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Predictive Control Compensation Strategy for Time Delay in Networked Control Systems

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Abstract. The time delay with random characteristics in networked control systems will reduce the control performance of the system. In order to improve the control performance of system, a predictive control compensation strategy for time delay in networked control systems based on time-stamp and improved implicit generalized predictive control algorithm is proposed. Firstly, the improved implicit generalized predictive control algorithm is used to calculate the control law according to the system historical output and control variable. Because the soft coefficient matrix and the input weighted control law with smoothing filtering are introduced, this improved implicit generalized predictive control algorithm reduces computation time and improves performance. Then, the data buffer is designed in sensor and actuator node. The sensor buffer stores and updates the system output, and sends it to the controller. The actuator buffer stores the control variable and selects the reasonable control variable from the control law according to time-stamp in the packet, and applies it to the controlled object. Finally, the effectiveness of predictive control compensation strategy for time delay in networked control systems in this paper is verified through different simulation conditions. The simulation results show that the proposed compensation strategy in this paper has good control and compensation effect, improve the output performance of the system, and ensure the stability of the control system. The simulation results also show that the compensation strategy needs less computing time and is more suitable for practical applications.

Keywords: improved implicit GPC, networked control systems, predictive control, time delay compensation

1 Introduction

With the rapid development of communication and network technology, the network has been applied to many industrial control applications. It plays a very important role [1]. Especially in some actual engineering scenarios, it is necessary to transmit signals through the communication network, which includes multi agent control system, distributed control system with multi nodes, wireless sensor network (WSN) and etc. The design and implement of the appropriate control methods suitable for networked control systems (NCS) has become one of research hot issues. As a distributed control system, NCS has many advantages, such as full opening, interoperability, low cost and high flexibility [2-3]. However, the introduction of the network in the control loop makes the analysis and design of the system very complicated. Some ideal assumptions used in conventional control theory, such as synchronous control, non delay sensing and execution are no longer applicable, so the existing theory must be reevaluated when applied to NCS.

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After the network is introduced into the control system, the characteristics of the network will inevitably increase the complexity of the control system. According to the network communication state and the network protocol used in the networked control systems, the network time delay has different characteristics, such as invariant, random, correlation or independence [4]. These different characteristics will bring many serious problems. One of the most obvious problems is the introduction of network induced time delay, which affects the performance of NCS and even leads to instability [5-6]. In order to solve this problem, many scholars have made a lot of research work. By adding data buffers to the network transport nodes, some scholars have converted the stochastic nonlinear network time delay system into a fixed time delay system and compensated it with modern control methods [7-8]. The method of adding data buffer is simple and easy to use, but it reduces the real-time performance of the system and is more conservative, because it changes the network time delay into the maximum time delay. Other scholars have established their dynamic models according to the different characteristics of network time delay, and then used some random control theory to compensate the time delay. These compensation strategies include robust control [9-10], neural network [11-13], fuzzy control [14-15], Markov jump system method [16-17], state feedback control [18-19], switching control method [20] and other time delay compensation methods. These compensation methods have made some progress. However, these methods generally have some shortcomings, such as the research object is too idealized, the parameters are difficult to be determined, the method is simple, the network model and control algorithm are too detailed and complex. It is therefore difficult to apply these compensation strategies directly in the actual applications. At the same time, some research results achieved the online compensation of time delay based on the network delay prediction. Because Smith predictor has good compensation effect for pure time-delay systems, it has been applied to network time delay compensation control in recent years [21-23]. However, when there is external interference in the system, it is difficult to match the Smith prediction model with the actual model, which affects the dynamic performance of the system.

The key research problems of this paper are discussed in details. There are three key problems that should be studied in this paper. The first key problem is how to find an effective control algorithm to calculate the control law under the networked control systems. This algorithm should have low complexity, less computation time and good performance. After control algorithm is determined, the second key problem is how to design effective controller, actuator and sensor. That is to say, the controller, the actuator and the sensor node cooperate with each other, and select the most appropriate control variable in the sequence of the control law and act on the controlled object. The third key problem is how to verify the effectiveness of time delay compensation strategy. The simulation environment should be able to simulate real networked control systems.

As we know, although the network induced time delay in a networked control systems is changing, if the compensation algorithm can estimate the time delay and choose an appropriate control variable from the control sequence, then influence of time delay will be eliminated. Based on the above description, networked predictive control compensation strategy is proposed in recent years. As a predictive control method, Clarke proposed generalized predictive control (GPC) in 1987. GPC algorithm has the basic characteristics of predictive control model, rolling optimization and feedback correction. It shows excellent control performance and robustness, and has been widely used in industrial process control. Some studies indicate that GPC is suitable for time delay compensation of networked control systems [24-27]. However, GPC algorithm needs to solve Diophantine equation and matrix inverse operation, which requires much online calculation time. Another reason is that the network induced delay is random, which needs larger prediction steps in GPC algorithm. The larger prediction step also leads to an increasing in computation time. Based on GPC, implicit generalized predictive control is proposed to identify the parameters of the controller directly. It does not need to solve the Diophantine equations, and save the online computing time. But implicit GPC also need to solve inverse operation of a matrix, which need large computation time. Therefore, this paper proposes an improved implicit GPC algorithm.

The motivation of this paper is as follows. Because the soft coefficient matrix is introduced, the input control increment is constrained. The calculation of matrix inversion is avoided by introducing the soft coefficient matrix constraints input control increment. Soften coefficient matrix can reduce the computation time and ensure rapidity of the system. At the same time, the input weighted control law with smoothing filtering is used to suppress overshoot of the system output. In this paper, the improved implicit GPC algorithm is used to obtain the control variable according to the system historical output value and control value. In the current networked control systems, both the actuator node and the sensor node have the basic computing and storage abilities, so that a data buffer with a certain length can be set at its input and output ports of these nodes. It can be assumed that if the updating rule of the buffer matches the prediction step of the predictive controller, which can compensate the influence of network time delay. The sensor buffer stores and updates the system output, and then sends it to the controller. The actuator buffer stores the control value and selects the appropriate control variable from the control sequences according to time-stamp in the packet. This control variable will be applied to the controlled object. The effectiveness of the time delay predictive control compensation method for networked control systems is verified by several simulation experiments.

The following provides a summary of the scientific contribution of this paper. The first is an improved implicit GPC algorithm with coefficient matrix and input weighted control law with smoothing filtering is proposed. The second is the data buffer is used in actuator and sensor node. The data buffer mechanism avoids the clock synchronization problem of the network and simplifies the complexity of the system implementation. The data buffer can also suppress the influence of packet loss. At last, interference and packet loss are considered in simulation. The simulation results reflect the actual NCS more realistically.

The structure of this paper is as follows. Section 2 introduces the preliminaries of networked control systems. Section 3 designs the predictive controller. Section 4 designs the time delay compensation strategy of this paper. Section 5 introduces the simulation results and verifies the effectiveness of the time delay compensation method. The conclusions and future works are provided in Section 6.

2 The Preliminaries

In order to facilitate the research, this paper makes the following assumptions.

(1) Each node in the networked control systems can communicate with each other.
(2) Single packet with time-stamp is transmitted in the network.
(3) The forward and feedback time delay are bounded.
(4) The sensor and actuator node use time-driven mode, the controller uses event-driven mode.

The structure of NCS in this paper is as shown in Fig. 1. As shown in Fig. 1, from the different process of time delay generation, the time delay in networked control systems include τ_{sc} - from sensor to controller, τ_{ca} - from controller to actuator, τ_c - the calculation time in the controller. τ_{sc} can be seen as forward channel delay, and $u(k)$ can be seen as feedback channel delay of networked control systems. Due to the development of hardware, the computation time τ_c in the system can be ignored. The predictive control algorithm is introduced in the controller node, and the buffer is set to select the appropriate control variable. The actuator node also designs the buffer. The buffer automatically updates the sort by time stamp when the packet arrivals, which can solve the problem of timing disorder. The actuator chooses the appropriate control variable and act on the controlled object. Then, the system output data collected from sensor will be transmitted to the controller through the network. The data transmitted by the actuator and sensor will be used for the identification parameters of the controller, which can solve the problem that the parameters of the controlled object model are time-varying.

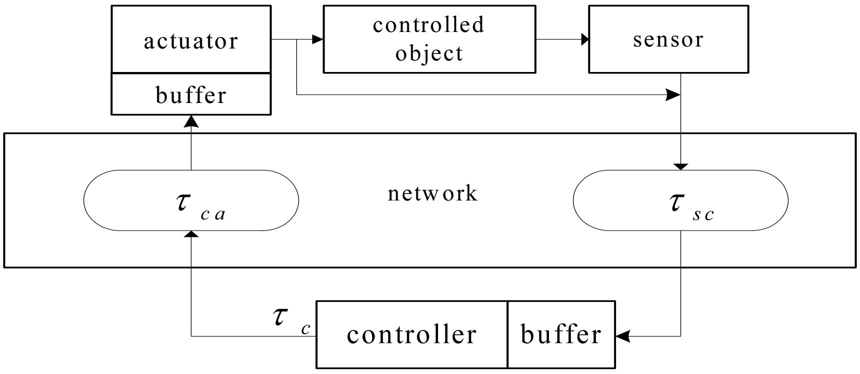

Fig. 1. The structure of networked control systems

In the process of data transmission, there is packet disorder, conflict and loss under the impact of time delay. The controller can recognize the newest sampling data through time-stamp mechanism. In the same way, the actuator can also recognize the latest control variable and perform the corresponding action. In addition, the actuator node adopts buffers and stores the newest control variable calculated by control algorithm. System can achieve stable control.

3 The Design of Predictive Controller

The system output $y(k)$ is transmitted by sensor node at sampling moment k . Because the influences of feedback time delay, the controller must compensate τ_{ca} in the computation process of the control law. τ_{ca} can be calculated according to the time-stamp between the clock of controller and received data from the sensor.

This paper uses an improved implicit GPC algorithm to calculate the control law. CARIMA (controlled auto regressive integrated moving average) model is used to represent the controlled object with non stationary noise [28].

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

Where

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

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

In order to improve the robustness of the system, the objective function needs to consider the impact of control variable $u(k)$ on the system in the future moment. The objective function is chosen as next equation.

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

Where P is maximum predicted length, M is control length, w is output expected value. In order to soften control effect, the output of controlled objective is not directly track the setting value, but track the reference trajectory. The reference trajectory is determined by setting value y_{ref} , output value y , and diffusion coefficient $\alpha(0 < \alpha < 1)$.

$$w(k+j) = a_j y(k) + (1 - a_j) y_{ref}, \ j = 1, 2, \cdots n. \tag{3}$$

The aim of GPC can be attributed to the solution for $\Delta u(k), \Delta u(k+1), \cdots, \Delta u(k+M-1)$ sequence. In order to minimize the objective function value, Diophantine equation is introduced to calculate the optimal predictive value.

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

It minimizes the objective function. The optimal control can be expressed as the next

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

GPC algorithm directly identifies the parameters of the original model. It needs to solve the Diophantine equation and recursively calculate the controller parameters online. The calculation time of control variable will become longer. Implicit GPC identifies parameters ***G*** and ***f*** directly, which avoids recursive solution of Diophantine equation, so it can decrease the computation time of algorithm [29].

By the optimal GPC control variable in Equation (5), the solution of matrix $\Delta \mathbf{U}$ must know matrix $\mathbf{G}$

and the open loop predictive vector ***f***. Implicit GPC makes use of input and output data according to the identification of ***G*** and ***f***. A total of P predictive controllers are obtained.

$$\begin{cases} y_M(k+1) = g_1\Delta u(k) + f\ (k+1) \\ y_M(k+2) = g_2\Delta u(k) + g_1\Delta u(k+1) + f\ (k+2) \\ \vdots \\ y_M(k+P) = g_P\Delta u(k) + \cdots + g_1\Delta u(k+P-1) + f(k+p) \end{cases}, \tag{6}$$

The Equation (6) shows that all the elements in the matrix $\mathbf{G}$ have appeared in the last equation, so the matrix $\mathbf{G}$ can be obtained by the identification of the last equation.

The Equation (6) in the last equation is written in the following form

$$\mathbf{y}_M(k+P) = \boldsymbol{\varphi}(k)\boldsymbol{\theta}(k), \tag{7}$$

In the above equation,

$$\boldsymbol{\varphi}(k) = [\Delta u(k), \Delta u(k+1), \cdots, \Delta u(k+P-1), 1],$$
$$\boldsymbol{\theta}(k) = [g_P, g_{P-1}, \cdots, g_1, f(k+p)]^{\mathrm{T}}.$$

According to the recursive least squares method, the matrix ***G***, the elements $g_1, g_2, \cdots, g_P$ and $f(k+p)$ in the vector $\mathbf{f}$ can be identified after $\boldsymbol{\theta}(k)$ is solved.

The implicit GPC algorithm identifies the controller parameters directly. That is meant the controller parameters are not required to be solved online. But in the calculation of the control law, the inverse operation of the control matrix is still needed. So the algorithm needs a large amount of computation time. It also cannot guarantee the matrix is reversible. There is a big security risk in the practical application when the control matrix is not reversible. According to the basic principle of predictive control, it can be known that the optimization variables are a set of control variable sequences of the optimization intervals. The control variable sequences include the current time and future time. But in the practical application, only the control variable at the current time act on the controlled object. The control variable at future time only affects performance index of the system. Therefore, the control variable sequence of the future does not need to be solved accurately, and it can be replaced by some control variable calculated off-line. This calculation mechanism can greatly reduce the on-line computation time of optimization and satisfy the requirement of real-time of optimization. The input control increment is constrained through soft coefficient matrix. The algorithm avoids the inversion computation of matrix, greatly reduces the amount of computation time, ensures the rapidity of the system, and retains the basic characteristics of GPC. The introduction of soft coefficient matrix has two advantages. The first is in the actual application, if the control variable changes too fast, not only the response of actuator is not timely, but also increases the abrasion of the actuator. Secondly, the input control variable can be well controlled within the constraints. It can suppress the overshoot of system output, and has a good control performance [30].

The definition of input softening coefficient β is

$$\Delta u(k+n) = (1 + \sum_{i=1}^{n} \beta^i)\Delta u(k) \quad (n = 1, \cdots, M-1), \tag{8}$$

Equation (8) can prevent the intense changes in the input signal, which means that the constraint on the change of the input signal. The control increment constraint matrix is as follows

$$\mathbf{Q} = [1, (1+\beta), \cdots, (1 + \sum_{j=1}^{M} \beta^j)]^{\mathrm{T}}, \tag{9}$$

There is

$$\Delta\mathbf{U} = \mathbf{Q}\Delta u(k) = [\Delta u(k), (1+\beta)\Delta u(k), \cdots, (1 + \sum_{j=1}^{M} \beta^j)\Delta u(k)]^{\mathrm{T}}. \tag{10}$$

Equation (2) can be expressed as a vector

$$J = (\mathbf{Y} - \mathbf{Y}_r)^{\mathrm{T}} (\mathbf{Y} - \mathbf{Y}_r) + \lambda \Delta \mathbf{U}^{\mathrm{T}} \Delta \mathbf{U}, \tag{11}$$

Equation (10) is substituted into Equation (11), let $\partial J / \partial \Delta \mathbf{U} = 0$,

$$\Delta u(k) = [(\mathbf{GQ})^{\mathrm{T}} (\mathbf{GQ}) + \lambda \mathbf{Q}^{\mathrm{T}} \mathbf{Q}]^{-1} (\mathbf{GQ})^{\mathrm{T}} [\mathbf{W} - \mathbf{F} y(k) - \mathbf{H} \Delta u(k-1)], \tag{12}$$

Then the control variable can be obtained by $\Delta u(k)$

$$u(k) = u(k-1) + \Delta u(k). \tag{13}$$

Due to the presence of soft matrix, it can be seen that no matter how the prediction steps changed, the control value is only $\Delta u(k)$. At the same time, $(\mathbf{GQ})^{\mathrm{T}} (\mathbf{GQ}) + \lambda \mathbf{Q}^{\mathrm{T}} \mathbf{Q}$ is scalar, which avoids the inversion calculation of matrix and reduces the computation time.

In order to suppress overshoot, $P-1$ predictive control variables are considered, which lead the better control performance. The control effect of implicit GPC is improved by using the input weighted control law with the smoothing filter. The current control variable is a weighted average value of the current and future control variables. The design of the controller is as follows

$$\begin{aligned} \Delta u'(k) &= \frac{\sum_{i=1}^{P} \lambda(i) \Delta u(k+i-1)}{\sum_{i=1}^{P} \lambda(i)} = \frac{\lambda(1)\Delta u(k) + \lambda(2)\Delta u(k+1) + \cdots + \lambda(N_u)\Delta u(k+N_u-1))}{\sum_{i=1}^{P} \lambda(i)} \\ &= \Delta u(k) + \frac{\alpha \lambda(2)}{\sum_{i=1}^{P} \lambda(i)} \Delta u(k) + \cdots + \frac{\lambda(N_u) \sum_{i=1}^{P-1} \alpha^i}{\sum_{i=1}^{P} \lambda(i)} \Delta u(k) \end{aligned}, \tag{14}$$

Where $\frac{\alpha \lambda(2)}{\sum_{i=1}^{P} \lambda(i)} \Delta u(k) + \cdots + \frac{\lambda(P) \sum_{i=1}^{P-1} \alpha^i}{\sum_{i=1}^{P} \lambda(i)} \Delta u(k)$ is compensation value at k moment.

The weighted coefficient λ can affect the control performance of the system. In the optimization process of the performance index, the range of weighted coefficient λ is from 0 to 1. The exponential function has excellent performance according to the literature [31]. In this paper, λ is expressed as Equation (15) based on simulation experiments.

$$\begin{cases} \lambda(i) = e^{-i/2} + 0.95, & i > 6 \\ \lambda(i) = 1, & 0 \le i \le 6 \end{cases}. \tag{15}$$

4 The Design of Compensation Strategy

The sensor nodes collect sampled signal include output signal $Y_s(k)$, control signal $U_s(k)$ and time-stamp t_s. These signals are transferred to the controller node. The control variable sequence $U(k)$ is calculated by improved implicit GPC algorithm through $Y_s(k)$ and $U_s(k)$ at controller node, then $U(k)$ is transferred to the actuator node. When actuator node receive these packets, the local time-stamp t_a of actuator is compared with the time-stamp t_s of the packet, the total delay $\tau(k)$ can be obtained, $\tau(k) = t_a - t_s$, then the suitable control variable at current time k will be chosen by $\tau(k)$ from control value sequence $U(k)$.

In the current NCS, most sensor nodes and actuator nodes have basic computing and storage capacity, so a buffer with certain length can be set in input and output ports of sensor and actuator nodes. If the setting and updating rules of buffer is match with the predictive length of controller, then the time delay in NCS can be compensated. The buffer in the actuator and sensor nodes are as shown in Fig. 2.

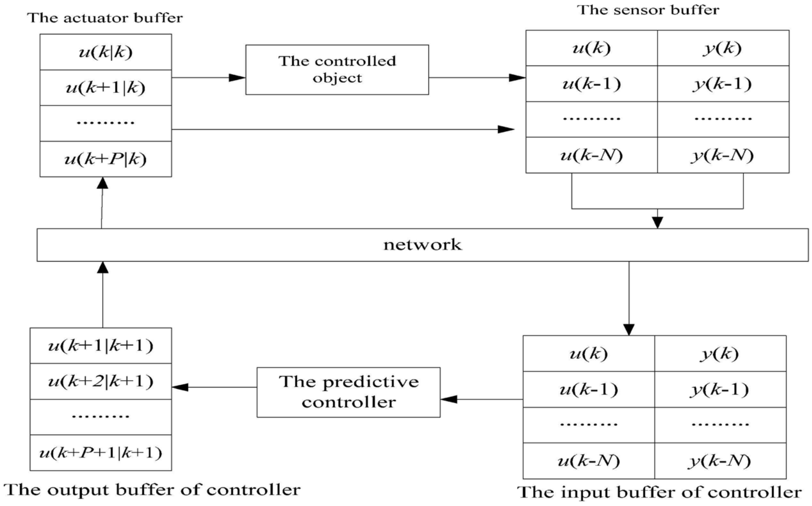

Fig. 2. The buffer design of sensor and actuator node

The function of the actuator buffer is store the control variables transferred through network by the controller, the length of control value sequence is P, satisfied $P \geq \frac{\tau_{\max}}{T} + 1$, $\tau_{\max}$ is the maximum time delay of system, T is system sampling period. The function of sensor buffer is store output sampling value, input control variables at current time and past sampling moments, N is the maximum value of n_a and n_b. n_a is output order, n_b is input order. According to some certain rules, the data in the head of buffer will be sent or executed, but the queue rules of data is determined by updating rules of node. The design method of each node is given as follows.

The design of the controller. The control algorithm of the controller is carried out based on improved implicit GPC algorithm. The system controller receives the data packet sent by the sensor. These data contain input and output information of the past sampling moments, that is:

$$[y_s(k), y_s(k-1), \cdots, y_s(k-n_a-1), u_s(k-1), u_s(k-2), \cdots, u_s(k-n_b-1)]. \tag{16}$$

Using information at moment τ_s, the future control variables can be obtained by improved implicit GPC algorithm. The control variable sequence is:

$$[\Delta u(k+1 \mid k), \Delta u(k+2 \mid k), \cdots, \Delta u(k+M-1 \mid k)]. \tag{17}$$

Considering the length of time delay, the parameters P satisfied $P \geq M$, and M satisfied $M-1 \geq \tau_d + 1$.

The design of sensors. According to the characteristics of the controlled object, the buffer unit is set to the appropriate length. The sensors use clock-driven mode, update data in the buffer in real-time, and send data to the controller. The updating process is as Fig. 3.

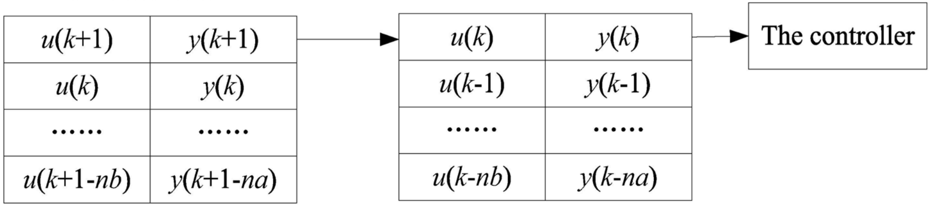

Fig. 3. The buffer updates process of sensors

The design of actuator. The actuator receives data from the controller at moment t_a. The actuator will read time-stamp t_s in the data, and compare t_s with local time t_a. The difference between t_s and t_a is total time delay of system. The total time delay can be expressed as: $\tau_d = t_a - t_s = \tau_{sc} + \tau_{ca}$. The buffer design of actuator is shown as Fig. 4. If the sampling period of system is T , let $n = \tau_d / T$, then $u(k+n \mid k)$ can be chosen as current control variable. If no new data arrives at the next cycle, then $u(k+n+1 \mid k)$ at next moment is chosen as control variable. The data in the buffer is updated until new data arrives. The control variable chosen method in sequence is shown as Fig. 5.

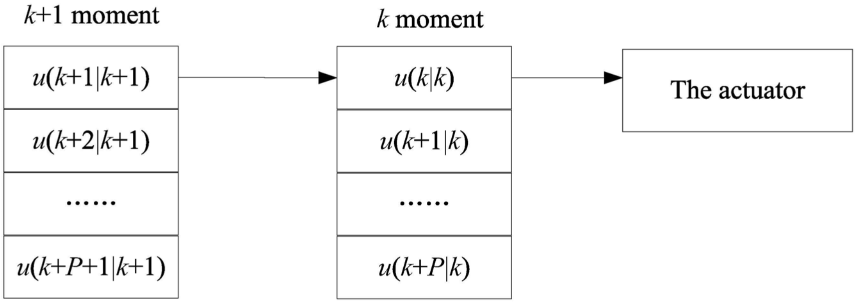

Fig. 4. The buffer design of actuator

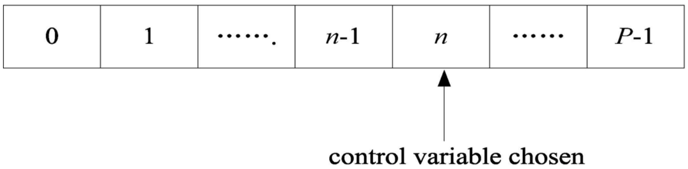

Fig. 5. The control value chosen method

In brief, the steps of predictive control compensation strategy for time delay in this paper are given as follows.

Step 1. Design the data buffer of sensors, actuator and controller.

Step 2. The sensor collects the data and sends them to controller. The controller calculates control variable by improved implicit GPC algorithm.

Step 3. The controller sends control variable sequence to actuator, the actuator calculates system time delay by time-stamp in the data, $u(k+n \mid k)$ in the buffer is chosen as the control variable at current moment, and sends it to the controlled object.

Step 4. The data buffer of sensor and actuator is updated.

Step 5. Repeat step 2 to step 4, until the control process ends.

5 Simulation

In order to illustrate the time delay compensation effect of predictive control method in this paper, the following model is chosen as the controlled object.

$$G(s) = \frac{100s+1}{s^2+100s+1}. \tag{18}$$

An IEEE 802.11b wireless NCS is built through True time toolbox. The sampling period is set as 10 ms, the network speed is taken as 80 000 bits/s, the minimum frame size is set as 80 bits, the packet size is 80 bits, and an interference node is added to the system. Interference node can make network delay random change. The structure of simulation system is as shown in Fig. 6. In order to compare the control effect, the standard GPC algorithm in literature [24], the implicit GPC algorithm in literature [25], improved implicit GPC in [27] and fuzzy self-adaptive PID algorithm in [15] are compared and simulated. The parameters of improved implicit GPC in this paper are chosen as $P = 7$, $M = 5$, $\alpha = 0.7$, $\beta = 0.5$. The data buffer of the controller, actuator and sensor node are designed as introduced in Section 4. The parameters of standard GPC in [24] are chosen as $P = 7$, $M = 5$. The parameters of implicit GPC in [25] are chosen as $P = 7$, $M = 5$, the weighting coefficient λ is 1, forgetting factor μ is 1, γ of

LSSVM is 3.625, σ^2 of LSSVM is 6.752, k_p and k_I is 0.5. The parameters of improved implicit GPC algorithm in [27] are chosen as $P=7$, $M=5$, $\beta=0.2$, $\partial=0.1$. The parameters of fuzzy self-adaptive PID controller in [15] are $K=0.03$, $\eta=2.5$, $k_{I0}=0.282$, $k_{d0}=0.0008$. Input reference signal is square wave with amplitude 1. The simulation time is 2 seconds.

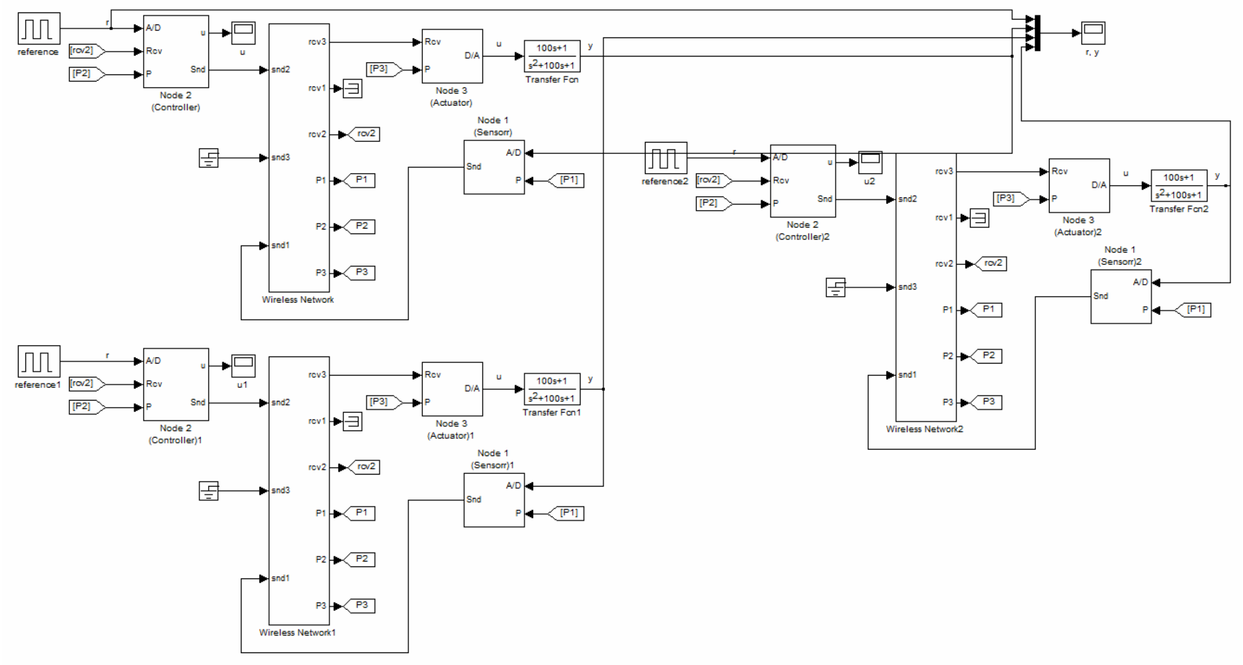

Fig. 6. The structure of simulation system

The simulations include normal condition without interference and without packet loss, with interference and without packet loss, without interference and with packet loss, with interference and with packet loss. The simulation results are as showed in Fig. 7 to Fig. 10.

Fig. 7 is output tracking curve without interference and without packet loss. When there is no interference in the system, the network bandwidth occupied by interference node is zero. Because there is no packet loss in the system, control and sensor information is not lost. The control performance of the system is affected only by time delay in NCS. It can be seen predictive control compensation method in this paper has better performance than the standard GPC in [24], the implicit PIGPC in [25], improved implicit GPC in [27] and fuzzy self-adaptive PID in [15]. The compensation method in this paper has faster response speed and smaller overshoot than the other methods. The performance of standard GPC is affected by the control horizon and the prediction horizon. Therefore, standard GPC has the worst performance in these compensation methods. Compare to standard GPC, because some improvements are employed, the implicit PIGPC and improved implicit GPC have better control performance. Because the fuzzy control algorithm and the parameters self-tuning, fuzzy self-adaptive PID algorithm achieve good control effect. Compare to other methods, the method in this paper can achieve the best time delay compensation effect. The reason of good compensation effect is that soften coefficient matrix can reduce the computation time and ensure rapidity of the system. At the same time, the input weighted control law with smoothing filtering is used to suppress overshoot of the system output. The compensation method in this paper can effectively suppress the influence of network time delay, and has faster regulation time and smaller overshoot.

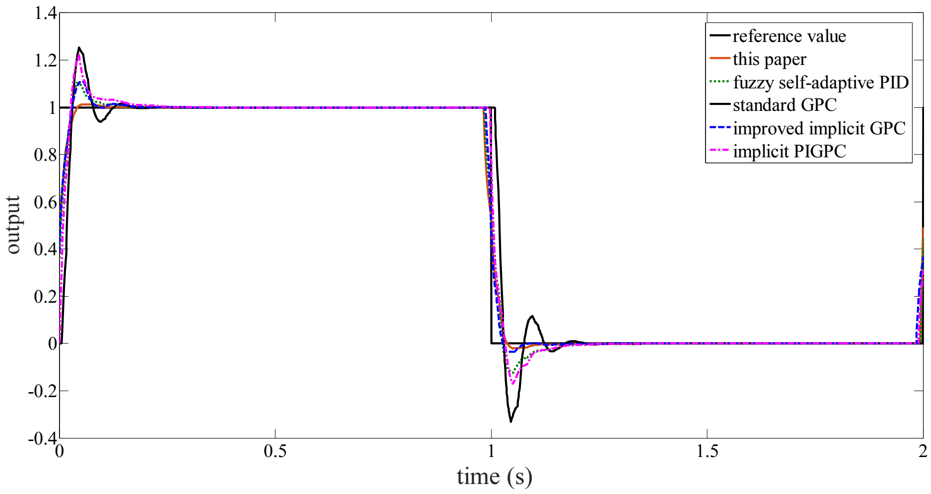

Fig. 7. Output tracking curve without interference and without packet loss

Fig. 8 is the output tracking curve with interference and without packet loss. The interference nodes in the simulation system occupy 20% of the network bandwidth. The pack loss possibility is 0. Because the influence of interference node, the change ranges of time delay will become large. The system performance will be affected by random time delay. It can be seen from Fig. 8, the overshoot of standard GPC will become much larger. After a longer period of time, the implicit PIGPC, the improved implicit GPC and fuzzy self-adaptive PID algorithm can converge to a steady state. However, the time delay compensation method of this paper converges quickly to the steady state and the overshoot is relatively small. The method in this paper can effectively suppress the influence of interference.

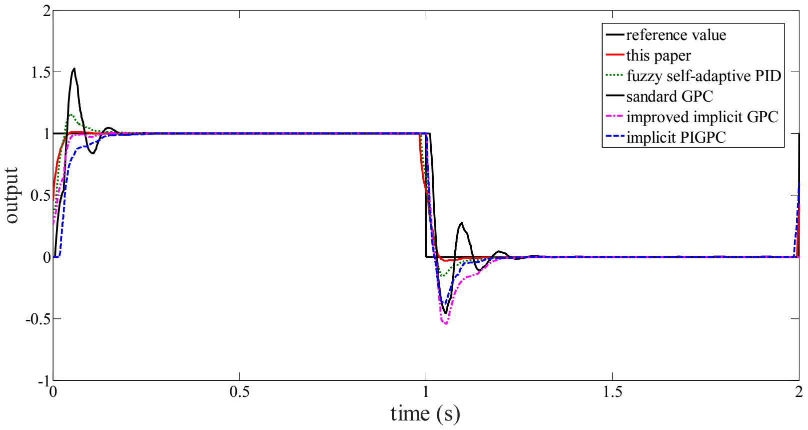

Fig. 8. Output tracking curve with interference and without packet loss

Fig. 9 is output tracking curve without interference and with packet loss. The packet loss possibility of IEEE802.11b network protocol is set to 5%. The packet loss of network will result in dynamic changes in time delay. At the same time, the collected information from the sensor node and calculated control variable of the controller will be lost. The overshoot of standard GPC will become larger. Standard GPC takes a long time to make the system stable. The adjustment time of the implicit IPGPC, improved implicit GPC and fuzzy self-adaptive PID algorithm is longer. Due to the presence of data buffer, the collected information from sensor node and calculated control variable of controller can be stored. The data buffer can make the compensation method in this paper is affected very little by packet loss.

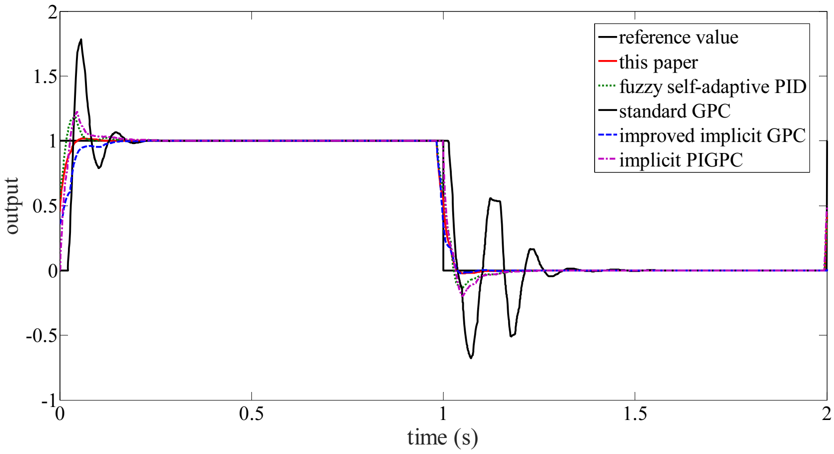

Fig. 9. Output tracking curve without interference and with packet loss

Fig. 10 is output tracking curve with interference and with packet loss. The interference node in the simulation system occupies 20% of network bandwidth. The packet loss possibility of IEEE802.11b protocol is set to 5%. The interference and packet loss make time delay more random and uncertain. The time delay compensation method of standard GPC cannot make the system stable. The implicit PIGPC and fuzzy self-adaptive PID are unable to adapt to the change of the simulation conditions. Although system finally can be stable after a period of time, the overshoot of system is very large. Although improved implicit GPC also has small overshoot, it has longer adjustment time. Compare to Fig. 7, Fig. 8 and Fig. 9, the control performance of time delay compensation method in this paper decreases very little. The stability and speediness of the system have been improved, the compensation of the time delay in the network control system has been realized better, and the system performance has been improved.

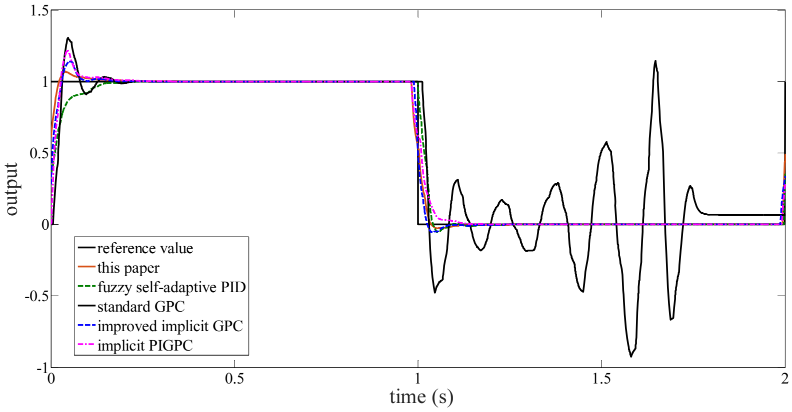

Fig. 10. Output tracking curve with interference and with packet loss

As can be seen from the simulation results, the time delay compensation strategy in this paper has fast response speed with short stable time. This algorithm has better convergence performance, and the overshoot is relatively small, so as to reduce the impact of time delay on the system, improves the system performance and robustness.

Table 1 shows the time required to calculate the control variable for each cycle under different simulation conditions. The configuration of the simulation computer is CPU: Intel i7-4770 3.4 GHz, Memory: 8 GBytes, Operating system: Windows 7 professional. As can be seen from Table 1, the calculation time of time delay compensation method in this paper is close to improved implicit PIGPC and fuzzy self-adaptive PID, and is shorter than standard GPC and implicit PIGPC. The calculation time of time delay compensation method is less than sampling period of system. It can be applied in practical applications.

Table 1. The computation time comparison with different simulation conditions

Simulation conditions	This paper (ms)	Implicit PIGPC (ms)	Standard PIGPC (ms)	Improved implicit GPC (ms)	Fuzzy self-adaptive PID (ms)
Without interference and without packet loss	1.235	2.012	2.361	1.237	1.375
Without interference and with packet loss	1.302	2.131	2.462	1.301	1.276
With interference and without packet loss	1.311	2.425	2.632	1.308	1.381
With interference and with packet loss	1.322	2.425	2.735	1.326	1.402

6 Conclusion and Future Work

In this paper, how to improve the control performance of networked control systems with random time delay is discussed. A predictive control compensation method based on time-stamp and improved implicit GPC is studied. The detailed buffer design of sensor and actuator nodes is given. The proposed improved implicit GPC can reduce the computation time and ensure rapidity of the system. The improved implicit GPC algorithm is used to calculate the control variable according to the system historical output value and control value. The sensor buffer stores and updates the system output, and sends it to the controller. The actuator buffer stores the control variable and selects the appropriate control variable from the control law according to time-stamp in the packet and applies it to the controlled object. Simulation results show that the proposed control method achieves satisfactory time delay compensation effect, improves the stability of the system. Meanwhile, the method in this paper needs shorter calculation time. The results of computation time show that the compensation method in this paper has shorter or closer time than other methods. It is more suitable for the actual networked control systems.

Although the time delay compensation method for networked control systems in this paper has achieved satisfactory results, there are still some limitations. Some further research works are needed. First of all, the research in this paper is focused on linear systems, but the inherent characteristics of nonlinear systems can cause great inconvenience to the analysis and design of networked control systems. Therefore, for nonlinear networked control systems, it is important to design the corresponding control law under the influence of network time delay and packet loss. Secondly, when the network congestion occurs, there will be no upper bound on the time delay, and then the network time delay compensation effect will be no longer ideal. Network congestion can be avoided only through a reasonable network scheduling algorithm. Network scheduling and delay compensation algorithm need to be considered together. Therefore, the co-design of control and scheduling is also the future research content of this paper. In summary, the networked control systems of nonlinear objects and the co-design of control and scheduling are the future research emphases of this paper.

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