UNIVERSIDAD SAN FRANCISCO DE QUITO (USFQ)

Colegio de Ciencias e Ingenierías

Study, Design and Comparison of Controllers Applied to a TITO Temperature Process.

Daniel Alexander Llive Salas

Héctor Edmundo Silva Ayala

Electrónica y Automatización

Trabajo de fin de carrera presentado como requisito

para la obtención del título de

Ingeniero en Electrónica

Quito, Enero de 2024

UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

Colegio de Ciencias e Ingenierías

HOJA DE CALIFICACIÓN

DE TRABAJO DE FIN DE CARRERA

Study, Design and Comparison of Controllers Applied to a TITO Temperature Process.

Daniel Alexander Llive Salas

Héctor Edmundo Silva Ayala

Nombre del profesor Tutor: Óscar Camacho, Ph.D.

Quito, Enero de 2024

© DERECHOS DE AUTOR

Nombres y apellidos:	Daniel Alexander Llive Salas
Código:	00207741
C.I.:	1721051306
Fecha:	Quito, Enero de 2024

Nombres y apellidos:	Héctor Edmundo Silva Ayala
Código:	00201983
C.I.:	1720533551
Fecha:	Quito, Enero de 2024

ACLARACIÓN PARA PUBLICACIÓN

UNPUBLISHED DOCUMENT

RESUMEN

Este trabajo compara un controlador Proporcional-Integral (PI) convencional y un controlador PI-Fuzzy para un sistema térmico de Dos Entradas y Dos Salidas utilizando TCLab. Se realizó un modelado empírico obteniendo las curvas de reacción del sistema. La validación del modelo se realizó comparando las curvas experimentales obtenidas con TCLab y las simuladas en Simulink. La aplicación de la matriz RGA utilizando el criterio de Bristol reveló la necesidad de desacoplar el sistema, lo que llevó al diseño e implementación de desacopladores para mejorar la respuesta del sistema térmico. Una vez obtenido el desacoplamiento, se realizó un estudio comparativo de ambos controladores (PI y PI-Fuzzy). Se evaluaron parámetros clave, destacando las diferencias en estabilidad, respuesta transitoria y robustez.

***Palabras clave*:** Modelado, controlador proporcional integral, controlador proporcional integral difuso, laboratorio de control de temperatura, matriz RGA, desacoplador, sistema multivariable.

ABSTRACT

This work compares a conventional Proportional-Integral (PI) controller and a PI-Fuzzy controller for a Two-Input, Two-Output thermal system using TCLab. Empirical modeling was performed by obtaining system reaction curves. Model validation was performed by comparing the experimental curves obtained with TCLab and those simulated in Simulink. The application of the RGA matrix using the Bristol criterion revealed the need to decouple the system, which led to the design and implementation of decouplers to improve the response of the thermal system. Once the decoupling was obtained, a comparative study of both controllers (PI and PI-Fuzzy) was conducted. Key parameters were evaluated, highlighting differences in stability, transient response, and robustness.

***Keywords*:** Modeling, Proportional Integral Controller, Proportional Integral Fuzzy Controller, Temperature Control Lab, RGA matrix, Decoupler, Multivariable System.

CONTENTS

List of Figures

List of Tables

DEDICATORIA

Deseo dedicar este logro a mi familia en su totalidad, en particular a mis padres, quienes han sido un soporte fundamental e inspiración a lo largo de todo este proceso. Asimismo, me gustaría dedicar este logro a mi tío Cristian, cuyo continuo respaldo y esfuerzos por impulsar mi desarrollo profesional han contribuido significativamente a mi adquisición de conocimientos en el ámbito industrial relacionado con mi carrera. Adicionalmente, quiero extender esta dedicatoria a todas aquellas personas que han formado parte y han brindado su constante apoyo a lo largo de este trayecto académico.

Daniel Llive

A mis padres, Héctor y Sonia, quienes han sido mis guías a lo largo de mi corta pero significativa vida. Su amor, sabiduría y apoyo incondicional han sido las fuerzas impulsadoras detrás de cada paso que he dado en este camino académico. A mis hermanas, Mishell, Grace y mi pequeña Sofía, quienes han sido un respaldo anímico constante. A mi familia, cuyo respaldo ha sido fuente de mi perseverancia. Este logro es un reflejo de la fuerza y dedicación que me han inspirado a lo largo de mi vida.

Héctor Silva

AGRADECIMIENTO

Quiero expresar mi más sincero agradecimiento en primer lugar a mi familia y a mis padres por su inquebrantable apoyo y dedicación a lo largo de mi travesía académica. Su aliento constante y comprensión han sido pilares fundamentales que han guiado mi camino hacia el logro de este importante hito. Agradezco también a todas las personas que han estado a mi lado durante este transcurso académico, brindándome su amistad, orientación y aliento. Su presencia ha enriquecido mi experiencia en esta prestigiosa universidad.

Finalmente, quiero extender mi gratitud al profesor que me guió en la elaboración de mi tesis, Oscar Camacho. Especialmente, quiero reconocer la destacada contribución de Marco Herrera, quien ha desempeñado un papel crucial en la realización de este trabajo. Sus valiosos consejos y enseñanzas sobre el tema presentado en este documento han sido fundamentales para mi comprensión y aplicación de técnicas de control de procesos, lo cual ha resultado en un desarrollo óptimo de esta investigación de titulación.

Daniel Llive

En primer lugar, agradezco a Dios por la vida, por guiarme por el camino de bien y permitirme cumplir mis objetivos. Agradezco a mis padres, por educarme con buenos hábitos y valores que han modelado mi camino, y por siempre apoyarme incluso en los momentos más difíciles. Agradezco profundamente a mis hermanas, familiares y seres queridos porque han enriquecido mi vida de maneras innumerables.

Agradezco a mi tutor de tesis, Oscar Camacho, por su orientación experta, paciencia y estímulo constante. También agradecer a Marco Herrera, ya que sus conocimientos y consejos fueron fundamentales para dar forma este trabajo. Finalmente, a mis amigos, compañeros de clase y profesores por el apoyo mutuo y enseñanza a lo largo de este camino académico; agradecer también a la USFQ por proporcionarme los recursos y el entorno apropiado para mi formación como profesional.

Héctor Silva

CHAPTER 1

INTRODUCTION

Multiple-Input Multiple-Output (MIMO) systems are more challenging to control compared to Single-Input Single-Output (SISO) systems due to the interaction between output variables(Arun and Mohan, 2018). To better manage these systems or processes (SISO or MIMO), used in industry, we work with controllers who control the behavior of the variables throughout the process(Aguilar-López et al., 2021). Fuzzy controllers were initially regarded as black boxes whose superior performance, especially in nonlinear systems, was difficult to quantify(Arun and Mohan, 2018). In the ongoing quest to improve the performance of thermal control systems, fuzzy PI / PD / PID controllers have emerged as promising alternatives to conventional PI/PD/PID controllers, particularly when dealing with complex nonlinear systems(Arun and Mohan, 2018). In (Ying, 2000) the fuzzy results of the SISO PI/PID are extended to the TITO cases.

Thus, in this paper, the study is focused on the evaluation of a PI controller and a PI-Fuzzy controller that are specifically compared in the context of the Temperature Control Lab (TCLab) for a Two Inputs, Two Outputs (TITO) system, where the TITO system will be represented by the TCLab, which has two heaters and two temperature sensors in its structure, representing a complex environment(de Moura Oliveira et al., 2020, Camacho et al., 2020).

The study will begin with modeling the TITO system by obtaining reaction curves for subsequent validation with simulated curves in MATLAB Simulink. Once the linear model was obtained from the excitation of the TCLab inputs, using the transfer function found during this process, it could be confirmed that the interaction between the variables is constant, and the application of a decoupler to eliminate such interactions between the variables of the TITO system (Morilla et al., 2013). With respect to the degree of interaction, a multivariable fuzzy controller with an integrated hierarchical structure was designed for each input-output pair to compensate for the uncertainty in the system parameters (Xu and Shin, 2011).

To approach the complex interaction between variables, fuzzy PI control schemes have been proposed, as well as tuned and decoupled PI strategies(Arun and Mohan, 2018). Some decentralized fuzzy control algorithms based on the direct decomposition of control laws are presented in(Gegov, 1995, Lu and Mahfouf, 2012, Xu and Shin, 2011). The design of decentralized controllers, crucial in MIMO systems, involves the precise definition of the pairings between variables using criteria such as the relative gain matrix (RGA) and time delays (Contreras et al., 2023). In this study, the TCLab's TITO system will be subjected to practical testing for accurate data and modeling. Comparison between standard PI and PI-fuzzy, supported by the design of specific decouplers, will provide detailed insight into the effectiveness of each control strategy. The stability of closed-loop fuzzy control systems was analyzed using the input-output passivity theory. The effectiveness of the proposed methodology was demonstrated through the results of IAE, ISE, and TVU values obtained at the end of the experimental work performed.

This paper is divided as follows: Section two describes the modeling of the system, section three shows the interaction analysis between the system variables, section four presents the design of decouplers, section five shows the design of multivariable controllers, section six presents the results, and finally, the conclusions.

CHAPTER 2

SYSTEM MODELING

This section presents the modeling of the process to be worked on. However, before starting, it is essential to understand that the TCLab uses two heaters, two temperature sensors, an Arduino, an LED, and feedback control, as seen in Fig.2.1(ApMonitor, 2022). However, the reference temperature is maintained by varying the heating output power. In addition, convection, radiation, and conduction transport thermal energy from the heater to the temperature sensor(Mejía et al., 2022).

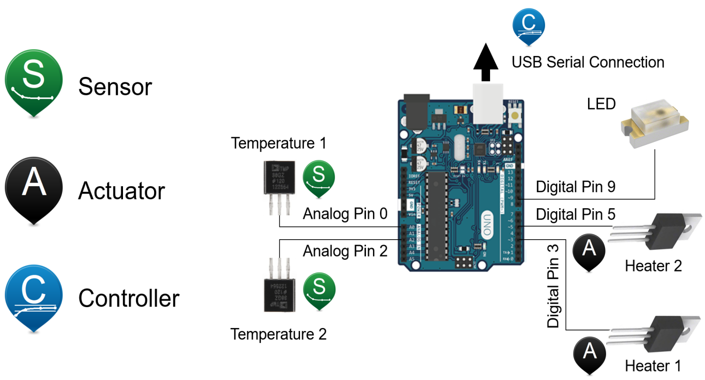

Figure 2.1: TCLab. Fuente: Adapted from ApMonitor (2022).

However, it must be taken into account that the process (TITO), as its name says, consists of two inputs and two outputs, where V_1 and V_2 represent the inputs, while Y_1 and Y_2 represent the outputs of the system, as can be seen in Fig.2.2.

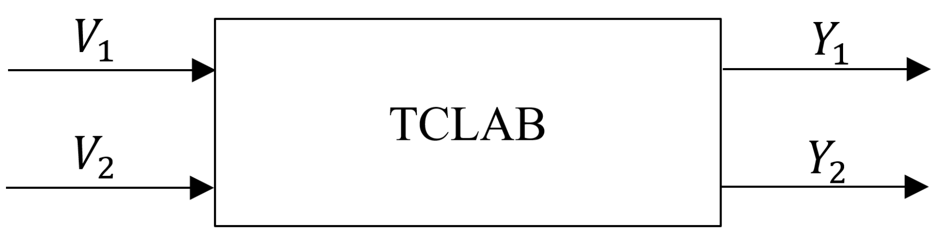

Figure 2.2: TITO Process TCLab.

However, the linear model of this process was obtained from the dynamic behavior of the system, which involves exciting the inputs through a step test, providing a reaction curve as a response (Camacho et al., 2020).

Nevertheless, since both outputs are affected either directly or indirectly by both inputs in this type of process, it is necessary to determine a 2x2 matrix whose elements are composed of the transfer functions corresponding to the behavior of each output in terms of the input. This matrix is expressed by the equation (2.1).

$$G(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \tag{2.1}$$

Where:

$$G_{11}(s) = \frac{\Delta Y_1}{\Delta V_1} = \frac{K_{11}e^{-t_{0(11)}s}}{\tau_{11}s + 1} \tag{2.2}$$

$$G_{12}(s) = \frac{\Delta Y_2}{\Delta V_1} = \frac{K_{12}e^{-t_{0(12)}s}}{\tau_{12}s + 1} \tag{2.3}$$

$$G_{21}(s) = \frac{\Delta Y_1}{\Delta V_2} = \frac{K_{21}e^{-t_{0(21)}s}}{\tau_{21}s + 1} \tag{2.4}$$

$$G_{22}(s) = \frac{\Delta Y_2}{\Delta V_2} = \frac{K_{22}e^{-t_{0(22)}s}}{\tau_{22}s + 1} \tag{2.5}$$

Therefore, based on the reaction curve method mentioned above, to find the parameters: *K*, τ and t_0 of the transfer functions presented in equations (2.2), (2.3), (2.4) and (2.5), the time it takes for the process to reach 28.3% and 63.2% of the total change in output is determined (Camacho et al., 2020).

It should be emphasized that *K* represents the static gain, τ represents the time constant, and t_0 represents the dead time of the process.

In this way, once both points are located, the aforementioned parameters can be represented by the following equations.

$$\tau = 1.5(t_2 - t_1) \tag{2.6}$$

$$t_0 = t_2 - \tau \tag{2.7}$$

$$K = \frac{\Delta Y}{\Delta V} \tag{2.8}$$

Taking into account the presented equations, the tests were carried out with different reference inputs for a duration of 1200 seconds, and the results were tabulated and averaged. In this way, an accurate model for this TITO system was achieved. These values can be found in tables 2.1 and 2.2.

Table 2.1: System modeling parameters for the output of Heater 1

$G_{11}(s)$				$G_{12}(s)$		
$V(t)\%$	K	t_0	τ	K	t_0	τ
20%	0.92	25.5	222	0.50	73.5	363
40%	0.85	31	205.5	0.45	114.75	288.75
60%	0.83	27.5	198	0.40	81.5	291
80%	0.82	35	178.5	0.40	100.5	246
Average	0.85	29.75	201	0.44	92.56	297.19

Table 2.2: System modeling parameters for the output of Heater 2

$G_{21}(s)$				$G_{22}(s)$		
$V(t)\%$	K	t_0	τ	K	t_0	τ
20%	0.55	67	337.5	1.13	12.5	246.75
40%	0.48	53	295.5	1.1	21	193.5
60%	0.48	66	256.5	1.039	17	190.5
80%	0.44	59.5	246	1.03	24	151.5
Average	0.49	61.37	283.87	1.07	18.62	195.56

2.1 Model validation

Once the data was averaged, the TITO system model was validated by simulating it using Simulink software. This simulation was carried out for a duration of 1200 seconds to verify if it complies with the dynamic behavior described by the system in real time.

On the other hand, since the tabulations were performed at different inputs, an intermediate value between them was chosen for the validation. In this case, the reference 60% was chosen for both inputs, as depicted in Fig.2.3 and Fig.2.4.

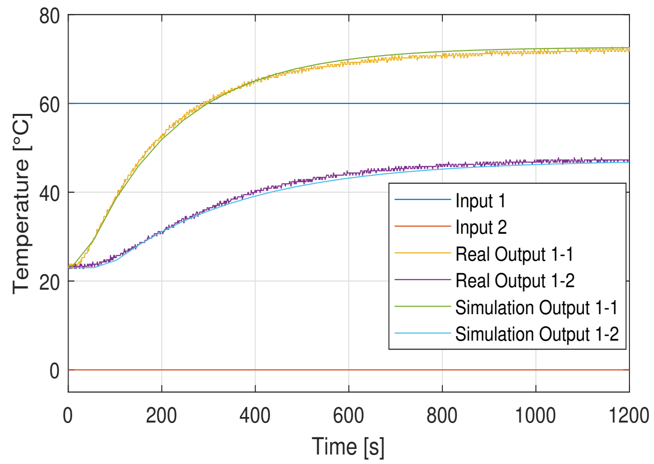

Figure 2.3: Validation for Heater 1 output.

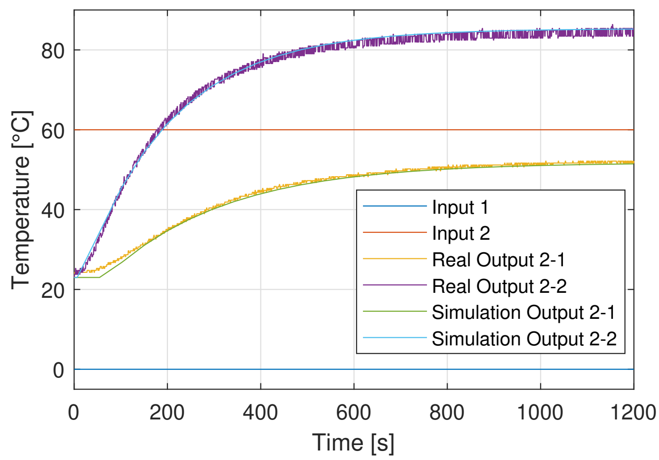

Figure 2.4: Validation for Heater 2 output.

Given the results obtained, it can be deduced that both the validation for the output of Heater 1 and Heater 2 is correct since it complies with the dynamic behavior described by the system in real-time.

Therefore, the matrix described in equation (2.1) can be expressed as follows:

$$G(s) = \begin{bmatrix} \frac{0.85e^{-29.75s}}{201s+1} & \frac{0.44e^{-92.56s}}{297.19s+1} \\ \frac{0.49e^{-61.37s}}{283.87s+1} & \frac{1.07e^{-18.62s}}{195.56s+1} \end{bmatrix} \tag{2.9}$$

In this way, we can proceed with the analysis of the interaction among the variables of this system in the next section of this article.

CHAPTER 3

INTERACTION ANALYSIS BETWEEN SYSTEM VARIABLES

Starting from the previously obtained equation (2.9), which represents the system model using the reaction curve given by (Camacho et al., 2020), the degree of interaction between the system variables is determined and quantified through the Relative Gain Array (RGA) matrix.

It is important to emphasize that interaction is one of the main characteristics in a multivariable system and occurs because an input variable influences all output variables in different ways, posing challenges for the execution of the process and the planning of a control system(Camacho et al., 2020).

The equation represents the RGA matrix as given in equation (3.1) and means the Hadamard product. However, we suggest reading (Camacho et al., 2020) and (Liptak et al., 2018).

$$\Lambda(G(s)) = G(s)o(G(s)^{-1})^T = K(K^{-1})^T \tag{3.1}$$

The Hadamard product provides a measure of the interaction of the process and indicates how the pairing of the variables should be performed (Camacho et al., 2020).

Thus, substituting equation (3.1) with the values of the steady-state gains of the process provided by equation (2.9) we arrive at the RGA matrix, which can be seen in equations (3.2) and (3.3).

$$\Lambda = \begin{bmatrix} 0.85 & 0.44 \\ 0.49 & 1.07 \end{bmatrix} \left[\begin{bmatrix} 0.85 & 0.44 \\ 0.49 & 1.07 \end{bmatrix}^{-1} \right]^T \tag{3.2}$$

$$\Lambda = \begin{bmatrix} 1.31 & -0.31 \\ -0.31 & 1.31 \end{bmatrix} \tag{3.3}$$

By applying the Bristol criterion to the obtained RGA matrix, it can be observed the system has a high interaction between the manipulated variables. Additionally, it can be indicated that there is a diagonal with 2 positive numbers and another diagonal with 2 negative numbers. Therefore, the diagonal with two positive numbers of this matrix is selected for pairing since choosing the diagonal containing negative numbers would generate stability problems when transitioning from an open loop to a closed loop. However, because the mating values are greater than one, it is evident that this TITO system is highly sensitive to parameter changes.

Finally, given the aforementioned reasons, the use of decouplers to eliminate the interaction between the manipulated variables of this system is justified and will be presented in the next section of this article.

CHAPTER 4

DECOUPLER DESIGN

This section presents the design of the decouplers due to the interaction between the system variables presented in the previous section. It should be emphasized that the purpose of the decouplers is to reduce the interaction between the manipulated variables, causing each controller to perform its work more independently in each of the system variables, allowing for an improvement in the system response.

4.1 System structure with decouplers

The structure of a system with decouplers can be seen in Fig.4.1. Where D(s) represents the decoupler and G(s) represents the system, while V_1, V_2 are the inputs and Y_1, Y_2 represent the outputs of the system.

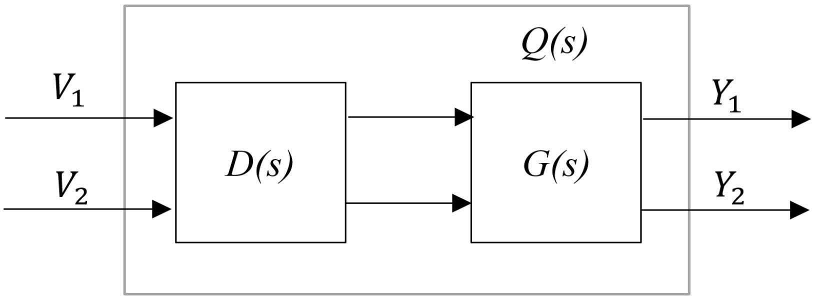

Figure 4.1: Structure of a system with decouplers

Therefore, for the design of the decouplers, we have (4.1):

$$D(s) = G(s)^{-1}Q(s) \tag{4.1}$$

Q(s) represents the apparent process. Therefore, by rewriting the expression in matrix form, we have the following.

$$D(s) = \begin{bmatrix} 1 & D_{12}(s) \\ D_{21}(s) & 1 \end{bmatrix} \tag{4.2}$$

where

$$D_{12}(s) = -\frac{G_{12}(s)}{G_{11}(s)} \tag{4.3}$$

$$D_{21}(s) = -\frac{G_{21}(s)}{G_{22}(s)} \tag{4.4}$$

Finally, replacing the values in the equation (4.2) leads to the following expression.

$$D(s) = \begin{bmatrix} 1 & \left[\frac{-88.44s-0.44}{252.61s+0.85}\right] e^{-62.81s} \\ \left[\frac{-95.82s-0.49}{303.74s+1.07}\right] e^{-42.75s} & 1 \end{bmatrix} \tag{4.5}$$

4.2 Decoupled system modeling

Taking into account the result obtained in equation (4.5), which represents the decouplers of the system, the system was modeled again implementing them. This modeling was performed following the same methodology presented in section II of this article; however, in this case, only one reference change was taken into account, which was a variation of 40 degrees. Therefore, the initial temperature set was 40 degrees Celsius and a reference change was made to 80 degrees Celsius at 1055 seconds. The results can be seen in Figs. 4.2 and 4.3.

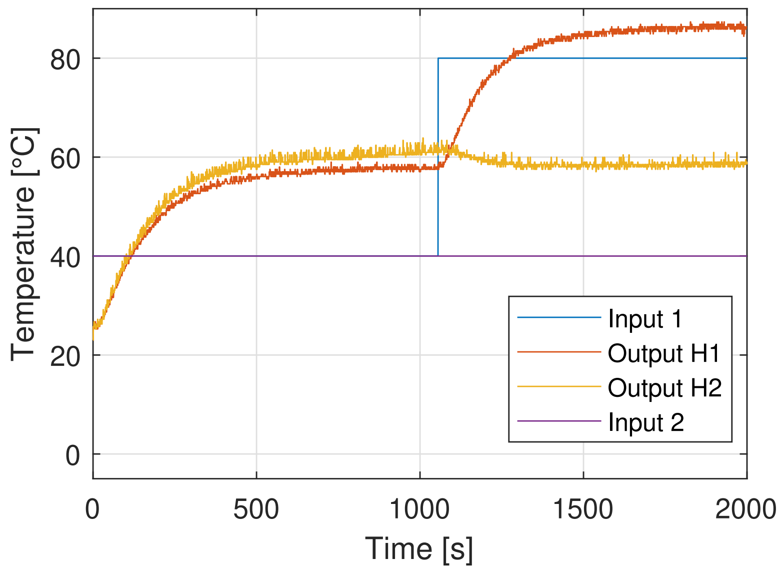

Figure 4.2: Model with decoupler for Heater 1 output

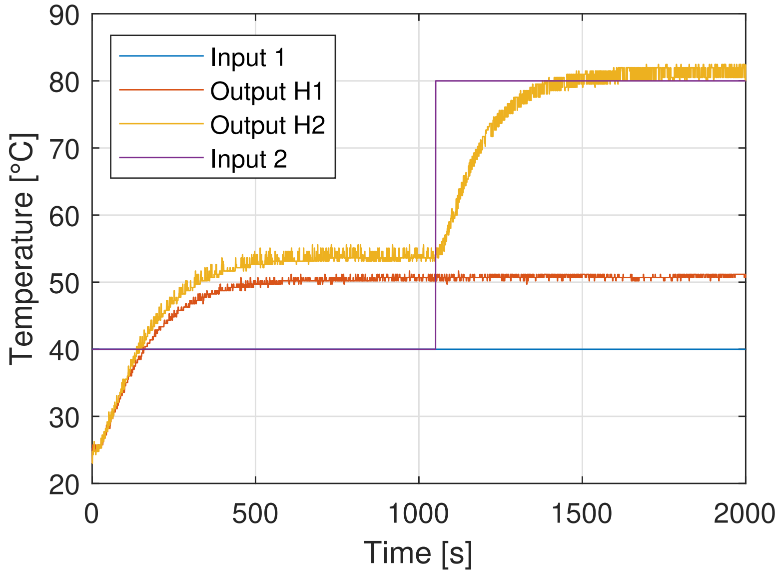

Figure 4.3: Model with decoupler for Heater 2 output

After applying the methodology presented in section II of this article, the obtained transfer functions representing this decoupled TITO system are given by the equations (4.6), and (4.7). Where equation (4.6) represents the model with decoupler for the output of Heater 1 and equation (4.7) represents the model with decoupler for the output of Heater 2.

$$H_1(s) = \frac{0.721e^{-19s}}{135s+1} \tag{4.6}$$

$$H_2(s) = \frac{0.456e^{-14.5s}}{160.5s+1} \tag{4.7}$$

It is important to emphasize that there is a significant difference between the system without the implementation of decouplers, as can be seen in Figs. 4.4 and 4.5, where the models without decouplers are shown for Heater 1 output and Heater 2 output.

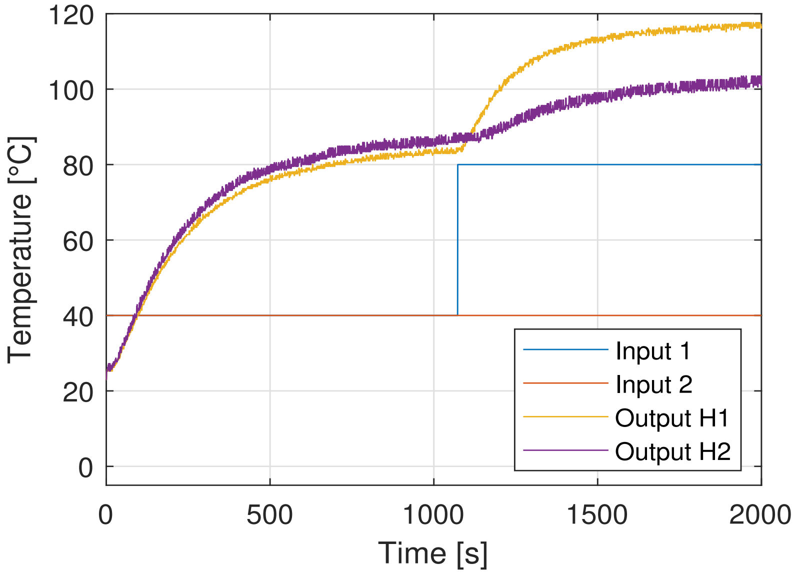

Figure 4.4: Model without decoupler for Heater 1 output

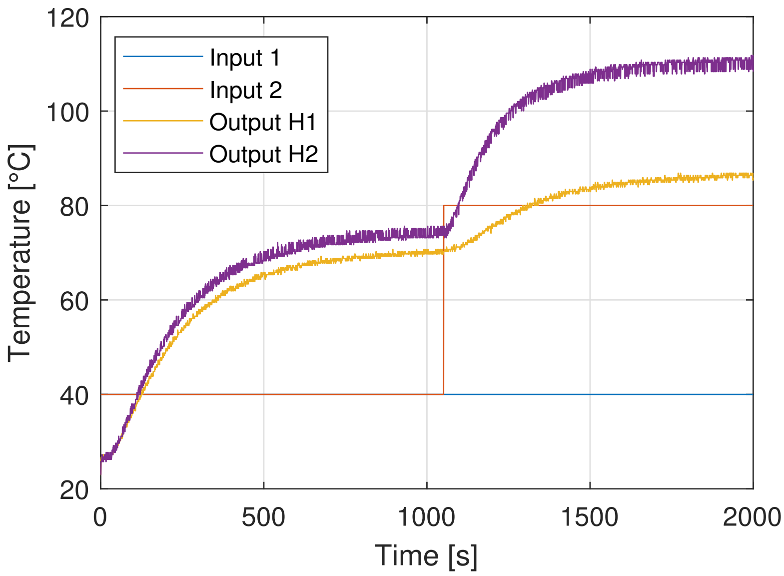

Figure 4.5: Model without decoupler for Heater 2 output

Finally, the models obtained for the decoupled system, expressed by the equations (4.6) and (4.7), will be used to carry out the design of the controllers for the TITO temperature process presented in this paper. This analysis will be carried out in the next section.

CHAPTER 5

DESIGN OF MULTIVARIABLE CONTROLLERS

This section presents the proposed controller designs based on the models that represent the decoupled system for this temperature TITO process represented in the previous section by equations (4.6) and (4.7), to subsequently analyze their differences and establish which controller is the most appropriate to use for this type of process.

5.1 Proportional Integral Derivative Controller

Taking into account that the 90% of industrial applications make use of PID controllers due to its simplicity and ease of tuning. The first design proposed to control this process was based on a PID controller using the Dahlin tuning method (Camacho et al., 2020), where the control scheme presented for this case can be seen in Fig.5.1. However, it can be observed that this control scheme is quite similar to the scheme of Fig.4.1 presented in section IV, the only thing that was added to that scheme is the control part.

It is important to note that the transfer functions $G_{11}(s)$ and $G_{22}(s)$ are already known and represent the dynamics of this system at the operating point. Furthermore $G_{21}(s)$ and $G_{12}(s)$ are the interactions of the system which must be canceled by using the decouplers obtained in the previous section. Finally, in the boxes representing $Controller_1$ and $Controller_2$ will be replaced in this case with the PID controllers to be implemented, whose names are given by $PID_1(s)$ and $PID_2(s)$, which will be analyzed in this section.

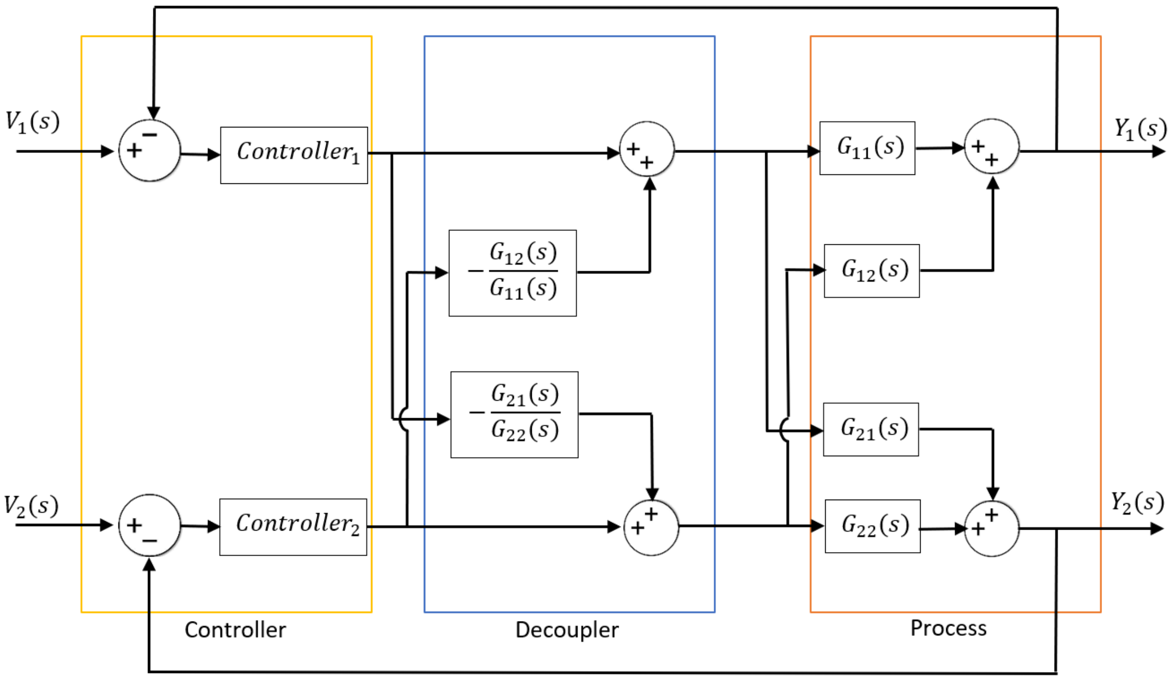

Figure 5.1: Control Scheme

5.2 PID Controller Tuning

Starting from the equations (4.6) and (4.7) obtained in Section IV of this article, the tuning technique applied is by means of Dahlin's method (Camacho et al., 2020), through equations (5.1), (5.2), (5.3) and (5.4).

$$Kp_1 = \frac{1}{2k_1}\left(\frac{t_{0_1}}{\tau_1}\right)^{-1} = 4.93 \tag{5.1}$$

$$Kp_2 = \frac{1}{2k_2}\left(\frac{t_{0_2}}{\tau_2}\right)^{-1} = 12.14 \tag{5.2}$$

$$\tau_{i_1} = \tau_1 = 135 \tag{5.3}$$

$$\tau_{i_2} = \tau_2 = 160.5 \tag{5.4}$$

Where Kp represents the gain, while τ_i represents the time constant of the proposed PI controller, which is presented in equations (5.5), (5.6), (5.7) and (5.8) to form the transfer function representing this PI controller.

However, it is important to emphasize that the decision was made to eliminate the derivative part of these controllers to avoid noise problems in the system. Thus, it can be stated that the result obtained is a proportional integral (PI) controller.

$$PID_1(s) = Kp_1 + \frac{Kp_1}{\tau_{i_1} s} \tag{5.5}$$

$$PID_1(s) = 4.93 + \frac{0.036}{s} \tag{5.6}$$

$$PID_2(s) = Kp_2 + \frac{Kp_2}{\tau_{i_2} s} \tag{5.7}$$

$$PID_1(s) = 12.14 + \frac{0.076}{s} \tag{5.8}$$

5.3 Proportional Integral Fuzzy Controller

During the last few years, two mainly different approaches to fuzzy logic controller (FLC) design have emerged: heuristic and model-based. The main motivation for heuristic-based design is that an experienced operator still manually controls many industrial processes. The process is also controlled by an automatic control system that requires additional manual online trimming by an experienced operator(Palm et al., 1997).

In this second design proposed to control the process, the approach was based on the fuzzy control model (Fuzzy); its tuning process was performed based on a heuristic method specifically for obtaining the tuning values in the controller (PI-Fuzzy 1 and PI-Fuzzy 2). The control scheme is shown in Fig. 5.1.

Using the heuristic method to obtain tuning values, it was found that the best value to tune this system was 0.35 a gain and saturation of [4,-4].

In the Fuzzy Logic Designer configuration in Matlab, the Fuzzy Logic Controller (FLC) was generated using Fuzzy Logic Designer to input the rules the error (e) with a working range [-100, 100] and the derivative of the error ($\dot{e}$) with a range [-4, 4], these data enter the Fuzzy Interference System (FIS) type Mamdani (which can be found from the Command Window of MATLAB by typing: 'fuzzy') and generate an output (u) with a range [-3, 3]. For the FIS variables, 7 Membership Function (MF) were used, so we have 49 rules from NG to PG (see table 5.1), with gaussmf type curves. This section of the rules can be found in detail at(Palm et al., 1997).

Table 5.1: An FLC in a diagonal form

e \ $\dot{e}$	NG	NM	NP	Z	PP	PM	PG
NG	uNG	uNG	uNG	uNG	uNM	uNP	uZ
NM	uNG	uNG	uNG	uNM	uNP	uZ	uPP
NP	uNG	uNG	uNM	uNP	uZ	uPP	uPM
Z	uNG	uNM	uNP	uZ	uPP	uPM	uPG
PP	uNM	uNP	uZ	uPP	uPM	uPG	uPG
PM	uNP	uZ	uPP	uPM	uPG	uPG	uPG
PG	uZ	uPP	uPM	uPG	uPG	uPG	uPG

CHAPTER 6

RESULTS

Following the design of the proposed controllers in the previous section of this article, this section presents the response of the multivariable controllers to the reference changes made. The aim is to evaluate the performance of both proposed controllers, namely a classical PI controller versus a PI-Fuzzy controller applied to the thermal system (TCLAB).

However, the experimental tests performed were developed with the same version of Matlab-Simulink 2023a software but on two different computers. The first computer has an Intel(R) Core(TM) i7-6600U CPU @ 2.60GHz 2.80 GHz. 12GB RAM and a 64-bit operating system. On the other hand, the second computer has an Intel(R) Core(TM) i5-7200U CPU @ 2.50 GHz 2.70 GHz. 8GB RAM and a 64-bit operating system.

It is important to emphasize that the tests should be performed under similar conditions without running more processes than the same software execution to obtain results similar to the previous simulation of this process. Therefore, considering the above-mentioned, the TCLab was connected to the computer through its USB port, while the heaters were connected through an electrical plug. Finally, the software execution time was configured for each test performed, which was 7000 seconds.

Thus, the responses of the outputs to a reference change in the system can be observed in Fig.6.1 and Fig.6.2, while the behavior of the control actions can be seen in Fig.6.3 and Fig.6.4. Initially, a reference of 60°C is applied to both inputs. From t=1400 seconds, there is a reference change to 80°C for the first input, and then from t=2800 seconds, this first input is reduced to 60°C. Finally, from t=4200 seconds, there is a reference change to 80°C for the second input, and then from t=5600 seconds, it is reduced to 60°C.

In figures 6.1 and 6.2 it can be seen that, thanks to the controllers, both outputs can follow the trajectory established by the changes in the temperature references made. It is important to note that the two temperature variables are completely decoupled. In this context, if the input of Heater 1 varies from 60°C to 80°C and the input of Heater 2 remains at 60°C, the only output affected will be that of Heater 1, while the output of Heater 2 will maintain the initial set reference temperature. On the other hand, if we modify the reference of Heater 2 and maintain the reference of Heater 1, the opposite will occur in the outputs; that is, the only output that will vary will be that of Heater 2.

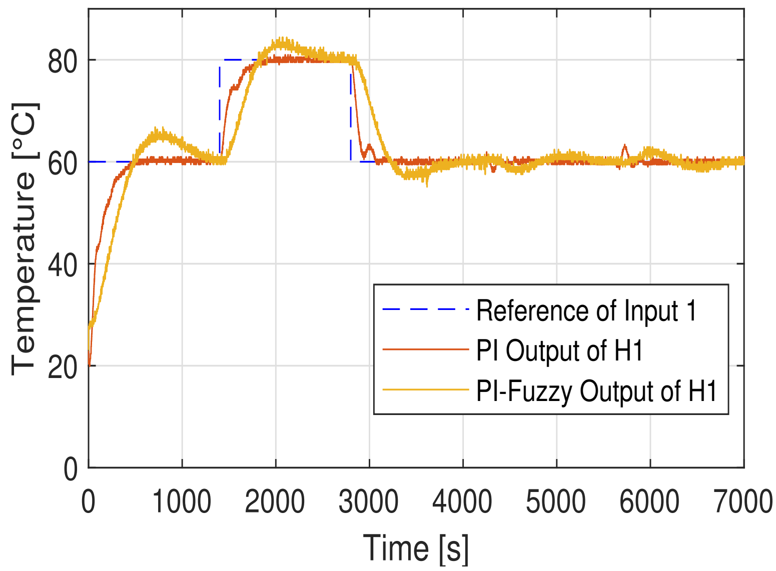

Figure 6.1: PI-Fuzzy vs PI Classic Heater 1 output

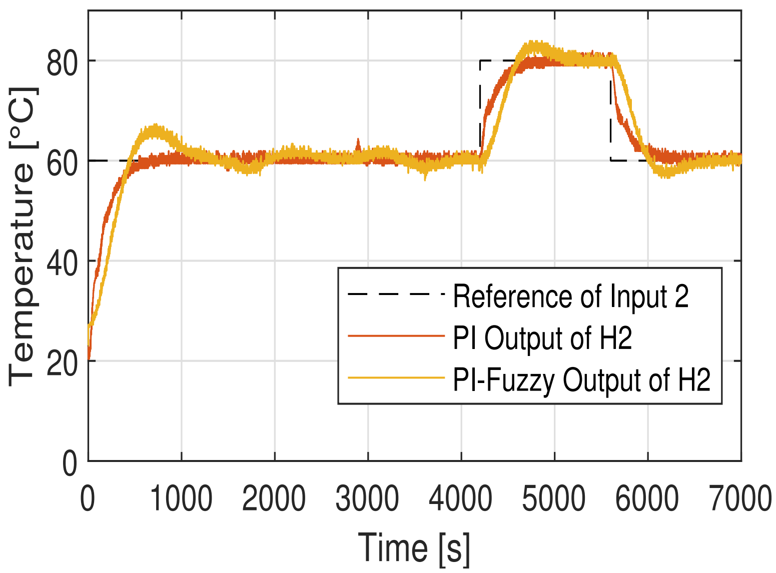

Figure 6.2: PI-Fuzzy vs PI Classic Heater 2 output

On the other hand, in the figures 6.3 and 6.4, it can be seen that the classical PI controller has a chattering effect; that is, it presents high-frequency oscillations which can deteriorate the actuator (Camacho et al., 2020, Liptak et al., 2018) and, as a consequence, it can reduce the useful life of the system.

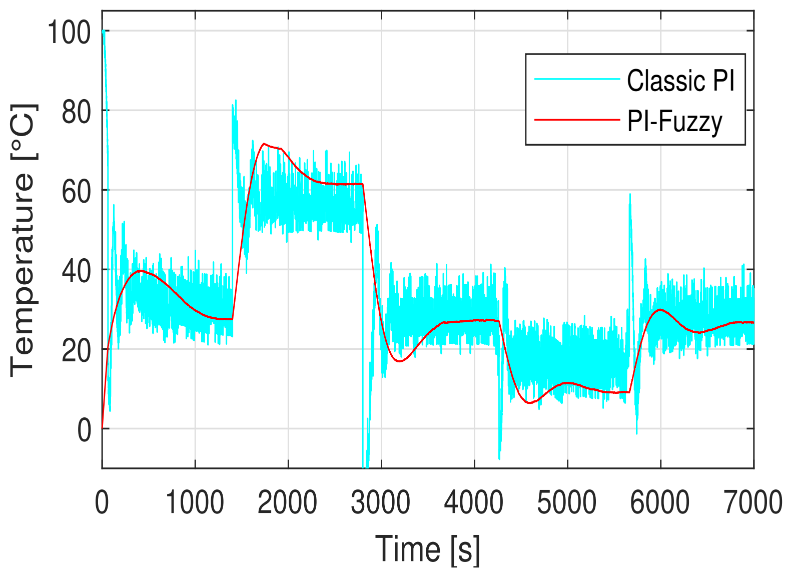

Figure 6.3: Control Action PI-Fuzzy vs PI Classic Heater 1

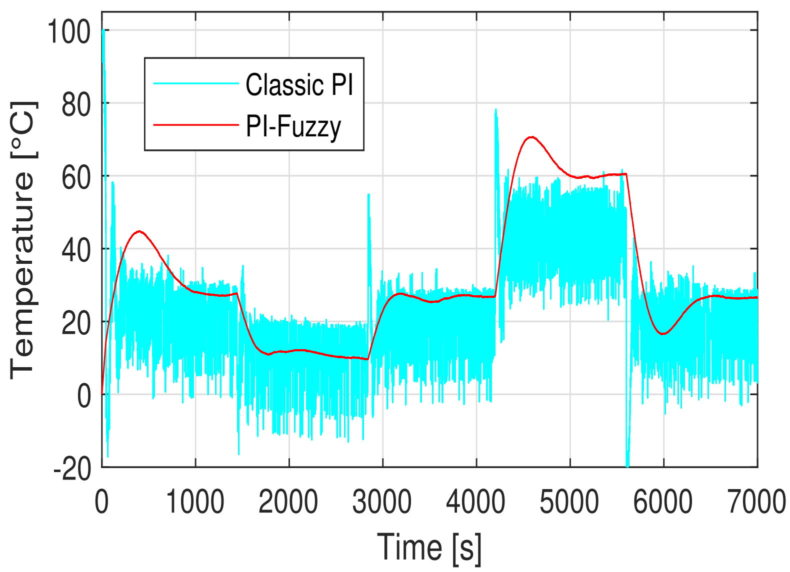

Figure 6.4: Control Action PI-Fuzzy vs PI Classic Heater 2

6.1 Controller Comparison

Through the experimental tests presented above, the performance indices integral absolute error (IAE), integral square error (ISE), and integral total error variation (TVU) were obtained. It should be emphasized that a performance indicator is a numerical tool that provides data to understand the performance of a system (Quiñónez et al., 2019).

The IAE (Integral of the Absolute Error) performance indicator measures the total magnitude of the accumulated error over time without giving preference to the duration of the error. It is commonly used as a performance criterion in controller tuning, where the goal is to minimize IAE to improve system response (Quiñónez et al., 2019).

On the other hand, the ISE performance indicator is useful when seeking to penalize errors during the state transition, as the square of the error will increase proportionally to the size of the error. However, errors that persist during a steady state are tolerated. Consequently, fast responses will be obtained, although they may have oscillatory characteristics (Quiñónez et al., 2019).

Similarly, the TVU performance indicator is based on examining the control signal, making it possible to evaluate fluctuations in the control effort. The application of this index makes it easier to obtain more gradual control signals, resulting in a reduction in the effort of the actuator and, therefore, reduces the wear time. (Quiñónez et al., 2019).

Finally, the maximum peak overshoot (MP) is also analyzed, which describes the maximum magnitude above the steady-state value that the response of a system reaches before stabilizing. The settling time (TS) is when the controlled signal stabilizes.

It is important to note that the performance indices mentioned above will allow a correct evaluation of the performance of both proposed controllers. These values are represented in Tables 6.1 and Table 6.2.

Table 6.1: Performance Indexes for Reference Change Test for Heater 1 Output

Controller	Heater 1				
	IAE	ISE	TVU	TS	MP[%]
PI	11080	172100	78200	694.5	0
PI-FUZZY	24770	347900	45180	1150	5.5108

Table 6.2: Performance Indexes for Reference Change Test for Heater 2 Output

Controller	Heater 2				
	IAE	ISE	TVU	TS	MP[%]
PI	15430	210500	97030	726.94	0
PI-FUZZY	24750	350200	44280	1125	4.8997

It is evident that, the implemented PI-FUZZY controller exhibits superior numerical values in IAE, ISE, TS and MP performance indices compared to the PI controller. Therefore, it is concluded that the PI controller demonstrates superior performance in terms of errors and settling time compared to the PI-FUZZY controller. In addition, the settling time of the PI-FUZZY controller is longer than that of the PI controller, indicating that the control action of the PI controller will be slower.

However, it is important to note that the PI controller exhibits a maximum impulse equal to 0, which implies that the system response does not exceed the final value of the reference change before stabilizing. Consequently, this controller presents a fast response without excessive oscillations.

In relation to the TVU performance index, it is observed that the PI-FUZZY controller has a lower magnitude compared to the PI controller. Therefore, it is deduced that the PI-FUZZY controller generates smoother control signals, thus decreasing the stress on the actuators and delaying the degradation time of the system.

CHAPTER 7

CONCLUSIONS

A proportional-integral (PI) controller and a PI-FUZZY controller were developed for implementation in a thermal process. The TCLab, a reference device for control applications, was used for the thermal system.

In the comparison process, a quantitative analysis of the system responses was carried out based on benchmark change tests, which allowed performance indicators to be obtained. It is concluded that in the case of Integral Absolute Error (IAE) and Integral Square-Error (ISE) the PI controller outperforms the PI-FUZZY controller, making the PI controller output response fast and without excessive oscillations.

However, it is important to emphasize that in the case of the Integral of Total Error Variance (TVU) the PI-FUZZY controller outperforms the PID controller, i.e., it does not exhibit a chattering effect as presented in the PID control action. Therefore, it generates smoother control signals, contributing to the reduction of the effort on the actuators and delaying the degradation time of the system.

BIBLIOGRAPHY

Aguilar-López, R., Mata-Machuca, J. L., and Godinez-Cantillo, V. (2021). A tito control strategy to increase productivity in uncertain exothermic continuous chemical reactors. *Processes*, 9(5).

ApMonitor (2022). Temperature control lab. `https://apmonitor.com/pdc/index.php/Main/ArduinoTemperatureControl`. Accessed in January 2024.

Arun, N. and Mohan, B. (2018). Modeling and computational aspects of nonlinear fuzzy tito pi/pd controller via height defuzzification. *IFAC-PapersOnLine*, 51(1):347–352.

Camacho, O., Rosales, A., and Rivas, F. (2020). Control de procesos. *Quito-Ecuador: EPN Editorial*.

Contreras, M., Herrera, M., Leica, P., and Camacho, O. (2023). Dynamic sliding mode controller applied to a temperature tito process. *International Journal of Automation and Control*, 17(2):227–248.

de Moura Oliveira, P., Hedengren, J. D., and Rossiter, J. (2020). Introducing digital controllers to undergraduate students using the tclab arduino kit. *IFAC-PapersOnLine*, 53(2):17524–17529. 21st IFAC World Congress.

Gegov, A. E. (1995). Decentralized fuzzy control of multivariable systems by direct decomposition. *Engineering Applications of Artificial Intelligence*, 8(2):201–209.

Liptak, B. G., Piovoso, M. J., Shinskey, F. G., Eren, H., Totherow, G. K., Jamison, J. E., Morgan, D., Hertanu, H. I., Marszal, E. M., Berge, J., et al. (2018). *Instrument engineers' handbook, volume two: Process control and optimization*. CRC press.

Lu, Q. and Mahfouf, M. (2012). Multivariable self-organizing fuzzy logic control using dynamic performance index and linguistic compensators. *Engineering Applications of Artificial Intelligence*, 25(8):1537–1547.

Mejía, C., Salazar, E., and Camacho, O. (2022). A comparative experimental evaluation of various smith predictor approaches for a thermal process with large dead time. *Alexandria Engineering Journal*, 61(12):9377–9394.

Morilla, F., Garrido, J., and Vázquez, F. (2013). Control multivariable por desacoplo. *Revista Iberoamericana de Automática e Informática industrial*, 10(1):3–17.

Palm, R., Driankov, D., and Hellendoorn, H. (1997). *Model based fuzzy control: fuzzy gain schedulers and sliding mode fuzzy controllers*. Springer Science & Business Media.

Quiñónez, K., Camacho, O., and Chávez, D. (2019). Application of nonlinear pid controllers to bioreactor processes. In *2019 IEEE 4th Colombian Conference on Automatic Control (CCAC)*, pages 1–6. IEEE.

Xu, C. and Shin, Y. C. (2011). A self-tuning fuzzy controller for a class of multi-input multi-output nonlinear systems. *Engineering Applications of Artificial Intelligence*, 24(2):238–250.

Ying, H. (2000). Tito mamdani fuzzy pi/pd controllers as nonlinear, variable gain pi/pd controllers. *International journal of fuzzy systems*, 2(3):192–197.