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A Universal Controller Used in NCSs with Long Time Delay and Short Time Delay

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Abstract. For different time delays in the networked control systems (NCSs), a universal controller used in NCSs with long time delay and short time delay is designed in this paper. The time delay monitor is placed beside the controller. It keeps on watching the network, and measuring the time delays of the network. Then, the short time delay state feedback controller and long time delay state feedback controller are all designed based on the length of the time delay. When the time delay measured by the monitor is short, the short time delay controller's parameters are invoked, otherwise the long time delay controller's parameters are invoked. At last, taking the servo motor NCS as an example to simulate the model established in this paper. The simulation results show that the controller designed in this paper can control the NCSs very well.

Keywords: long time delay, NCSs, short time delay, universal controller

1 Introduction

The control systems which exchanging information between controller, sensor and actuator through networks are called networked control systems (NCSs) [1-3]. NCSs are widely applied in remote control, networked robots, and mobile sensor networks [4-9]. Many scholars at home and abroad proposed many different strategies and methods in the controlling of the NCSs.

In the modeling of discrete networked system with fixed time delay, Ray introduced augmented state [10]. This method is understandable for the NCSs with periodic time delay, but the calculation is very complicated which will increase the time delay. Xianghui Zhao established NCSs as a Lurie system with multi-time delays using augmented state, and gave stability condition based on Newton-Leibniz formula [11].

Luck proposed that changing the uncertain time delay into certain time delay using buffering queue. So, the NCS can be changed into an invariant system which is easier to analyse and design [12]. Bin Tang compensated the performance loss of the system which is caused by time delay and data packet lost using optimal prediction state estimator [13]. Baofeng Wang established the discrete time-invariable system with multi-state Markovian as the one with two-state Markovian model [14]. In this method, the controller and actuator adopt clock driving, which caused the state information can't be used in time. The control performance is conservative.

Nilsson changed the influence of random time delay into linear quadratic Gaussian question [15]. Zhu researched the stochastic optimal control of the linear NCSs under the quadratic performance index [16]. In addition, there are stochastic stabilization methods [17-19], stochastic $H\infty$ control method [20], stochastic H2 control method [21]. The optimal stochastic control method has better performance than

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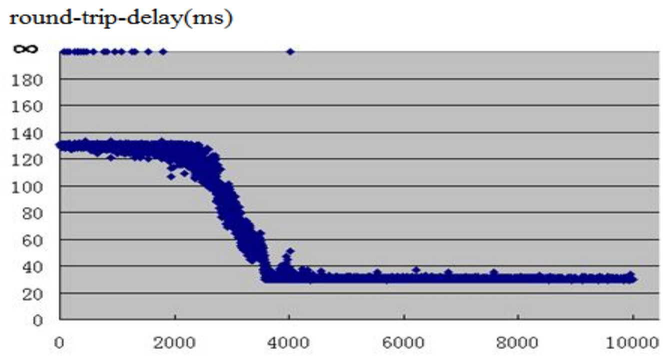
the buffer queue method, but it needs more storage space.

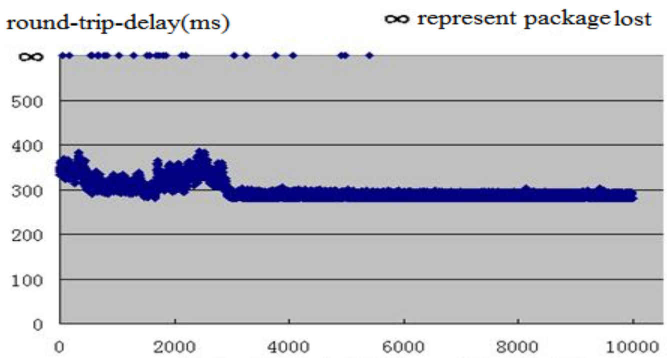
The NCSs with long time delay and short time delay is taken as an object in this paper. To solve the problems in the models before, the controller in this paper takes event-driven mode, which reduces time delay. What's more, the model in this paper is a universal controller. The controller can invoke the best control mode automatically no matter long time delay or short time delay.

2 Time Delay Measurement and Controller Design

Based on the time delay measurement between client and server [22], time delay is varying randomly. We measured time delays between Tsinghua and Hefei Unicom, and time delays between Tsinghua and Yahoo. Fig. 1 shows ten thousand times of time delay between Tsinghua and Hefei Unicom, and ten thousand times of time delay between Tsinghua and Yahoo.



(a) Time delays between Tsinghua and Hefei unicom



(b) Time delays between Tsinghua and Yahoo

Fig. 1. Time delays between client and server

Fig. 1 shows that the time delays between Tsinghua and Hefei Unicom are changing between 0ms and 150ms basically. Time delays between Tsinghua and Yahoo are changing between 260ms and 400ms basically. They are changing within limits. So, we can design a universal controller which can provide proper parameters whether the time delay is short or long (The time delay can be measured using the time delay monitor).

The NCSs researched in this paper are composed of controller, actuator, controlled object, sensor, network, and time delays monitor. The structure of NCSs is shown in Fig. 2. The actuator and sensor take clock driven mode. They have the same clock and sampling period h. The controller takes event driven mode. Time delays monitor measures time delay τ. If $\tau < h$, the system will invoke short time delay state feedback controller, if $\tau \geq h$, the system will invoke long time delay state feedback controller.

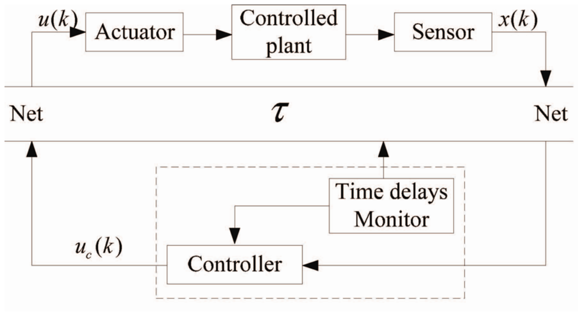


Fig. 2. Structure of the state feedback controller

The time delay monitor's interface is shown in Fig. 3. The measurement process is developed in Delphi. It calls API instructions of the operating system to send and receive data packages, then stores these measurement data into the SQL Server database. It does some statistics and data analysis at last.

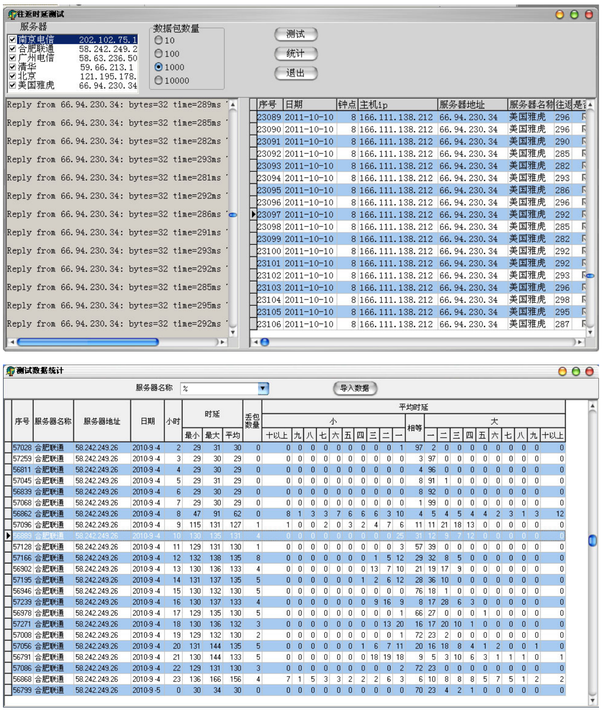


Fig. 3. The time delay monitor's interface

For simple, im-1, im, im+1 represent the (m-1)th, m-th, and (m+1)th sampling time. $S \triangleq \{i_1, i_2, \ldots\} \subseteq N$ It represents effective sampling times' gather. N_{drop} represents the biggest number of consecutive lost packages. $1 \le j \le k$ is the gather of consecutive lost packages. $\eta(i_m)$ is the number of the sampling periods from im to im+1. D is the gather of $\eta(i_m)$, $D \triangleq \{1, 2, \ldots, N_{drop} + 1\}$.

3 Short Time Delay Controller Design

3.1 System Modeling

The discrete system state equations are shown in equation (1) and equation (2).

When $\tau_k \in (0, h]$:

$$\begin{cases} \mathbf{x}(k+1) = \mathbf{F}\mathbf{x}(k) + \mathbf{G}\mathbf{u}(k) \\ \mathbf{u}(k+1) = \mathbf{u}_c(k) = -\mathbf{L}\mathbf{x}(k) \end{cases} \quad (1)$$

When $\tau_k \in (h,\infty)$:

$$\begin{cases} \mathbf{x}(k+1) = \mathbf{F}\mathbf{x}(k) + \mathbf{G}\mathbf{u}(k) \\ \mathbf{u}(k+1) = \mathbf{u}(k) \end{cases} \tag{2}$$

If $\tau_k \in (0,h]$, the control data calculated based on the k-th sampling data will affect the controlled object at the (k+1)th sampling time. The equation is shown as below.

$$u(k+1)=Uc(k)= - Lx(k) \tag{3}$$

If $\tau_k \in (h,\infty)$, the sampling data is lost, and the control data will be unchanged.

$$u(k+1)=u(k) \tag{4}$$

Suppose that: $\mathbf{z}(i_m) = \begin{pmatrix} \mathbf{x}(i_m) \\ \mathbf{x}(i_{m-1}) \end{pmatrix}$ is the augmented state. The transformation equations from sampling instant im to sampling instant im+1 are shown as below according to the system state equation (1) and (2).

$$\begin{aligned} &\mathbf{z}(i_{m+1}) = \mathbf{M}_{\eta(i_m)}\mathbf{z}(i_m) \\ &\mathbf{M}_{\eta(i_m)} = \begin{pmatrix} \mathbf{F}^{\eta(i_m)} - \sum_{j=0}^{\eta(i_m)-2} \mathbf{F}^j\mathbf{GL} & -\mathbf{F}^{\eta(i_m)-1}\mathbf{GL} \\ \mathbf{I} & 0 \end{pmatrix} \end{aligned} \tag{5}$$

Suppose that: $\mathbf{z}(l) = \begin{pmatrix} \mathbf{x}(l) \\ \mathbf{x}(i_m) \end{pmatrix}$, $i_m < l < i_{m+1}$, the transformation equations between invalid data packets and effective data packets are shown as below.

$$\begin{aligned} &\mathbf{z}(l) = \bar{\mathbf{M}}_i\mathbf{z}(i_m) \\ &\bar{\mathbf{M}}_i = \begin{pmatrix} \mathbf{F}^{l-i_m} - \sum_{j=0}^{l-i_m-2} \mathbf{F}^j\mathbf{GL} & -\mathbf{F}^{l-i_m-1}\mathbf{GL} \\ \mathbf{I} & 0 \end{pmatrix} \end{aligned} \tag{6}$$

Thereinto, i∈S, l∈(im,im+1).

3.2 Stability Analysis

The stability conditions of this NCS can be obtained by Lyapunov function.

Theorem 3.1. Suppose that L is taken as the feedback factor of the state feedback controller. If there are two positive definite matrix $\mathbf{P}_i \in R^{2n\times 2n}$ and $\mathbf{P}_j \in R^{2n\times 2n}$ which satisfies conditions below.

$$\begin{aligned} &\mathbf{M}_i^T\mathbf{P}_j\mathbf{M}_i - \mathbf{P}_i < 0 \\ &\mathbf{M}_i = \begin{pmatrix} \mathbf{F}^i - \sum_{j=0}^{i-2} \mathbf{F}^j\mathbf{GL} & -\mathbf{F}^{i-1}\mathbf{GL} \\ \mathbf{I} & 0 \end{pmatrix} i,j \in D \end{aligned} \tag{7}$$

Thereinto, Mi is $\mathbf{M}_{\eta(i_m)}$ in equation (5).

Certification: For the feedback NCSs, Lyapunov function is defined as below:

$$\mathbf{V}(i_m) = \mathbf{z}^T(i_m)\mathbf{P}_{\eta(i_m)}\mathbf{z}(i_m) \tag{8}$$

If $\eta(i_{m+1}) = j$, $\eta(i_m) = i$, $i,j \in D$, equation $\mathbf{V}(i_m) = \mathbf{z}^T(i_m)\mathbf{P}_i\mathbf{z}(i_m)$ and $\mathbf{V}(i_{m+1}) = \mathbf{z}^T(i_m)\mathbf{M}_i^T\mathbf{P}_j\mathbf{M}_i\mathbf{z}(i_m)$ can be obtained. Based on inequation (7), inequation (9) can be obtained.

$$\begin{aligned}\Delta\mathbf{V} &= \mathbf{V}(i_{m+1}) - \mathbf{V}(i_m) \\ &= \mathbf{z}^T(i_m)(\mathbf{M}_i{}^T\mathbf{P}_j\mathbf{M}_i - \mathbf{P}_i)\mathbf{z}(i_m) < 0\end{aligned} \tag{9}$$

Thereinto, $\mathbf{z}(i_m) \neq 0$.

Define that $\|\bullet\|$ is Euclidean norm of the vector or spectral norm of the matrix. $\alpha \triangleq \max_{i\in S}\|\bar{\mathbf{M}}_i\|$ is taken as assistant.

Equation (9) shows that $\lim\limits_{i_m\to\infty}\mathbf{z}(i_m) = 0$. What's more, $\|\mathbf{z}(l)\| = \|\bar{\mathbf{M}}_i\mathbf{z}(i_m)\| \leq \alpha\|\mathbf{z}(i_m)\|$ when $i_m < l < i_{m+1}$. So, $\lim\limits_{l\to\infty}\|\mathbf{z}(l)\| = 0$ ($l \neq i_m$). Summarize the two conditions above, we obtain that $\lim\limits_{l\to\infty}\|\mathbf{z}(l)\| = 0$ ($l \in N$). So, the system is asymptotic stability.

Corollary: If there is a common positive definite matrix $\mathbf{P} \in R^{2n\times 2n}$ who satisfies the inequation below, this system is asymptotic stable.

$$\mathbf{M}_i{}^T\mathbf{P}\mathbf{M}_i - \mathbf{P} < 0 \tag{10}$$

3.3 Feedback Gain Design

Theorem 3.2. If there are two positive definite matrix $\mathbf{P}_i$ and $\mathbf{Q}_i$ who satisfy conditions below:

$$\begin{cases}\begin{bmatrix}-\mathbf{P}_i & * \\ \mathbf{M}_i & -\mathbf{Q}_j\end{bmatrix} < 0 \quad (i,j\in D) \\ \mathbf{M}_i = \begin{pmatrix}\mathbf{F}^i - \sum\limits_{j=0}^{i-2}\mathbf{F}^j\mathbf{GL} & -\mathbf{F}^{i-1}\mathbf{GL} \\ \mathbf{I} & 0\end{pmatrix}\end{cases} \tag{11}$$

$$\mathbf{P}_j\mathbf{Q}_j = \mathbf{I} \quad (j\in D) \tag{12}$$

The NCSs will be asymptotic stable.

Certification: Schur complement lemma can change inequation (7) to the inequation (12).

$$\begin{cases}\begin{bmatrix}-\mathbf{P}_i & * \\ \mathbf{M}_i & -\mathbf{P}_j^{-1}\end{bmatrix} < 0 \\ \mathbf{M}_i = \begin{pmatrix}\mathbf{F}^i - \sum\limits_{j=0}^{i-2}\mathbf{F}^j\mathbf{GL} & -\mathbf{F}^{i-1}\mathbf{GL} \\ \mathbf{I} & 0\end{pmatrix}\end{cases} \tag{13}$$

Taking $\mathbf{Q}_j = \mathbf{P}_j^{-1}$ into inequation (13), the inequation (14) can be obtained which certified the theorem 3.2.

$$\begin{aligned}&\begin{bmatrix}-\mathbf{P}_i & * \\ \mathbf{M}_i & -\mathbf{Q}_j\end{bmatrix} < 0 \\ &\mathbf{M}_i = \begin{pmatrix}\mathbf{F}^i - \sum\limits_{j=0}^{i-2}\mathbf{F}^j\mathbf{GL} & -\mathbf{F}^{i-1}\mathbf{GL} \\ \mathbf{I} & 0\end{pmatrix}\end{aligned} \tag{14}$$

The feedback gain can be obtained by CCL(Cone Complementarity Linearization) algorithm. Its process is shown as below:

①Base on theorem 3.2, feasible solution $(\bar{\mathbf{P}}_i(0), \bar{\mathbf{Q}}_i(0), \bar{\mathbf{L}}(0))$ can be obtained.

②The minimum value is solved based on CCL algorithm.

$$\min \quad \text{tr}[\sum_{i=1}^{N_{drop}+1} \mathbf{P}_i\overline{\mathbf{Q}}_i(k)+\overline{\mathbf{P}}_i(k)\mathbf{Q}_i] \tag{15}$$

$$\text{Subject to}\begin{cases}\text{theorem3.2}\\ \begin{bmatrix}\mathbf{P}_i & \mathbf{I}\\ \mathbf{I} & \mathbf{Q}_i\end{bmatrix}\geq 0\end{cases} \tag{16}$$

$(\mathbf{P}_i,\mathbf{Q}_i,\mathbf{L})$ is obtained through this step, $\overline{\mathbf{P}}_i(k)$ and $\overline{\mathbf{Q}}_i(k)$ are the results of step ①.

③If the $\mathbf{L}$ obtained satisfies theorem 3.1, the system is stable, otherwise it will go to step ④.

④If $k > N$ (N is the biggest recurring number), the calculation is finished, otherwise it will go to step ⑤.

⑤Letting $k = k+1$, $(\overline{\mathbf{P}}_i(k),\overline{\mathbf{Q}}_i(k),\overline{\mathbf{L}}(k)) \triangleq (\mathbf{P}_i,\mathbf{Q}_i,\mathbf{L})$, then go to step ②.

3.4 Parameter Optimization

In order to improve the performance of the NCSs, EDA algorithm which combined with stability conditions is used to optimize parameters.

The tunning parameters are taken as vector $\mathbf{L}$.

$$\mathbf{L} = (l_1 \quad l_2 \quad \cdots \quad l_m)$$

The target function of the optimization can be taken as below:

$$\begin{aligned}&C = \lambda C_1 + (1-\lambda)C_2\\ &C_1 = \begin{cases}0 & \sigma\% \leq o\%\\ (\sigma\% - o\%)/o\% & \sigma\% > o\%\end{cases}\\ &C_2 = \begin{cases}0 & T_s \leq T_o\\ (T_s - T_o)/T_o & T_s > T_o\end{cases}\end{aligned} \tag{17}$$

$\sigma\%$ and T_s are the overshoot and adjusting time of the normal NCSs. $o\%$ and T_o are the overshoot and adjusting time of the ideal NCSs(there is no time delay and lost packets). The performance indicator C_1 ensures that the overshoot of the system is as small as possible, and C_2 ensures that the adjusting time of the system is as short as possible. λ takes value from [0,1]. $\mathbf{L}$ takes value from the area which satisfies theorem 3.1.

4 Long Time Delay Controller Design

When $\tau \geq h$, we call it long time delay network. It satisfies condition $Nh \leq \tau \leq (N+1)h$.

Definition 4.1. In the transformation process from state value x(im) to x(im+1), variables are defined as below:

①im: the current effective data package's sampling instant.

②im+1: the next effective data package's sampling instant.

③im-k: the sampling data package's sampling instant for calculating the control value at the imth instant, thereinto, k≥1.

④im-k+j: the sampling data package's sampling instant for calculating the control value at the im+1th instant, thereinto, 1≤j≤k.

⑤im-N-1: the minimum value of im-k, k≤N+1.

The augmented states are shown as below:

$$\mathbf{z}(i_m)=\left[x(i_m)^{\mathrm{T}} \quad \cdots \quad \mathbf{x}(i_{m-k+j})^{\mathrm{T}} \quad \cdots \mathbf{x}(i_{m-k+n})^{\mathrm{T}} \quad \cdots \quad \mathbf{x}(i_{m-k})^{\mathrm{T}} \quad \cdots \quad \mathbf{x}(i_{m-N-1})^{\mathrm{T}}\right]^{\mathrm{T}}$$

$$\mathbf{z}(i_{m+1})=\left[\mathbf{x}(i_{m+1})^{\mathrm{T}} \quad \cdots \quad \mathbf{x}(i_{m-k+j+1})^{\mathrm{T}} \quad \cdots \mathbf{x}(i_{m-k+n+1})^{\mathrm{T}} \quad \cdots \quad \mathbf{x}(i_{m-k+1})^{\mathrm{T}} \quad \cdots \quad \mathbf{x}(i_{m-N})^{\mathrm{T}}\right]^{\mathrm{T}}$$

(1) If there is no new control value arrives between the im instant and the im+1 instant, equation (18) will be established.

$$\mathbf{z}(i_{m+1})=\mathbf{M}_{i,j,k}\mathbf{z}(i_m) \tag{18}$$

Thereinto,

$$\mathbf{M}_{i,j,k}=\begin{bmatrix} \prod^1 & \delta(1,k)\prod^2 & \delta(2,k)\prod^2 & \cdots & \delta(N+1,k)\prod^2 \\ 1 & & & 0 & \\ & \ddots & & & \\ & & \ddots & & \\ 0 & & & 1 & 0 \end{bmatrix}$$

$\prod^1=\mathbf{F}^{i_{m+1}-i_m}$

$\prod^2=\sum_{l=0}^{i_{m+1}-i_m-1}\mathbf{F}^l\mathbf{GL}$

$i\in\{1,2,\cdots,N_{drop}+1\},\ j=0,k=\{1,2,\cdots,N+1\},$

$\delta(n,k)=\begin{cases}1, n=k\\ 0, n\neq k\end{cases}$

(2) If there is new control value arrives between the im instant and the im+1 instant, equation (19) will be established.

$$\mathbf{z}(i_{m+1})=\mathbf{M}_{i,j,k}\mathbf{z}(i_m) \tag{19}$$

Thereinto,

$$\mathbf{M}_{i,j,k}=\begin{bmatrix} \prod^0 & \overbrace{0 \ \cdots \ 0}^{k-j-1} & \prod^{k-j} & \cdots & \prod^{k-n} & \cdots & \prod^{k} & \overbrace{0 \ \cdots \ 0}^{N+1-k} \\ 1 & & 0 & & 0 & & 0 & \\ 0 \quad 1 & & \vdots & & \vdots & & \vdots & \\ \vdots \quad \ddots & & \vdots & & \vdots & & \vdots & \\ \vdots & 1 & 0 & & \vdots & & \vdots & \\ \vdots & & 1 & & \vdots & & \vdots & \\ \vdots & & 0 & \ddots & 0 & & \vdots & \\ \vdots & & \vdots & & 1 & & \vdots & \\ \vdots & & \vdots & & 0 & \ddots & 0 & \\ \vdots & & \vdots & & \vdots & & 1 & \\ \vdots & & \vdots & & \vdots & & 0 & \ddots \\ 0 & & 0 & & 0 & & 0 & 1 \quad 0 \end{bmatrix}$$

$\prod^0=\mathbf{F}^{i_{m+1}-i_m}$

$\prod^{k-j}=-\sum_{l=0}^{i_{m+1}-i_{m-k+j}-N-2}\mathbf{F}^l\mathbf{GL}$

$\prod^{k-n}=-\mathbf{F}^{i_{m+1}-i_{m-k+n+1}-N-1}\sum_{l=0}^{i_{m-k+n+1}-i_{m-k+n}-1}\mathbf{F}^l\mathbf{GL}$

$$\prod^{k} = -\mathbf{F}^{i_{m+1}-i_{m-k+1}-N-1}\sum_{l=0}^{i_{m-k+1}+N-i_m}\mathbf{F}^{l}\mathbf{GL}$$

$$i \in \{1,2,\cdots,N_{drop}+1\}, 1 \le k \le N+1, 0 < j \le k$$

Definition 4.2. In the transformation process from state value $\mathbf{x}(i_m)$ to $x(i_m^p)$ ($i_m < i_m^p < i_{m+1}$), variables are defined as below.

i_{m-k+j} : the sampling data package's sampling instant for calculating the control value at the i_m^p th instant, thereinto, $1 \le j \le k$.

(1) If there is no new control value arrives between the i_m^p instant and the i_{m+1} instant, equation (20) will be established.

$$\begin{gathered}\mathbf{z}(i_m^p) = \left[\mathbf{x}(i_m^p)^{\mathrm{T}} \quad \cdots \quad \mathbf{x}(i_{m-k+1})^{\mathrm{T}} \quad \cdots \quad \mathbf{x}(i_{m-N})^{\mathrm{T}}\right]^{\mathrm{T}} \\ \mathbf{z}(i_m^p) = \bar{\mathbf{M}}_{p,j,k}\mathbf{z}(i_m)\end{gathered} \tag{20}$$

Thereinto,

$$\bar{\mathbf{M}}_{p,j,k} = \begin{bmatrix} \prod^1 & \delta(1,k)\prod^2 & \delta(2,k)\prod^2 & \cdots & \delta(N+1,k)\prod^2 \\ 1 & & & 0 & \\ & \ddots & & & \\ & & \ddots & & \\ 0 & & & 1 & 0 \end{bmatrix}$$

$$\prod^1 = F^{i_m^p - i_m}$$

$$\prod^2 = \sum_{l=0}^{i_m^p - i_m - 1} F^l GL$$

$$i_m < i_m^p < i_{m+1}$$

$$i \in \{1,2,\cdots,N_{drop}\}, j = 0, k = \{1,2,\cdots,N+1\},$$

$$\delta(n,k) = \begin{cases} 1, n = k \\ 0, n \ne k \end{cases}$$

(2) If there is new control value arrives between the i_m^p instant and the i_{m+1} instant, equation (21) will be established.

$$\mathbf{z}(i_m^p) = \bar{\mathbf{M}}_{p,j,k}\mathbf{z}(i_m) \tag{21}$$

Thereinto,

$$\bar{\mathbf{M}}_{p,j,k} = \begin{bmatrix} \prod^0 & \overbrace{0 \ \cdots \ 0}^{k-j-1} & \prod^{k-j} & \cdots & \prod^{k-n} & \cdots & \prod^{k} & \overbrace{0 \ \cdots \ 0}^{N+1-k} \\ 1 & & 0 & & 0 & & 0 & \\ 0 & 1 & \vdots & & \vdots & & \vdots & \\ \vdots & \ddots & \vdots & & \vdots & & \vdots & \\ \vdots & 1 & 0 & & \vdots & & \vdots & \\ \vdots & & 1 & & \vdots & & \vdots & \\ \vdots & & 0 & \ddots & 0 & & \vdots & \\ \vdots & & \vdots & & 1 & & \vdots & \\ \vdots & & \vdots & & 0 & \ddots & 0 & \\ \vdots & & \vdots & & \vdots & & 1 & \\ \vdots & & \vdots & & \vdots & & 0 & \ddots \\ 0 & & 0 & & 0 & & 0 & 1 \quad 0 \end{bmatrix}$$

$$\prod^{0} = \mathbf{F}^{p}$$

$$\prod^{k-j} = -\sum_{l=0}^{i_m^p - i_{m-k+j} - N - 2} \mathbf{F}^{l}\mathbf{GL}$$

$$\prod^{k-n} = -\mathbf{F}^{i_m^p - i_{m-k+n+1} - N - 1} \sum_{l=0}^{i_{m-k+n+1} - i_{m-k+n} - 1} \mathbf{F}^{l}\mathbf{GL}$$

$$\prod^{k} = -\mathbf{F}^{i_m^p - i_{m-k+1} - N - 1} \sum_{l=0}^{i_{m-k+1} + N - i_m} \mathbf{F}^{l}\mathbf{GL}$$

$$i \in \{1,2,\cdots,N_{drop}\}, 1 \le k \le N+1, 0 < j \le k \; i_m < i_m^p < i_{m+1}$$

The stability conditions, feedback gain and the optimal value's calculation of the NCS with long time delay are the same as the third section.

5 Example

Taking the servo motor NCS as an example to proof the effectiveness of the method proposed in this paper. The state is shown in the vector $\mathbf{x}_p = [\theta, \omega]^T$. θ and ω are the output angle and angular velocity of the DC servo motor. The state equation is shown in equation (22).

$$\dot{\mathbf{x}}_p(t) = \begin{bmatrix} 0 & 1 \\ 1 & -153 \end{bmatrix} \mathbf{x}_p(t) + \begin{bmatrix} 0 \\ 1632 \end{bmatrix} \mathbf{u}(t) \qquad \textbf{(22)}$$

The sampling period of the system is 50ms. The short time delays measured by the time delay monitor are shown in Fig. 4. In the figure, the circle represents data lost. Fig. 4 shows that the time delays are basically under a sampling period. So, we can use the parameters of short time delay controller to control the system.

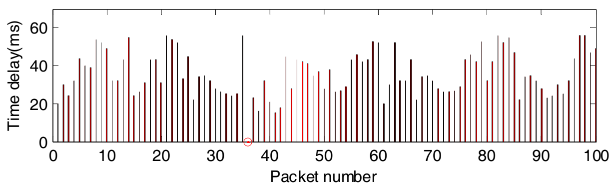


Fig. 4. Short time delays of the network

Fig. 5 shows the state curves of the controller with normal and optimized parameters under the same network condition. The normal state feedback gain of the controller is: L1=[0.214 0.0053], and the optimized state feedback gain of the controller is: L2=[0.362 0.0082].

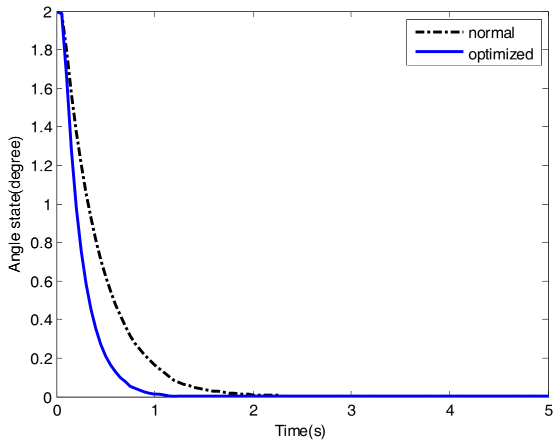


Fig. 5. state curves of the controller

The long time delays measured by the time delay monitor are shown in Fig. 6. It shows that most of the time delays are in the scope of [150ms 200ms]. We can take $Nh \le \tau \le (N+1)h$, $N=3$. So, we can use the parameters of long time delay controller to control the system.

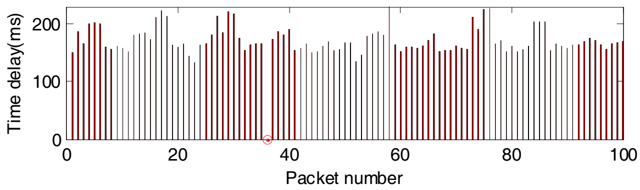


Fig. 6. Long time delays of the network

Fig. 7 shows the state curves of the controller with normal and optimized parameters under the same network condition. The normal state feedback gain of the controller is: L1=[0.110 0.0012], and the optimized state feedback gain of the controller is: L2=[0.146 0.0010].

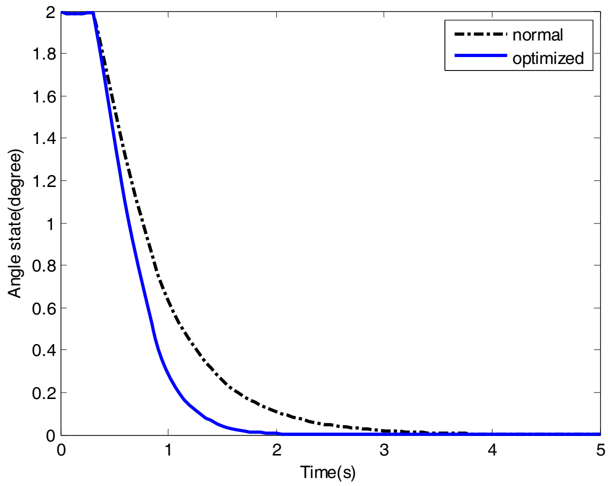


Fig. 7. state curves of the controller

The two groups of simulation show that: the NCS in this paper is stable with the controller designed in this paper. What's more, the performance of the system can be improved after the state feedback gain being optimized.

6 Conclusions

For different geographical distances, there are always different network time delays in the NCSs. So, a network time delay monitor was established in this paper. It measured time delays for networks. Then, a universal controller used in long time delay and short time delay NCSs was designed based on the different time delays. The model was analyzed in this paper. Through simulating, the results showed that the universal controller designed in this paper can achieve good performance. The model proposed in this paper provided a solution for the practical engineering.

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