A New Smith Predictor and Fuzzy Immune Control for Hybrid Networked Control Systems

Du Feng, Du Wencai, Lei Zhi

Abstract—**To aim at time-variant or uncertain network delays in the hybrid networked control systems (HNCS) of the wired and wireless, as well as Smith predictor models and real models of the controlled plants might be mismatch, a novel approach is proposed that a new Smith predictor combined with fuzzy immune control for the HNCS. Because new Smith predictor hides predictor models of the network delays into real network data transmission processes, further all network delays no longer need to be measured, identified or estimated on-line. It is applicable to some occasions that network delays are random, time-variant or uncertain, possibly large compared to one, even tens sampling periods, at the same time, there are some data dropouts in closed loops. Based on IEEE 802.11 b/g (WLAN) and CSMA/CD (Ethernet) respectively in the inner and outer closed loops, the results of simulation show validity of the control scheme, and indicate that system has better dynamic performance and robustness.**

Index Terms—**Hybrid networked control systems (HNCS), wireless networked control systems (WNCS), network delay, Smith predictor.**

I. Introduction

A wireless networked control systems (WNCS) is one in which a control loop is closed via the wireless network. The WNCS have many compelling applications, for example, the wireless sensor networks have found important applications in environmental monitoring, agriculture, building and industrial automation, machine condition monitoring, intelligent transportation systems, health care, surveillance, and defense. On the other hand, there has also been an increasing trend for control systems to utilize digital communication networks for exchanging information between sensor and controller and/or controller and actuator as well as between subsystems or systems that share the same communication networks due to flexibility and significant cost saving introduced by networks.

The network is a factor that should not be neglected because of the use of the communication network shared by other applications, and communication delays and packet losses may occur [1]-[4]. These issues become more significant in wireless where there commonly exist the fading time varying throughput in the communication channels as well as the constraints and uncertainties, such as, the limited energy, bandwidth, and computing power, channel fading, time varying capacity, out-of-sequence data, transmission delays, packet losses, etc. There is an imperative need for new theory and algorithms for control, estimation and decision making that take these uncertainties and constraints into consideration and address interplay among communication, computing and control. These problems have stimulated a strong research interest in the WNCS within the control community.

Many of the research works based on assuming the network delay is constant [5]-[7], or distribution is known, or delay is shorter than one sampling period, delay through the introduction of buffer is larger than one sampling period [8]. Based on Smith predictor, but need to measured on-line, identified or estimated network delays[9]-[11], etc. These overfull postulates might produce impractical results and might limit their applications. Although delay is an important factor that needs to be considered for control systems implemented over industrial network, it has not been well defined or studied by standards organizations defining network protocols [12].

The biology immune system is characterized by its strong robustness and self-adaptability even when encountering many disturbances and uncertain conditions. It has become a new research field as an intelligent information process system after the neural network and evolutionary computation [13], and has obtained some research fruits [14], such as pattern recognition, robot control, adaptive control etc. Besides, fuzzy controller can realize any linear and nonlinear functions. Therefore, based on the immune feedback law, some studies [15]-[18] further proposed fuzzy immune control to advance the control performance such as robust and adaptive ability.

In this paper, a novel approach is proposed that new Smith predictor combined with the fuzzy immune control for the hybrid networked control systems (HNCS) of the wired and wireless. It enhances the system robustness and realizes double Smith dynamic prediction compensations for the delays of the network and controlled plants. Furthermore, the network delays in the return network paths can totally be eliminate, while remove the all delays in the forward path from the loops. Therefore, the traffics on the return network paths do not need to be scheduled, thereby allows utilizing the capacity of the communication channel more effectively than static or dynamic scheduling could, and simultaneously increases system robustness when there are data dropouts in return network paths. Where network delays are allowed to be random, time-variant and uncertain, possibly large compared to one, even tens sampling periods and they are no need to be measured, identified or estimated on line. Based

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on IEEE 802.11 b/g (WLAN) in the inner closed loop and CSMA/CD (Ethernet) in the outer closed loop, the results of simulation show validity of the control scheme, and indicate that system of the HNCS has better dynamic performance and robustness.

This paper is organized for the four sections as follows: section II analyzes the Smith predictor and proposes a new Smith predictor for the WNCS and HNCS, and introduces the fuzzy immune control for the HNCS. The simulation is described in section III, and conclusions in section IV.

II. Problem Description

A. Structure of the WNCS

In the WNCS, the network delay is primary factor which influences on the system performance. The typical structure of the WNCS is shown as fig.1.

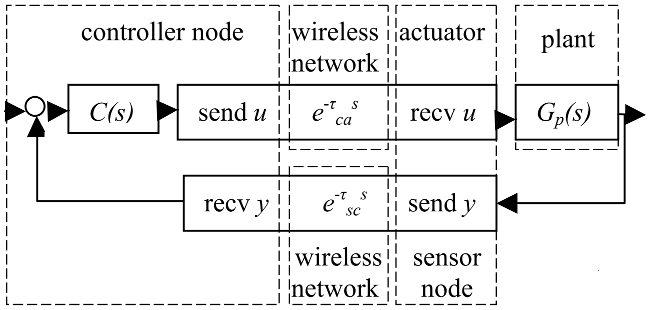

Fig. 1 Structure of the WNCS.

We assume that sensor is time-driven; controller and actuator are event-driven, and the actuator and sensor are co-located on the same node. Where $G_p(s)$ is controlled plant without delay, the $C(s)$ is controller, the r and y are input and output of system respectively, the τ_{sc} and τ_{ca} are network delays, the τ_{sc} is from sensor to controller, and the τ_{ca} is from controller to actuator. The total network delay ($\tau = \tau_{sc} + \tau_{ca}$) is larger than one, even tens sampling periods. The closed loop transfer function is given by

$$y(s)/r(s) = C(s)e^{-\tau_{ca}s}G_p(s)\big/(1 + C(s)e^{-\tau_{ca}s}G_p(s)e^{-\tau_{sc}s}) \quad (1)$$

From the (1), we can be seen that $e^{-\tau_{ca}s}$ and $e^{-\tau_{sc}s}$ have been contained in the denominator of the closed loop transfer function. They can degrade the performances of the WNCS and even cause system instability.

B. Smith Predictor for the WNCS

The internal compensation loop is closed around controller side of wireless network, the Smith predictor can be described as Fig.2.

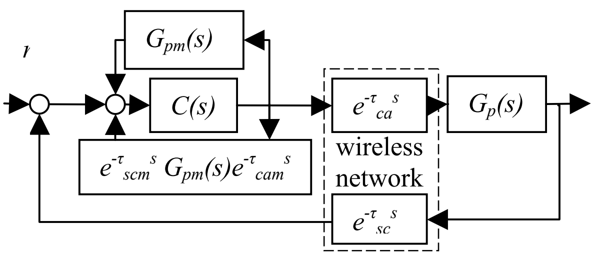

Fig. 2 WNCS with Smith predictor

Where $G_{pm}(s)$ is prediction model of the $G_p(s)$, the τ_{scm} and τ_{cam} are prediction values of the τ_{sc} and τ_{ca} respectively. The closed loop transfer function of the system is given as follows

$$\begin{aligned} y(s)/r(s) = C(s)e^{-\tau_{ca}s}G_p(s)/(1 + C(s)e^{-\tau_{ca}s}G_p(s)e^{-\tau_{sc}s} \\ - C(s)e^{-\tau_{cam}s}G_{pm}(s)e^{-\tau_{scm}s} + C(s)G_{pm}(s)) \end{aligned} \quad (2)$$

When $\tau_{cam} = \tau_{ca}$, $\tau_{scm} = \tau_{sc}$, $G_{pm}(s) = G_p(s)$, the prediction models can approximate the true models, the above (2) is reduced to

$$y(s)/r(s) = C(s)e^{-\tau_{ca}s}G_p(s)\big/(1 + C(s)G_p(s)) \quad (3)$$

According to the (3), the fig.2 can be treated as fig.3.

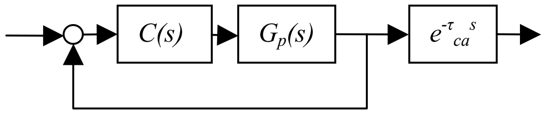

Fig. 3 Equivalent control system

Though Smith predictor can totally eliminate the delay τ_{sc} in the return path, remove the delay τ_{ca} in the forward path from the closed loop, when the prediction models can accurately approximate the true models, and the delays can be totally compensated. However, the above-mentioned Smith predictor has some problems:

1) It is difficult to satisfy complete compensation conditions. First, because of uncertainty of wireless network delay, it is hard to get the precise prediction models of the τ_{sc} and τ_{ca}. Secondly, on account of the clock of network nodes might be asynchronous [19], it is difficult to get the exact values of delays by measurement on-line, identification or estimate. Thirdly, owing to network delays result in vacancy sampling and multi-sampling, the Smith predictor will bring errors of compensation model.
2) Because network delay τ_{ca} occurs in a process that is controller transmission data to actuator, therefore it is impossible that data are truly predicted in the controller node beforehand, no matte method is adopted, and the prediction error of delay τ_{ca} is always existent.
3) When network delay large compared to one, even tens sampling periods, a lot of memory units are required for storing old data, consume memory resources and increase calculation delays, shorten life of the wireless nodes.
4) When the controlled plant includes delay τ_p, the denominator of transfer function in the (3) will contain exponent $e^{-\tau_p s}$. Therefore, the stability of the WNCS should be affected.

C. New Smith Predictor for the WNCS

We aim at existent problems of the fig.2, if the controlled plant with delay τ_p is know, a new Smith dynamic predictor is shown in Fig. 4. Where τ_{pm} is prediction value of the τ_p, thus the closed loop transfer function of the WNCS is given as follows

$$y(s)/r(s) = C(s)e^{-\tau_{ca}s}G_p(s)e^{-\tau_p s} / (1 + C(s)G_{pm}(s) + C(s)e^{-\tau_{ca}s}(G_p(s)e^{-\tau_p s} - G_{pm}(s)e^{-\tau_{pm}s})e^{-\tau_{sc}s}) \quad (4)$$

When $\tau_{pm} = \tau_p$, $G_{pm}(s) = G_p(s)$, the prediction models can accurately approximate true models, above (4) is reduced to

$$y(s)/r(s) = C(s)e^{-\tau_{ca}s}G_p(s)e^{-\tau_p s} \big/ (1 + C(s)G_p(s)) \quad (5)$$

As can be seen from the (5), the effects of the delays have been completely eliminated from the denominator of the (5).

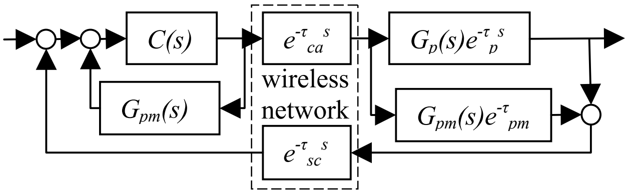

Fig. 4 WNCS with new Smith predictor.

According to the (5), the fig.4 can be treated as fig.5.

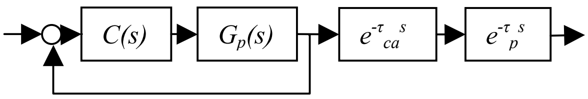

Fig. 5 Equivalent control system

From the fig.4 to fig. 5 and the (5), we can see

1) New Smith predictor realizes the double Smith dynamic prediction compensation on structure for the delays of network and dead time delay of the controlled plant.
2) The all delays of the forward path are removed from the closed loop and appear as gain blocks before the output, and the time-variant uncertain network delay in the return path is totally eliminated from the system. Further, it can cancel effects of the network delays and the dead time delay of the controlled plant for the system stability in the closed loop, and it enhances the control quality.
3) Because the network delays on the return path can totally be eliminated, therefore the traffic on the return path does not need to be scheduled, and the output signal of the sensor, whenever possible, can be transmitted back to remote controller node on line. This allows utilizing the capacity of the communication channel more effectively than static or dynamic scheduling could. On the other hand, increases system robustness when there are data packet dropouts on the return path of the WNCS.
4) The new Smith predictor is the real-time, on-line and dynamic predictor, and it doesn't include the predictor models of all network delays on actualization. Because the information flow passed through the network delays which are true network delays in the data transmission process, therefore network delays no longer need to be measured, identified or estimated on line. Therefore it reduces the requirement of the clock synchronization of the nodes. Furthermore, it avoids estimate errors which are brought due to inaccurate model, and avoids nodes memory resource to be wasted when the network delays are identified or estimated. At the same time, it avoids compensation errors, which are brought by network delays owing to vacancy-sampling and multi-sampling.

D. Structure of the HNCS

The cascade control is a common control structure in process control systems, servomechanisms and position control of the robot etc [20]. The reason for cascade control instead of single loop control is that it can give a much better compensation for disturbances, and has faster response [21]. Usually, a cascade control system consists of two control loops; an inner closed loop is embedded within an outer closed loop [22]. The hybrid networked control system (HNCS) with the cascade control structure is shown in fig.6.

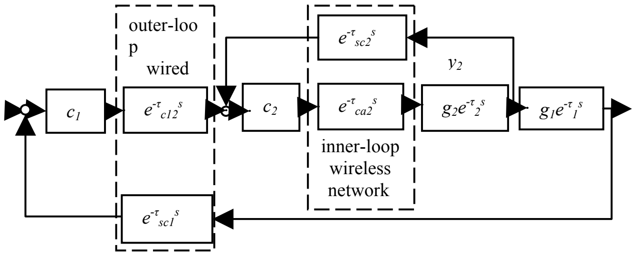

Fig. 6 Structure of the HNCS

In the outer-loop, the r is input of system, and y is output of the controlled plant $g_1(s)e^{-\tau_1 s}$. The τ_{sc1} and τ_{c12} are network delays respectively. The τ_{sc1} is from sensor to controller $c_1(s)$, and the τ_{c12} is from the $c_1(s)$ to controller $c_2(s)$. In the inner-loop, the y_2 is output of the controlled plant $g_2(s)e^{-\tau_2 s}$. The τ_{sc2} and τ_{ca2} are wireless network delays respectively. The τ_{sc2} is from sensor to the $c_2(s)$, and the τ_{ca2} is from the $c_2(s)$ to actuator, this actuator is used for implementing control to the controlled plant $g_2(s)e^{-\tau_2 s}$. We assume that sensors are time-driven; controllers and actuator are event-driven. In the Fig.3, the closed-loop transfer function can be given by

$$y(s)/r(s) = c_1(s)e^{-\tau_{c12}s}c_2(s)e^{-\tau_{ca2}s}g_2(s)e^{-\tau_2 s}g_1(s)e^{-\tau_1 s} \big/ (1 + c_1(s)e^{-\tau_{c12}s}c_2(s)e^{-\tau_{ca2}s}g_2(s)e^{-\tau_2 s}g_1(s)e^{-\tau_1 s}e^{-\tau_{sc1}s} + c_2(s)e^{-\tau_{ca2}s}g_2(s)e^{-\tau_2 s}e^{-\tau_{sc2}s}) \quad (6)$$

From the (6), we can see that all delays have been contained in the denominator. Their existence will degrade system performance and even cause system instability.

E. HNCS with the New Smith Predictor

By means of the method from the Fig.4, the system of the fig.6 can be treated as fig.7.

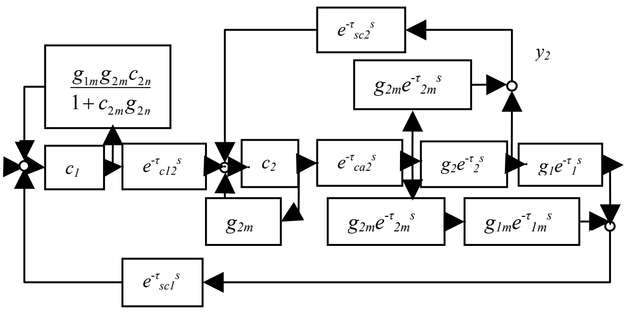

Fig. 7 HNCS with new Smith predictor

The closed loop transfer function of the Fig.7 is given by

$$\frac{y(s)}{r(s)}=\frac{\dfrac{c_1(s)e^{-\tau_{c12}s}c_2(s)e^{-\tau_{ca2}s}g_2(s)e^{-\tau_2 s}g_1(s)e^{-\tau_1 s}}{(1+c_2(s)g_{2m}(s))}}{(1+A+B+\dfrac{c_1(s)c_{2m}(s)g_{2m}(s)g_{1m}(s)}{(1+c_{2m}(s)g_{2m}(s))})} \tag{7}$$

$$A=\frac{c_2(s)e^{-\tau_{ca2}s}(g_2(s)e^{-\tau_2 s}-g_{2m}(s)e^{-\tau_{2m}s})e^{-\tau_{sc2}s}}{(1+c_2(s)g_{2m}(s))} \tag{8}$$

$$\begin{aligned}B=&c_1(s)e^{-\tau_{c12}s}c_2(s)e^{-\tau_{ca2}s}(g_2(s)e^{-\tau_2 s}g_1(s)e^{-\tau_1 s}-\\&g_{2m}(s)e^{-\tau_{2m}s}g_{1m}(s)e^{-\tau_{1m}s})e^{-\tau_{sc1}s}\big/(1+c_2(s)g_{2m}(s))\end{aligned} \tag{9}$$

When $g_{1m}(s) = g_1(s)$, $g_{2m}(s) = g_2(s)$, $\tau_{1m} = \tau_1$, $\tau_{2m} = \tau_2$, $c_{2m}(s) = c_2(s)$, above (7) is reduced to

$$\frac{y(s)}{r(s)}=\frac{c_1(s)e^{-\tau_{c12}s}c_2(s)e^{-\tau_{ca2}s}g_2(s)e^{-\tau_2 s}g_1(s)e^{-\tau_1 s}}{(1+c_2(s)g_2(s)+c_1(s)c_2(s)g_2(s)g_1(s))} \tag{10}$$

According to the Fig.7 and the (10), we can see

1) The new Smith predictor can cancel effects from the τ_{sc1} and τ_{c12}, the τ_{sc2} and τ_{ca2}, the τ_1 and τ_2 for system stability, and realizes double Smith dynamic prediction compensations for the network delays and the dead time delays of the controlled plants on structure.
2) In the Fig.7, there are no τ_{sc1m} and τ_{c12m}, τ_{sc2m} and τ_{ca2m}, and the network delays no longer need to be measured on-line, identified or estimated, allow network delays to be random, time-variant or uncertain. If only satisfies $g_{1m}(s) = g_1(s)$, $g_{2m}(s) = g_2(s)$, $\tau_{1m} = \tau_1$, $\tau_{2m} = \tau_2$, $c_{2m}(s) = c_2(s)$, the Smith predictor is always effective.
3) Because the nodes of the HNCS are all intelligent nodes, it is easy to be implemented.
4) The $c_2(s)$ often adopts P controller, and the $c_1(s)$ can adopt PID control, also adopt intelligent control strategy when the controlled plant is time-variant, or nonlinear, as well as the Smith predictor models might be imprecise.

F. Fuzzy Immune Control

As is known, immune is a special physiological reaction in biosome, corresponding antibody is produced to resist attacking antigen, which is destroyed by phagocytosis or particular enzyme generated by antibody. Immune system is composed of antibody and lymphocyte, which is made up of T cells (auxiliary cell T_h and suppressor cell T_s) produced by thymocyte and B cells created by marrow. When antigen invades organism and is digested by surrounding cells, messages are sent to T_h and T_s cells, and B cell is stimulated to create more antibody so as to eliminate antigen. If quantity of antigen is large, much more auxiliary cells T_h yield, but number of suppressor cell T_s reduces, which results in more B cell production; if antigen becomes less, number of T_s increases and that of T_h decreases, which results in decrease of B cell. Synergism between suppressor mechanism and main feedback mechanism is realized via immune system quick response to antigen and stabilizing immune system [23].

Based on the immune feedback theory, assuming the number of k^{th} generation of antigen is $\varepsilon(k)$, the output of auxiliary cell T_h is $T_h(k)$, impact of T_s on B is $T_s(k)$, and all impetus that B cell received is

$$S(k)=T_h(k)-T_s(k) \tag{11}$$

Where $T_h(k) = k_1\varepsilon(k)$, $T_s(k) = k_2 f(s(k), \Delta s(k))\varepsilon(k)$. If number of antigen $\varepsilon(k)$ is supposed to be equivalent to the error $e(k)$, and overall impetus $S(k)$ that B received is equivalent to $u(k)$, following control scheme is gained

$$\begin{aligned}u(k)&=k_1e(k)-k_2f(u(k),\Delta u(k))e(k)\\&=K(1-\eta f(u(k),\Delta u(k)))e(k)\\&=k_{p1}e(k)\end{aligned} \tag{12}$$

Where $K = k_1$ is control of response speed, $k_{p1}=K(1-\eta f(u(k), \Delta u(k)))$ is proportional gain, the $\eta = k_2 / k_1$ is used to control the stabilization effect, and $f(u(k),\Delta u(k))$ is a selected nonlinear function.

In order to determine $f(u(k),\Delta u(k))$, fuzzy control theory is utilized to acquire an approximate function. Following control rules are defined to determine $f(u(k), \Delta u(k))$:

1) If $u(k)$ is P and $\Delta u(k)$ is P then $f(u(k), \Delta u(k))$ is N.
2) If $u(k)$ is P and $\Delta u(k)$ is N then $f(u(k), \Delta u(k))$ is Z.
3) If $u(k)$ is N and $\Delta u(k)$ is P then $f(u(k), \Delta u(k))$ is Z.
4) If $u(k)$ is N and $\Delta u(k)$ is N then $f(u(k), \Delta u(k))$ is P.

In the rules above, we use fuzzy logical AND, OR operation of Zadeh, adopt common used anti-fuzzy way of mom to obtain the output $f(u(k),\Delta u(k))$ of fuzzy controller, so as to construct fuzzy immune PID controller. We can assure negative feedback when $0 \le \eta f(u(k),\Delta u(k)) \le 1$, that is, assure the system stable, $\eta f(u(k),\Delta u(k)) \ge 1$ represents positive feedback control. If $\eta = 0$ or $f(u(k),\Delta u(k)) = 0$, the controller is just as a regular linear PID controller. So output of immune PID controller is

$$\begin{aligned}u(k)=u(k-1)+k_{p1}((e(k)-e(k-1))+k_ie(k)\\+k_d(e(k)-2e(k-1)+e(k-2))\end{aligned} \tag{13}$$

While the k_{p1} is regulated by fuzzy immune scheme, the k_i and k_d is modified online using fuzzy control scheme to adapt well to different e and error change rate ec.

III. Simulation Experiment

We select the simulation software TrueTime 1.5 [24]. In the inner closed loop, wireless network adopts IEEE 802.11b/g (WLAN), data rate is 800,000 bits/s, transmit power is 20.00 dbm, receiver signal threshold is -48.00 dbm, path loss exponent is 3.5, act timeouts is 0.00004 s, error coding threshold is 0.03, the distance between nodes is 20 m, and maximum signal reach is 86.67 m. In the outer closed loop, the wired network adopts CSMA/CD (Ethernet), and data rate is 80,000 bits/s. There are some data dropouts in the inner and outer closed loops, and loss probability is 0.5 in outer closed loops. The sampling periods of the sensors are 0.01s, and the reference signal r adopts square wave signal and its amplitude is from −0.5 to 0.5 in the outer closed loop.

In the inner closed loop, we select three selfsame controlled plant2, plant4 and plant6. They are the first-order plus dead time delay systems as follows:

$$G_{p\_inner}(s)e^{-\tau_{p\_inner}s} = 6e^{-0.01s} \big/ (s+2) \quad (14)$$

Their predictor models are given by

$$G_{pm\_inner}(s)e^{-\tau_{pm\_inner}s} = 6e^{-0.01s} \big/ (s+2) \quad (15)$$

In the outer closed loop, also select three selfsame controlled plant1, plant3 and plant5, and they are the second order plus dead time delay systems as follows:

$$G_{p\_outer}(s)e^{-\tau_{p\_outer}s} = 1770e^{-0.02s} \big/ (s^2+60s+1770) \quad (16)$$

Their predictor models are given by

$$G_{pm\_outer}(s)e^{-\tau_{pm\_outer}s} = 1770e^{-0.02s} \big/ (s^2+60s+1770) \quad (17)$$

The HNCS1 and HNCS2 are composed by the plant1 and plant2, plant3 and plant4, respectively, simultaneously are implemented controls by new Smith predictor combined with fuzzy immune PID plus P controls, and their outputs are *y1* and *y3* respectively. The HNCS3 is composed by the plant5 and plant6, simultaneously is implemented controls by the fuzzy immune PID plus P control, and its output is *y5*.

In order to research system robustness, we change model parameters of the HNCS2, and make model parameters of Smith predictors and true controlled plant3 and plant4 are mismatch. Where true controlled plant4 in the inner closed loop is changed from the (14) to the (17) as follows

$$G_{c\_inner}(s)e^{-\tau_{c\_inner}s} = 12e^{-0.02s} \big/ (2s+5) \quad (17)$$

At the same time, the controlled plant3 in the outer closed loop is changed from the (16) to the (18) as follows

$$G_{c\_outer}(s)e^{-\tau_{c\_outer}s} = 2160e^{-0.03s} \big/ (s^2+65s+1570) \quad (18)$$

But, the Smith predictor model parameters of true controlled plant3 and plant4 are always unchanged to keep the (15) and (17) in entire simulation process. Meanwhile, all tuned parameters of the controllers completely depend on the (14) and (16), where fuzzy immune controller parameters are K = 0.260, k_i = 0.240, k_d = 0.190, η = 0.680; and proportion gain of the P controller is $k_{p\text{-}inner}$ = 2. In the simulation process, data from the samplings and controls are encapsulated in the same data package for the wired or wireless network transmission.

The simulation result is displayed in fig.8 to fig.16.

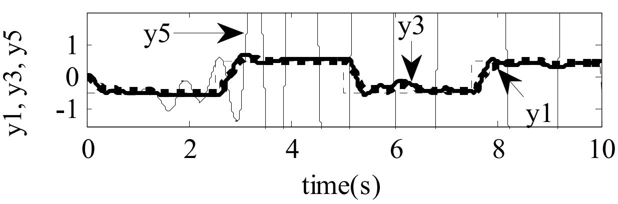

Fig. 8 Outputs *y1*, *y3* and *y5*. The *y1* and *y3* are new Smith predictor combined with fuzzy immune plus P control (model parameters of true plant3 and plant4 with its Smith predictors are mismatching). The y5 is fuzzy immune plus P control.

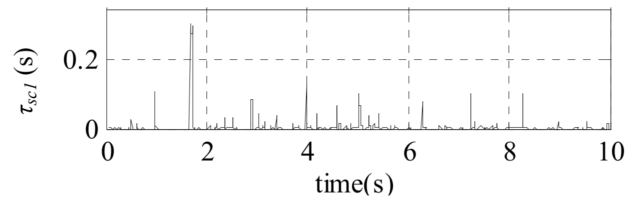

Fig.9 Network delay τ_{sc1} is from sensor1 to controller1

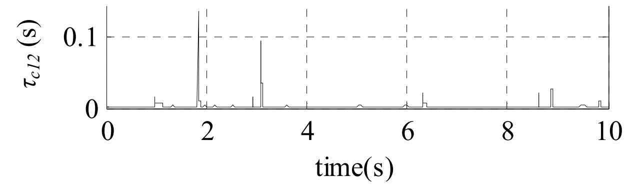

Fig.10 Network delay τ_{c12} is from controller1 to controller2

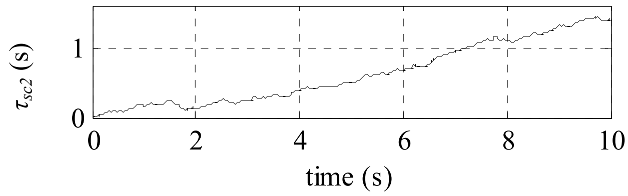

Fig.11 Network delay τ_{sc2} is from sensor2 to controller2

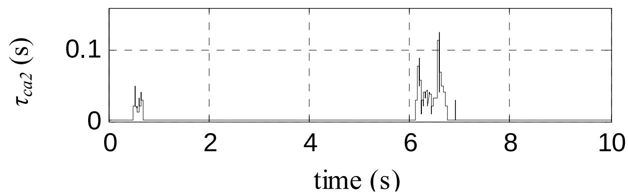

Fig.12 Network delay τ_{ca2} is from controller2 to actuator2

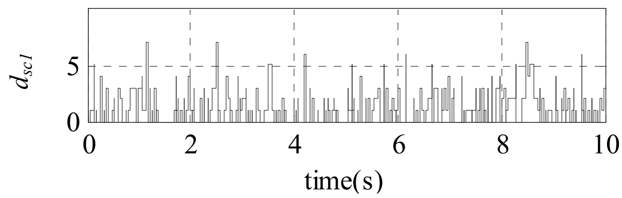

Fig. 13 Data dropout d_{sc1} is from sensor1 to controller1

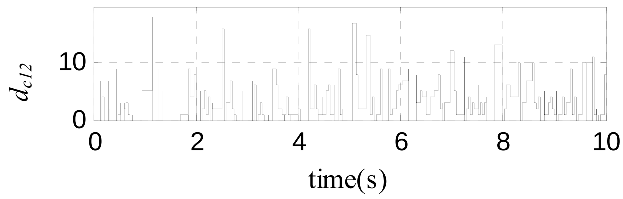

Fig. 14 Data dropout d_{c12} is from controller to actuator

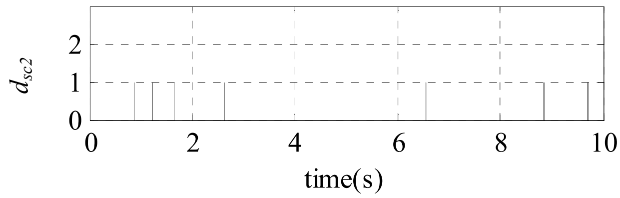

Fig. 15 Data dropout d_{sc2} is from sensor2 to controller2

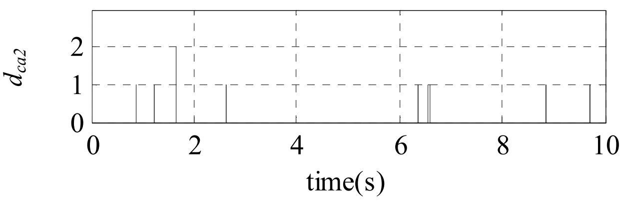

Fig. 16 Data dropout d_{ca2} is from controller2 to actuator2

From the fig.8 to fig.16, we can see

1) The network delays τ_{sc1}, τ_{c12} and τ_{ca2} are random, time-variant or uncertain, and τ_{sc2} is time-variant. The maximums of the τ_{sc1}, τ_{c12} and τ_{ca2} are respectively 0.308s, 0.138s and 0.122s, their all exceed ten sampling periods (one sampling period is 0.01s).
2) In the outer closed loop, the data packet dropout d_{sc1} maximum is 7, and the d_{c12} is 18. In the inner closed loop, the d_{sc2} maximum is 1, and the d_{ca2} is 2. However lost messages consume the network bandwidth, but never arrive at the destination.
3) The *y1* (thick dot line) and *y3* (thick real line) is timely in tracking square wave in the fig.8, and the overshoot is less, they completely satisfies performance requirement. At the same time, it also indicates that systems with new Smith predictor have stronger robustness although the true model parameters of the plant3 and plant4 are mismatching to compare with their Smith predictor model parameters.
4) The *y5* give overshoot at 1.385s, along with increase and fluctuation of the network delays and data dropouts. Finally, results in system instability after 3.115s, therefore the *y5* doesn't satisfy requirement.

Simulation results show that new Smith predictor combined with fuzzy immune control is effective for the HNCS.

III. CONCLUSION

In order to overcome influences of network delays, a novel approach is proposed that new Smith predictor combined with fuzzy immune control for the HNCS. Its structure is simple, and has stronger robustness. Therefore it will have wide engineering application prospect.

REFERENCES

[1] J. Y. Wei, "Stability analysis of decentralized networked control systems," *Proceedings of the 7th World Congress on Intelligent Control and Automation*, June 25-27, 2008, Chongqing, China, pp 5477–5482.

[2] X. L. Zhu and G. H. Yang, "New results on stability analysis of networked control systems," *2008 American Control Conference* Westin Seattle Hotel, Seattle, Washington, USA. June 11-13, 2008. pp. 3792–3797.

[3] W. Zhang, M. S. Branicky,S. M. Phillips, "Stability of networked control systems," *IEEE Control Syst. Magn.*, vol.21, No.2, pp.84–99, 2001.

[4] Y. Ge, Q. G Chen and M. Jiang, Z.A. Liu. "Stability analysis of networked control systems with data dropout and transmission delays," *Proceedings of the 7th World Congress on Intelligent Control and Automation*, June 25 - 27, 2008, Chongqing, China, pp 7986–7981.

[5] L. Dugy, E. I. Verriest, "Stability and control of time-delay systems," New York: Springer, 1998.

[6] J.P. Richard, "Time-delay systems: an overview of some recent advances and open problems," *Automatica*, vol. 39, no. 10, pp. 1667–1694, 2003.

[7] K. Watanabe, E. Nobuyama, A. Kojima, "Recent advances in control of time delay systems VA tutorial review," *in Proc. IEEE Conf. Decision and Control*, 1996, pp. 2083–2088.

[8] Y. S. Xiong, L. Yu, J. M. Xu, "Design of sliding mode predicting controller for network control system," *Electric Drive Automation*, 25(4): 39–40, 2003.

[9] P. Chen, Y. Dong, S. Ji, "The study of Smith prediction controller in NCS based on time delay identification," 2004 *8th Conference on Control, Automation, Robotics and Vision Kunming. China*, 6-9th, December, 2004.

[10] K. B. Fite, J. E. Speich, M. Goldfarb, "Transparency and stability robustness in two-channel bilateral telemanipulation," *ASME Journal of Dynamic Systems, Measurement t, and Control*, 2001.

[11] P. H. Bauer, M .L. Sichitiu, C. Lorand et al. "Total delay compensation in LAN control systems and implications for scheduling," *Proceedings of the American Control Conference Arlington*, VA June 25-27, 2001, pp. 4300–4305.

[12] J. P. Thomesse, "Fieldbus technology in industrial automation," *Proc. IEEE*, vol. 93, no. 6, pp. 1073–1101, Jun. 2005.

[13] S. Gutnikov, Y. Melnikov, "A simple non-linear model of immune response," *Chaos, Solutions and Fractals*, 2003, 16: pp. 125–132.

[14] D. G. Peng, H. Zhang, P. Yang, et al. "A novel immune feedback controller and its applications for main stream temperature system," *Proceedings of the IEEE International Conference on Automation and Logistics August* 18 - 21, 2007, Jinan, China, pp. 1625–1629.

[15] J. L. Castro, M. Delgado, "Fuzzy systems with defuzzification are universal approximates," *IEEE Trans. Syst., Man, Cybern.*, vol. 26, pp.149–152, 1996.

[16] Y. Ding, "A nonlinear PID controller based on fuzzy-tuned immune feedback law," *Proc. of the 3th World Conference on Intelligent Control and Automation*, pp.1576–1580, China, 2000.

[17] X. Gao, Y. Zhao, W. Guo, and X. Yu, "Simulation and research of fuzzy immune adaptive PID control in coke oven temperature control system," *Proc. of the 6th World Conference on Intelligent Control and Automation*, pp.3315–3319, China, 2006.

[18] S. Wang, Y. Jiang and H.Yang, "Chaos optimization strategy on fuzzy immune- PID control of the turbine governing system," *Proc. of the IEEE International Conference on Intelligent Robots and Systems*, pp.1594–1598, China, 2006.

[19] S. Johannessen, "Time synchronization in a local area network", *IEEE Control Syst. Mag.*, 24: 61–69, 2004.

[20] Jang P S and Jung S. "Guidance and control of a mobile robot using neural network correction based on a remotely located sensor," *Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems* October 9 - 15, 2006, Beijing, China, pp.1464–1469.

[21] Guo C G, Song Q and Cai W J. "A neural network assisted cascade control system for air handling unit," *IEEE Transaction on Industrial Electronics*, Vol. 54, No. 1, February 2007, pp. 620–628.

[22] Talasaz A, Shooshtari A N. "Closed-loop pressure control based on Smith predictor for gas distribution network". *2007 Information, Decision and Control*, 2007, pp. 266–271.

[23] L. H. Fang, Z. Z. Wu, A. G. Wu, et al. " Fuzzy immune self-regulating PID control of networked control system," *International Conference on Computational Intelligence for Modeling Control and Automation, and International Conference on Intelligent Agents, Web Technologies and Internet Commerce* (CIMCA-IAWTIC'06), 2006.

[24] O. L. Martin, H. K. Dan, C. Anton, "TrueTime 1.5-reference manual," *Department of Automatic Control,* Lund University, Sweden, January,2007.