Temperature and humidity control in greenhouses using the Takagi-Sugeno fuzzy model

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Abstract— The control of air temperature and humidity concentration in greenhouses is described by means of simultaneous ventilation and heating systems. To solve the problem of bi-linearity of greenhouse models, this paper proposes the construction of a Takagi-Sugeno (T-S) fuzzy model from a simplified nonlinear dynamic model of the greenhouse climate. Using this T-S fuzzy model, the stability analysis and control design problems can be reduced to sufficient conditions expressed as linear matrix inequalities (LMIs). This paper shows that it is possible to successfully control the greenhouse climate by using T-S fuzzy models and the parallel distributed compensation (PDC) concept. Simulation results for several tests showing the good performance and stability obtained with the proposed design methodology are presented.

Key-words: greenhouses, Takagi-Sugeno fuzzy model, stability, Lyapunov function, LMIs.

I. INTRODUCTION

As is well known, greenhouses are structures that allow the creation of an indoor microclimate for crop development, protecting it from adverse outdoor conditions. This microclimate is controlled by artificial actuation such as heating and ventilation to provide the best environmental conditions for the crops.

To obtain this objective, many greenhouses use a conventional PID control, but this control strategy may not be suitable to guarantee the desired performance due to the interaction between the different variables in the greenhouse and that constraints are not considered. Motivated by these disadvantages, inherent in linear control methods, several techniques, which use advanced control, have been proposed to deal with climate control problems in greenhouses. Optimal and predictive control have provided control strategies in greenhouse climate systems to decide about heating and ventilation and produce control actions that regulate air temperature and CO_2 concentration [5], [6], [12], [14]. Most techniques are not designed specifically in order to enable simultaneous control of air temperature and humidity concentration in the greenhouses [1], [7], [11]. However, humidity control has an important role in economic optimal

greenhouse climate management, and has a great effect on crop growth and production.

Recently, Lafont and Balmat (2004) have used fuzzy control theory for identification and control of greenhouse systems, based on input-output data, to construct Takagi-Sugeno fuzzy models (T-S). The Majority of the fuzzy control techniques available, which deal with climate regulation in the greenhouses, do not present tests to ensure the stability of the fuzzy controller and no constraints are imposed on the control [2].

This work focuses on the physical behavior of an empty greenhouse: it can be considered as a first step for the design of controllers that use the models that include the crops. Then, we propose to derive a Takagi-Sugeno (T-S) fuzzy model from a given nonlinear dynamic model of an empty greenhouse system, since this nonlinear system can be readily obtained. We will show that this representation, under the form of a valid linear model on a restricted domain [9], [16], offers an easier interpretation of the behavior of the greenhouse system and consequently allows a better resolution of the control problem. Then, the concept of parallel distributed compensation (PDC) [4], [9], [10] will be used to design a fuzzy controller from the greenhouse T-S fuzzy model. The stability of the obtained T-S fuzzy model is determined by checking a common Lyapunov function for all the subsystems described by the Takagi-Sugeno (T-S) fuzzy model [15], [16].

This paper is organized as follows: Section 2 presents preliminary results for the T-S Fuzzy modeling of a nonlinear dynamic system and the stability of the resulting feedback system. In section 3, a fuzzy model of the greenhouse is derived from its original dynamic model. Simulation results and conclusions are given in sections 4 and 5.

II. PRELIMINARY RESULTS

A. T-S Fuzzy Modeling

The use of Takagi-Sugeno fuzzy models (T-S) for the representation of the nonlinear systems, is generally justified because, thanks to this approach, a nonlinear problem can be decomposed into several linear problems which describe the dynamics of a nonlinear system in different "local" regions.

Typically, the Takagi-Sugeno fuzzy system is described as a set of N rules using membership functions F_l^i and fuzzy variables $z_l(k)$ as follows:

Rule i: IF $z_1(k)$ is F_1^i and $\ldots$ and $z_l(k)$ is F_l^i

$$\text{THEN } \begin{cases} x(k+1) = A_i x(k) + B_i u(k), \\ y(k) = C_i x(k), \end{cases} \tag{1}$$

where A_i, B_i and C_i are constant matrices of appropriate size, $x(\cdot) \in \mathbb{R}^n$ is the state, $u(\cdot) \in \mathbb{R}^m$ is the control and $y(\cdot) \in \mathbb{R}^p$ is the output. It has been shown in [16] that the overall global model can be structured as follows:

$$\begin{cases} x(k+1) = \sum_{i=1}^{N} \alpha_i(z(k))(A_i x(k) + B_i u(k)), \\ y(k) = \sum_{i=1}^{N} \alpha_i(z(k))C_i x(k), \end{cases} \quad (2)$$

where $\alpha_i(z(k))$'s are the so-called *normalized activation function* in relation with sub-model i^{th} such that: $\alpha_i(z(k)) =$

$$\dfrac{\prod_{j=1}^{l} F_j^i(z_j(k))}{\sum_{i=1}^{N} \prod_{j=1}^{l} F_j^i(z_j(k))}, \ \alpha_i(z(k)) \geq 0.$$

B. Stability analysis

We will use the concept of parallel distributed compensation (PDC) [4], [9], [10] to design fuzzy regulators for the discrete-time T-S fuzzy system (2). In the PDC approach, each control rule is designed from a corresponding rule of a T-S fuzzy system. The fuzzy controller shares the same fuzzy sets with the T-S fuzzy system (1).

Rule i: IF $z_1(k)$ is F_1^i and ... and $z_l(k)$ is F_l^i
            THEN $u(k) = -K_i x(k),$ (3)

where $i = 1 \ldots N$ and N is the number of IF-THEN rules. The fuzzy controller is given by the following fuzzy interpolation of local controllers:

$$u(k) = \sum_{i=1}^{N} \alpha_i(z(k))K_i x(k), \quad (4)$$

where $u(k)$ is the nonlinear feedback controller.
Hence, by substituting (4) in (2), the closed-loop system is as follows:

$$x(k+1) = \sum_{i=1}^{N} \sum_{j=1}^{N} \alpha_i(z(k))\alpha_j(z(k))(A_i - B_i K_j)x(k) \quad (5)$$

The stability of system (5) is guaranteed by the following relaxed stability conditions [9].

Theorem 2.1: The fuzzy control system of the T-S model (5) is stabilizable in the large if there exists a $P > 0$, $M \geq 0$ and $Y_i, i = 1, 2, \ldots, N$, $1 < s \leq N$ such that the following LMI conditions hold:

$$\begin{bmatrix} X - (s-1)M & XA_i^T - Y_i^T B_i^T \\ A_i X - B_i Y_i & X \end{bmatrix} > 0, i = 1 \ldots N,$$

$$\begin{bmatrix} X + M & \frac{1}{2}(XA_i^T + XA_j^T - Y_i^T B_j^T - Y_j^T B_i^T) \\ * & X \end{bmatrix} \geq 0,$$
$$i < j \leq N,$$

The feedback gain K_i, a common matrix P and a common matrix Q can be obtained as $K_i = Y_i X^{-1}, P = X^{-1}$ $Q = PMP$.

III. THE GREENHOUSE MODEL

In a greenhouse, the state climate can be represented by two variables, namely, *inside air temperature*, and *absolute humidity*. A simplified greenhouse climate model adequate for control purposes describes the dynamic behavior of the state variable with the following two differential equations [11]:

A. Energy balance

The energy fluxes affecting the greenhouse air are due to the exchanges with outside air by *ventilation* (E_v), and through the *cover* (E_c), to the energy supply (E_h) by a *heating system* and the *energy contribution by solar radiation* (E_s). This balance can be written as follows:

$$T_a(k+1) = \frac{t_s}{C_{cap,q}}(E_h - E_v - E_c + E_s) + T_a(k), \quad (6)$$

$E_v = C_{cap,q,v}V(T_a - T_0), E_c = h_T(T_a - T_0), E_s = \tau S_0$ and the symbols are described in table I. The two control variables that appear in this balance are *the heating supply* (E_h), and the *ventilation rate* (V).

B. Water vapor balance

The greenhouse air exchanges water with the outside air by ventilation (W_v) and through the cover (W_c), following the dynamic model:

$$w_a(k+1) = t_s(-W_v - W_c) + w_(k), \quad (7)$$

where $W_v = \frac{V}{C_{cap,h}}(w_a - w_0)$ and $W_c = \frac{h_w}{C_{cap,h}}(w_a - w_0)$.

The model presented above is a discretized model with several simplifications (an empty greenhouse has been considered), the use of such a model is justified by the fact that its main usage is for control design.

C. Exact fuzzy modeling of the greenhouse

The objective of this section is to derive a T-S fuzzy model by applying the model-based fuzzy control design methodology described in [9], based on the nonlinear equations (6) and (7).

$$T_a(k+1) = \frac{t_s h_T}{C_{cap,q}}(T_0 - T_a) + \frac{t_s C_{cap,q,v}}{C_{cap,q}}V(T_0 - T_a) +$$
$$\frac{t_s}{C_{cap,q}}E_h + \frac{t_s \tau}{C_{cap,q}}S_0 + T_a(k),$$

$$T_a(k+1) = (1 - a_1)T_a + a_2 V(T_0 - T_a) + a_3 E_h +$$
$$a_1 T_0 + a_4 S_0, \quad (8)$$

$$w_a(k+1) = \frac{t_s}{C_{cap,h}}V(w_0 - w_a) + \frac{t_s h_w}{C_{cap,h}}(w_0 - w_a) +$$
$$w_a(k),$$

$$w_a(k+1) = a_5 V(w_0 - w_a) + (1 - a_6)w_a + a_6 w_0(k), \quad (9)$$

$$\text{where :} \quad a_1 = \frac{t_s h_T}{C_{cap,q}}, \quad a_2 = \frac{t_s C_{cap,q,v}}{C_{cap,q}}, \quad a_3 = \frac{t_s}{C_{cap,q}},$$

$$a_4 = \frac{t_s \tau}{C_{cap,q}}, \quad a_5 = \frac{t_s}{C_{cap,h}}, a_6 = \frac{t_s h_w}{C_{cap,h}}.$$

Equations (8) and (9) can be written as:

$$\begin{bmatrix} T_a(k+1) \\ w_a(k+1) \end{bmatrix} = \begin{bmatrix} 1-a_1 & 0 \\ 0 & 1-a_6 \end{bmatrix} \begin{bmatrix} T_a(k) \\ w_a(k) \end{bmatrix} +$$
$$\begin{bmatrix} a_3 & a_2(T_0 - T_a) \\ 0 & a_5(w_0 - w_a) \end{bmatrix} \begin{bmatrix} E_h \\ V \end{bmatrix} + \begin{bmatrix} a_1 & a_4 & 0 \\ 0 & 0 & a_6 \end{bmatrix} \begin{bmatrix} T_0 \\ S_0 \\ w_0 \end{bmatrix}.$$

Considering the solar radiation, outside temperature and absolute humidity as disturbances, the model without disturbances is as follows:

$$\begin{bmatrix} T_a(k+1) \\ w_a(k+1) \end{bmatrix} = \begin{bmatrix} 1-a_1 & 0 \\ 0 & 1-a_6 \end{bmatrix} \begin{bmatrix} T_a(k) \\ w_a(k) \end{bmatrix} +$$
$$\begin{bmatrix} a_3 & a_2(T_0 - T_a) \\ 0 & a_5(w_0 - w_a) \end{bmatrix} \begin{bmatrix} E_h \\ V \end{bmatrix}.$$

In this model, there are two nonlinear terms: $a_2V(T_0 - T_a)$ and $a_5V(w_0 - w_a)$. Thus, to prevent the control system from working in unfavorable conditions for crop growth and development, we impose limitations on the inside temperature T_a and absolute humidity w_a. These bounds are represented by the linear inequality constraint, $T_{a,min} \leq T_a \leq T_{a,max}, w_{a,min} \leq w_a \leq w_{a,max}$. Then, for the nonlinear terms, we define $z_1(k) = a_2(T_0 - T_a)$ and $z_2(k) = a_5(w_0 - w_a)$, which can be written as:

$$z_1(k) = M_1\underline{\beta} + M_2\overline{\beta} \text{ and } z_2(k) = N_1\underline{\alpha} + N_2\overline{\alpha},$$

where $\underline{\beta} \leq z_1(k) \leq \overline{\beta}$, $\underline{\alpha} \leq z_2(k) \leq \overline{\alpha}$, $M_1 + M_2 = 1$, and $N_1 + N_2 = 1$. In the end, we arrive at the following T-S fuzzy model:

If $z_1(k)$ is M_1 and $z_2(k)$ is N_1
Then $\quad x(k+1) = A_1x(k) + B_1u$,

$$A_1 = \begin{bmatrix} 1-a_1 & 0 \\ 0 & 1-a_6 \end{bmatrix}, \quad B_1 = \begin{bmatrix} a_3 & \underline{\beta} \\ 0 & \underline{\alpha} \end{bmatrix}.$$

If $z_1(k)$ is M_1 and $z_2(k)$ is N_2
Then $\quad x(k+1) = A_2x(k) + B_2u$,

$$A_2 = A_1, \quad B_2 = \begin{bmatrix} a_3 & \underline{\beta} \\ 0 & \overline{\alpha} \end{bmatrix}.$$

If $z_1(k)$ is M_2 and $z_2(k)$ is N_1
Then $\quad x(k+1) = A_3x(k) + B_3u$,

$$A_3 = A_1, \quad B_3 = \begin{bmatrix} a_3 & \overline{\beta} \\ 0 & \underline{\alpha} \end{bmatrix}.$$

If $z_1(k)$ is M_2 and $z_2(k)$ is N_2
Then $\quad x(k+1) = A_4x(k) + B_4u$,

$$A_4 = A_1, \quad B_4 = \begin{bmatrix} a_3 & \overline{\beta} \\ 0 & \overline{\alpha} \end{bmatrix}.$$

The closed loop system is given by:

$$x(k+1) = \sum_{i=1}^{4}\sum_{j=1}^{4} h_i(z(k))h_j(z(k))(A_i + B_iK_j)x(k). \quad (10)$$

Remark 3.1: As we have mentioned already, in this paper, the fuzzy model is derived from a simplified nonlinear model, where the canopy transpiration in the water vapor balance has been ignored (empty greenhouse) and has been limited to two state variables (T_a, w_a). However, if we try to construct the T-S fuzzy model for the nonlinear greenhouse system which contains more state variables and take into account the transpiration and photosynthesis of the crop, a large number of rules are required to exactly represent the nonlinear dynamics of the greenhouse. Reducing the number of rules offers the possibility to minimize the effort in the analysis and design of control systems. It has already been proved that this approach is useful in practice [8], [13].

D. Constraints on the outputs

To ensure an optimal climate in greenhouses, we propose considering constraints on the outputs. For this, the following conditions are added to those of Theorem 2.1 to ensure the optimal climate in the greenhouse.

Theorem 3.1: Assume that the initial condition $x(0)$ is known. The constraint $\parallel y(t) \parallel_2 \leq \lambda$ is enforced at all times $t \geq 0$ if the LMIs

$$\begin{bmatrix} 1 & x(0)' \\ x(0) & X \end{bmatrix} \geq 0,$$

$$\begin{bmatrix} X & XC_i' \\ C_iX & \lambda_i^2 I \end{bmatrix} \geq 0,$$

hold, where $X = P^{-1}$.

Proof: The proof is given in [9]. ∎

In this work, we consider air temperature T_a and humidity concentration w_a as outputs:

$$\begin{bmatrix} y_1(k) \\ y_2(k) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} T_a \\ w_a \end{bmatrix}$$

IV. SIMULATION RESULTS AND DISCUSSION

In the following, we present some simulations to show the applicability of the proposed method, with various outside climates (considered constant) and from several initial conditions. During the night, the system was able to achieve the desired climatic condition and the imposed constraints were fulfilled, because there is no disturbance coming from the sun. However, the solar radiation effect can be observed during the day and a stationary error can also be observed in "Fig. 5" and "Fig.6".

Exp.	T_0	w_0	S_0	T_{init}	w_{init}
t_1	0	90	0	14	60
t_2	4	85	0	10	57
t_3	7	88	0	14	65
t_4	0	95	0	6	55
t_5	0	90	0	18	55

The constraints on outputs are imposed as follows:

- $T_a(k)$ is constrained so as not to surpass the $1°C$ band around the optimal reference $24°C$.
- $w_a(k)$ is constrained so as not to surpass the 5% band around the optimal reference 75%.

"Fig.1", "Fig.2", "Fig.3" and "Fig.4" show the behavior of the controlled greenhouse's climate during night. The most important result of this control strategy is that the fuzzy controller can guarantee the stability of the greenhouse system; moreover, there were no energy losses by ventilation. "Fig.4" shows that the ventilation system was stopped when the heating system had to provide the heat.

The resolution of the (LMIs) in Theorem 2.1, for test (t_1), leads to the following:

$$K_1 = \begin{bmatrix} -94 & -58151 \\ 0 & -3 \end{bmatrix}, K_2 = \begin{bmatrix} -94 & -58151 \\ 0 & -3 \end{bmatrix},$$

$$K_3 = \begin{bmatrix} -94 & 66542 \\ 0 & -3 \end{bmatrix}, K_4 = \begin{bmatrix} -94 & 66542 \\ 0 & -3 \end{bmatrix},$$

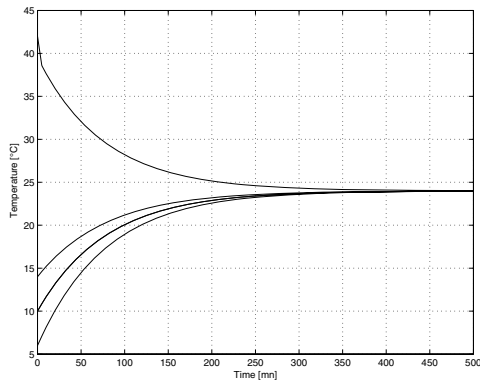$$P = \begin{bmatrix} 0.1024 & 0 \\ 0 & 0.1063 \end{bmatrix}.$$

Fig. 1.   Evolution of the air temperature

V. CONCLUSION

In this work, a fuzzy controller has been proposed for temperature and humidity regulation in a greenhouse, taking into account the presence of constraints in the output variables. The five cases studied in this paper, and others tests (not shown here) that have been performed, show that the robust fuzzy controller effectively achieves the desired climate conditions in a greenhouse, which shows the importance of the use of a T-S fuzzy model in the regulation of a very complex process with high nonlinearity such as a greenhouse climate. In the next work, we will test the stability and robustness of the fuzzy controller for a more detailed greenhouse model with more variables which represent the real state of a greenhouse.
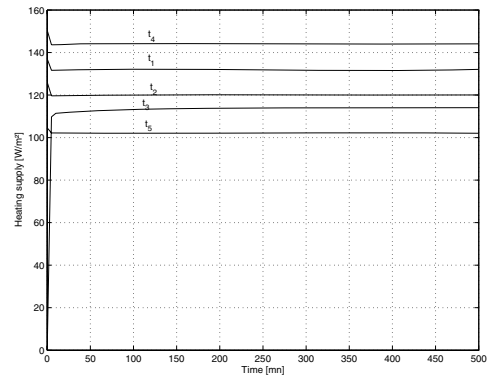

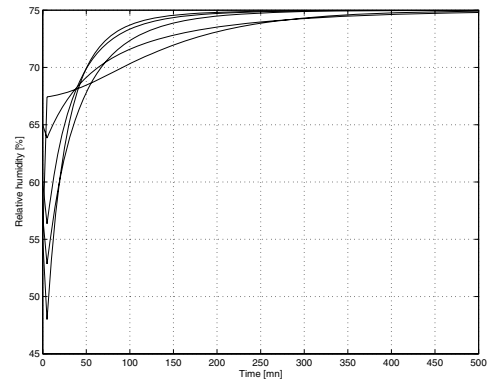Fig. 2.   Evolution of the heating supply
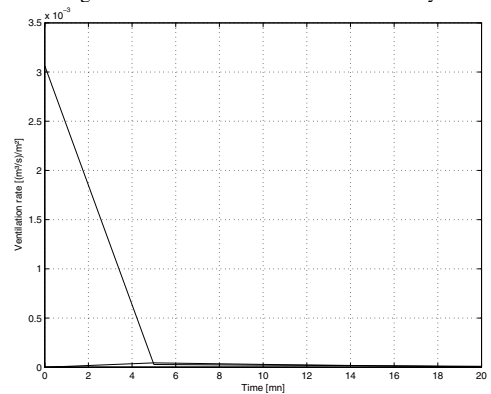

Fig. 3.   Evolution of the relative humidity

Fig. 4.   Evolution of the ventilation rate
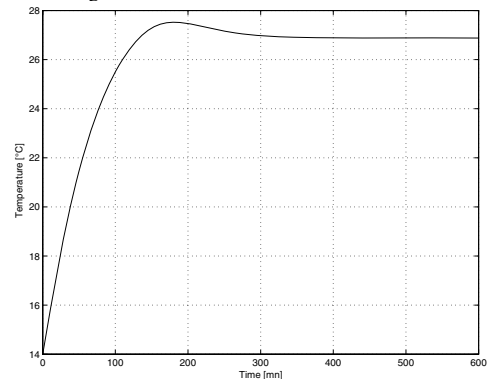

Fig. 5.   Evolution of the air temperature, $(S_0 = 400Wm^{-2})$
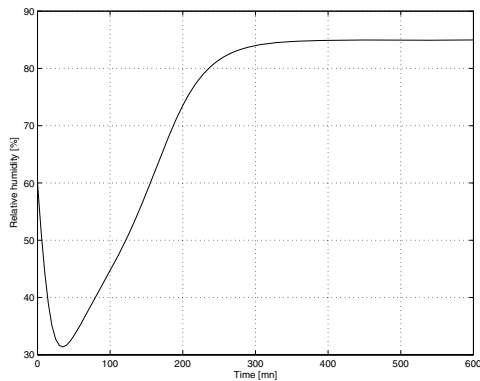
Fig. 6. Evolution of the relative humidity, $(S_0 = 400Wm^{-2})$

TABLE I

LIST OF SYMBOLS, VALUES AND UNITS

$C_{cap,q}$	heat capacity of greenhouse air (Nominal value = 30000), $Jm^{-2\circ}C^{-1}$
$C_{cap,q,v}$	heat capacity per volume unit of greenhouse air,(Nominal value = 1290), $Jm^{-3\circ}C^{-1}$
$C_{cap,h}$	volumetric capacity of greenhouse air for humidity (Nominal value = 4.1), m
h_T	heat transmission coefficient through the greenhouse cover (Nominal value = 6.1), $Wm^{-2\circ}C^{-1}$
h_w	leakage air exchange through greenhouse cover (Nominal value = $0.75x10^{-4}$), ms^{-1}
τ	heat load coefficient due to solar radiation (Nominal value = 0.2)
t_s	sampling time, s
S_0	outside solar radiation, Wm^{-2}
T_a	greenhouse air temperature, C
T_0	outside temperature, C
w_a	humidity concentration in greenhouse, kgm^{-3}
w_0	outside humidity concentration, kgm^{-3}
w_{init}	initial humidity concentration in greenhouse, kgm^{-3}
T_{init}	initial greenhouse air temperature, C
V	ventilation rate, $m^3s^{-1}m^{-2}$
E_h	energy supply by heating system, Wm^{-2}
E_c	energy exchange by transmission through the cover, Wm^{-2}
E_v	energy exchange by ventilation, Wm^{-2}
E_s	heat load by solar radiation, Wm^{-2}
W_v	exchange of humidity by ventilation, $kgm^{-3}s^{-1}$
W_c	exchange of humidity through the cover, $kgm^{-3}s^{-1}$

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