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ROBUST CONTROL OF GREENHOUSE CLIMATE EXPLOITING MEASURABLE DISTURBANCES

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Abstract: This paper presents the development and implementation of robust control techniques based on the quantitative feedback theory (QFT) aimed at achieving adequate values of inside greenhouse temperature in spite of uncertainties and disturbances acting on the system. A modification of classical design approaches has been included to incorporate feedforward action (exploiting the availability of measurements of disturbances, which in the particular case of greenhouses are the main energy source) and an antiwindup action to account for frequent saturations in the control signal. Results obtained with this scheme using a validated nonlinear simulator of greenhouse dynamics are also included. *Copyright © 2002 IFAC*

Keywords: Robust control, feedforward compensation, agriculture, control nonlinearities, bilinear systems.

1. INTRODUCTION

This paper deals with the development and implementation of robust control techniques based on the quantitative feedback theory (QFT) aimed at achieving desired values of inside greenhouse temperature in spite of uncertainties and disturbances acting on the system. The main objective of greenhouses crop production is to increment the economic benefits of the farmer by means of finding a trade-off between the improvement of the quality of the horticultural products and the cost of obtaining adequate climate conditions using new greenhouse structures and automatic control strategies. As a basic requirement, climate control helps to avoid extreme conditions (high temperature or humidity levels, etc.) which can cause damage to the crop and to achieve adequate temperature integrals that can accelerate the crop development and its quality while reducing pollution and energy consumption.

The greenhouse is a complex dynamical system which behaviour can be described in terms of a system of nonlinear differential equations describing mass balances (water vapour fluxes and CO_2 concentration) and energy transfer (radiation and heat) in the plastic cover, soil surface, one soil layer and crop. These processes depend on the outside environmental conditions, structure of the greenhouse, type and state of the crop and on the effect of the control actuators (typically ventilation and heating to modify inside temperature and humidity conditions, shading and artificial light to change internal radiation, CO_2 injection to influence photosynthesis and fogging/cooling for humidity enrichment). The coefficients of the equations vary with operating conditions in such a way that, from the system dynamics point of view, the greenhouse can be considered a smooth dynamical system which dynamics are operating point dependent. The classical approach in QFT method is to include the effect of disturbances acting on the system as unmodelled dynamics or to formulate the problem as a disturbance rejection one. In the case of greenhouse climate, the disturbances have the important role of being the main energy source in the system and thus, they should be exploited to minimize the energy consumption and to help to achieve the desired set points. A modification to the standard formulation has been performed to include a feedforward controller previously developed by some of the authors (Rodríguez *et al.*, 2001*a*) and antiwindup action in combination with the robust controller to exploit the effect of measurable disturbances.

The paper is organized as follows. In §2, a brief description of the greenhouse dynamics is performed, including a description of the real greenhouse which model is used for simulation purposes. §3 is devoted to explain the robust control approaches developed in this paper, including feedforward and antiwindup schemes. In §4, some simulation results are shown and finally, §5 presents some conclusions.

2. GREENHOUSE DYNAMICS AND EXPERIMENTAL PLANT

The greenhouse climate can be described by a dynamic model represented by a system of differential equations as a function of state variables (internal air temperature and humidity, cover temperature, soil surface temperature, PAR radiation, etc.), input variables (natural ventilation, shade screen and pipe heating systems), system variables, system parameters and disturbances (outside air temperature and humidity, outside solar radiation, wind speed and direction, etc.). Disturbance variables have a dominant role and coherent action onto the formation of the greenhouse environment.

Under several hypothesis, some authors of this paper have developed a validated nonlinear model of a typical plastic cover Mediterranean greenhouse including both climate conditions and crop development (Rodríguez *et al*., 2001*b*). This model is being used as a test-bed for the development and simulation of several control schemes, as the one presented in this paper. The following physical processes have been included in the balances: solar and thermal radiation absorption, heat convection and conduction, crop transpiration, condensation and evaporation. This model has been validated using one-minute measurements from a real "Araba" greenhouse (Fig. 1) located in El Ejido, Almería (South-East Spain). It is a plastic-made two symmetric curved slope roof with five North-South oriented naves of 7.5 x 40 m (1500 m^2 of soil surface and 5.5 m. high), laid on a structure made of galvanized steel. The control actuators and measured variables are those indicated in the first paragraph of this section.

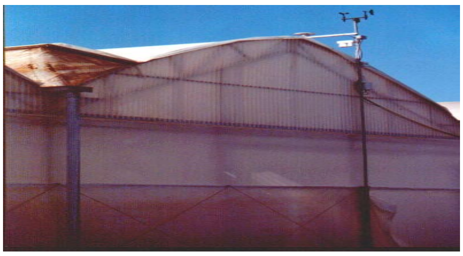


Fig. 1. Detail of the Araba greenhouse

3.DEVELOPMENT OF ROBUST CONTROLLERS

3.1 The quantitative feedback theory approach

Quantitative Feedback Theory (QFT) is a robust control design method (Horowitz, 1982) that uses a two-degrees of freedom (2DoF) feedback scheme (Fig. 2), where it is assumed that the uncertain system is represented by a transfer function $P(s)$ belonging to a set of plants $\wp$, while $G(s)$ and $F(s)$ are respectively the compensator and pre-compensator to be synthesised in order to meet robust stability and performance specifications.

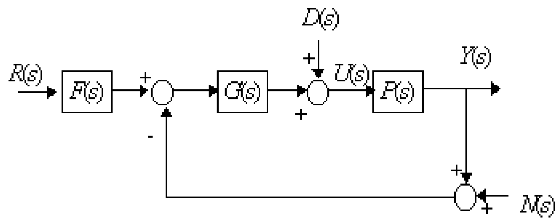


Fig. 2. A 2DoF feedback system

In QFT, closed loop specifications are given in the frequency domain, as admissible bounds on closed loop transfer functions. Then, specifications are combined with the uncertainty of the system (in the form of *templates*) to obtain limits or *boundaries* on the frequency shape of the compensator $G(s)$. In addition, nominal specifications are used to shape the pre-compensator $F(s)$.

3.2 Inclusion of a feedforward term in the 2DoF control system

As has been pointed out by (Sigrimis and Rerras, 1996), solar radiation has a strong immediate effect on the internal conditions and produces frequent oscillations (i.e., under passing clouds) in the controlled variables. In practice a time running average filter can be used when the measurements of this variable are used for control purposes. Outside temperature and humidity suffer slow variations and their measurements can be directly used for disturbance attenuation. Wind velocity includes a steady component, corresponding to the mean wind speed, and a transient component, corresponding to the gusting of the wind about the mean value. Mean wind velocity affects the air exchanges of the greenhouse or else the heat balance and can be also used for control purposes.

Although the control objective is to achieve a desired temperature integral for crop growing purposes, large changes in environmental variables affecting the greenhouse climate influence the net profit (Tap *et al*., 1993) , even leading to dangerous situations (e.g. condensation) as a consequence of the surpassing of temperature or humidity limits. Due to this reason, it is important to exploit the effect of disturbances in the inside conditions of the greenhouse by using adequate feedforward controllers. The feedforward term (Rodríguez *et al*., 2001*a*) is based on steady-state balance using a simplified bilinear model of the system which coefficients are fixed and calculated for a certain range of typical operating conditions:

$$c_{ter,a}\frac{dX_{t,a}}{dt} = c_r P_{r,e} + c_h(X_{t,h} - X_{t,a}) - (\phi_v + \phi_c)(X_{t,a} - P_{t,e}) + c_s(X_{t,s} - X_{t,a}) + \lambda Evap \qquad (1)$$

where $P_{r,e}$ is the solar radiation, $P_{t,e}$ is the outside temperature, $X_{t,h}$ is the temperature of the heating tubes, $X_{t,s}$ is the temperature of the soil, ϕ_v is the heat transfer coefficient due to ventilation, ϕ_c is the heat transfer coefficient from inside of the greenhouse out (assumed positive), c_r is the solar heating efficiency, c_h is the a heat transfer coefficient of the heating system and , c_s is the a heat transfer coefficient from soil to inside air. A term accounting for latent energy fluxes has been included in the balance (λ *Evap*), where λ is the vaporisation energy of water and *Evap* the evapotranspiration. ϕ_v is calculated by using a nonlinear expression (Rodríguez *et al.*, 2001) including inside and outside temperature, wind velocity ($P_{v,e}$), volumetric flow rate ($V_{h,efec}$, related with the vents aperture by a geometrical transformation) and several constants (length of the vents c_{lv}, gravity constant c_g, etc.) and coefficients (discharge coefficient c_d , and wind effect coefficient c_w) that have also been fixed. The value of the fixed coefficients in the mentioned equations have been obtained using input/output data obtained at the greenhouse and by iterative search in the range of values given by different authors using genetic algorithms.

By using the simplified representation of the heat balance given in equation (1) and considering a steady state balance, it is possible to derive a correlation for the input variables (ventilation and heating) as function of the environmental conditions and the inside temperature. The series feedforward controller is obtained by substituting the air temperature $X_{t,a}$ by the desired temperature *trff*. Thus, each sampling instant the following calculations have to be performed (only calculations for diurnal operation are included):

1. $$\phi_v = \frac{c_r P_{r,e} - \phi_c (trff - P_{t,e}) + c_s (X_{t,s} - trff)}{(trff - P_{t,e})} \qquad (2)$$

2. $$V_{h,efec} = \left\{ \left[\frac{\phi_v}{c_{den,a} c_{c-sp,a}} \frac{3 c_g (trff - P_{t,e})}{c_{lv} c_d P_{t,e}} + (c_w P_{v,e}^2)^{3/2} \right]^{2/3} - c_w P_{v,e}^2 \right\} \frac{P_{t,e}}{c_g (trff - P_{t,e})}$$

where a low-pass filter has been applied to solar radiation and wind speed disturbances to avoid sudden changes in the control signals. Notice that neither the latent heat nor the heating tubes terms have been included, as data used for the experiments shown in this paper were obtained with the crop in the early stages of its development and without using heating systems.

The inclusion of the feedforward term in series with the plant (Fig. 3) allows to explicitly take into account the measured value of the disturbances in such a way that the control signal provided by the feedback controller is the reference temperature to the feedforward term. Notice that if the model used by the feedforward term was an exact one, the system constituted by the feedforward term in series with the plant should have a steady state gain near unity. Unfortunately, the simplicity of the models (fixed coefficients) in comparison with a large complex simulation model of the real system (in which several coefficients change depend on operating conditions) and the uncertainty in the system (it is impossible to exactly model the greenhouse dynamics) advices the use of robust control techniques to account for the mentioned sources of uncertainties. To demonstrate this, Fig 4. shows the results obtained when implementing only the feedforward term in open-loop (without feedback controller). As can be seen, if the greenhouse dynamics should correspond to model described in equation (1), the response obtained with the system should be that expected from theoretical results. Nevertheless, due to model mismatches the real behaviour presents a different behaviour.

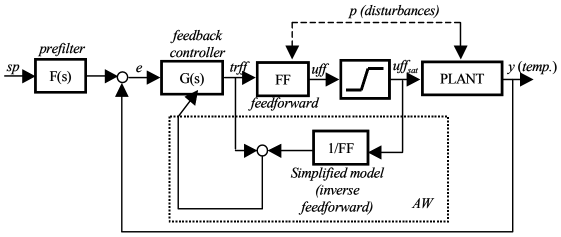


Fig. 3. Control scheme

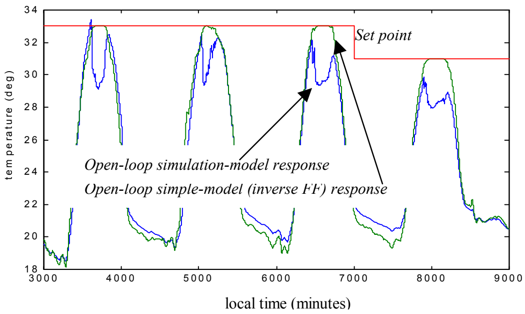


Fig. 4. Open loop effect of feedforward action

3.3. Inclusion of antiwindup action

Another feature of the system is that it suffers from frequent saturations of the input signal (vents) due to disturbances and operating point changes and deficient sizing of vents (often occurs), strongly limiting the control bandwidth. Due to this fact, as the controller must include integral action to track the set point temperature, the use of an antiwindup scheme is of advice. In the classical approach, both the vents aperture demanded by the control system and that provided by the saturation block or actuator should feed the antiwindup block. The problem that arises in this application is that the control signal provided by the robust controller is the reference temperature of the feedforward controller (Fig. 3), which provides the vents aperture depending on the measurements of environmental variables. So, the first input point to the antiwindup block has been displaced to the output of the feedback controller. Fortunately, when saturation occurs in the vents aperture, the corresponding reference temperature of the feedforward controller can be on-line calculated taking into account the actual value of disturbances, in such a way that the scheme reproduces the classical one. In order to guarantee global stability, the results presented in (Baños and Barreiro, 2000, Moreno *et. al.*, 2002) can be applied with the proposed approach.

3.4. Robust control design

In order to design the robust controller, the input-output description of the system composed by the feedforward term in series with the plant has been approximated by an uncertain first order system (step response tests shown that this approximation could be adopted), in which typical steady state gain and time constant mainly depend on the step input amplitude and can vary between the following bounds:

$P(s)=\dfrac{k}{\tau s+1}$, with $k\in[0.3,10]$, $\tau\in$ [360,1080] s.

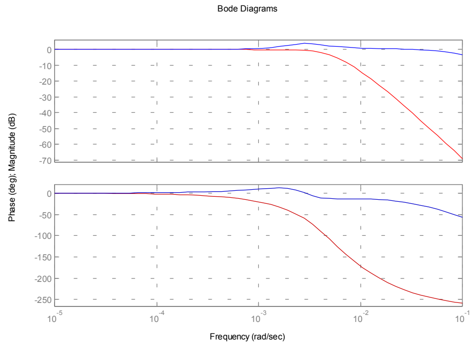


Fig. 5. Frequency domain specifications

Due to the uncertainty in the system, robust control can be used, and Horowitz's method is chosen, as done in other applications related to greenhouse climate (Linker *et al.*, 1999).

The first step in this method is to choose performance and stability specifications. Fig.5 shows the performance specifications.

As far as stability specifications is concerned, a gain margin of 5 dB and phase margin of 45º are desired:

$$\left|\frac{G(j\omega)P(j\omega)}{1+G(j\omega)P(j\omega)}\right|\leq 2.3dB,\forall P\in\wp,\forall\omega>0 \qquad (3)$$

with $\wp=\left\{\dfrac{k}{\tau s+1}:k\in[0.3,10],\tau\in[360,1080]\right\}$.

Note that (3) does not guarantee stability for the closed loop system, due to presence of the actuator saturation, see for example (Moreno *et. al.*, 2002).

A controller $\{F,G\}$ must be designed in order to assure that the closed loop transfer function T (from reference to output) lies within envelopes in Fig. 5, and the stability specification in (3) is achieved, with

$$T\in\Im=\left\{F(s)\frac{G(s)P(s)}{1+G(s)P(s)}:P\in\wp\right\}.$$

In order to proceed with the design of the controller, the value sets (Barmish, 1988), which describe the system uncertainty in the Nichols chart, are computed (Fig. 6).

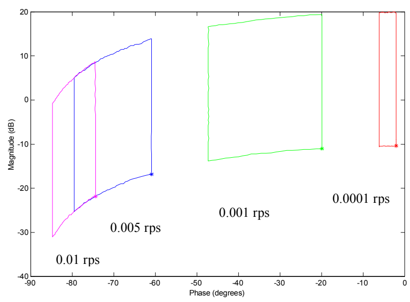


Fig. 6. System value sets.

Taking into account the typical time constants involved in this problem and specifications, this is a low frequency problem and so, the selected frequency points (rad/s) for the design are *W*=[0.0001, 0.001, 0.005, 0.01], leading to values of $\Delta|T(j\omega)|$=[0.0063, 0.6777, 5.5564, 14.7622] respectively.

Using the algorithm in (Moreno *et al.*, 1997), the performance and stability boundaries are computed, and the nominal open loop transfer function (Fig. 7) using computer tools (Borguesani *et al.*, 1995).

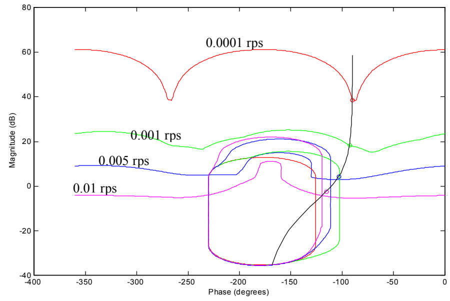


Fig.7. Nominal open-loop and bounds at design frequencies in *W*.

The resulting controller G is given by equation:

$$G(s)=\left(10+\frac{0.028}{s}\right)\left(\frac{0.021}{s+0.021}\right)$$

Finally, the precompensator F to achieve the nominal specification is: $F(s)=\left(\dfrac{0.017}{s+0.0017}\right)$

Fig. 8 shows the final result of the design for the considered set of plants $\wp$.

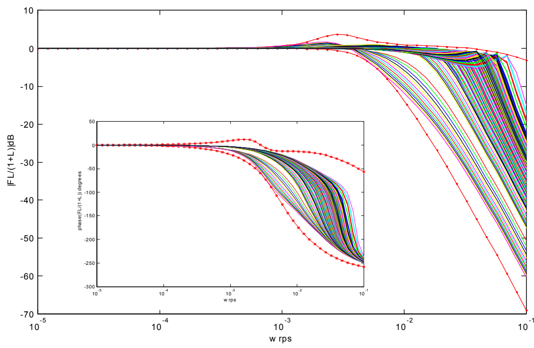
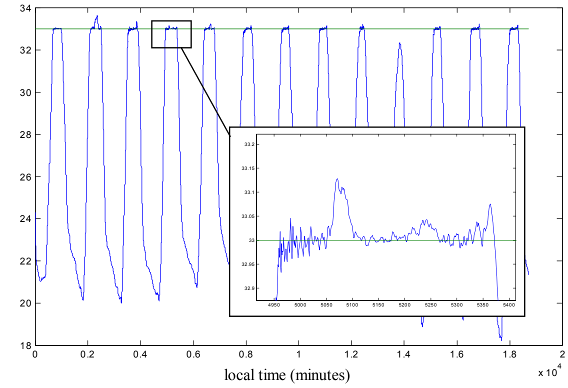


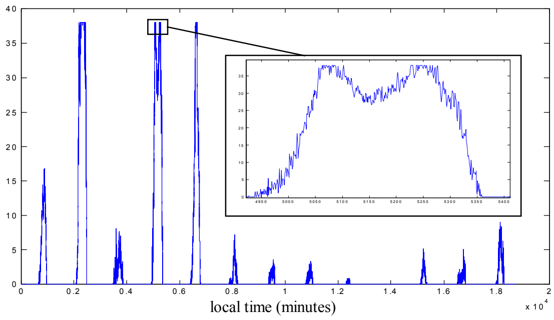
Fig. 8. Closed loop specifications (dashdot) and frequency responses (solid) of the controlled system.

4. RESULTS

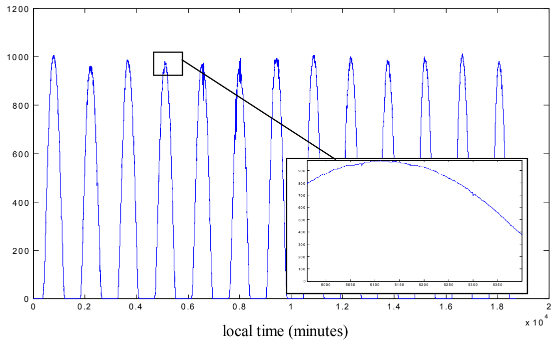
In this section, some illustrative results of the proposed approach are shown and discussed. Fig. 9 shows the evolution of a test covering 13 complete days in summer time with a fixed set point and a shading screen covering the greenhouse. Although the control scheme has been developed for operation during sun-shining conditions, it has not been turned off during the night to shown the performance of the antiwindup block even in such strongly adverse situation (the vents are completely closed during the night and so, large feedback errors feed the controller). The evolution of the outside solar radiation corresponds to clear day conditions, except during the fifth and sixth day in which drops of more than 100 W/m^2 occurs. Outside temperature conditions are also varying and wind velocity experiments quite large variations during all the days, covering values from 0 to 12 m/s which large influence the system behaviour when vents are opened. Due to the size of the figures, a zoom of a region has been included.



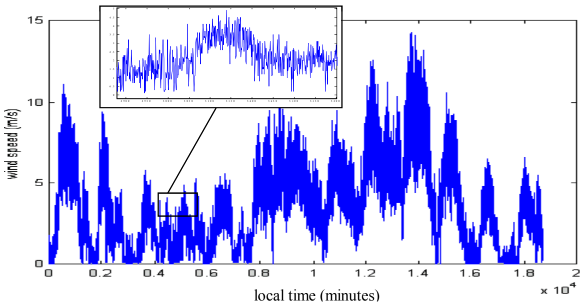
(a) Set point and inside air temperatures (deg)



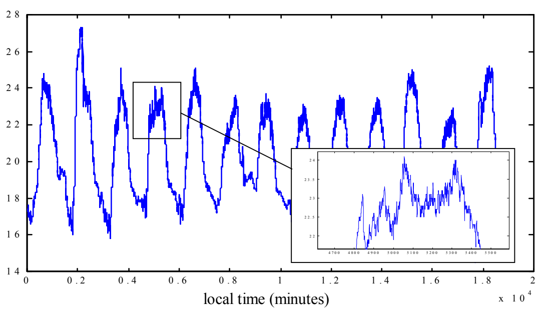
(b) Vents aperture (º)



(c) Global solar radiation (W/m$_2$)



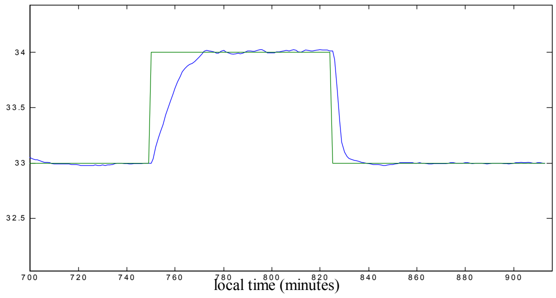
(d) Outside wind speed (m/s)



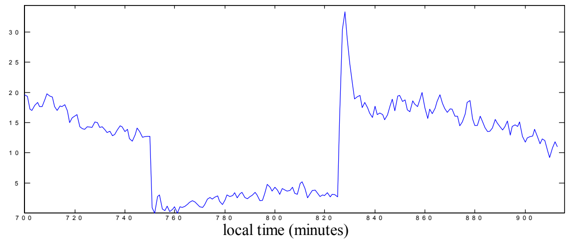
(e) Outside temperature (deg)

Fig. 9. Complete 13-days simulation

As can be seen, the tracking and disturbance rejection capabilities are adequate in those cases in which the vents are not saturated. When saturation occurs, no degrees of freedom are available to control the temperature. After saturation, the performance of the system is quite good, as is expected due to the use of the antiwindup scheme. As can be seen in Fig. 9(b), the control signal suffers from large excursions covering the whole control range. This figure reflects the main drawback of the approach used in this paper: as the controller tends to quickly react to changes in disturbances (mainly due to the structure of the feedforward term), the control system is prone to over-actuate, thus increasing electricity costs associated to the motors moving the vents (even when filtering the disturbances before entering the feedforward term). The design can be improved by finding a trade-off between fast tracking and associated costs (by including stronger filters within the feedforward term or by including design restrictions in the control effort).

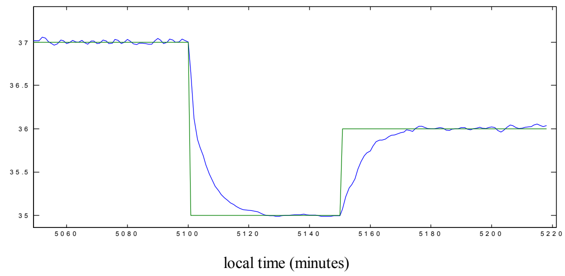


(a) Set point and inside air temperatures (deg)

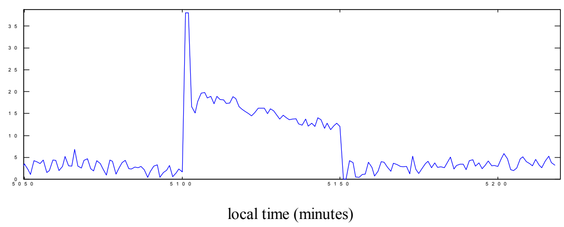


(b) Vents aperture (º)

Fig. 10. Response to set point changes

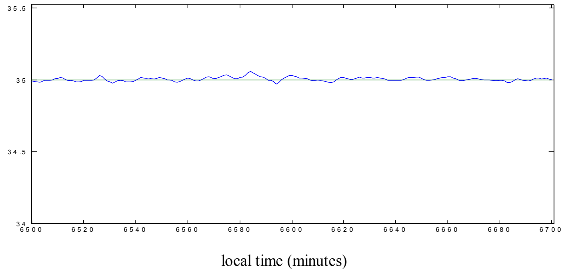


(a) Set point and inside air temperatures (deg)

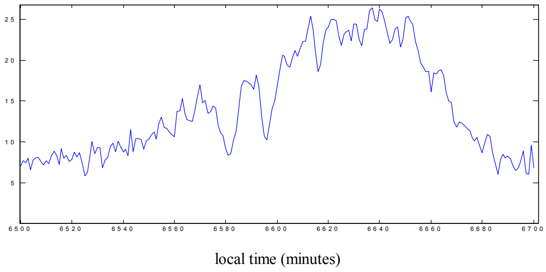


(b) Vents aperture (º)

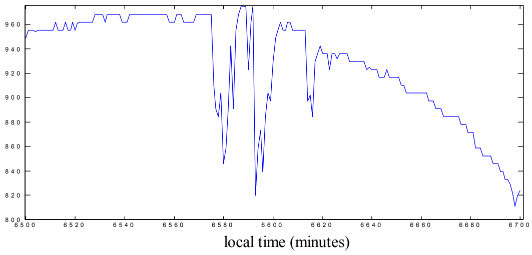
Fig. 11. Response to set point changes



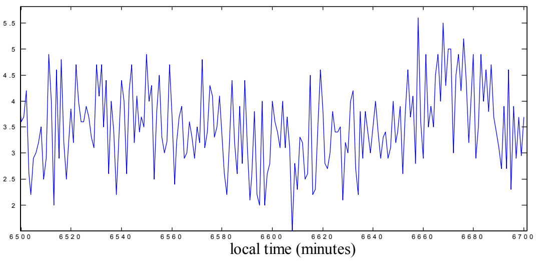
(a) Set point and inside air temperatures (deg)



(b) Vents aperture (º)



(c) Outside global solar radiation (W/m^2)



(d) Wind speed (m/s)

Fig. 12. Disburbance response capabilities

Fig. 10 and 11 show typical responses to set point changes and Fig. 12 shows the disturbance rejection capabilities of the system. Fig. 10 corresponds to wind speed conditions of 7 m/s and clear-day solar radiation between 900 and 1000 W/m^2. Set point changes of ±2 ºC have been performed around 33ºC.

Due to the nonlinear nature of the system, different closed-loop time constants are obtained, but lying inside the specifications, even in the case in which the model used to develop the feedforward term is not a good approximation of the real system. Fig. 11 shows another test under low wind speed (around 2 m/s) conditions (notice that coefficients of the feedforward term were calculated for wind speed conditions around 6 m/s and thus, modeling errors are larger in this case). As can be seen, the tracking capabilities are also quite acceptable in this case. Finally, Fig. 12 shows the response under passing clouds and varying low wind speed conditions. It can be seen how the control system quickly reacts to changes in solar radiation in order to compensate for the temperature drop following a cloud (tracking error less than 0.2ºC).

5. CONCLUSIONS

An approach for robustly controlling the inside temperature of a greenhouse in the face of uncertainties and disturbances acting on the system has been presented, including feedforward compensation and antiwindup action. The results presented are quite promising. After analyzing the results, it has to be pointed out that more improvements can be performed by limiting control efforts which lead to an increase in production costs.

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REFERENCES

Baños, A. and A. Barreiro (2000). Stability of nonlinear QFT designs based on robust absolute stability criteria. *Int. Journal of Control*, **73**, pp. 74-88.

Barmish, B. R. (1988). New tools for robustness analysis. In: Proc. of the 27th IEEE Conference on Decision and Control, Austin, TX, pp. 1-6.

Borguesani, C., Y. Chait and O. Yaniv (1995). *The Quantitative Feedback Theory Toolbox for MATLAB*. The MathWorks, MA.

Horowitz, I. (1982). *Quantitative feedback theory*. IEEE Proc.,129 (D-6), 215-226.

Linker, R., P.O. Gutman, I. Seginer (1999). Robust controllers for simultaneous control of temperature and CO2 concentration in greenhouses. *Control Engineering Practice*, 7, pp. 851-862.

Moreno, J.C., A. Baños, and F.J. Montoya (1997). An Algorithm for Computing QFT Multiple-valued Performance Bounds. In: Proc. Symp. on QFT and other Frequency Domain Methods and Applications, pp. 29-32. Univ. Stratchclyde (Scotland).

Moreno, J.C., A. Baños and M. Berenguel (2002). Design of robust compensators for linear systems with actuator saturation using QFT. Submitted to *Int. Journal of Control*.

Rodríguez, F., M. Berenguel and M.R. Arahal (2001a). Feedforward controllers for greenhouse climate control based on physical models. ECC01, Portugal.

Rodríguez, F., M. Berenguel and A. Baille (2001b). A Model of Greenhouse Crop Production. Part I: Model Development. Part II; Model Validation. Internal Report, Univ. Almería, Spain.

Sigrimis, N. and N. Rerras (1996)., A Linear Model for Greenhouse Control, *Trans. of the ASAE*, 39(1) pp. 253-261.

Tap, R.F., L.G. van Willigenburg,, G. van Straten and E.J. van Henten (1993), Optimal control of greenhouse climate: computation of the influence of fast and slow dynamics. Proc. 12th IFAC World Cong., 10, pp. 321-324, Sydney.