International Journal of Control and Automation
Vol.9, No.1 (2016), pp.231-240
http://dx.doi.org/10.14257/ijca.2016.9.1.21

The Time-Delay Compensation Method for Networked Control System Based on Improved Fast Implicit GPC

Zhongda Tian*, Shujiang Li, Yanhong Wang, Xiangdong Wang and Quan Zhang

College of Information Science & Engineering, Shenyang University of Technology, Shenyang 110870, China
E-mail: tianzhongda@sut.edu.cn

Abstract

Aiming at the compensation problem of random time-delay in networked control system, a new network time-delay compensation method based on improved fast implicit generalized predictive control (GPC) is proposed. The buffer is established respectively including the forward output, feedback input of controller and the input of actuator, the network induced time-delay is compensated, and it will avoid the control data transmission. Then an improved fast implicit generalized predictive control with differential effect is used for time-delay compensation. Simulation results demonstrate that the proposed method reduces the system regulation time and restrain the overshoot, has good compensation effect.

Keywords*: networked control system, improved fast implicit GPC, time-delay compensation, random time-delay*

1. Introduction

Networked control system (NCS) is a real-time feedback control system between sensors, actuators and controller signals transmitted over the network [1]. Since the network is introduced in the control loop, the NCS analysis becomes more complex. The time-delay in NCS has an impact on the performance of system, and even causes instability [2].

Aiming at the time-delay compensation problem for networked control system, there are a large number of research results. The literature [3] predict time-delay using auto regression model, and at the same time, the improved GPC algorithm is used for time-delay compensation. The literature [4] using predict algorithm compensate time-delay, decrease the time-delay of forward channel by adding the control and compensation structure. The literature [5] proposed a minimum prediction step and predictive control vector compensate for time-delay, simulation results show the effectiveness of the algorithm. The literature [6] using the linear neural network with time stamp for online time-delay prediction, obtained satisfactory control performance in motor speed control system. The literature [7] using the least squares and nonlinear time series modeling algorithm to predict the Internet time-delay, a control system of tank based on actual test network is shown the dynamic performance of the system is improved. The literature [8] using predictive control through RTT time-delay for vehicular sensor networks, LMS algorithm used for system modeling, simulation results show that the algorithm can overcome the time delay and data loss. The sliding mode algorithm based on T-S fuzzy model is used for transform delay system into non-delay system [9], the simulation results show the effectiveness of this method. The literature [10] using predictive control sequences respectively compensate feedback induced time-delay and data loss of control channel, but how to detect induced time-delay and data loss is a key problem. Aiming at the network with random time-varying, the network generalized predictive control

ISSN: 2005-4297 IJCA

algorithm based on state space model is proposed to access the effectively tracking performance [11]. The literature [12] using unbiased gray model to predict the time-delay of the Internet, the prediction accuracy and control effect is good.

In summary, most of algorithms in above research results are too complex, real-time performance is poor, it is difficult to be used into the reality applications, depends too much on the network model, and the actual network model are difficult to be established. In this paper, a new improved fast implicit generalized predictive control algorithm is proposed for the networked control system time-delay compensation. This method does not need to establish accurate network models, only need to estimate the forward channel and feedback channel time-delay based on time stamp, combined the improved fast implicit generalized predictive control algorithm, channel time-delay is used for select the output control value in actuator, and achieved good control effect.

2. Fast Implicit Generalized Predictive Control Algorithm

Generalized predictive control has the characteristics of adaptability, robustness, has a good control effect for system with large time-delay [13]. CARIMA model is used to represent a real process with non stationary noise.

$$A(q^{-1})y(t) = B(q^{-1})u(t-1) + C(q^{-1})\varepsilon(t)/\Delta \quad (1)$$

Wherein

$$A(q^{-1}) = 1 + a_1 q^{-1} + \cdots + a_{na} q^{-n}$$
$$B(q^{-1}) = b_0 + b_1 q^{-1} + \cdots + b_{nb} q^{-n}$$
$$C(q^{-1}) = c_0 + c_1 q^{-1} + \cdots + c_{nc} q^{-n}$$

In the Equation (1), $y(t)$ is output, $u(t)$ is input, q^{-1} is shift operator, $\Delta = 1 - q^{-1}$ is differential operator, $\varepsilon(t)$ is uncorrelated random sequence, A, B, C are polynomial function of q^{-1}.

In order to enhance the robustness of the system, considering the effect of current time control value on the objective function, the objective function is selected as:

$$\min J(t) = E\left\{\sum_{j=1}^{P}[y(t+j) - w(t+j)]^2 + \sum_{j=1}^{M}\lambda(j)[\Delta u(t+j-1)]^2\right\} \quad (2)$$

P is the maximum length for prediction, M is control length, w is output expected value. In order to smooth the control effect, the objective control output is not directly track the setting value, but tracking reference trajectory. The reference trajectory is decided by setting value y_{ref}, output y and diffusion coefficient $a(0 < a < 1)$.

$$w(k+j) = a_j y(k) + (1 - a_j) y_{ref} \quad (3)$$

Generalized predictive control problem can be reduced to obtain the appropriate sequence $\Delta u(k), \Delta u(k+1), \cdots, \Delta u(k+M-1)$, so that to minimize the objective function value, the Diophantine equation is introduced to obtain the optimal prediction value, that is:

$$y(k+j) = G_j(q^{-1})\Delta u(k+j-1) + F_j(q^{-1})y(k)\ (j = 1, 2, \ldots n) \quad (4)$$

The optimal control for minimum target function is:

$$\Delta U = (G^T G + \lambda I)^{-1} G^T (w - f) \quad (5)$$

Generalized predictive control algorithm needs to solve the Diophantine equation, the control value can be obtained when controller parameters are solved, but computation time is so long. The implicit generalized predictive control algorithm directly identification controller parameters, does not need recursive solve Diophantine equation, which can save computation time. The implicit generalized predictive control algorithm can improve the speed of operation, but also need to calculate the inverse matrix. So the Literature [14] proposed a fast implicit generalized predictive control algorithm. The algorithm adopts flexible control increment method to avoid computing the inverse of matrix. The input softness factor is $\beta, \beta \in (0,1)$, the next equations can be obtained:

$$\Delta u(k+j) = 1 + \sum_{j=0}^{j} \beta^j \Delta u(k),\ j = 0,1,...M-1 \quad (6)$$

$$\Delta U(k) = [1, 1+\beta, \cdots, 1+\sum_{j=0}^{M-1} \beta^j]^T \times \Delta u(k) \quad (7)$$

The Equation (2) is rewritten as vector form.

$$J(k) = [Y(k+1) - W(k+1)]^T \times [Y(k+1) - W(k+1)] \quad (8)$$

The current control increment value can be obtained through minimization performance index $J(k)$ of Equation (8).

$$\Delta u(k) = (G_2^T G_2)^{-1} G_2^T \times (W(k+1) - f(k+1)) \quad (9)$$

Wherein

$$G_2 = G \times H, H = [1, 1+\beta, ..., \sum_{j=1}^{M-1} \beta^j]^T \quad (10)$$

Because $G_2^T G_2$ is a scalar quantity, thus avoiding the calculation of inverse matrix, so the current control value $u(k)$ is

$$u(k) = u(k-1) + \Delta u(k) \quad (11)$$

In order to obtain the control increment value of the next step, $\Delta u(k)$ calculated by Equation (9) as a known quantity, combined with $y(k+1)$ and the original set point to softening trajectory, it is able to calculate the next control incremental value $\Delta u(k+1)$ reliability.

$$\Delta u(k+1) = (G_2^T G_2)^{-1} G_2^T \times (W'(k+1) - f'(k+1)) \quad (12)$$

Thus, the output $y(k+1|k)$ at k+1 time can be predicted by the information at k time, $y(k+1|k)$ can be seen as approximation value of $y(k+1)$. The $y(k+1|k)$ is put into Equation (11) can obtained $\Delta u(k+1)$, then obtained $\Delta u(k+j)$.

3. Improved Fast Implicit Generalized Predictive Control Time-Delay Compensation Method

The time-delay of networked control system shown in Figure 1 can be divided into the feedback channel delay τ_{sc}, forward channel delay τ_{ca} and computing delay τ_c. The computing delay can be negligible. In this paper, controller, actuator and sensor will use time driven mode, so the forward channel and feedback channel delay need compensation respectively.

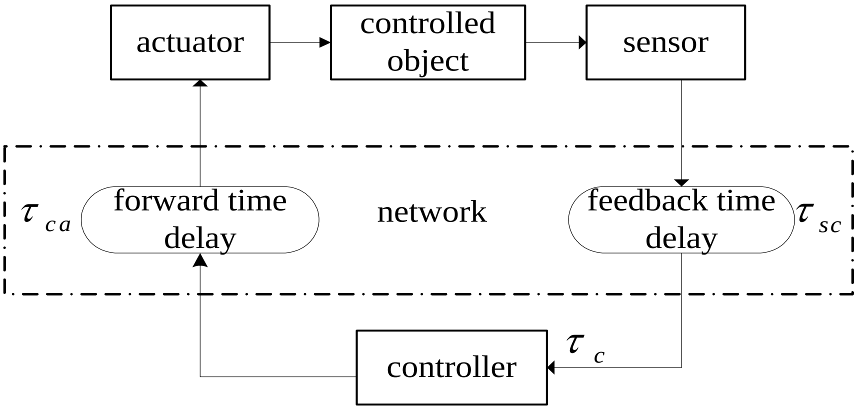

Figure 1. Networked Control System Structure

3.1. The Controller Node Algorithm Design

At time k, assuming before $u(k+d)$ (d is the forward channel time-delay bound) control value is known, the control sequence as $u(k|k-1), u(k+1|k), \cdots, u(k+d-1|k+d-2)$, $u(k+d|k+d-1)$ and $y(k+d|k+d-1)$ is as known quantity, $u(k+d|k+d-1)$ will be calculated, and it and other predictive control value can be packaged as:

$$U(k) = [u(k|k-1, u(k+1|k), ..., u(k+d|k+d-1)] \tag{13}$$

And then $U(k)$ will be sent to the actuator through the network, the actuator only save the most recent data. Because the existence of time-delay, at time k, any one of $U(k-d), U(k-d+1), \cdots, U(k)$ can be selected by actuator, that is also means at time k, any one of $U(k-d), U(k-d+1), \cdots, U(k)$ maybe in the buffer of actuator, but observe the following queue:

$$\begin{aligned} &U(k-d) = [u(k-d|k-d-1), u(k-d+1, k-d), \cdots, u(k|k-1) \\ &U(k-d+1) = [u(k-d+1|k-d), u(k-d+2|k-d+1), \cdots, u(k+1|k)] \\ &\qquad \vdots \\ &U(k) = [u(k|k-1), u(k+1|k), \cdots, u(k+d|k+d-1)] \end{aligned} \tag{14}$$

It can be found the control value in all queue $U(k-d), U(k-d+1), \cdots, U(k)$ at time k is $u(k|k-1)$, current control value is:

$$u(k) = u(k|k-1) \tag{15}$$

Similarly can get

$$\begin{aligned} u(k+1) &= u(k+1 \mid k) \\ u(k+2) &= u(k+2 \mid k+1) \\ &\vdots \\ u(k+d) &= u(k+d \mid k+d-1) \end{aligned} \quad (16)$$

Then the controller can know which control value be selected at time *k*, avoid the actuator send data back to the controller, reduce the two parameter models identification time interval, enhance the robustness of the system.

There are two buffers in the controller node, one is input buffer and the other is output buffer. In the input buffer of controller, it stores the output signal of controlled object. The design of input buffer is designed as Figure 2.

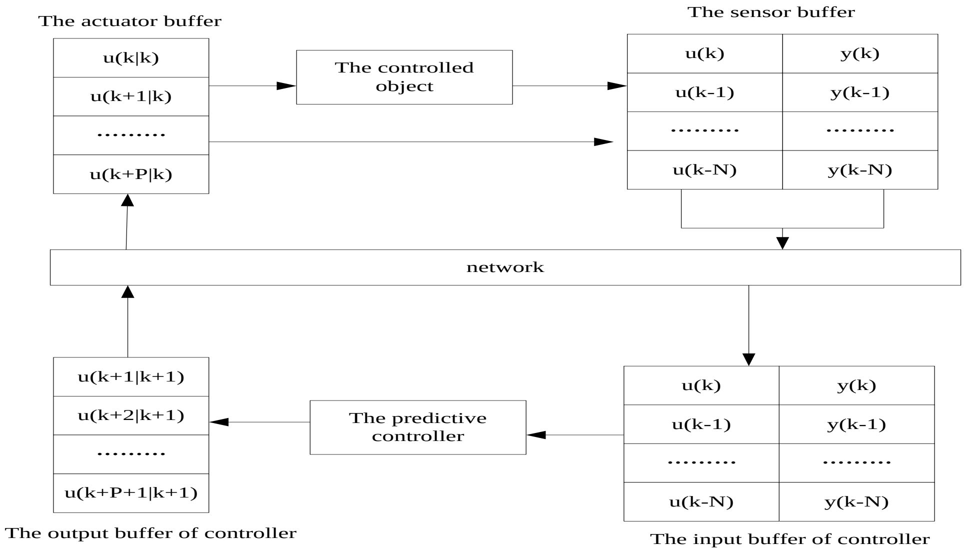

Figure 2. The Design of Input Buffer

In the output buffer, the controller calculate the predictive signal sequence, put the new calculated control value $u(k+d \mid k+d-1)$ in the tail of queue and delete the first value $u(k \mid k-1)$, then packing and sending, the output buffer is designed as Figure 3.

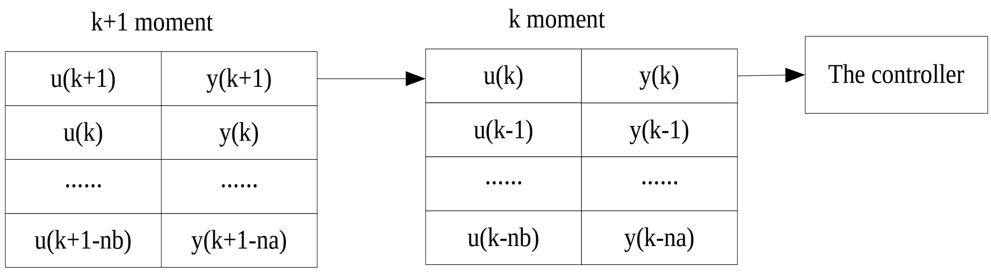

Figure 3. The Design of Output Buffer

In the actuator nodes, these signals will be queued and selected according to the queue rules. In the original predictive control algorithm, the controller can not know which control signal is used by actuator. But through the new predictive control algorithm, the controller can know which control signal will be used by actuator at current time, the input buffer only need one queue. The rule of updating queue is when a new signal is arrived, put it in the tail of queue and delete the head of queue.

3.2. The Actuator Node Algorithm Design

According to the real conditions and network protocol, the buffer with appropriate length is determined. As new predictive control algorithm in the paper, according to the input and output before $k+d$ time, the predictive control value $u(k+d\,|\,k+d-1)$ will be calculated, and is packed as one packet with the old control value. At last, the predictive control sequence is transferred to the buffer of actuator, at this time, the data in the actuator buffer is:

$$u(k\,|\,k-1), u(k+1\,|\,k), \cdots, u(k+d\,|\,k+d-1) \qquad (17)$$

The actuator selects the right control value that will be executed according to the time, the actuator buffer always keep the newest control signal.

To sum up, the time-delay compensation method is: set the input and output buffer for the actuator, save the $y(k)$ and output control value $u(k)$. $u_0(k)$ is determined by sensor output signal $y_0(k)$ and sensor time t_s. At the controller node, the future control value $\Delta U(k)$ is predicted by fast implicit generalized predictive control algorithm by past output signal and control value at certain time, the calculated result and controller current time t_c is sent to actuator. At actuator node, when the packet data is received, compare local time t_a with t_c, then the forward channel time-delay can be get, the output control value can be determined by this time-delay.

3.3. Improved Fast Implicit GPC Algorithm

According to the time-delay compensation method, the actuator is made by a clock driven, when the time-delay is non-integer multiple of the sampling period, the newest control value can not be applied to the controlled object immediately, but need wait for the next integer times sampling period to be applied to the controlled object. It is easy to cause the system response speed slow and big overshoot, so it is necessary to improve it.

If the actuator uses event driven, it will appear the multi rate sampling, increased the difficulty of model parameter identification. That will increase the difficulty of controller design, so the actuator still use clock driven. In order to accelerate the response speed of the system and restraining overshoot, the next step control increment value is used for the compensation on the Equation (10), the real control value can be obtained as:

$$u'(k) = u(k) + \partial \Delta u(k+1), \partial \in (0,1) \qquad (18)$$

Through the above equations, it is equivalent to an increase of the differential effects on control system; it will accelerate the response speed of the system.

4. Simulation

The controlled object model can expressed as Equation (19), the improved fast implicit generalized predictive control algorithm parameters are $P=5, M=5, \beta=0.2, \partial=0.1$. Because the controller uses the clock driven, therefore, the forward channel time-delay and feedback channel time-delay can not be combined. Simulations for $\tau_{ca}=T, \tau_{sc}=T$ and $\tau_{ca}, \tau_{sc} \in [0,3T]$ are be done respectively, the simulation results obtained as shown in Figure 4 to Figure 7.

$$G_p(s) = \frac{1}{s^2+10s+1} \qquad (19)$$

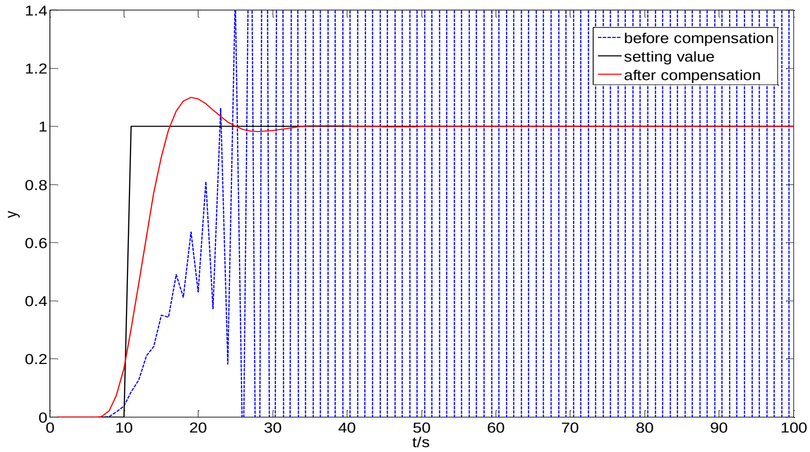

Figure 4. Output Comparison when $\tau_{ca} = T, \tau_{sc} = T$

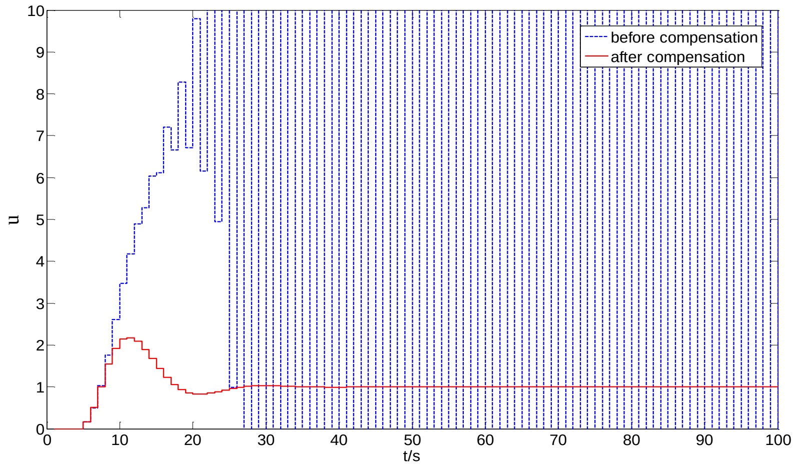

Figure 5. The Control Value Comparison when $\tau_{ca} = T, \tau_{sc} = T$

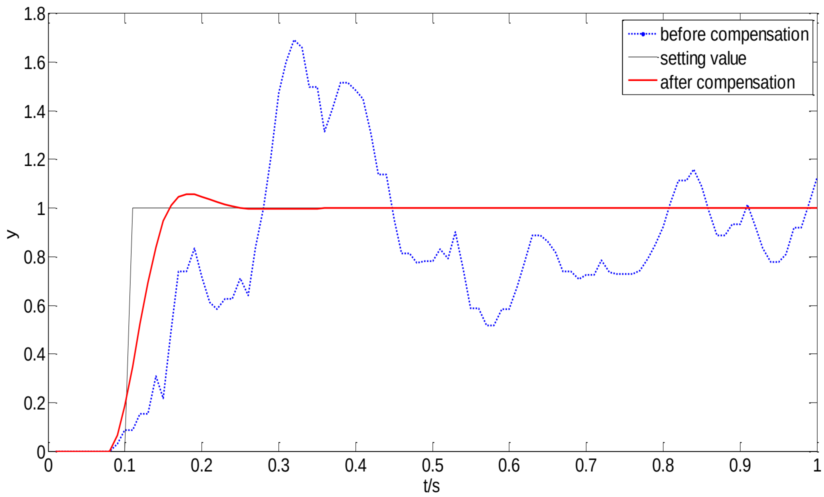

Figure 6. The Step Response Comparison when $\tau_{ca}, \tau_{sc} \in [0, 3T]$

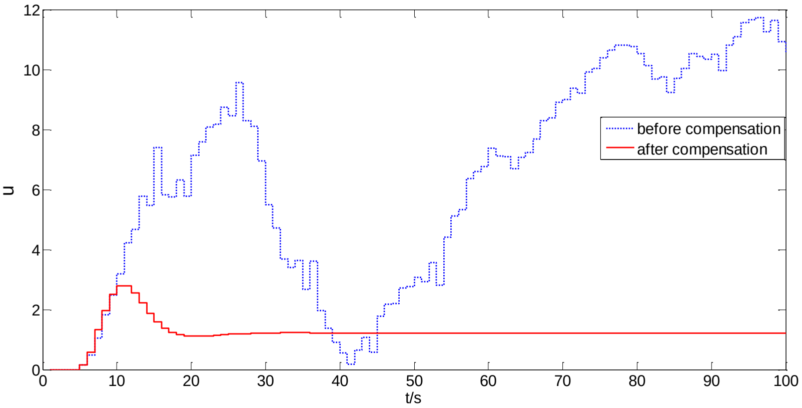

Figure 7. The Control Value Comparison when $\tau_{ca}, \tau_{sc} \in [0, 3T]$

From Figure 4 and Figure 5 can be seen, when the fixed time-delay existence, there is overshoot and long regulation time before time-delay compensation, but the overshoot and regulation time are reduced after time-delay compensation, it proves time-delay compensation algorithm can compensate the fixed time-delay well.

The Figure 6 and Figure 7 can be found, when random time-delay is existence, the overshoot and regulation time after compensation is reduced compared with before compensation, it proves time-delay compensation algorithm can compensate the random time-delay well also, so the time-delay compensation method in this paper is effective.

5. Conclusions

This paper proposed a time-delay compensation method for networked control system. The controller node and the actuator node compensation algorithm is designed through the time stamp. A new improved fast implicit generalized predictive control algorithm is presented for the control value computation in controller. The Matlab simulation on fixed and random time-delay verify the compensation effect of time-delay compensation method achieved satisfactory results.

Acknowledgements

This work is supported by the Liaoning Province Doctor Startup Fund (20141070), and the Natural Science Foundation of Liaoning Province (2013020022).

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Authors

Zhongda Tian born in 1978. Received his PhD degree from Northeastern University of Control Theory and Control Engineering. He is a Lecturer in Shenyang University of Technology. His research interests include time series prediction, time-delay compensation and scheduling for networked control system.

Shujiang Li born in 1966. PhD and Professor in Shenyang University of Technology. His research interests include complex industrial process modeling and intelligent optimal control theory.

Yanhong Wang born in 1967. PhD and Professor in Shenyang University of Technology. Her research interests include production scheduling and optimization, advanced manufacturing information system.

Xiangdong Wang born in 1959. PhD and Professor in Shenyang University of Technology. Her research interests include complex industrial process modeling and intelligent optimal control theory.

Quan Zhang born in 1967. PhD and Associate Professor in Shenyang University of Technology. His research interests include production scheduling and optimization, advanced manufacturing information system.

