representation of the fuzzy system rules.



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Thus, following are the respective rules for each input:

- If $e[n-1]$ is $\mu_{N,1}$, then $u[n]$ is $v_{N,1}$.
- If $e[n-1]$ is $\mu_{P,1}$, then $u[n]$ is $v_{P,1}$.
- If $e[n-2]$ is $\mu_{N,2}$, then $u[n]$ is $v_{N,2}$.
- If $e[n-2]$ is $\mu_{P,2}$, then $u[n]$ is $v_{P,2}$.
- If $u[n-1]$ is $\mu_{N,3}$, then $u[n]$ is $v_{N,3}$.
- If $u[n-1]$ is $\mu_{P,3}$, then $u[n]$ is $v_{P,3}$.
- If $u[n-2]$ is $\mu_{N,4}$, then $u[n]$ is $v_{N,4}$.
- If $u[n-2]$ is $\mu_{P,4}$, then $u[n]$ is $v_{P,4}$.

4.2. *PI controller*

The controller has the form

$$C(z) = k_p + \frac{K_i}{1-z^{-1}} = \frac{(K_p+K_i)-K_p z^{-1}}{1-z^{-1}} \quad (6)$$

In general terms, it can be expressed as

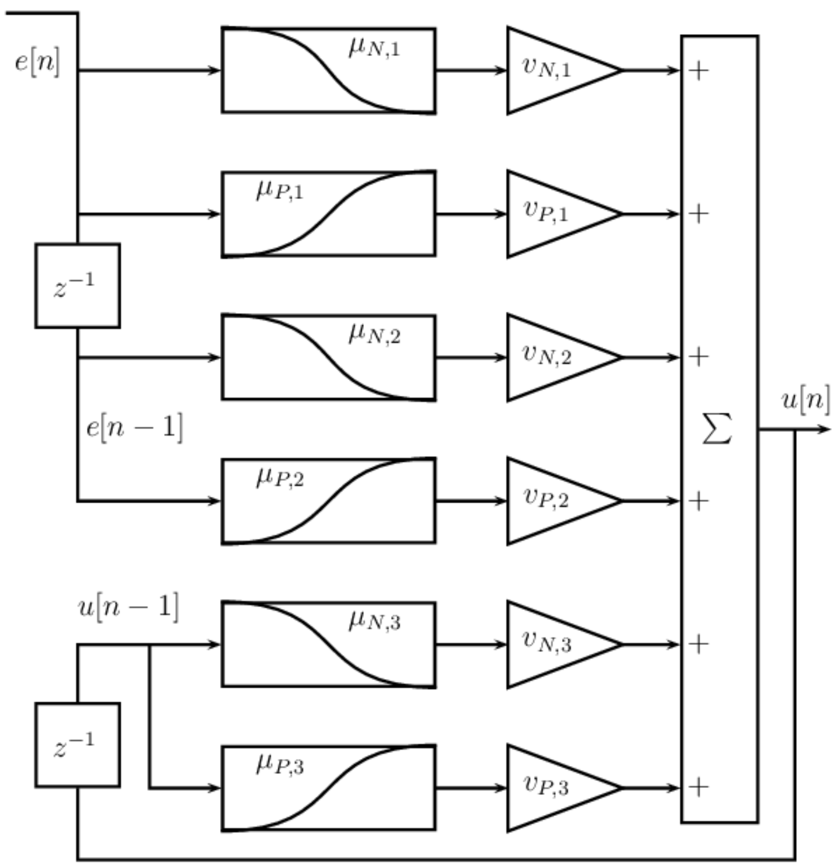
$$C(z) = \frac{b_0 - b_1 z^{-1}}{1-z^{-1}} \quad (7)$$

Thus, the equation in discrete time of the PI controller corresponds to

$$u[n] = u[n-1] + b_0 e[n] - b_1 e[n-1] \quad (8)$$

Concerning the differential equation for this controller, Figure 7 shows the proposed implementation.

Figure 7: PI compact fuzzy system.



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4.3. PD controller

The PD controller can be represented as follows:

$$C(z) = K_p + K_d(1 - z^{-1}) = (K_p + K_d) - K_d z^{-1} \quad (9)$$

A general expression for this would be

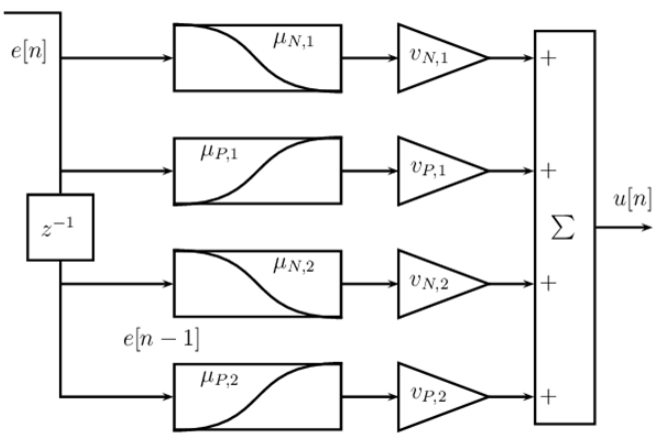
$$C(z) = b_0 - b_1 z^{-1} \quad (10)$$

The corresponding equation in discrete time is expressed as

$$u[n] = b_0 e[n] - b_1 e[n-1] \quad (11)$$

Then, using the respective fuzzy sets for negative and positive values is obtaining the scheme in Figure 8.

Figure 8: Compact PD fuzzy system.



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4.4. PID controller

In this case, the PID controller is described as

$$C(z) = K_p + \frac{K_i}{1 - z^{-1}} + K_d(1 - z^{-1}) \quad (12)$$

After the operations, the obtained result is expressed as follows:

$$C(z) = \frac{(K_p + K_i + K_d) - (K_p + 2K_d)z^{-1} + K_d z^{-1}}{1 - z^{-1}} \quad (13)$$

In general, it can be written as

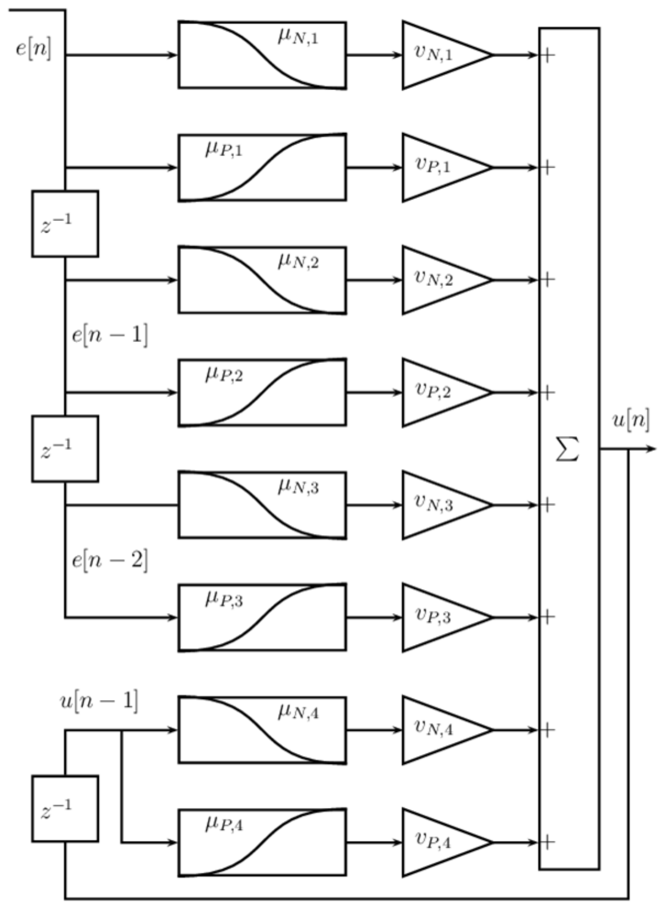
$$C(z) = \frac{b_0 - b_1 z^{-1} + b_2 z^{-1}}{1 - z^{-1}} \quad (14)$$

The respective difference equation for this controller is

$$u[n] = u[n-1] + b_0 e[n] - b_1 e[n-1] + b_2 e[n-2] \quad (15)$$

Thus, Figure 9 shows the respective compact fuzzy PID controller.

Figure 9: PID compact fuzzy system.



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5. Optimization process

To implement the optimization process, we use a function to establish the dynamics of the plant with the control system, where the parameters of controller X are taken as input and the response of the control system, $M(X)$, as output. We use the result of this function to calculate the performance index to be optimized

$J(X)$. Thus, we perform the optimization process using a function that implements the respective performance index.

Vector X represents the set of parameters of the controller, n depicts the discrete time variable and N represents the total number of datasets used. We calculate the performance function corresponding to the mean square error as follows:

$$J = \frac{1}{N}\sum_{n=1}^{N}\left(y_{ref}(n) - y_{out}(n,X)\right)^2 \qquad (16)$$

Additionally, the implementation process uses the 'FMINUNC' function of MATLAB®, which employs the quasi-Newton BFGS algorithm (a method where a successive matrix approach of [10] is performed).

6. Results

In this section, we present the results obtained during the optimization of the compact fuzzy controllers, with the optimization variables corresponding to the parameters of the membership functions $\mu_{N,i}$, $\mu_{P,i}$ and the respective actuators $v_{N,i}$, $v_{P,i}$. The parameters of the thermal system are used based on those proposed in [4], with the initial and desired temperatures of 35°C and 25°C, respectively. Table 1 shows the values of the objective function for the controllers both before and after optimization.

Table 1: Values of the objective function.

System	G	PI	PD	PID
Before	126.0260	126.0380	126.0260	126.0260
After	4.0952	3.3863	1.5980	2.7933

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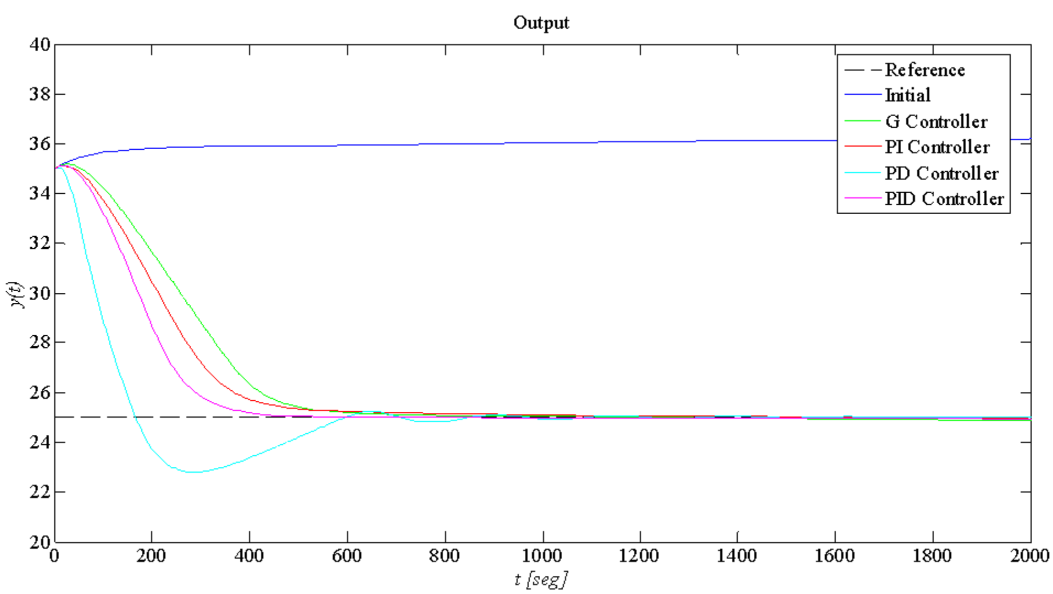
Figure 10 presents the results of the optimization process; it demonstrates the system response without optimization and the system output with each controller after being optimized.

From Table 1 and Figure 10, the fuzzy controller without optimization has a high error value. Then, after the optimization process, the proposed controllers allow the system to reach the reference value. The best performance value is obtained for the PD control; however, the reference is passed before stabilizing. Although considering this may not be the desired option, the PID controller demonstrates the best performance.

Figure 10: Results of the optimization process.



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7. Conclusions

In this paper, we established that it is possible to perform the optimization of different compact fuzzy controllers suitable for the temperature regulation of a thermal system.

Moreover, the initial search point for the considered optimization process allows for proper tuning of the controllers.

From the optimization process, an improvement in the performance of compact fuzzy controllers is observed. Thus, the optimization strategy is used to demonstrate a quick adjustment of the controller parameters.

In the future, we hope to develop more models of compact fuzzy controllers suitable for adaptive control processes.

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