

## Research Article

# Fuzzy Coordinated PI Controller: Application to the Real-Time Pressure Control Process

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This paper presents the real-time implementation of a fuzzy coordinated classical PI control scheme for controlling the pressure in a pilot pressure tank system. The fuzzy system has been designed to track the variation parameters in a feedback loop and tune the classical controller to achieve a better control action for load disturbances and set point changes. The error and process inputs are chosen as the inputs of fuzzy system to tune the conventional PI controller according to the process condition. This online conventional controller tuning technique will reduce the human involvement in controller tuning and increase the operating range of the conventional controller. The proposed control algorithm is experimentally implemented for the real-time pressure control of a pilot air tank system and validated using a high-speed 32-bit ARM7 embedded microcontroller board (ATMEL AT91M55800A). To demonstrate the performance of the fuzzy coordinated PI control scheme, results are compared with a classical PI and PI-type fuzzy control method. It is observed that the proposed controller structure is able to quickly track the parameter variation and perform better in load disturbances and also for set point changes.

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## 1. INTRODUCTION

The classical controllers like PI or PID controllers are widely used in process industries because of their simple structure, assure acceptable performance for industrial processes and their tuning is well known among all industrial operators. However, these controllers provide better performance only at particular operating range and they need to be retuned if the operating range is changed. Further, the conventional controller performance is not up to the expected level for nonlinear and dead time processes. In the present industrial scenario, all the processes require automatic control with good performance over a wide operating range with simple design and implementation. This provides the motivation for online tuning, where the focus is on the automatic online synthesis and tuning of the conventional controller parameters, that is, using the online data, the adopted intelligent system can continually learn which will ensure that the performance objectives are met. The online tuning of a conventional controller through an intelligent technique is one of the ways to automate the operator's task and to obtain

the better controller performance over a wide operating range. Among the various intelligent control techniques, fuzzy logic provides a formal methodology for implementing humans' heuristic knowledge and it will be considered as an obvious solution for tuning the conventional controllers. The fuzzy logic control (FLC) in various forms is being designed and implemented for several control applications [1–3]. FLC usually embeds the intuition and experience of a human operator, recently it has been used in the form of supervisor for a number of applications [4–7]. Specifically, a fuzzy inference system is used to tune the PI controller gains depending on the current operating conditions of the controlled system.

In industrial environments, the control algorithm development and its implementation cost should be feasible for real-time control application. In this context, the use of embedded microcontrollers seems to be particularly suitable, since the cost of the microcontroller nowadays is very low-, high-processing speed with lesser amount of power consumption and also suitable to industrial environments. Further developing the application program and downloading

into the microcontroller is very simple. Successful application of microcontroller-based real-time control has been reported [8–10]. Moreover, the embedded microcontroller can be used for remote monitoring and control through a network-based control structure [11].

Pressure control is one of the primary task in areas-like steam generation in industrial power plants, reaction control in chemical industry, heating, ventilating, and air conditioning (HVAC) system, oil well drilling, automobile emission control, and so on, [12–15]. In general, the pressure control is a dynamic and nonlinear process, frequent controller tuning is necessary based on the process operating conditions [16]. This paper reports the design and implementation of a fuzzy-PI hybrid controller structure in which the fuzzy controller is adapted to track error and process input of a feedback system and tune the classical PI controller for set point changes and load disturbances. The performance of the proposed control algorithm is compared to conventional feedback controllers. The controller parameters for the conventional method were computed via the Cohen and Coon (CC) tuning method, from an open loop process reaction curve experiments.

## 2. DESIGN OF A FUZZY COORDINATED PI CONTROLLER

The prime objective of the controller design is to achieve better control performance in terms of stability and robustness for the set point changes and load disturbances. Paramasivam and Arumugam [17] and Ketata et al. [18] have proposed different methods of designing a hybrid control structure using fuzzy logic system. He et al. [19] and Visioli [20] have used the fuzzy system in such a way to modify the parameters of the conventional controller. The hybrid control structure consists of a simple upper-level intelligent controller and a lower-level classical controller. The upper-level controller provides a mechanism to the main goal of the system, whereas the lower-level controller should deliver the solutions to particular situation. In the proposed control structure, a rule-based mamdani-type fuzzy controller is used in the upper level and a conventional PI controller is selected for the lower level. The structure of the fuzzy-coordinated PI controller is shown in Figure 1. In usual practice, the error ( $e$ ) and error change ( $\Delta e$ ) parameters were preferred whereas designing the antecedent of the fuzzy rules for control applications. But in the present application, a modified control structure has been applied in which the fuzzy system utilize the error ( $e$ ) and process input ( $u$ ) and detects the possible deviation from a prescribed course so that it can able to tune the conventional controller for set point changes and load disturbances.

### 2.1. Fuzzy tuning of PI controller

In the hybrid control structure, the fuzzy system is used to modify either the system set point or scaling factor of a conventional controller. The present method focuses the input scaling factor modification of a classical PI controller. The PI controller is usually implemented as follows:

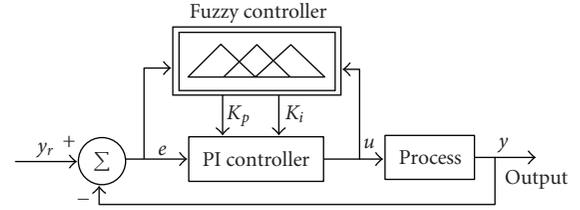


FIGURE 1: Fuzzy-coordinated PI controller structure.

TABLE 1: Effects of the gain parameters.

Gain parameter	Effects of increasing gain		
	Rise time	Overshoot	Settling time
$K_p$	Decrease	Increase	Small change
$K_i$	Decrease	Increase	Increase

$$u_{PI} = K_p e(t) + T K_i \sum_{n=0}^t e(n) \quad (1)$$

$$e(t) = y_r(t) - y(t),$$

where  $K_p$ ,  $K_i$  are the proportional and integral gains. The controller output, process output, and the set point are denoted as  $u_{PI}$ ,  $y$ ,  $y_r$ , respectively. In the conventional PI controller, the values of  $K_p$  and  $K_i$  in (1) are adjusted by the operator according to the changes in process condition. By developing a rule-based intelligent fuzzy coordinate hybrid controller structure, these parameters can be modified online according to the changes in process condition without much intervention of operator and further it will enhance the conventional controller performance over a wide operating range.

### 2.2. Rule base and membership functions of the fuzzy controller

The upper-level fuzzy system of the proposed control structure contains operator knowledge in the form of IF-THEN rules to decide the gain factors according to the current trend of the controlled process. In this proposed hybrid controller structure, the control rules of the fuzzy system have been developed using the general domain knowledge about the conventional controller tuning [21]. The effect of variation in gain parameters on rise time, overshoot, and settling time of a PI controller are illustrated in Table 1.

In the proposed method, the control rules are developed with the error and process input as a premise and the proportional and integral gains are consequent of the each rules. The structure of the fuzzy rule is written as

$$\text{IF } e \text{ is NS and } u \text{ is LOW THEN } K_p \text{ is HIG and } K_i \text{ is MID.} \quad (2)$$

Table 2 shows the fifteen linguistic fuzzy rules which have been used in the fuzzy coordinated PI control structure. The linguistic values of each input and output fuzzy variables divide their universe of discourse into adjacent intervals to

TABLE 2: Rule base for fuzzy-coordinated PI controller.

Input		Output	
Error ( $e$ )	Process input ( $u$ )	$K_p$	$K_i$
NB	LOW	VHIG	HIG
	MED	HIG	MED
	HIG	MED	MED
NS	LOW	HIG	MED
	MED	MED	LOW
	HIG	LOW	VLOW
ZE	LOW	MED	LOW
	MED	LOW	LOW
	HIG	VLOW	VLOW
PS	LOW	LOW	VLOW
	MED	LOW	MED
	HIG	VLOW	HIG
PB	LOW	MED	VLOW
	MED	HIG	VLOW
	HIG	HIG	MED

form the membership functions. Each membership function of a fuzzy variable is assigned with an abbreviated linguistic value-like MED (medium), VHIG (very high), and so on. The membership function converts the degree of fuzziness into the normalized interval (0, 1). The triangle membership functions are selected in the present controller and its degree of fuzziness is expressed as

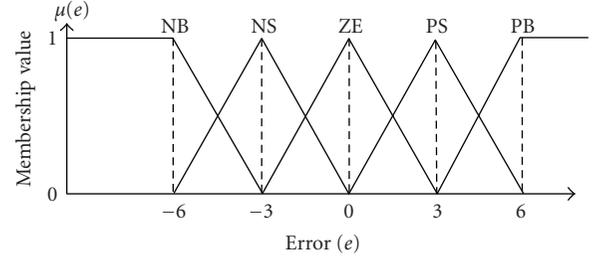
$$\mu_\delta(x) = \begin{cases} 0, & \text{for } x < a \\ \frac{x-a}{b-a} & \text{for } a \leq x < b \\ \frac{c-a}{b-a} & \text{for } b \leq x \leq c \\ 0, & \text{for } x > c. \end{cases} \quad (3)$$

The triangle shape membership functions with 50% of overlapping for the input and output fuzzy variables are shown in Figures 2 and 3. The scaling coefficients of each fuzzy variable are initially selected from the earlier experimental data in [22], and their values have been fine tuned during the implementation in order to obtain the desired results. In the present system, the measured pressure signal is converted into a 10-bit binary equivalent and the binary number is mapped with the universe discourse.

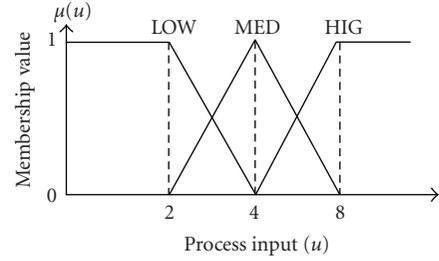
For the fuzzy implication, the intersection minimum operation has been used, the center average defuzzification [23] has been selected to find the crisp value of outputs. The center average defuzzification is defined as

$$\mu_{(K_p, K_i)} = \frac{\sum_{i=1}^R b_i \mu_i}{\sum_{i=1}^R \mu_i}, \quad (4)$$

where  $\mu_{(K_p, K_i)}$  are the gain outputs,  $b_i$  denotes the center of the membership function of the consequent of  $i$ th rule and  $\mu_i$  denotes the membership value for the  $i$ th rule's premise.

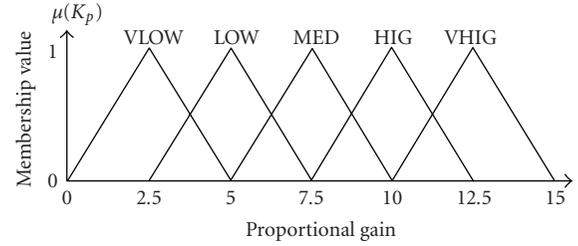


(a)

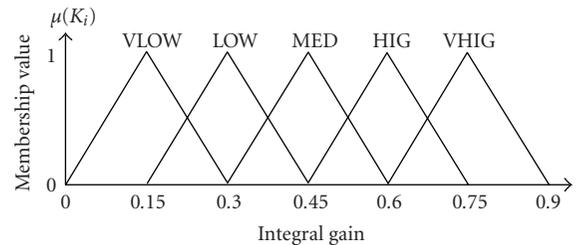


(b)

FIGURE 2: Fuzzy output membership functions (a) error (b) process input.



(a)



(b)

FIGURE 3: Fuzzy output membership functions (a) proportional gain (b) integral gain.

To demonstrate the performance of the proposed control technique, the performance of the PI-type fuzzy and the conventional PI controllers have been studied and compared for the pressure process. The rule base and membership functions of PI-type fuzzy controller have been designed using the operative knowledge about pressure process. The controller parameters for the conventional PI controller were

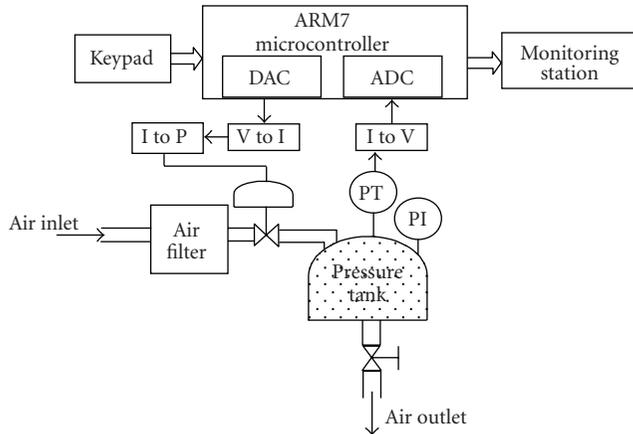


FIGURE 4: Schematic diagram of the pilot pressure regulating system.

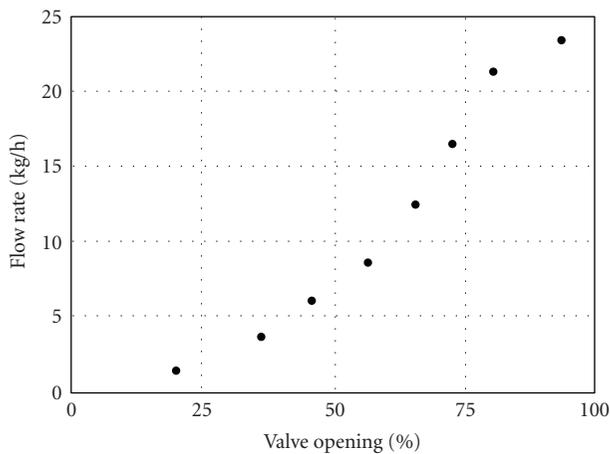


FIGURE 5: Control valve characteristics.

obtained through CC controller tuning method, from an open loop process reaction curve experiments.

### 3. DESCRIPTION OF THE EXPERIMENTAL SETUP

The schematic diagram of a pilot pressure regulating system is shown in Figure 4. It consists of a miniature pressure tank inlet of which is connected to an air compressor through a 50 mm 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. A pressure transmitter attached to the pressure tank is used to measure tank pressure and provides 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 order to reach the desired set pressure. A decreasing sensitivity type equal percentage electropneumatic control valve characteristic shown in Figure 5 is used for inlet air flow manipulation.

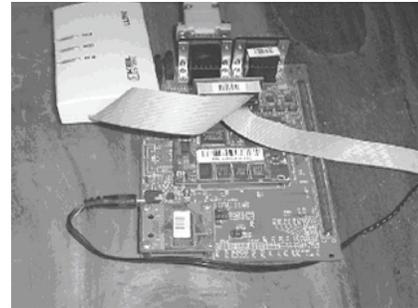


FIGURE 6: The AT91M55800A-embedded microcontroller target board.



FIGURE 7: Photograph of the experimental system.

### 4. IMPLEMENTATION OF THE FUZZY COORDINATED PI CONTROLLER

The proposed fuzzy coordinated PI control algorithm source code has been developed and downloaded into the target ARM7 microcontroller. The host (PC) machine and the target microcontroller were interfaced using  $\mu$ LINK programming device for downloading the application code. A subminiature embedded microcontroller target board with a 32-bit advanced RISC architecture (ATMEL AT91M55800A) has been selected to implement the proposed control algorithm and is shown in Figure 6. Its features are one MByte onboard flash memory, network application capable processor (NCAP) facilities, 32 MHz operating clock frequency, RS-232 transceiver for three serial interfaces, and onboard ADC and DAC for real-time interfacing [24]. The photograph of the experimental setup is shown in Figure 7. Flow chart for the various steps involved in the development of fuzzy-coordinated PI control algorithm is shown in Figure 8.

### 5. EXPERIMENTS AND RESULTS

To start with the compressor, it has been switched on and the air flow from the compressor was allowed continuously to the pressure tank to reach the set pressure. The pressure transmitter measures the tank pressure and gives an output

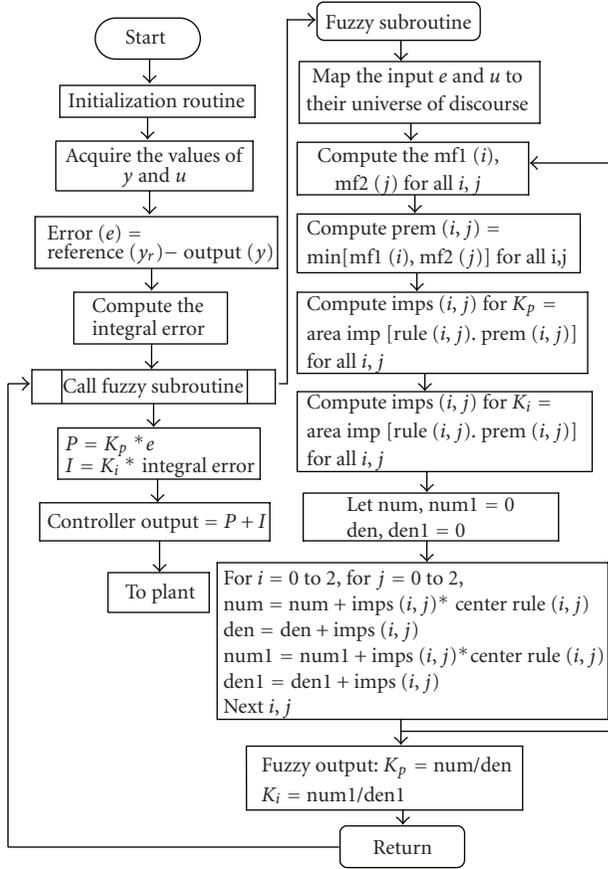
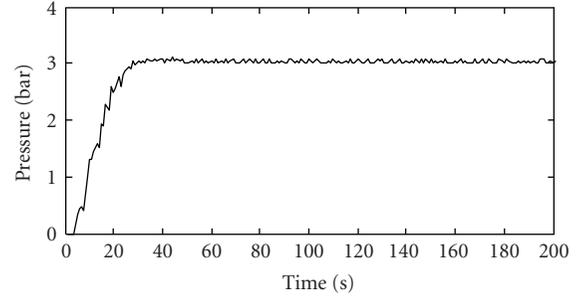


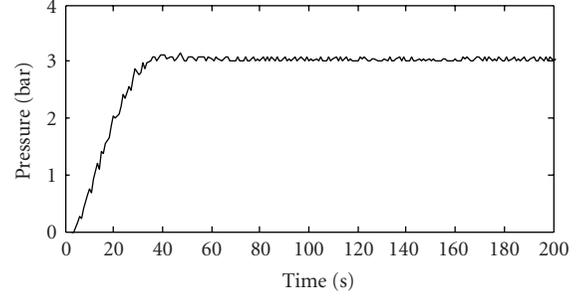
FIGURE 8: Flow chart of the various steps in the development of fuzzy-coordinated PI control algorithm.

current signal (4–20 mA) which will be converted to 0–5 volts using a current to voltage converter. The inbuilt 10-bit ADC of ARM7 microcontroller converts this analog voltage signal into the corresponding binary equivalent. The error value is computed by comparing the process output and the set point. The outlet valve was set at a fixed opening to allow a constant air flow rate from the pressure tank during the test period. By using error and process input, the hybrid control algorithm provides the controller output which will manipulate the inlet air flow rate to maintain tank pressure at the set level. The sampling rate has been fixed at 0.5 second for pressure measurement.

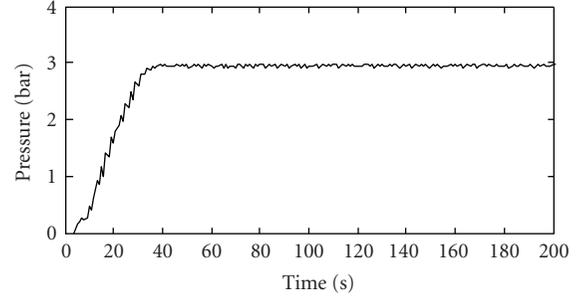
An ARM7 microcontroller-based real-time experiments have been conducted for pressure regulation in a pilot air tank system using PI, PI-type fuzzy, and fuzzy-coordinated PI control algorithms. The controller parameters of the conventional PI controller are obtained through CC tuning method. The system output response of the fuzzy-coordinated PI controller, PI controller, and PI-type fuzzy controller for the set pressure level of 3 bar and 4 bar are shown in Figures 9 and 10. From the output response, it is observed that the fuzzy-coordinated PI control algorithm makes the system to reach the set pressure quickly without any overshoot and steady-state error. On the other hand, the



(a) Fuzzy-coordinated PI controller



(b) Conventional PI controller



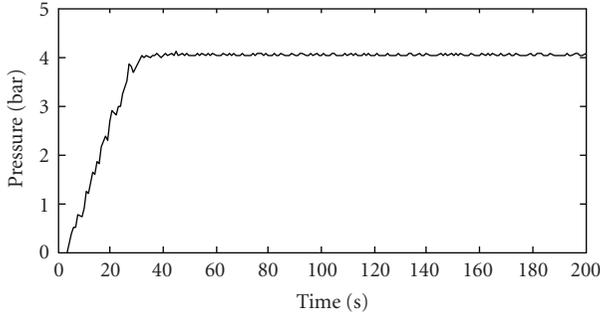
(c) PI-type fuzzy controller

FIGURE 9: Experimental results, output responses of different controllers for the set pressure level of 3 bar.

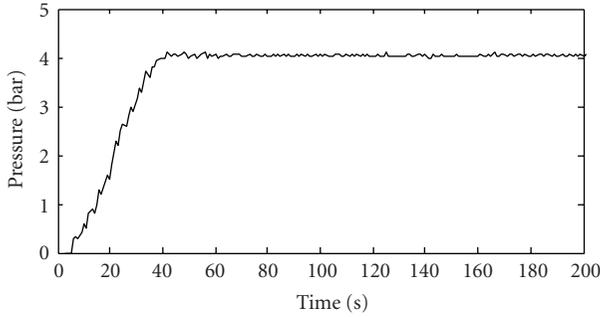
conventional-type PI control algorithm needs much time to reach the set pressure. However, the PI-type fuzzy control algorithm consumes lesser time than the PI controller, but having a small steady-state error. It is concluded that fuzzy-based hybrid controller performance is better in terms of settling time and steady-state error than the conventional PI and PI-type fuzzy control methods for pressure control process.

The performance of the proposed control algorithm has been tested for set-point variation at steady-state condition by varying the set pressure. The response of the set-point variation from 3 bar to 4 bar and 4 bar to 3 bar of different controllers is shown in Figures 12 and 13. From the results, the fuzzy-based hybrid controller instantly responds to the set point changes and makes the system to settle within a short time than the PI and PI-type fuzzy controller.

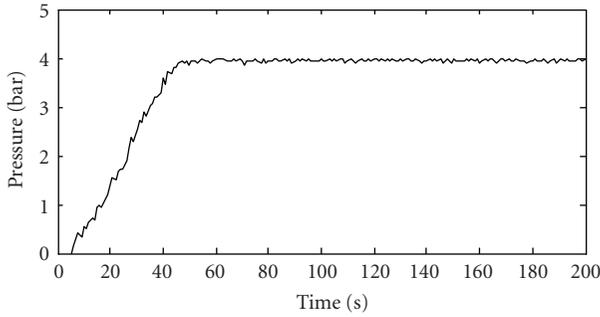
In order to compare the performance of different control algorithms, the integral of the square of the error (ISE), integral of the absolute value of the error (IAE), integral of



(a) Fuzzy-coordinated PI controller



(b) Conventional PI controller



(c) PI-type fuzzy controller

FIGURE 10: Experimental results, output responses of different controllers for the set-pressure level of 4 bar.

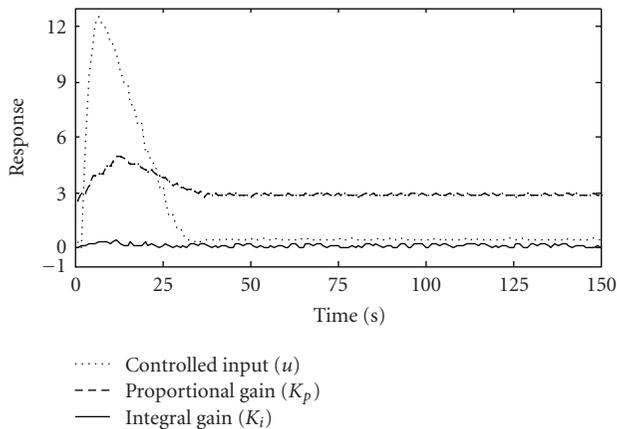
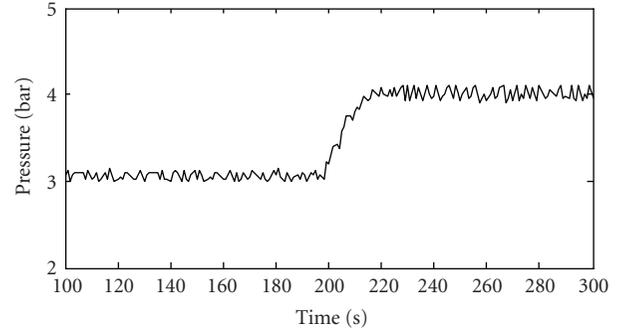
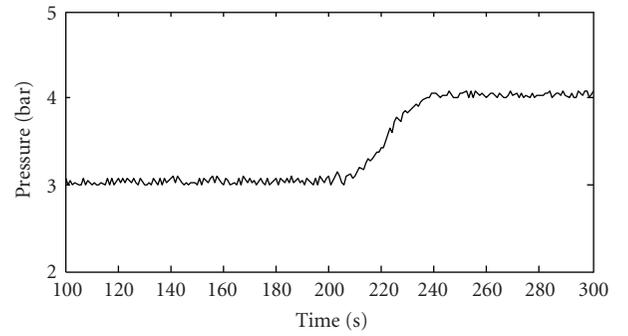


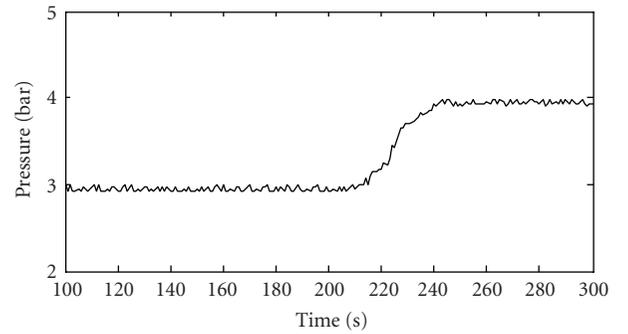
FIGURE 11: Experimental results of fuzzy-coordinated PI controller, control input, and PI gains tuning for the set pressure level of 4 bar.



(a) Fuzzy-coordinated PI



(b) Conventional PI controller



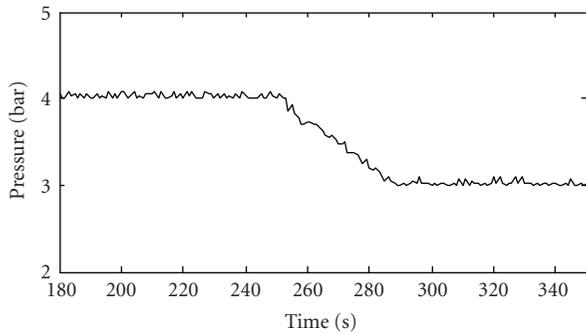
(c) PI-type fuzzy controller

FIGURE 12: Experimental results, output responses of different controllers for set point change from 3 bar to 4 bar.

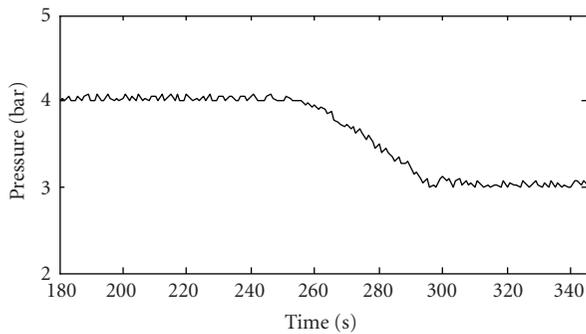
time-weighted absolute error (ITAE), and root mean square error (RMSE) criteria have been used. The ISE, IAE, ITAE, and RMSE are given as

$$\begin{aligned}
 \text{ISE} &= \int_0^{\infty} e^2 dt, \\
 \text{IAE} &= \int_0^{\infty} |e| dt, \\
 \text{ITAE} &= \int_0^{\infty} |e|t dt, \\
 \text{RMSE} &= \sqrt{\frac{\sum_{k=1}^N (y_r - y(k))^2}{N}},
 \end{aligned} \tag{5}$$

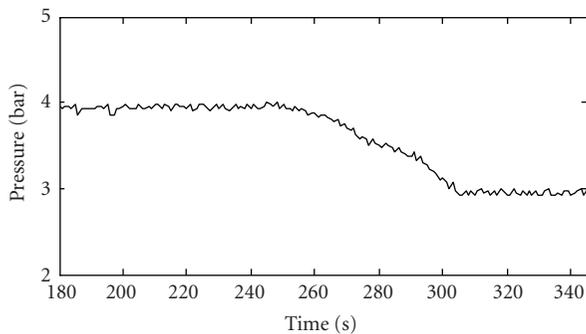
where  $e$  is the usual error (i.e.,  $y_r - y$ ),  $y_r$  is the reference pressure in bar,  $y$  is the actual output pressure in bar, and



(a) Fuzzy-coordinated PI controller



(b) Conventional PI controller

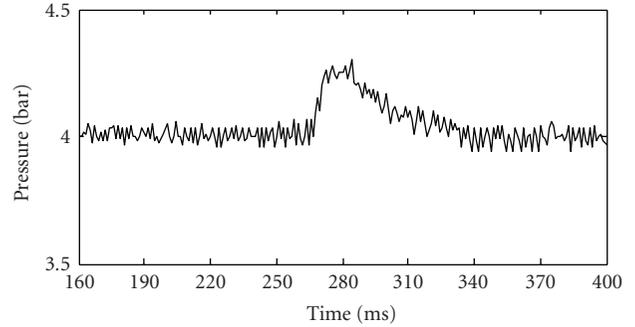


(c) PI-type fuzzy controller

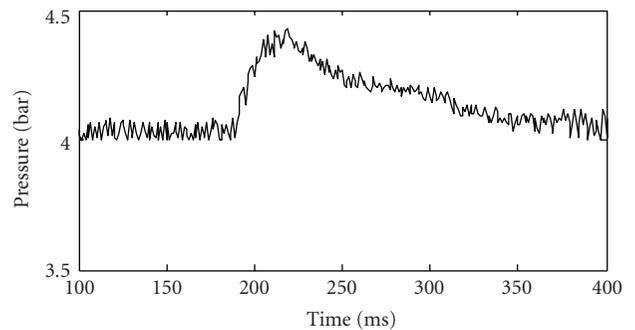
FIGURE 13: Experimental results, output responses of different controllers for set point change from 4 bar to 3 bar.

$N$  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.

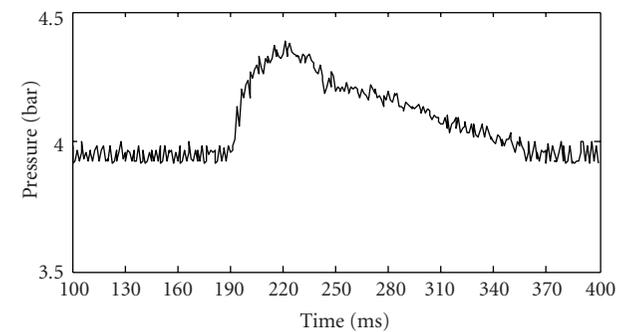
The comparison table indicates that the proposed fuzzy-coordinated PI controller has small value for all types of error criteria (ISE, IAE, ITAE, and RMSE) than the conventional controllers. By considering the settling time, the proposed algorithm demonstrates the improved performance than the other methods. To study the robustness of the controllers for load disturbances, a disturbance has been applied in such a way to increase and decrease the process input at steady-state condition. The system output responses for load disturbances are shown in Figures 14 and 15. The



(a) Fuzzy-coordinated PI controller



(b) Conventional PI controller



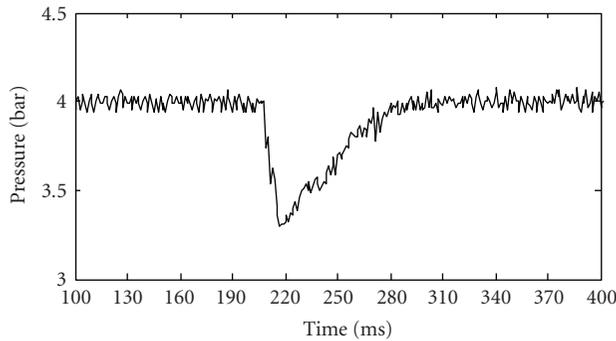
(c) PI-type fuzzy controller

FIGURE 14: Experimental results, load disturbance response of controllers for increasing the process input.

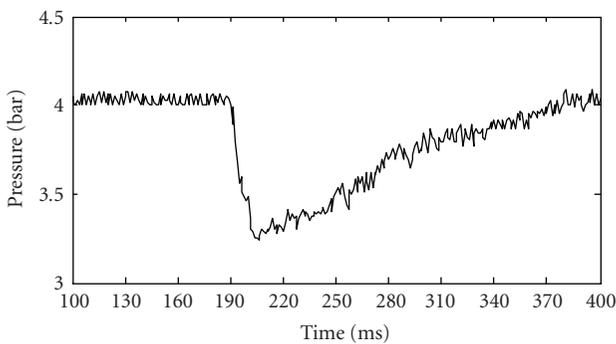
results of conventional-type PI and PI-type fuzzy controllers are not good enough for load disturbances because of the poor tracking performance for parameter variation. It is also observed that the system output cannot reach steady state even after long time. However, in the case of fuzzy-coordinated PI controller, the results are better for load disturbances. Since the fuzzy system can be able to track the input disturbances instantly by using its input parameters  $e$  and  $u$ , thereby necessary modification is made in the conventional controller part to bring the system output quickly to the set value. From the results of load disturbances, it is obvious that the disturbance rejection ability of the proposed technique is superior to conventional techniques.

TABLE 3: Performance comparison of different control algorithms.

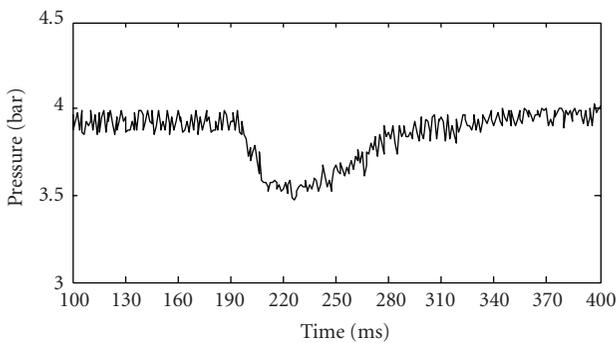
Type of control	ISE		IAE		ITAE		RMSE		Settling time ( $t_s$ ) sec	
	3 bar	4 bar	3 bar	4 bar						
PI control	28.36	36.97	17.63	20.12	54.65	64.23	0.529	0.618	42.3	50.6
PI-type fuzzy control	26.41	35.14	16.26	18.47	52.06	57.21	0.516	0.611	40.7	47.4
Fuzzy-coordinated PI control	17.04	28.38	11.97	14.57	36.71	45.35	0.427	0.536	33.2	39.1



(a) Fuzzy-coordinated PI controller



(b) Conventional PI controller



(c) PI-type fuzzy controller

FIGURE 15: Experimental results, load disturbance response of controllers for decreasing the process input.

## 6. CONCLUSION

In this paper, the stability, fast tracking capability for parameter variation, and robustness of different controller algorithms were studied experimentally for a pilot pressure control system. The experimental analysis proved that the proposed fuzzy-coordinated PI control scheme maintains the

tank pressure at set level without any steady-state error unlike PI-type fuzzy controller. By keeping the merits of PI and FLC, the proposed control scheme makes the system output to reach the set level faster than PI and PI-type controllers. From the results of the load disturbances and set point changes, the proposed hybrid controller proves its robustness with aid of fast parameter tracking capability. However, the performance of the PI and PI-type fuzzy controller was not good enough for load disturbances because of the poor tracking capability. It was found that from the demonstrated results, the proposed fuzzy logic-based hybrid control scheme is well suited to pressure control and other types of dynamic processes. Further, the microcontroller-based embedded controller proved to be better tool for implementing the hybrid control algorithm with low cost and simple design technique.

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