Online Adaptive Fuzzy Logic Controller Using Neural Network for Networked Control Systems

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Abstract— **Networked Control Systems are used for controlling remote plants via shared data communication networks such as Ethernet. These systems have found many applications in industrial, medical and space sciences fields. However there are some drawbacks in these systems, which make them challenging to design. One of the most common problems in these systems is the stochastic time delay. Packet switching in internet brings about the randomly varying delay time and consequently makes these systems instable. Convenient controllers such as PID and PI type controllers which are just match with a constant delay time could not be a solution for these systems. Fuzzy logic controllers due to their none-linear characteristic which is compatible with these systems are potentially a wise option for their control purpose. Fuzzy logic controller could become adaptive by means of neural networks and beneficial to deal with the varying time delay problem. Further, they do have more capabilities to tackle packet dropouts and dynamically system variables. This paper introduces a novel control method which addresses the time delay varying problem effectively. This novel method suggests an online adaptive fuzzy logic controller which have been controlled and adapted through the neural network. This designed controller is applied to an AC 400 W servo motor as a remote plant in order to position control it via Ethernet. The measurement of round-trip time (RTT) is used to estimate the online time delay as a parameter in online adaptive fuzzy logic controller. The rule-based table of designed fuzzy logic controller rotates in relation to this estimated time delay. The value of rotating is obtained from a trained neural network. Comparison of results from simulations of different controllers and their comparison indicate that this novel designed controller provides a better performance over the varying time delay. The proposed method follows the input easily, despite classical methods which result in an unstable system especially over the large time delays as large as 600 ms.**

Keywords—**Data Communication Networks, Networked Control Systems, Neural Networks, Online Adaptive Fuzzy Logic Controller, Rules-Table Rotation.**

I. INTRODUCTION

Networked control systems (NCSs) are spatially distributed systems in which the communication between sensors, actuators and controllers occurs through a shared band-limited digital communication network [1], [2]. This multipurpose shared network connecting, spatially distributed elements, creates a flexible architecture which generally reduces installation and maintenance costs. NCSs have been finding application in a broad range of areas such as mobile sensor networks [3], remote surgery [4], haptics collaboration over the Internet [5]–[7], and automated highway systems and unmanned aerial vehicles [8], [9]. Murry et al. in [10] has identified control over networks as one of the key future directions for control. However, application of a shared network versus several dedicated independent connections, introduces new challenges. Drops and variable delays in NCSs are two major problematic issues that were addressed in [11], [12]. Packet dropouts and finite level quantization make NCSs unstable [12]. When the delay time is less than the sampling time of NCSs, results show that the time delay has insignificant effect on control system. However, delay time greater than the sampling time degrade the performance of the NCSs [13]. Many controllers such as conventional PID and fuzzy logic controllers are utilized to stabilize the NCS closed loop feedback and to reduce the error. Classical Smith predictor is one of the controllers which are efficient for time delay processes [13], [14]. Lai and Hsu proposed an adaptive Smith predictor as a controller for NCS in [14]. Despite showing relatively a good performance, there are some drawbacks in these controllers. For instance, the accuracy of the model depends on plant transfer function estimation .Moreover; each new plant requires changing the controller design. Practically estimation of plant transfer function is not exact .Recently Pan et al. in [15] and Dezong et al. in [16] have shown that fuzzy logic controllers offer a better performance in tackling packet dropouts and varying time delay, at the same time are more compatible with nonlinear processes. W. Du and F. Du proposed a Smith predictor integrated with fuzzy adaptive PID controller for the NCSs in [17]. However they did not measure the network delay online. They applied fuzzy logic controller for tuning the coefficients of PID controller. This paper first, suggests a fuzzy logic controller (without PID controller) to position control of an AC 400 W servo motor via Ethernet. At the next step, it proposes a novel control method which is an online adaptive fuzzy logic controller for the similar application. This research provides the advantages of no PID controllers application while offers an adaptive controller which it's fuzzy Logic rules are rotating during the plant control. The round-trip time (RTT) is measured online and this value is utilized as, t_m, time delay parameter. Then, this time delay value is mapped to an angle by means of trained neural network. This neural network has been already trained by

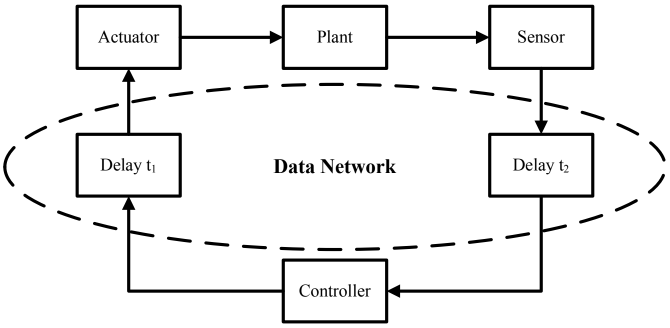


Figure 1. A SISO Networked Control System structure.

different time delays in adaptive fuzzy logic controller. Results verify the better performance of this novel design which its fuzzy logic controller rules-table rotates through a trained neural network. The fact is that in communication networks time delay could exceed 200ms (vs. 400ms, 600ms). However, results from [17] and [18] show that the response would be degraded in these systems for time delays over 200ms despite the application of designed offline controllers. This paper proposed method has shown an improved response especially in the case of time delays over 200ms. Even with time delay of 600ms, there is no degradation in step response.

This paper includes the following sections. In Section II, NCSs, stochastic time delay and packet dropouts are introduced. Section III ,first describes, designing a fuzzy logic controller in order to position control of an AC 400 W servo motor and next introduces a novel adaptive fuzzy logic controller with a rotating rules-table by means of trained neural network. Section IV contains the related simulations and equations. This paper ends with conclusion in section V.

II. NETWORKED CONTROL SYSTEMS

Due to quantum leaps in communication systems, in recent years, it has become more common to apply a shared communication channel such as Ethernet or CAN bus etc. for transmission of the control signal and the measured output. This method helps reducing the wiring costs as well as eliminates the necessity for maintaining dedicated communication channels for each control parameter [15]. However, this type of networked control system is not a perfect solution and own its various unsolved issues such as transmission delays and packet dropouts [12], [15] which can degrade control performance. The SISO (single input-single output) NCS structure in the closed loop model is shown in Figure 1.As illustrated in this figure, t_1 and t_2 indicates, time-delays induced in the network structure for the controller-to-actuator direction and the sensor-to-controller direction, respectively. Basically, the induced network delay varies according to the network load, scheduling policies, number of nodes, and different protocols. Time-varying characteristic of these NCSs makes the design and modeling of them more complicated. The total time-delay can be categorized into three classes, based on the parts where they occur, namely, the server node, the network channel, and the client node [20], [21]. In addition, the round-trip time (RTT) measurement is crucial as it provides of accurate delay measurements periodically [19]–[21]. RTT is defined as the total time delay in SISO NCSs. Obviously the longer distances increase, the delay time of a network since more nodes are involved and consequently results in a larger RTT. In a classical Smith predictor design, the value of t_m is constant and usually equals to average approximation of delay time between two nodes in the network. The value of RTT could be applied to fuzzy logic controller for compensating of variable delay. Normally in a fuzzy logic controller rules-base table is constant during the control process action. In this paper suggested method, RTT applied by neural network mapping, generates a rotating Rules-Table.

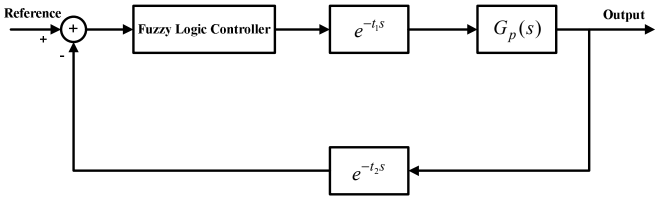


Figure 2. Fuzzy Logic Controller.

III. FUZZY RULES-TABLE ROTATION

As it has been already mentioned, an online adaptive fuzzy logic controller could be a solution for tackling the stochastic time delay problem in NCSs. However it controls with simple PID or PI controllers which shows limited potentials, especially in nonlinearity processes. Recently proved that fuzzy logic controller is the best option for controlling nonlinear processes while make the system more robust against the varying time delay [15] and [16]. In the following parts, first a fuzzy logic controller is designed then a classical Smith predictor would be integrated with this designed fuzzy logic controller based on our plant. Finally a novel rotating rules-table online adaptive fuzzy logic controller is described.

A. Designing Fuzzy Logic Controller

To implement a NCS controller, first the output of plant is measured and then it would be compared with a reference signal. This comparison generates the error signal. The error signal and derivation of error signal are both inputs for the fuzzy logic controller. Here in this paper, the plant is an AC 400 W servo motor which its position as an output is measured with an encoder with gain 10^4 P/R. The coefficients of the equivalent PI controller for this plant are Kp=0.0001 and Ki= 0.00000001, [14]. The open loop position control is obtained from Equation (1).

$$G_P(s) = \frac{10^4(0.058s + 3.221)}{s(0.0001s^2 + 0.019s + 1}$$

(1)

$$\dot{x} = \begin{bmatrix} -190 & -78.125 & 0 \\ 128 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} x + \begin{bmatrix} 2048 \\ 0 \\ 0 \end{bmatrix} U \tag{2}$$

$$y = \begin{bmatrix} 0 & 22.13 & 1228.7 \end{bmatrix} x \tag{3}$$

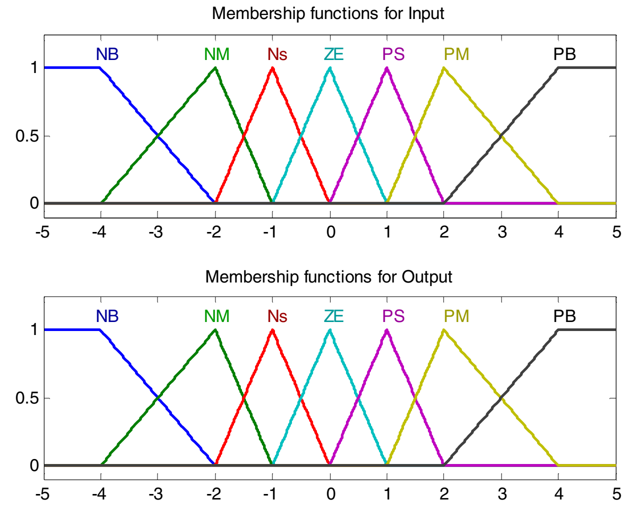


Figure 3. Membership functions for input and output.

Equations (2) and (3) represent the continuous-state space form of transfer function described in Equation (1). In Figure 3, seven triangular membership functions have been devoted to either, input (error and derivation of error) and output. In Figure 3, the fuzzy linguistic variables (NB, NM, NS, ZE, PS, PM, PB) represent (Negative Big, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium and Positive Big) respectively. Here are provided some design specifications, applied in this fuzzy logic controller: 1) The inference, used in this design is Mamdani-type, 2) Fuzzy logic "and operator" was implemented by "min" method while the fuzzy logic implication is based on the "min" method as well, 3) The fuzzy logic output has been determined through the center of gravity method by means of defuzzification, 4) Fuzzy rules are opted based on Table 1 which contains 49 rules,5) Due to high gain of encoder the scaling factor value selected for fuzzy logic controller output is ,10^{-4}.

B. Classical Smith Predictor with Fuzzy Logic Controller

Classical Smith predictor is one of the controllers which are efficient for time delay process [13], [14]. Here a classical Smith predictor is designed for comparing the results. In this classical Smith predictor which is shown in Figure 4, G_C is the designed fuzzy logic controller described in section III. A. G_P is the transfer function of the plant while $\hat{G}_P$ is the estimation of plant transfer function. Usually t_m is the approximation of total time delay from controller to plant and plant to controller. If t_m is the appropriate estimation of overall time delay the performance of system will be reasonable. t_m is assumed 200 ms in the simulation. $\hat{G}_P$, is the estimation of G_P, and practically difference between these two transfer functions results in instabilities and increases of the error of response. This is the main problem for classical Smith predictor and online adaptive Smith predictor. In this paper classical smith predictor with fuzzy logic controller was assumed ideal, thus the Gp and $\hat{G}_P$ are equal in the simulations. The fuzzy rules are selected based on Table I.

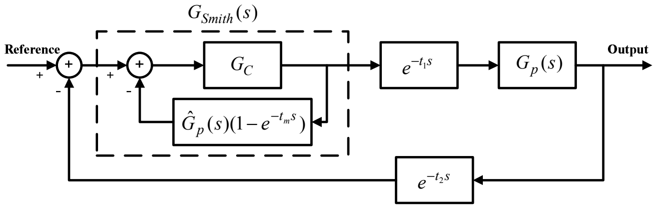


Figure 4. A control structure of Smith predictor.

TABLE 1. RULE BASES FOR ERROR, ERROR DERIVATION AND FLC OUTPUT (WITHOUT ROTATION).

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

C. Designing Rules-Table Rotation of Online Adaptive Fuzzy Logic Controller Using Neural Network

RTT is estimated in network [13], [20] and then this measurement would be applied to online fuzzy logic controller. In this stage the designed fuzzy logic controller in part A would be integrated with an online neural network. The measurement of round-trip time (RTT) is applied for estimating of online time delay which in turn provides the value for rotation angle of fuzzy rules-table. As already mentioned, the controller in this paper has not included any PID or PI method. The nonlinear fuzzy logic controller does have the potential to control the complicated and nonlinear processes while is more robust against the dynamically system variables specially occurs at the beginning of the process.

Thus, this paper has suggested a control method which integrated fuzzy logic controller with a neural network. Figure 5, shows the structure of this proposed controller. Here in this Figure, the value of RTT is mapped to an angle by neural network. The structure of neural network has two-layer feedforward. First this neural network is trained by several set point time delays. It means the value of rotation for several time delays is obtained manually Then these values will be applied for training the neural network.

The value of angle for rotating rules-table in online adaptive fuzzy logic controller, changes periodically based on the RTT value. Fuzzy rules are opted based on Table 2, but other parameters (membership functions, fuzzy logic operators and fuzzy logic method) are similar to data in section III.A. Equation (4) shows the mapping relation of the error and variation of the error in new coordinate. Matrix A, in Equation (5) is the rotation transform matrix which rotates coordinates

$$\begin{bmatrix} e_{new} \\ \dot{e}_{new} \end{bmatrix} = A\begin{bmatrix} e \\ \dot{e} \end{bmatrix} \tag{4}$$

$$A = \begin{bmatrix} -\sin\phi & \cos\phi \\ \cos\phi & \sin\phi \end{bmatrix} \tag{5}$$

TABLE 2. RULE BASES FOR ERROR, ERROR DERIVATION AND FLC OUTPUT (ROTATION TABLE).

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

by the angle of φ radian. The rules-rotation structure of fuzzy logic controller and trend of rotation is shown in Figure (6).

IV. SIMULATION RESULTS

A closed loop NCS unit in this paper includes these sections: online adaptive fuzzy logic controller, neural network, plant, data communication network. In order to analyse the whole unit each section should be analysed separately. This paper has applied the state equations to plot the step response of this NCS. At this first stage, transform functions of plant and controller are converted to state equations. Since the data transmitted over the network is digital these equation states need to be discretized state space equation to be able to simulate the processes. Equation (6) shows the discrete state-space form of process. While A, B, C and D are the continuous state space matrices then their equal discrete state space matrices (Ad, Bd, Cd, Dd) would be obtained from (7), (8), (9), (10). By substituting the Equations (2), (3) in to Equations (6-10), discrete state space form of plant is obtained and represented in Equations (11), (12).

$$\begin{cases} x[k+1] = A_d x[k] + B_d u[k] \\ y[k] = C_d x[k] + D_d u[k] \end{cases} \tag{6}$$

$$A_d = e^{AT} \tag{7}$$

$$B_d = \left(\int_0^T e^{A\tau} d\tau \right) B \tag{8}$$

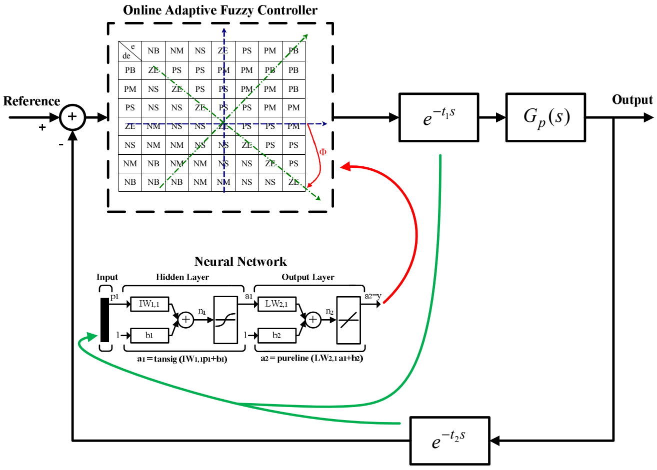
$$C_d = C \tag{9}$$

$$D_d = D \tag{10}$$

$$x[k+1] = \begin{bmatrix} 0.0066 & -0.2973 & 0 \\ 0.4870 & 0.7295 & 0 \\ 0.0035 & 0.0089 & 1 \end{bmatrix} x[k] + \begin{bmatrix} 7.7924 \\ 7.0909 \\ 0.0277 \end{bmatrix} U[k] \tag{11}$$

$$y[k] = \begin{bmatrix} 0 & 22.13 & 1228.7 \end{bmatrix} x[k] \tag{12}$$

In these simulations a random delay time is provided to analysis the feedback of NCS. The total of command delay, t_1, and forward delay, t_2, generates the total time delay (RTT) which is shown in Figure 7. After training of neural network, the biases and weights values are obtained shown in Table III. Neural network functions for layer 1 and layer 2 are "tansig" and "pureline" respectively. The sampling time is assumed 0.01 second and the model of NCS is based on the model described in [22]. Here in this paper the simulations and comparisons of the step response are provided among three controllers type: 1) Online adaptive fuzzy logic Controller, 2) Classical Smith predictor with fuzzy controller and 3) Pure fuzzy logic controller. The results are illustrated in Figure 8. Results show that the online adaptive fuzzy logic controller offer a better performance compared to other two controllers. As can be seen the output signal of online adaptive fuzzy logic method does have small overshoot and fast response. Therefore this controller is recommended for networked control systems purposes. W. Du and F. Du have suggested a Smith predictor integrated with adaptive fuzzy-PID controller for the NCSs in [17]. However they did not measure the network delay online. They applied a fuzzy logic controller just for tuning the coefficients of PID controller, which means that their suggested controller is worked offline. They also have designed in [18] a RBF neural network control with Smith predictor for NCSs which is worked offline as well. In communication networks time delay could exceeds 200ms (vs. 400ms, 600ms). The results from [17], [18] show that response would degrade with time delays over 200ms. In [17], [18], it was assumed that the maximum of burst time delay is about 200ms while this time delay was applied discretely. Our proposed method has more improved response especially when the time delay is over 200ms even with the time delay of 600ms there is no degradation in step response. In the spite of applying this large value of time delay continuously, results in Figure 9 show that this does not have any more effects on the step response as well.

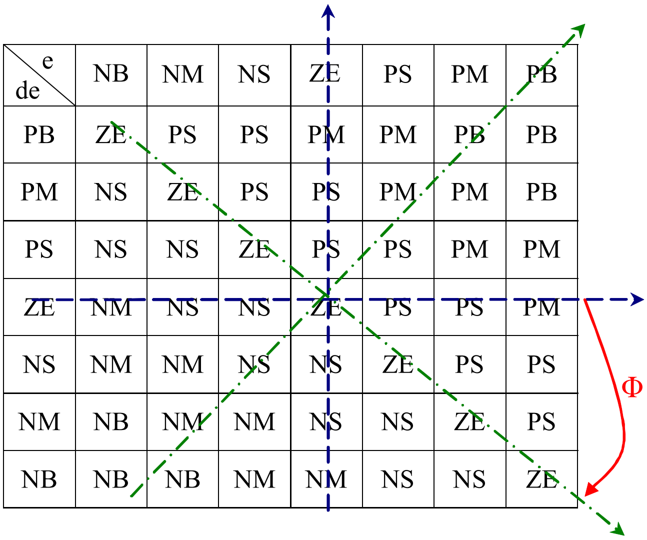


e de	NB	NM	NS	ZE	PS	PM	PB
PB	ZE	PS	PS	PM	PM	PB	PB
PM	NS	ZE	PS	PS	PM	PM	PB
PS	NS	NS	ZE	PS	PS	PM	PM
ZE	NM	NS	NS	ZE	PS	PS	PM
NS	NM	NM	NS	NS	ZE	PS	PS
NM	NB	NM	NM	NS	NS	ZE	PS
NB	NB	NB	NM	NM	NS	NS	ZE

Figure 5. Structure of Online Adaptive Fuzzy Logic Controller Using Neural Network.

V. CONCLUSIONS

NCSs have found widely application in various fields recently. However there are some drawbacks in their structure such as varying time delay and packet dropouts, which makes the control design of these systems challenging. Conventional PID and fuzzy logic controller are mostly designed to address the instability problems in NCSs. Fuzzy logic controllers with the great potential in tackling the nonlinear processes and making NCSs more robust against the dynamically variable parameters could be a more reasonable option for NCSs. Moreover, a rotating Rules-Table fuzzy logic controller is a great solution for stochastic time delay.



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

Figure 6. Rotating of Fuzzy Rules-Table .

TABLE 3. WEIGHTS ANSD BIASES VALUES FOR NEURAL NETWORK.

$net.IW\{1\} = \begin{bmatrix} -0.0057 \\ -0.2547 \end{bmatrix}$	$net.LW\{2\} = \begin{bmatrix} -0.3566 & -0.8011 \end{bmatrix}$
$net.b\{1\} = \begin{bmatrix} 1.1243 \\ 24.6125 \end{bmatrix}$	$netb\{2\} = 1.0024$

Thus according to above mentioned characteristic of both fuzzy logic controller and rules-table rotation, this paper have proposed a novel controller for NCSs. This novel design have integrated a rotating rules-table fuzzy logic controller with a neural network to position control a 400 W servo motor as a remote plant via Ethernet. Simulation results and their comparison for three different method of controlling over this plant verified that this novel controller design is more beneficial especially over the big value of delay times as large as 600 ms.

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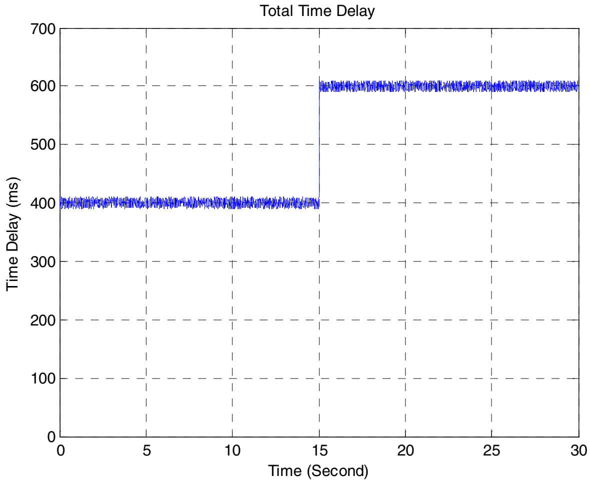

Figure 7. Varying time delay applied in this paper simulations.

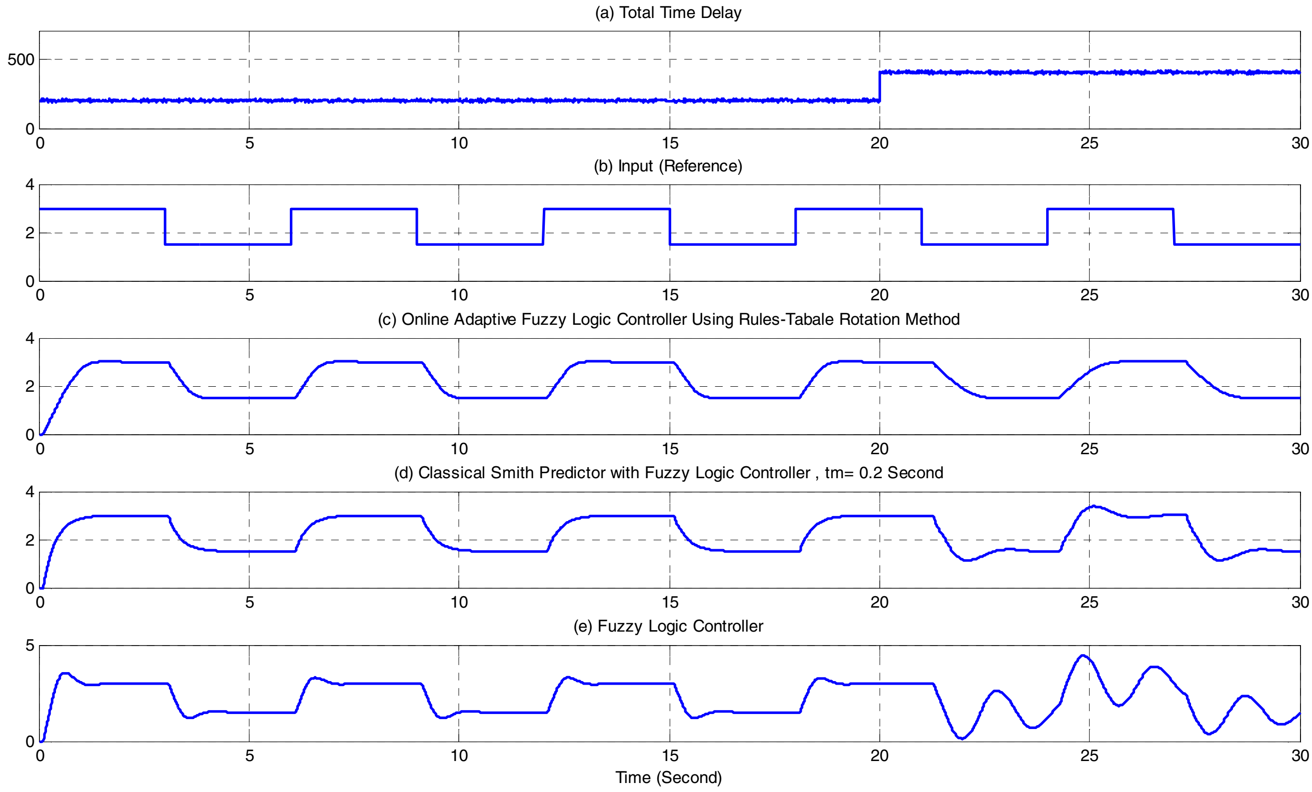

Figure 8. Simulation results; a) Time delay; b) Reference signal; c) Online adaptive fuzzy logic controller using rules-table rotation; d) Classical Smith predictor with fuzzy logic controller; e) Fuzzy logic controller.

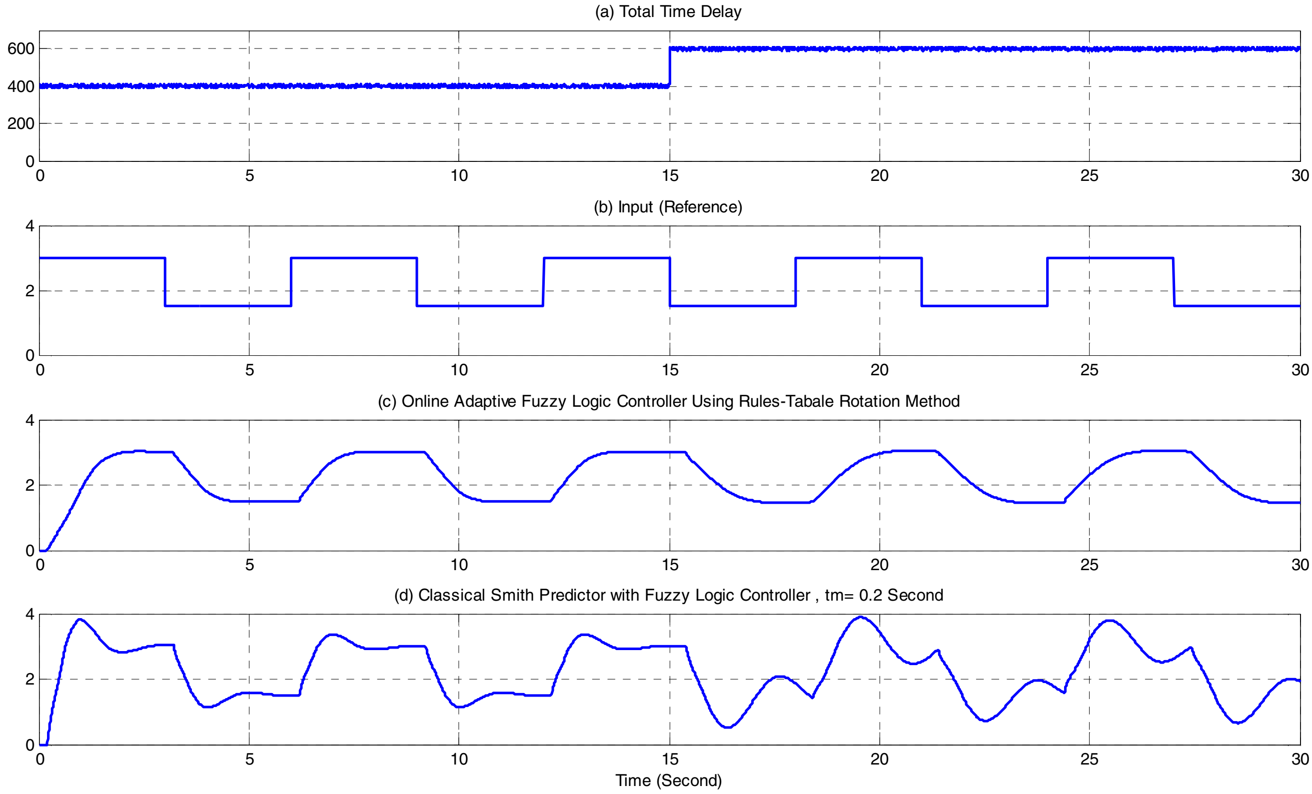

Figure 9. Simulation results (The maximum delay time is about 600 ms); a) Time delay; b) Reference signal; c) online adaptive fuzzy logic controller using rules-table rotation; d) Classical Smith predictor with fuzzy logic controller.