MASKAY 9(2), Nov 2019
ISSN 1390-6712
Recibido (Received): 2019/03/05
Aceptado (Accepted): 2019/05/05

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 can have detrimental effects on crop development and production, especially in greenhouses with natural ventilation that experience low temperatures at night and rapid fluctuations due to wet winds. To address this issue, we propose a robust controller based on Quantitative Feedback Theory (QFT) from a Smith predictor structure for the dead-time system. This controller, which offers high stability based on the gain margin, the phase margin, and the rejection of disturbances in the system output, is designed to mitigate these variations. To assess its practical value, we compared this QFT controller with a PID controller based on performance indices related to the transient response and error in the presence of changes in the point of operation and charge disturbances. The final results clearly demonstrated the superior dynamic response of the QFT controller, suggesting its potential for improving temperature control in greenhouses and enhancing crop productivity.**

***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**

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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. Different strategies have been developed for temperature control to improve the efficiency of greenhouse crops 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].

Our research was meticulously conducted, focusing on the design of a robust controller based on the Quantitative Feedback Theory (QFT) and a structure from a Smith predictor structure for a dead-time system applied to temperature control of the greenhouse. This structure was chosen for its high stability based on the gain margin, the phase margin, and the rejection of disturbances in the system output. We began by modeling the temperature behavior inside a greenhouse and designing a robust QFT controller (Section II). The system stability and controller´s behavior against external disturbances, in contrast with a PID controller, were thoroughly validated. The proposed control strategy's performance was then inferred to demonstrate robust stability and rejection of disturbances with minimum effort of the control signal (Section III). Finally, we drew conclusions based on the comprehensive study (Section IV).

II. METHODOLOGY

A. Mathematical model identification

Equation (1) defined a mathematical model that related the greenhouse's temperature gradient with the duty cycle applied to the AC-AC converter for a heating system. 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

DOI: 10.24133/maskay.v9i2.1162

(RBS), the greenhouse natural system, and the identified system response. Likewise, the RBS signal related to the input and output of the system and was configured with amplitude between [0.25 – 0.75] of the duty cycle of the PWM signal, applied to the AC-AC ON-OFF converter [7], with a bandwidth $BW = 0.00468$ 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.

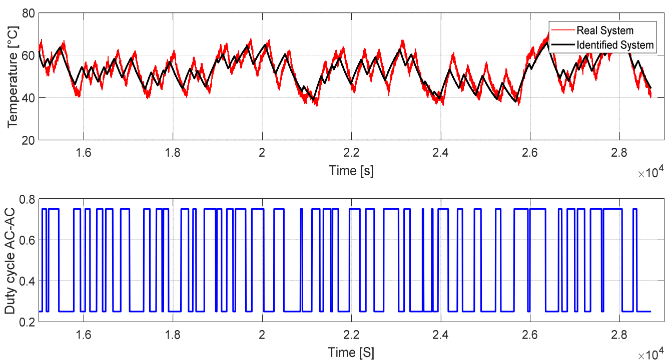

Fig. 1. RBS signal for natural system and identified system.

Considering the RBS signal shown in Fig. 1, first-order transfer functions with dead time were 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 relates the temperature inside the greenhouse with the duty cycle of the PWM signal applied to the AC-AC ON-OFF converter.

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

B. QFT controller design

The uncertainty space is one of the most relevant aspects and pillars for QFT controller 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 the Mathematical model identification made in the previous 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, considering the system's bandwidth. 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 have 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, a 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 controller G using a quantitative approach. Fig. 2 proposes a structure based on the Smith predictor concept for dead time.

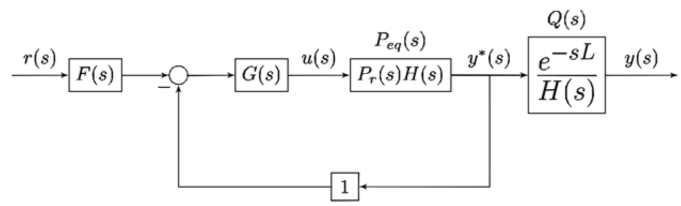

Fig. 2. Modified Smith predictor equivalent diagram.

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).

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

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

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

Moreover, a QFT controller considering the Smith predictor was designed for an uncertainty process. The choice of $\hat{P}_r \cdot e^{-s \cdot \hat{L}}$ is a critical factor because $Q(s)$ degrades the system for each value $H(s)$ takes in the uncertainty space. So this, one first algorithm was proposed for a plant set selection $\hat{P}_r \cdot e^{-s \cdot \hat{L}}$ 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 $\hat{P}_r \cdot e^{-s \cdot \hat{L}}$ 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. $A \cdot (T_{eq}(j\omega))$ represents the model template area $\hat{P}_r \cdot e^{-s \cdot \hat{L}}$, and $A \cdot (T(j\omega))$ represents the nominal plant template P_r.

$$I_{cost} = \frac{1}{n_\omega} \cdot \sum_{\omega \in \Omega} \frac{A\left(T_{eq}(j\omega)\right)}{A\left(T(j\omega)\right)} \tag{5}$$

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

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

Since greenhouses are subject to external disturbances and present 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 the rejection of load disturbances in the temperature inside the greenhouse given by (8).

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

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

Hence, parameters δ_u (ω) and δ_S (ω) were quantified, either as constants or from transfer functions that represent the desired dynamics of the plant under a closed loop [16], [17]. The criterion used for robust stability was defined with δ_u (ω) = 1.3 [15]. In this way, the rejection of disturbances in the greenhouse was defined from the parameter δ_S (ω) 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. The pole assignment method was applied to define the transfer function δ_S (ω)[16].

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

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

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

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

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

The 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 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).

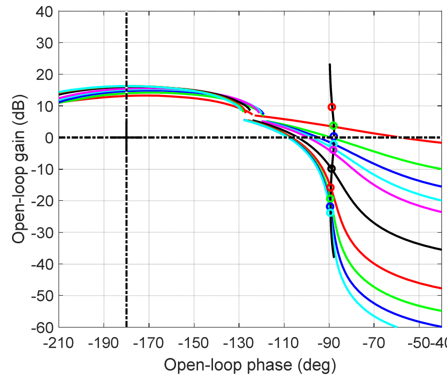

Fig. 3. QFT Controller response for L_o.

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

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 ± 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).

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

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

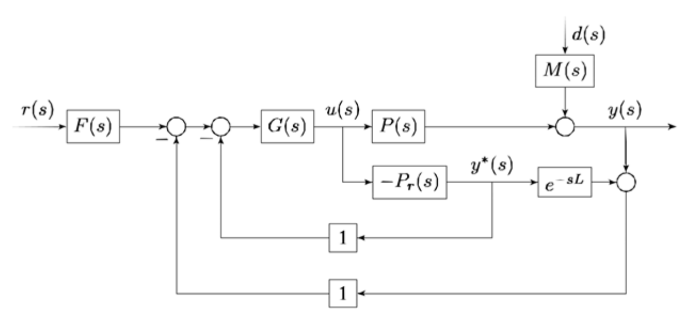

Fig. 4. Controller block diagram with Smith predictor structure.

Fig. 4 shows the block diagram that allows the QFT and PID controllers to be implemented. To implement the QFT controller, the transfer function given by (12) was introduced on the G (s) block, and to implement the PID controller, the transfer function given by (13) was introduced on the *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, a real-time control algorithm was implemented to interact physically with the process. Hence, Tests were carried out to validate the system's stability and the controller's performance against external disturbances in reference to the greenhouse temperature.

Fig. 5 displays the system response for 40°C. The system dynamic response presented an overshoot of less than 1%. Also, the settling time was approximately 1000 s, and the control signal remained close to 15% of the duty cycle.

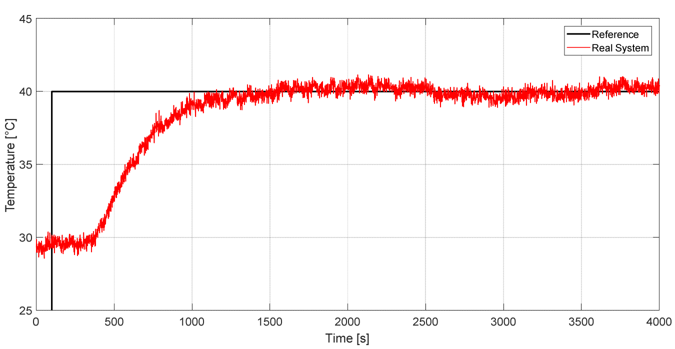

Fig. 5. QFT controller response at 40°C.

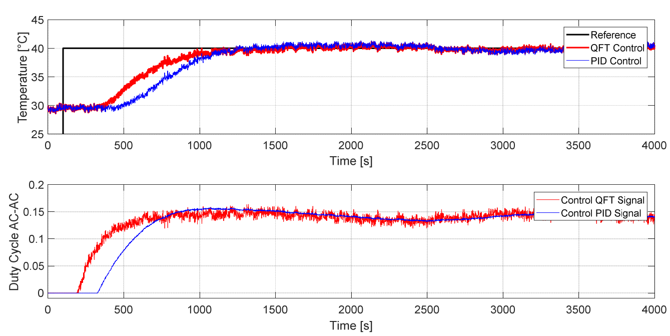

Fig. 6. QFT and PID controllers response at 40°C.

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 were noticed in comparison with the PID controller, which presented an overshoot of close to 3%, a more significant effort in the control signal and a slower response. The settling time of the QFT controller was close to 1000 seconds in contrast to the PID controller, which approached 1200 seconds. In addition, the QFT controller presented high sensitivity to noise in the sensor, while the derivative filter made the PID controller more robust. 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 50°C.

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

TABLE II
Performance Indices Based on QFT and PID Controller's Stability

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

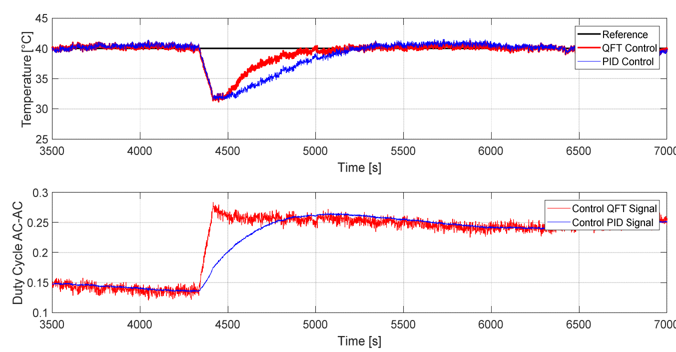

Fig. 7. System response in the presence of QFT and PID controller disturbances.

TABLE III
QFT and PID Controllers' Indices Performance in the 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, the 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 for 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 its stability. Likewise, the effects of external disturbances 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 by 12%, with a decrease of 1% in the overshoot and 3% in the effort of the control signal, compared to PID controller results. Lastly, implementing an experimental system for acquiring real-time data from the greenhouse allowed the demonstration of high sensitivity to noise in QFT controller sensing, in contrast to the low sensitivity of the sensing in the PID controller. This condition raised the need for a more exhaustive study to improve the sensitivity in QFT controllers.

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