FUZZY LOGIC CONTROLLER FOR REAL TIME NETWORKED CONTROL SYSTEM

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Abstract: *With the development and attenuation of network technology, research and application of Networked Control System (NCS) received more attention from scholars. Even though the NCS make it easy and convenient to control large systems, the use of limited bandwidth network channels into control system brings some problems. This paper focuses on control and monitor of a Networked pressure process system with networked induced delays and noises using MATLAB. Two control strategies are proposed in this project, IMC based PI controller with Smith predictor technique and Fuzzy Logic Controller. The work has been carried out with the help of UDP communication. Experimental result shows that the Fuzzy Logic Controller (FLC) can counteract the effects of networked induced delays and noises. The transient responses of the system are analyzed for the designed controllers.*

Keywords: *MATLAB, PI, Pressure Process Analyzer, Smith Predictor, Fuzzy Logic Controller, Networked Control System*

1. INTRODUCTION

The advent of communication networks, however, introduced the concept of remotely controlling a system, which gave birth to Networked Control Systems (NCS). Network control system with its notable advantages and has been applied in variety of control applications, it has become a hot topic of research in the control community [4]. The so-called Network Control System (NCS) is described as, the input and output signals of control system form a closed-loop through a real time network, (i.e) information between each nodes of control systems (actuators, sensors and controllers) are transmitted and received via the network [7, 10]. Significant advantages of NCS over traditional control system are low cost, easy extensible, resource sharing, high reliability, simple installation and maintenance. Apart from the advantages, with the introduction of network the closed loop system faces the problems like transmission channel constrains, packet dropouts, quantization noise, network induced delays [1]. Above mentioned issues may affect the stability and even degrades the performance of closed-loop control system. The NCS can be performed in two ways (i.e.)

a) Direct Structure
b) Hierarchical Structure

This paper deals with the former structure which has a sensor and an actuator of a control loop connected directly to a network. In this case, a sensor and an actuator are attached to a plant, while a controller is separated from the plant by a network connection. Set point is given to the controller. The communication can be made through several kinds of protocol. This paper takes the network communication via UDP communication. It is always a key point to analyze the stability of closed-loop system affected by time varying transmission delays in NCS [12]. Delays are induced by the exchange of data via the feedback and feed forward channels. Network delays in NCS can be categorized from the direction of data transfer as the sensor-to-controller delay and the controller -to- actuator delay. The total network delay has been calculated as $\tau = \tau_{ca} + \tau_{sc}$, which is larger than one sampling period. This time delay term will limits the controller gain and thereby limiting the possible amount of control action for the delay dominant system. When the system contains time delay, the closed loop performance will be degraded and even destabilize the stable loop because of the limitations imposed by the time delays [13]. This paper also concentrates on how the performance varies under normal and noisy environment in networked system [5]. Smith Predictor control is used here to compensate the delay produced by the involvement of network [3]. Moreover Fuzzy control logic, an intelligent control have also been used to study the performance under noisy environment in networked system [2, 8, 15].

The performance of the networked control DC motor is studied for various controllers like PID, fuzzy modulated PID and Fuzzy Logic Controller by introducing simulated delays, losses, disturbances and missing of signals in the feed forward and feedback network [8]. Various researches have been proved on the stability analysis for nonlinear systems using fuzzy control [16-19].

2. Plant Dynamics

Pressure process control is the wide sought of control in process control industries. Pressure like liquid pressure, gas pressure and vapor pressure are generally controlled in process industries. For analysis and design of controller, there is a requirement of knowing the mathematical model of Pressure process analyzer.

The basic principle is that the mass of gas stored in cylindrical vessel of fixed volume at constant temperature varies directly with its pressure. The model of the plant is shown in the Figure 1.

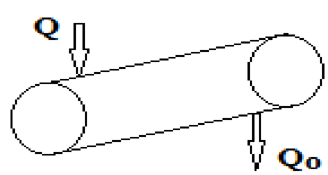

Fig. 1 Model of the Pressure process analyzer tank

For constant air density ρ, a mass balance yields,

$$\frac{dm}{dt} = \rho Q - \rho Q_0 \tag{1}$$

where Q and Q_o are the input and output pressure of the cylindrical vessel. The mass accumulation term in Eq. (1) can be written as,

$$\frac{dv}{dt} = Q - Q_0 \tag{2}$$

The plot of the process to a step change in input is referred as process reaction curve method. Using the process reaction curve method, the open loop transfer function of the process is found as Eq. (3),

$$\frac{Y(s)}{U(s)} = \frac{K}{\tau s + 1} \tag{3}$$

where Y(s) and U(s) are the Laplace transform of output and input variable; K the process gain is found by Eq. (4),

$$K = \frac{P_i - P_f}{V_f - V_i} \tag{4}$$

where P_i and P_f are value of pressure at initial and final time and V_i and V_f are the initial and final valve setting of the pressure process.

The value of K is found to be 1.7. τ is the time constant which can be calculated by finding the time corresponding to 63.2% of final steady state value of the open loop response which is found to be 8.6 seconds. By substituting the values of K and τ in Eq. (3) the transfer function model of Pressure Process analyzer is obtained as Eq. (5),

$$\frac{Y(s)}{U(s)} = \frac{1.7}{8.6s + 1} \tag{5}$$

3. PI CONTROLLER

A successful operations of automatic control system requires anti-jamming capability, stability and ability to meet the given performance index. Since the physical structure and the working process of the controlled object are constant, the output value of the given signal could not meet the needs of system. Therefore, a controller needs to be included. PI (Proportional Integral) control is a widely used control method for fast process. It has huge advantage in the fields of control engineering.

PI controller has simple structure, excellent stability, reliability performance and convenient adjustability. When the structure and the parameters of the controlled object cannot be completely acquired or cannot manifest a clear mathematic model, PI control technology becomes more useful. Because it was designed for the situation where users cannot thoroughly learn about a system with a controlled object, or cannot obtain the system parameters by using the effective measuring methods. PI controller structure is shown in the Figure 2.

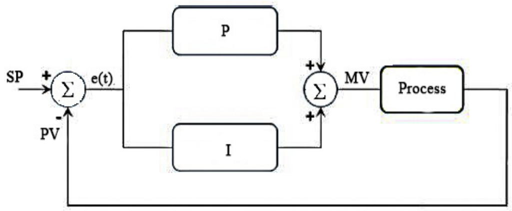

Fig. 2 PI controller structure

where, MV-Manipulated Variable; PV-Process Variable; SP - Set Point; P - Proportional Controller; I - Integral Controller. The PI controller is mathematically denoted as Eq. (6),

$$G_c = K_p + \frac{K_i}{s} \tag{6}$$

Where, G_c - Controller transfer function, K_p - Proportional gain, K_i - Integral gain.

Integral control action added to the proportional controller converts the original system into high order. Hence the control system may become unstable for a large value of K_p since roots of the characteristic equation may have positive real part. In this control, proportional control action tends to stabilize the system, while the integral control action tends to eliminate or reduce steady-state error in response to various inputs. As the value of T_i (Integral time) is increased, the overshoot get decreases and the speed of response is reduced.

4. Parameter Estimation

A more comprehensive model-based design method, Internal Model Control (IMC) was developed by Morari. The IMC method is based on assumed process model and leads to analytical expressions for controller settings. The IMC approach has the advantage that it allows model uncertainty and tradeoffs between performance and robustness to be considered in a more systematic fashion. The IMC tuning relationship for first order system is given by Eq. (7) & (8),

$$K_p = \frac{\tau}{K * \tau_c} \tag{7}$$

$$K_i = \frac{1}{\tau} \tag{8}$$

The PI controller tuning parameter is obtained using the above IMC tuning relationship. The parameters are found to be K_p= 0.6022 and K_i = 0.1162.

5. Smith Predictor Control Strategy

Smith's [1957] principle provides a criterion for selecting a control strategy for time delay processes and dead-time compensation techniques. The technique is an approach to control of systems with long dead times [6]. The block diagram of Smith predictor is shown in the Figure 3. The closed loop transfer function is given by Eq. (9),

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{G_c(s)G_p(s)e^{-\theta s}}{(1+G_c(s)G_m(s)+(G_c(s)G_p(s)e^{-\theta s} - G_c(s)G_m(s)e^{-\tilde{\theta} s}))} \tag{9}$$

As the process and the model are equal the Eq. (9) becomes

$$\frac{Y(s)}{Y_{sp}(s)} = \frac{G_c(s)G_p(s)e^{-\theta s}}{1+G_c(s)G_m(s)} \tag{10}$$

Thus inclusion of smith predictor compensator removes the delay from the characteristic equation there by allowing increase value for controller gain as shown in Eq. (10).

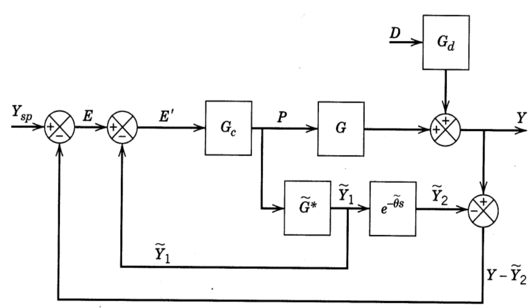

Fig. 3 Block diagram of smith predictor controller

A Smith predictor achieves some form of derivative action required for compensating dead time in first- order processes by a lag in its feedback path. By matching the lag in the smith predictor to the lag in the dead time process, the input manipulated variable follows the process lag exactly but delayed by the dead time. The delayed predictor output is compared to the measured process output and the resulting model error quantity is added to the current predictor output to correct for predictor deficiencies, provided that the model is a true representation of the process and there are no further disturbances to the process during the dead time period. It is observed that the optimal predictor part of the controller algorithm changes also with the time delay. The Smith predictor is an optimal dead time compensator for only those systems having disturbances for which the optimal prediction is a constant over the period of the dead time.

6. Fuzzy Logic Controller

Fuzzy logic is an algorithm based on a linguistic control strategy, which is derived from expert knowledge system into an automatic control strategy. The operation of a FLC is based on qualitative knowledge about the system being controlled [2]. It only uses simple mathematical calculation to simulate the expert knowledge. A fuzzy logic controller has four main components as shown in Figure 4.

a) Fuzzification
b) Inference engine
c) Rule base
d) Defuzzification

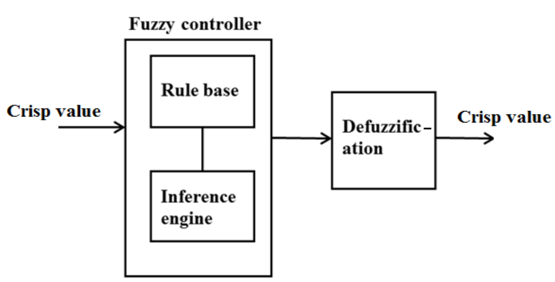

Fig. 4 Structure of fuzzy logic controller

Error range is selected based on the speed measurement range and universe of discourse and scaling factor selected based on the trial and error method. The universe of discourse partitioned using seven linguistic variables as shown in Figure 5.

Error range	:	-100 to +100
Universe of discourse	:	-1 to +1
Scaling factor	:	0.00125

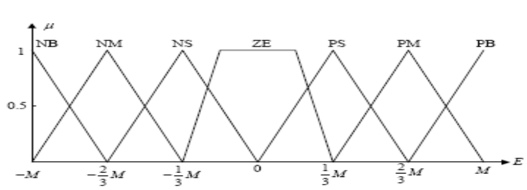

Fig. 5 Fuzzification structure for error

Derivative error range is selected based on the closed loop response of the system. The universe of discourse and scaling factor selected based on the trial and error method. The universe of discourse partitioned using seven linguistic variables as shown in Figure 6.

Derivative of Error range	:	100 to +100
Universe of discourse	:	1 to +1
Scaling factor	:	0.000586

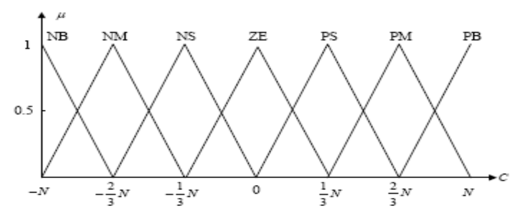

Fig. 6 Fuzzification structure for derivative error

The change in output range is selected based on the closed loop response of system. The universe of discourse and scaling factor selected based on the trial and error method. The universe of discourse partitioned using seven linguistic variables as shown in Figure 7.

Derivative of Error range	:	-1 to 1
Universe of discourse	:	-10 to +10
Scaling factor	:	1.8

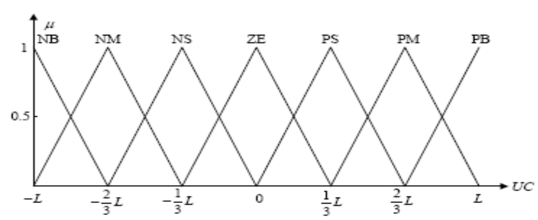

Fig. 7 Fuzzification structure for change in output

The decision making logic, uses the fuzzy control action from the knowledge of the control rules and linguistic variable definitions. The rules formed are in “If Then” format and formally the ‘If’ side is called the conditions and the ‘Then’ side is called the conclusion. The system is able to execute the rules and compute a control signal depending on the measured inputs error e(t) and change in error de(t). Fuzzy control rule is the core of the design of fuzzy controller, which is in fact a set including a series of fuzzy condition statements [14].

The principle of determining fuzzy rules is to ensure the static and the dynamic performances of the system output are optimal through the action of the output of fuzzy controller. It's well-known that the fuzzy control rules for a single-input–single-output. Controller can be derived from step response. Figure 8 shows the typical step response curve of a closed-loop system

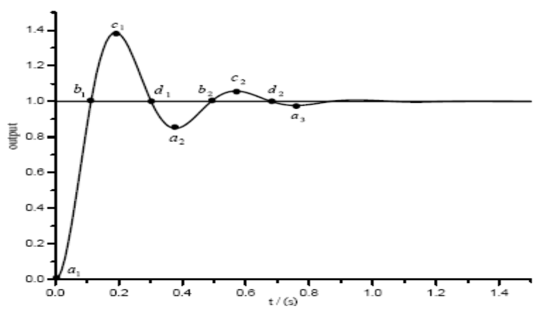

Fig. 8 Typical step response of a closed-loop system

In Figure 8, characteristic points are classified into four groups and fuzzy control rules can be formulated by examining these characteristic points. Fuzzy control rules are described as follows is shown in Table 1.

Rule 1: If E is PB and EC is ZE then UC is PB
Rule 2: If E is PM and EC is ZE then UC is PM
Rule 3: If E is PS and EC is ZE then UC is PS
Rule 4: If E is ZE and EC is ZE then UC is ZE

Where, E - Error; EC – Change in Error; UC – Change in output

Table 1 Fuzzy control rule table

e / de	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

7. UDP Communication

The communication between a plant and a controller in a Network environment, implemented with the help of MATLAB/Simulink with Real time windows target tool box and UDP protocol.

First, install the setup of real time kernel in both the PC so that real time communication takes place. Then, make the Simulink model for the plant and controller to communicate. With the plant and controller present in remote location, the controller will generate the control data based plant output data and transmit the control signal to the plant using UDP packet. This loop is two way communications. Data is send through the network in the form of packets from controller to plant and vice versa. The complete system structure is shown in the Figure 9.

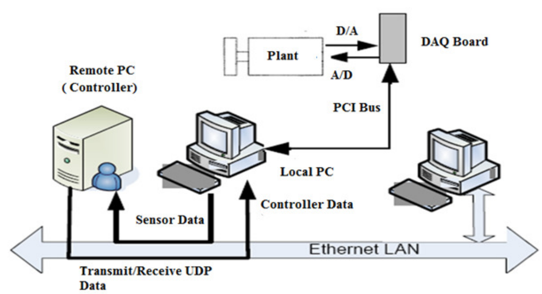

Fig. 9 Complete NCS system structure

Internet Protocol (IP) Suite has the set of network protocols used for the Internet, in which the User Datagram Protocol (UDP) is the core member. On an IP network two PCs are connected then they can communicate through UDP, where computer application sends information in the form of datagram from one PC to other PC. UDP has no handshaking signals hence it is unreliable communication. UDP use minimum protocol hence it is a simple transmission model. UDP is unreliable communication so that it has no guarantee for delivery; duplicate protection and ordering. UDP send the data in the form of datagram as a packet. UDP has no guarantee to the upper layer protocol for message delivery. UDP use checks sum method for error checking. It has no retransmission hence it is used in real time application. UDP use IP address and port number for communication between source and destination.

The steps involved in creating the network are given below.

- Install the real-time kernel in MATLAB and the command used to install is “rtwintgt -install” as shown in Figure 10
- Press the letter “y” to confirm the installation process.
- Make new model. Add a Packet block from Simulink library

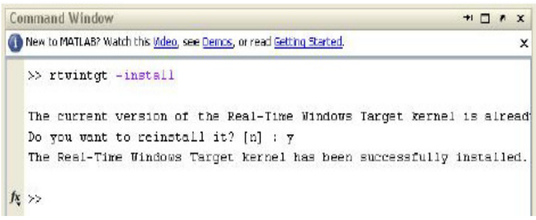

Fig. 10 MATLAB command window for install real-time kernel

- Change Packet Output block parameters as follows – Install new board > Standard Devices > UDP Protocol
- Board Setup> enter local UDP port, IP address of the remote PC and the remote UDP port
- Sample time as required
- Output packet size – 8
- Output packet field data types - '1*double'

The block parameters dialog box looks as shown in Figure 11. The sample time is a parameter that indicates, during simulation, the block produces outputs and if appropriate, updates its internal state. The sample time is also specified by the user.

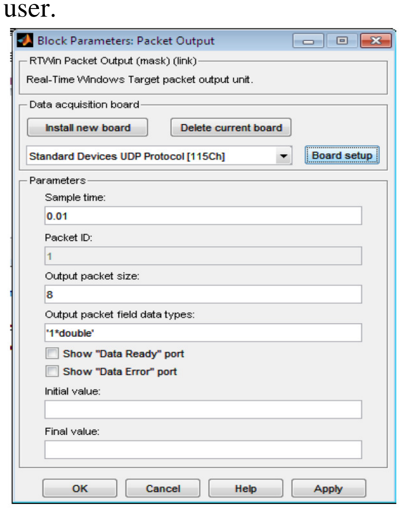

Fig. 11 Packet output block parameter

The board setup dialog box is shown in Figure 12. The address of the UDP standard device is specified using the Board setup dialog box.

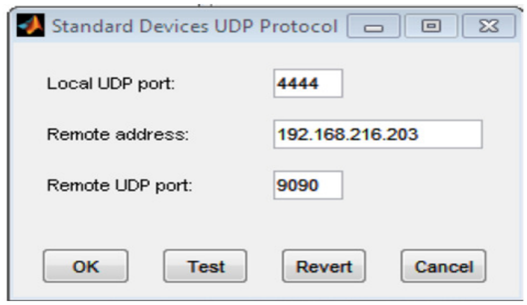

Fig. 12 Board setup dialog box

8. Network Demonstration

With the aroused interest in NCS, Figure 13 shows the laboratory test demonstrating the real time networked transfer of packets for the monitor and control of the plant.

Let the plant be the Pressure Process analyzer. As the air input 20 psi is given to the plant by the air regulator of 0-2.1 bar, the pressure inside the tank will be sensed by the piezoelectric transducer (0-6 bar) which is the conventional 4-20 mA , it is then converted to voltage by I to V converter (0 – 10 V). The converted voltage is given to the DAQ card (NI PCI 6251) via the ELVIS kit for the conversion of A/D which in turn feed to the PC with MATLAB, which constitute the target system.

Simulink model of a system will be in remote system as shown in Figure 15. The transmitting simulink model with set point is put in host PC as in Figure 14. The output of the controller is send via UDP packet data to plant which is available in remote PC. The control signal (0 – 100 %) for the control valve is of equal characteristic type to get settle in order to maintain the pressure inside the cylindrical vessel. This can be achieved by sending the control signal to the DAQ card for the conversion of digital to analog data which is again given to V/I converter. The converted current is given to current to pressure converter (I/P - 3 to 15 psi) for the successful operation of the control valve. The plant sends and receives the signals via the UDP packet.

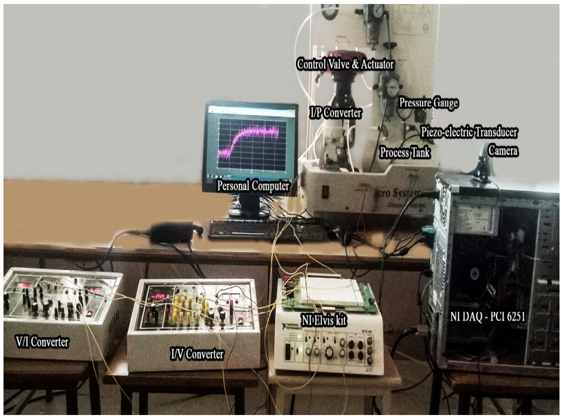

Fig. 13 Hardware setup of wireless control of pressure process analyzer

A mentioned using MATLAB package, the input set point is fixed in the host PC. The feedback signals from the pressure process station whose pressure has to be controlled are received. The error detector detects the difference between the set pressure and the output pressure. The error signal is send through the network to the remote station from the host station. Figure 14 demonstrate the model of the host.

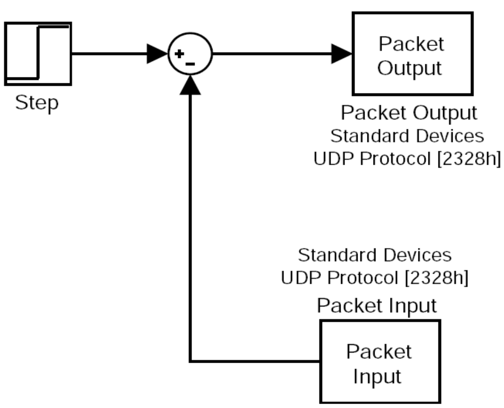

Fig.14 Model of the Host

The remote station receives the signal through the network along with the generated noisy signal. Figure 15 shows the model of the remote station along with the controller and the DAQ session. The Fuzzy Logic Controller takes the input as error and the derivative of the error. They compute the control signal as explained in the section 6. The analog output is send to the pressure station via the DAQ card. The analog output of the pressure station is send back to the host station (UDP 2328h) as shown in Figure 14.

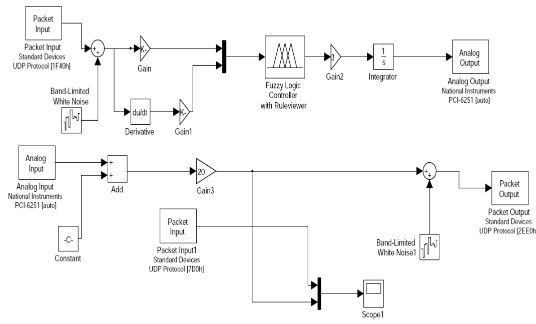

Fig.15 Model of the Remote Network

9. RESULT ANALYSIS

Direct connection (without network) involves dedicated connection between the personal computer and pressure process station. The pressure step input signal (Set point) is given as 20 psi. The sampling period of 0.01 seconds is specified. The step response of the Simulink model of a system without network is shown in Figure 16. Figure 16 can be concluded that in the absence of delay in system PI controller tuned by IMC technique shows a satisfactory response with settling time 8.2 seconds and no overshoot.

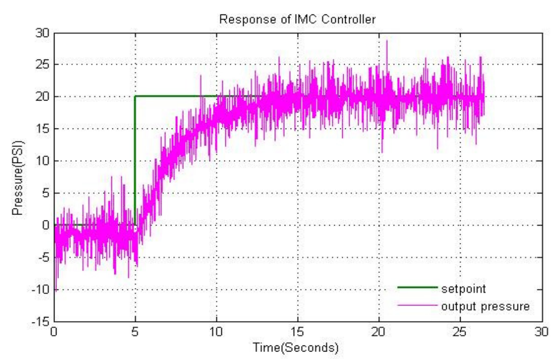

Fig. 16 Step response of simulink model of a system without network

The Figure 17 shows the oscillator response of the PI controller used in a Networked Control System (NCS). The transmitting simulink model with set point is put in host PC. The output of the controller is send via UDP packet data to plant which is available in remote PC. The plant sends and receives the signals via the UDP packet. The performance degradation is due to the presence of time delay that exhibit in the network data transfer. It can be concluded that in the presence of network itself exhibit delay.

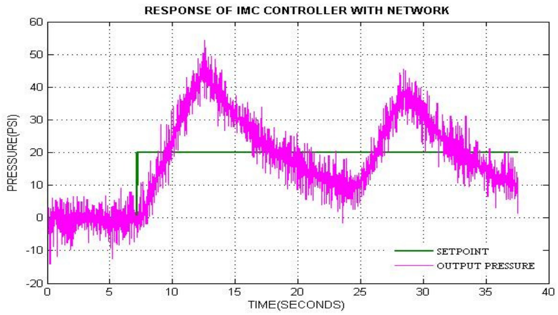

Fig. 17 Step response of simulink model of a system with network

The Figure 18 shows the closed loop response of Networked Control System with Smith predictor technique. The delay estimation technique involves sending the clock signal from local PC to remote PC via UDP packet and estimating the time it takes to reach the local PC. The delay was found to be 0.006 seconds. This delay information is used in delay estimation in simulink block to counteract the constraints of network delay. The Smith predictor technique can overcome the effects of network induced delay. The settling time was found to be 11.2 seconds with no overshoot.

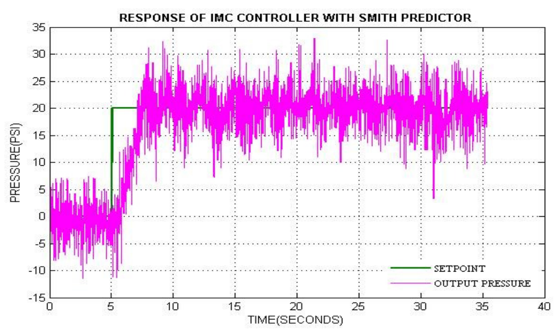

Fig. 18 Step response of simulink model of a system with smith predictor technique

Noises are due to poor workmanship in the cables and Electromagnetic Interference. Simulink model of a system in remote network in noisy environment and host network have been developed [9]. Band limited white noise is used in both forward and reverse path with noise power 0.25 and seed 23341. The Figure 19 shows the closed loop response with noisy environment. The Smith predictor technique can overcome the effects of network induced delay as in Figure 18, but cannot overcome the effects of network noises as shown in Figure 19.

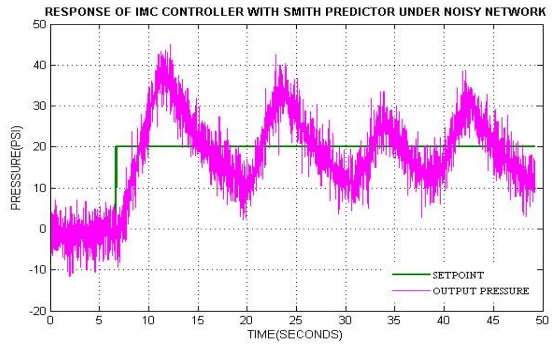

Fig. 19 Step response of simulink model of a system with smith predictor technique under noisy environment

The transient response of the Pressure process station is studied with and without network using fuzzy logic controller and software used for this MATLAB/Simulink environment with real time windows target tool box. Fuzzy rules are specified in Fuzzy Logic Controller with Rule viewer Simulink block. Figure 20 shows the response of simulink model of a fuzzy controlled system without network.

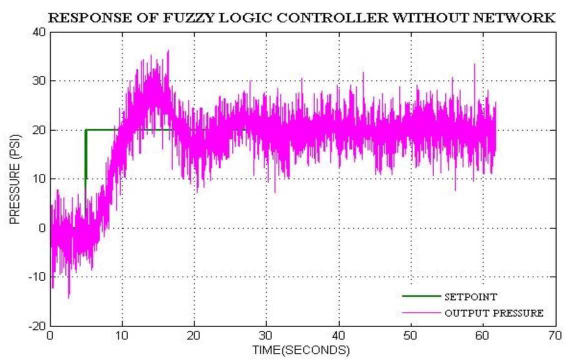

Fig.20 Step response of simulink model of a system without network

Simulink model of a system in remote network in noisy environment and host system network has been developed and the band limited white noise is used in both forward and reverse path with noise power 0.25 and seed 23341. Figure 21 show that fuzzy logic controller produces stable output even in the presence of noises under NCS. The settling time of FLC under noisy environment is 28.7 seconds and 33% overshoot. It is evident that FLC produces better and stable performance when compared to IMC based Smith Predictor.

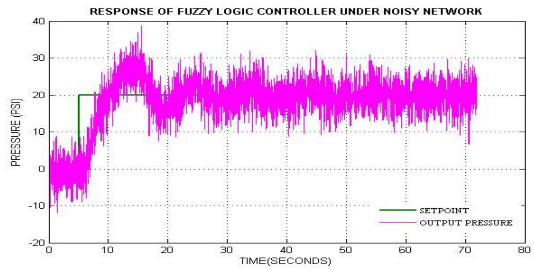

Fig 21.Step response of simulink model of system with network under noisy environment

The performance index of the designed controllers for with and without network environment is shown Table 2.

Table 2 Performance index table for designed controllers

Description	Responses
IMC Controller without Network	Stable
IMC Controller with Network	Unstable
IMC Controller with Smith predictor technique in Network	Stable
IMC Controller with Smith predictor technique in Noisy network	Unstable
Fuzzy Logic Controller without network	Stable
Fuzzy Logic Controller in Noisy network environment	Stable

10. CONCLUSION

NCS are distributed control systems that use networks in feedback loop. Use of such networks induces delay and noises in the closed loop. This paper dealt with development of a real - time Networked Pressure Process System using MATLAB/Simulink. In this paper real time network is established and discussed. The conventional PI controller and FLC are implemented for the NCS and it is analyzed for the system with and without network environment. It is evident from the results that FLC is stable in the presence of noise in the network. Thus, FLC can be used in industries where network noise is inevitable. Controllers discussed in this paper are not adaptive to match with the stochastic behavior of network characteristics. Improving the transient response of the system shall be the next work by changing the scaling factor and membership function. The process can be controlled and monitored using mobile applications through WNCS (Wireless Network Control System) [11].

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