A Hybrid Fuzzy Logic and PID Controller for Control of Nonlinear HVAC Systems

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Abstract- Heating, Ventilating and Air Conditioning (HVAC) plant is a multivariable, nonlinear and non minimum phase system, which control of this plant, is very difficult. This paper presents a new approach to control of HVAC system. The proposed method is a hybrid of fuzzy logic and PID controller. Simulation results show that this control strategy is very robust, flexible and alternative performance. To evaluate the usefulness of the proposed method, we compare the response of this method with PID controller. The simulation result shows that our method has the better control performance than PID controller.

Keywords: HVAC System, Fuzzy Logic, PID Controller

h_w Enthalpy of liquid water

h_{fg} Enthalpy of water vapor

W_s Humidity ratio of supply air

C_p Specific heat of air

M_o Moisture load

T_2 Temperature of supply air

V_s Volume of thermal space

f Volumetric flow rate of air

W_o Humidity ratio of outdoor air

V_{he} Volume of heat exchanger

W_3 Humidity ratio of thermal space

T_o Temperature of outdoor air

Q_o Sensible heat load

T_3 Temperature of thermal space

ρ Air mass density

gpm Flow rate of chilled water

1 Introduction

In recent years, fuzzy logic controllers, especially PID type fuzzy controllers have been widely used in industrial processes owing to their heuristic nature associated with simplicity and effectiveness for both linear and nonlinear systems. In fact, for single-input single output systems, most of fuzzy logic controllers are essentially of PD type, PI type or PID type with nonlinear gains. Because of the nonlinearity of the control gains, fuzzy PID controllers possess the potential to achieve better system performance over conventional PID controllers provide the nonlinearity can be suitably utilized. On the other hand, due to the existence of nonlinearity, it is usually difficult to conduct theoretical analyses to explain why fuzzy PID controllers can achieve better performance. Consequently it is important, from both theoretical and practical points of view, to explore the essential nonlinear control properties of fuzzy PID controllers, and find out appropriate design methods which will assist control engineers to confidently utilize the nonlinearity of fuzzy PID controllers so as to improve the closed-loop performance.

This paper is organized as follows: In section 2, the whole structure of the proposed fuzzy PID controller is shown. Section 3 describes the HVAC system and its mathematical model. Section 4 shows the simulation results that compare the linear PID and fuzzy PID. Some conclusion and remarks is discussed in section 5.

2 Fuzzy PID Controller

The block diagram of the control system with a fuzzy controller is shown in Fig. 1. The fuzzy controller can be viewed as a natural extension of the conventional PID control algorithm with a fuzzy- neural implementation [1]. The structure of the fuzzy PID (FPID) controller includes two blocks of the traditional fuzzy controller: a fuzzyfier and an inference engine. As usually, the traditional fuzzy controller works with input signals of the system error *e* and the change rate of error *de*. The system error is defined as the difference between the set point *r(k)* and the plant output *y(k)* at the step *k*, i.e.:

$$e(k)=r(k)-y(k) \tag{1}$$

The change rate of the error *de* at the step *k* is:

$$de(k)=e(k)-e(k-1) \tag{2}$$

As a third input signal, the FPID can use the accumulative error δ:

$$\delta e(k) = \sum e(i) \qquad (3)$$

The most used digital PID control algorithms can be described with the well-known discrete equation:

$$u(k) = k_p e(k) + k_i \delta e(k) + k_d de(k) \qquad (4)$$

where $k_d = k_p(T_d/T_k)$, $k_i = k_p(T_i/T_k)$ (5)

T_k is the sample time of the discrete system, T_i is the integral time constant of the conventional controller, T_d is the differential time constant, k_p is the proportional gain, and $u(k)$ is the output control signal.

The Sugeno's fuzzy rules into the FPID can be composed in the generalised form of 'if-then' statements to describe the control policy and can be represented as:

$R^{(n)}$: if e is $E_i^{(n)}$ and de is $dE_i^{(n)}$ and δe is $\delta E_i^{(n)}$

Then $f_u^{(n)} = k_p^{(n)} e(k) + k_d^{(n)} de(k) + k_i^{(n)} \delta e(k) + k_0$ (6)

where e, de, δe are the described input variables and k_p, k_i and k_d are the same constants as in (5). This way the similarity between the equation of the conventional digital PID controller (4), (5) and the Sugeno's output functions f_u in the equation (6) could be found. The fuzzy implication can be performed by means of the product composition [2]:

$$\mu_u^{(n)} = \mu_e^{(n)} * \mu_{de}^{(n)} * \mu_{\delta e}^{(n)} \qquad (7)$$

where $\mu_e^{(n)}$, $\mu_{de}^{(n)}$ and $\mu_{\delta e}^{(n)}$ specify the membership values upon fired fuzzy sets of the corresponding input signals. For a discrete universe with N quantisation levels in the controller output, the control action u_F is expressed as a weight average of the Sugeno's output functions f_u and their membership values μ_u of the quantisation levels [3]:

$$u_F = \frac{\sum_{i=1}^{N} f_{ui} \mu_{ui}}{\sum_{i=1}^{N} \mu_{ui}} \qquad (8)$$

3 HVAC System

The consumption of energy by heating, ventilating, and air conditioning (HVAC) equipment in commercial and industrial buildings constitutes 50% of the world energy consumption [4]. In spite of the advancements made in computer technology and its impact on the development of new control methodologies for HVAC systems aiming at improving their energy efficiencies, the process of operating HVAC equipment in commercial and industrial buildings is still an low-efficient and high-energy consumption process [4]. Classical HVAC control techniques such as ON/OFF controllers (thermostats) and proportional- integral-derivative (PID) controllers are still very popular because of their low cost. However, in the long run, these controllers are expensive because they operate at very low energy efficiency and fail to consider the complex nonlinear characteristics of the multi-input multi-output (MIMO) HVAC systems and the strong coupling actions between them.

The problem of HVAC control can be posed from two different points of view. In the first, one aims at reaching an optimum consumption of energy. In the second, that is more common in HVAC control, the goal is keeping moisture, temperature, pressure and other air conditions in an acceptable range. Several different control and intelligent strategies have been developed in recent years to achieve the stated goals fully or partially. Among them, PID controllers [5,6], DDC methods [7,8], optimal [9,10,11], nonlinear [12] and robust [13,14] control strategies, and neural and/or fuzzy [15-18] approaches are to be mentioned. We have also dealt with this problem and provided novel solutions in [19-22]. The purpose of this paper is to suggest another control approach, based on fuzzy PID controller to achieve faster response with reduced overshoot and rise time.

3.1 HVAC Model

In this part, we give some explanations about the HVAC model we have used. For simulation of HVAC systems, some different models have been proposed and considered. In [18,19] a linear first order model of the system with a time delay is put forward, while the nonlinearity of the HVAC systems is considered in [17]. In this paper, we used the model developed in [4], since it aims at controlling the temperature and humidity of the Variable Air Volume (VAV) HAVC system, however SISO bilinear model of the HVAC system for controlling the temperature has been given in [16]. Below, we describe the mathematical structure of a MIMO HVAC model used throughout this paper. The state space equations governing the model are as follows:

$$\dot{x}_1 = u_1 \alpha_1 60(x_3 - x_1) - u_1 \alpha_2 60(W_s - x_2) + \alpha_3(Q_o - h_{fg} M_o)$$

$$\dot{x}_3 = u_1 \beta_1 60(-x_3 + x_1) + u_1 \beta_1 15(T_o - x_1) - u_1 \beta_3 60(0.25 W_o + 0.75 x_2 - W_s)$$

$$\dot{x}_2 = u_1 \alpha_1 60(W_s - x_2) + \alpha_4 M_o$$

$$y_1 = x_1$$

$$y_2 = x_2 \qquad (9)$$

In which the parameters are:

$u_1 = f, u_2 = gpm, x_1 = T_3, x_2 = W_3, x_3 = T_2$

$\alpha_1 = 1/V_s, \alpha_2 = h_{fg}/C_p V_s, \alpha_3 = 1/\rho C_p V_s,$

$\alpha_4 = 1/\rho V_s, \beta_1 = 1/V_{he},$

$\beta_2 = 1/\rho C_p V_{he}, \beta_3 = h_w/C_p V_{he}$ (10)

And the numerical values are given in table 1.

Also, the actuator's transfer function can be considered as:

$$G_{act}(S) = k/(1 + \tau S) \qquad (11)$$

In which k and τ are the actuator's gain and time constant. The schematic structure of the HVAC system is given in figure 1. The system has delayed behavior which is represented via linearized, first order and time delay system. Furthermore, the model represents a MIMO system in which one of the I/O channels has a right half plane zero, meaning that it is non-minimum-phase.

Table1: Numerical Values for system parameters

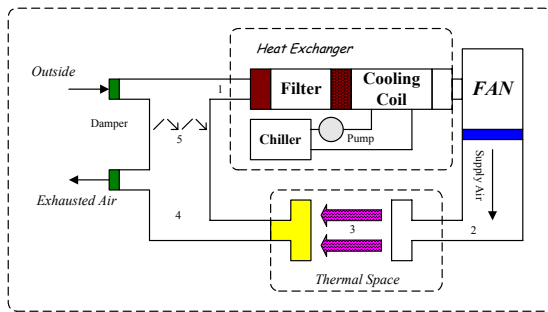|	
$\rho = .074 \ lb / ft^3$	$C_p = .24 \ Btu / lb.°F$
$V_s = 58464 \ ft^3$	$T_o = 85°F$
$M_o = 166.06 \ lb / hr$	$V_{he} = 60.75 \ ft^3$
$W_s = .007 \ lb / lb$	$W_o = .0018 \ lb / lb$
$Q_o = 289897$	$\tau = .008 \ hr, k = 5$

Figure1. Model of the HVAC system

4   Simulation Results

In this section, we describe the circuits we have used for controlling the HVAC plant. The actual plant model involves four input and three output processes, of which two inputs can be manipulated for achieving desired performance levels. Our initial attempt to consider an SISO problem in which temperature set point tracking was the main goal proved futile, because the rest of the system could not be regarded as disturbances and unmodeled dynamics. The response speed caused the other outputs increase beyond acceptable levels. Next, we tried to achieve the design goals via two separate fuzzy PID controllers (Figure 2). We wished to track temperature and humidity to their respecting set point levels of 73°F and 0.009, while maintaining the supply air temperature within the range of 40°F to 100°F. This proved very satisfactory (Figure 3 and 4). The performance levels achieved via the two alternative approaches are outlined in table 2.
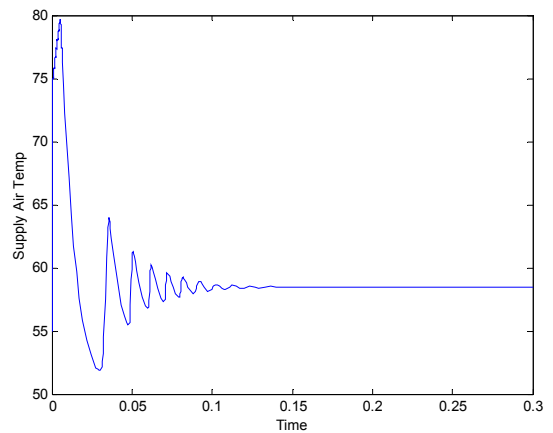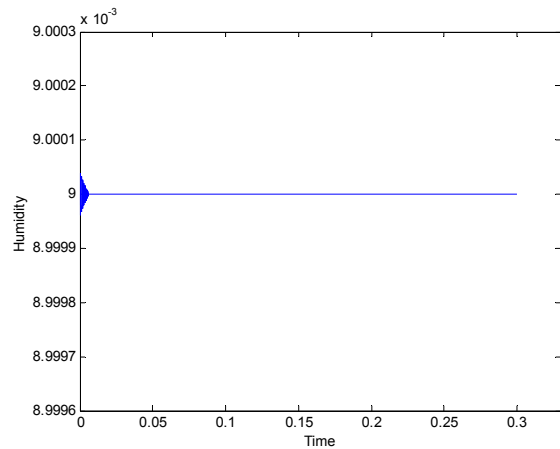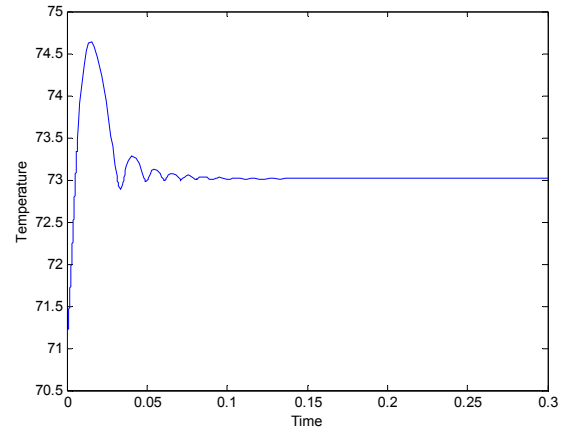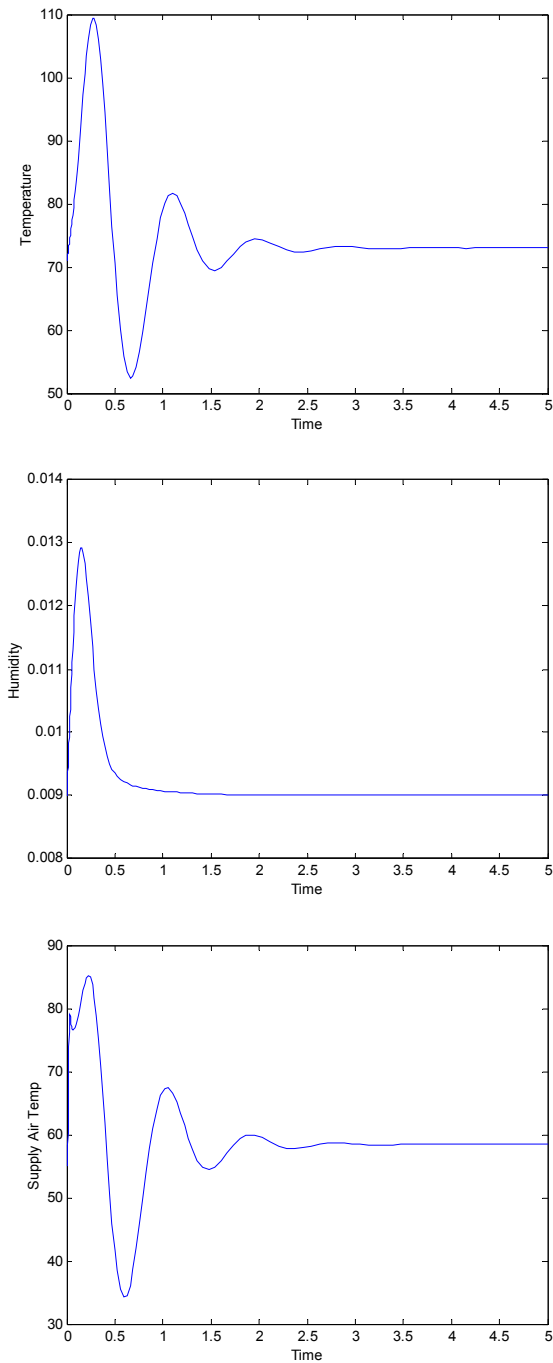

Figure 3. HVAC system responses with Fuzzy PID controller

Figure 4. HVAC system responses with PID controller

Table 2- Performance characteristics of HVAC system with two Fuzzy PID and PID controllers

	S-SError (Temp-Humi)	RiseTime (Temp-Humi)	POS (Temp-Humi)
Fuzzy PID	0.01%- 0.00%	0.001-0.0002	02.28- 0.00
PID	0.00%- 0.00%	0.009-0.002	49.96-43.33

We examined the robustness of these controllers with respect to external disturbances. To do that, we fed the plant with time-variable heat and moisture disturbance signals in the form given in figure 5.
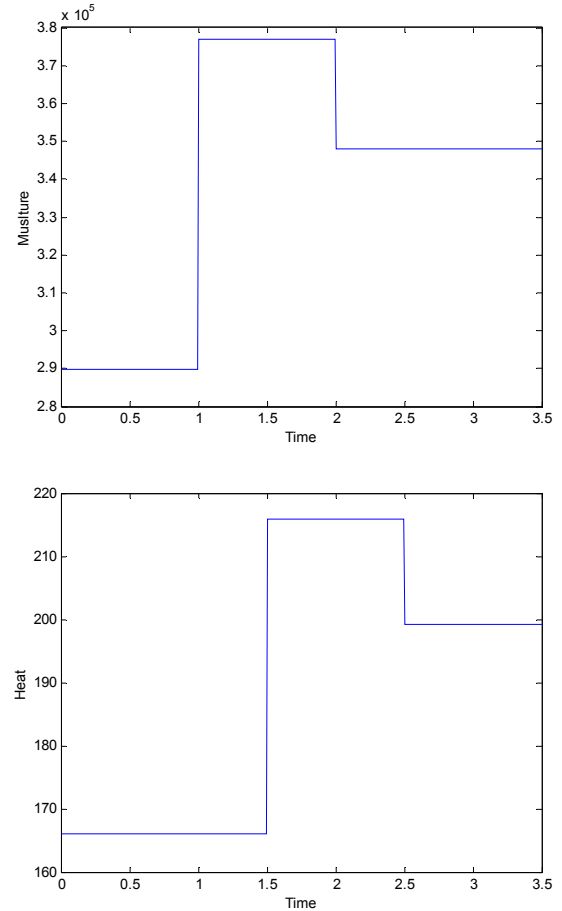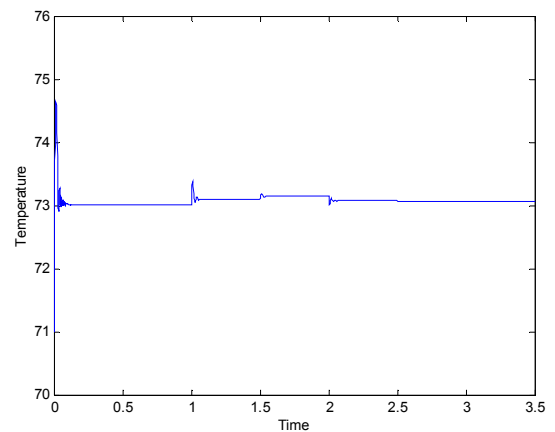

Figure 5. The heat and moisture disturbance signals for robustness consideration
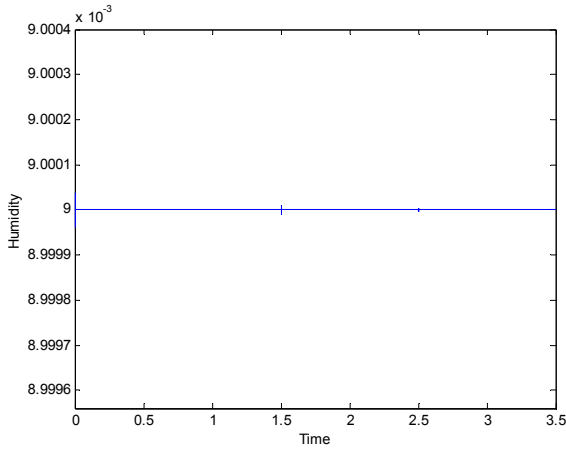
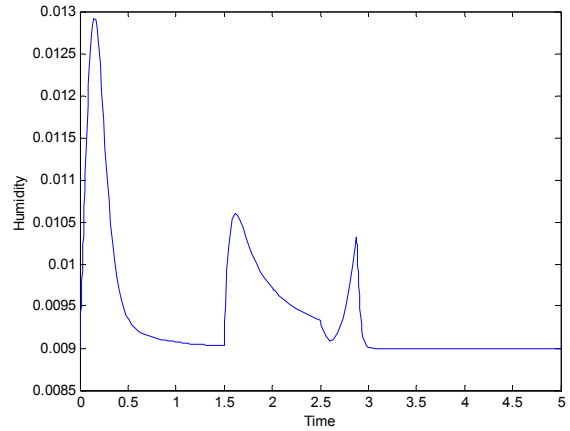Figure 6. HVAC system responses of the Fuzzy PID controller with the presence of disturbance variations
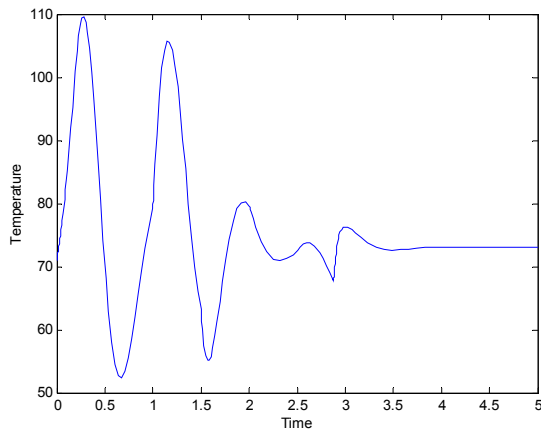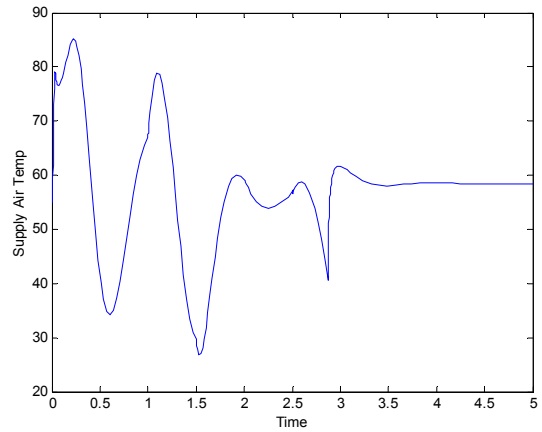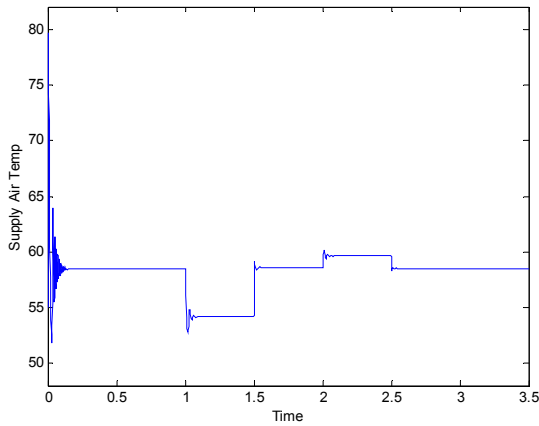

Figure 7. HVAC system responses of the PID controller with the presence of disturbance variations

5 Conclusion

In this paper, we showed the applicability of fuzzy PID controller to the fulfillment of complex tasks of adaptive set point tracking and disturbance rejection of a HVAC system. The control of the non-minimum phase, multivariable, nonlinear and nonlinearizable plant with constraints on its supply air temperature is indeed a demanding task from control theoretic viewpoint. The controller presented in this paper possessed excellent tracking speed and robustness properties. The comparison with a PID controller is only meant to signify the extent of the goal overfulfillment and should by no means imply that no other intelligent and adaptive controller can perform as well.

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