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A Fuzzy Logic Based Supervisory Hierarchical Control Scheme for Real Time Pressure Control

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Abstract: This paper describes a supervisory hierarchical fuzzy controller (SHFC) for regulating pressure in a real-time pilot pressure control system. The input scaling factor tuning of a direct expert controller is made using the error and process input parameters in a closed loop system in order to obtain better controller performance for set-point change and load disturbances. This on-line tuning method reduces operator involvement and enhances the controller performance to a wide operating range. The hierarchical control scheme consists of an intelligent upper level supervisory fuzzy controller and a lower level direct fuzzy controller. The upper level controller provides a mechanism to the main goal of the system and the lower level controller delivers the solutions to a particular situation. The control algorithm for the proposed scheme has been developed and tested using an ARM7 microcontroller-based embedded target board for a nonlinear pressure process having dead time. To demonstrate the effectiveness, the results of the proposed hierarchical controller, fuzzy controller and conventional proportional-integral (PI) controller are analyzed. The results prove that the SHFC performance is better in terms of stability and robustness than the conventional control methods.

Keywords: Pressure control, supervisory hierarchical fuzzy controller (SHFC), fuzzy controller, ARM7 processor, embedded controller

1 Introduction

Modern industrial processes require automatic control to have high performance and the controller design and implementation to be simple for wide operating range. Most of the industrial processes are controlled using the conventional proportional-integral (PI) or proportional-integral-derivative (PID) controller because they have a simple structure, acceptable performance for the linear system, and their tuning is well known to most of the industrial operators. However, these controllers perform well only at a particular operating range and they need to be retuned if the operating range is changed. The performance of the conventional controllers is not satisfactory for nonlinear and dead time processes[1−4]. Moreover, if a process becomes too complex to be described by analytical models, it is unlikely to be efficiently controlled by the conventional approaches[5]. On the other hand, the fuzzy logic controller (FLC) has found good applications in complex, ill-defined and nonlinear cases. Unlike the conventional controllers, FLC is robust and its performances are less sensitive to parametric variations[6,7]. Fuzzy logic is used to build controllers even when no mathematical model of the system is available. Thus, it is considered as an effective tool for dealing with uncertainties. However, the performance of the conventional FLC is not up to the expected level for all types of industrial control applications because of the following reasons. First, the design of conventional fuzzy controllers is performed in an ad hoc manner, so at least some of the controller parameters are often difficult to choose. Second, a fuzzy controller constructed for the nominal plant may later perform inadequately if significant and unpredictable plant parameter variations occur, or if there arise noises or some type of disturbances or some other environmental effects. Therefore, the knowledge-based FLC is preferred wherever there are complex and nonlinear processes with different structures[8−12].

Generally, the knowledge-based control technique is applied in two different ways of control[13]. The first is called direct expert control, where the knowledge-based system influences the process directly with a manipulating signal. The second is called supervisory expert control, where the knowledge-based system is placed on top of the controller to form a hierarchical control system that supervises the system behavior globally. Combining both methods would give rise to a supervisory hierarchical expert controller. The control algorithm and its implementation cost are the key factors in industrial control. In this context, the use of embedded microcontrollers seems to be a better choice, since it has high processing speed, small power consumption, low cost and is suitable for industrial environments. Furthermore, it is easy to develop the application software and implement microcontrollers. Successful applications of microcontroller based real-time control have been reported recently[14−16]. Besides, the latest embedded microcontroller can be used for remote monitoring and control through a network-based control structure[17].

Pressure control is one of the primary tasks in such areas like steam generation in industrial power plants, reaction control in the chemical industry, heating, ventilating and air conditioning (HVAC) systems, oil well drilling, automobile emission control, etc. In general, the pressure processes are dynamic and their control through the conventional methods are not up to the expected level[18−20]. This paper addresses the design and implementation of a supervisory hierarchical fuzzy controller (SHFC) structure with a simple knowledge-based fuzzy controller as the supervisor for tuning input scaling factor of a direct fuzzy controller.

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The performance of the proposed control structure has been tested by regulating the pressure in a nonlinear pilot pressure control system using an ARM7 (AT91M55800A) based target embedded microcontroller board. The results are compared with conventional control schemes. The experimental results show that the SHFC performance is better in terms of stability and robustness than the conventional PI and fuzzy control methods.

The remainder of this paper is organized as follows. Section 2 describes the experimental setup of the pressure control system. Section 3 presents the controller design and describes the fuzzy rules, membership functions, and defuzzification method. The real-time implementation of the proposed control algorithm is presented in Section 4. Experimental results and discussion are presented in Section 5. Some conclusions are drawn in Section 6.

2 Experimental setup of the pressure control system

The schematic diagram of the pilot pressure control plant is shown in Fig. 1, where PT denotes pressure transmitter, PI denotes pressure indicator, "V to I" denotes voltage to current converter, "I to V" denotes current to voltage converter, and "I to P" denotes current to pressure converter. It consists of a miniature pressure tank whose inlet is connected with an air compressor through a 50 mm size control valve. At the bottom of the tank, an outlet is provided with a manually operating gate valve to allow the air flow at a constant rate. An accurate pressure transmitter connected with the pressure tank is used to measure tank pressure and provide an output current in the range of 4 to 20 mA. In this closed loop pressure regulating system, the inlet air flow rate is manipulated by changing the control valve position in such a way as to attain the desired pressure.

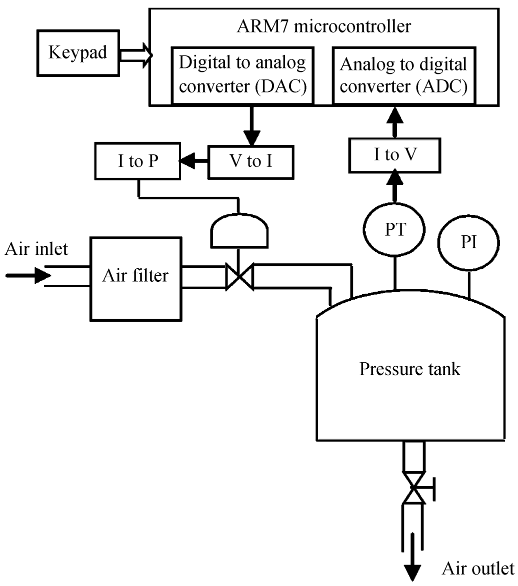

Fig. 1 Schematic diagram of the pressure control plant

An increasing sensitive type nonlinear electro-pneumatic control valve (see Fig. 2) is used for inlet flow manipulation. The pressure control system also has a dead time of 1.4 s which is calculated from the open-loop experiment.

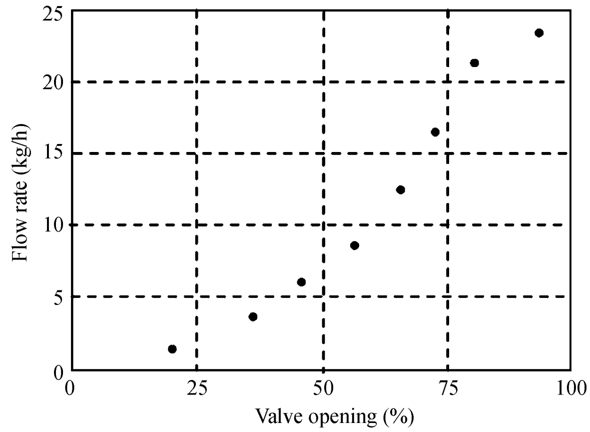

Fig. 2 Control valve characteristics

3 Controller design

The prime objective of the proposed controller design is to improve the controller performance in terms of stability and robustness. The industrial pressure plants are usually connected with several parallel operating plants, such as in an industrial steam generating boiler connected with steam network of a high pressure (HP) header, intermediate pressure (IP) level, and low pressure (LP) level. To provide a smooth and trouble-free supply of those steam consuming processes, the steam pressure should be stabilized as close to the set level. In addition, the industrial pressure plants may be exposed to frequent load changes caused by the trips and the start-ups of the steam consuming processes. To overcome such load disturbances and to stabilize the output for the input variations, the controller has to be designed with an on-line tuning method. Hence, the supervisory system based on-line tuning method to improve the stability and robustness of the controller is emphasized in the design. Lin and Huang[21], and Paramasivam and Arumugam[22] proposed some different methods for designing the fuzzy supervisory controller. Visioli[23], Abd El-Geliel and El-Khazendar[24] used the fuzzy supervisory controller for scaling factor modification. In most of the reported works, the error and change in error have been used as decision-making parameters of the supervisory system. The controller performance using these parameters is not always good enough for load disturbances[25]. To overcome such disadvantages, the error (e) and process input (u) have been chosen as the decision-making input parameters of the supervisory system. Using these two inputs, the supervisory system is able to recognize the process variations easily, and subsequent modifications are made in the primary controller loop. The structure of the proposed SHFC is shown in Fig. 3. The control structure consists of a simple upper-level rule-base (supervisory) controller and a lower level rule-base (direct) fuzzy controller. A standard Mamdani type FLC has been applied in both upper and lower level of this hierarchical control structure. The supervisory fuzzy system determines the scaling factor for the direct fuzzy controller at each sampling time by evaluating the inputs $e(k)$ and $u(k)$.

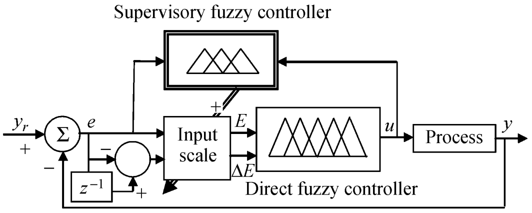

Fig. 3 Structure of the supervisory hierarchical fuzzy control scheme

3.1 The direct fuzzy controller

Based on the earlier research results of this process[26] and underlying domain knowledge about pressure tank systems, we design the direct fuzzy controller. The universe of discourse of each input and output are divided into adjacent intervals with overlap. The membership functions are introduced to characterize each interval, and using fuzzy logic, a continuous input and output mapping is made. The universe of discourse of inputs and output are determined based on the operating range of the process. During the experimentation, these values are finely tuned to obtain a better controller performance. In the case of direct fuzzy controller, five membership functions in triangular shape with 50% of overlap have been chosen for the inputs E, ΔE, and output (u). The linguistic descriptions of input membership functions are NB (negative big), NS (negative small), ZE (zero), PS (positive small) and PB (positive big). The output membership functions are VS (very small), SM (small), MD (medium), HI (high), and VH (very high). The fuzzy membership functions for inputs and output are shown in Figs. 4 and 5. The intersection minimum operation has been selected for the fuzzy implication. For the two-input fuzzy system, it is generally expressed as

$$\mu_{A_i(x_1)\cap A_i(x_2)} = \min\{\mu A_i(x_1), \mu A_i(x_2)\} \qquad (1)$$

where $A_i(x_1)$ and $A_i(x_2)$ are input fuzzy sets. The rule-base of the direct fuzzy controller relates the premise (E and ΔE) to consequent (u). The values of E and ΔE at each sampling time are determined by

$$E(k) = e(k)K_e(k) \qquad (2)$$
$$\Delta E(k) = \Delta e(k)K_d(k) \qquad (3)$$
$$\Delta e = e(k-1) - e(k)$$

where E and ΔE are the error and change in error inputs of the direct fuzzy controller with scaling factor taken into account, K_e and K_d are the scaling factors, Δe is the change in error, and k represents the sampling instant. The structure of the control rules of the direct fuzzy controller with two inputs and an output is expressed as

If E is PS and ΔE is NS, **then** u is MD. (4)

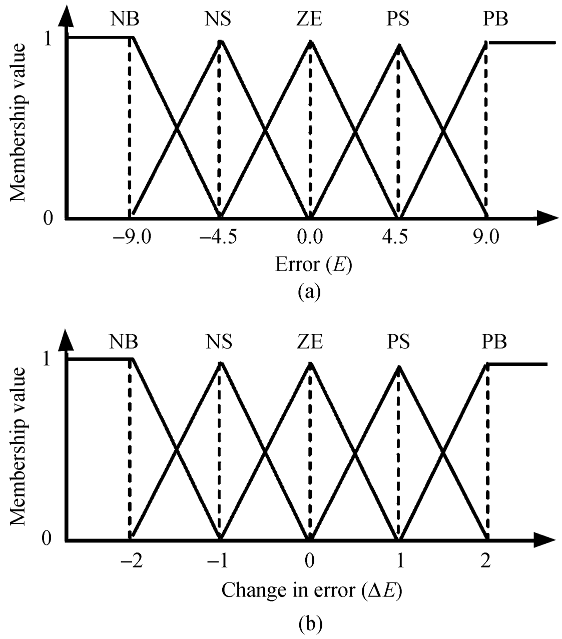

Fig. 4 Input membership functions of the direct fuzzy controller. (a) Error; (b) Change in error

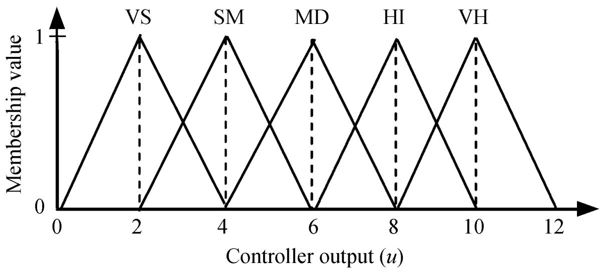

Fig. 5 Output membership functions of the direct fuzzy controller

Table 1 lists 25 linguistic fuzzy rules for the direct fuzzy controller. The center average defuzzification[27] has been made to find the crisp value of the output. The center average defuzzification is defined as

$$u^{\rm crisp} = \frac{\sum_{i=1}^{R} b_i\mu_i}{\sum_{i=1}^{R} \mu_i} \qquad (5)$$

where $u^{\rm crisp}$ is the output of the fuzzy controller, b_i denotes the centre of the membership function of the consequent of the i-th rule, μ_i denotes the membership value for the i-th rule′s premise, and R represents the total number of fuzzy rules.

Table 1 Linguistic fuzzy rules for the direct fuzzy controller

		ΔE				
	u	NB	NS	ZE	PS	PB
	NB	ZE	ZE	SM	MD	MD
	NS	ZE	SM	SM	MD	HI
E	ZE	SM	SM	MD	HI	VH
	PS	SM	MD	HI	HI	VH
	PB	MD	HI	HI	VH	VH

3.2 Supervisory fuzzy controller

The rule-base supervisory fuzzy controller is designed to tune the input scaling factor of the direct fuzzy controller in a closed-loop system. The on-line scaling factor modification is adapted in the proposed control scheme, thus enhancing the controller performance and significantly reducing the intervention of human operation in real-time industrial control applications. The universe of discourse of input and output of the supervisory fuzzy controller is selected based on the maximum allowable range of the process. Three triangle-shaped membership functions are used for both the inputs and outputs. The membership functions of input e is denoted by NE (negative), ZE (zero), and PE (positive), the input u and outputs K_e and K_d are denoted by LOW (low), MED (medium), and HIG (high). Figs. 6 and 7 show the input and output membership functions. The rule-base of the supervisory fuzzy controller has been designed in the light of the operative knowledge about the process. A typical fuzzy control rule of the proposed supervisory system is expressed as

$$\textbf{If } e \text{ is NE and } u \text{ is MED,}$$
$$\textbf{then } K_e \text{ is LOW and } K_d \text{ is HIG.} \tag{6}$$

The linguistic fuzzy rules of the supervisory fuzzy system are given in Table 2. Intersection minimum operation (1) has been used for the fuzzy implication, and center average defuzzification method (5) is used to compute the crisp value of the outputs.

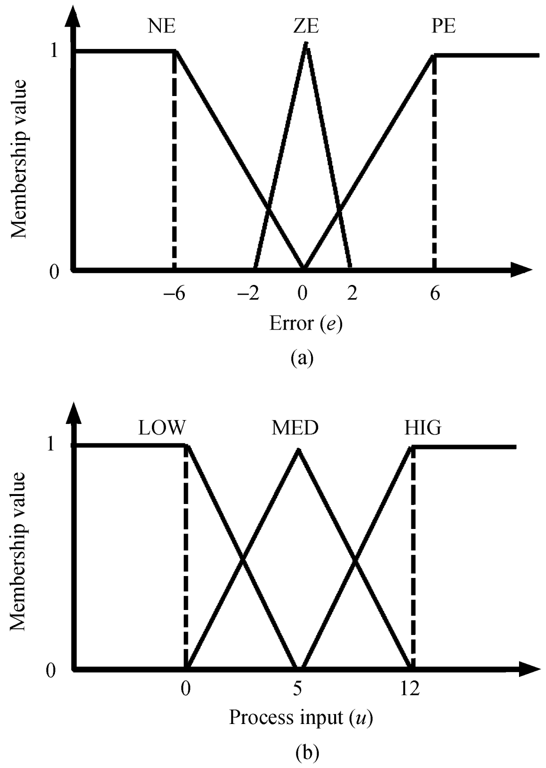

Fig. 6 Supervisory fuzzy controller input membership functions. (a) Error; (b) Process input

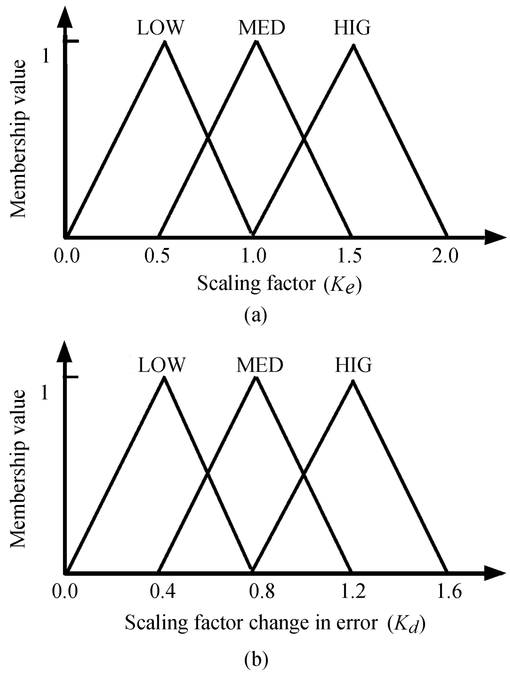

Fig. 7 Supervisory fuzzy controller output membership functions. (a) Scaling factor for error (K_e); (b) Scaling factor for change in error (K_d)

Table 2 Linguistic fuzzy rules for the supervisory fuzzy controller

Input		Output	
e	u	K_e	K_d
	LOW	LOW	HIG
NE	MED	LOW	HIG
	HIG	MED	MED
	LOW	LOW	HIG
ZE	MED	MED	MED
	HIG	HIG	LOW
	LOW	HIG	LOW
PE	MED	HIG	LOW
	HIG	HIG	LOW

4 Real-time implementations

The proposed SHFC scheme has been tested for a real-time pressure control application using an ARM7 based embedded microcontroller board. ARM7 is a 32 bit advanced reduced instruction set computing (RISC) architecture processor, having one mega byte (MB) on-board flash memory, network application capable processor (NACP) features, RS-232 trans-receiver and onboard analog-to-digital converter (ADC) and digital-to-analog converter (DAC) for real time interfacing[28]. The photograph of the ARM7 embedded microcontroller board and the experimental setup is shown in Figs. 8 and 9. The control algorithm code is initially developed with a host machine (PC) and then dumped into a target ARM7 (ATMEL AT91M55800A) microcontroller. Fig. 10 shows the flow chart for the supervi-

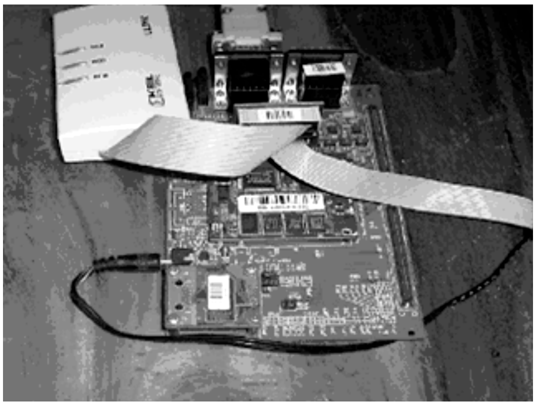

Fig. 8 ATMEL (AT91M55800A) embedded microcontroller target board

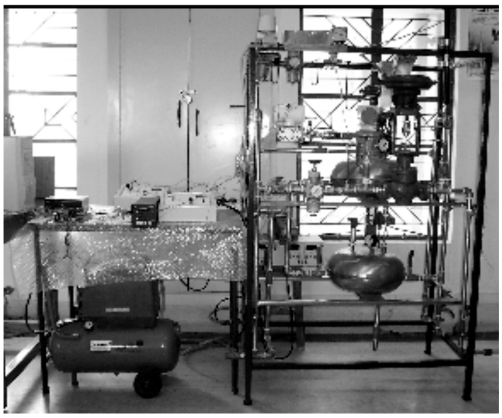

Fig. 9 Photograph of the experimental system

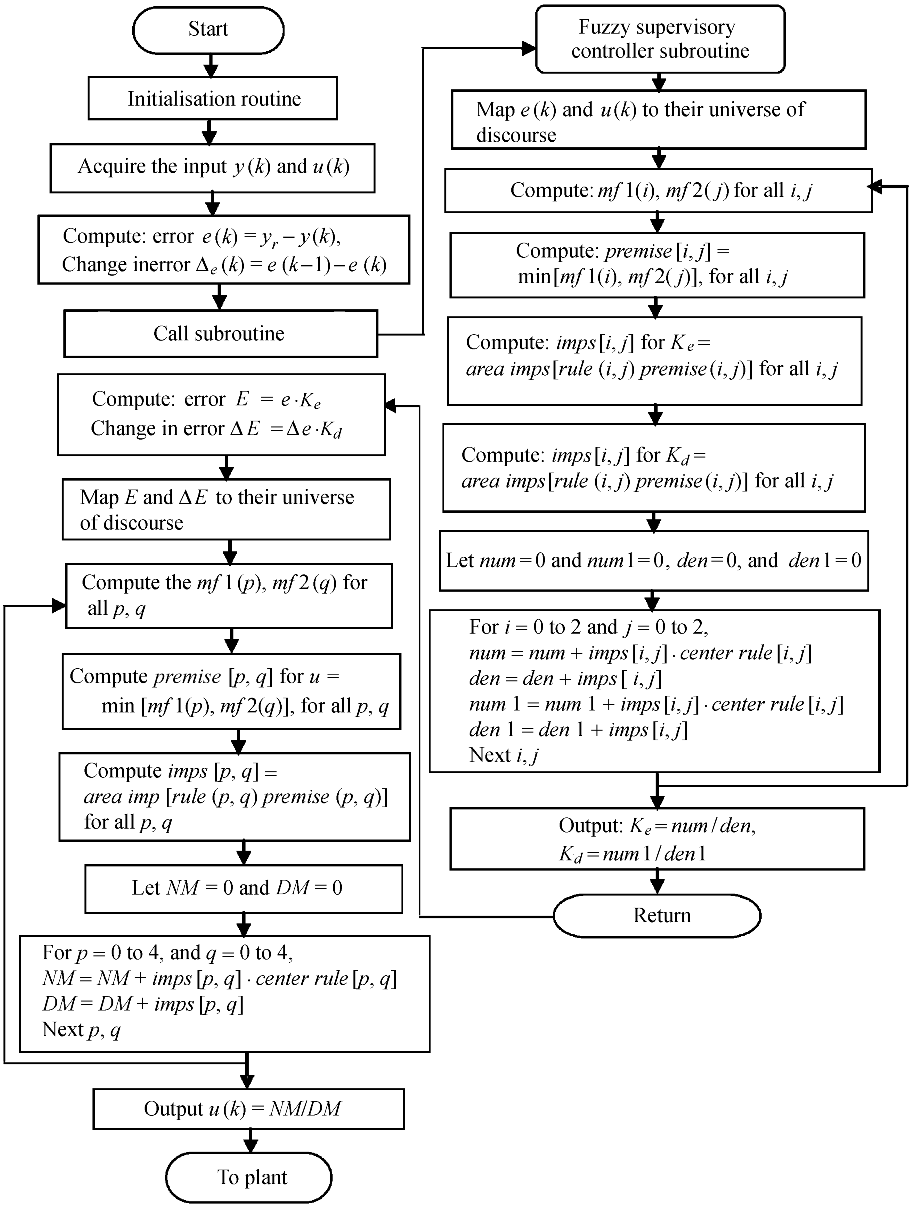

Fig. 10 Flow chart for the supervisory hierarchical fuzzy control

sory hierarchical fuzzy control algorithm, where $mf1$ denotes membership function 1, i.e., membership function associated with input 1, $mf2$ denotes membership function 2, i.e., membership function associated with input 2, *imps* denotes implications, *area imps* denotes membership value of implied fuzzy set, NM denotes numerator, DM denotes denominator, and center rule is center value of membership function, i.e., center of the output membership function.

The pressure processes are dynamic in nature and their stability and robustness depend on various system parameters in the real-time control. The sampling period is one of the key aspects and it has stronger impact on system stability and robustness. Then, sampling period is usually predetermined based on the size of the application program, the processor operating clock frequency, and nature of the process variable. Therefore, the sampling time has to be optimized to obtain better controller performance. In the present application, the sampling time has been fixed at 0.4 s, since the control algorithm has many inner loops. For the constant outlet flow-rate, the pressure control system has a single input, a valve position, a single output, and a tank pressure. During the experimentation, the air flow is maintained continuously at inlet with the help of a portable air compressor with pressure up to 8 bar. A precision pressure transmitter measures the tank pressure and provides the output signal in the range of 4–20 mA. By applying a current to voltage converter, the current signal is proportionally converted into 0–5 V. The built-in 10 bit ADC of the ARM7 microcontroller converts this analog voltage signal into the corresponding binary equivalent. The outlet valve is set at a fixed opening to allow a constant air flow rate from the pressure tank during the test.

5 Experimental results and discussion

Real-time experiments have been conducted in a pilot air tank system using different control algorithms and the results are compared to demonstrate the performance of the proposed SHFC. The controller parameters of the conventional PI controller were obtained with Cohen and Coon (CC) controller tuning method. The system output responses for different controllers with a set pressure level of 3 bar and 4 bar are shown in Figs. 11 and 12. The output responses clearly demonstrate that the supervisory hierarchical fuzzy control algorithm makes the system reach the set pressure faster than the conventional method without any overshoot or steady state error, while the conventional fuzzy control algorithm produces steady state error even after fine tuning was made. The system output responses using the conventional PI control algorithm show small overshoot before reaching the steady state. It is concluded that the SHFC performance is better in terms of settling time and steady state error than the conventional PI and fuzzy control methods for pressure control process.

The stability of the proposed control algorithm has been tested for set-point variation at steady state condition by changing the set pressure level. The system responses for the set-point changes from 3.5 to 4 bar and 3 to 2 bar of different control schemes are shown in Figs. 13 and 14. From the results, it is seen that the proposed SHFC instantly responds to the set-point change and makes the system settle within a short time. Thus, the results obviously demonstrate that the stability of the proposed controller is fit for set-point changes. The effectiveness of the proposed control algorithm is demonstrated by comparing the integral of the square of the error (ISE), integral of the absolute value of

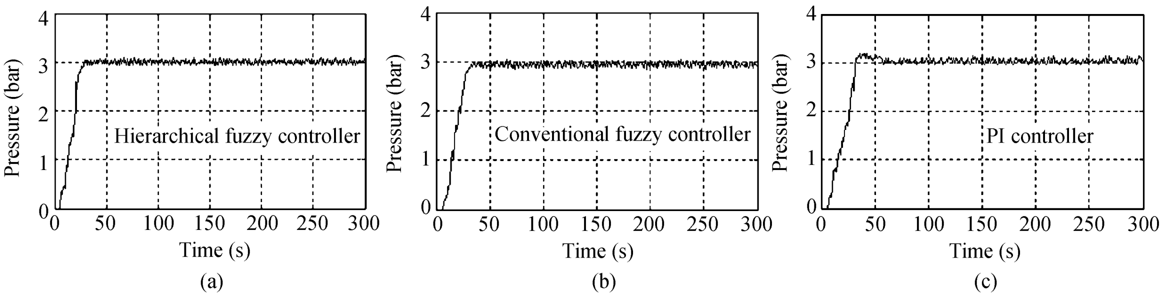

Fig. 11 Pressure control system output responses for the set pressure level of 3 bar. (a) Supervisory hierarchical fuzzy controller; (b) Conventional fuzzy controller; (c) PI controller

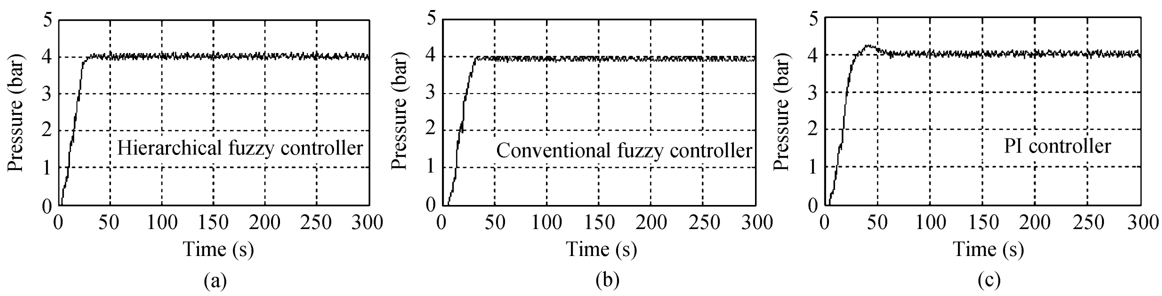

Fig. 12 Pressure control system output responses for the set pressure level of 4 bar. (a) Supervisory hierarchical fuzzy controller; (b) Conventional fuzzy controller; (c) PI controller

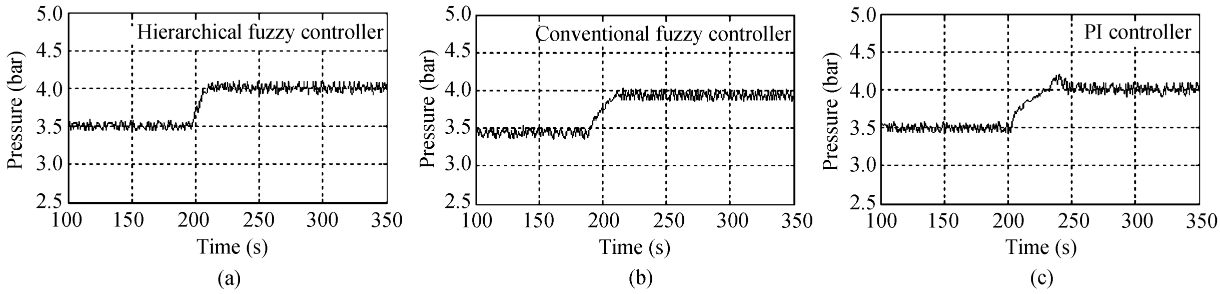

Fig. 13 Pressure control system responses for set-point change from 3.5 to 4 bar. (a) Supervisory hierarchical fuzzy controller; (b) conventional fuzzy controller; (c) PI controller

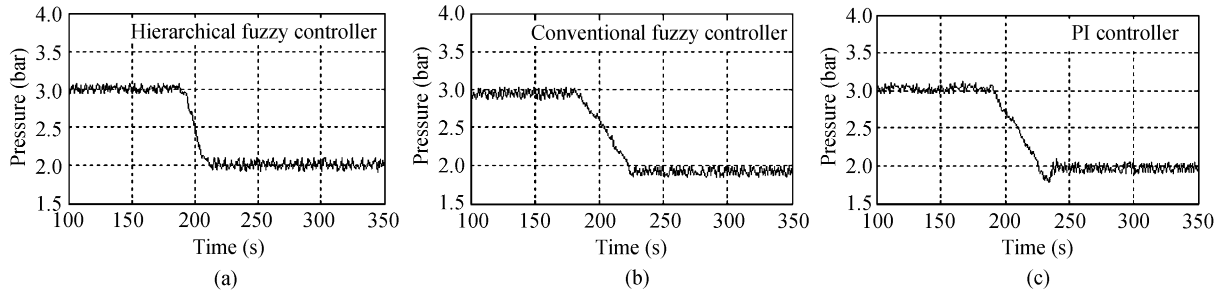

Fig. 14 Pressure control system responses for set-point change from 3 to 2 bar. (a) Supervisory hierarchical fuzzy controller; (b) Conventional fuzzy controller; (c) PI controller

Table 3 Performance comparison of different control algorithms

Type of	ISE		IAE		RMSE		% of peak overshoot		Settling time t_s (s)	
control	3 bar	4 bar	3 bar	4 bar	3 bar	4 bar	3 bar	4 bar	3 bar	4 bar
PI control	31.36	37.97	21.63	23.12	0.619	0.728	19	23	56	54
Fuzzy control	28.41	34.14	19.26	22.47	0.574	0.649	0	0	41	46
Supervisory hierarchical fuzzy control	19.04	26.38	10.97	12.72	0.387	0.426	0	0	29	32

the error (IAE), root mean square error (RMSE), settling time, and overshoot. The ISE, IAE, and RMSE are given as

$$\mathrm{ISE} = \int_0^\infty e^2 \mathrm{d}t \tag{7}$$

$$\mathrm{IAE} = \int_0^\infty |e| \mathrm{d}t \tag{8}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{t=1}^{N} (y_r - y(t))^2}{N}} \tag{9}$$

where e is the error, i.e., $y_r - y$, y_r is the reference pressure in bar, y is the measured output pressure in bar, and N is the number of samples ($N = 100$). The performance comparison of different control algorithms for the set-pressure level of 3 bar and 4 bar are presented in Table 3.

In order to test the robustness of the controller, the load disturbances have been applied by changing the outlet air flow rate of the pressure tank. The manually operated outlet valve is adjusted in such a way to increase and decrease the tank pressure suddenly at steady state. The output responses of SHFC, conventional fuzzy controller and PI controller for the load disturbances are shown in Fig. 15. The conventional PI and fuzzy controllers are not suitable to treat load disturbances because these controllers are designed with fixed input gain and have poor tracking performance for parameter variations. It is observed that for the system output and load disturbances by using conventional methods it takes a very long time to reach an actual set pressure. However, in the case of SHFC, the results are better for load disturbances. The supervisory fuzzy system can track parameter variations easily through the supervisory mechanism and make essential modification in the direct fuzzy controller in order to bring the system output to the actual set pressure quickly. From the results of load disturbances, it is concluded that the disturbance rejection ability of the proposed technique is superior to conventional techniques.

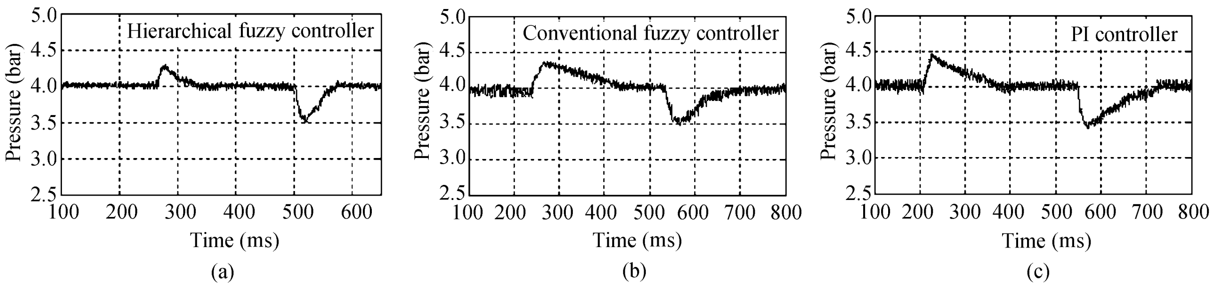

Fig. 15 Pressure control system responses for load disturbances. (a) Supervisory hierarchical fuzzy controller; (b) Conventional fuzzy controller; (c) PI controller

6 Conclusions

The stability and robustness of different controller algorithms have been studied experimentally for a pilot pressure control system. The output results proved that the proposed supervisory hierarchical fuzzy control scheme maintains the tank pressure at set level without any overshoot and steady state error. Considering the error criteria such as ISE, IAE, RMSE, and settling time, the proposed control scheme is better than the classical controllers. From the results of the set-point changes, the stability of the proposed controller was good. With the aid of the supervisory technique, the proposed controller identifies the process variations quickly and provides good controller performance for the load disturbances. The performance of the conventional PI and fuzzy controllers was not up to the expected level for load disturbances because of the poor tracking of parameter variations. The proposed supervisory hierarchical control scheme is fit for pressure control applications. In addition, the microcontroller based control technique is proved to be an ideal tool for implementing the hybrid control algorithms with a low cost and simple design technique.

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