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Application of T-S Fuzzy Controllers on an HVAC System

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Abstract— This paper focuses on designing fuzzy controllers for a kind of Heating, Ventilation, and Air Conditioning (HVAC) systems. A kind of fuzzy method based on T-S fuzzy models with nonlinear local feedbacks is applied to a specific HVAC system. Firstly, an augmented HVAC system model is got based on an existing model. Then control with T-S fuzzy systems with nonlinear local models is reviewed. The control gain is got by solving a set of linear matrix inequalities (LMIs) where H_∞ performance is considered. Finally, simulations and comparisons are executed to illustrate the effectiveness of this kind of fuzzy methods.

Keywords— Fuzzy control, T-S fuzzy models, H_∞ control, HVAC systems.

LIST OF SYMBOLS

$\Delta W_z(t)$	=increment of zone moisture content
$\Delta T_z(t)$	=increment of zone temperature
$\Delta T_{sec}(t)$	=increment of secondary off coil temperature
$\Delta \dot{V}_{pri}(t)$	=increment of primary air volume flow rate
$\Delta T_{w,in}(t)$	=increment of inlet chilled water temperature
$\Delta M_{gain}(t)$	=increment of moisture load
$\Delta Q_{gain}(t)$	=increment of sensible cooling load
ρ_a	=air density
V_z	=zone volume
W_{pri}	=moisture content of the primary air
C_a	=specific heat of dry air
T_{pri}	=primary air temperature
a	=constant coefficients
b	=constant coefficients

$M_c C_c$	=dynamic constant
A_a	= effective heat transfer area of the second air loop
C_w	=specific heat of water
ρ_w	=specific density of water
$\dot{V}_w$	=volume flow rate
A_w	= effective heat transfer area of water
$\dot{V}_{pri,op}$	=primary air volume flow rate
$W_{z,op}$	=zone moisture content
$M_{gain,op}$	=moisture load
$T_{z,op}$	=zone temperature
$Q_{gain,op}$	=sensible cooling load
$T_{sec,op}$	=off coil temperature of the secondary air
$T_{w,in}$	=inlet chilled water temperature

I. INTRODUCTION

Since heating, Ventilation, and Air Conditioning (HVAC) systems have become the major sources of the energy consumption in buildings [1,2], many efforts have been made aiming to design effective control methods for HVAC systems. Despite the traditional on/off and PID control, with the fast development of computing and communication technology, it is feasible to adopt more complex control methods, such as nonlinear control and robust control [3-5], model predictive control (MPC) [6-8], fuzzy logic and neural network controllers (see [9] and references therein).

It is shown that T-S fuzzy models are universal approximators of nonlinear systems [10], where linear local models are blended by fuzzy rules. Since the development of T-S fuzzy models [11], it has attracted a lot of research interests and been adopted in many applications. For HVAC systems, application of T-S fuzzy systems can be seen in [8], [12,13]. In contrast to the conventional fuzzy method which uses linear local models, a novel fuzzy control scheme which adopts nonlinear local models is firstly proposed in [14]. By applying the new fuzzy control method, the number of fuzzy rules could be decreased and the computational burden could be reduced.

In this paper, the fuzzy method in [14] is applied to the control of a specific HVAC system-active chilled beam (ACB) system, which is a multi-input multi-output (MIMO) system with severe nonlinearity and external disturbances. H_∞ control is considered and the control law is acquired by solving a set of LMIs.

The rest of the paper is organized as follows: Section II shows the augmented HVAC system model based on the original model. Section III describes the fuzzy modeling and fuzzy control scheme with nonlinear local models and nonlinear local feedbacks. Simulations which compare 2 different control strategies are illustrated in Section IV. Finally, some conclusions are drawn in Section V.

II. AUGMENTED HVAC SYSTEM MODEL

The main effort is to control the zone temperature and humidity (see Fig. 1). The original dynamic model of the ACB system can be seen in [15].

Fig.1 Zone relative humidity and temperature control.

The original control input is the air volume flow rate. However, in this ACB system, there exists severe coupling and nonlinearity of this input. In order to decrease the complexity of designing T-S fuzzy systems, the dynamic model of the valve is added to the original system model. The model of valves can be depicted by (1).

$$\Delta \dot{V}_{pri}(t) = -\frac{1}{\tau_v} \Delta \dot{V}_{pri}(t) + \frac{k}{\tau_v} \rho(t) \quad (1)$$

where $\rho(t)$ is the control input signal of the valve, τ_v is the time constant of the valve, k is a constant gain. Thus, the

increment model of the augmented HVAC system can be described as follows:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + G\phi(t) + Ed(t) \\ y(t) &= Cx(t) \end{aligned} \quad (2)$$

where

$$\begin{aligned} x(t) &= \begin{bmatrix} \Delta W_z(t) \\ \Delta T_z(t) \\ \Delta T_{sec}(t) \\ \Delta \dot{V}_{pri}(t) \end{bmatrix} \quad u(t) = \begin{bmatrix} \rho(t) \\ \Delta T_{w.in}(t) \end{bmatrix} \\ \phi(t) &= \frac{W_{pri} - W_{z.op} - \Delta W_z(t)}{V_z} \Delta \dot{V}_{pri}(t) \\ d(t) &= \begin{bmatrix} \Delta M_{gain}(t) \\ \Delta Q_{gain}(t) \end{bmatrix} \\ A &= \begin{bmatrix} -\frac{\dot{V}_{pri.op}}{V_z} & 0 & 0 & 0 \\ 0 & f_1(\Delta \dot{V}_{pri}(t)) & f_2(\Delta \dot{V}_{pri}(t)) & 0 \\ 0 & f_3(\Delta \dot{V}_{pri}(t)) & f_4(\Delta \dot{V}_{pri}(t)) & 0 \\ 0 & 0 & 0 & -\frac{1}{\tau_v} \end{bmatrix} \\ B &= \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & f_5(\Delta \dot{V}_{pri}(t)) \\ \frac{k}{\tau_v} & 0 \end{bmatrix} \\ G &= \begin{bmatrix} -1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \\ E &= \begin{bmatrix} \frac{1}{\rho_a V_z} & 0 \\ 0 & \frac{1}{C_a \rho_a V_z} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \\ C &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \end{aligned}$$

$$f_1(\Delta \dot{V}_{pri}(t)) = -\frac{\dot{V}_{pri.op} + \Delta \dot{V}_{pri}(t) + a(\dot{V}_{pri.op} + \Delta \dot{V}_{pri}(t))^b}{V_z}$$

$$f_2(\Delta \dot{V}_{pri}(t)) = \frac{a(\dot{V}_{pri.op} + \Delta \dot{V}_{pri}(t))^b}{V_z}$$

$$\begin{aligned}
f_3(\Delta \dot{V}_{pri}(t)) &= \frac{\left[C_a \rho_a a(V_{pri.op} + \Delta \dot{V}_{pri}(t))^b - \frac{C_w \rho_w \dot{V}_w c_w \dot{V}_w^{e_w} A_w}{C_w \rho_w \dot{V}_w + \frac{c_w \dot{V}_w^{e_w} A_w}{2}} \left(\frac{1}{2} - \frac{C_a \rho_a a(V_{pri.op} + \Delta \dot{V}_{pri}(t))^b}{c_a (a(V_{pri.op} + \Delta \dot{V}_{pri}(t))^b)^{e_a} A_a} \right) \right]}{M_c C_c \left(\frac{C_a \rho_a a(V_{pri.op} + \Delta \dot{V}_{pri}(t))^b}{c_a (a(V_{pri.op} + \Delta \dot{V}_{pri}(t))^b)^{e_a} A_a} + \frac{1}{2} \right)} \\
f_4(\Delta \dot{V}_{pri}(t)) &= \frac{\left[C_a \rho_a a(V_{pri.op} + \Delta \dot{V}_{pri}(t))^b + \frac{C_w \rho_w \dot{V}_w c_w \dot{V}_w^{e_w} A_w}{C_w \rho_w \dot{V}_w + \frac{c_w \dot{V}_w^{e_w} A_w}{2}} \left(\frac{1}{2} + \frac{C_a \rho_a a(V_{pri.op} + \Delta \dot{V}_{pri}(t))^b}{c_a (a(V_{pri.op} + \Delta \dot{V}_{pri}(t))^b)^{e_a} A_a} \right) \right]}{M_c C_c \left(\frac{C_a \rho_a a(V_{pri.op} + \Delta \dot{V}_{pri}(t))^b}{c_a (a(V_{pri.op} + \Delta \dot{V}_{pri}(t))^b)^{e_a} A_a} + \frac{1}{2} \right)} \\
f_5(\Delta \dot{V}_{pri}(t)) &= \frac{\frac{C_w \rho_w \dot{V}_w c_w \dot{V}_w^{e_w} A_w}{C_w \rho_w \dot{V}_w + \frac{c_w \dot{V}_w^{e_w} A_w}{2}}}{M_c C_c \left(\frac{C_a \rho_a a(V_{pri.op} + \Delta \dot{V}_{pri}(t))^b}{c_a (a(V_{pri.op} + \Delta \dot{V}_{pri}(t))^b)^{e_a} A_a} + \frac{1}{2} \right)}
\end{aligned}$$

III. FUZZY MODELING AND CONTROL

A. fuzzy modeling and control scheme

Considering the following nonlinear system:

$$\begin{aligned}
\dot{x}(t) &= f(x(t)) + g(x(t))u(t) + h(x(t))w(t) \\
z(t) &= f_z(x(t)) + g_z(x(t))u(t) + h_z(x(t))w(t)
\end{aligned} \quad (3)$$

where $x(t) \in R^n$ is the state, $u(t) \in R^m$ is the control input, $f(\cdot)$, $g(\cdot)$, $h(\cdot)$, $f_z(\cdot)$, $g_z(\cdot)$, $h_z(\cdot)$ are nonlinear functions.

Assume that $f(x(t))$ can be separated into two parts:

$$f(x(t)) = f_a(x(t)) + f_b(x(t))\bar{\phi}(t) \quad (4)$$

where

$$\bar{\phi}(t) = \begin{bmatrix} \bar{\phi}_1(t) \\ \bar{\phi}_2(t) \\ \vdots \\ \bar{\phi}_s(t) \end{bmatrix}$$

satisfies

$$\bar{\phi}_i(t) \in co\{E_{Li}x(t), E_{Ui}x(t)\} \quad 1 \leq i \leq s \quad (5)$$

Then

$$(E_{Li}x(t) - \bar{\phi}_i(t))(E_{Ui}x(t) - \bar{\phi}_i(t)) \leq 0 \quad (6)$$

Define $\phi_i(t) = \bar{\phi}_i(t) - E_{Li}x(t)$, $E_i = E_{Ui} - E_{Li}$, then

$$-\phi_i(t)(E_i x(t) - \phi_i(t)) \leq 0 \quad (7)$$

Substituting $\phi_i(t) + E_{Li}x(t)$ for $\bar{\phi}_i(t)$ in (4), then system (3) can be rewritten as follows:

$$\begin{aligned}
\dot{x}(t) &= \bar{f}_a(x(t)) + g(x(t))u(t) + h(x(t))w(t) + f_b(x(t))\phi(t) \\
z(t) &= \bar{f}_{za}(x(t)) + g_z(x(t))u(t) + h_z(x(t))w(t) + f_{zb}(x(t))\phi(t)
\end{aligned} \quad (8)$$

where

$$\begin{aligned}
\bar{f}_a(x(t)) &= f_a(x(t)) + f_b(x(t))E_L x(t) \\
\bar{f}_{za}(x(t)) &= f_{za}(x(t)) + f_{zb}(x(t))E_L x(t)
\end{aligned}$$

System (8) can be represented with the following T-S fuzzy model:

Plant Rule i:

IF $v_1(t)$ is Γ_{i1} and $v_2(t)$ is Γ_{i2} , ..., $v_p(t)$ is Γ_{ip}

$$\dot{x}(t) = A_i x(t) + B_{1i} w(t) + B_{2i} u(t) + G_i \phi(t)$$

THEN $z(t) = C_{1i} x(t) + D_{1i} w(t) + D_{2i} u(t) + G_{zi} \phi(t)$

where $i=1, \dots, r$. r is the number of fuzzy rules. $v_i(t)$ are premise variables. Γ_{ij} are fuzzy sets.

Accordingly, the control law is obtained as follows:

Control Rule i:

IF $v_1(t)$ is Γ_{i1} and $v_2(t)$ is Γ_{i2} , ..., $v_p(t)$ is Γ_{ip}

THEN $u(t) = K_{ai}x(t) + K_{bi}\phi(t)$

The final control output is got:

$$u(t) = K_a(\alpha)x(t) + K_b(\alpha)\phi(t) \quad (9)$$

where $K_a(\alpha) = \sum_{i=1}^r \alpha_i(v(t))K_{ai}$, $K_b(\alpha) = \sum_{i=1}^r \alpha_i(v(t))K_{bi}$.

Above fuzzy modeling and control scheme is defined in [14]. It can be seen that this kind of fuzzy control method is different from the conventional method that it uses nonlinear local models rather than linear local models. It is easy to find that the number of fuzzy rules can be decreased with this method since the nonlinear term $\phi(t)$ can be reserved without becoming a premise variable.

B. Controller computation

H_∞ controller design for fuzzy method with nonlinear local feedbacks is given by solving a set of LMIs.

Lemma 1 [14]. For a prescribed $\gamma > 0$, if there exist matrices $Q = Q^T > 0$, L_{ai} , L_{bi} , $0 \leq i \leq r$, Λ satisfying

$$\Xi_{ii} < 0, 1 \leq i \leq r \quad (10)$$

$$\frac{1}{r-1}\Xi_{ii} + \frac{1}{2}(\Xi_{ij} + \Xi_{ji}) < 0, 1 \leq i \neq j \leq r \quad (11)$$

where

$$\Lambda = \text{diag}[\lambda_1 \quad \dots \quad \lambda_s]_{s \times s} \quad (12)$$

$$\Xi_{ij} = \begin{bmatrix} He(A_i Q + B_{2i} L_{aj}) & * & * & * \\ \Lambda G_i^T + L_{bj}^T B_{2i}^T + E Q & -2\Lambda & * & * \\ B_{1i}^T & 0 & -\gamma^2 I & * \\ C_{1i} Q + D_{2i} L_{aj} & G_{zi} \Lambda + D_{2i} L_{bj} & D_{1i} & -I \end{bmatrix} \quad (13)$$

Then $K_{ai} = L_{ai} Q^{-1}$, $K_{bi} = L_{bi} \Lambda^{-1}$, and the fuzzy system with nonlinear local models is asymptotically stable and H_∞ performance is fulfilled.

For comparison, the controller design which adopts T-S fuzzy systems with linear local models is shown below.

Lemma 2 [14]. For a prescribed $\gamma > 0$, if there exist matrices $Q = Q^T > 0$, L_i , $0 \leq i \leq r$ satisfying

$$\Omega_{ii} < 0, 1 \leq i \leq r \quad (14)$$

$$\frac{1}{r-1}\Omega_{ii} + \frac{1}{2}(\Omega_{ij} + \Omega_{ji}) < 0, 1 \leq i \neq j \leq r \quad (15)$$

$$\Omega_{ij} = \begin{bmatrix} He(A_i Q + B_{2i} L_j) & * & * \\ B_{1i}^T & -\gamma^2 I & * \\ C_{1i} Q + D_{2i} L_j & D_{1i} & -I \end{bmatrix} \quad (16)$$

Then $K_i = L_i Q^{-1}$, and the fuzzy system with linear local models is asymptotically stable and H_∞ performance is fulfilled.

IV. SIMULATION

Numerical values of parameters are shown in Table 1. From Table 1, it can be seen that the main operating point of the system is set to $x_{op} = [0.0092 \quad 24 \quad 19 \quad 0.036]^T$.

Table 1
Summary of numerical values used for simulations.

Parameter	Value	Unit	Parameter	Value	Unit
ρ_a	1.184	kg/m ³	ρ_w	1000	kg/m ³
$M_{gain,op}$	1.705e-4	kg/s	$\dot{V}_w$	0.04	L/s
W_{pri}	0.0052	kg/kg	V_z	50.4	m ³
C_a	1006	J/kg°C	e_w	0.5	
$c_w A_w$	788.436		T_{pri}	18	°C
a	4.9934		τ_v	29	s
b	1.214		e_a	0.5	
$M_c C_c$	5946		$T_{z,op}$	24	°C
$c_a A_a$	697.674		$Q_{gain,op}$	786	W
$W_{z,op}$	0.0092	kg/kg	$T_{sec,op}$	19	°C
C_w	4200	J/kg°C	$T_{w,in}$	14	°C
$\dot{V}_{pri,op}$	0.036	m ³ /s	k	5	

Setting initial states $x(0) = [0.012 \quad 25 \quad 24 \quad 0.046]^T$.

The control input limitations are set as:

$$\|u_1(t)\|_2 \leq 0.003, \quad \|u_2(t)\|_2 \leq 5$$

Disturbance is involved in the systems as follows:

$$d(t) = \begin{cases} \begin{bmatrix} 0.0003 \\ 200 \end{bmatrix}, & 2000s \leq t \leq 2100s \\ 0, & \text{others} \end{cases}$$

Simulations are executed in MATLAB on HP desktop (3.4 GHz Intel Core i7, 8GB RAM). The aforementioned two control methods are considered:

Method 1: T-S fuzzy systems with linear local models are adopted for the ACB system. The fuzzy membership degrees are shown in Fig. 2 and Fig. 3.

Fig. 2 Membership degree of x_1 .

Fig. 3 Membership degree of x_4 .

The control gain is computed as follows:

$$K1 = \begin{bmatrix} 2.6794e4 & 0 & 0 & -8.5794 \\ 0 & -1.9042e4 & -45.9375 & 0 \end{bmatrix},$$

$$K2 = \begin{bmatrix} 2.6794e4 & 0 & 0 & -8.5794 \\ 0 & -6.3449e4 & -144.7916 & 0 \end{bmatrix},$$

$$K3 = \begin{bmatrix} 3.7999e5 & 0 & 0 & -122.4609 \\ 0 & -1.9042e4 & -45.9375 & 0 \end{bmatrix},$$

$$K4 = \begin{bmatrix} 3.7999e5 & 0 & 0 & -122.4609 \\ 0 & -6.3449e4 & -144.7916 & 0 \end{bmatrix}.$$

Method 2: T-S fuzzy systems with nonlinear local models are adopted for the ACB system. In this method, the fuzzy membership degree is only given to x_4 (see Fig. 3). The nonlinear term $\phi(t)$ which is reserved in the T-S fuzzy model is defined as follows:

$$\phi(t) = (0.004 + x_1)x_4 / 50.4$$

Then

$$\phi(t) \in \{6.349e-6x_4, 1.524e-4x_4\}, E = [0 \quad 0 \quad 0 \quad 1.461e-4]$$

The control gain is computed as follows:

$$K_{a1} = \begin{bmatrix} 8.1346e4 & 0 & 0 & -14.0370 \\ 0 & -2.8197e4 & -34.4401 & 0 \end{bmatrix},$$

$$K_{a2} = \begin{bmatrix} 8.1346e4 & 0 & 0 & -14.0370 \\ 0 & -1.0353e5 & -108.7830 & 0 \end{bmatrix},$$

$$K_{b1} = \begin{bmatrix} -3.27e4 \\ 0 \end{bmatrix},$$

$$K_{b2} = \begin{bmatrix} -3.27e4 \\ 0 \end{bmatrix}.$$

The simulation results can be seen from Fig. 4-7. Fig. 4 and Fig. 5 show the relative humidity and the temperature of the zone, respectively. It can be seen that the system can reach steady states by both two methods. The disturbances are introduced from 2000s to 2100s. When the disturbances are removed, the system can still return to steady state. And the control performances of the two methods are almost the same. However, from Table 2, it can be seen that the time cost of the two methods are very different. It shows that computational

burden can be reduced adopting T-S fuzzy system with nonlinear local models.

Fig. 4 Curve of zone relative humidity.

Fig. 5 Curve of zone temperature.

Fig. 6 Curve of secondary off coil temperature.

Fig. 7 Curve of primary air volume flow rate.

Table 2

Computing time cost of controller gains using different control methods.

	Method 1	Method 2
Time cost	0.2005 s	0.0822 s

V. CONCLUSION

This paper launches an application of a fuzzy control method with nonlinear local feedbacks for the control of a MIMO HVAC system. H_∞ performance is adopted and the fuzzy controller is computed by solving a set of LMIs. Comparison of control performance between T-S fuzzy systems with linear local models and T-S fuzzy systems with nonlinear local models is discussed. The computational burden can be reduced adopting T-S fuzzy system with nonlinear local models.

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