Fuzzy control applied to the regulation of the temperature inside a greenhouse *

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1 Introdction

Greenhouses are building structures that allow the creation of an indoor microclimate for crop development, protecting it from adverse outdoor conditions. Moreover this microclimate can be modified by artificial actuations such as heating, ventilation in order to provide the best environmental conditions. In this sense, several researchers used the optimal control and predictive control to develop algorithms which decide about heating and ventilation and produce temperature, humidity and carbon dioxide control actions (ref).

In this paper, we are interested in the application of fuzzy control to this problem (references). The standard additive model (SAM) theorem extended to a class of nonlinear dynamical systems is used to represent the Exact Fuzzy model (TSK) of greenhouse, which is a nonlinear dynamical system (ref.).

The nonlinear plant is firstly approximated by a Takagi-Sugeno type fuzzy model, where the local dynamics in different state space regions are represented by linear models. The overall model of the system is achieved by fuzzy "blending" of these linear models. In the control design, for each local linear model, a linear feedback control is designed. The resulting controller, is again a fuzzy blending of each of the individual linear controller (refer).

The stability of the system is checked by sufficient conditions which call upon the tools LMIs (Linear Matrix Inequalities) (ref).

This paper is presented as follows: In section 2, one presents a dynamic model which describes the thermal behavior of the greenhouse. The TSK Fuzzy modeling of a nonlinear dynamic system, stability of the modeled system and controlled closed loop system and the SAM theorem extended to a class of nonlinear dynamic systems are given in section 3. Exact Fuzzy model to the greenhouse is given In section 4. Simulation results and conclusions are given in sections 5 and 6.

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2 Problem Position

The model presented here simulates the dynamics of the climat of an empty greenhouse. In the greenhouse climate model used here, the state of greenhouse climate is represented by one variable namely, inside air temperature. The greenhouse climate model describes the dynamic behaviour of the state variables with the following differential equation (ref):

2.1 Energy balance

The energy fluxes affecting the greenhouse air are due to ventilation, E_v,heating,E_h,and to convection the cover,E_c, and the floor,E_f. This balance writes(symbols are detailed in table I):

$$\begin{aligned} \rho_a.C_a.\frac{V_g}{A_g}\frac{dT_a}{dt} &= E_v + E_h + E_c + E_f + E_s \\ E_v &= \rho_a C_a V(T_a - T_0) \\ E_c &= h_c\frac{A_c}{A_g}(T_c - T_a) \\ E_f &= h_f(T_f - T_a) \\ E_s &= \alpha_s S_0 \end{aligned} \tag{1}$$

The variables that appear in this balance is the heating supply,E_h. It is considered that the renewal rate between the air intern of the greenhouse and the air extern remains constant, $V = cts$.

3 TSK Fuzzy Modeling

In this paper, we restrict ourselves to the regulation of the temperature by using equation (1) The corresponding fuzzy system is of the following form:
Rule i; IF $x_1(t)$ is $M_{i1}$and $x_2(t)$ is $M_{i2}\dots$ and $x_n(t)$ is M_{in} THEN

$$\dot{X}(t) = A_iX(t) + B_iu(t) \tag{2}$$

Where,

$$\begin{aligned} X^T &= [x_1, x_2, \dots x_n] \\ u^T &= [u_1, u_2, \dots u_n] \end{aligned}$$

for $i = 1, 2, \dots r$. Where r is the total number of IF-THEN rules. $M_{ij}$is a fuzzy set.
Given X, u, the final output of the fuzzy system is inferred as

$$\dot{X} = \frac{\sum_{i=1}^{r} w_i(X)\left\{A_iX + B_iu\right\}}{\sum_{i=1}^{r} w_i(X)} \tag{3}$$

Where,

$$w_i(X) = \prod_{j=1}^{n} M_{ij}(x_j(t))$$

and

$$w_i(X) \geq 0, \sum_{i=1}^{r} w_i(X) > 0$$

for all t and $i = 1, 2, \dots r$. $M_{ij}(x_j(t))$ is the grade of membership of $x_j(t)$ in M_{ij}. Each linear component

$$\dot{X}(t) = \sum_{i=1}^{r} h_i(X)A_iX(t) + B_iu(t) \tag{4}$$

Where,

$$\begin{aligned} h_i(X) &= \frac{w_i(X)}{\sum_{j=1}^{r} w_j(X)} \\ \sum_{i=1}^{r} h_i(X) &= 1 \\ \text{and } \ h_i(X) &\geq 0 \text{ for } \ i = 1, 2, \dots, r. \end{aligned}$$

This means that the overall system in (4)is a convex combination of 'r' fuzzy subsystems.

3.1 Stability of the controlled continuous-time system in closed-loop

We use the concept of PDC [references] and optimality results using local concept approach, to design stable and optimal fuzzy controller for fuzzy system in (4). The fuzzy controller shares the same fuzzy sets with the fuzzy model. For each rule, we can use linear control design.
Rule i;
IF $x_1(t)$ is$M_{i1}$and $x_2(t)$ is $M_{i2}\dots$ and $x_n(t)$ is M_{in} THEN

$$u_i(t) = -F_iX(t)$$

Where, $i = 1, 2, \dots r$.
Hence, the fuzzy controller is:

$$\begin{aligned} u(t) &= -\frac{\sum_{i=1}^{r} w_i(X)F_iX(t)}{\sum_{i=1}^{r} w_i(X)} \\ &= -\sum_{i=1}^{r} h_i(X)F_iX(t) \end{aligned} \tag{5}$$

The overall controller (5) is again a convex combination of individual control laws. Even though, the individual control laws is linear, the overall controller is nonlinear. Substituting (5) in (3), we have

$$\dot{X} = \frac{\sum_{i=1}^{r}\sum_{j=1}^{r} w_i(X)w_j(X)[A_i - B_iF_j]X(t)}{\sum_{i=1}^{r}\sum_{j=1}^{r} w_i(X)w_j(X)} \tag{6}$$

This is a convex sum of fuzzy subsystems $[A_i - B_iF_j]$ where $i = 1, 2, \dots, r$et $j = 1, 2, \dots, r$. Hence, if all these r^2subsystems in (6) are stable, then for continuous-time case, the overall controlled system is stable. Alternately, the above closed-loop system is stable. Alternately, the above closed-loop system is stable if there exists a common positive definite matrix, P such that:

$$\begin{aligned} (A_i - B_iF_j^T)P + P(A_i - B_iF_j) < 0, \\ i = 1, 2, \dots, r; j = 1, 2, \dots, r. \end{aligned} \tag{7}$$

4 Exact fuzzy modeling of the Greenhouse

The equation (1) can be written in the following form:

$$\frac{dT_a}{dt} = [a_1(\frac{T_0}{T_a} - 1) + a_2(\frac{T_c}{T_a} - 1) \quad (8)$$
$$+a_3(\frac{T_f}{T_a} - 1) + a_4\frac{S_0}{Ta}]T_a + a_5E_h$$

$$\frac{dT_a}{dt} = [\frac{1}{T_a}(a_1T_0 + a_2T_c + a_3T_f + a_4S_0) \quad (9)$$
$$-(a_1 + a_2 + a_3)]T_a + a_5E_h$$

$$\frac{dT_a}{dt} = f(T_0, T_c, T_f, S_0)T_a + a_5E_h \quad (10)$$

Where:

$$\begin{aligned} a_1 &= V\frac{A_g}{V_g} \\ a_2 &= \frac{h_cA_c}{\rho_aC_aV_g} \\ a_3 &= \frac{A_gh_f}{\rho_aC_aV_g} \\ a_4 &= \frac{\alpha_sA_g}{\rho_aC_aV_g} \\ a_5 &= \frac{A_g}{\rho_aC_aV_g} \end{aligned}$$

T_0, T_c, T_f, S_0 are assumed to be available by using adequate sensors at each sampling time. The general form of this total system is

$$\dot{X} = A(X)X + B(X)u \quad (11)$$

Where $X = T_a$, $B(X) = B = a_5$ and $B_i = B$ for $A(.) = [f(T_a)]$ $i = 1, 2$.
There is one scalar valued nonlinear auxiliary function of state inside the system matrix A(.).

4.1 Permise variable for Exact fuzzy modeling

By using the theorem SAM, the function f(.) requires 2 membership functions to represent it exactly in a predetermined domain, knowing their bounds in that domain. And these membership functions are represented as:

$$M_{j1} = \frac{\beta - f(T_a)}{\beta - \alpha}$$

$$M_{j2} = 1 - M_{j1}$$

for $j = 1, 2$.
Where,

$$\beta = max(f(T_a)) \quad and \quad \alpha = min(f(T_a))$$

We need $2^1 = 2$ rules to represent this nonlinear system. Now the exact fuzzy model of the system can be expressed using the membership functions [rfere]:
Rule:1 IF f(.) is M_{11} THEN

$$\dot{X} = A_1X + Bu, \quad A_1 = [\alpha]$$

Rule:2 IF f(.) is M_{21} THEN

$$\dot{X} = A_2X + Bu, \quad A_2 = [\beta]$$

The corresponding convex weighting coefficients can be written using the results in [refer]:

$$h_1 = \frac{M_{11}}{M_{11} + M_{21}}$$

$$h_2 = \frac{M_{21}}{M_{11} + M_{21}}$$

Thus the exact Fuzzy model of nonlinear system above is

$$\dot{X} = \sum_{i=1} 2h_i(X)[A_iX + Bu] \quad (12)$$

5 LMI Approach

For each of the subsystem in (12),the Linear Matrix Inequalities is used to find simultaneously the common matrix $(P > 0)$ to the 2 subsystems and the regulators (F_i), as:

$$(A_i - BF_i)^TP + P(A_i - BF_i) < 0$$
$$P > 0$$

let us use the well known change of variables $P^{-1} = X$ and $Y_i = F_iX$ and by multiplying each side of the above inequality by X; we obtain:

$$(LMI) : \begin{cases} X > 0 \\ XA_i^T + A_iX - B_iY_i - Y_i^TB^T < 0, \\ F_i = Y_iX^{-1} \end{cases}$$

6 Simulation Results

For simulation purpose, we wishe to regulate the temperature of air inside a greenhouse of dimensions $A_g = 15m^2$; $A_c = 60.5m^2$; $h_g = 4m$, around a temperature of $24C$, the initial temperature of the greenhouse is $14C$, the various temperatures used here are not realistic measurements, thus for one journey of November in Marrakech we have:

$$\begin{aligned} 9C \leq T_c \leq 20C \\ 14C \leq T_f \leq 25.5C \\ 8C \leq T_0 \leq 18C \\ 0w/m^2 \leq S_0 \leq 300w/m^2 \\ 10C \leq T_a \leq 33C \end{aligned} \tag{13}$$

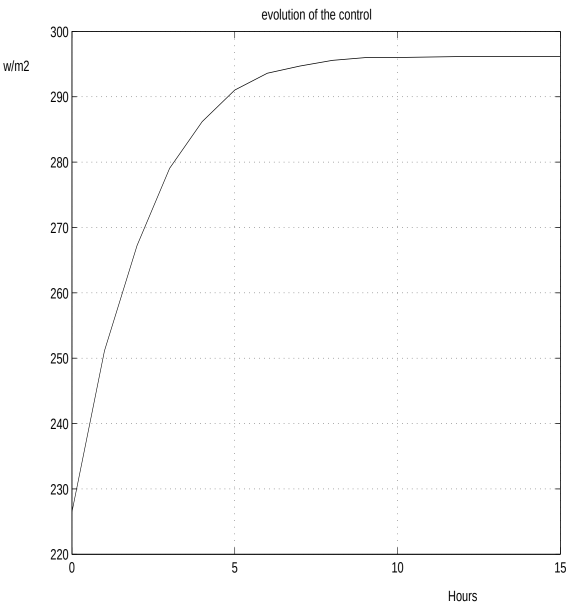
In equation (11), $\frac{dT_a}{dt} = \dot{X}$ is expressed in K/h.

In this domain, we have the following bounds for the auxiliary function:

$$\alpha = -577.15 \quad \beta = -60.237$$

The simulation results for the desired inside air temperature in greenhouse $T_a = 24C$, and the fuzzy control are presented in Figure1 and Figure2. The resolution of the LMI leads to the following,

$$P = 0.18182, \ F1 = -770.78 \ , F2 = -79.848$$



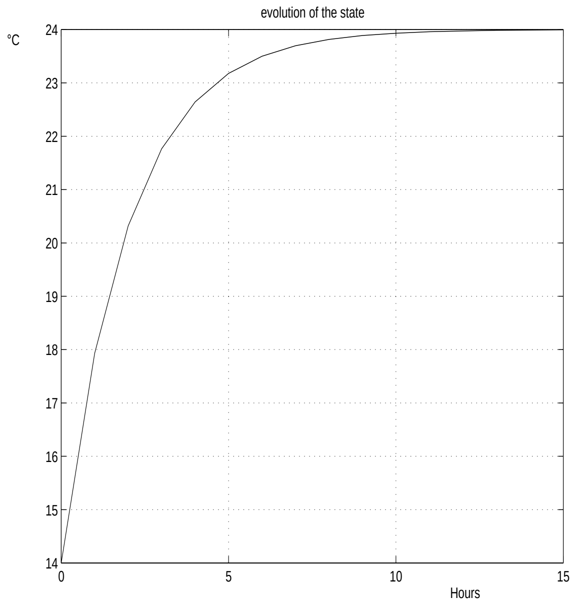


Table List of symbols, values and units

Symbol	Meaning	Value/unit
A_c	Cover area of the greenhouse	m^2

7 Conclusion

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