Main Stream Temperature Control System Based on Smith-PID Scheduling Network Control

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***Abstract*—This paper is concerned with the controller design problem for a class of networked main stream temperature control system with long random time delay and packet losses. To compensate the effect of time delay and packet losses, a gain-scheduling based Smith-PID controller is proposed for the considered networked control systems (NCSs). Moreover, to further improve the control performance of NCSs, genetic algorithm is employed to obtain the optimal control parameters for gain-scheduling Smith-PID controller. Simulation results are given to demonstrate the effectiveness of the proposed methods.**

Keywords- Network control systems (NCSs); Gain-scheduling based Smith-PID; main stream temperature system; time delay; packet loss.

I. INTRODUCTION

In recent years, Networked control systems (NCSs) have received increasing attentions. NCSs are a class of cotnrol systems where sensors, actuators, estimator units and control units are connected through communication networks[1]. NCSs have many advantages, such as low cost, simplified maintenance and diagnosis, increased system flexibility, and so on. However, because of the insertion of network, NCSs inevitably have the problems of random time delay, packet out-of-order and packet losses, etc.

The stability and performance of NCSs have been studied by many researchers recently, such as paper [2-4]. In [5] and [6], the problem of designing H∞ controllers for networked control systems with both network-induced time delay and packet out-of-order was studied. Many kinds of time delay in the network system were introduced in [7]. It applied the algorithms of discrete-time sliding mode forecast control to make a simulation on servo system, which is controlled by network control system. In [8], the problem of designing guaranteed cost controller is studied for a class of uncertain time delay networked control system. More Networked controllers were designed in [9-12]. For more details on this subject, we refer the reader to [13-16] and the references therein.

Aiming at the problem of random time delay of the networked control systems, the gain-scheduling based Smith-PID controller is designed in this paper. The Smith controller is used to compensate the long time delay of the system, and the gain-scheduling based PID scheduling controller is used to solve the problem of random time delay of the networked control systems. The two controllers were combined together to control the long time delay networked control systems better.

The structure of this paper is organized as follows. The introduction of the Networked control system is given in Section I. The problem formulation is given in Section II. The controllers design is introduced in Section III. In this section, the Smith control design and the gain-scheduling networked control design are introduced respectively. As an example, the gain-scheduling based Smith-PID controller is used in the main stream temperature control system. The simulation is done in Section IV and the numerical and experimental results are provided. The conclusion is given in Section V.

II. PROBLEM FORMULATION

The main stream temperature control system is composed of six modules. They are temperature detecting module, temperature setting module, alarming module, controlling unit module, temperature displaying module, actuator module. The general block diagram is shown in figure 1.

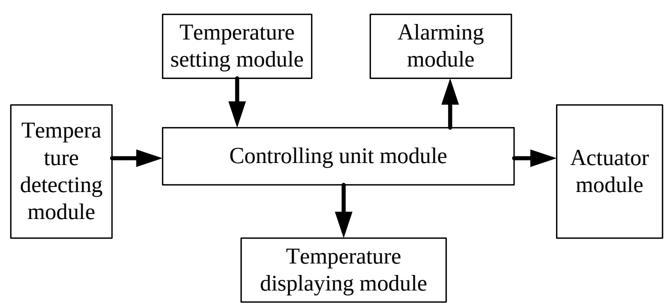

Figure1. The general block diagram of the main stream temperature control system

The main stream temperature system is controlled through network in this paper. Therefore, there are many problems to solve, such as random time delay, packet out-of-order and packet losses. The gain-scheduling based Smith-PID control method is proposed in this paper to solve the aforementioned problems. There is long time delay in the main stream temperature system, and the time delay is different when the system is using different number of sub-loops. Moreover, there is also random time delay in the network. In this paper, we combine the aforementioned two kinds of time delay together. It is worth noting that, during the controller design stage, we also take the packet out-of-order and packet losses of network into consideration.

III. Controller Design

A. Smith-PID Control Design

The single loop control system with pure delay is shown in figure 2, whose closed-loop transfer function is shown as follows:

$$\phi(s) = \frac{Y(s)}{R(s)} = \frac{G_c(s)G_0(s)e^{-\tau s}}{1+G_c(s)G_0(s)e^{-\tau s}} \quad (1)$$

Its characteristic equation is:

$$1+G_c(s)G_0(s)e^{-\tau s} = 0 \quad (2)$$

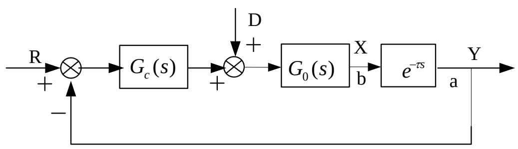

Figure2. The single loop control system with pure delay

Obviously, there is pure delay in the characteristic equation. If τ is big enough, the system will be unstable. That is the essence that the long time delay process is hard to control[20]. $e^{-\tau s}$ appears in the characteristic equation, because the feedback signal is cited from the point a of the system. If the feedback signal is cited from the point b, the pure delay part is removed outside of the control circuit. As shown in figure 3. After time delay τ, the controlled variable Y will repeat changes of X.

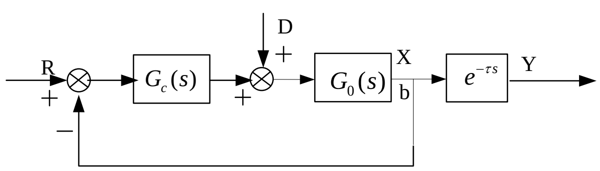

Figure 3. Improved single loop control system with pure delay

Because the feedback signal X has no delay, the response of the system is greatly improved. Point b is not exist or limited by the physical conditions in the practical system. So, the feedback signal can't be cited from the point b. According to this problem, Smith proposed artificial model method. The structure is shown in figure 4.

If the model is accurate, such as $G_0(s) = G_m(s)$, $\tau=\tau_m$, and there is no load disturbance(D=0). $Y=Y_m$, $E_m=Y-Y_m=0$, $X=X_m$. So, X_m can change X as the first feedback loop and the pure delay part is moved outside of the control loop. If the model is inaccurate or there is load disturbance in the control process, X is not equal to X_m, $E_m=Y-Y_m \neq 0$, and the control precision is not a great satisfaction. So, E_m is used to realize the second feedback loop. This is the control strategy of Smith predictor controller.

B. Scheduling Network Control Design

The time-delay of the networked control systems is varying all the time.

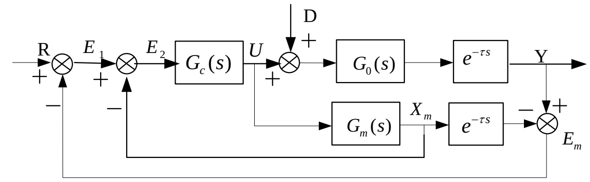

Figure 4. Smith predict control system

We can use scheduling network control to solve this problem. The block diagram of the networked control system is shown in figure 5.

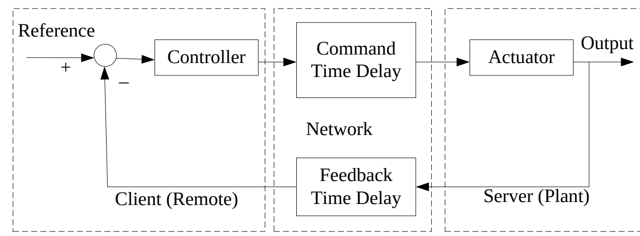

Figure 5. The block diagram of the networked control system

Suppose that: the time delay τ is varying in the three rang [a, a+h], [a+h, a+2h], [a+2h, a+3h](Thereinto, h and a are arbitrary real numbers). The parameters of the PID controller are k=f{Kp, Ki, Kd}. When τ is varying in the rang [a, a+h], the k is big. When τ is varying in the rang [a+h, a+2h], the k is middle. When τ is varying in the rang [a+2h, a+3h], the k is little. With the parameter τ is varying in the three rang, different parameters of the PID controller can be selected to make the networked control systems running quickly and stable. That is so called Scheduling PID Network Controller.

The different parameters suit different τ can be optimized by the adaptive online genetic algorithm.

C. gain-scheduling based Smith-PID Network Control Design

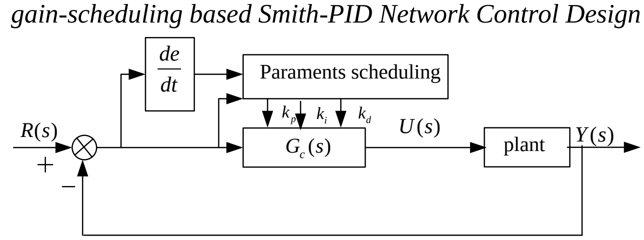

Figure 6. The structure of the Smith-PID scheduling network control

The Smith-PID controller is used to compensate the long time delay of the system, and the gain-scheduling based PID controller is used to solve the problem of packet out-of-order and packet losses of the system. The two controllers were combined together to control the long time delay networked control systems better. The structure of the gain-scheduling based Smith-PID network control is shown in figure 6.

D. Genetic Algorithm

The parameters of PID are optimized by the genetic algorithm. The genetic algorithm is introduced as follows.

The setting principles of the parameters of PID based on the genetic algorithm are proposed as below:

1) The determination and the expression of parameters

First of all, the ranges of parameters should be determined. The ranges are usually given by users, and then been coded according to the demanding of precision[17-18]. Every parameter is expressed by selecting binary word serial, and relationships between them are established[19]. Then, the binary word serials are combined together to a long binary word serial. The long word serial is the operation object of genetic algorithm.

2) The selection of the initial population

The process of genetic algorithm is realized by programming. So, the initial population will be generated randomly by computer. For the binary programming, the random numbers between 0~1 are generated. Then, the random number between 0~0.5 will express 0, and the random number between 0.5~1 will express 1. What's more, the complex degree of the calculation will be considered when determining the size of the population.

3) The determination of the fitness function

For the normal optimizing method, one group parameters can be obtained under the restrained conditions. The best one can be selected in the group of parameters. There are three aspects of index to measure a control system: stability, accuracy, and rapidity. The rise time reflects the rapidity of the system. The shorter of the rise time, the quicker of the control process, the better of the quality of the system.

If the dynamic performance of the system is pursued only, the obtained parameters will probably making the control signal too big. This will lead to the unstable of the system because of the saturation characteristic of the system. We will add control variable into the objective function to prevent the oversize of the control energy. To control the system better, the control variable, error and rise time are given as constraints. Because the fitness function is related with the objective function, the objective function will be taken as the fitness function to optimizing parameters after determination.

4) The operation of the genetic algorithm

First of all, the fitness proportion method is used to copy, and the copy probability is obtained. The product of copy probability and the number of every generation of word serial is taken as the copy number of the next generation. The one who has bigger copy probability will has more descendants in the next generation. The one who has smaller copy probability will has smaller descendants in the next generation.

Through copying, crossing and variation, the new population is obtained from the initial population. The population is induced into the fitness function after decoding to observe if the termination conditions are satisfied or not. If the termination conditions are not satisfied, the operations above are repeated until they are satisfied.

The termination conditions are decided by specific problems. Only if all the target parameters are in the specified ranges, the calculation will be terminated.

The operating process above can be expressed in figure 7.

The steps of optimizing the parameters k_p, k_i, k_d using the genetic algorithm is introduced as follows:

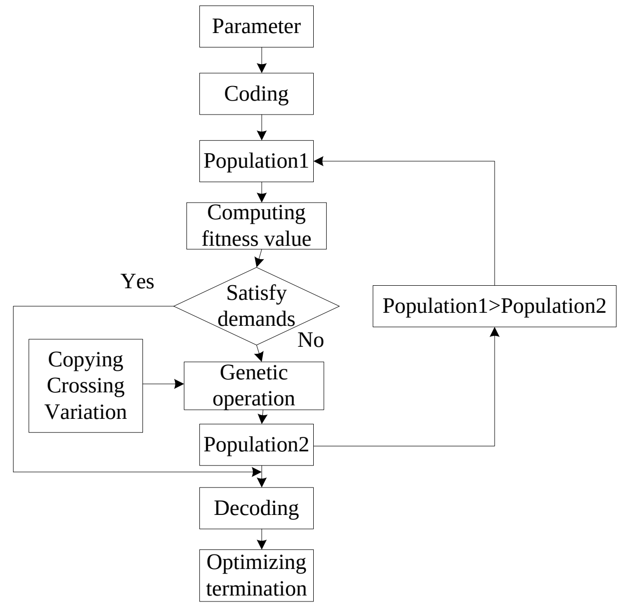

Figure 7. The flow chart of the genetic algorithm

1) Determining the range and the length of every parameter and coding.

2) N individuls are generated randomly and they composed of the initial population P(0).

3) Decoding the individuls of the population to the responding parameters. These parameters are used to solve the cost function value J and the fitness function value f, f=1/J.

4) The operation is done to the population P(t) using copying operator, crossing operator and variation operator. So, the next generation of population P(t+1) is generated.

5) The steps 3) and 4) are repeated until the parameters are converging or reaches the predetermined index.

The cost function is designed as follows:

$$fitness = \min\left(\int_0^\infty t^2 \times |e(t)|\, dt\right) \quad (3)$$

where e(t) is the error between the output signal of NCS and the expected signal. The binary word serials are decoded into the control parameters in reality. These parameters are used in the discrete NCS controller. Then, simulation about NCS is done. Last, the fitness degree of individual is computed based on the time domain response curve of the controlled object.

There are four advantages for the genetic algorithm when setting the parameters of PID:

1) Compared with the simplex method, the genetic algorithm has good optimizing parameters. It overcomes the sensitivity of the simplex method to the initial values of the parameters. In the situation of improper selection of the initial condition, genetic algorithm can also find the proper parameters to make the control target meets the requirement. What's more, the simplex method will cost too long time or cause failure optimization. The genetic algorithm can solve the questions very well.

2) Compared with the expert setting method, it has the advantages of simple and quick. It needs no complex rules, and can receive optimal value through simple copy, cross, and variation. It avoids plenty of collection work of knowledge database and simulation in the expert setting method.

3) The genetic algorithm is doing parallel operations from many points. It overcomes the blindness of begging from one point. So, its speed is faster and it avoids falling into the local optimal solution too early.

4) The genetic algorithm is not only used in single target optimization but also multiple target optimizations. The genetic algorithm will find the proper parameters in the prescribed scopes based on different system.

IV. SIMULATION

Take the main stream temperature control system as an example. The transfer function of the main stream temperature control system is $W(s) = \frac{e^{-300s}}{1500s^2 + 1501s + 1}$. Suppose that: the time delay τ is 300s at the begging, turns to 280s from 200s, and turns to 260s from 400s.

The normal Smith-PID controller is used to control the main stream temperature control system first. Through repeated debugging, there are three result curves shown as below.

When the parameters of the PID controller are Kp=6.2, Ki=0.01, Kd=1.1, the input-output curve of the system is shown in figure 8.

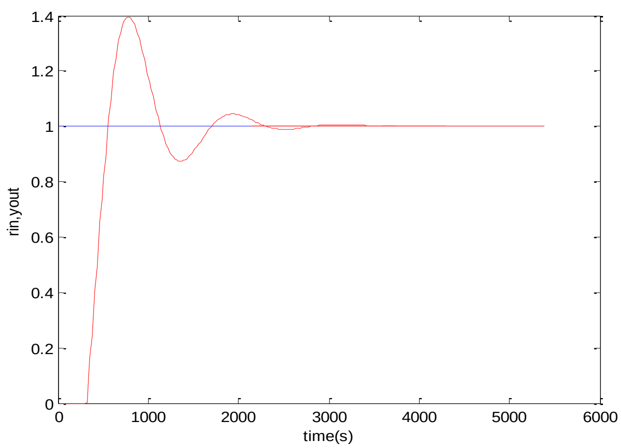

Figure 8. The simulation result with the normal Smith-PID controller

The gain-scheduling based Smith-PID network controller is used to control the main stream temperature control system. Through optimizing by the genetic algorithm, the parameters of the PID controller are Kp=16.81, Ki=0.0114, Kd=13.31 at the begging. When the time delay of the system turns to 280, the parameters of the PID controller turn to Kp=21.81, Ki=0.01529, Kd=17.31. When the time delay of the system turns to 260, the parameters of the PID controller turn to Kp=33.01, Ki=0.01852, Kd=19.31. The simulation result of the system is shown in figure 9.

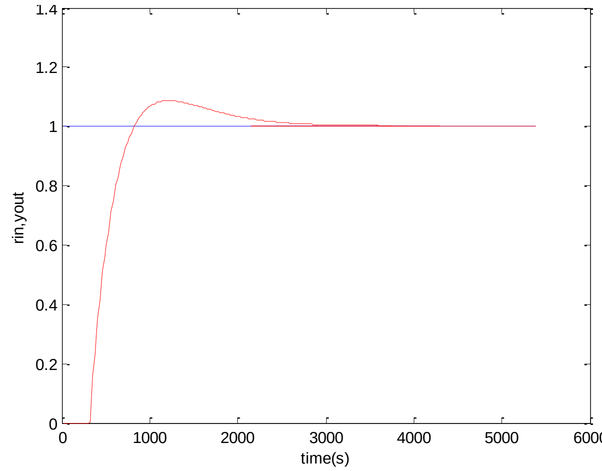

Figure 9. The simulation result with the proposed controller

From the simulation results we can see that the proposed gain-scheduling based Smith-PID network controller shows better control performance than normal Smith-PID controller, which demonstrates the effectiveness of the proposed method.

V. CONCLUSIONS

The result curves of the simulation show that the normal Smith-PID controller can not adapt the varying of the time delay very well. Its control effect to the networked control system is not very satisfied. The Smith-PID scheduling network controller proposed in this paper can adjust the parameters of the PID controller on time with the varying of the time delay. So, it can fit the varying of the time delay better. Because the parameters of the PID controller are the best in every period, the anti-interference ability of the system is very strong too. The input-output curve of the system with Smith-PID scheduling network controller shows that the Smith-PID scheduling network controller can obtain satisfied control effect.

In future work, we will consider the stability analysis of the considered NCSs during the controller design stage. Moreover, we will also extend the results to the case where full state measurement is not available.

ACKNOWLEDGMENT

The authors would like to thank the editor and the anonymous reviewers for their valuable comments and suggestions to improve the quality of the paper. This work was supported by the National Science Foundation of China under Grants 61004021.

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