Real-time QFT Control for Temperature in Greenhouses

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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 dead-time system is proposed. This structure offers a 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 12%, with a decrease of 1% in the overshoot and 3% in the effort of the control signal, compared to PID controller results.

Keywords: QFT controller, robust control, temperature control, Smith predictor

1. 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 (Yingchun and Yue 2010). 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 (Visioli and Zhong 2011), according to the Smith predictor structures type for predictive control (Tian 2014), modified Smith Predictor (Gurban and Andreescu 2014) and multivariable controllers for greenhouses (Giraldo, Flesch, and Normey-Rico 2016). With the use of these structures, the gain margin, the phase margin and the bandwidth restrictions imposed by dead time systems have been improved (Esparza, Núñez, and González 2012).

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 modelling of the temperature behavior inside a greenhouse (section 2) was used to design a robust QFT controller (section 3), 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 (section 4) that showed the robust stability and rejection of disturbances with minimum effort of the control signal. Finally, conclusions were drawn regarding the study carried out (section 5).

2. MODELLING

2.1 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. 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 real system and the identified system response.

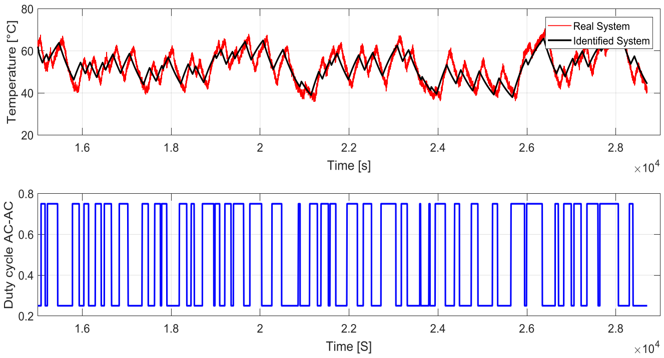

Fig. 1. RBS signal for real system and identified system

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 (García, García, and Amorós 1999), 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 Fs = 1 Hz and the number of samples was 15000.

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

$$Gp(s) = \frac{Ke^{-Ls}}{Ts + 1} \tag{1}$$

3. QFT CONTROLLER DESIGN

3.1. Uncertainty space

The uncertainty space is one of the most relevant aspects and pillars for QFT controllers design (Mario Garcia-Sanz and Houpis 2012). 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.1, based on identification tests at different points of operation of the heating system at the greenhouse. Therefore, a family of plants were 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 1. Parametric Uncertainty

Parameter	Variation	
	Minimum	Maximum
Static Gain K	60.32	90.48
Time Constant T [s]	171.12	256.68
Dead _Time L [s]	96.4	144.6

3.2 Smith predictor applied to QFT control

The performance of a controller with a conventional Smith predictor is affected by its sensitivity to the process parametric variation (Ahmadi and Nikravesh 2016), and external disturbances (Visioli and Zhong 2011). 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 (Alfaro and Vilanova 2016), auto tuning models of PID controllers (Deniz and Tan 2016) and in PID controllers with systems that present variable dead time (de Oliveira, Souza, and Palhares 2017).

Hence, a robust design of a Smith predictor based on the consideration of the bandwidth and a quantitative approach of the compensator was proposed (M. Garcia-Sanz and Guillen 1999), taking on a structure grounded in the concept of the modified Smith predictor (Mario Garcia-Sanz 2017), 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 to mitigate the effects of dead time to facilitate the design of the controller G using a quantitative approach. In the Fig 2, a structure based on Smith predictor concept for dead time is proposed.

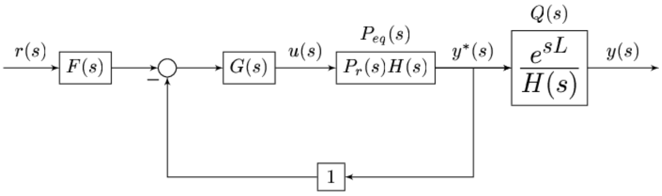

Fig. 2. Modified Smith predictor equivalent diagram

Thus, transfer function $H(s)$ is given by (2), the equivalent plant is given by (3) and the system input-output rate is given according to (4).

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

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

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

Moreover, a QFT controller considering Smith predictor was designed for an uncertainty process. The choice of $\hat{P}_r e^{-s\hat{L}}$ 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 $\hat{P}_r e^{-s\hat{L}}$ 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 $3dB$, additionally from the second algorithm, a single plant $\hat{P}_r e^{-s\hat{L}}$ 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 and $\hat{P}_r e^{-s\hat{L}}$ y $A(T(j\omega))$ represents nominal plant template P_r.

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

Therefore, transfer function given by (6), was calculated with the algorithms proposed (Mario Garcia-Sanz 2017) for the frequency range in matter.

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

3.3 Controller performance specifications

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) (Martínez 2001), and in the rejection of load disturbances in the temperature inside the greenhouse given by (8).

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

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

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 (Houpis, Sheldon, and D'Azzo 2003; Cohen et al. 1994). The criterion used for robust stability was defined with $\delta_u(\omega) = 1.3$. In this way, the rejection of disturbances of the greenhouse, was defined from the parameter $\delta_S(\omega)$ given by (9) (Elso, Gil-Martinez, and Garcia-Sanz 2017). 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 (Houpis, Sheldon, and D'Azzo 2003).

$$\delta_S(\omega) = \frac{s^2 + 0.002554\,s}{s^2 + 0.005108\,s + 6.533x10^{-6}} \tag{9}$$

3.4 QFT controller bounds.

Firstly, an $L(j\omega)$ value must be obtained which fits the inequalities established in the performance specifications, where $L(j\omega) = G(j\omega)P(j\omega)$, based on the controller performance specifications given by (7) and (8), in addditon 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 (Gil-Martínez and García-Sanz 2003).

In order to solve the control problem, a quadratic inequality was proposed for each performance specification (Chait and Yaniv 1993), as shown by (10) and (11).

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

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

3.5 Loop-shaping of QFT robust controller

Loop-shapping 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 $ge^{j\emptyset}$ that complies is what manages to take the function of the loop L_o on the contours of each specification (Gil-Martínez and García-Sanz 2003). 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 (Martínez 2001). The transfer function of the QFT controller is given by (12).

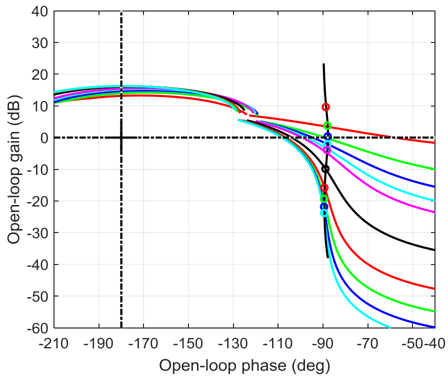

Fig 3. QFT Controller response for L_o

$$G(s) = \frac{0.0014s^3 + 0.0014s^2 + 0.018s + 9.8x10^{-5}}{s(1.9x10^{-9}s^2 + 1.6x10^{-6}s + 1)} \tag{12}$$

3.6 PID controller design

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 $K = 5.5x10^{-5}$. Proportional gain $K_p = 0.0028$, integral gain $K_i = 5.184$, derivative gain $K_d = 0.835$, and derivative filter constant $Nd = 0.183$ (Visioli 2006) was normalized on equation (14). This was based on parameters given by (13).

$$G_{PID}(s) = \frac{0.086386(s^2 + 0.0039\,s + 6x10^{-5})}{s^2 + 0.1\,s} \tag{13}$$

$$G_{PID} = K_p + K_i\frac{1}{s} + K_d\frac{Nd}{1+Nd\frac{1}{s}} \tag{14}$$

Fig 4. Shows the block diagram that allows to implement 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.

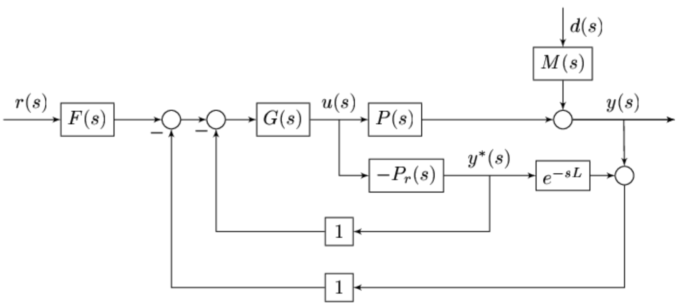

Fig 4. Controller block diagram with Smith predictor structure

4. 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 to Fig.5, the system response is displayed for $40\ °\ C$, which it is observed that the system dynamic response presented an overshoot of less than1%. Also, settling time was approximately$1000\ s$, and control signal remained close to 15% of duty cycle.

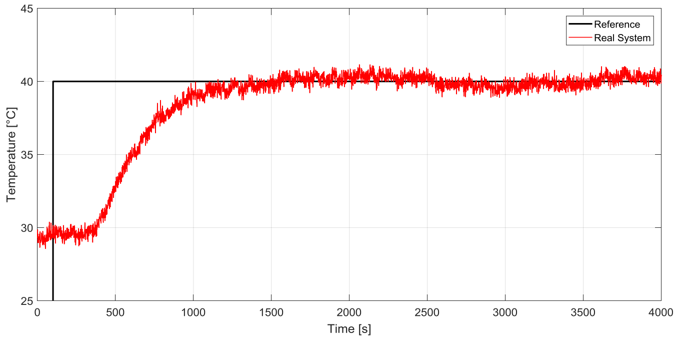

Fig. 5. QFT controller response at $40°C$

Likewise, Fig 6 represents a conventional PID and QFT controller with 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 steady state close to zero. Table 2 lists the performance indices for tests at $40\ °C$ and at $50\ °C$.

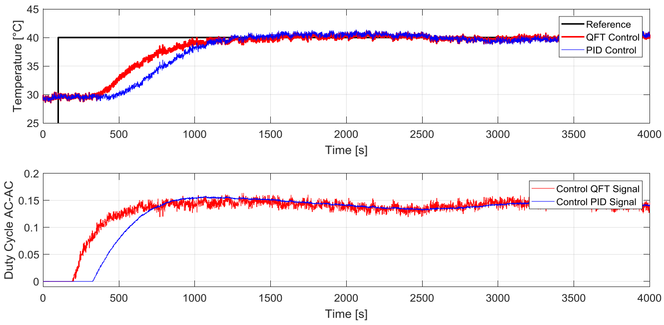

Fig. 6. QFT and PID controllers response at 40°C

Table 2. 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

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 QFT and PID controller's behavior.

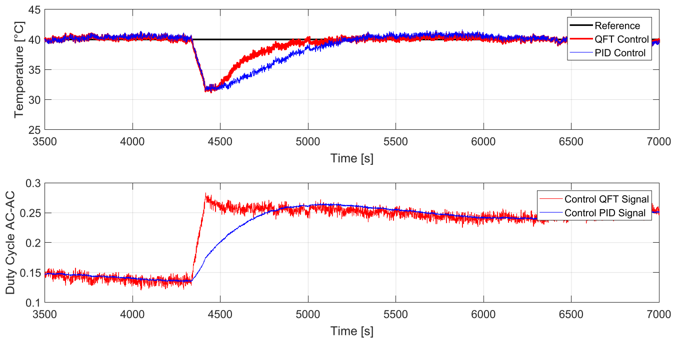

Fig.7. System response in presence of QFT and PID controller disturbances

Last of all, it is appreciated that QFT controller lasted $850\ s$ to compensate the disturbance, while PID controller lasted $690\ s$. Additionally, QFT controller presented an abrupt control action without straining the actuator, while PID controller presented a smoother response. Both controllers showed an error in steady state close to zero after compensating the disturbance. QFT controller control signal showed a 10% increase to compensate the temperature change, while PID controller showed a 13% increase. Table 3 shows indices performance for tests at $40\ °C$ of temperature.

Table 3. QFT and PID controllers' indices performance in presence of external disturbances

Temperature	40°C	
Controller	QFT	PID
$t_s\ [s]$	850	960
$E_p\ [°C]$	0	0
ΔD	10%	13%

5. CONCLUSION

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.

Lastly, implemented experimental system for the acquisition of real-time data from the greenhouse allowed to 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.

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