Time Delay Processing In Networked Control System Using Smith Predictor and ANN Based Error Predictor

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Abstract: ***Networked control system is essentially a closed loop system with a plant and controller, with the plant located in a remote area and controlling done through data communication networks. This depicts a nonlinear plant with stochastic time delay. This paper offers comparison of three models one of which is a novel method. Fuzzy logic controller is the best option amongst the conventional controllers like PI, PID being flexible and nonlinear. Promising robust control systems are possible with FLC in combination with new adaptive systems. Neural network is used to make FLC adaptive; however the method used is new. Classic method for time delay is Smith predictor which is also used here. Time delay can go up to 600ms, hence the operating range for simulations. Plant selected to run the simulations is an AC 400W servomotor.***

Keywords: Artificial Neural Network, Fuzzy Logic Controller, Networked Control System, Smith Predictor, Time Delay.

1. Introduction

Most accepted definition for a networked control system (NCS) is, "spatially distributed systems in which the communication between sensors, actuators and controllers occurs through a shared band limited digital communication networks" [1], [5]. According to the prevailing opinions, control over networks is one of the key future extensions [2]. Applications of NCSs justify this prediction. Some of the many applications are remote surgery, mobile sensor network, unmanned aerial vehicle and automated highway systems. When the data communication is in the digital domain two issues to be addressed are packet drop outs and finite level quantization. Digital communication via shared networks contributes one another complication- stochastic delay. These issues combines makes the system unstable. Observation suggests that a delay less than sampling time cannot be harmful.

Comprehending facts from shared data communication, controller is expected to be efficient enough to stabilize the system and tackle delay problems other than conventional duty of error reduction via feedback. Panet et al. and Dezong et al. in [8] and [9] respectively filter out fuzzy logic controller from other controllers for NCS's application. They proved that numbers for fuzzy controllers stands out for tackling delay and packet dropouts. Also compatibility of FLC is more for nonlinear processes.

Use of Smith predictor in networked control was identified by Lai and Hsu in [7]. Recently efforts are made to enhance the Smith predictor efficiency using adaptive mechanisms. Here Smith predictor is utilized in its classical format along with fuzzy logic controller. Simplicity of concept and application is the major reason behind this approach. This arrangement itself will avoid delay problems up to a range of 400ms.

However the range of delay in data communication spans to 600ms, which calls for another method to tackle delay problems. Error can be predicted in proportion to the delay using the rules table of fuzzy logic controller. Neural network can perform this task. Artificial neural network (ANN) is one of the best adaptive mechanisms and the soul of intelligent control. Adaptation by prediction is the specialty here. To illustrate afore mentioned methods, system chosen is an SISO networked control system as depicted in Figure 1. Itinerary of this paper is as follows. First task is designing a fuzzy logic control system exclusively for controlling position of an AC 400W servomotor. An FLC acting alone is the first system in the line, next comes FLC and Smith predictor. How a Smith predictor helps to avoid time delay is also tried to explain briefly. Third one is FLC with rules table rotation. ANN is manually trained before applying to the FLC with various delay inputs. Output of ANN leads to new pair of errors.

This paper is arranged in six sections. First includes a briefing on networked control systems. It is followed by the design of fuzzy logic controller and model1. Next section is about model 2 and Smith predictor which is its heart. Model3 which include Artificial Neural Network is discussed in the V chapter. Simulations results and analysis occupy the following sections. Last section is the conclusion.

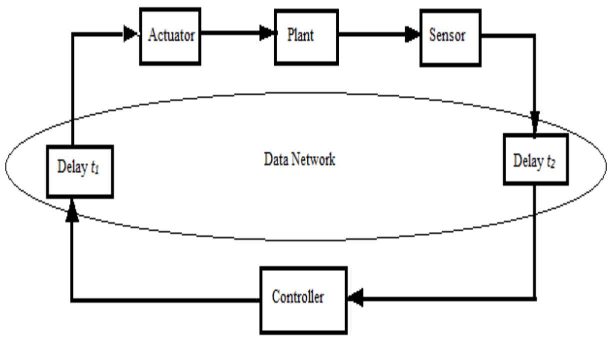

Figure 1: Block diagram of SISO networked control systems

2. Networked Control Systems

While attempting to explain NCS, one may have to cover numerous subjects as NCS is an interdisciplinary area. Two major subjects NCS contain are data communication and control system. The advent of digital communication over the years pushed usage of shared communication network as channel, to name a few Ethernet, CAN-Controller Area Network etc. to communicate between controller and actuator and sensor and controller. This has economical advantages over independent networks as channel. While saying that shared networks their complications to deal with, packet dropouts and stochastic transmission time delay. Figure 1 given, describes a Single Input Single Output (SISO) NCS at a block level. t_1 is the sensor to controller delay and t_2 is the controller to actuator delay. These delays are preceded by an adjective stochastic because the multiple factors affecting time delay in this network cannot be extracted into an equation. Main factors effecting NCS transmission time delay are, number of routers implanted throughout the channel, protocol obeyed by the network and scheduling policies. There is one more delay, computational delay which is inherent to any control system, but in most of the cases these comes in the range of tens of milliseconds and hence can be ignored. To execute the second and third models total time delay in the system need to be known, a term is used to represent this total time delay- RTT (Round Trip Time). This calculation is done using the time stamped data packets in the network layer level.

3. Model 1: Fuzzy Logic Controller

Model 1 is the simplest model among the three. Fuzzy logic controller is solely tried in this system. Obviously fuzzy logic controller alone cannot do anything about the delay, however it act as a reference model from which other two important models can be made. The rotation angle manually determined is derived from this model and also the performance at each step is evaluated keeping the response of the system without any delay as a reference. In [8] and [9] it is stated that fuzzy controller gives robust performance even for nonlinear system. Design of the fuzzy logic controller depends on the plant and not on any other factors, which implies that simply an FLC is designed for a servomotor here.

3.1 Designing a Mamdani fuzzy logic controller for AC servomotor

By definition a servomotor is an automatic device that uses error sensing feedback to correct the performance of a mechanism, being specific for this application- position control. Precisely position of the AC servo motor will serve as actual output, desired or reference input will be the input to system. A transfer function representing plant dynamics and characteristics is given in [8] which is quoted here in (1). State space representation of the system also is given in (2) and (3). These values will be used during simulation of the system. AC servomotor has an in built encoder that contributes a gain of 10^4.

$$G(s) = \frac{863.19}{S^2 + 105.58s} \quad (1)$$

The inference type fuzzy controller to be designed is Mamdani type, and Mamdani type has a rules table. Before that the type of membership function to implement the rule is decided as triangular membership function. Both 5x5 and 7x7 rules table are used for servomotor, 7x7 proved to be more accurate [22]. The seven membership functions representing both error and derivative of error are given in Figure 2. Linguistic variable each membership function represents is explained below.

NB- Negative Big NM- Negative Medium
NS- Negative Small ZE- Zero
PS- Positive Small PM- Positive Medium
PB- Positive Big

Since it is position control it is safe to assume same membership functions and variables to inputs and output. Therefore Figure 2 represents both inputs and output. Rules table assigned for the Mamdani type controller is given in Table 3. The encoder gain addition is deducted by a gain of 10^{-4} as a scaling factor of controller output. Other steps to complete design are, describing the type of implication, aggregation and Defuzzification which are min method, max operator and centroid method respectively. Following the convention and operator represents min method.

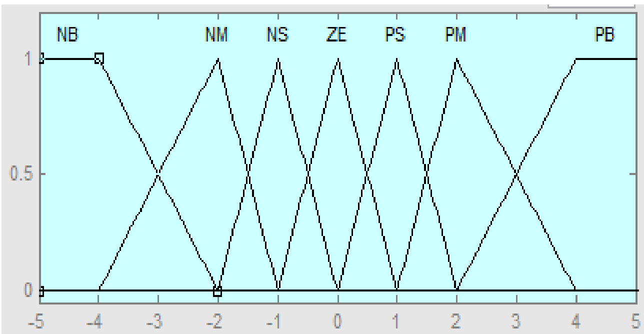

Figure 2: Membership function for input

Table 1: Rules table for FLC

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

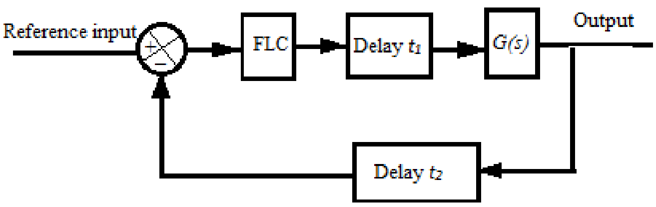

Figure 3: Model 1

Block level representation of 1st model is given in Figure 3. As mentioned before it is the simplest model of all and it act as a reference model. It will go to unstable state with delay increment.

4. Model 2: Smith Predictor

Model 2 is an improvement over model 1. This is one of the most preferred conventional manners to manage system with pure time delay. Simulation results from section 6 justify this fact. In this classical Smith predictor arrangement is attached with fuzzy logic controller. Without any algorithm or coding requirement a fair amount of delay problems can be tackled.

4.1 Designing classical Smith predictor

Smith predictor is the invention of O J Smith in 1957. It's a predictive controller for time delay systems [5], [7]. Understanding the working of Smith predictor is necessary to apply the same in this context. Let *G(s)* be plant, *C(s)* be controller, and t total time delay. Then transfer function of the system without any time delay is,

$$G(s) = \frac{G(s)C(s)}{1+G(s)C(s)} \tag{2}$$

Transfer function of the system when the plant have a delay of t seconds is,

$$T_d(s) = \frac{G(s)C(s)e^{-ts}}{1+G(s)C(s)e^{-ts}} \tag{3}$$

This delay will make controller act on the wrong input. If the controller is also delayed or the delay acts on the system not just on the plant, a stable system with desired output can be designed. Let $C_s(s)$ be the new controller to fulfill this requirement. Equation defining this new controller can be obtained as given,

$$\frac{C_s(s)G(s)e^{-ts}}{1+C_s(s)G(s)e^{-ts}} = \frac{G(s)C(s)}{1+G(s)C(s)}e^{-ts}$$

$$C_s(s) = \frac{C(s)}{1+G(s)C(s)(1-e^{-ts})} \tag{4}$$

From the above derived equation for the control structure Smith predictor will be as given in Figure 4. In this $G_s(s)$ represents the predicted model of the functioning plant. One pointed to be noted in this scenario is that efficiency of a Smith predictor depends on the accuracy of the model used in the controller part to represent the plant.

Block level representation of model 2 can be formed now. In Figure 5 *C(s)* is the fuzzy logic controller designed in the former section. $G_s(s)$ is the predicted model of the actual plant *G(s)*. There are two visible feedback loops in this; outer loop is the obvious loop that generates error by comparing input and output. Inner loop engages controller for t seconds with the predicted model. This system avoids the situation of controller acting on obsolete data.

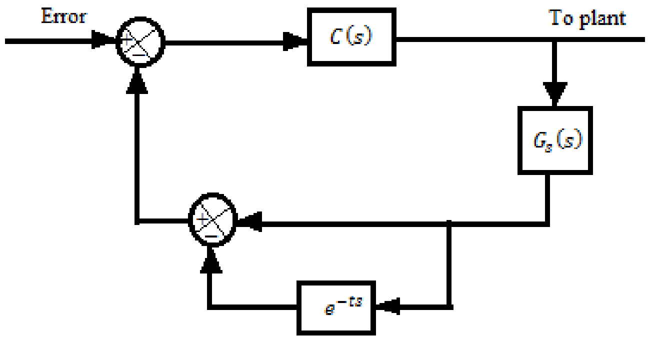

Figure 5: Smith Predictor

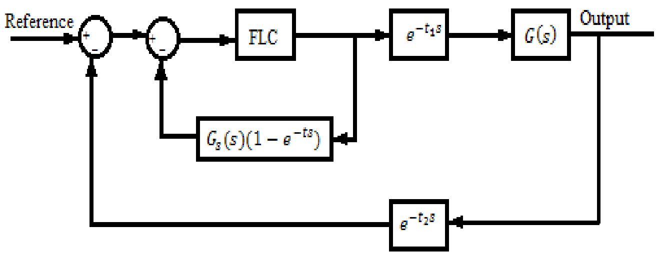

Figure 6: Model 2

5. Model 3: ANN Error Predictor

This model is the most advanced one and as the results would suggest later, the best among three. It uses artificial neural network as adaptive system to fuzzy logic controller. What is the changing parameter that controller needs adaptation to? Answer is time delay. Elaborating according to the situation, the position encoder signal send from the plant will reach controller after a time delay and this controller signal again reach plant after a delay. This controller signal is of no use and also it degrades the system performance. In [10] it is observed that rules table of FLC follows a particular angle. In other words error and derivative of error of FLC follows and repeat a path. If it is possible to predict this angle according to the time delay, that opens window to the best time delay processing method. Since this delay-angle proportion does not obey any equations a learning machine is required- Artificial Neural Network (ANN) provides this.

5.1 Designing ANN error predictor for FLC

First challenge in the design is computation of total time delay or RTT. This task is done in the network level using time labeled data packets. This delay is the input of the ANN. ANN will compute corresponding angle. Suggested network is a feed forward network with two layers. Figure 6 represents the layers of ANN. Before implementing neural network to the system, it needs to be trained. Since the domain of the communication network is digital, several inputs and respective outputs are taken manually and fed to the network. After this it will be ready to implement.

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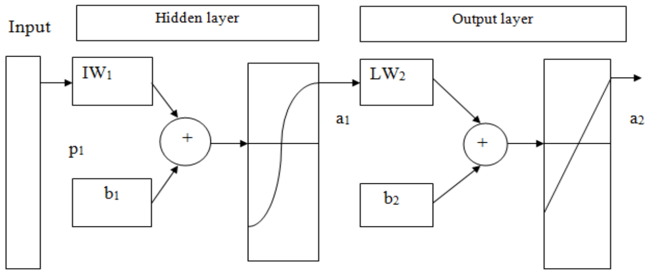

Figure 7: ANN structure

Neural network gives the angle. Since the FLC inputs are error and derivative of error, this angle must leads to new error and derivative of error. [11] gives a relation as below,

$$\begin{bmatrix} e_n \\ \dot{e}_n \end{bmatrix} = A \begin{bmatrix} e \\ \dot{e} \end{bmatrix} \tag{5}$$

$$A = \begin{bmatrix} \cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi \end{bmatrix} \tag{6}$$

The error predictor is therefore is not just the neural network but includes the calculation above mentioned. φ is the angle obtained from ANN. Model 3 using this neural is given in Figure 8. Error predictor includes neural network and error mapping algorithm.

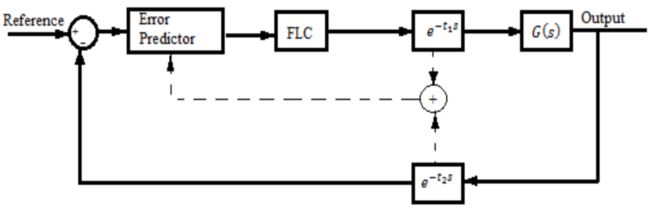

Figure 8: Model 3

6. Simulation Results

Result and analysis is essentially interpreting the step responses of each model at different delays. As the delay increases system response tends to degrade. As mentioned before response of the 1st model without delay is the reference to all other responses because it can be considered as ideal response. Figure 8 illustrates the response of the 1st model, the response is good. Reference signal is also there in red lines. There is no overshoot and less rise time and settling time. As a delay of 100ms is introduced to the system response become slow as shown in Figure 9. Still there is no overshoot, but large increase in settling time and rise time can be observed.

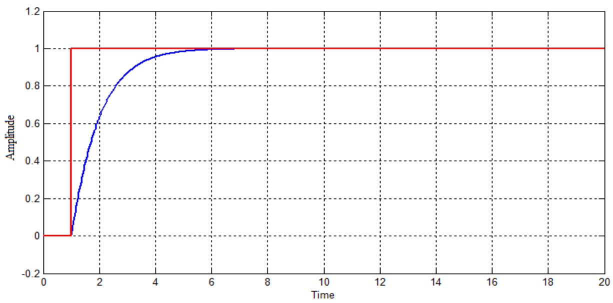

Figure 8: Model 1: without delay

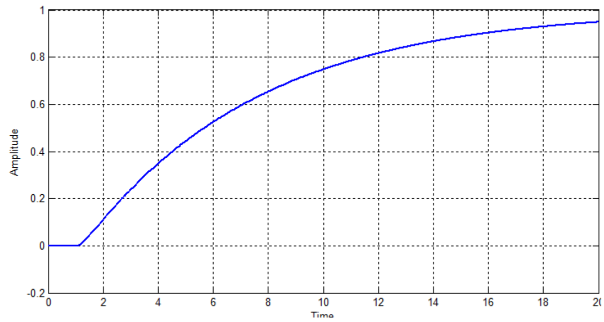

Figure 9: Model 1: with delay

Mode 2nd have Smith predictor to manage delay. Response of this model for 100ms is promising. It is portrayed in Figure 10 but when the delay is increased response starts degrading. Response for 200ms and 300ms is shown in Figure 11 and 12 respectively. A slight overshoot with delay is observed and the system response as a whole is slowing down.

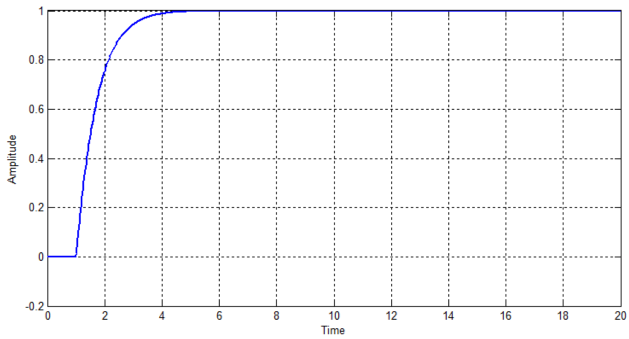

Figure 10: Model 2: with a delay of 100ms

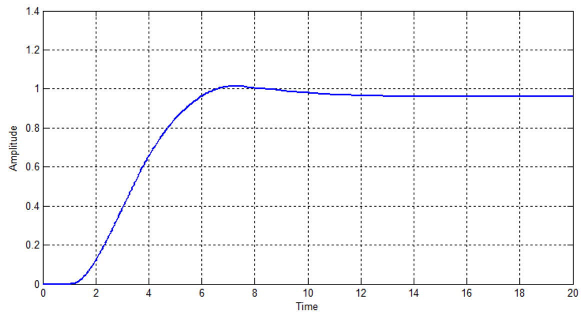

Figure 11: Model 3: with a delay of 200ms

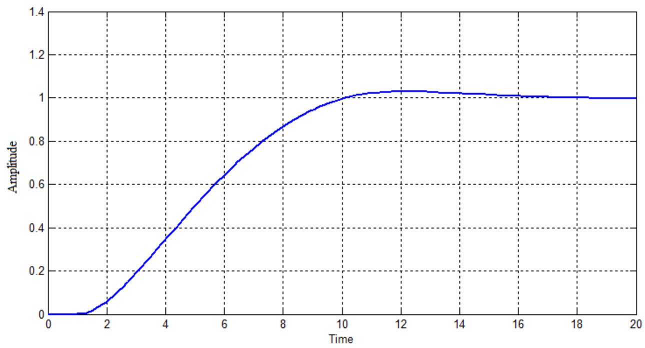

Figure 12: Model 2: with a delay of 300ms

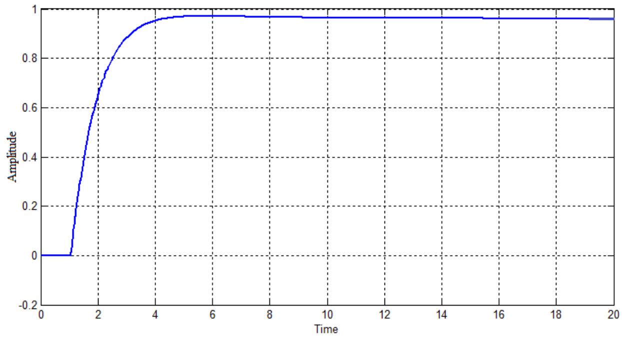

Figure 14: Model 3: with a delay of 300ms

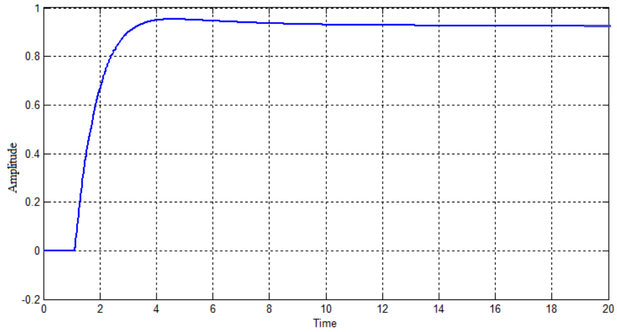

Figure 15: Model 3: with a delay of 400ms

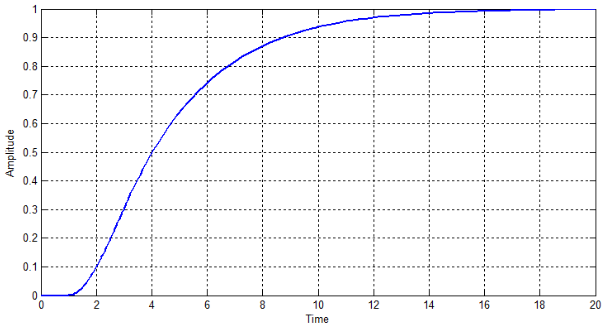

Figure 15 Model 3: with a delay of 600ms

Next analysis is of model 3 which consists of artificial neural network named as error predictor. Different responses for this is depicted in Figure 13, 14 and 15. other than the slight decrease in gain the system response is promising. One way to improve system response is by training the neural network with more delay.

7. Conclusion

Multi-facet applications of NCSs are reflected in the importance given to research and development in this area. The major improvement required is in the case of delay processing. This paper suggests three methods and made three model ideas out of it. Fuzzy Logic Controller proved to be the best option for controller mainly because of the compatibility and flexibility with nonlinear processes. Also results shows that FLC with Smith predictor and with artificial neural network is giving promising result in delay tackling. Smith predictor is already proved to be a good option for delay processing; this is stressed once more here. An idea of error predictor is derived using the artificial neural network. Results highlight that it is the best option among three.

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