Improving Heat Transfer Efficiency in Heating Ventilation and Air Conditioning Systems Using a Robust Fuzzy PID Controller

FARZAN RASHIDI

Faculty of Engineering, Islamic Azad University of Bushehr
BUSHEHR, IRAN

Abstract- High levels of measurement noise, nonlinear and non minimum phase, and conflicting performance requirements pose challenging problems for improving heat transfer efficiency and flow control in HVAC systems. This paper extends the theoretical development of the Energy Delivery Efficiency (EDE) concept to include supply air latent effects and economizer operation, defines how ideal HVAC systems should be operated and controlled so that energy use is minimized while meeting required outdoor ventilation flow, and evaluates the extent to which heating and cooling energy use of such ideal HVAC systems. A new controller, based on fuzzy PID controller is presented, to be used to control heating systems in intermittently occupied buildings. Comparisons with classical control methods demonstrate that the proposed fuzzy PID controller gave superior results in terms of the control and optimization of the recovery time after setback. For each case, the differences in comfort and energy consumption between the different types of room were studied.

Keywords: HVAC System, Fuzzy Logic, PID Controller, Heat Transfer, Robust 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 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.

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 controller. Some conclusion and remark are discussed in section 5.

2 Fuzzy PID Controller

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

$$e(k)=r(k)-y(k) \qquad (1)$$

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

$$de(k)=e(k)-e(k-1) \qquad (2)$$

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 generalized form of 'if-then' statements to describe the control policy and can be represented as [20]:

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

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

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]:

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

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 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]:

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

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 [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 [13,21,22,16,17] approaches are to be mentioned. We have also dealt with this problem and provided novel solutions in [18,8,19]. 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 that we have used. For simulation of HVAC systems, some different models have been proposed and considered.

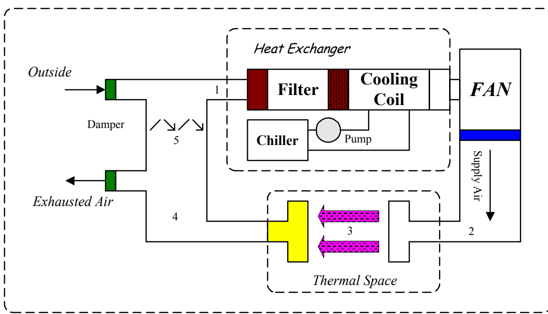

Figure1. Model of the HVAC system

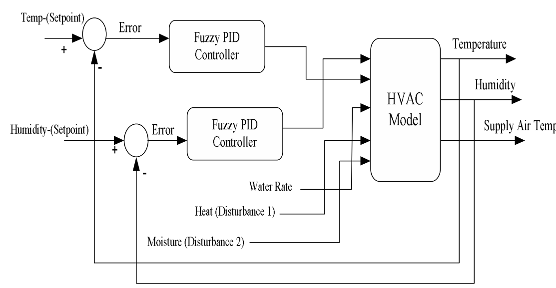

Figure 2: Control circuit with two controllers

In [17,18] 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 [22]. 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:

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

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

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

$$y_1 = x_1$$

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

In which the parameters are:

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

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.

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.

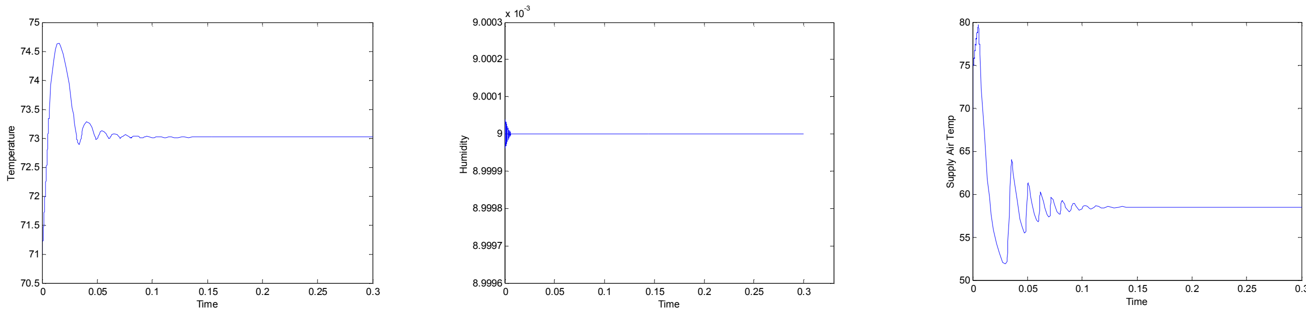

Figure 3. HVAC system responses with Fuzzy PID controller

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.

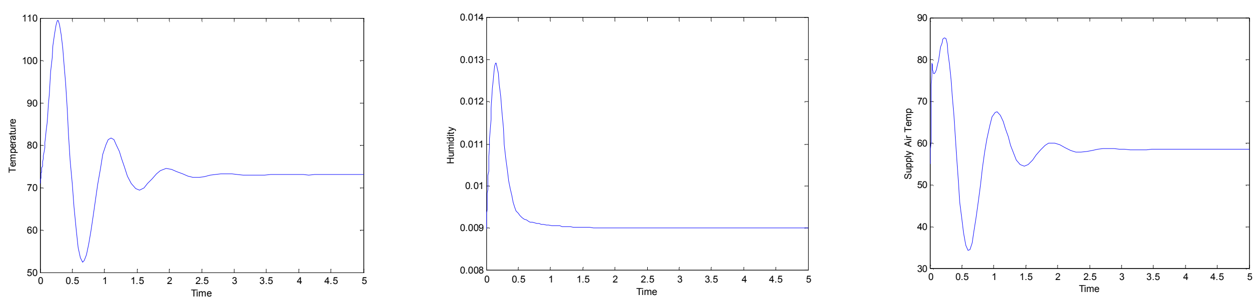

Figure 4. HVAC system responses with PID controller

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. 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.

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%-0.0	0.001-0.000	02.28- 0.00
PID	0.0%-0.0%	0.009-0.002	49.96-43.33

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.

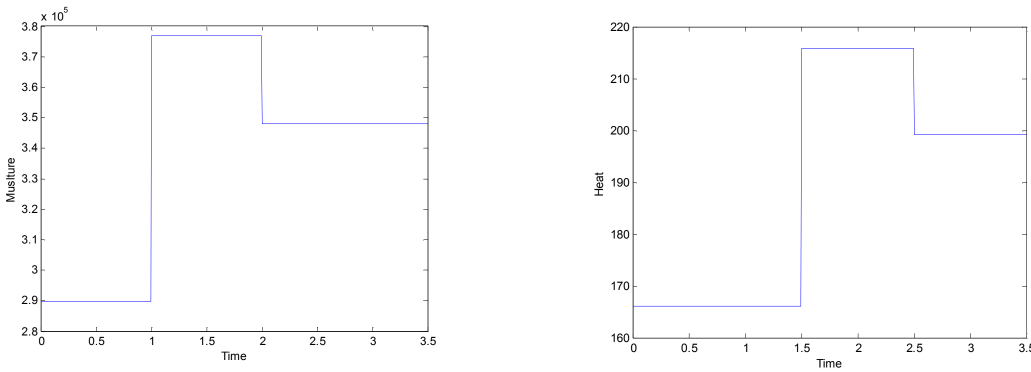

Figure 5. The heat and moisture disturbance signals for robustness consideration

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 suitably.

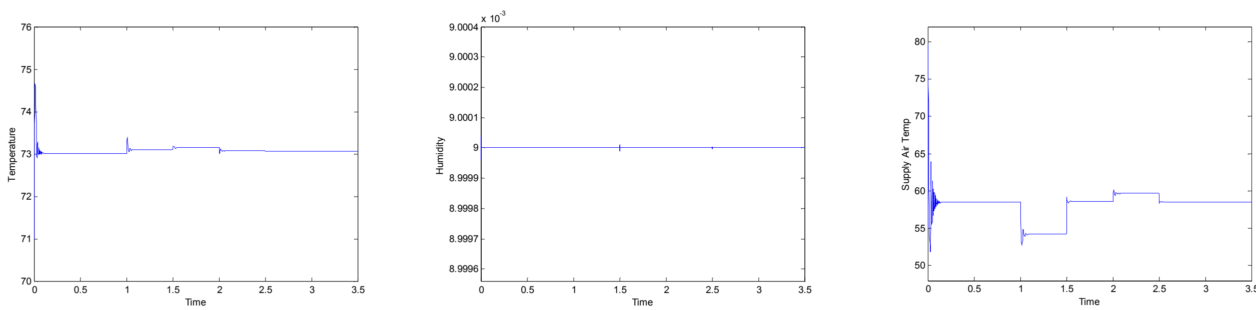

Figure 6. HVAC system responses of the Fuzzy PID controller with the presence of disturbance variations.

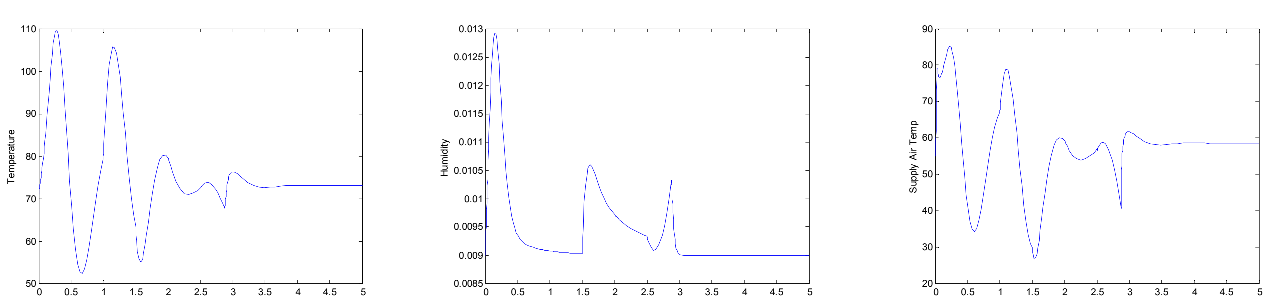

Figure 7. HVAC system responses of the PID controller with the presence of disturbance variations.

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, 1996

[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

[17] Underwood, C. P., “Robust Control of HVAC Plant I: Modeling” Proceeding of CIBSE, Vol. 21, No. 1, 2000

[18] Underwood, C. P., “Robust Control of HVAC Plant II: Controller Design” Proceeding of CIBSE, Vol. 21, No. 1, 2000

[19] Underwood, C. P., “HVAC Control Systems: Modeling, Analysis and Design” E & FN SPON Publication, 1999

[20] Xu. F. L., S.-Z. He, S. Tan, and P.-Z. Wang, “Fuzzy self-tuning of PID controllers,” Fuzzy Sets Syst., vol. 56, pp. 37–46, 1993.

[21] Zaheeruddin, M., “Optimal Control of A Single Zone Environment Space” Building and Environment, 1992

[22] Zaheeruddin, M., “The Design and Simulation of A Sub-Optimal Controller for Space Heating” ASHRAE Transaction, Volume 99, 1993