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New Smith predictive fuzzy immune PID control algorithm for MIMO networked control systems

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Abstract

Aiming at the problem of network-induced delays for multi-input multi-output networked control systems (MIMO NCS), a new Smith predictive fuzzy immune PID algorithm is introduced to effectively reduce the adverse effect of network-induced delays about stability in MIMO NCS, firstly, by using the v-norm type to decouple the coupling plant. Based on the generalized plant after decoupling, the new Smith predictor is designed. Then, an modified fuzzy immune feedback control algorithm is used to tune PID controller parameters online. When there is a model mismatch or parameter perturbation, the set-point tracking performance and robustness of output response can be significantly optimized. The proposed algorithm does not contain the network delay prediction model and does not need to measure, estimate, or identify the network delay. It can be used in MIMO NCS where the network bandwidth is constrained and the network-induced delays are large. Numerical examples with Ethernet protocol are built to illustrate the correctness and effectiveness of this new algorithm.

Keywords: New Smith predictor, Improved fuzzy immune PID (proportion integration differentiation) algorithm, Multi-input multi-output networked control systems (MIMO NCS), Network-induced delays

1 Introduction

Sensor, controller, and actuator nodes transmit data via networks, which form a kind of complex network control system (NCS). The rapid development of interdisciplinary research has made NCS successfully applied in modern industry [1, 2]. Multi-input multi-output networked control systems (MIMO NCS) is constructed when the plant contains multiple input and multiple output variables [3]. MIMO NCS can not only achieve remote control, but also enable nodes to share information and resources. The practical challenges faced by MIMO NCS are more complicated when compared to single-input single-output (SISO) NCS. For example, each output is usually controlled and influenced by several inputs at the same time, that is, coupling or cross influence. Due to the insertion of the wired or wireless communication network, the intelligent nodes in the control system compete for network resources, which will cause some extended problems, for instance, network-induced delays, packet losses, packet disorder, and network scheduling [4].

Considering the random delay and packet loss problem caused by network bandwidth constraint, the classical Smith predictor has strong advantages in compensating delay and has been successfully applied in SISO NCS [5]. In [6], an adaptive Smith predictor has been studied, where the predictive delay is adapted based on the delay information. In [7], a digital Smith predictor based on delay compensator is proposed. Based on linear matrix inequalities, the uncertain system model is remodeled as Lyapunov equation for the stability analysis. In [8], a controller is designed in terms of Smith predictor and incomplete differential proportion integration differentiation (PID) method. The output has superior performance when there are large delays in network channels. In addition, a modified Smith predictor is proposed in [9] to reduce the negative effects of network-induced delays and disturbance. In [10], a Smith predictor is designed to compensate the delay and combined with proportion differentiation (PD) control

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algorithm and neural network to diminish estimation error.

In [5–10], Smith predictor can only be applied to the case where the prediction models of the plant and the delays are determined. However, it is very hard to accurately predict both models of time delay and plant. In [11], two modified Smith predictors have been given to compensate for delay effects. They do not need to know the prediction model of network delay. Zhang et al. [12] introduce a modified Smith predictor and presents an adaptive PID control method to overcome the effect about model errors of the plant. The study in [5–12] considers the SISO NCS, rather than the Smith compensation of MIMO NCS. Garrido et al. and Giraldo et al. [13, 14] have studied the Smith predictor of MIMO control systems, but focused on the decoupling instead of network delays.

Recently, some other research methods on the network-induced delays of MIMO NCS are progressing steadily [15]. For the short delay issue of MIMO NCS less than one sampling period, the following references have been studied. Ma and Zhao [16] construct a modified Lyapunov function and obtains the asymptotically stability conditions for MIMO NCS. The output controller design method is obtained based on stability analysis. In [17], based on dynamic matrix control (DMC) of the MIMO impulse response model, a MIMO network DMC algorithm for stochastic delay is established, and the problem of system stability is transformed into a class of LMI solvable problem. Zhao and Hua [18] propose a new discrete-time MIMO reset controller design method to handle the MIMO NCS network-induced delay problem. In the above studies, the network delays are considered to be short delays of less than one sampling period. It is assumed that both delays (sensor to controller, SC; controller to actuator, CA) are equal. In addition, there are no data packet losses between the channels. The main idea is to model the stochastic delays as determinate constant delays before compensating. The conclusions reached are rather conservative and cannot be applied to MIMO NCS with long network delays.

Aiming at problems of the delays caused by modeling error and communication constraints, [19] proposes an iterative algorithm for solving MIMO NCS stability criteria and static output feedback control laws with time-varying delays. Li et al. [20] model the MIMO NCS with bounded delays, packet loss, and packet timing disorder as a Markov chain jump linear system and raise a guaranteed performance control design algorithm. Du et al. [21] model the MIMO NCS as a switched system and obtain asymptotically stable conditions with bilinear matrix inequalities. In [22], for a kind of complex MIMO NCS with network delay, packet loss, and interference, it gives the proportional term of the controller that satisfies the network transmission conditions to ensure the integrity of the system. Aim at the double-input double-output NCS with stochastic delays, reference [23] uses a recursive optimal control algorithm to improve system output performance. Garone et al. [24] design linear quadratic Gaussian (LQG) optimal controllers for MIMO NCS with time delays. Wu et al. [25] consider that CA delays are stochastic and variant at any moment but upper bound.

Yang et al. [26] model the random delay as a Bernoulli distribution system that satisfies certain probability. In [27], the random delay is constructed as a Takagi-Sugeno fuzzy system. Then, it designs a controller to overcome the influence of delays. In [28], a virtual observer is set up for MIMO NCS with large network-induced delays. First, the input and output time delays are integrated and then assigned them to the output. Then, an observer is used in the virtual plant with time delays. In [29], for wired and wireless heterogeneous MIMO NCS between sensors and controllers, the communication topology of distributed sensor nodes is described by a direct graph. Then, the Markov chain and Bernoulli distribution are adopted to characterize the network-induced delays and packet dropouts respectively. In [30], for a case of up-link and down-link channels with limited bandwidth and affected by Gaussian noise, the two-degree-of-freedom controller and the Youla parameter optimization method are used to achieve the optimal tracking response.

The above research on the network-induced delays of MIMO NCS usually needs to estimate the delays, build mathematical models, and add buffer compensation delays. For multi-loop MIMO NCS, if buffers are added to each channel, the delays will be artificially increased, which will reduce the stability of the system. On the other hand, it is usually assumed that the constraints such as time delays and packet losses are independent of each loop, which is not valid for MIMO NCS with couplings. In actual MIMO NCS, the network delays are usually random, time-varying, and uncertain and are usually longer than a few tens of sampling periods. It is hard to accurately predict the network delays [31]. These factors have caused more challenges compared to other control system without time delay.

The rest of this manuscript is made up of the following parts. Firstly, the methods/experimental is presented in Section 2. Then, the problem formulation of MIMO NCS with network-induced delays is given in Section 3. In succession, Section 4 develops new Smith predictor. Section 5 uses the improved fuzzy immune to adjust the PID parameters. In Section 6, the correctness and superiority of the modified method are proved by some illustrative simulations. Finally, Section 7 is the summary of the article.

2 Methods/experimental

With respect to the problems of delay compensation in MIMO NCS, a modified control method in terms of new Smith predictive and improved fuzzy immune PID method is proposed. This method first decouples the system using v-norm type. A new Smith predictor was applied to move the network delays out of the MIMO closed loop control system. Then, a robust controller adopts improved fuzzy immune PID control algorithm that uses fuzzy rules to adjust the three nonlinear functions of the proportional, integral, and differential parameters, respectively. Finally, the illustrative instance is built under the Ethernet environment in MATLAB software. The simulation result indicates that this method can overcome large delays and packet losses and has stronger robustness.

3 Problem formulation

The common structure of the MIMO NCS, in which a network exists in forward and feedback paths simultaneously, is illustrated in Fig. 1 [21, 32].

As shown in Fig. 1, the system includes the plant matrix **G**(s), r sensors, m actuators, and controller matrix **C**(s). The SC delays are $\tau_{sc}^1,\ \tau_{sc}^2\cdots\ \tau_{sc}^r$, while the CA delays are $\tau_{ca}^1,\ \tau_{ca}^2\cdots\ \tau_{ca}^m$.

For systematic analysis, we make assumptions as follows:

Assumption 1 *Clock driven is adopted by all sensor nodes, and the same sampling period is T where $T > 0$; event driven are used by controller nodes and actuator nodes*

Assumption 2 *After every sensor samples the plant, the single is transmitted to the controller by single data packet*

Assumption 3 *Because the rapid development of hardware, the delays caused by sensor sampling are included in SC delays, while the delays caused by controller calculating are included in CA delays*

For a class of MIMO NCS, simplified structure is shown in Fig. 2, which contains n sensor nodes, n actuator nodes, and a centralized controller node.

In Fig. 2, **G**(s) represents the matrix of multivariable plant. Usually, the expression of **G**(s) is as follows:

$$\mathbf{G}(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) & \cdots & G_{1n}(s) \\ G_{21}(s) & G_{21}(s) & \cdots & G_{2n}(s) \\ \vdots & \vdots & \ddots & \vdots \\ G_{n1}(s) & G_{n1}(s) & \cdots & G_{nn}(s) \end{bmatrix} \tag{1}$$

where $G_{ij}(s) = G_{oij}(s)e^{-\theta_{ij}s}$ and $i, j = 1, 2\ldots, n$.. $G_{oij}(s)$ is the stable, proper, and delay-free transfer function, and θ_{ij} denotes the corresponding dead time delays. The system contains n input variables and n output variables. In Fig. 2, $\mathbf{D}(s) = [D_1(s)\ D_2(s)\ \ \cdots D_n(s)]$ is the vector of load disturbance. **C**(s) represents controller matrix, $e^{-\boldsymbol{\tau}_{sc}s}$ are the SC delays, and $e^{-\boldsymbol{\tau}_{ca}s}$ are CA delays. The reference input vector is $\mathbf{R}(s) = [R_1(s)\ R_2(s)\ \ \cdots R_n(s)\ ]$ and output vector is $\mathbf{Y}(s) = [Y_1(s)\ Y_2(s)\cdots Y_n(s)]$.

According to the expression of **G**(s), there is an interrelated coupling effect in plant. That is, a change in one input signal in the system will cause the quantities of multiple outputs to change, and each output is also affected not only by one input. For the complex MIMO

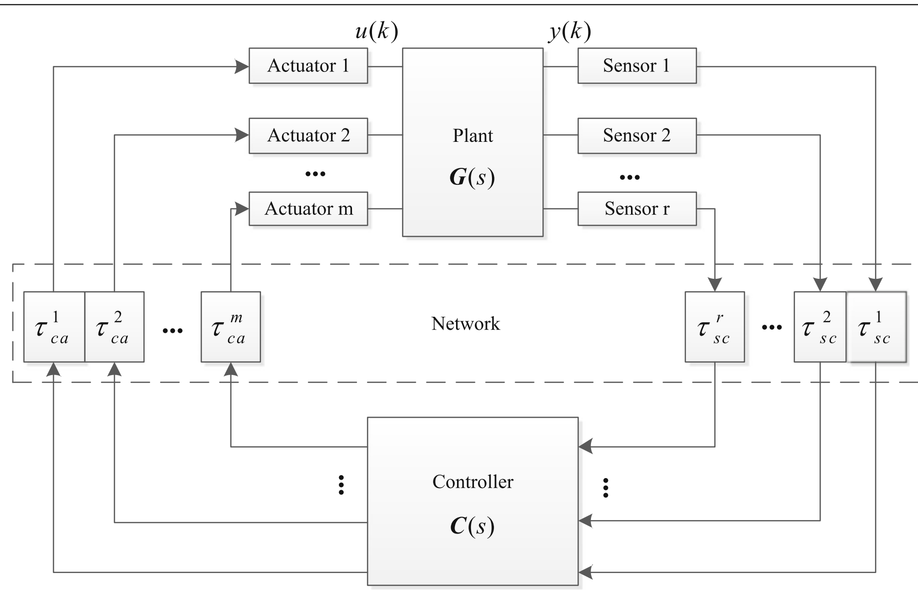

Fig. 1 The structure of MIMO NCS

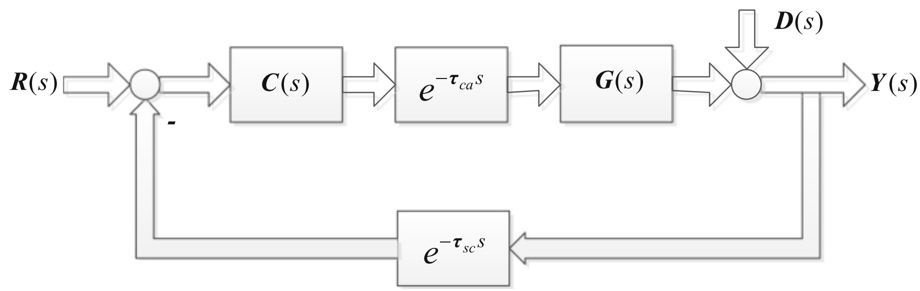

Fig. 2 The simplified structure of MIMO NCS

NCS, the essence of control, first of all, needs to design a reasonable decoupling device to eliminate the coupling between the loops. That is, the plant is corrected to weaken or eliminate the correlation among the loops, and the multivariable system turns into several independent single loop systems. Therefore, $\mathbf{G}(s)$ needs to satisfy its determinant which is not equal to 0, that is, $\det[\mathbf{G}(s)] \neq 0$. Only when the plant is steady and nonsingular can decoupling control be realized.

From Figs. 1 and 2, it can be seen that MIMO NCS differs from conventional multivariable control systems in that signals between nodes are transmitted over the network. Due to the limited network bandwidth, data collisions and network congestion often occur when multiple nodes transmit data in the network, and network-induced delays are inevitable. The network-induced delays of MIMO NCS are random, time-varying, and uncertain. The set-point response transfer function matrix and disturbance response transfer function matrix of MIMO NCS available in Fig. 2 are shown below.

$$\begin{aligned}\mathbf{H}_r(s) &= \mathbf{G}(s)\left[\mathbf{I}+\mathbf{C}(s)e^{-\boldsymbol{\tau}_{ca}s}\mathbf{G}(s)e^{-\boldsymbol{\tau}_{sc}s}\right]^{-1}e^{-\boldsymbol{\tau}_{ca}s}\mathbf{C}(s)\\ \mathbf{H}_d(s) &= \left[\mathbf{I}+\mathbf{C}(s)e^{-\boldsymbol{\tau}_{ca}s}\mathbf{G}(s)e^{-\boldsymbol{\tau}_{sc}s}\right]^{-1}\end{aligned} \tag{2}$$

From Eq. (2), we can find that the characteristic equation is $\left|\mathbf{I}+\mathbf{C}(s)e^{-\boldsymbol{\tau}_{ca}s}\mathbf{G}(s)e^{-\boldsymbol{\tau}_{sc}s}\right| = 0$. It contains the delay exponential terms $e^{-\boldsymbol{\tau}_{ca}s}$ and $e^{-\boldsymbol{\tau}_{sc}s}$. Since the delay $\boldsymbol{\tau}_{ca}$ occurs after the controller, it is impossible to predict its exact value. In addition, the network-induced delays make the internal coupling of the multivariate plant more complex, and the dynamic performance and stability analysis of MIMO NCS become more difficult. Therefore, designing an appropriate controller eliminates the network-induced delay index terms $e^{-\boldsymbol{\tau}_{ca}s}$ and $e^{-\boldsymbol{\tau}_{sc}s}$ from the transfer function matrix. Considering the compensation and control of network delays from the structure is the focus of this paper. At the same time, it is necessary to make the system output responses have the ability to overcome the uncertain disturbances.

4 The principle of new Smith predictor

4.1 V-norm decoupling control

The classic Smith predictor and v-norm decoupling structure of MIMO NCS are depicted in Fig. 3. $\mathbf{G}(s)$ and $\mathbf{C}(s)$ denote the plant transfer function matrix and the centralized controller, respectively. $\mathbf{N}(s)$ is the decoupler that is decoupling the plant to single loops. The v-norm decoupling matrix is composed of the forward matrix $\mathbf{W}(s)$ and the feedback matrix $\mathbf{K}(s)$. $\mathbf{G}_m(s)$ denotes the transfer function matrix of generalized plant prediction model after decoupling. $\mathbf{R}(s)$ refers to reference input vector, and $\mathbf{D}(s)$ refers to input interference vector. $\mathbf{Y}(s)$ stands for the output vector. $e^{-\boldsymbol{\tau}_{sc}s}$ and $e^{-\boldsymbol{\tau}_{ca}s}$ are network delays; $e^{-\boldsymbol{\tau}_{scm}s}$ and $e^{-\boldsymbol{\tau}_{cam}s}$ are network delay prediction models.

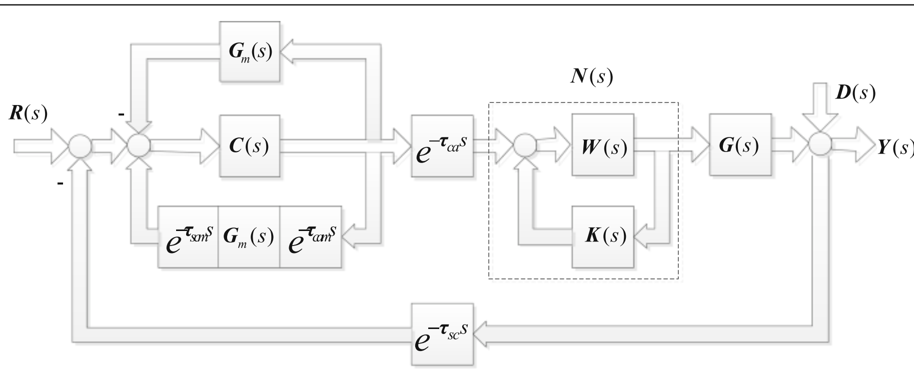

Fig. 3 The classic Smith predictor and v-norm decoupling structure

In Fig. 3, open loop decoupling control is first performed on $\mathbf{G}(s)$ so that $\mathbf{G}_k(s) = \mathbf{G}(s)\mathbf{N}(s)$ becomes a diagonal matrix. From Fig. 3, $\mathbf{G}_k(s) = \mathbf{G}(s)\mathbf{N}(s) = \mathbf{G}(s)(\mathbf{I} - \mathbf{W}(s)\mathbf{K}(s))^{-1}\mathbf{W}(s)$ can be obtained and make the following transformation:

$$\mathbf{G}_k^{-1}(s) = \mathbf{W}^{-1}(s)(\mathbf{I}-\mathbf{W}(s)\mathbf{K}(s))\mathbf{G}^{-1}(s) \tag{3}$$

$$\left(\mathbf{W}^{-1}(s)-\mathbf{K}(s)\right)_{ij} = \left(\mathbf{G}_k^{-1}(s)\mathbf{G}(s)\right)_{ij} \tag{4}$$

Since $\mathbf{W}(s)$ represents a diagonal matrix and the diagonal elements of $\mathbf{K}(s)$ are all zero, they can be obtained as follows:

$$\mathbf{W}(s) = \mathbf{N}_{ii}(s) = \mathbf{G}_{ii}{}^{-1}(s)\mathbf{G}_k(s) \quad (i = 1, 2 \ldots n) \tag{5}$$

$$\mathbf{K}(s) = \mathbf{N}_{ij}(s) = -\mathbf{G}_k{}^{-1}(s)\mathbf{G}_{ij}(s) \tag{6}$$

$\mathbf{W}(s)$ is chosen as the unit matrix to simplify the decoupling process. Then, $\mathbf{N}_{ii}(s) = \mathbf{G}_{ii}{}^{-1}(s)\mathbf{G}_k(s) = \mathbf{I}$, so $\mathbf{G}_k(s) = \mathbf{G}_{ii}(s)$. But, in order to make the decoupling compensation off-diagonal element $\mathbf{K}(s)$ available, let $\mathbf{G}_k(s) = \mathbf{G}_{ii\_}(s)$ where $\mathbf{G}_{ii\_}(s)$ is the minimum phase part of the diagonal elements of the plant. In addition, the off-diagonal elements of this decoupled matrix are $\mathbf{N}_{ij}(s) = -\mathbf{G}_{ii\_}{}^{-1}(s)\mathbf{G}_{ij}(s)$.

4.2 Classic Smith predictor for MIMO NCS

After decoupling control, the generalized plant $\mathbf{G}_k(s)$ is a diagonal matrix. In Fig. 3, we first calculate the inner loop on the controller side.

$$\mathbf{C}^*(s) = [\mathbf{I} + \mathbf{C}(s) \times (\mathbf{G}_m(s) - e^{-\boldsymbol{\tau}_{\mathrm{scm}}s}\mathbf{G}_m(s)e^{-\boldsymbol{\tau}_{\mathrm{cam}}s}]^{-1}\mathbf{C}(s) \tag{7}$$

For the outer loop after decoupling, the transfer function matrix of closed loop is shown below.

$$\mathbf{Y}(s) = [\mathbf{I} + \mathbf{G}_k(s)e^{-\boldsymbol{\tau}_{\mathrm{ca}}s}\mathbf{C}^*(s)e^{-\boldsymbol{\tau}_{\mathrm{sc}}s}]^{-1} \mathbf{G}_k(s)e^{-\boldsymbol{\tau}_{\mathrm{ca}}s}\mathbf{C}^*(s)\mathbf{R}(s) \tag{8}$$

Substituting (7) into (8), we can get

$$\mathbf{Y}(s) = \left[\mathbf{I} + \mathbf{G}_k(s)e^{-\boldsymbol{\tau}_{\mathrm{ca}}s}\mathbf{T}^{-1}(s)\mathbf{C}(s)e^{-\boldsymbol{\tau}_{\mathrm{sc}}s}\right]^{-1} \mathbf{G}_k(s)e^{-\boldsymbol{\tau}_{\mathrm{ca}}s}\mathbf{T}^{-1}(s)\mathbf{C}(s)\mathbf{R}(s) \tag{9}$$

where $\mathbf{T}(s) = \mathbf{I} + \mathbf{C}(s)(\mathbf{G}_m(s) - e^{-\boldsymbol{\tau}_{\mathrm{scm}}s}\mathbf{G}_m(s)e^{-\boldsymbol{\tau}_{\mathrm{cam}}s})$. If $\mathbf{G}_m(s) = \mathbf{G}_k(s)$, and the estimation models of the network-induced delays are accurate, that is, $e^{-\boldsymbol{\tau}_{\mathrm{cam}}s} = e^{-\boldsymbol{\tau}_{\mathrm{ca}}s}$ and $e^{-\boldsymbol{\tau}_{\mathrm{scm}}s} = e^{-\boldsymbol{\tau}_{\mathrm{sc}}s}$, the transformation of formula (9) is obtained:

$$\mathbf{Y}(s) = \mathbf{G}_k(s)e^{-\boldsymbol{\tau}_{\mathrm{ca}}s}[\mathbf{I} + \mathbf{C}(s)\mathbf{G}_k(s)]^{-1}\mathbf{C}(s)\mathbf{R}(s) \tag{10}$$

It can be proved that the characteristic equation of the system is as follows:

$$|\mathbf{I} + \mathbf{C}(s)\mathbf{G}_k(s)| = 0 \tag{11}$$

From Eq. (11), we can see that the characteristic equation of the system no longer contains the network delay, and there is no dead time delay in both $\mathbf{C}(s)$ and $\mathbf{G}_k(s)$. Therefore, the Smith predictor can overcome the impact of the network delays on MIMO NCS stability. However, accurate predictions of network delays are difficult. And delay $\boldsymbol{\tau}_{\mathrm{ca}}$ occurs in the process of data transmission from controller to actuator. Advance precise prediction in the controller node is impossible with the delay of subsequent data transmission. Regardless of the prediction method used, there will be prediction errors between $\boldsymbol{\tau}_{\mathrm{cam}}$ and $\boldsymbol{\tau}_{\mathrm{ca}}$.

4.3 New Smith predictor method for MIMO NCS

We address the deficiencies in Section 4.2, a new modified dynamic Smith predictor is presented in Fig. 4. The key to the modified Smith predictor for MIMO NCS is that the information flows via the network delays which are the real data packet transmission delays. Therefore, we do not need to measure, estimate, or identify the network-induced delays online. It realizes the compensation of the delay from the structure and avoids adding buffer to estimate delays and saves network bandwidth resources.

The transfer function matrix in Fig. 4 of the inner loop consisting of $\mathbf{C}(s)$ and $\mathbf{G}_m(s)$ is:

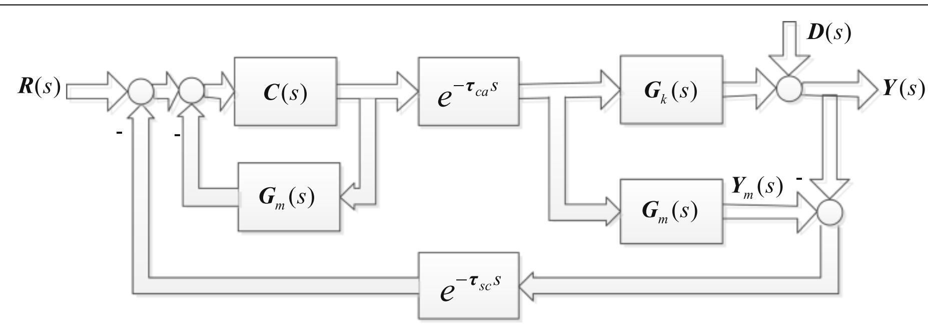

Fig. 4 The new Smith predictor for MIMO NCS

$$\mathbf{C}^*(s) = [\mathbf{I} + \mathbf{C}(s)\mathbf{G}_m(s)]^{-1}\mathbf{C}(s) \tag{12}$$

The transfer function matrix of the inner loop consisting of $\mathbf{C}(s)$, $e^{-\boldsymbol{\tau}_{ca}s}$, $\mathbf{G}_m(s)$, and $e^{-\boldsymbol{\tau}_{sc}s}$ is:

$$\mathbf{B}^*(s) = [\mathbf{I} + e^{-\boldsymbol{\tau}_{ca}s}\mathbf{C}(s)e^{-\boldsymbol{\tau}_{sc}s}\mathbf{G}_m(s)]^{-1}e^{-\boldsymbol{\tau}_{ca}s}\mathbf{C}(s) \tag{13}$$

Then, the outer loop is:

$$\begin{aligned}\mathbf{Y}(s) = {}&[\mathbf{I} + \mathbf{G}_k(s)\mathbf{B}^*(s)e^{-\boldsymbol{\tau}_{ca}s}\mathbf{C}^*(s)e^{-\boldsymbol{\tau}_{sc}s}]^{-1}\\ &\mathbf{G}_k(s)\mathbf{B}^*(s)e^{-\boldsymbol{\tau}_{ca}s}\mathbf{C}^*(s)\mathbf{R}(s)\end{aligned} \tag{14}$$

If $\mathbf{G}_m(s) = \mathbf{G}_k(s)$, the (14) can be transformed as follows:

$$\mathbf{Y}(s) = \mathbf{G}_k(s)e^{-\boldsymbol{\tau}_{ca}s}[\mathbf{I} + \mathbf{C}(s)\mathbf{G}_k(s)]^{-1}\mathbf{C}(s)\mathbf{R}(s) \tag{15}$$

The characteristic equation of the system is:

$$|\mathbf{I} + \mathbf{C}(s)\mathbf{G}_k(s)| = 0 \tag{16}$$

Similarly, from Eq. (16), it can be seen that when the new Smith predictor is used, the characteristic equation no longer contains the estimated exponential terms of the network-induced delays. It effectively reduces the stability influence to the system. From Fig. 4 and Eq. (15), compared with the new Smith controller and the classic Smith controller, the superiority of this method is that the actual transmission delays of the network data replace the estimation models of the network-induced delays, thus eliminating the need to measure, estimate, and identify the network delays. Therefore, the new Smith method can reduce the output deviation due to inaccurate estimation models. Furthermore, during the process of the sensor sending data packet to the controller, the network-induced delay $\boldsymbol{\tau}_{sc}$ is completely eliminated from the closed loop characteristic equation. The controller can be triggered by the sensor signal regular, but we do not have to worry about the delay and packet loss in this process. When the system bandwidth resources are limited, the system can tolerate a certain amount of packet losses.

5 Improved fuzzy immune PID algorithm

Due to the model errors produced by mismatch or disturbance, Smith predictor cannot fully realize compensation. An improved fuzzy immune PID approach is used to strengthen the robustness of the MIMO NCS when there is a prediction error or network bandwidth constraint.

5.1 Immune system mechanism

The immune feedback system is an important functional of the human body, and it is responsible for immune defense, immune surveillance, and immune self-stability. The immune system produces antibodies that are resistant to foreign antigens. Lymph is composed of T cells and B cells. T cells are produced by the thymus including T_H and T_S. B cells are formed in the bone marrow. They are very important for the body immunity. After the antigen invades the body, the T cells sense the invading antigen and then stimulate B cells to excrete antibodies. After a period of immune response, the differentiation of suppressor cells T_S is accelerated. It secretes inhibitory factors and inhibits the function of T_H cells and B cells to exert negative feedback regulation. When there are more antigens, there are more T_H cells in the body, but there are fewer T_S cells, which will produce more B cells. The number of antibodies is much more. Conversely, the antibody will decrease. After a while, the body tends to balance. A perfect and harmonious immune feedback system is that the body has a faster response speed to the invasion of antigen and can be stabilized quickly. The simplified immune system mechanism is shown in Fig. 5 [33].

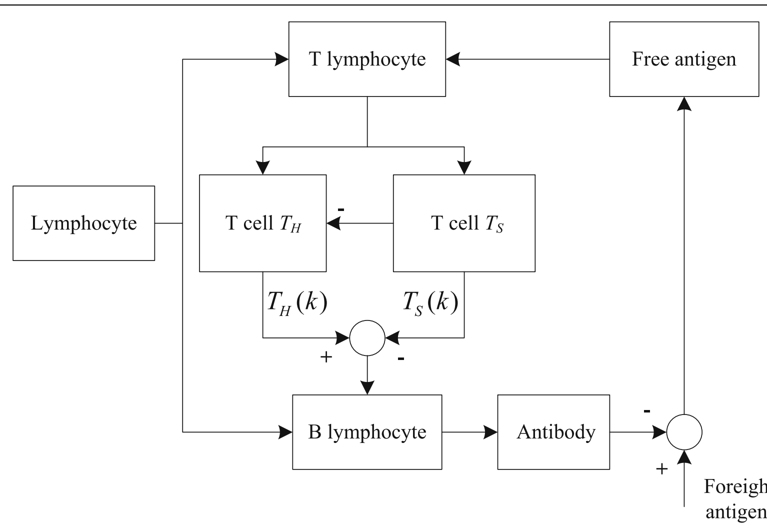

Fig. 5 The immune system mechanism

Inspired by the biological immune feedback mechanism, similar immune feedback PID controllers are hot in control engineering field. The coefficients of proportional, integral, and differential are usually adjusted in terms of the changes of the control signal output variable u. The immune feedback controller will have a fast response time and a small overshoot when the PID parameters and nonlinear functions $f(\cdot)$ are reasonable. And when the system is subject to external disturbance, it has strong robustness. It is assumed that the k-generation antigens are $\sigma(k)$, the cells produced by T_H cells after stimulation are $T_H(k)$, and the cells that suppress the antibody secretion of T_S cells are $T_S(k)$. After $T_H(k)$ and $T_S(k)$ act on B cells, the antibody produced by all the stimuli received by B cells is $S(k)$, which has the following formulation descriptions.

$$\begin{aligned} T_H(k) &= k_1\sigma(k) \\ T_S(k) &= k_2 f(\cdot)\sigma(k) \\ S(k) &= T_H(k) - T_S(k) = (k_1 - k_2 f(\cdot))\sigma(k) \end{aligned} \tag{17}$$

where $f(\cdot) = f(S(k), \Delta S(k))$ represents nonlinear function of cell inhibition and excitation changes. If the antigen number $\sigma(k)$ is regarded as the error $e(k)$, the B cell receiving the stimulus is regarded as the control signal output $u(k)$. We can get the feedback control rules in Eq. (18):

$$u(k) = K[(1 - \eta f(u(k), \Delta u(k))]e(k) = k_P e(k) \tag{18}$$

where $K = k_1$ and $\eta = \frac{k_2}{k_1}$. In the immune feedback control systems, K and η are particularly important parameters. Increasing the value of K will promote response speed, while increasing the value of η will reduce the output response overshoot. If the parameters are chosen properly, the system output will have better output performance. The output of the general fuzzy immune PID method is presented in (19).

$$\begin{aligned} u(k) = u(k-1) + k_p[k_{p1}(e(k) - e(k-1)) \\ + k_{i1}e(k) + k_{d1}(e(k) - 2e(k-1) + e(k-2))] \end{aligned} \tag{19}$$

where

$$\begin{cases} K_P = K[(1 - \eta f(u(k), \Delta u(k))]k_{p1} \\ K_I = K[(1 - \eta f(u(k), \Delta u(k))]k_{i1} \\ K_D = K[(1 - \eta f(u(k), \Delta u(k))]k_{d1} \end{cases} \tag{20}$$

K_P, K_I, and K_D are variable proportional gains, integral gains, and differential gains, respectively [34]. Based on Eq. (20), the parameters of the PID controller simultaneously enlarge or reduce the same multiple. However, the influence of parameters about proportional, integral, and differential on the system is different. The classic fuzzy immune PID control method is not the optimal to deal with the parameters. In the following, this paper turns the output of the modified fuzzy controller into three nonlinear functions corresponding to the PID parameters in order to realize an independent, online control of MIMO NCS.

5.2 Improved fuzzy immune PID algorithm

The nonlinear expression $f(u(k), \Delta u(k))$ is difficult to obtain in immune feedback control structure. An improved fuzzy approach is proposed to describe the nonlinear function of PID. The rules are determined by the control variables of the system, which has better flexibility and adaptive performance. Fuzzy logic controller has two inputs and three outputs. The two inputs are the output signal $u(k)$ and the change rate of output $\Delta u(k)$, respectively. The outputs are three nonlinear functions $f_P(\cdot)$, $f_I(\cdot)$, and $f_D(\cdot)$ that adjust the PID parameters separately. The structure of new Smith predictor combined with improved fuzzy immune PID controller is displayed in Fig. 6.

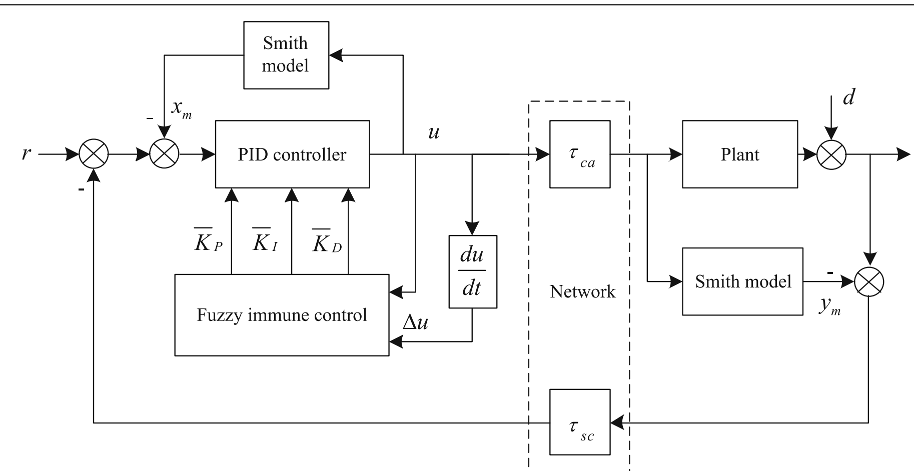

Fig. 6 The new Smith predictor and improved fuzzy immune PID algorithm

Equation (21) gives the improved fuzzy immune PID expression.

$$u(k) = u(k-1) + \overline{K}_P(e(k)-e(k-1)) + \overline{K}_I e(k) + \overline{K}_D(e(k)-2e(k-1) + e(k-2)) \tag{21}$$

where

$$\begin{cases} \overline{K}_P = K_1(1-\eta_1 f_P(u(k), \Delta u(k))) \\ \overline{K}_I = K_2(1-\eta_2 f_I(u(k), \Delta u(k))) \\ \overline{K}_D = K_3(1-\eta_3 f_D(u(k), \Delta u(k))) \end{cases} \tag{22}$$

As described in Eq. (22), the modified fuzzy immune PID control parameters $\overline{K}_P$, $\overline{K}_I$, and $\overline{K}_D$ are adaptively adjusted by different nonlinear functions. $\overline{K}_P$ is mainly regulated by $f_P(\cdot)$. $\overline{K}_I$ is mainly regulated by $f_I(\cdot)$. $\overline{K}_D$ is mainly regulated by $f_D(\cdot)$. $f_P(\cdot)$, $f_I(\cdot)$, and $f_D(\cdot)$ are the functions that control the signal $u(k)$ and its rate of change $\Delta u(k)$. The inputs and outputs use a set of Z membership function, triangle membership function, and S membership function. $\{FD, FZ, FX, L, ZX, ZZ, ZD\}$ represents the seven fuzzy set states of the input and output. The fuzzy logic uses "and," and the defuzzification method is "centroid." According to the dynamic balance rule of the immune feedback control system, the fuzzy control rules of nonlinear functions $f_P(\cdot)$, $f_I(\cdot)$, and $f_D(\cdot)$ can be obtained as Table 1.

Combining the membership function and fuzzy theory in Table 1, the nonlinear functions $f_P(\cdot)$, $f_I(\cdot)$, and $f_D(\cdot)$ can be tuned online. Refer to the change of the output form of any loop of the MIMO NCS to optimize the output performance of the system.

6 Illustrative examples

In this section, simulation experiments are performed for a coupled NCS. Double-input double-output NCS model is built in MATLAB/TRUETIME, the sampling period $T = 0.010$s. The network protocol selects Ethernet with stochastic, time-varying, and uncertain delays. The initial network bandwidth is set to 880 kb/s, no packet loss, the minimum frame length is 40 bit, and the interference node is occupied 58% of the network bandwidth. The output performance of the double-input double-output NCS can be analyzed in terms of plant matches, parameter perturbation, or network environment changes. The reference signals are step signals. Their amplitudes are 10 triggered at $t = 0.500$s and 8 triggered at $t = 5.000$s.

6.1 Simulation of model matches the generalized plant

6.1.1 Example design

The transfer function matrix of double-input double-output control plant is given by the following:

$$\mathbf{G}(s) = \begin{bmatrix} \dfrac{1}{0.01s+1} & -\dfrac{1.25}{0.025s+1} \\ \dfrac{0.25}{0.0125s+1} & \dfrac{1}{0.02s+1} \end{bmatrix} \tag{23}$$

We address the deficiencies in Section 4.1, the decoupling segment $\mathbf{W}(s)$ is the unit matrix, and the determined decoupler is as follows:

$$\mathbf{K}(s) = \begin{bmatrix} 0 & -\dfrac{0.0125s+1.25}{0.025s+1} \\ -\dfrac{0.005s+0.25}{0.0125s+1} & 0 \end{bmatrix} \tag{24}$$

The Smith model of initial generalized plant matrix $\mathbf{G}_m(s) = \begin{bmatrix} \frac{1}{0.01s+1} & 0 \\ 0 & \frac{1}{0.02s+1} \end{bmatrix}$. The domains of the control single are $\{-3, 3\}$ in both loops; the domains of deviation change ratio are $\{-2.25, 2.25\}$. The domains of the output functions $f_P(\cdot), f_I(\cdot), f_D(\cdot)$ are $\{-0.225, 0.225\}$, $\{-0.045, 0.045\}$, and $\{-2.25, 2.25\}$ respectively. The initial parameter of PID coefficient of loop 1 is $K_{a1} = 0.003$; $K_{a2} = 0.040$; $K_{a3} = 0.100$, $\eta_{a1} = 0.010$; $\eta_{a2} = 0.010$; $\eta_{a3} = 0.600$. The initial defined value of PID coefficient of loop 2 is $K_{b1} = 0.004$; $K_{b2} = 0.090$; $K_{b3} = 0.100$, $\eta_{b1} = 0.010$; $\eta_{b2} = 0.010$; $\eta_{b3} = 0.600$. The network delay distributions between the nodes are presented in Figs. 7 and 8. The output responses are shown in Figs. 9 and 10, in which the figures contain partial enlarged details for ease of comparison.

Table 1 Fuzzy rules of the three nonlinear functions $f_P(\cdot)$, $f_I(\cdot)$, and $f_D(\cdot)$

	u						
	FD	FZ	FX	L	ZX	ZZ	ZD
FD	ZD/FD/ZX	ZD/FD/ZX	ZZ/FD/Z	ZZ/FZ/L	ZX/FZ/L	ZX/L/ZD	L/L/ZD
FZ	ZD/FD/FX	ZD/FD/FX	ZZ/FZ/FX	ZZ/FZ/FX	ZX/FX/L	L/L/ZX	L/L/ZZ
FX	ZZ/FZ/FD	ZZ/FZ/FD	ZZ/FX/FZ	ZX/FX/FX	L/L/L	FX/ZX/ZX	FZ/ZX/ZZ
Δ*u* L	ZZ/FZ/FD	ZX/FX/FZ	ZX/FX/FZ	L/L/FX	FX /ZX/L	FZ/ZX/ZX	FZ/ZZ/ZZ
ZX	ZX/FX/FD	ZX/FX/FZ	L/L/FX	FX/ZX/FX	FX/ZX/L	FZ/ZZ/ZX	FZ/ZZ/ZX
ZZ	L/L/FZ	L/L/FX	FX/ZX/FX	FZ/ZZ/FX	FZ/ZZ/L	FZ/ZD/ZX	FD/ZD/ZX
ZD	L/L/ZX	FX/L/L	FX/ZX/L	FZ/ZZ/Z	FZ/ZD/L	FD/ZD/ZD	FD/ZD/ZD

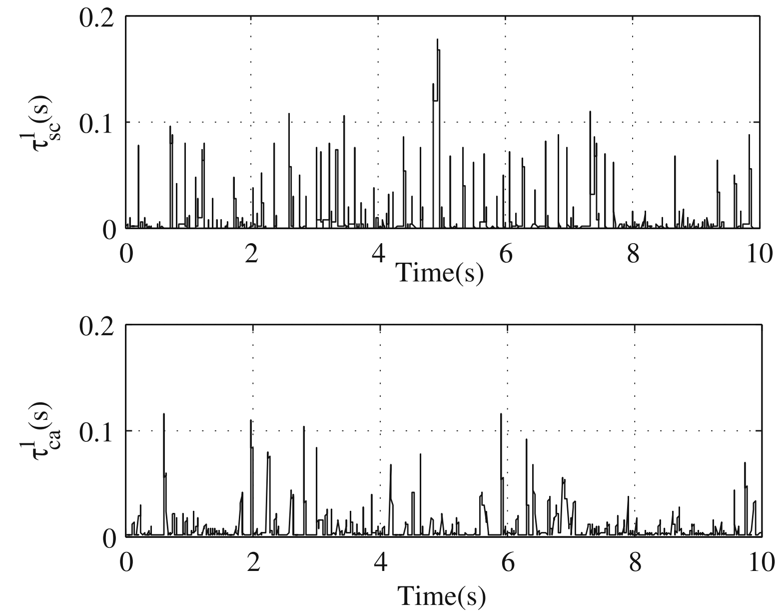

Fig. 7 The SC and CA delay distributions of loop 1 when the model matches the generalized plant

6.1.2 Results and discussion

From Figs. 7 and 8, we can see that the network-induced delays are random, uncertain, and changing over time. When the sampling period $T = 0.010s$, in the first loop, the maximum of SC delays reaches 0.176 s and exceeds 17 sampling periods; the maximum value of CA delays reaches 0.115 s and exceeds 11 sampling periods. Similarly, in the second loop, the maximum of SC delays is 0.187 s, which reaches 18 sampling periods; the CA delays are more than 11 sampling periods. From the output responses in Figs. 9 and 10, it can be noticed that under large network delay circumstances, both the proposed algorithm and the new Smith fuzzy with convention immune PID method can quickly track the set-point step response and maintain the system stable in two loops. On the contrary, the output without new Smith compensation is unstable and has a large overshoot whether in loop 1 (the green curve in y_1) or loop

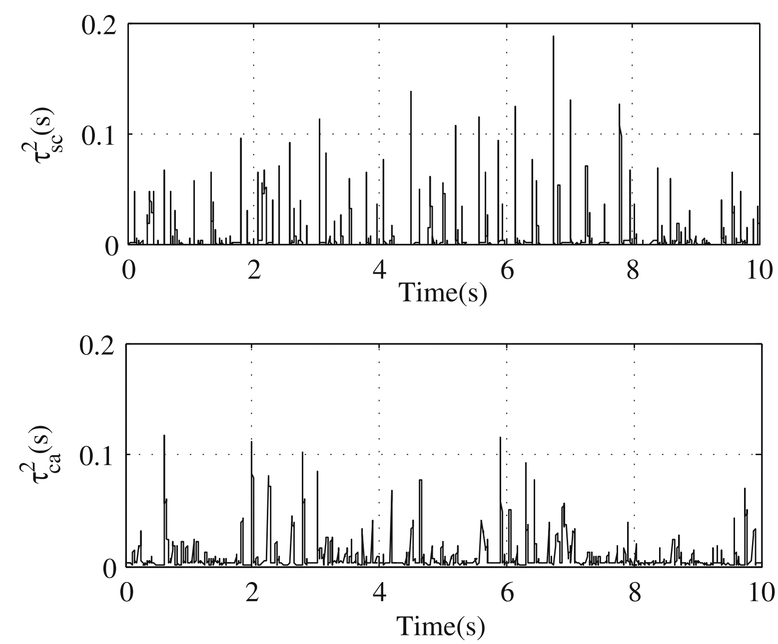

Fig. 8 The SC and CA delay distributions of loop 2 when the model matches the generalized plant

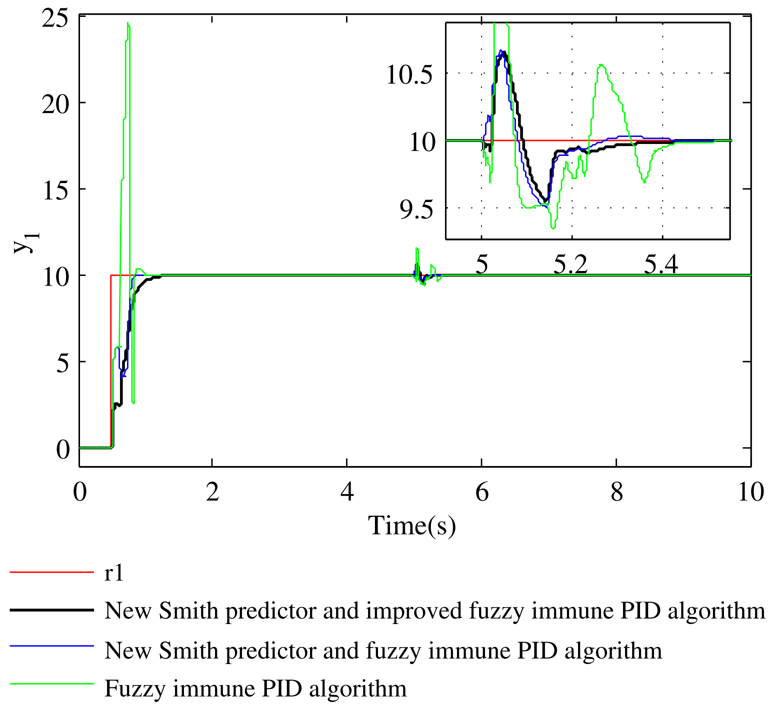

Fig. 9 The step responses of loop 1 when the model matches the generalized plant

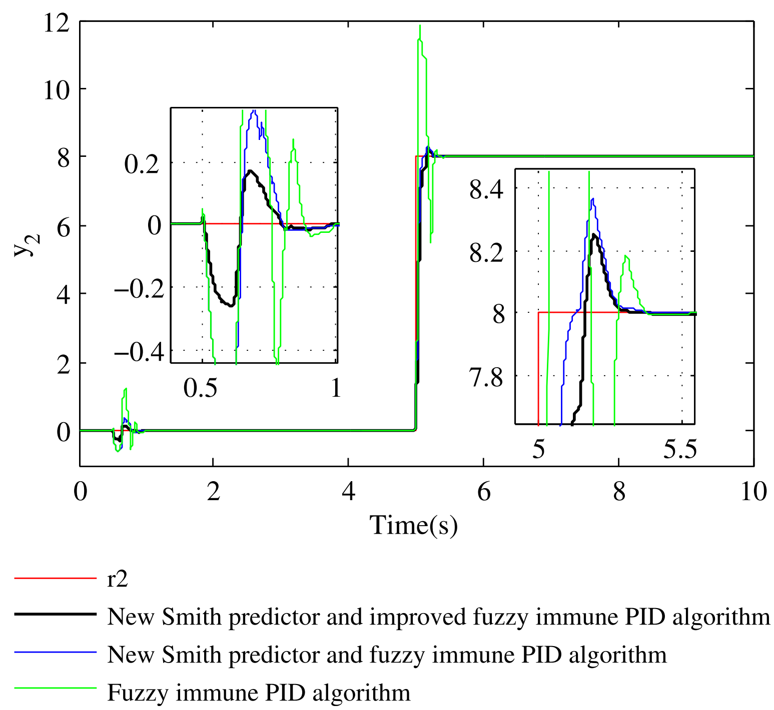

Fig. 10 The step responses of loop 2 when the model matches the generalized plant

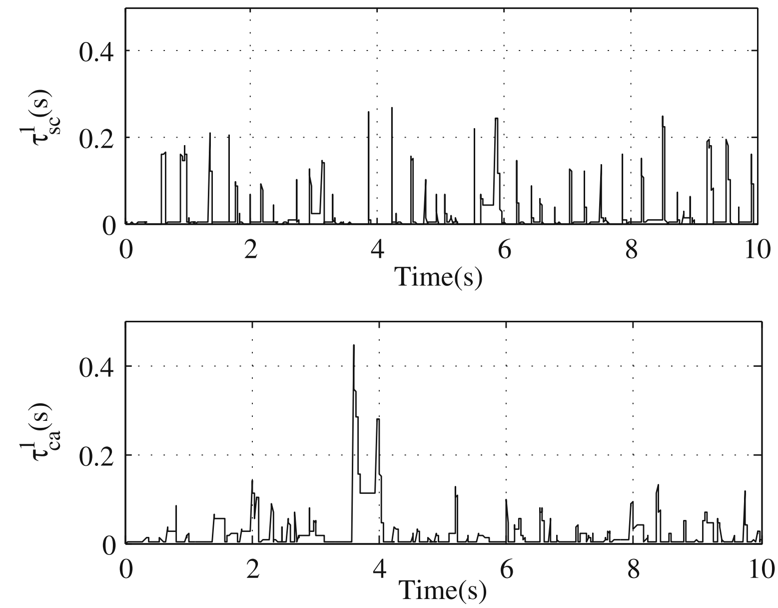

Fig. 11 The SC and CA delay distributions of loop 1 when parameter perturbation and communication network change

2 (the green curve in y_2). It indicates that the proposed new Smith and improved fuzzy immune PID algorithm has superior output performance compared with the other two algorithms.

6.2 Robust simulation of parameter perturbation and communication network changes

6.2.1 Example design

To illustrate the robustness of the new modified Smith predictor and improved fuzzy immune PID approach, network bandwidth is reduced to 700 kb/s. The network packet loss rate is set to 0.35, and the plant becomes as follows:

$$\mathbf{G}(s) = \begin{bmatrix} \frac{1.02}{0.03s+1}e^{-0.02s} & \frac{-1.27}{0.027s+1}e^{-0.02s} \\ \frac{0.27}{0.0127s+1}e^{-0.02s} & \frac{1.02}{0.04s+1}e^{-0.02s} \end{bmatrix} \tag{25}$$

The network delay distributions between the nodes are shown in Figs. 11 and 12. The packet dropout distributions

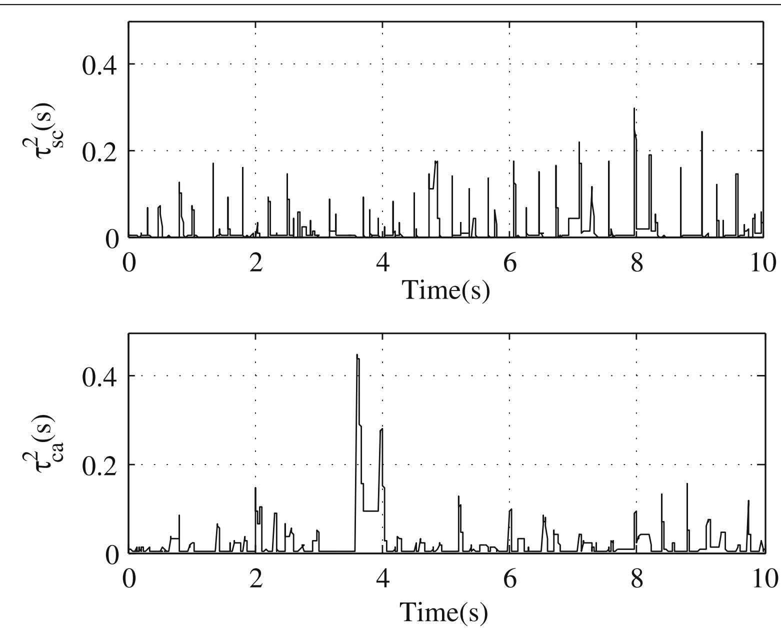

Fig. 12 The SC and CA delay distributions of loop 2 when parameter perturbation and communication network change

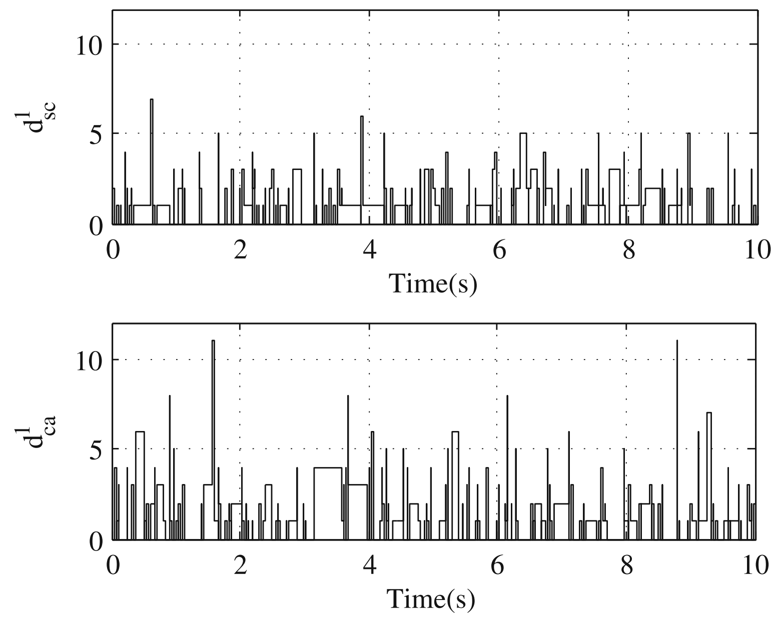

Fig. 13 The SC and CA packet dropout distributions of loop 1 when parameter perturbation and communication network change

between the nodes are indicated in Figs. 13 and 14. The output response curves are denoted in Figs. 15 and 16, where partial enlargements are included to facilitate comparison results.

6.2.2 Results and discussion

From Figs. 11 and 12, we can notice that after the network bandwidth is reduced, the nodes compete for network resources. Congestion causes some packets in the network channel to fail to reach the destination node in time. As a result, the data packet dropouts occur and the network delays also increase. In the first loop, the maximum of SC delays is up to 0.265 s, which are more than 26 sampling periods; the maximum of CA delays is up to 0.444 s, which exceeds 44 sampling periods. In the second loop, the maximum of SC delays rises to 0.294 s, which exceeds 29 sampling periods. The maximum of CA delays rises to 0.451 s, which exceeds 45 sampling

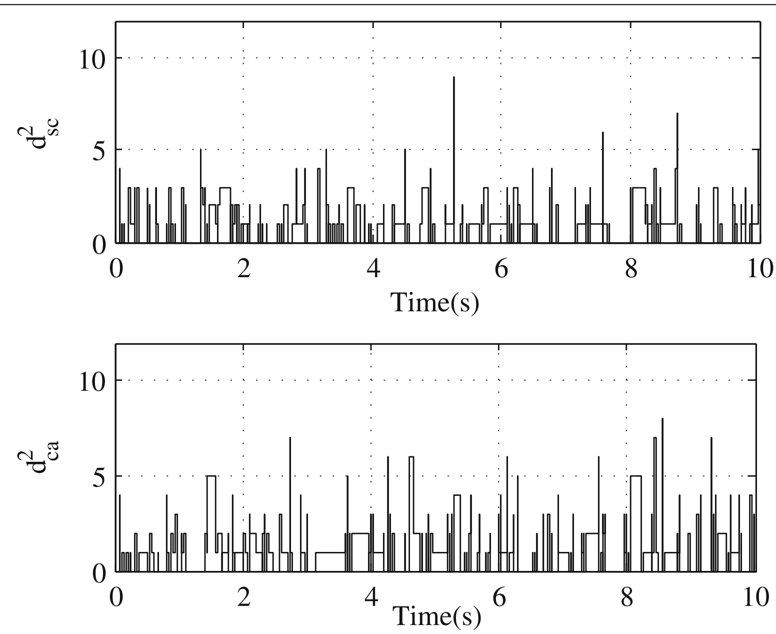

Fig. 14 The SC and CA packet dropout distributions of loop 2 when parameter perturbation and communication network change

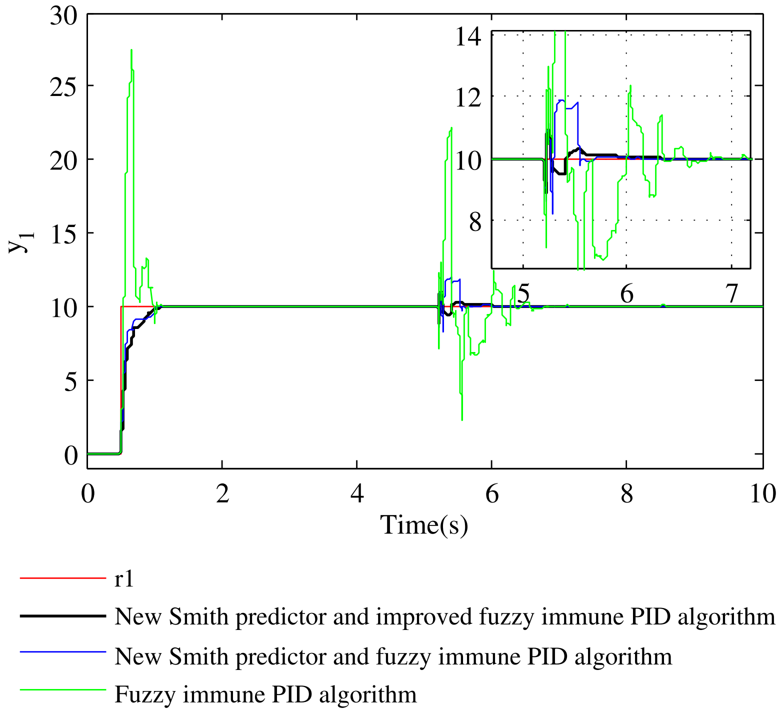

Fig. 15 The step responses of loop 1 when parameter perturbation and communication network change

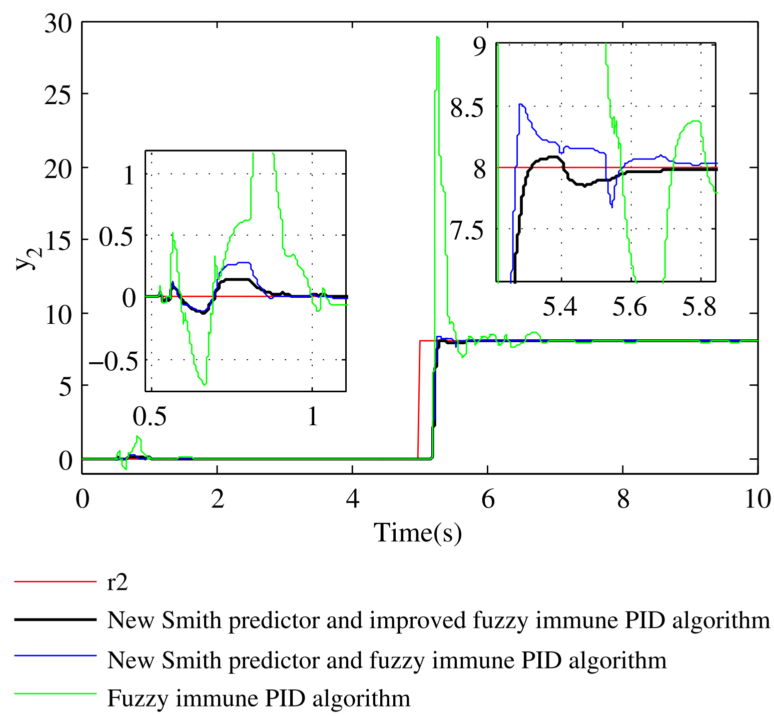

Fig. 16 The step responses of loop 2 when parameter perturbation and communication network change

periods. Figures 13 and 14 show that there are data packet losses in the network channels. The distributions of packet losses are changing at any time. In the first loop, the maximum values of SC and CA packet dropouts are 7 and 11 respectively. In the second loop, the maximum values of SC and CA packet dropouts are 9 and 8 respectively.

When there are large network delays and data packet dropouts, as can be noticed from Figs. 15 and 16, the new Smith predictor and improved fuzzy immune PID show better set-point responses with small overshoot and are much smoother. Compared with the other two algorithms, this proposed algorithm has strong robustness and anti-interference ability.

7 Conclusions

Focusing on the structure of MIMO NCS, a new Smith predictive fuzzy immune PID algorithm is applied to implement compensation for network-induced delays. It combines the advantages of Smith compensation method and artificial fuzzy immune algorithm. Under the assumption of perfect control, the network delay exponential term is eliminated. The proposed algorithm does not need to measure, estimate, and identify delays and is suitable for MIMO NCS where the network-induced delays are large and time-varying. The illustrative examples indicate that the output responses of the proposed algorithm can meet the system control performance requirements in terms of rise time, overshoot, etc. When uncertainties such as plant parameter perturbation and network packet dropouts occur, the new Smith predictive fuzzy immune PID controller can also more quickly recover the system to a stable state with superior robustness and anti-interference capability.

Abbreviations

CA: Controller to actuator; DMC: Dynamic matrix control; LQG: Linear quadratic Gaussian; MIMO NCS: Multi-input multi-output networked control systems; NCS: Networked control system; PD: Proportion differentiation; PID: Proportion integration differentiation; SC: Sensor to controller; SISO: Single-input single-output

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Authors' contributions

FD conceived and designed new Smith predictor; YT and FD performed the fuzzy immune PID algorithm and experiments; YT wrote the manuscript; YC analyzed the data; and YZ checked the language errors. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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