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Robust control of networked control systems with randomly varying time-delays based on adaptive Smith predictor

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Abstract

In this paper, we deal with the robust control of network induced delay and randomly varying time-delay (RVTD) controlled plant in networked control systems (NCS). The control problem of NCS becomes more challenging to attain the robust stability when time-delay appears in form of a time-varying signal in the closed loop of NCS. These in turn make the conventional control methods, e.g., normal mathematical model of Smith predictor, more complicated to meet the quality requirements of NCS. To overcome these inherent challenges, we essentially analyzed the existing techniques, and then propose a novel adaptive Smith predictor to efficiently reduce the effect of time-delays for high efficient and accurate control. Hence, the delay-dependent NCS becomes the delay-independent NCS, we proposed a necessary and sufficient conditions for the robust stability and performance of NCS in general formulation. By using the H∞ loop-shaping - McFarlane and Glover controller design method based on co-prime factor robustness and Linear Matrix Inequality (LMI), a robust controller has been suggested. The simulation results via TrueTime Beta2.0 platform demonstrate the usefulness and effectiveness of the proposed method.

Keywords**:** *networked control system, neural networks, adaptive Smith predictor, time-delay estimation, robust controller, Linear Matrix Inequality.*

1. Introduction

In the last three decades, networked control systems (NCS) have gained intensive attention from researchers. The most serious problems that cause poor performance, instability, and even collapse of NCS, are randomly varying time-delays (RVTD) and the plant model uncertainty. These problems can be addressed in two aspects: time-delay compensation and a proposed approach to solving the robust control problem. Regarding concentration of the time-delay compensation aspect, many different control methodologies have been proposed to reduce the effect of time-delay in the process control loop. Among them, Smith predictor is widely used as an effective compensator for large time-delay control systems (Astrom, Hang, & Lim, 2003; Bahill, 1983; Feng, Pan, & Han, 2003; Salt, Casanova, & Piz, 2010; Meng, Jia, Du, & Yu, 2010; Lai, & Hsu, 2010; Bolea, Puig, & Blesa, 2011). However, under the effect of RVTD, adaptive Smith predictive technique consisting of the on-line time-delay estimation and an adaptive control schemes can be adopted as a feasible solution. In this regard, the existing approaches mainly focus on either control scheme through the use of appropriate Lyapunov-Krasovskii functionals (Ge, Hong, & Lee, 2003) or estimation methods (Notari & Ohnishi, 2008; Huang, Kuo, & Tseng, 2007; Dang, Guan, Tran, & Li, 2011; Dang, Guan, &Tran, 2012). Especially, related to time-delay estimation methods, the time-delay, as a simple technique, is considered either constant or slowly varying forms (Agarwal & Canudas, 1987). The effect of these two forms of time-delay is reduced by approximately transforming them into frequency domain. More sophisticatedly, despite the fact that the time-delay is randomly varying in a slow or fast manner, it is mitigated by applying the Neuro-Fuzzy based time-delay estimation using discrete cosine transform coefficients (Shaltaf, 2007; Shaltaf, & Mohammad, 2009). Furthermore, the problem of RVTD was efficiently overcame in our previous works (Dang, Guan, Tran, & Li, 2011; Dang, Guan, & Tran, 2012) due to a combination of design of control and estimation schemes. However, the mentioned methods did not consider NCS in a class of uncertain time-delay system, which may render the proposed designs less efficient and robust.

The robust control aspect of NCS has received a considerable amount of attention in recent years. Cloosterman, Wouw, & Heemels, 2006; Jiang, & Fang, 2013; Tran, Guan, Dang, Cheng, & Yuan, 2013; Pan, Das, & Gupta, 2011 analyzed the stability of NCS with time-varying delays. Peng, C., et al., 2007, proposed a method for robust state feedback controller design of NCS with interval time-varying delay (Peng, Tian, & Tade, 2007). Considering state feedback controllers, the closed-loop NCS is described as a discrete-time linear uncertain system, and the uncertain part reflects on consequences problems of Smith predictor it is that does not handle the disturbance. Therefore, it is not able to reset the steady state error. Addressing this problem, Ioan et al., 2005, proposed the robustness of modified Smith predictor controller based on variable structure algorithms for nominal controller (Ioan, Ioana, & Raluca, 2005). In addition, the design of a filter to improve the robustness of NCS with the low pass transfer function to filter the error signal between the delayed output measurement and the delayed output open-loop model (Mu, Liu, & Rees, 2005).

In this paper, we propose a new approach to using adaptive Smith predictor NCS model consisting of a network, a robust controller, and a RVTD estimator to examine the robust stability and performance of NCS. The robust controller has been designed, using the H∞ loop-shaping controller design method based on Linear Matrix Inequality (LMI) and co-prime factor robustness. Joining the plant identification with RVTD estimator in the adaptive Smith predictor model to aim at mitigating the effect of RVTD, we investigate the robust stability and performance of the method of Dang et al. (2011; 2012) in respect of RVTD (Dang, Guan, Tran, & Li, 2011; Dang, Guan, & Tran, 2012).

The paper is organized as follows: Section 2, we analyze the Smith predictor structure of NCS. Section 3, the necessary and sufficient conditions for the robust stability and performance of Smith predictor NCS model are displayed in a general formulation and the robust controller design method is presented. Section 4 is composed of the designed controller with RVTD estimation schemes. Section 5, the overall adaptive Smith predictor NCS structure with plant identification based on neural network is proposed. Section 6, a numerical example is given. Section 7 draws conclusion.

2. Problem formulation

2.1 Structure of NCS

A structure of NCS can be described as in Figure 1. Typically, it includes a model of controlled plant without delay, G_p, the model of controller, K, an input, r, and an output, y. Network induced delay is characterized by controller-to-actuator delays, τ_{ca}, and sensor-to-controller delay, τ_{sc}. The closed loop transfer function is given below:

$$\frac{y(s)}{r(s)} = \frac{K(s)e^{-\tau_{ca}s}G_p(s)}{1+K(s)e^{-\tau_{ca}s}G_p(s)e^{-\tau_{sc}s}} \qquad (1)$$

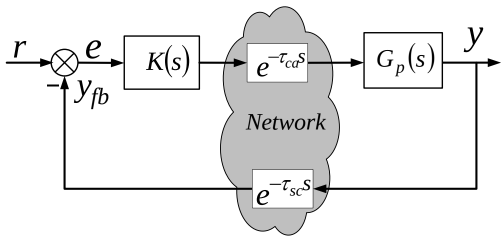

Figure 1 Structure of NCS

As can be observed from (1), the existence of τ_{cs} and τ_{ca} may reduce the quality of NCS.

2.2 Analysis of Smith predictor structure of NCS

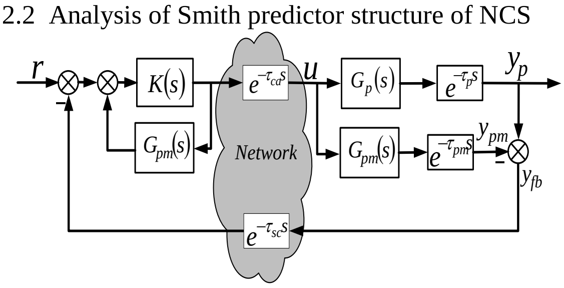

Figure 2 Smith predictor **s**tructure of NCS

Essentially, the controlled plant always generates a certain delay together with τ_{ca} and τ_{cs} becoming τ_p which makes the problem of time-delay compensation more problematic. Thus, the Smith predictor is added to NCS model as shown in Figure 2. Based on the Smith predictor, the time-delay compensation is now easier because its objective is suppressing the delay caused by τ_p. In fact, while the plant model is available, the variant and random delays in the network result in difficulty attaining the full suppression. Related to such problems, some researchers presented new Smith predictor models for NCS (Dang, Guan, Tran, & Li, 2011; Dang, Guan, & Tran, 2012; Du, Du, & Lei, 2009). In this paper, the Smith predictor structure of the NCS is summarized as follows.

Let G_p be the plant model with delay τ_p and G_{pm} with delay τ_{pm} be the predict model of G_p. For this structure, the close loop transfer function is approximately given by (2):

$$\frac{y_p(s)}{r(s)} = \frac{K(s)e^{-\tau_{ca}s}G_p(s)e^{-\tau_p s}}{1+K(s)G_{pm}(s)+K(s)e^{-\tau_{ca}s}\left[G_p(s)e^{-\tau_p s}-G_{pm}(s)e^{-\tau_{pm}s}\right]e^{-\tau_{sc}s}} \quad (2)$$

We have $\tau_p s = \tau_{pm} s$ and $G_p(s) = G_{pm}(s)$ by assuming that the predicted model is determined accurately. Consequently, we obtain (3) by reducing (2).

$$\frac{y_p(s)}{r(s)} = \frac{K(s)e^{-\tau_{ca}s}G_p(s)e^{-\tau_p s}}{1+K(s)G_p(s)} \quad (3)$$

Thus, we have obtained the transfer function of NCS model in Figure 2 as follows:

$$\frac{y_p(s)}{r(s)} = \frac{K(s)G_p(s)}{1+K(s)G_p(s)}e^{-\tau_{ca}s}e^{-\tau_p s} \quad (4)$$

As can be seen from (4), the effect of the network delays and controlled plant delay has been completely eliminated from the denominator of NCS transfer function. Therefore, the NCS can be separated and become two parts, one part is the closed loop control system and the other part appears as gain blocks before the output. However, it is practically difficult to obtain this result because of the following reasons:

- When the plant model is not accurately determined, it may cause the nominal control system instability.
- In case the delay of the plant cannot be estimated precisely, the difference between the fact and the model is significant, and the stability of NCS thus becomes unacceptable.
- When the time-delay of the system randomly varies in a large range, it causes the time-delay estimator over the stability bound of itself. Then, the output response of NCS is certainly unstable.
- In fact, the plant model can be determined exactly but the delay in models of the network and plant varies randomly. As a result, it is difficult to achieve perfect Smith predictor.

The detailed solutions for the above existing problems will be discussed and solved in the following sections.

3. Robust controller synthesis

In the real world, where the model does not present the exact plant parameter, nominal stability and performance are not sufficient and this will be more serious when using the nominal controller in Smith predictor model. A robust Smith predictor was proposed to compensate the round trip delay with the case of time-varying uncertain delays (Chen, Lin, & Hwang, 2007). Mu et al. presented a method to improve the robustness of networked control systems subject to random transmission time-delay (Mu, Liu, & D. Rees, 2005). Unlike the methods introduced in above papers, we use loop-shaping McFarlane and Glover method for studying the robust stabilization problem based equivalence adaptive Smith predictor model of NCS when time-delay of system varies randomly.

3.1 Preliminaries and motivation

The whole system will be assumed to be linear, finite dimensional and time-invariant. The following notation used the rational matrix transfer function of plant and the controller denoted $G_p(s)$ or G_p and $K(s)$ or K, respectively. There are common ways of representing unstructured uncertainty in the nominal system (K. Zhou, J. Doyle, & K. Glover 1995; M. Vidyasagar, 1985), such as, co-prime factors, additive perturbations, and multiplicative perturbations. We choose the co-prime factors for this robust stabilization problem giving a natural weighting to the uncertainty in the absence of coverage information, which is provided in term of the closed loop performance and allowable perturbation set. We assume the controlled plant G_p is the form of the nominal plant with shaping function and can be described as:

$$G_p = W_1 G W_2 \quad (5)$$

Let the realization of state-space system is denoted as:

$$G = (A, B.C, D) \quad (6)$$

Where the *A*, *B*, *C* and *D* are appropriately the dimensioned real constant matrices, $G(s) = C\,(sI - A)^{-1}B + D$. From (4), we can rebuild NCS in Figure 2, and obtain the new reduction NCS model as given in Figure 3.

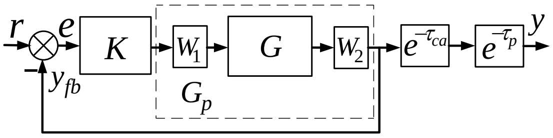

Figure 3 Equivalent to Smith predictor Structure of NCS

We consider state-space system $G = (A, B, C, D)$ representation

$$\dot{x} = \mathrm{Ax} + \mathrm{B}\omega \quad (7)$$

$$\dot{z} = C\mathrm{x} + \mathrm{D}\omega \quad (8)$$

where $\chi(t) \in R^n$ is the state vector, ω (t) $\in R^{n\omega}$ is the system input, and $z(t) \in R^{nz}$ is the measurement output. We have definition 1 (Turner, & Bates, 2007) below:

Definition 1. *Consider the LTI system G with state space equations (7), (8). Suppose G is stable, the H∞ norm of G can be defined as the largest singular value of its frequency response across frequency, that is*

$$\|G\|_\infty = \sup \sigma(G(j\omega)) \quad (9)$$

The *H∞* norm of an LTI system can be computed as the solution to a particular linear matrix inequality optimization problem in the Bounded Real Lemma (Turner, & Bates, 2007) as follows.

Lemma1. *(Bounded Real Lemma) Suppose the system given in (7), (8) is stable. The H∞ norm of G is smaller than γ if and only if there exists a symmetric matrix P such that*

$$\begin{pmatrix} A^T P + PA & PB & C^T \\ B^T P & -\gamma I & D^T \\ C & D & -\gamma I \end{pmatrix} < 0 \quad (10)$$

$$P > 0 \quad (11)$$

3.2 Loop-shaping using H∞ robust stabilization

From the closed loop in equivalent to Smith predictor of NCS in Figure 3, the existence of a static *H∞* loop-shaping output feedback controller is equivalent to the existence of a positive definite matrix *R*. It is possible to derive simple sufficient linear conditions by using LMI formulation. The approach *H∞* synthesis is based on the normalized co-prime factor of certain open loop plant that meets robust stability and performance requirements together.

The left co-prime factorization (LCF) is given in this paper, so that similar results can be obtained by duality by the right co-prime factorization (Glover, Sefton, & McFarlane, 1992).

Definition 2. *Matrices N, M ∈ H∞ constitutes a LCF of G if and only if:*

(i) $G = NM^{-1}$

(ii) *M is invertible, that is det(M) ≠ 0*

(iii) *There exists* $\tilde{V}$, $\check{U} \in$ *H∞ such that*

$$\tilde{V}M + \tilde{U}N = I \quad (12)$$

Let G_s is strictly proper system of considered state space system *G* with minimal realization:

$$G = (A, B.C, 0) \quad (13)$$

where G_s represents the shaped plant, that has a minimal normalized LCF $G_s = M^{-1}N$. The algebraic Riccati equation of the generalized RCF is given as:

$$AZ + ZA^T - ZC^T CZ + BB^T = 0 \quad (14)$$

where $L = -ZC^T$ and the matrix Z is the unique symmetric positive semi-definite solution of (14).

From (14) and the Bounded Real Lemma, we have the existence conditions for the full order γ suboptimal *H∞* loop-shaping output feedback controller (Turner,& Bates, 2007) as follows.

Theorem 3.1. *Let $L = -ZC^T$ where $Z \geq 0$ is the stabilizing solution to (14).There exists an output feedback controller K such that*

$$\left\| \begin{bmatrix} K \\ I \end{bmatrix} (I + G_s K)^{-1} M^{-1} \right\| < \gamma \quad (15)$$

if $\gamma > 1$ and if there exist a positive definite matrices R and S solving the inequalities

$$R(A + LC) + (A + LC)^T R - \gamma C^T C < 0 \quad (16)$$

$$\begin{pmatrix} AR + RA^T - \gamma BB^T & RC^T & -L \\ CR & -\gamma I & I \\ -L^T & I & -\gamma I \end{pmatrix} < 0 \quad (17)$$

$$\begin{pmatrix} R & I \\ I & S \end{pmatrix} < 0 \quad (18)$$

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Let us return to the stability and performance problem of Smith predictor NCS model in Figure 2, this model can be equivalent to the simple model in Figure 4. Before the robust stability condition for the above class of uncertainty is considered, the robust stability condition under general assumption is presented.

Assumption 1. *The predict nominal plant can accurately approximate the true nominal plant with* $G_{pm} = G_p$ *and* $\tau_{pm} = \tau_p$.

Assumption 2. *The nominal plant is strictly proper system, that has minimal normalized LCF* $G_s = NM^{-1}$.

The solution to find out the existence conditions for the full order γ *suboptimal* H_∞ *loop-shaping output feedback controller is given as follows:*

Theorem 3.2. *Consider the Smith predictor NCS model in Figure 2 with satisfying assumption 1 and assumption 2. There exists a static output feedback controller K if satisfying system of LMIs is given by*

$$\left\| \begin{bmatrix} K \\ I \end{bmatrix} (I + G_s K)^{-1} M^{-1} \right\| < \gamma \tag{19}$$

if $\gamma > 1$ *and if there exist a positive definite matrices R and S solving the inequalities*

$$R(A+LC) + (A+LC)^T R < 0 \tag{20}$$

$$\begin{pmatrix} AR + RA^T - \gamma BB^T & RC^T & -L \\ CR & -\gamma I & I \\ -L^T & I & -\gamma I \end{pmatrix} < 0 \tag{21}$$

where $L = -ZC^T$, $Z \geq 0$ *is the stabilizing solution to (14).*

Proof: *When the predicted nominal plant can accurately approximate the true nominal plant with* $G_{pm} = G_p$ *and* $\tau_{pm} = \tau_p$ *, then we have the equivalent simple NCS model in Figure 4. NCS becomes the control system with the delay of network and the delay of controlled plant removed from of closed loop and appeared as a gain block before the output. The time-varying network delay in the return path is totally eliminated from NCS. As a result, NCS has become the similar closed loop control system without affecting the delays. Let's consider the equivalence system in Figure 4, it shows that a reduced order controller can be synthesized if the matrices R and S satisfy the addition rank constraint*

$$Rank(I - RS) \leq k \tag{22}$$

The static output feedback controller can be obtained if Rank($I - RS$ *) = 0 when* $R = S^{-1}$ *. Following Theorem 3.1, we have (21). If we set* $R = S^{-1}$ *then we eliminated the quadratic term* $-\gamma C^T C$ *in (16) and obtained (20). We have thus proved Theorem 3.2.*

3.3 Designing the static H∞ loop-shaping robust controller

An *H∞* synthesis procedure that meets stability and performance requirements together in the approach of loop-shaping method. McFarlane and Glover (McFarlane, & Glover, 1990) proposed the approach based on the normalized co-prime factor of a certain open loop plant, known as a shaped plant, focusing on co-prime factor robustness. The full order static loop-shaping robust controller can be computed numerically by solving the inequalities in (20) and (21) of Theorem 3.2.

The design problem can be described by four steps as follows.

- Step 1: Select W_1 and W_2 to get the desired open loop shape and compute the full-order McFarlane and Glover solution, ensure that the γ_opt is small enough.
- Step 2: Compute matrix R > 0 and scalar variable γ solution by solving the inequality in (20) and (21) of the proposed Theorem 3.2.
- Step 3: If LMI in (20) and (21) is feasible then combine the controller *K* with the shaping function W_1 and W_2 in form $K_r = W_1 K W_2$.
- Step4: Construct the resulting parameters of robust controller with the adaptive Smith predictor NCS structure proposed in Figure 8, using the Matlab-Simulink software to get the simulation results.

4. Randomly varying Time-delay estimation schemes

Obviously, the perfect predicted model of the plant is difficult to obtain. If we use some methods such as estimating or identifying the real model of the plant, we have only the approximately model. Thus, finding out the exact model is a big challenge with control systems using Smith predictor model. This issue will be addressed in the next section. First, we assume that the $G_{pm} = G_p$ can be found out when considering NCS model in Figure 4, the time-delay cannot affect the stability and performance of the closed loop control system but it may reduce the performance, even the instability of NCS if the time-delay is uncertain or varies with large amplitude. Next, we deal with the robust stability and performance problem of NCS model in Figure 4 by comparing two following estimation time-delay schemes to expand our previous works. The first one is fuzzy estimation scheme (Dang, Guan, Tran, & Li, 2011) and the second one is neural network estimation scheme (Dang, Guan, & Tran, 2012) under the effect of RVTD.

4.1 Randomly varying time-delay fuzzy estimation scheme

An area *A(k)*, which slowly increases and reaches to a certain constant when y_p and y_m are overlapped so that we obtain $\tau(k)_{pm} = \tau(k)_p$. *A(k)* can be described by Huang *et al.* (Huang, Kuo, & Tseng, 2007)

$$A(k) = \int_0^k \left| y_p(t) - y_{pm}(t) \right| dt \tag{23}$$

An RVTD fuzzy estimation scheme (TDFES) has two important components. The first one is on-line calculation modulator consisting of a double-input, y_p and y_{pm}, and the second one is a double-output, e and Δe, respectively. The outputs at each sampling time are given by equation (24), (25) as follows:

$$e(k+1) = A(k+1) - A(k) \tag{24}$$

$$\Delta e(k+1) = e(k+1) - e(k) \tag{25}$$

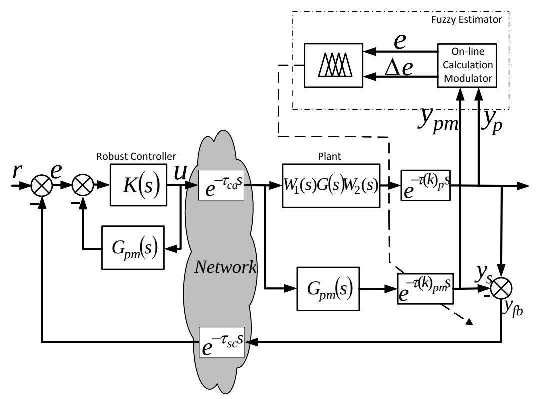

Figure 4 Joint robust controller with the TDFES in the Smith predictor NCS structure.

Notice that *A(k)* described in (23) depends on the difference between y_{pm} and y_p. Clearly, *A(k)* increases gradually and is fixed at a constant value until y_{pm} coincides with y_m as shown in Figure 5.

The component of the RVTD fuzzy estimation scheme is the fuzzy controller used to generate time-delay compensation. In the fuzzy controller, *e(k)* and *e(k+1)* are considered as inputs and $\tau(k)_{pm}$ is output, these membership function collections are separately described as

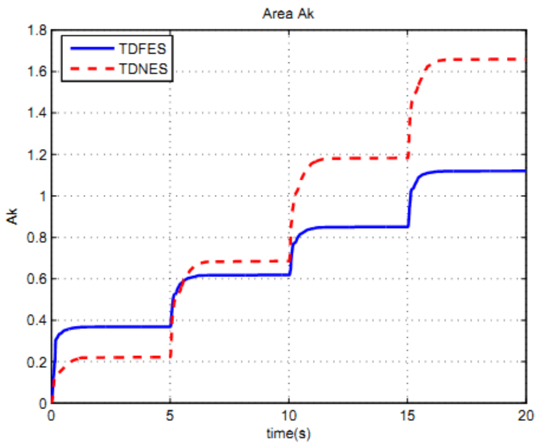

Figure 5 Area Ak represented by the difference between y_{pm} and y_p with RVTD compensation, ranges of random variable of RVTD ∈ [0,5].

e(k): S, M S, M, M B, B
Δe(k):PM, PS, ZZ, NS, NM
$\tau(k)_{pm}$*: PB, PM, ZZ, NM, NB*

The fuzzy rules are established the same as in the method of Dang *et.al* (Dang, Guan, Tran, & Li, 2011). We find out the optimal fuzzy time-delay estimator corresponding to its control surface in reference to experimental studies as illustrated in Figure 6.

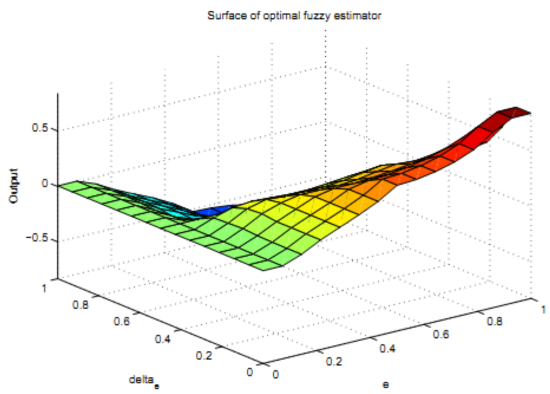

Figure 6 The surface of optimal fuzzy time-delay estimator

The estimated time-delay, $\tau(k)_{pm}$, increases from 0 to $\tau(k)_p$. When $\tau(k)_{pm} = \tau(k)_p$, y_m and y_p become overlapped, at the same time, the Smith predictor model is approximate with the plant model leading to the result that NCS is considered to be stable.

4.2 Randomly varying time-delay neural network estimation scheme

In our RVTD neural network estimation scheme (TDNES), based on a neural network controller, we designed RVTD neural network estimator for compensator RVTD of the NCS. The adaptability of neural network controller is totally better than that of the fuzzy controller, especially under nonlinear and randomly varying characteristics of the object. To ensure fast convergence in neural network estimation scheme, we use Levenberg-Marquardt algorithm designed to approach second order training speed without computing an exact form of Hessian matrix.

Actually, under the assumption that the error function is some kind of squared sum, to reduce the complicated computation of Hessian matrix for fast convergence, the Hessian matrix can be approximated by equation:

$$H = J^T J \tag{26}$$

The performance index to be optimized is defined as:

$$F(\mathrm{W}) = E^T E \tag{27}$$

where $W = [W_1 W_2 \ldots W_N]^T$ consists of all weights of the network, $E = \left[\varepsilon_1 \cdots \varepsilon_{k1} \varepsilon_{12} \cdots \varepsilon_{k2} \cdots \varepsilon_{1p} \cdots \varepsilon_{kp}\right]^T$, the cumulative error vector comprising the error for all the training examples, N is the number of the weights, p is the number of patterns, and k is the number of the network outputs.

From equation (27) the Jacobian matrix is defined as

$$J = \begin{vmatrix} \frac{\partial_{e_{11}}}{\partial_{W_1}} & \frac{\partial_{e_{11}}}{\partial_{W_2}} & \cdots & \frac{\partial_{e_{11}}}{\partial_{W_N}} \\ \frac{\partial_{e_{21}}}{\partial_{W_1}} & \frac{\partial_{e_{21}}}{\partial_{W_2}} & \cdots & \frac{\partial_{e_{21}}}{\partial_{W_N}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial_{e_{kp}}}{\partial_{W_1}} & \frac{\partial_{e_{kp}}}{\partial_{W_2}} & \cdots & \frac{\partial_{e_{kp}}}{\partial_{W_N}} \end{vmatrix} \tag{28}$$

Then the update can be adjusted to

$$W_{t+1} = W_{t+1} - (J^T J + \mu I)^{-1} J^T E_T \tag{29}$$

where μ is a learning parameter of the algorithm, I is identity unit matrix, J and is Jacobian of m outputs error with respect *to* n weights of the neural network.

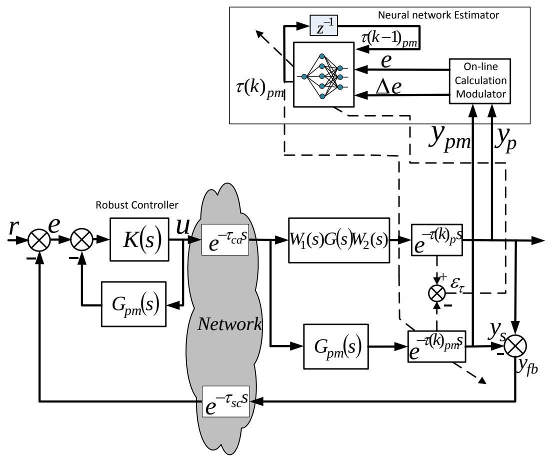

Figure 7 Joint robust controller with the TDNES in the Smith predictor NCS structure

In this study, we choose a fourth-layered feed-forward neural network including input layer, two hidden layers, and output layer, by adopting 3-5-10-1 structure network. The input layer has three inputs, $\tau(k)_{pm}(i-1)$, $\Delta e(k)$, and $e(k)$. The hidden layers include five and ten neurons per one layer with sigmoid activation function. The output layer has one linear neuron. The training epoch is 3000 to estimate the RVTD of the system in Figure 7. The training process consists of two phases. In the first phase, initial learning parameters are built by offline training. In the second phase, based on the initial learning results, online training is executed and did not stop until the algorithm is completely converged.

5. Plant identification based on neural network

When the plant is uncertain and nonlinear, the Smith predictor model in Figure 4 and Figure 7 become worse if we do not know exactly the mathematic model G_{pm} of the plant. Theoretically, the plant identification based on neural network using Levenberg-Marquardt algorithm can approximate any nonlinear functions by offline and online learning method. Thus, NCS continuously adapts to the change of the controlled plant and reduces the effect of the uncertain plant. We propose the overall adaptive Smith predictor NCS structure in Figure 8 which combined the plant identification model with the online time-delay estimator using TDNES or TDFES.

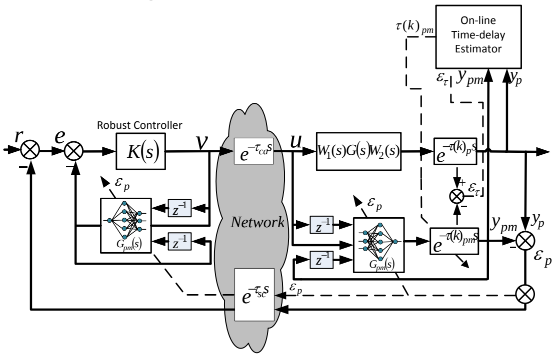

Figure 8 Joint the plant identification based on neural network with the time-delay estimator in the overall adaptive Smith predictor NCS structure.

Through this method, an effect brought by the uncertainty of the plant will be overcome and the predicate of the robustness of the Smith predictor is improved. We choose a fourth-layered feed-forward neural network including an input layer, two hidden layers, and an output layer, by adopting 3-10-20-1 structure network. The input layer has three inputs, the hidden layers include ten and twenty neurons per one layer with sigmoid activation function for enhance quality of the identification system. The output layer is set at one linear neuron. The performance index to be optimized is defined as equation (27) and the update rule can be adjusted using equation (29) with the Jacobian matrix given in equation (28). The training epoch is 5000 with initial learning parameters which are built by offline training, and online training is executed and did not stop until the algorithm is completely converged.

6. Numerical example

We use the simulation software TrueTime2.0 Beta1 (Anton, Dan, & Martin, 2009) based CSMA/AMP to prove the effectiveness of our proposed models/methods. NCS deployed includes sensor nodes, controller nodes, actuator nodes, interference nodes and controlled plant.

The parameters of the network are normally set as follows: The data rate is 80000*bits/s*, the minimum frame size is 80*bits/s*, the probability distribution of data packet dropout of network takes values from 0 to 0.3, the sampling period of sensor is 0.01*s*, the reference signal *r* is signal generator with square amplitude from −5 to 5 and frequency is 0.1*Hz*, the controlled plant is used following the form of a transfer function

$$G_p(s)e^{-\tau(k)_p s} = 5\frac{700}{s^2+30s+5}\frac{s+1}{0.3s+1}e^{-\tau(k)_p s} \tag{30}$$

We selected the shaping function $W_1 = 5$, $W_2 = \frac{s+1}{0.3s+1}$ and nominal plant $G = \frac{700}{s^2+30s+5}$, which can be transferred to state-space as *G = (A, B, C, D)*

$$A = \begin{bmatrix} -30 & -2.5 \\ 2 & 0 \end{bmatrix}, B = \begin{bmatrix} 16 \\ 0 \end{bmatrix} \tag{31}$$

$$A = \begin{bmatrix} 0 & 21.875 \end{bmatrix}, D = 0 \tag{32}$$

The time-delay takes the shape of sinusoidal signal (Shaltaf & Abdallah, 2000) $\tau(k)_{pm}(t) = 0.3\sin(3+0.1t^2)$, where is uniform random in the range [0,10].

We design the static $H\infty$ loop-shaping robust controller using the McFarlane and Glover method with four steps as presented in section 3. First, we solves two LMIs in (20) and (21) after that, we calculates scalar variable γ_0, we have $\gamma_0 = 2.216$. In this paper, we use the optimal solution of $\gamma = 1.1\gamma_0 = 2.4376$ and then compute matrix *R* to obtain the result.

$$R = \begin{bmatrix} 0.5366 & -17.1412 & 0.1376 \\ -0.0059 & 0.4451 & 0.0022 \\ -0.0114 & -0.6816 & 0.8368 \end{bmatrix} \quad (33)$$

Then we have the robust controller $K = (A_c, B_c, C_c, D_c)$

$$A_c = \begin{bmatrix} -115.65 & -32781.14 & -0.5131 \\ 2 & -630.37 & 0 \\ -3.7697 & -1256.2 & -1.0153 \end{bmatrix} \quad (34)$$

$$B_c = \begin{bmatrix} 1231.9 \\ 28.81 \\ 49.42 \end{bmatrix} \quad (35)$$

$$C_c = \begin{bmatrix} 0.4712 & 21.86 & -0.2897 \end{bmatrix}, D_c = 0 \quad (36)$$

Therefore, we combine the robust controller K with adaptive Smith predictor in NCS model and then use Matlab-Simulink to simulate. Finally, based on our simulation results, we carefully consider the responses of control signal, and output signal tracking error in both small and large range of time-delay variable t when evaluating the performance of robust control.

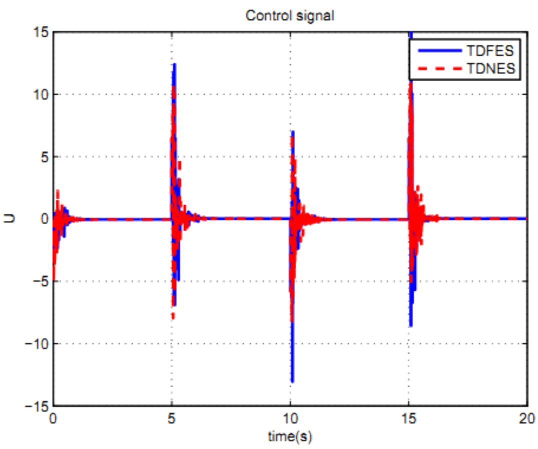

Figure 9 Response of control signal compensation time-delay (t ∈ [0,2])

In case of time-delay compensation, when $t\in$ [0,2], the responses of control signal, output signal and tracking error are illustrated in Figure 9, Figure 10, and Figure 11 respectively.

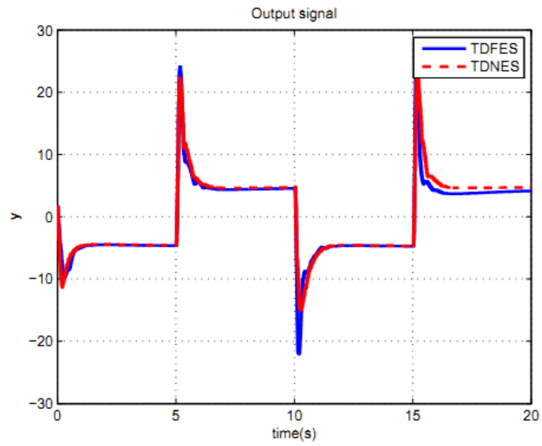

Figure 10 Response of output signal with compensation time-delay (t ∈ [0,2])

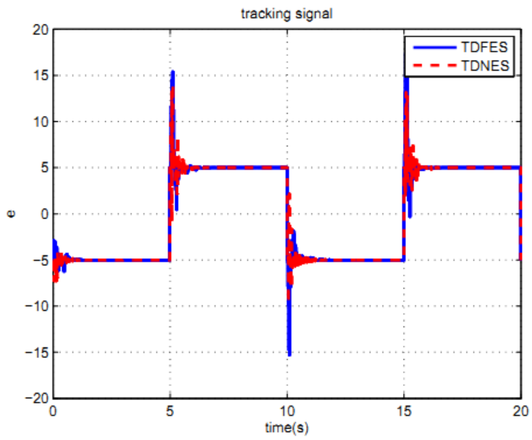

Figure 11 Response of tracking error with compensation time-delay (t ∈ [0,2])

The results indicate that the amplitudes of control signal and output signal of TDNES are always smaller than TDFES while the tracking error Figure 11 shows that the performance of TDNES is better than TDFES.

In addition, we consider the system under the larger range of t, i.e., [0,5], the responses of output signal and control signal in Figure 13, and Figure 14, respectively, show the stability and performance of system reduced small amount even when the range of the time-delay increases. It demonstrates that the system under the effect of time-delays is robust stability.

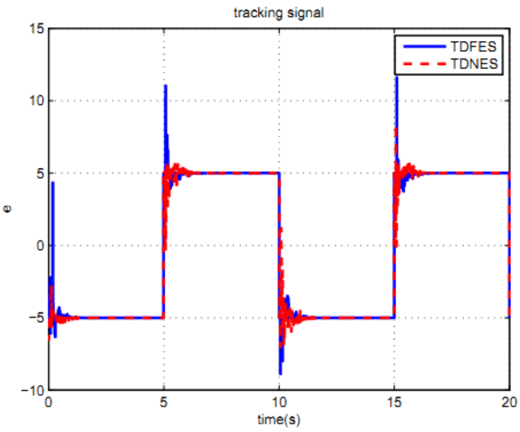

Figure 12 Response of tracking error with compensation time-delay (t ∈ [0,5])

The tracking error in Figure 12 indicated the performance of TDNES out performs TDFES. Under the very large range of*t*, for example, [0,10], the responses of control signal and output signal of TDFES show in Figure 15 and Figure 16, respectively, both oscillate with large amplitude.

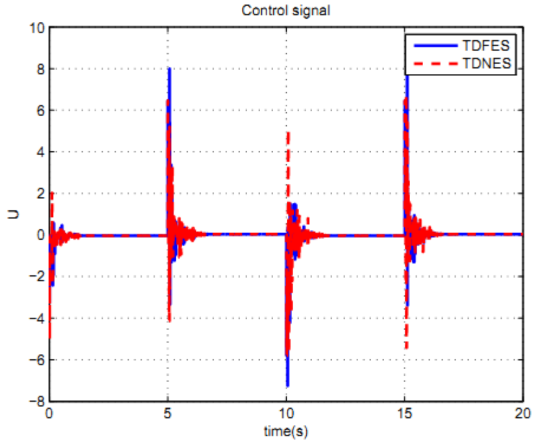

Figure 13 Response of control signal with compensation time-delay (t ∈ [0,5])

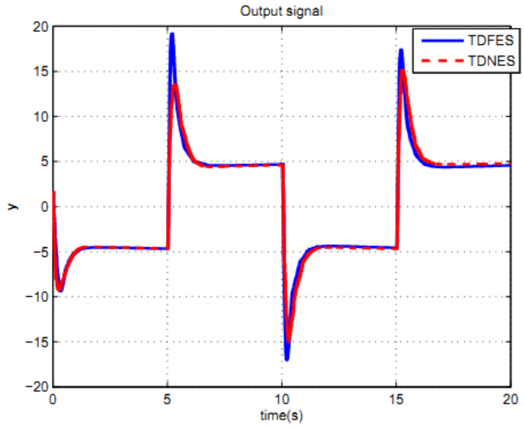

Figure 14 Response of output signal with compensation time-delay (t ∈ [0,5])

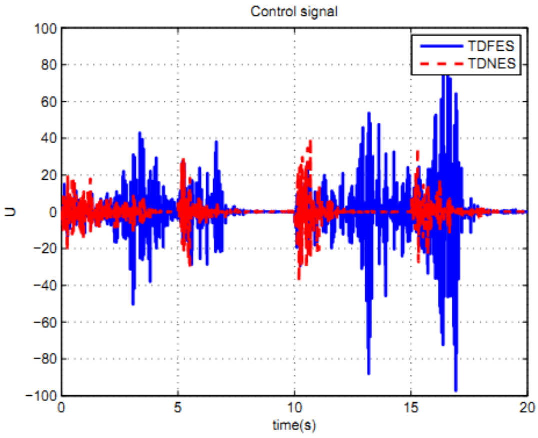

Figure 15 Response of control signal with compensation time-delay (t ∈ [0,10])

The tracking error responses show in Figure 17 become unstable while the TDNES's tracking error responses still keep the stability despite the oscillating amplitude increases and the performance decreases. Clearly, the larger the range of t, i.e., the larger the range of RVTD, the worse the performance of each system.

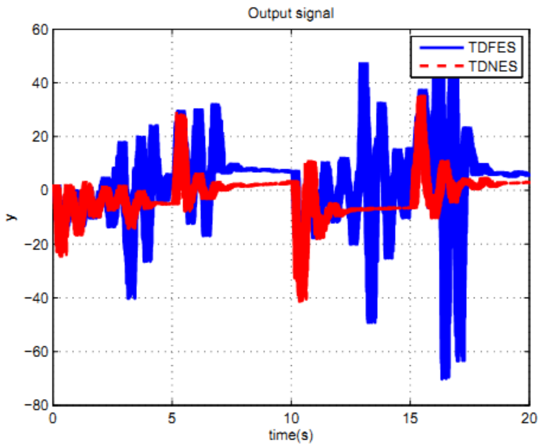

Figure 16 Response of output signal with compensation time-delay (t ∈ [0,10])

We can conclude that the proposed adaptive Smith predictor NCS model combined with the robust controller can obtain the stability and better performance. The TDNES gives better performance than the TDFES does in all cases. Even when the range of RVTD is very large, the TDFES becomes unstable but TDNES still obtain the stabilization.

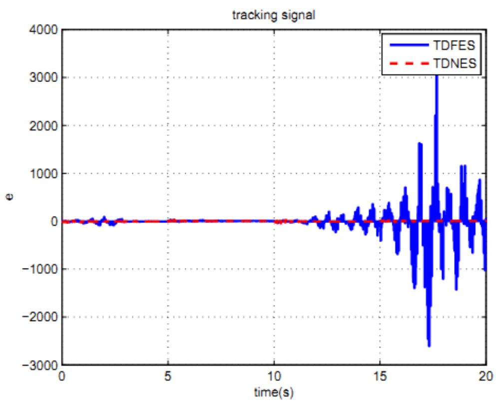

Figure 17 Response of tracking error with compensation time-delay (t ∈ [0,10])

7. Conclusion

The robust controller combined with the time-delay estimator in the adaptive Smith predictor NCS structure has been proposed in this paper. Under the effect of the uncertainty controlled plant, the designed robust controller obtains the necessary stability. Besides, for compensating the time-delays of NCS, the fuzzy and neural network time-delay estimator obtains very good robust performance. The feasibility and effectiveness of the proposed method are investigated by simulation results. Further studies can extend the findings of this paper by considering the adaptive Smith predictor NCS structure under the effect of the disturbances and noise to a perfect model.

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