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AN INTELLIGENT NONINTERACTING TECHNIQUE FOR CLIMATE CONTROL OF GREENHOUSES

N. Sigrimis[1], K.G. Arvanitis[1], K.P. Ferentinos[2], A. Anastasiou[1]

[1] *Agricultural University of Athens, Dept. of Agricultural Engineering, Iera Odos 75, 11855, Athens, GREECE, email: n.sigrimis@computer.org, karvan@aua.gr*
[2] *Cornell University, Department of Agricultural and Biological Engineering, Ithaca, NY 14853, USA, email: kpf3@cornell.edu*

Abstract: A new approach to system linearization and decoupling is presented for climate control of greenhouses and more specifically for the operation of heating/cooling and moisturizing. High-level programming, which provides an easy way to building models, is a feature of most research but also field control systems. The method is applicable to any air-conditioning system and is expected to gain wide acceptance in modern SCADA systems with extended computational capabilities. *Copyright ã 2002 IFAC*

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1. INTRODUCTION

Several studies and research applications involving environmental control of greenhouses have been performed by many researchers (Gates and Overhults, 1991; Stanghellini and van Meurs, 1992; Zhang and Barber, 1993; Chao and Gates, 1996; Arvanitis *et al*., 2000*;* Chao *et al*., 2000; Zolnier *et al*., 2000). Most of the studies on analysis and control of the environment inside greenhouses have been based on the concept of energy and mass balance and physical modeling. These concepts are very effective to clarify the concepts of environmental control, to refine environmental control strategies and to gradually lead to economic optimization, the ultimate objective of environmental control.

Many dynamic models for greenhouse environment exist in the literature, and they are of nonlinear nature. The central state variable is typically air temperature, with relative humidity (or absolute humidity) and carbon dioxide concentration also considered. Disturbances to a greenhouse or other plant thermal environment occur primarily from solar radiation, outside temperature (conduction heat transfer and ventilation heat transfer) and interactions with occupants (plants), the controlled heating and ventilating equipment, and the floor. However, it is worth noting that, for the most part, the system is subjected to relatively low frequency disturbances. Indeed, most of these disturbances are considered as "loads" and a quasi-steady state analysis often suffices for design purposes. The most common transient disturbance is a step change, either from switching equipment, changing set points or variable cloud cover.

The fact that temperature and humidity are coupled, and the actuators (*i.e.* windows) are usually subject to changing characteristics (the gain is largely perturbed by cross product terms with disturbances, such as wind velocity, outside temperature, *etc.*) has not been treated analytically to provide a robust control scheme. The practical controllers do meet the control requirements using many expert types of actuator adjustments and ad hoc compensators. To demonstrate some salient features of greenhouse environmental control, an example of a coupled, nonlinear controller for air temperature and humidity is presented.

2. F/F LINEARIZATION AND DECOUPLING

Consider the analytic nonlinear system

$$\dot{\mathbf{x}} = \mathbf{a}(\mathbf{x},\mathbf{v}) + \mathbf{B}(\mathbf{x},\mathbf{v})\mathbf{u}\ ,\ y_i = h_i(\mathbf{x}) \qquad (1)$$

where $\mathbf{x} \in \Re^n$, is the state vector, $u_i, y_i \in \Re$, i=1,…,p, is the i^{th} control input and output, respectively, and $\mathbf{v} \in \Re^d$ is the external disturbance vector. In (1) $\mathbf{a}(\mathbf{x},\ \mathbf{v})$, $\mathbf{B}(\mathbf{x},\ \mathbf{v})$, and $\mathbf{h}(\mathbf{x})$ are analytic matrix valued functions.

In the case where, system disturbances, **v,** are unknown (or cannot be measured), there is no general theoretical framework, in order to control a system of the form (1). However, in the case where disturbances can be measured, and system (1) can be brought to the form

$$y_i^{(r_i)} = f_i(\mathbf{x},\mathbf{v}) + \mathbf{g}_i^T(\mathbf{x},\mathbf{v})\mathbf{u}\ \ ,\ i=1,\dots,p \qquad (2)$$

where r_i is the relative degree of the ith system output (Isidori, 1981), then, assuming that matrix $\mathbf{D}(\mathbf{x},\mathbf{v})$ of the form

$$\mathbf{D}(\mathbf{x},\mathbf{v}) = \begin{bmatrix} \mathbf{g}_1^T(\mathbf{x},\mathbf{v}) \\ \vdots \\ \mathbf{g}_p^T(\mathbf{x},\mathbf{v}) \end{bmatrix}$$

is nonsingular, the control law of the form

$$\mathbf{u} = \mathbf{D}^{-1}(\mathbf{x},\mathbf{v})\left\{ -\begin{bmatrix} f_1(\mathbf{x},\mathbf{v}) \\ \vdots \\ f_p(\mathbf{x},\mathbf{v}) \end{bmatrix} + \begin{bmatrix} \hat{u}_1 \\ \vdots \\ \hat{u}_p \end{bmatrix} \right\} \qquad (3)$$

where $\hat{u}_i$, i=1,…,p, is a set of external inputs, renders the closed-loop system, I/O linearized, decoupled and disturbance isolated, having the form

$$y_i^{(r_i)} = \hat{u}_i \qquad (4)$$

provided that, the system states are measurable.

Note that, to bring system (1) in the form (2), it is necessary that, if a disturbance appears in an equation in (1), a control input to be also present in the same equation, allowing elimination of the disturbance by feedforward action. Note that, this feedforward action is inherently present, due to the terms involved in matrices $\mathbf{D}(\mathbf{x},\mathbf{v})$ and $f_i(\mathbf{x},\mathbf{v})$.

Note also that if $\sum_{i=1}^{p} r_i < n$, then, system (1) contains some additional unobservable states, called internal dynamics. The *zero-dynamics* of (1) are the internal dynamics of the system when the outputs of the system are kept at *zero* by the input. For the closed system to be stabilizable, the system zero-dynamics must be stable (Isidori, 1981).

Obviously, the closed-loop system (4) can now be controlled by adding an "outer loop" control, to satisfy some control specifications. This outer control loop may be based on any conventional linear control strategy, such as pole placement, model matching, H^∞-control, and can be as simple as a PID controller. For example, in pole placement control, application of the outer control law

$$\hat{u}_i = -\sum_{j=0}^{r_i-1} a_{ij} y_i^{(j)} + b_i \tilde{u}_i \qquad (5)$$

brings the new closed-loop system to the form

$$y_i^{(r_i)} + \sum_{j=0}^{r_i-1} a_{ij} y_i^{(j)} = b_i \tilde{u}_i$$

Furthermore, in the case of set-point tracking, to compensate disturbances, which have not been taken into account in (1) or parametric uncertainties, and to attain asymptotic convergence of the error to zero, despite these uncertainty, an additional control loop with integral action (*e.g.* a PID controller) must be used in most cases. More sophisticated control strategies, such as adaptive controllers, can also be used in some cases.

3. GREENHOUSE VENTILATION MODEL

3.1. Greenhouse dynamic model

The dynamic model of energy and mass balances of greenhouse air is shown to be highly nonlinear. A simple greenhouse heating-cooling ventilating model can be obtained by considering the differential equations, which govern sensible and latent heat, as well as water balances on the interior volume. These differential equations are as follows:

$$\frac{dT_{in}(t)}{dt} = \frac{1}{\rho C_p V}\left[q_{heater}(t) + S_i(t) - \lambda q_{fog}(t)\right] - \frac{\dot{V}(t)}{V}\left[T_{in}(t) - T_{out}(t)\right] - \frac{UA}{\rho C_p V}\left[T_{in}(t) - T_{out}(t)\right] \qquad (6a)$$

$$\frac{dw_{in}(t)}{dt} = \frac{1}{V} q_{fog}(t) + \frac{1}{V} E(S_i(t), w_{in}(t)) - \frac{\dot{V}(t)}{V}\left[w_{in}(t) - w_{out}(t)\right] \qquad (6b)$$

where T_{in} is the interior temperature (^oC), T_{out} is the outside temperature (^oC), V is the greenhouse volume (m^3), UA is the heat transfer coefficient (WK^{-1}), ñ is the air density (kg/m^3), C_p is the specific heat of air (J/(kg.K)), q_{heater} is the heat provided by the greenhouse heater (W), S_i is the intercepted solar radiant energy (W), q_{fog} is the water capacity of the fog system (gr/s), ë is the latent heat of vaporization (2257 J/g), $\dot{V}$ is the ventilation rate (m^3/sec), w_{in} and w_{out} are the interior and exterior absolute humidity (absolute water content, g/m^3), respectively, and $E(S_i,w_{in})$ is the evapotranspiration rate of the plants (g/s).

3.2. Greenhouse thermal model.

Temperature and relative humidity are commonly measured air properties, highly coupled through non-linear thermodynamic laws. For example

$$w = f(T, RH, P) = \frac{0.62198 \cdot P_{ws}(T) \cdot RH}{P - P_{ws}(T) \cdot RH} \qquad (7)$$

where w is the absolute humidity (g/m^3), P is atmospheric pressure (kPa) and P_{ws} is saturation pressure of water vapor. This thermodynamic equation can be used to convert relative humidity to absolute water content. This conversion provides a first step towards a state decoupled and linearized system. The relation between saturation pressure of water vapor (in Pa) and temperature (in K) can be evaluated by the following polynomial, whose coefficients A_1 to A_7 can be found in Albright (1990).

$$\ln(P_{ws}) = A_1/T + A_2 + A_3 T + A_4 T^2 + A_5 T^3 + A_6 T^4 + A_7 \ln(T) \qquad (8)$$

For a specific environmental condition, that is specific temperature T and absolute humidity w, the enthalpy H_o (in KJ Kg^{-1} of dry air) is given by:

$$H_o = 1.006 \cdot T + w \cdot (2501 + 1.805 \cdot T) \qquad (9)$$

We define a specific enthalpy change (H_s) as the energy per unit volume (Jm^{-3}) carried by the ventilating air. A thermal balance, neglecting enthalpy of incoming air and conductive heat losses from the greenhouse, yields

$$H_s \cdot \dot{V} = S_i \Rightarrow H_s = \frac{S_i}{\dot{V}} \qquad (10)$$

The actuating capacity q_{fog}^{max} is selected to ensure that ventilation air changes ($\dot{V}^{max}$) can be saturated under any load conditions. Moreover, let w_{wet}^{s}, w_{fog}^{s} be the water carrying capacity of the saturated air for wet-pad and fog system operation, respectively, and q_{wet}^{s}, q_{fog}^{s} be the effective water carrying capacity, from w_{out} to saturation, for wet-pad and fog systems respectively (see Figure 1). The actuating limit is $q_{fog}^{max} = q_{fog}^{s} \dot{V}$.

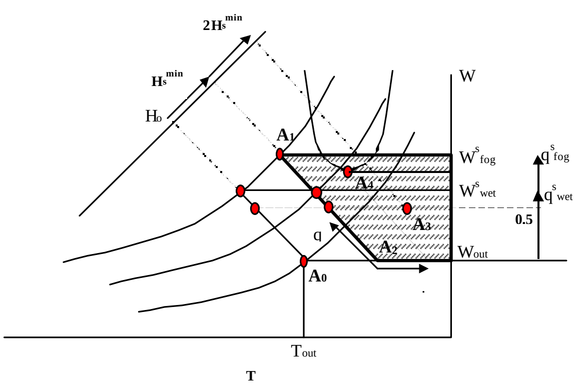

Fig. 1. Actuation limits defined by psychrometric properties.

Maximum cooling is achieved when maximum evaporated water is used for a given ventilation rate. Then a controls capacity or controls feasible region is defined based on maximum ventilation capacity. In this condition the minimum specific enthalpy is

$$H_s^{min} = \frac{1}{\dot{V}^{max}} S_i \qquad (11)$$

Equation (10) defines the feasible regime to the right of line A1A2, drawn as the locus of $H_o + H_s^{min}$, as shown in Figure 1. For example at half capacity, $q = q_{fog}^{max}/2$ and $\dot{V} = \dot{V}^{max}/2$, that is $H_s = 2H_s^{min}$, starting from outside conditions at point <A_0>, the operating point will be <A_3> instead of <A_1> at full capacity. Equation (7) defines the lower horizontal line of the regime. The upper horizontal line, which transverses point <A1>, can be defined if we assume saturation in equation (7) (*i.e.* RH=1) and then substitute the calculated w (which, in this case, equals w_{fog}^{s}), in equation (9). This leads to an expression of enthalpy at saturation (H_{sat}) as a function of temperature and pressure, *i.e.*,

$$H_{sat} = 1.006T + \frac{0.62198 P_{ws}(2501 + 1.805 \cdot T)}{P - P_{ws}} \qquad (12)$$

Then, by setting equation (10) equal to equation (12), the point <A1> is defined (Figure 1).

The decision for a desired point of operation inside the feasible region relies on the cost function

$$J = c_1(T_{in,sp} - T_{in,d})^2 + c_2(RH_{in,sp} - RH_{in,d})^2 + c_3 \dot{V} + c_4 q_{fog}$$

Depending on the outside air conditions and the load S_i, the achievable conditions, for any cost, may not be the desirable ones ($T_{in,d}$, RH_{ind}). A rule base can be used to assign values for cost parameters c_1 and c_2 so as to equalize the risk on the crop from the deviations ($T_{in,sp}$-$T_{in,d}$) and ($RH_{in,sp}$-$RH_{in,d}$). In an attempt to use complete functionals for cost calculations, without resorting to fuzzy rules for cost assignments, the following extended cost function is used

$$J = c_1(T_{in,sp} - T_{in,d})^2 + \frac{c_1^*}{|T_{in,sp} - T_{in,max}|} + c_2(RH_{in,sp} - RH_{in,d})^2 + \frac{c_2^*}{1 - RH_{in,sp}} + c_3\dot{V} + c_4 q_{fog} \qquad (13)$$

The added new terms are weighted such that the calculated set-points for temperature and humidity are kept away from an absolute maximum temperature (chosen by intuition and constraints for crop safety) and from the saturation line (risk of disease).

Using equations (7)-(12), the load Env(S,T_o,RH_o) and a gradient descent method to minimize (13), the precompensator and command generator (PCG) of Figure 2 calculates the realizable desirable target conditions $T_{in,sp}$ and $w_{in,sp}$, as well as the control values of q_{og} and $\dot{V}$, which can be used as feed-forward values, and other variables useful for the calculations at the controller. q_{fog} and $\dot{V}$ are expressed in terms of temperature and absolute humidity by setting equations (6a) and (6b) equal to zero at steady state. The search space of the optimization algorithm is limited by three major constraints, as can be seen in Figure 1:

$$\dot{V} \le \dot{V}^{max},\ H \ge H_s^{min} \text{ and } w \le w_{fog}^{s}(\dot{V}) \qquad (14)$$

The PCG has all the required logic to compute realizable set-points and avoid pitfalls (*i.e.* singular values in Ä calculations of equation (13) given below) by post-processing the solution arrived by equation (16). The pseudocode of the operation of the PCG is shown in Table 1.

3.3. Control model.

For summer operation, q_{heater} in equation (6a) is set to zero. It is worth noticing that, in a first approximation the evapotranspiration rate $E(S_i(t), w_{in}(t))$ is in most part related to the intercepted solar radiant energy, through the following simplified relation

$$E(S_i(t), w_{in}(t)) = \alpha \frac{S_i(t)}{\lambda} - \beta_T w_{in}(t) \qquad (15)$$

where á is an overall coefficient to account for shading and leaf area index, and âÔ is an overall coefficient to account for thermodynamic constants and other factors affecting evapotranspiration (*i.e.* stomata, air motion, *etc*).

On the basis of these observations, relations (6a) and (6b) take the forms

$$\frac{dT_{in}(t)}{dt} = \frac{1}{\rho C_p V}\left[S_i(t) - \lambda q_{fog}(t)\right] - \frac{\dot{V}}{V}\left[T_{in}(t) - T_{out}(t)\right] - \frac{UA}{\rho C_p V}\left[T_{in}(t) - T_{out}(t)\right] \qquad (16a)$$

$$\frac{dw_{in}(t)}{dt} = -\frac{\beta_T}{V} w_{in}(t) + \frac{1}{V} q_{fog}(t) + \frac{\alpha}{\lambda V} S_i(t) - \frac{\dot{V}}{V}\left[w_{in}(t) - w_{out}(t)\right] \qquad (16b)$$

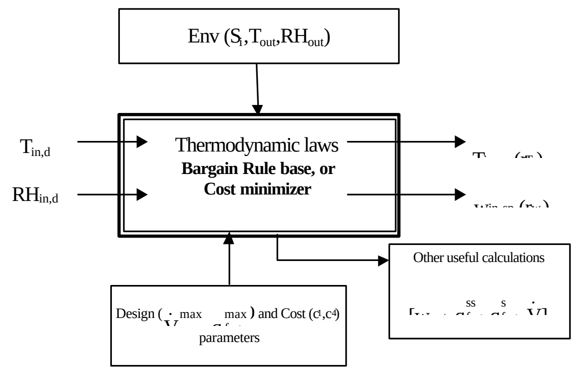

Fig. 2. Precompensator and Command Generator (PCG) calculating feasible control targets

Table 1. Pseudocode of the operation of PCG

Step	Operation
1.	Read system characteristics ($\dot{V}^{max}$, q_{fog}^{max}) and cost parameters ($c_1 - c_4$)
2.	Read environmental conditions (S_i, T_{out}, RH_{out})
3.	Read desired temp. ($T_{in,d}$) and RH ($RH_{in,d}$)
4.	Transform $\dot{V}$ and q_{fog} in terms of T_{out}, w_{out}, S_i, $T_{in,sp}$, $RH_{in,sp}$ (eq. 6a and 6b = 0)
5.	Compute J
6.	Call Optimization Algorithm to minimize J subject to constraints (14)
7.	Return optimal $T_{in,sp}$ and $RH_{in,sp}$
8.	When env. conditions change: go to step 2.

Equations (16) are coupled nonlinear equations that cannot be put into the rather familiar form of an affine analytic nonlinear system, due to their complexity appearing as the cross-product terms between control and disturbance variables. However, relations (16) can alternatively be written in the form (2), where, in the present case, and

$$\mathbf{x} = [x_1 \quad x_2]^T \mathrel{\hat{=}} [T_{in} \quad w_{in}]^T \ ,\ \mathbf{y}=\mathbf{x}\ ,\ r_1=r_2=1$$

$$\mathbf{u} = [u_1 \quad u_2]^T \mathrel{\hat{=}} [\dot{V} \quad q_{fog}]^T$$

$$\mathbf{v} = [v_1 \quad v_2 \quad v_3]^T \mathrel{\hat{=}} [S_i \quad T_{out} \quad w_{out}]^T$$

$$f_1(\mathbf{x},\mathbf{v}) = -\frac{UA}{\rho C_p V} x_1(t) + \frac{1}{\rho C_p V} v_1(t) + \frac{UA}{\rho C_p V} v_2(t)$$

$$f_2(\mathbf{x},\mathbf{v}) = -\frac{\beta_T}{V} x_2(t) + \frac{\alpha}{\lambda V} v_1(t)$$

$$\mathbf{g}_1^T(\mathbf{x},\mathbf{v}) = \left[\frac{1}{V}\left(v_2(t) - x_1(t)\right) \quad -\frac{\lambda}{\rho C_p V}\right]$$

$$\mathbf{g}_1^T(\mathbf{x},\mathbf{v}) = \left[\frac{1}{V}\left(v_3(t) - x_2(t)\right) \quad \frac{1}{V}\right]$$

Disturbance variables of the greenhouse heating-cooling ventilating model can be easily measured by the instrumentation installed in the greenhouse meteorological cage. Furthermore, the complexity of such systems is rather eased by the fact that the system state changes slowly and some state dependent parameters (*i.e.* β_T) can be considered constant (*i.e.* quasi-static system operation). Therefore, in the present case, a combined scheme of feedback with simultaneous feedforward linearization is plausible.

4. CONTROL OF THE VENTILATION MODEL.

In this section, the control method presented in section 2, is applied to the above greenhouse ventilation model. Thus, matrix $\mathbf{D}(\mathbf{x},\mathbf{v})$ is given by

$$\mathbf{D}(\mathbf{x},\mathbf{v}) = \frac{1}{V}\begin{bmatrix} v_2(t) - x_1(t) & -\dfrac{\lambda}{\rho C_p} \\ v_3(t) - x_2(t) & 1 \end{bmatrix}$$

whose determinant Ä(t) is given by

$$\Delta(t)=\frac{1}{V^2}\left[v_2(t)-x_1(t)+\frac{\lambda}{\rho C_p}\left(v_3(t)-x_2(t)\right)\right] \quad (17)$$

which must be nonzero, for the system to be I/O linearized, decoupled and disturbance isolated. Note that, in the present case, the sum of the relative degrees equals system dimension, so there is no internal or zero dynamics. Note also that, in the case where, Ä(t)=0, the input $u_1(t)$ affects the system states $x_1(t)$ and $x_2(t)$, with exactly the same way as $u_2(t)$, and thereby decoupling, as well as feedback-feedforward linearization is impossible.

By applying the control law of the form (3) the closed-loop system takes on the form: $y_i^{(1)}=\hat{u}_i$, i=1,2. Moreover, in order to fix the dynamics of the output y_i, we apply the outer control laws of the form

$$\hat{u}_i=-a_{i0}y_i+b_i\tilde{u}_i \triangleq -\frac{1}{\tau_i}\left(y_i-\tilde{u}_i\right) \ , \ i=1,2$$

and we obtain $y_i^{(1)}+\frac{1}{\tau_i}y_i=\frac{1}{\tau_i}\tilde{u}_i$, i=1,2, or in transfer function form

$$H_i(s)=\frac{1}{\tau_i s+1} \ , \ i=1,2 \quad (18)$$

where, τ_i, i=1,2, are the time constants of the new closed-loop systems. The above control algorithm can be summarized in the following two relations

$$u_1(t)=Q^{-1}(t)\left[\frac{\rho C_p}{\tau_1}\tilde{u}_1(t)+\frac{\lambda V}{\tau_2}\tilde{u}_2(t)-(\alpha+1)v_1(t)-UAv_2(t)\right.$$
$$\left.\left(UA-\frac{V\rho C_P}{\tau_1}\right)x_1+\left(\beta_T\lambda-\frac{V\lambda}{\tau_2}\right)x_2\right]$$

$$u_2(t)=\frac{\left(\left(UA-\frac{V\rho C_p}{\tau_1}\right)x_1+\frac{V\rho C_p}{\tau_1}\tilde{u}_1-v_1-UAv_2\right)\left(x_2(t)-v_3(t)\right)}{Q(t)}$$
$$+\frac{\rho C_p\left(-x_1(t)+v_2(t)\right)\left(\left(\beta_T-\frac{V}{\tau_2}\right)x_2+\frac{V}{\tau_2}\tilde{u}_2-\frac{\alpha}{\lambda}v_1\right)}{Q(t)}$$

where $Q(t)=\rho C_p\left[v_2(t)-x_1(t)\right]+\lambda\left[v_3(t)-x_2(t)\right]$ and is depicted in Figure 3.

The greenhouse interior temperature and relative humidity are measured by a thermometer and a hygrometer, respectively, which usually are located a certain distance from the greenhouse ventilators and the fog or wet-pad system. Hygrometers also present a lag time themselves. Hence, the changes in the temperature and absolute humidity are determined after a certain time delay. Moreover, transport delays as well as unmodeled dynamics contribute to additional time lags. Therefore, an overall dead time, d_1 and d_2, must be considered for each output, y_1 and y_2, respectively. However, one must keep in mind that the nonlinear feedback-feedforward control law, which renders the overall system linear and decoupled, relies on current state and disturbance measurements. Therefore, time delays may affect the feedback-feedforward linearization procedure and could degrade its performance. In order to avoid this problem, one must select ô$_1$ and ô$_2$, which are related to the speed of the closed-loop system response, to be large enough, resulting to a relatively slow closed-loop system. For example, a choice of ô$_1$>4d_1 and ô$_2$>4d_2 appears to be quite satisfactory compromise between the speed of the closed-loop system response and the performance of the feedback-feedforward linearizing control law. However, when faster responses are desired, then to avoid problems interwoven with the performance of the feedback-feedforward linearization procedure, one must utilize a Smith predictor, which, in addition, can compensate for large times delays d_1 or d_2.

As it will be shown in the next section, the proposed control algorithm, based on feedback/feedforward linearization and outer loop controllers, is quite robust to system parametric uncertainty as well as load disturbances. In particular, a 10% uncertainty can be easily tolerated by the proposed controller. However, in the case of large parameter variations (*e.g.* plant growth that affects the greenhouse thermal capacity as well as evapotranspiration), one must apply more sophisticated control algorithms (like robust control or adaptive control algorithms) in order to compensate for such variations. Research on these topics (*e.g.* along the lines reported in Sigrimis *et al.*, 1999; Arvanitis *et al. 2000*) is currently in progress.

5. SIMULATION RESULTS.

In this section, the effectiveness of the proposed control scheme will be demonstrated by a case study. In particular, we consider here a greenhouse having an area of 1000 m^2 and a height of 4 m. The greenhouse is equipped by a shading screen, which reduces the incident solar radiant energy by 60%. The maximum water capacity of the fog system is 26 $g/min/m^3$. Maximum ventilation rate corresponds to 20 alternations of the greenhouse air per hour. Parameter á/ë takes the value 3.32×10^{-3} g/min/W, while â$_T$ is negligible. The heat transfer coefficient is 25 $kW.K^{-1}$. Finally, we consider that unmodelled

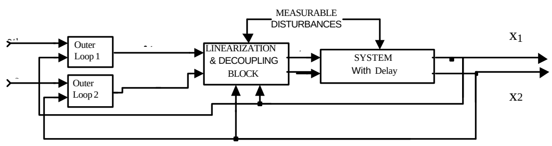

Fig. 3. Overall control strategy in case of small time delays and/or a slow desired response.

system as well as sensor dynamics contributes an overall dead time of 0.5 min in both temperature and humidity measurements. That is $d_1 = d_2 = 0.5\,\text{min}$.

A simulation study has been accomplished in order to perform simultaneous temperature and humidity control in the greenhouse, in case of real weather conditions. To this end, weather data from a full summer day (June 3, 1999) in Arizona, U.S.A., have been used. Set points for w_{in} and T_{in} have been obtained as outputs of the PCG block, and are illustrated in Figures 4 and 5, together with the trajectories of w_{in}, w_{out} and T_{in}, S_i, T_{out}, respectively. Obviously, the tracking performance of the proposed controller is remarkable. Finally, Figure 6 illustrates the controller outputs for this case.

6. CONCLUSIONS

The presented method of decoupling a highly nonlinear and coupled system proved to be very effective in meeting formal requirements for control such as set-point tracking and disturbance rejection. The precompensator block to compute actuation limits and gains and variable change, using air psychrometric properties is a powerful approach to enable decoupling and linearization around the operating point. The method is currently implemented in MACQU system (Sigrimis *et al.*, 2000) to be placed in field operation.

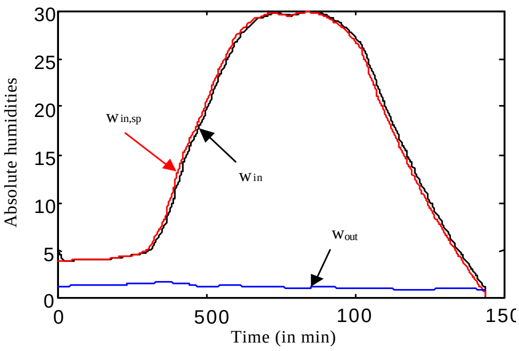

Fig. 4. Absolute humidity trajectories in case of simultaneous absolute humidity and temperature tracking

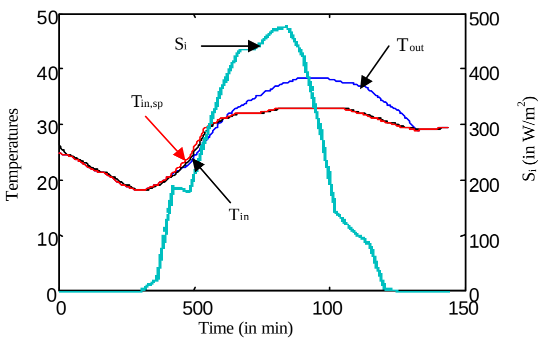

Fig. 5. Temperature trajectories in case of simultaneous absolute humidity and temperature tracking

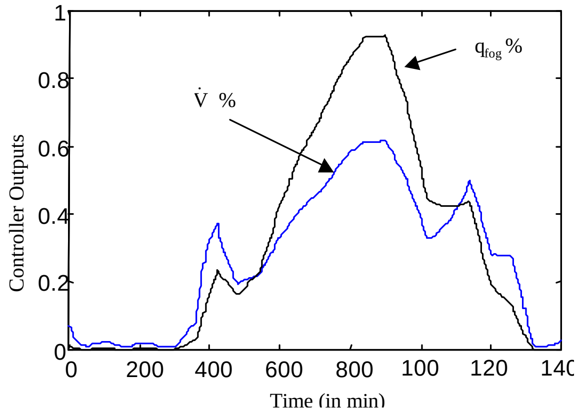

Fig. 6. Controller outputs in case of simultaneous absolute humidity and temperature tracking

REFERENCES

Albright, L.D. *Environment Control for Animals and Plants*. ASAE Pbl., St. Joseph, Michigan.

Arvanitis, K.G., P.N. Paraskevopoulos and A.A. Vernardos, 2000. Multirate adaptive temperature control of greenhouses. *Comp. Electronics Agric.*, **26**, 303-320.

Chao, K. and R.S. Gates, 1996. Design of switching control systems for ventilated greenhouses. *Trans. ASAE*, **39**, 1513-1523.

Chao, K., R.S. Gates and N. Sigrimis, 2000. "Fuzzy logic controller design for staged heating and ventilating systems. *Trans. ASAE*, **43**, 1885-1894.

Gates, R.S. and D.G. Overhults, 1991. Field evaluation of integrated environmental controllers. *ASAE Paper No. 91-4037*, St. Joseph, Mich.: ASAE Publ..

Isidori, A., 1981. *Nonlinear Control Systems*. Springer Verlag, Berlin.

Sigrimis, N., K.G. Arvanitis, I.K. Kookos and P.N. Paraskevopoulos, 1999. H^{∞}-PI controller tuning for greenhouse temperature control, *Proc. 14th IFAC Triennial World Congr.*, **K**, 485-490, Beijing, China, July 5-9, 1999.

Sigrimis N, K.G. Arvanitis and G.D. Pasgianos, 2000. Synergism of high and low level systems for the efficient management of greenhouses. *Comp. Electronics Agric.*, **29**, 21-39.

Stanghellini, C., van Meurs, W.T.M., 1992. Environmental control of greenhouse crop transpiration. *J. Agric. Eng. Res.*, **51**, 297-311.

Zhang, Y. and E.M. Barber, 1993. Variable ventilation rate control below the heat-deficit temperature in cold-climate livestock buildings. *Trans. ASAE*, **36**, 1473-1482.

Zolnier, S., R.S. Gates, J. Buxton and C. Mach, 2000. Psychrometric and ventilation constraints for vapor pressure deficit control. *Comp. Electronics Agric.*, **26**, 343-359.