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Fuzzy Immune Control Based Smith Predictor for Networked Control Systems

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***Abstract*—According to the fact that network is a class of discrete event system. Discrete-event simulation tool SimEvents is used to build network dynamic model so as to simulate network-induced delay and packet dropout in networked control systems. The concept of round trip time is introduced to estimate network-induced delay, which is compensated by Smith compensator. By using the control algorithm composed of immune feedback control and PI control, we achieved the goal of overcoming control deviation caused by changes of object model. The simulation results illustrate that the fuzzy immune PI control based Smith predictor provides better performance.**

***Index Terms*—networked control systems, SimEvents, Smith compensator, fuzzy immune PI control**

I. Introduction

Networked control systems (NCS) have emerged as a significant topic for research with the development of networks, computers and control methodologies. It is a fully distributed, network-based real-time feedback control system [1]. Sensors, controllers, actuators and other devices are located in different geographical space and information is exchanged by network. NCS has the characteristics of resources sharing, remote operation and control, high flexibility, high reliability, easy to install and maintain. Thus it is widely applied in manufacturing plants, automobiles, aircraft and many other applications.

The insertion of communication network in control loop will contribute to the network-induced delay and packet dropout in the process of transmission which can result in the degradation of system performance and even lead to instability. In order to maintain stability and achieve good control performance, there are two main research directions which are carried out in NCS design. One approach is to study from the network point of view, such as improve the communication protocol, congestion control, avoidance algorithms and network scheduling methods [2][3]. The other is to study from the control point of view which treats the network structure and protocol as given conditions so as to design the system structure, and improve control algorithm to guarantee system stability. The paper takes the second case into consideration. Within the framework of discrete control system of the independent random delay less than a sampling period and delay with Markov properties Nilsson discuss LQG optimal controller design [4]. Luck and Ray established a buffer zone at the end of the controller and actuator to make the random delay determined, then used the deterministic method to design the linear state feedback controller based on observer [5]. Tipsuwan and Chow introduces the concept of the network round-trip time (RTT) to dynamically schedule the controller gain and achieve the purpose of optimal control by changing the controller gain and not changing the structure [6]. Tingna Shi and Sujuan Wang regard the plant and network as a time-varying system, and then use Smith compensator to compensate [7]. Nikolai et al. present two methods: adaptive Smith predictor and robust control based approach, which need clock synchronization protocol in each device and end-to-end upper bound delay estimate separately [8].

The methods mentioned above almost use augmented vector to model and analyze the generalized object, which is composed of communication network and controlled object. However, system analysis and controller design would be greatly complicated because of systematic complexity. In this paper, communication network is modeled alone, and then is connected in series with controlled object. We use RTT to estimate the network-induced delay in real time which is dynamically compensated by Smith predictor. Finally, we combine Smith predictor with fuzzy immune PI control to improve the system control performance.

II. System Description

A. System Architecture

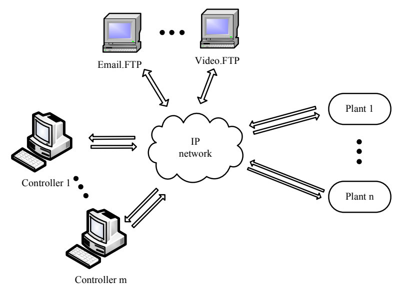

Figure 1. Networked control systems over IP network

There are two general NCS configurations: direct structure and hierarchical structure [9]. In this paper, we consider a distributed networked control systems configured over an IP network as shown in Fig. 1. The IP network links all network control devices. In this paper, we assume that the control devices use UDP (User Datagram Protocol) as the transport layer protocol on the IP network to avoid delays from

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retransmissions. Controller converts the difference of reference signal and the sensor signal which is sent across the IP network from plant into numerical feedback data for control response. The control signal from the controller is then sent back to actuators via the IP network as packets.

In order to facilitate analysis, we consider single-input single-output networked control systems whose basic structure shown in Fig. 2, where, r is the reference signal, u is the control signal, u_{com} is the control signal transmitted through network, y is the output signal, y_m is the sensor sampling signal, y_{com} is the sensor sampling signal transmitted through network.

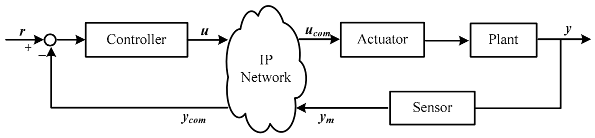

Figure 2. Networked control systems architecture

B. Simevents

As the randomness and distributivity of information, network can be treated as a class of discrete event system. At present, the existing special network simulation software such as NS2, OPNET are both based on discrete-time technology. They provide a wealth of network simulation model library and high-level language programming interface, but there is much faultiness in simulation of dynamic system [10].

SimEvents extends Simulink with tools for discrete-event simulation of the transactions between components in the system architecture. We can use the architecture model to analyze performance characteristics such as end-to-end latencies, throughput, and packet loss. SimEvents can also be used to simulate a process, such as a mission plan or a manufacturing process, so as to determine resource requirements or identify bottlenecks. Libraries of predefined blocks, such as queues, servers, and switches, enable us to represent the components in system architecture or process flow diagram. We can accurately represent system by customizing operations such as routing, processing delays, and prioritization. In short, SimEvents and Simulink provide an integrated environment for modeling hybrid dynamic systems containing continuous-time, discrete-time, and discrete-event components. Typical examples occur in communications, automotive, electronic systems, sensor networks, and other distributed control applications. Thus in this paper SimEvents is applied to establish the network model of NCS.

C. Network Model

UDP is a connection-less protocol that runs on top of IP network, which offers a direct way to send and receive datagram over an IP network. In order to avoid delay from retransmission assuming UDP as transport layer protocol in NCS, we need to make sure that the process data enter the output buffer queue of network device waiting to send according to the FIFO strategy. Droptail is used as data loss strategy of buffer queue, that is, all the new received data is discarded when the value of queue length reaches its maximum. According to the above conditions we build the network model of NCS which is shown in Fig. 3, where port 1 represents input data into network, port 2 represents output data transmitted through network.

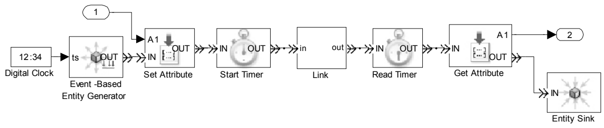

Figure 3. Network model of NCS

III. Design of Smith Compensator

A. Dynamic Estimation of Round-trip Time

Actual IP network delays are not constant, but stochastic in nature. To estimate actual IP network delay, RTT is introduced. In the context of computer network, the signal is generally a data packet, and the RTT time is also known as the ping time. In this paper, RTT means the total time from the sender sending data to the sender receiving confirmation from the receiver. Because UDP is treated as the transport layer protocol in the paper, there is no direct confirmation signal returned to the signal source, and sample packet with timestamp sent to the controller can be regarded as the confirmation signal. Thus controller get timestamp by solving sample packet, then get round-trip time through subtracting timestamp from the current time of controller, denoted by $\hat{\tau}(t)$. RRT reflects the overall network transmission delay directly and can be regarded as delay estimate which is dynamic compensated by Smith predictor.

B. Design of Smith Compensator

Smith predictor is a common control method used in time-lag system. Networked control system with Smith predictor shown in Fig. 4, where , $G_c(s)$ is the controller, $G_p(s)$ is the controlled object, $\hat{G}_p(s)$ is the estimation model of the controlled object, $e^{-\hat{\tau}(t)s}$ is the estimation model of network delay, other parameters mean the same as Fig. 2.

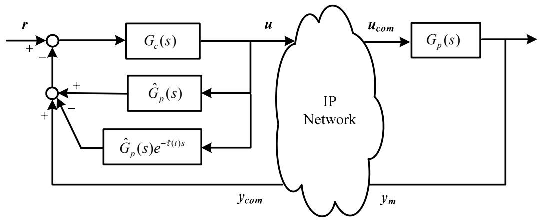

Figure 4. NCS with Smith Compensator

The dynamic characteristics of controller decide the system control performance, in which the delay of control channel has a major impact on control performance, while the delay of the control channel is composed of pure lag time of controlled object and network delay time. So the system control performance is mainly affected by network delay time when the dynamic characteristic of controlled object is almost unchanged. However, the actual dynamic characteristics of controlled object will change within a certain range and the estimation model of network delay will exist error for the problem of clock synchronization. Thus, system just only with Smith compensator can not achieve a satisfied result. It is necessary to introduce an effective method of control to overcome the adverse effect caused by variation of model and network delay error of the system.

IV. Fuzzy Immune Control Algorithm

A. Immune Feedback Principle

Immunity is a physiological response of organisms. Biological immune system can produce antibodies to protect against violations from foreign antigens. There will be a series of reactions after antigens combine with antibodies. Antigens will be destroyed by the apoptosis and special enzymes. Biological immune system consists of lymphocytes and antibody molecules. Lymphocytes are made up of T cells (T cells are divided into helper cells T_H and suppressor cells T_S) and B cells produced by thymus and bone marrow respectively. When antigens invade the organism and digested by surrounding cells, information is send to T cells then stimulates B cells. B cells produce antibodies to eliminate antigens. T_H cells increase with increasing antigens, while T_S cells are small, so that it will produce more B cells. With the reduction of antigen T_S cells increase, it inhibits the production of T_H cells, as a result, B cells reduce. After a period of time, the immune system tends to balance. The cooperation between the inhibition mechanism and the main feedback mechanism is completed through the rapid reaction of immune mechanism to antigen and stability of the immune system.

Based on the above immune feedback principle, we assumed that: the number of k generation of antigen is $\varepsilon(k)$, the output of helper cells T_H stimulated by antigen is $T_H(k)$, the impact of T_S to B cells is $T_S(k)$, then the total stimulus received by B cells as follows:

$$\begin{aligned} S(k) &= T_H(k) - T_S(k) \\ T_H(k) &= k_1\varepsilon(k) \\ T_S(k) &= k_2 f(S(k), \Delta S(k))\varepsilon(k). \end{aligned} \tag{1}$$

Where, $f(S(k),\Delta S(k))$ is an unknown nonlinear function in terms of the ability to inhibit the stimulation of cells.

If the value of antigen $\varepsilon(k)$ is deviation $e(k)$, and B cells in the total stimulation received are input $u(k)$, then the feedback control law shows as follows:

$$u(k) = K\{1-\eta f[u(k),\Delta u(k)]\}e(k) = k_{p1}e(k) \tag{2}$$

Where, $k_{p1} = K\{1-\eta f[u(k),\Delta u(k)]\}$, $K = k_1$ represents response speed of the system, $\eta = k_2 / k_1$ represents the stability of the control system. Equation (2) shows that the control based on immune feedback principle is actually a nonlinear proportional control, and the proportional varies with the output of the controller. Taking variables K , η and f into comprehensive consideration then a better control performance can be obtained.

B. Fuzzy rules

The fuzzy control is based on expert experience and control rules to build fuzzy rules. There is no need to build accurate mathematical model of controlled object, so using fuzzy control to approximate the nonlinear function f is a good choose. In this paper, fuzzy controller is designed as two inputs and one output. Taking the rate of errors and errors itself in immune controller as the controller input. The controller output is nonlinear function f . The input and output volume are divided into seven fuzzy sets, namely {NB, NM, NS, Z, PS, PM, PB}. Domain of input and output are set at (-1, +1). The membership function of the input variables and output variable are selected as the triangle function. Based on the principles of "cells accept the greater stimulus, the suppression will be smaller" and "cells accept smaller stimulate, the suppression will be greater ", setting out the fuzzy rules table as showed in Table 1.

TABLE I. Fuzzy Rules

u	***△u***						
	NB	***NM***	***NS***	***Z***	***PS***	***PM***	***PB***
NB	PB	PB	PB	PM	PS	PS	Z
NM	PB	PB	PM	PS	Z	Z	Z
NS	PB	PM	PS	Z	Z	NS	NS
Z	PM	PS	Z	Z	NS	NS	NM
PS	PS	Z	Z	NS	NS	NM	NB
PM	PS	Z	NS	NS	NM	NB	NB
PB	Z	Z	NS	NM	NB	NB	NB

V. Simulation Results

Taking a DC motor as the controlled object into simulation, the transfer function is described by:

$$G_p(s) = \frac{2029.826}{(s+26.29)(s+2.296)}. \tag{3}$$

PI controller is described by:

$$G_c(s) = \frac{K_P(s + K_I / K_P)}{s}. \tag{4}$$

The output of PI controller, as the error signal of the immune feedback controller, which is connected with the immune feedback controller, namely fuzzy immune PI controller. The initial parameters of PI controller is set as the best value which be gotten when the network is not considered, K_P =0.1701, K_I =0.378. We set immune feedback parameters K =0.8, η =0.6, use step signal as the reference signal of the system, and use the network model to simulate the data transmission delay and packet loss in NCS. Then the following three conditions are researched: model matching with small network load, delay and no packet dropout; model matching with high load, delay and packet dropout; model mismatching. Simulation results are shown in Fig. 5 to 7.

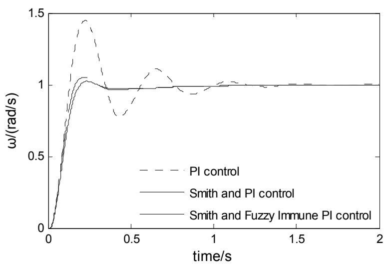

Figure 5. Step responses in model matching with small network load, delay and no packet dropout

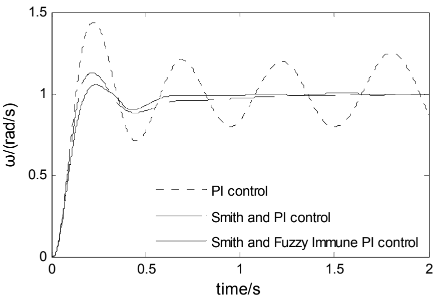

Figure 6. Step responses in model matching with high load, delay and packet dropout

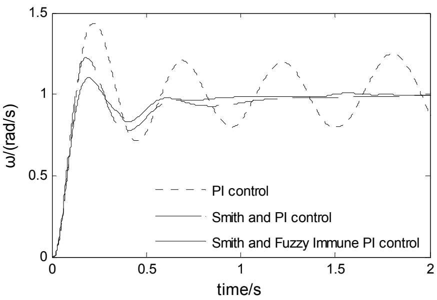

Figure 7. Step responses in model mismatching

Known from Fig. 5 to 7, when the network load is low, all of the three control algorithms can perform stability, but fuzzy immune PI control with Smith compensator and PI control with Smith compensator show more quick response and better stability than that of PI control. However, when the system is more and more overloaded, PI control divergence, other two methods still remain stable despite of fluctuations. When the model deviation with the actual object fuzzy immune PI control with Smith compensator get a better control performance than PI control with Smith compensator.

VI. CONCLUSION

In this paper, the network model is established by discrete-event simulation tool SimEvents to carry out network-induced delay and packet dropout in networked control systems. Network delay is estimated by introducing the concept of round-trip time and compensated by Smith predictor. Furthermore, the paper simulates three kinds of control algorithm in terms of three different situations. The results showed the Smith compensator with fuzzy immune control has better control performance than that of Smith compensator with fuzzy immune control and PI control.

REFERENCES

[1] Walsh G.C., Hong Ye and Bushnell L.G., “Stability Analysis of Networked Control Systems, ” Control Systems Technology, vol. 10, May. 2002, pp. 438-446

[2] Yu-Chu Tian, David Levy, “Compensation for control packet dropout in networked control systems,” Information Sciences, vol. 178, Mar. 2008, pp. 1263-1278

[3] Walsh G.C., Hong Ye, “Scheduling of networked control systems,” Control Systems Magazine, vol. 21, Feb. 2001, pp. 57-65

[4] J. Nilsson, “Real-time Control Systems with Delays,” Ph.D. dissertation, Dept. Automatic Control, Lund Institute of Technology, Lund, Sweden, January 1998.

[5] R. Luck, A. Ray, “An Observer-based Compensator for Distributed Delays,”. Automation, vol. 26,Sep. 1990, pp. 903-908

[6] Yodyium Tipsuwan, Mo-Yuen Chow, “On the Gain Scheduling for Networked PI Controller Over IP Network,” Mechatronics, vol. 9, Sept. 2004, pp. 491-498

[7] Tingna Shi, Sujuan Wang, Hongwei Fang and Zhengwei Chen, “Fuzzy Immune PI Control of Networked Control System Based on ADW Time-Delay Prediction,” 2008 Fifth International Conference on Fuzzy Systems and Knowledge Discovery, Oct. 2008, pp. 76-80.

[8] Nikolai Vatanski, Jean-Philippe Georges, Christophe Aubrun, Eric Rondeau and Sirkka-Liisa Jämsä-Jounela, “Networked control with delay measurement and estimation,” Control Engineering Practice, vol.17, Feb.2009, pp. 231-244

[9] Yodyium Tipsuwan, Mo-Yuen Chow, “Control methodologies in networked control systems,” Control Engineering Practice, vol.11, Oct.2003, pp. 1099-1111.

[10] Xianchao Xu, Zhongjie Wang, “Networked Modeling and Simulation Based on SimEvents,” 2008 Asia Simulation Conference-7th International Conference on System Simulation and Scientific Computing, Oct. 2008, pp. 1421-1424 .