

Real-time QFT Control for Temperature in Greenhouses

Control QFT en tiempo real para la temperatura en invernaderos

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Abstract—Sudden changes in a greenhouse environment negatively impact the development and production of crops, especially in greenhouses with natural ventilation when temperatures are low at night and change rapidly due to wet winds. To mitigate these variations, a design of a robust controller based on Quantitative Feedback Theory (QFT) as from a Smith predictor structure for the dead-time system is proposed. This structure offers high stability based on the gain margin, the phase margin, and the rejection of disturbances in the system output. This design was contrasted with a PID controller based on performance indices, according to the transient response and error in the presence of changes in the point of operation and charge disturbances. Final results showed that the dynamic response of the QFT controller improved compared to PID controller results.

Index Terms— QFT controller, robust control, temperature control, Smith predictor

Resumen—Los cambios repentinos en el ambiente del invernadero tienen un impacto negativo en el desarrollo y la producción de cultivos, especialmente en invernaderos con ventilación natural cuando las temperaturas son bajas en la noche y cambian rápidamente debido a los vientos húmedos. Para mitigar estas variaciones, se propone el diseño de un controlador robusto basado en la Teoría de Realimentación Cuantitativa, (por su sigla en inglés QFT), a partir de una estructura tipo predictor de Smith para sistemas con tiempo muerto. Este esquema ofrece una alta estabilidad basada en el margen de ganancia, el margen de fase y el rechazo de las perturbaciones en la salida del sistema. El diseño se contrastó con un controlador PID basado en índices de desempeño, de acuerdo con la respuesta transitoria y el error ante la presencia de cambios en el punto de operación y las perturbaciones de carga. Los resultados finales mostraron que la respuesta dinámica del controlador QFT mejoró en comparación con los resultados del controlador PID.

Palabras Claves—Controlador QFT, control robusto, control de temperatura, predictor Smith

I. INTRODUCTION

FOOD production in greenhouses with controlled environmental variables (temperature, humidity & CO₂ content) is an alternative to achieve crops with high

production rates, high quality, and low energy cost. In order to improve the efficiency of greenhouse crops, different strategies have been developed for temperature control since this variable strongly impacts the development of the plants [1]. One of these strategies is based on the development of algorithms that allow mitigating the effects of dead time when it is dominant on the process dynamics [2], according to the Smith predictor structures type for predictive control [3], modified Smith Predictor [4] and multivariable controllers for greenhouses [5]. With the use of these structures, the gain margin, the phase margin and the bandwidth restrictions imposed by dead time systems have been improved [6].

Thus, this development was oriented to the design of a robust controller based on the Quantitative Feedback Theory (QFT) and a structure as from a Smith predictor structure for dead-time system applied to temperature control of the greenhouse to scale with a heating system since this structure offers a high stability based on the gain margin, the phase margin, and the rejection of disturbances in the system output. Thereby, it was started from modeling of the temperature behavior inside a greenhouse was used to design a robust QFT controller (Section II), in which the system stability and controller's behavior against external disturbances in contrast with a PID controller were validated. Likewise, it was inferred the proposed control strategy performance that showed the robust stability and rejection of disturbances with minimum effort of the control signal (Section III). Finally, conclusions were drawn regarding the study carried out (Section IV).

II. METHODOLOGY

A. Mathematical model identification

A mathematical model that related the temperature gradient of the greenhouse with the duty cycle applied to the AC-AC converter for a heating system was defined by (1). Besides, the parametric variation of the plant temperature and the system uncertainty space were quantified for the design of the QFT controller temperature.

Therefore, Fig.1 shows a random binary excitation signal (RBS), the greenhouse real system and the identified system response. Likewise, RBS signal related the input and output of the system and was configured with amplitude between [0.25 – 0.75] of the duty cycle of PWM signal, applied to the AC-AC ON-OFF converter [7], with a bandwidth

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$BW = 0.00468$ Hz, which was selected from the response of the temperature to a step input signal of 50% of the PWM duty cycle applied to the AC-AC converter. The sampling frequency was $F_s = 1$ and the number of samples was 15000.

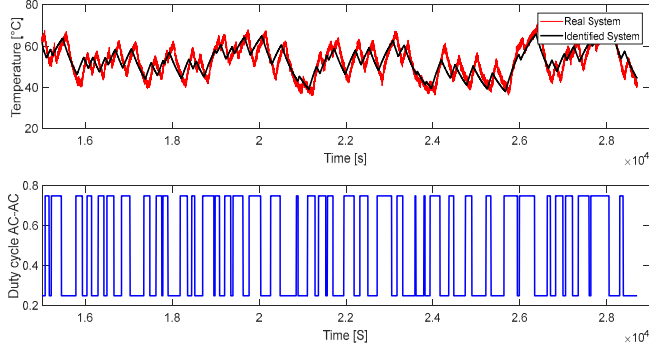


Fig. 1. RBS signal for real system and identified system.

Considering RBS signal shown by Fig. 1 first-order transfer functions with dead time was identified, where dead time is $L = 120.5$ s, the system time constant is $T = 213.9$ s, and the static system gain is $K = 75.4$. This model is represented by (1), which related the temperature inside the greenhouse, with the duty cycle of the PWM signal applied to the AC-AC ON-OFF converter.

$$Gp(s) = \frac{K \cdot e^{-L \cdot s}}{T \cdot s + 1} \quad (1)$$

B. QFT controller design

The uncertainty space is one of the most relevant aspects and pillars for QFT controllers design [8]. Hence, for the developed controller, an uncertainty interval was established for the static gain K , time constant T , and dead time L , listed in Table I, based on identification tests. Those tests are similar to Mathematical model identification made in before section, at different points of operation of the heating system at the greenhouse. Therefore, a family of plants was evaluated against a set of frequencies of interest between 0.0001 rad/s and 0.1 rad/s, taken into consideration the bandwidth of the system. Thus, a phase [°] - magnitude [dB] representation of the plants set on the Nichols chart was obtained for each frequency.

TABLE I
PARAMETRIC UNCERTAINTY

Parameter	Lower limit	Upper limit
Static Gain K	60.32	90.48
Time Constant T (s)	171.12	256.68
Dead Time L (s)	96.4	144.6

The performance of a controller with a conventional Smith predictor is affected by its sensitivity to the process parametric variation [9], and external disturbances [2]. However, dead time compensation techniques based on a modified Smith predictor scheme has been used successfully in the tuning of PID controllers with two degrees of freedom [10], auto-tuning models of PID controllers [11] and in PID controllers with

systems that present variable dead time [12].

Hence, robust design of a Smith predictor based on the consideration of the bandwidth and a quantitative approach of the compensator was proposed [13], taking on a structure grounded in the concept of the modified Smith predictor [14], for a system P_r with dead time L . The structure uses an estimated plant without delay \hat{P}_r in an internal loop with an estimated pure delay \hat{L} , which allows mitigating the effects of dead time to facilitate the design of the controller G using a quantitative approach. In Fig. 2, a structure based on the Smith predictor concept for dead time is proposed.

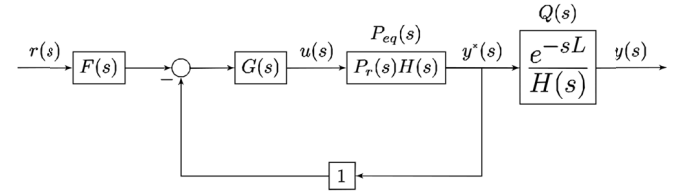


Fig. 2. Modified Smith predictor equivalent diagram.

Thus, transfer function $H(s)$ is given by (2), the equivalent plant $P_{eq}(s)$ is given by (3) and the system input-output rate $y(s)/r(s)$ is given according to (4).

$$H(s) = \left(1 - e^{-s\hat{L}}\right) \cdot \frac{\hat{P}_r(s)}{P_r(s)} + e^{-sL} \quad (2)$$

$$P_{eq}(s) = P_r(s) \cdot H(s) = \left(1 - e^{-s\hat{L}}\right) \cdot \hat{P}_r(s) + P_r(s) \cdot e^{-sL} \quad (3)$$

$$\frac{y(s)}{r(s)} = \frac{P_{eq}(s) \cdot G(s)}{1 + P_{eq}(s) \cdot G(s)} \cdot Q(s) \quad (4)$$

Moreover, a QFT controller considering Smith predictor was designed for an uncertainty process. The choice of $\hat{P}_r \cdot e^{-s\hat{L}}$ is a critical factor due to $Q(s)$ degrades the system for each value that $H(s)$ takes in the uncertainty space. So this, one first algorithm was proposed for a plant set selection $\hat{P}_r \cdot e^{-s\hat{L}}$ such that $|Q(s)| \leq m_d$ in the frequency range of interest of the controller $0 \leq \omega \leq \omega_{BW}$, where m_d is set to 3dB [14], additionally from the second algorithm, a single plant $\hat{P}_r \cdot e^{-s\hat{L}}$ of the set was selected that satisfied the first algorithm and allowed to minimize the cost function given by (5), where n_ω equals the number of frequencies of interest. $A(T_{eq}(j\omega))$ represents the model template area $\hat{P}_r \cdot e^{-s\hat{L}}$ and $A(T(j\omega))$ represents nominal plant template P_r .

$$I_{\cos t} = \frac{1}{n_\omega} \cdot \sum_{\omega \in \Omega} \frac{A(T_{eq}(j\omega))}{A(T(j\omega))} \quad (5)$$

Therefore, the transfer function given by (6), was calculated with the algorithms proposed [14] for the frequency range in the matter.

$$\hat{P}_r(s) = \frac{80.3}{195.3 \cdot s + 1} \quad (6)$$

Since greenhouse is subject to external disturbances and presents variation in the parameters due to different environmental conditions, two performance specifications were defined based on the recommended minimum robust stability of 5dB for gain margin and 45° for phase margin given by (7) [15], and in the rejection of load disturbances in the temperature inside the greenhouse given by (8).

$$\left| \frac{y}{r} \right| = \left| \frac{L(j\omega)}{1+L(j\omega)} \right| < \delta_u(\omega) \quad (7)$$

$$\left| \frac{y}{d} \right| = \left| \frac{1}{1 + L(j\omega)} \right| < \delta_s(\omega) \quad (8)$$

Hence, parameters $\delta_u(\omega)$ and $\delta_s(\omega)$ were quantified, either as constants or from transfer functions that represent the desired dynamics of the plant under closed loop [16], [17]. The criterion used for robust stability was defined with $\delta_u(\omega) = 1.3$ [15]. In this way, the rejection of disturbances of the greenhouse was defined from the parameter $\delta_s(\omega)$ given by (9) [18]. Therefore, this was determined as a transfer function that represents the desired dynamics of the plant before a disturbance. Consequently, a settling time of 1500 s was chosen for the output before a step type disturbance, as a condition of the sensitivity function of the system. To define the transfer function $\delta_s(\omega)$, the pole assignment method was applied [16].

$$\delta_s(\omega) = \frac{s^2 + 0.002554 \cdot s}{s^2 + 0.005108 \cdot s + 6.533 \times 10^{-6}} \quad (9)$$

Firstly, an $L(j\omega)$ value must be obtained which fits the inequalities established in the performance specifications, where $L(j\omega) = G(j\omega) \cdot P(j\omega)$, based on the controller performance specifications given by (7) and (8), in addition, to the transfer functions that represent the parameters $\delta_u(\omega)$ and $\delta_s(\omega)$. Thus, the control problem focused on determining a unique $G(j\omega)$ controller that meets all the performance specifications established from the plant with uncertainty $P(j\omega)$ in the frequency range of interest [19].

In order to solve the control problem, a quadratic inequality was proposed for each performance specification [20], as shown by (10) and (11).

$$p^2 \cdot \left(1 - \frac{1}{\delta''}\right) \cdot g^2 + 2 \cdot p \cdot \cos(\phi + \theta) \cdot g \geq 0 \quad (10)$$

$$p^2 \cdot g^2 + 2 \cdot p \cdot \cos(\phi + \theta) \cdot g + \left(1 - \frac{1}{\delta_s^2}\right) \geq 0 \quad (11)$$

Loop-shaping technique introduces a $G(s)$ controller that modifies the loop function L_o until it complies with the constraints imposed by the contours of the performance specifications, this way the unique controller $g \cdot e^{j\phi}$ that

complies is what manages to take the function of the loop L_o on the contours of each specification [19]. Fig. 3 shows the response in the frequency of interest. This was achieved by adding poles and zeros to the L_o loop function until the desired response was reached [15]. The transfer function of the QFT controller is given by (12).

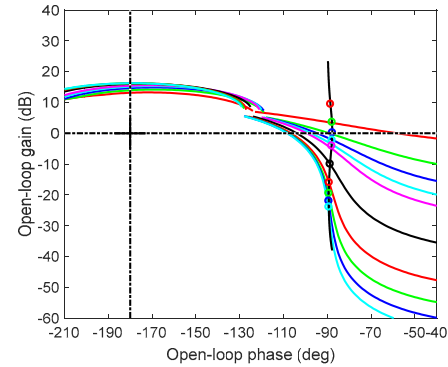


Fig. 3. QFT Controller response for L_o .

$$G(s) = \frac{0.0014 \cdot s^3 + 0.0014 \cdot s^2 + 0.018 \cdot s + 9.8 \times 10^{-5}}{s \cdot (1.9 \times 10^{-9} \cdot s^2 + 1.6 \times 10^{-6} \cdot s + 1)} \quad (12)$$

The PID controller was designed from the transfer function $P_r(s)$ and performance affixed indices for the QFT controller design associated with its transient response. Since Control System Toolbox in Matlab®, PID controller parameters were tuned, this is given by (13). An integrator, a complex zero at $0.00196 \pm 0.00775j$ and a pole on $P = -0.1$ was added. Besides, the gain was set at $K = 5.5 \times 10^{-5}$. Proportional gain $K_p = 0.0028$, integral gain $K_i = 5.184$, derivative gain $K_d = 0.835$, and derivative filter constant $Nd = 0.183$ [21] was normalized on equation (14). This was based on parameters given by (13).

$$G_{PID}(s) = \frac{0.086386 \cdot (s^2 + 0.0039 \cdot s + 6 \times 10^{-5})}{s^2 + 0.1 \cdot s} \quad (13)$$

$$G_{PID}(s) = K_p + K_i \cdot \frac{1}{s} + K_d \cdot \left(\frac{Nd}{1 + Nd \cdot \frac{1}{s}} \right) \quad (14)$$

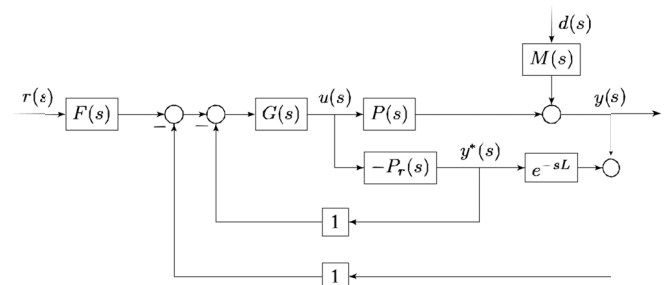


Fig. 4. Controller block diagram with Smith predictor structure.

Fig. 4 shows the block diagram that allows implementing the QFT controller and PID controller. In this way, to

implement the QFT controller, transfer function given by (12) was introduced on $G(s)$ block, and to implement the PID controller, transfer function given by (13) was introduced on $G(s)$ block.

III. RESULTS AND DISCUSSION

To begin with, an experimental system for real-time data acquisition of the greenhouse was implemented, in which the control action was coded into a signal by pulse width modulation (PWM) to determine on and off times on the solid-state relay AC-AC converter. Likewise, in Matlab®, Simulink Desktop Real-Time, real-time control algorithm was implemented to interact physically with the process. Hence, Tests were carried out to validate the stability of the system and the performance of the controller against external disturbances in reference to the greenhouse temperature.

Taking a look at Fig. 5, the system response is displayed for 40°C, which it is observed that the system dynamic response presented an overshoot of less than 1%. Also, settling time was approximately 1000 s, and the control signal remained close to 15% of duty cycle.

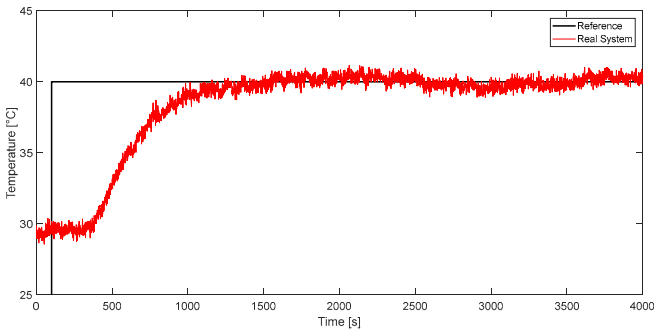


Fig. 5. QFT controller response at 40°C.

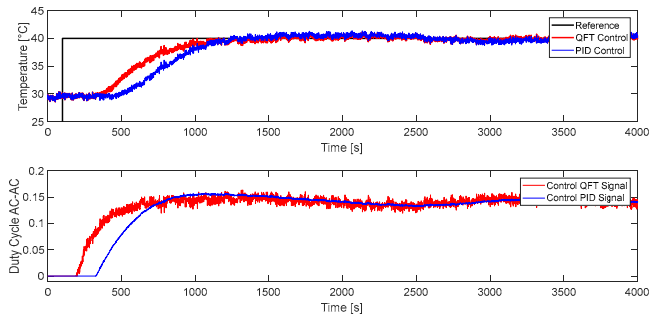


Fig. 6. QFT and PID controllers response at 40°C.

Likewise, Fig. 6 represents a conventional PID and QFT controller with a modified Smith predictor response at 40°C. Therefore, it is observed that the QFT controller presented an overshoot of less than 2%, besides that, a lower effort in the control signal and a fast response was noticed in comparison with PID controller that presented an overshoot close to 3%, a greater effort in the control signal and a slower response. The settling time of the QFT controller was close to 1000 s in contrast to the PID controller that approached 1200 s. In addition, QFT controller presented high sensitivity to noise in

the sensor, while the PID controller was more robust by the derivative filter. In the same way, both controllers showed an error in a steady state close to zero. Table II lists the performance indices for tests at 40°C and at 50°C.

QFT controller response to an external variation of the temperature inside the greenhouse was validated, which it was subjected to a disturbance at 4000 s. Temperature disturbance is based on a turbine activation that is connected to the greenhouse, which forced the external wind circulation, causing that the temperature inside the greenhouse sudden decrease. Fig. 7 shows the QFT and PID controller's behavior.

TABLE II
PERFORMANCE INDICES BASED QFT AND PID CONTROLLER'S STABILITY

Temperature	40°C		50°C	
Controller	QFT	PID	QFT	PID
t_s (s)	1000	1200	1050	1300
M_p (%)	2	3	0	3
E_p (°C)	0	0	0	0.5

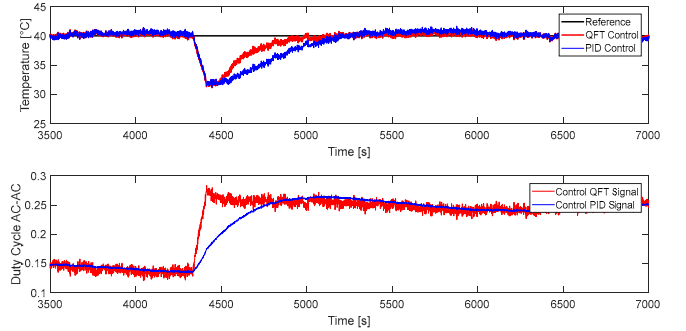


Fig. 7. System response in presence of QFT and PID controller disturbances.

TABLE III
QFT AND PID CONTROLLERS' INDICES PERFORMANCE IN PRESENCE OF EXTERNAL DISTURBANCES

Temperature	40°C	
Controller	QFT	PID
t_s (s)	1000	1200
E_p (°C)	850	960
ΔD	0	0

Finally, it is appreciated that the QFT controller lasted 850 s to compensate for the disturbance, whereas the PID controller lasted 690 s. In addition, QFT controller presented an abrupt control action without straining the actuator, whereas the PID controller presented a smoother response. Both controllers showed an error in a steady state close to zero after compensating the disturbance. QFT controller control signal showed an increase of 10% to compensate for the temperature change, whereas the PID controller showed an increase of 13%. Table III shows indices performance for tests at 40°C of temperature.

IV. CONCLUSIONS

The proposed controller applied to the range of uncertainty

for the temperature system parameters quickly mitigated the effects of the dead time, which favored the system tuning and therefore its stability. Likewise, external disturbances effects and changes in the point of operation with minimum effort of the control signal were mitigated. It also kept within controller performance specifications such as settling time and the overshoot. Final results showed that the dynamic response of the QFT controller improved 12%, with a decrease of 1% in the overshoot and 3% in the effort of the control signal, compared to PID controller results. Lastly, implemented an experimental system for the acquisition of real-time data from the greenhouse allowed demonstrate high sensitivity to noise in QFT controller sensing, in contrast to the low sensitivity of the sensing in PID controller. This condition raised the need for a more exhaustive study to improve the sensitivity in QFT controllers.

REFERENCES

- [1] K. Yingchun and S. Yue, "A Greenhouse Temperature and Humidity Controller Based on MIMO Fuzzy System," in *2010 International Conference on Intelligent System Design and Engineering Application*, 2010, vol. 1, pp. 35–39.
- [2] A. Visioli and Q. Zhong, *Control of Integral Processes with Dead Time*. London: Springer-Verlag, 2011.
- [3] Z. D. Tian, "Algorithm and Implementation of Smith Predictive Control," *Appl. Mech. Mater.*, vol. 687–691, pp. 60–63, Nov. 2014.
- [4] E. H. Gurban and G.-D. Andreescu, "Comparison of modified Smith predictor and PID controller tuned by genetic algorithms for greenhouse climate control," 2014, pp. 79–83.
- [5] S. A. C. Giraldo, R. C. C. Flesch, and J. E. Normey-Rico, "Multivariable Greenhouse Control Using the Filtered Smith Predictor," *J. Control Autom. Electr. Syst.*, vol. 27, no. 4, pp. 349–358, Aug. 2016.
- [6] C. Esparza, R. Núñez, and F. González, "Model Reference Adaptive Position Controller with Smith Predictor for a Shaking-Table in Two Axes," in *Advances in Computational Intelligence*, 2012, pp. 271–282.
- [7] J. M. B. García, A. A. García, and E. F. Amorós, *Electrónica de potencia: teoría y aplicaciones*. Universidad Politécnica de Valencia. Servicio de Publicaciones, 1999.
- [8] M. Garcia-Sanz and C. H. Houpis, *Wind Energy Systems: Control Engineering Design*. CRC Press, 2012.
- [9] A. H. Ahmadi and S. K. Y. Nikraves, "Robust Smith Predictor (RSP)," in *2016 24th Iranian Conference on Electrical Engineering (ICEE)*, 2016, pp. 1510–1515.
- [10] V. M. Alfaro and R. Vilanova, *Model-Reference Robust Tuning of PID Controllers*. Cham: Springer International Publishing, 2016.
- [11] F. N. Deniz and N. Tan, "A Model Identification Method for Tuning of PID Controller in a Smith Predictor Structure," *IFAC-Pap.*, vol. 49, no. 10, pp. 13–18, Jan. 2016.
- [12] F. S. S. de Oliveira, F. O. Souza, and R. M. Palhares, "PID Tuning for Time-Varying Delay Systems Based on Modified Smith Predictor" This work has been supported by the Brazilian agencies CAPES, CNPq, and FAPEMIG., *IFAC-Pap.*, vol. 50, no. 1, pp. 1269–1274, Jul. 2017.
- [13] M. Garcia-Sanz and J. G. Guillen, "Smith predictor for uncertain systems in the QFT framework," in *Progress in system and robot analysis and control design*, Springer, London, 1999, pp. 239–250.
- [14] M. Garcia-Sanz, *Robust Control Engineering: Practical QFT Solutions*. CRC Press, 2017.
- [15] M. G. Martínez, "Síntesis de controladores robustos mediante el análisis de la compatibilidad de especificaciones e incertidumbre," <http://purl.org/dc/dcmitype/Text>, Universidad Pública de Navarra, 2001.
- [16] C. H. Houpis, S. N. Sheldon, and J. J. D'Azzo, *Linear Control System Analysis and Design: Fifth Edition, Revised and Expanded*. CRC Press, 2003.
- [17] N. Cohen, Y. Chait, O. Yaniv, and C. Borghesani, "Stability analysis using Nichols charts," *Int. J. Robust Nonlinear Control*, vol. 4, no. 1, pp. 3–20, 1994.
- [18] J. Elso, M. Gil-Martínez, and M. García-Sanz, "Quantitative feedback control for multivariable model matching and disturbance rejection," *Int. J. Robust Nonlinear Control*, vol. 27, no. 1, pp. 121–134, Jan. 2017.
- [19] M. Gil-Martínez and M. García-Sanz, "Simultaneous meeting of robust control specifications in QFT," *Int. J. Robust Nonlinear Control*, vol. 13, no. 7, pp. 643–656, 2003.
- [20] Y. Chait and O. Yaniv, "Multi-input/single-output computer-aided control design using the quantitative feedback theory," *Int. J. Robust Nonlinear Control*, vol. 3, no. 1, pp. 47–54, Jan. 1993.
- [21] A. Visioli, *Practical PID Control*. London: Springer-Verlag, 2006.