Single Neuron PID-Smith Pre-estimate Controller for Networked Control Systems

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ABSTRACT

In the field of industrial control of nonlinear systems, the traditional PID control can not get the satisfied control results. Through single-neuron PID-Smith pre-estimate controller combines PID with Smith pre-estimate controller, a single-neuron PID-Smith pre-estimate controller is proposed to solve the problems of networked control systems (NCSs), such as networked-induced delays, data loss and so on. The simulation results represent it has good dynamic performance, the short transition process, and small overshoot, compared to the conventional Smith pre-estimate controller. The output is rather stable, and has good learning and adaptive abilities.

Keywords: Smith estimate control; networked control systems (NCSs); single-neuron PID-Smith pre-estimate controller

1. INTRODUCTION

With the rapid development of control theory and communication technology, control loops that are closed over a communication network have become more and more popular. Feedback control systems wherein the control loops are closed through a real-time network are called networked control systems (NCSs) which have received increasing attention in recent years because of the popularization and advantages of using network cables in control systems. Although the notion of NCSs is quite new and the theory is still in its infancy, fruitful research work can be found in the most popular journals in both fields of control theory and communication networks, considering interesting and challenging issues which are induced by the network usage in NCSs, such as random network-induced delays, data packets dropout, and so on [1-5].

So far, most research work on NCSs, especially in dealing with the network-induced delay, which is introduced by the inserted network and greatly degrades the performance of the system at certain conditions, has been done by the control theory community. Various methodologies in conventional control theory, such as the theories of time-delay systems, switched systems, stochastic control, optimal control and so on, have found their applications in NCSs [6, 7]. In this kind of research, the characteristics of the network are assumed to be given in advance, and thus a conventional time-delay system, rather than an NCS is considered.

However, it is the communication network which replaces the direct connections between sensors, controllers and actuators in conventional control systems that makes NCSs distinct from the latter. Thus, it is necessary to take the characteristics of the network into account in the study of NCSs. a model-based approach [8] and scheduling algorithms [9] have been provided, to reduce the number of packet exchanges among the network nodes. Quantization problems have been investigated by many researchers for both linear systems [10, 11] and nonlinear systems [12]. In [11], Elia and Miter considered the quadratic stabilization for SISO systems by using quantized state feedback. In [13], Fu and Xie extended the method of [11] to MIMO systems and generalized their results to the problems of performance control. In [14], the quantized-state feedback and quantized observer-based output feedback were considered for a class of continuous linear time-invariant systems. However, most of the references cited above only considered one quantiser and their methods could not be directly applied to the NCSs when considering the effect of network-induced delay.

In this paper, a single-neuron PID-Smith pre-estimate controller is proposed to solve the networked-induced time delays in NCSs. A single neuron is the basic unit of neural network with self-learning and adaptive capacity, and its structure is simple. Combing the single neuron with PID, you can control the complex processes and parameters' time-varying effectively in NCSs.

The model of NCSs with networked-induced delays is described in Section 2. The optimization of the sampling period is presented in Section 3.The design of the single-neuron PID-Smith pre-estimate controller is described in Section 4. The simulation is presented in Section 5. In the end, we give concluding remarks in Section 6.

2.MODEL OF NCS WITH NETWORKED-INDUCED DELAYS

The time delays in NCSs include computing time of network nodes and network transmission time. However, network-induced delays are unique to NCSs, which mainly relate to two aspects: first, the time delays are induced when a variety of information is transmitted in the channels of the network; second, because there are many control loops transmitting information through network in NCSs, the information can produce collision, jam and lost phenomenon, which results in transmission delays. The network-induced delays generated by the latter are more important. The network transmission delays are related to the network rate, the size of transmission information and the media access protocol.

A NCS is composed of a set of control subsystems. The set of n control subsystems is $\{Loop_1,\ldots,Loop_i\ldots,Loop_n\}$. The $Loop_i$ is a periodic task. In our task model $Loop_i(h_i,d_i,c_i,b_i)$, each control loop is characterized following parameters:

h_i: the execution period of the control loop i.

d_i: the relative time of the control loop i .

c_i: the task transmission period of the control loop i.

b_i: the transmission block time of the control loop i.

As the network is a shared transmission channel for a set of control subsystems, and the information transmission of all subsystems occupies a certain amount of time of the network resources, NCSs exist information block and information wait phenomenon, which result in time-delays. So, it is necessary to schedule network resources of NCSs properly.

In order to maintain the stability of NCSs, we need to analyze each control loop. The system model of $Loop_i$ is given as follow.

$$\begin{aligned} \dot{x}_i(t) &= A_i x_i(t) + B_i u_i(t-\tau_i) \\ y_i(t) &= C_i x_i(t) \end{aligned} \tag{1}$$

Proposition 1: If the network-induced τ_i is less than sampling period h_i, the discrete system model is given as follow.

$$\begin{aligned} x_i[(k+1)h_i] &= G(h_i)x_i(kh_i) + H_0(h_i,\tau_i)u_i(kh_i) + H_1(h_i,\tau_i)u_i[(k-1)h_i] \\ y_i(kh_i) &= C_i x_i(kh_i) \\ u_i(kh_i) &= -L_i(h_i,\tau_i)x_i(kh_i) \end{aligned} \tag{2}$$

where $G(h_i)=e^{A_i h_i}$, $H_0(h_i,\tau_i)=\left(\int_0^{h_i-\tau_i} e^{A_i t}dt\right)B_i$, $H_1(h_i,\tau_i)=e^{A_i(h_i-\tau_i)}(\int_0^{\tau_i} e^{A_i t}dt)B_i$, L_i is a gain matrix.

The performance of each control subsystem is tested by the performance index function J_i.

$$J_i = \lim \frac{1}{t}\int_0^t \begin{vmatrix} x_i(t) \\ u_i(t) \end{vmatrix} Q_i \begin{vmatrix} x_i(t) \\ u_i(t) \end{vmatrix} dt \tag{3}$$

where Q_i is a positive semi-definite matrix.

3. OPTIMIZATION OF SAMPLING PERIOD OF NCSS

In the NCSs, in order to guarantee the performance of the control object, it normally takes a relatively fast sampling rate, but the reduction of sampling period will increase network packets transmission frequency and the burden of network scheduling. So, at the requirements of the sampling period, the scheduling and the control are contradictory. Sensors of network nodes adjust sample periods, which is restricted by control objects stability and network schedulability.

3.1 Selection of Objective Function

Larger or smaller sampling period may result in deterioration of system output performance. So, the determination to optimize the sampling period is critical for the co-design of scheduling and control. On one hand, from the perspective of the control performance objectives, NCS sampling period is smaller, and the performance is better; On the other hand, from the perspective of the scheduling performance, because of the network bandwidth limitations, the reduction of sampling period should be limited. Basing on the contradiction mentioned above, the use of sampling period optimization method can solve the conflicts between control performance and network scheduling performance.

The problem of optimizing sampling period can be attributed to the optimization problem of making the performance index function (objective function) of each control loop be a minimum, with constraint of network schedulability and NCS stability. Optimum objective function of NCSs is expressed as J_{all}.

$$J_{all} = \sum_{i=1}^{n} p_i J_i \tag{4}$$

where p_i is the weight coefficient, corresponding to the network control system of priority, whose value is greater and the priority of control system is correspondly higher; J_i is the performance index function of each control loop.

3.2 Conditions for System Stability

If sampling period of control system is too large or too small, it will affect the performance of NCS. In order to ensure system stability and control to satisfy some certain performance requirements, we need to choose the sampling period rightly for NCSs.

$$h_{i\_\max} = \frac{h_{bw}}{20} - 2\tau_i \tag{5}$$

where h_{bw} is the network bandwidth.

3.3 Scheduling Constraints of Sampling Period

In order to transmit the system control information effectively in the network, and to satisfy real-time requirements of control tasks, we need to allocate and schedule network resources to ensure that the control tasks information should achieve delivery in a certain period of time, and network utilization is improved. In this paper, only single-packet transmission of information is considered and we analyze the packet transmission way. Transmission scheduling of NCSs is featured by the characteristics of non-preemptive priority.

Using different scheduling algorithms, the scheduling constraints of sampling period is different. In this paper, we use EDF scheduling algorithm for scheduling of network resources, in order that the tasks of each sub-control system have a characteristics of specificity, and cannot be interrupted by other information, to ensure that information transmission achieves before the deadline. For n control tasks with independent periods and characteristics of non-preemptive priority, when they satisfy the following inequality, NCSs can schedule transmission tasks, moreover, the tasks who have a shorter period have a higher priority.

$$\sum_{i=1}^{N} \frac{c_i}{h_i} \le 1 \tag{6}$$

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where h_i and c_i are respectively the transmission period of control task and the transmission time of control task. The inequality above is a sufficient condition for that whether NCSs can be schedulable, rather than a necessary condition. According to conditions analysis of system stability, the sampling period must meet (5), so that it constitutes a necessary and sufficient condition.

4.SINGLE-NEURON PID-SMITH PRE-ESTIMATE CONTROLLER DESIGN

Smith pre-estimate control is a control method, which is widely used to compensate for time-delay objects. In actual applications, PID controller connects with compensation part parallelly, and the compensation part is Smith predictor.

4.1 Principle of Smith Pre-estimate Controller

Smith pre-estimate control introduces compensation part in feedback control system, and the closed-loop transfer function is given as follow.

$$H_b(s)=\frac{D(s)G_p(s)e^{-\tau s}}{1+D(s)G_p(s)e^{-\tau s}} \qquad (7)$$

where $D(s)$ is the transfer function of common regulator, $G_P(s)$ is the transfer function of control object, $G_P(s)e^{-\tau s}$ is the transfer function without time-delay part of control object, $e^{-\tau s}$ is the time-delay part of transfer function. From equation (7), we can see, the denominator of closed-loop transfer function contains time-delay part $e^{-\tau s}$. Unit feedback control system that control the object contains time-delay part make the whole system unstable. If the value of τ is large enough, the system will also become unstable. In order to improve the stability of

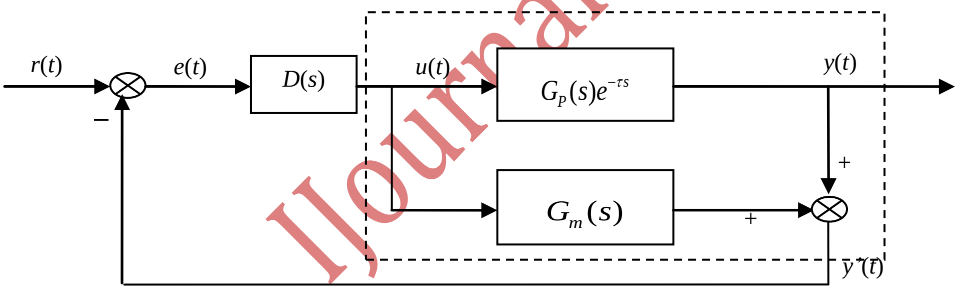

Figure 1 Time-delay System Control Structure with Smith Compensator

feed-back loop control and separates the pure time-delay part from other parts in the transfer function of control channel, to pre-estimate the dynamic characteristics of the system that is given a certain signal and then be compensated by the pre-estimate controller, which tries to reflect the time-delay amount to the regulator in advance, so that regulator can take action in advance to reduce the amount of overshoot and accelerate the adjustment process. If the estimation model is accurate, this method can obtain better control effect, and eliminate the adverse effects of time-delays on the system, and allow the quality of system be the same as that with no time-delays

Proposition 2: We start with a discussion of general feedback control system, which is a unit time-delay such large time-delay system, the control object connects with Smith pre-estimate controller that contains a feedback compensation part, whose transfer function is $G_m(s)$. The structure of the system is presented as figure 1.

From figure 1, we can see, the closed-loop transfer function of compensated system is:

$$\begin{aligned} H_s &= \frac{D(s)G_p(s)e^{-\tau s}}{1+D(s)G_m(s)+D(s)G_p(s)e^{-\tau s}} \qquad (8) \\ &= \frac{D(s)G_p(s)e^{-\tau s}}{1+D(s)[G_m(s)+G_p(s)e^{-\tau s}]} \end{aligned}$$

If $G_m(s)=G_p(s)(1-e^{-\tau s})$, the equation (8) can also be presented:

$$H_{bp}(s)=\frac{D(s)G_p(s)e^{-\tau s}}{1+D(s)G_p(s)} \qquad (9)$$

The role of Smith pre-estimate controller is to make the time-delay system into the system without time-delays and then to control it. However, because Smith predictor has a high accuracy requirement of its model and is sensitive to the model error, when the network latency is high, the control effect of the system is not well, the value of overshoot is large and the settling time is long. Because the network delay is time-varying, in order to overcome the impact of model error, we need take measures to transfer Smith pre-estimate control for NCSs.

4.2 Single-Neuron PID-Smith Pre-estimate Control

4.2.1 Single-Neuron Model

For the i^{th} neuron, x_1, x_2, ..., x_N the are received informations of neuron, and w_{i1}, w_{i2}, ..., w_{iN} are connecting strengths, known as the right. We make use of certain operations to combine all the input signals, in order to give the total effect, known as the net input, presented by net_i. According to different computing ways, the net input has a variety of expression, which includes a linear weighted sum, known as $net_i=\sum_{j=1}^{N} w_{ij}x_j$, which causes the state of neuron i to change. The output y_i of neuron i is the current state of function g (.), known as the activation function (state of activation). In this way, the mathematical expression of the above-mentioned model is:

$$net_i=\sum_{j=1}^{N} w_{ij}x_j-\theta_i \qquad (10)$$

$$y_i=g(net_i) \qquad (11)$$

where θ_i is the threshold value of neuron i.

If taking into account the role of the time delay of output and input, equation (11) can be revised to:

$$y_i(k+1)=g(net_i) \qquad (12)$$

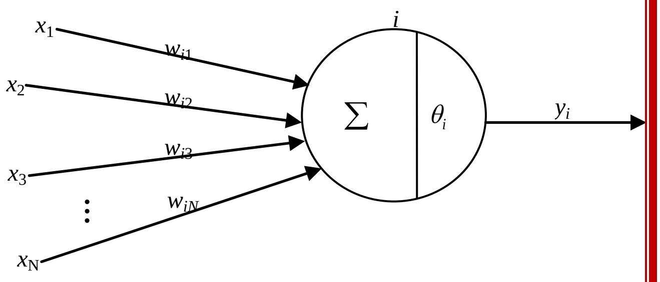

Figure 2 Model of Neuron

4.2.2 Design of Controller Algorithm

Neuron is a basic unit of neural networks with self-learning and adaptive capacity, its structure is simple, and it is easy to calculate. However, traditional PID modem also has a simple structure, its adjustment is convenient, and the parameter tuning is closely linked with the project indicators. If combining PID with neuron, we can solve the problems that traditional PID modem cannot be easy to tune the parameters on-line in a real-time environment, and cannot control some complex processes and systems with lowly time-varying parameters effectively.In conventional analog regulation systems, PID algorithm can also be written in the following expression:

$$u(t)=K_P\left[e(t)+\frac{1}{T_I}\int e(t)dt+T_D\frac{de(t)}{dt}\right] \qquad (13)$$

where T_I is the proportion coefficient, T_D is the differential-time constant, and K_P is the integral- time constant. The corresponding the incremental digital PID algorithm is:

$$\Delta u(k)=K_Pe(k)+K_I[e(k)-e(k-1)]+K_D[e(k)-2e(k-1)+e(k-2)] \qquad (14)$$

where $K_I=K_PT/T_I$ is the integral coefficient, $K_D=K_PT_D/T$ is the differential coefficient, and T is sampling time.

In the digital control system, if K_P, K_I, K_D are regulated well, the system can achieve effective control. Single- neuron PID control algorithm is:

$$\Delta u(k)=K\{w_1e(k)+w_2[e(k)-e(k-1)]+w_3[e(k)-2e(k-1)+e(k-2)]\} \qquad (15)$$

where w_1, w_2, w_3 are three right values, and K is the coefficient of neurons.

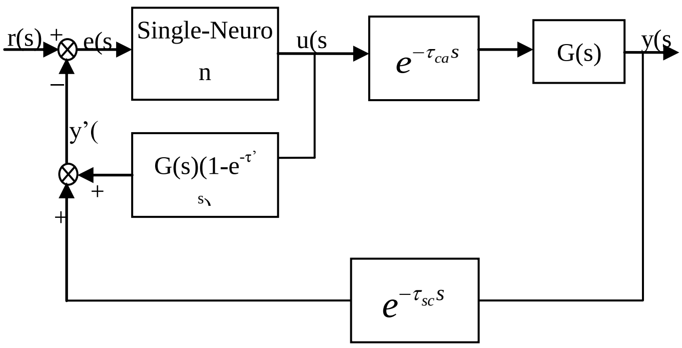

Figure 3 Structure of Single-Neuron PID-Smith

The single-neuron weighted coefficients are relative to single-neuron inputs, single-neuron output and single-neuron output error. So, the single-neuron adaptive PID control uses supervised *Hbb* learning algorithms:

$$u(k) = u(k-1) + K\sum_{i=1}^{3}\overline{w_i}(k)x_i(k) \tag{16}$$

$$\overline{w_i}(k) = \frac{w_i(k)}{\sum_{i=1}^{3}|w_i(k)|} \tag{17}$$

$$\begin{cases} w_1(k+1) = w_1(k) + \eta_I z(k)u(k)x_1(k) \\ w_2(k+1) = w_2(k) + \eta_P z(k)u(k)x_2(k) \\ w_3(k+1) = w_3(k) + \eta_D z(k)u(k)x_3(k) \end{cases} \tag{18}$$

where η_I, η_P, η_D are respectively integral learning rate, proportional learning rate, and differential learning rate. *z(k)*is the output error signal $z(k) = r(k) - y(k) = e(k)$, and the adjustment laws of the parameters η_I, η_P, η_D and K are as follows:

(1) The initial weighted coefficients $w_1(0)$, $w_2(0)$, $w_3(0)$ can be selected randomly.

(2) The choices of learning rates η_I, η_P, η_D are that because of the standardization of learning algorithm, the values of learning rates can be larger, and the values can be adjusted in accordance with the overshoot of dynamic process.

(3) The value of K is determined by PSD (Proportional Summation Derivative)[15].

5. SYSTEM SIMULATION

Proposition 3: Control of the object is given as follows:

$$G(s) = \frac{2029.826}{(s+26.29)(s+2.296)} \tag{19}$$

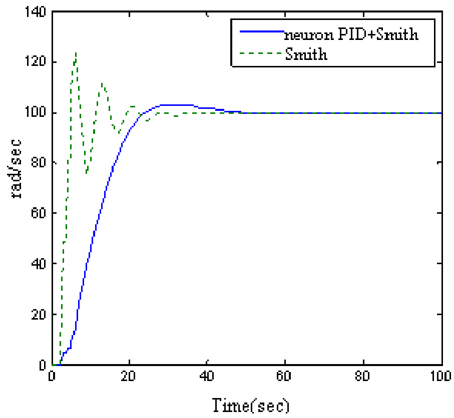

Figure 4 τ_{ca} and τ_{sc} are between 0.1s and 0.5s

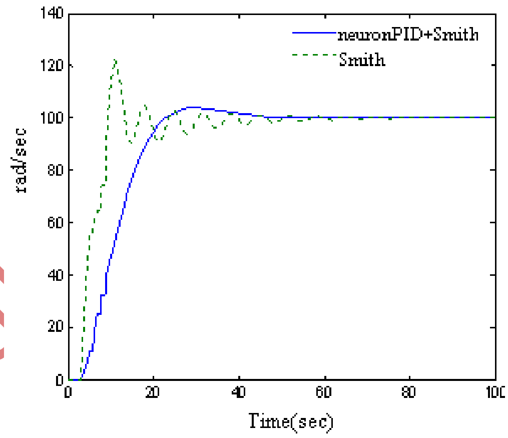

Figure 5 τ_{ca} and τ_{sc} are between 0.5s and 1.5s

We use single-neuron PID-Smith pre-estimate control method and Smith pre-estimate control method respectively to simulate. In the PI control, we let K_p = 0.1, K_I = 0.25, and step command signal be 100*rad / s*. The initial simulation parameters of single-neuron PID are w_1 = 0.3, w_2 = 0.1, w_3 = 0.2, η_I = 0.3, η_P = 0.35,η_D = 0.3, and K = 0.04.

From figure 4 and figure 5, we can see that whether the time delays of the network is less than the sampling period or not, the single-neuron PID-Smith pre-estimate control method has better dynamic performance. Compared to traditional Smith pre-estimate control method, the former has shorter overshoot, more stable output, and better dynamic performance.

6. CONCLUSION

A single-neuron PID-Smith pre-estimate controller is proposed to solve the problems of NCSs. The controller not only has a good ability of dealing with dynamic problems, but also addresses the problems of traditional Smith pre-estimate controller, such as larger overshoot, unstable output, and so on. It has a good ability of learning to adapt to the changes of signals and time delays.

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