Design of a Fuzzy Based Digital PID Controller for Control of Nonlinear HVAC Systems

VAHID JOHARI MAJD, FARHAD BESHARATI and FARZAN RASHIDI

Faculty of Engineering, Tarbiat Modarres University
Tehran – Iran

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 discrete 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 discrete PID (DPID) controller. The simulation results show that our method has the better control performance than DPID controller.

Keywords: HVAC System, Fuzzy Logic, discrete PID Controller, Fuzzy discrete PID, Robust, multivariable, nonlinear.

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 discrete 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 discrete PD type, PI type or PID type with nonlinear gains. Because of the nonlinearity of the control gains, fuzzy discrete PID controllers possess the potential to achieve better system performance over conventional discrete 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 discrete 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 discrete PID controllers, and find out appropriate design methods which will assist control engineers to confidently utilize the nonlinearity of fuzzy discrete PID controllers so as to improve the closed-loop performance.

This paper presents a new approach to control of HVAC system. The proposed method is a hybrid of fuzzy logic and discrete PID controller. Simulation results show that this control strategy is very robust, flexible and alternative performance.

2 Fuzzy Based Discrete PID Controller

In this section, we describe the design of the FPIC: its mathematical derivation and technical contents. We have used a fuzzy PI control unit arrangement, called the derivative-of-output, which is often desirable if the reference input contains discontinuity [6]. For this arrangement, the derivation of the fuzzy control law is performed in the output of the fuzzy PID controller. It should be mentioned that the fuzzy PID controller that we designed is a digital controller. We first start with a continuous conventional PID controller and then use the standard bilinear transform to convert it to the corresponding digital controller. We first describe the design principle and basic structure of the fuzzy PID controller. The output of the conventional analog PID controller in the frequency s-domain, is given by

$$u_{PID} = k_p e(t) + k_i \int e(t)dt + k_d \frac{de(t)}{dt}$$

and its frequency domain form is

$$U_{PID}(s) = \left(k_p + \frac{k_i}{s} + k_d s \right) E(s) \qquad (1)$$

where k_p, k_i and k_d are the proportional, integral and derivative gains respectively, and E (s) is the tracking error signal. This equation can be transformed into the discrete version for computer aided control systems by applying the bilinear transformation $s = \frac{2}{T}\left(\frac{1-z^{-1}}{1+z^{-1}}\right)$, where T>0 is the sampling time, which result in the following form:

$$U_{PID}(z) = \left(k_p - \frac{k_i T}{2} - \frac{2k_d}{T} + \frac{k_i T}{1-z^{-1}} + \frac{k_d}{T}\frac{1}{1+z^{-1}} \right) E(z)$$

Letting

$$K_p = k_p - \frac{k_i T}{2} - \frac{2k_d}{T},\ K_i = k_i T,\ K_d = \frac{k_d}{T}$$

The fuzzy controller can be viewed as a natural extension of the conventional discrete PID control algorithm with a fuzzy implementation [2]. The structure of the fuzzy discrete PID (FDPID) 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.:

$e(k)=r(k)-(k)$ (2)

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

$de(k)=e(k)-e(k-1)$ (3)

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

$\delta e(k)=\sum e(i)$ (4)

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

$u(k)=K_p e(k)+K_i \delta e(k)+K_d de(k)$ (5)

where u(k) is the output control signal.

The Sugeno's fuzzy rules into the FPID can be composed in the generalized 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 *kp* , *ki* and *kd* 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 *fu* in the equation (6) could be found. The fuzzy implication can be performed by means of the product composition [12]:

$\mu_u^{(n)} = \mu_e^{(n)} * \mu_{de}^{(n)} * \mu_{\delta e}^{(n)}$ (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* quantization 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 quantization levels [15]:

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

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 [5]. 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 [6]. 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 [14,4], DDC methods [5,6], optimal [10,9,7], nonlinear [11] and robust [3,1] control strategies, and neural and/or fuzzy [13,16,17] approaches are to be mentioned. We have also dealt with this problem and provided novel solutions in [15]. The purpose of this paper is to suggest another control approach, based on fuzzy DPID 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 that we have used. For simulation of HVAC systems, some different models have been proposed and considered. In [17] 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 [16]. In this paper, we used the model developed in [14], 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 [12]. 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:

$$\begin{aligned}
&\dot{x}_1 = u_1\alpha_1 60(x_3 - x_1) - u_1\alpha_2 60(W_s - x_2) + \\
&\alpha_3(Q_o - h_{fg}M_o) \\
&\dot{x}_3 = u_1\beta_1 60(-x_3 + x_1) + u_1\beta_1 15(T_o - x_1) \\
&-u_1\beta_3 60(0.25W_o + 0.75x_2 - W_s) \\
&\dot{x}_2 = u_1\alpha_1 60(W_s - x_2) + \alpha_4 M_o \\
&\\
&y_1 = x_1 \\
&\\
&y_2 = x_2
\end{aligned} \tag{9}$$

In which the parameters are:

$$\begin{aligned}
&u_1 = f, u_2 = gpm, x_1 = T_3, x_2 = W_3, x_3 = T_2 \\
&\alpha_1 = 1/V_s, \alpha_2 = h_{fg}/C_pV_s, \alpha_3 = 1/\rho C_pV_s, \\
&\alpha_4 = 1/\rho V_s, \beta_1 = 1/V_{he}, \\
&\beta_2 = 1/\rho C_pV_{he}, \beta_3 = h_w/C_pV_{he}
\end{aligned} \tag{10}$$

And the numerical values are given in table 1. Also, the actuator's transfer function can be considered as:

$$G_{act}(z) = \frac{2}{k}\left(\frac{1 - z^{-1}}{1 + z^{-1}}\right) \tag{11}$$

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

$\rho = .074\ lb/ft^3$	$C_p = .24\ Btu/lb.°F$
$V_S = 58464\ ft^3$	$T_o = 85°F$
$M_O = 166.06\ lb/hr$	$V_{he} = 60.75\ ft^3$
$W_S = .007\ lb/lb$	$W_O = .0018\ lb/lb$

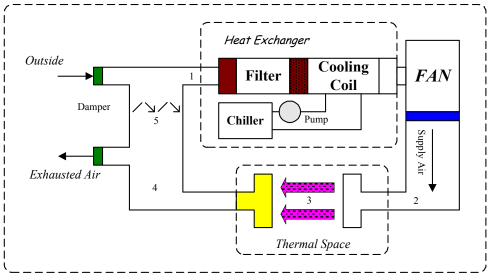

Figure1. Model of the HVAC system

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.

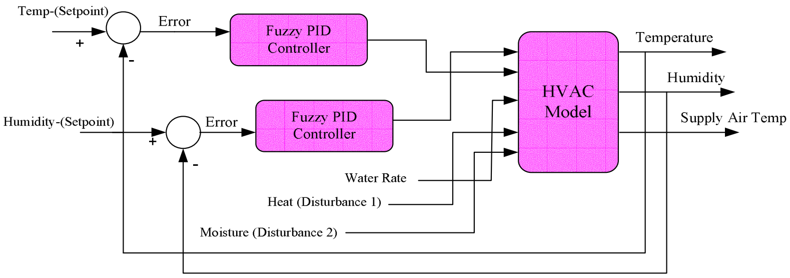

Figure 2: Control circuit with two controllers

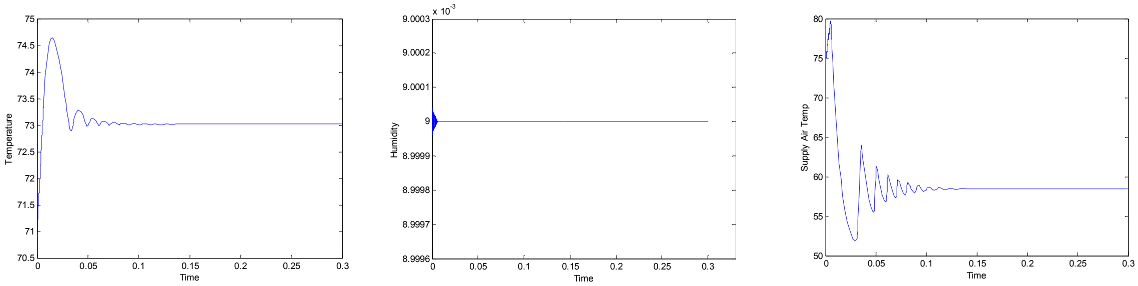

Figure 3. HVAC system responses with Fuzzy DPID controller

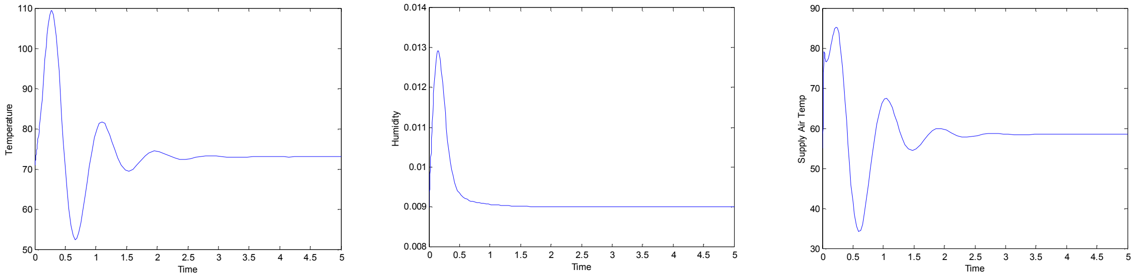

Figure 4. HVAC system responses with DPID controller

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

	S-SError (Temp-Humi)	RiseTime (Temp-Humi)	POS (Temp-Humi)
Fuzzy DPID	0.01%-0.00%	0.001-0.0002	02.28- 0.00
DPID	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. As observed in the figure 5, there is some deterioration from the nominal amounts of the two external disturbances. The responses of the two Fuzzy PID controllers and of the two PID controllers are given in the figures 6 and 7. As shown figure 6 and 7, the fuzzy PID controller shows the better control performance than PID controller in terms of settling time, overshot and rise time. The outputs of the system, with the presence of disturbance variations, show that the fuzzy PID controller can track the inputs suitably. But the performance of PID controller is too slow.

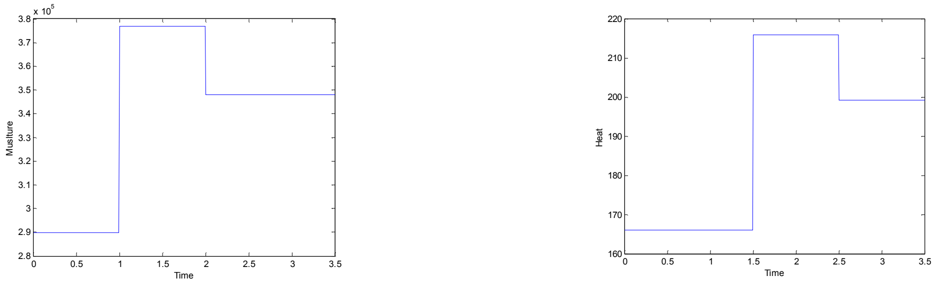

Figure 5. The heat and moisture disturbance signals for robustness consideration

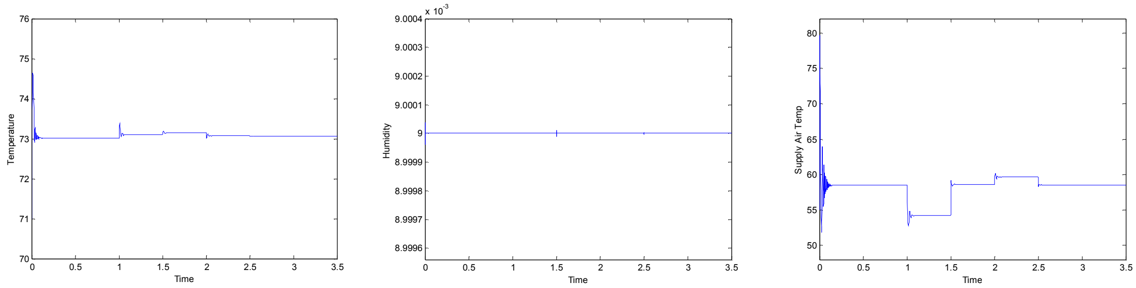

Figure 6. HVAC system responses of the Fuzzy DPID controller with the presence of disturbance variations.

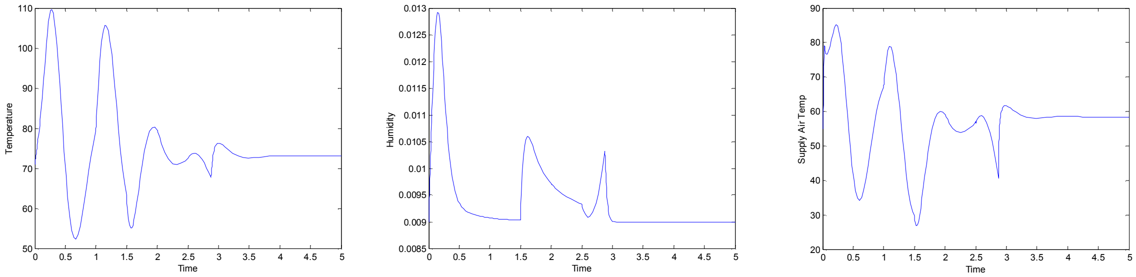

Figure 7. HVAC system responses of the DPID controller with the presence of disturbance variations.

5 Conclusion

In this paper, we showed the applicability of fuzzy DPID 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 DPID 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 suitably.

References

[1] Alber, T. P., Chan, W. L., Chow, T. T., “A Neural Network-Based Identifier/Controller for Modern HVAC Control” ASHRAE Transaction, Volume 100, 1994

[2] G. Chen, “Conventional and fuzzy PID controllers: An overview”, Int. J. Intell. Control Syst., vol. 1, pp. 235–246, 1996.

[3] Curtiss, P. S., Kreider, J. F., Branenuehl, M. J., “Local and Global Control of Commercial Building HVAC Systems Using Artificial Neural Networks”, ACC, 1994

[4] Fargus, R. S., Chapman, C., “Implementation of Commercial PI-Neural Controller for Building Services” IEE, Savoy Place, 1999

[5] Geng, G., Geary, G. M., “On Performance and Tuning of PID Controllers in HVAC Systems” Conference on Control Application, 1993

[6] Hartman, T. B., “Direct Digital Controls for HVAC Systems” MC Graw-Hill, 1993

[7] Hepworth, S. J., Dexter, A. L., “Neural Control of Nonlinear HVAC Plant” Conference on Control Application, 1994

[8] Jian, W., Wenjian, C., “Development of an Adaptive Neuro-Fuzzy Method for Supply Air Pressure Control in HVAC System” IEEE, 2000

[9] Miller, R. C., Seem, J. E., “Comparison of Artificial Neural Network with Traditional Methods of Predicting Return Time from Night or Weekend Setback” ASHRAE Transaction, Volume 97, 1991

[10] Newman, H. M., “Direct Digital Controls for Building Systems” John Wiley, 1994

[11] Osman, A., Mitchell, J. W., Klein, S. A., “Application of General Regression Neural Network in HVAC Process Identification and Control” ASHRAE Transaction, Volume 102,

[12] Petrov, M., I.Ganchev and I.Dragotinov. “Design Aspects Of Fuzzy PID Controllers”, 5th International Conference on Soft Computing Mendel’99, June 9-12 1999, Brno, Czech Republic, pp.277-283.

[13] Rashidi. F., Lucas. C., “Applying CBRL (Context Based Reinforcement Learning) to Multivariable Control of a HVAC System”, Trans. Of WSEAS, 2003

[14] Serrano, B. A., Velez-Reyes, M., 1999, “Nonlinear Control of A Heating, Ventilation and Air Conditioning Systems with Thermal Load Estimation” IEEE Transaction on Control Systems Technology, Volume 7, (1)

[15] T. Takagi and M. Sugeno, “Fuzzy identification of systems and its applications to modeling and control,” IEEE Trans. Syst., Man, Cybernetic., vol. 15, pp. 116–132, 1985.

[16] Tigrek, T., Dasgupta, S., Smith, T. F., “Nonlinear Optimal Control of HVAC Systems” Proceedings of IFAC, 2002