Load Minimization Design for Dual-rate Internet-based Control Systems

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Abstract: This paper presents a design method for Internet-based control systems in a dual-rate configuration to achieve load minimization and dynamic performance specifications. It avoids the complexity of large scale system design by focusing on individual control systems. In the dual-rate configuration, the plant under control is first stabilized by a local controller with a high sampling rate. The remote PID controller, which regulates the output according to the desirable reference, adopts a low sampling rate to reduce load on the network. The upper bound of the remote PID controller's sampling time which meets the requirement on control performance is derived and a simple tuning method for the remote PID controller is presented. Simulation and real-time examples are provided for illustration.

1. INTRODUCTION

Internet-based control systems use the Internet for remote control and monitoring of plants. They are easy-to-access and not limited to any geographical location. Internet-based control systems have found their applications in many areas, such as telerobots, manufacturing industry, and virtual laboratories, see T.C. Yang [2006], A. Srivastava et al. [2003]. In 2001 Oboe developed a telerobotics system which allows the Internet users to command a robot in real time with both visual and force feedback, R. Oboe [2001]. At Integrated Manufacturing Lab of UC Berkeley, a World-Wide-Web design to fabrication tool called Cyber cut was developed, see H. Sung et al. [2001]. To facilitate engineering education, many universities have started virtual laboratories for their students to perform experiments outside their campus, see G.P. Liu et al. [2007], J.W. Overstreet et al. [1999], S.H. Yang et al. [2002]. As the Internet technology develops and matures, Internet-based control systems are expected to be more popular in the future.

Many researchers have been working on Internet-based control systems during the past few years. Because random time delays caused by the Internet undermine the stability of the closed-loop control systems, intensive research was done on stability analysis and methods to tackle instability and uncertainty. Many control methodologies were proposed in the time-triggered control literature as well, see Y. Tipsuwan et al. [2003], Z.H. Guan et al. [2006]. However, due to the difficult nature of the delay and jitter, few encouraging and simple result has found so far. Adopting a different approach to solve the stability issue is necessary.

Considering the Internet-based control systems with limited computation and communication capacities, the event-based control systems, see A. Cervin et al. [2007] has been suggested as an alternative to time-triggered control systems. Research literature in this area covers many topics, including reducing process state variance and control action frequency by defining minimum inter-event time, see E. Johannesson et al. [2007], evaluating and reducing the jitter in the control systems, see M. Lluesma Camps et al. [2006], G. Buttazzo et al. [2007], and implementing computer tools to improve the control performance, see A. Cervin et al. [2006].

Parallelly, research has also been done on how the sampling time selection affects the control performance in time-triggered control systems, see J.Y. Yu et al. [2004], F.L. Lian et al. [2002]. It is found that when the sampling time becomes smaller in a distributed networked control system, although the performance improves in the beginning, it deteriorates eventually. That is because a small sampling time also means a heavy load on the network, which would cause long time delays or data transfer failures. Nevertheless, nobody has worked out how the control performance is affected by the sampling time. In other words, the question about what values the sampling time should take given a specific requirement on the control performance remains open.

Furthermore, although most of the design methods proposed so far ensure system stability, they are unable to meet certain requirements on control performance, such as overshoot and settling time of step response. To meet the control performance requirements of networked control systems is constrained by the limit of load on the Internet. The load on the Internet, represented by the sampling time of the control system, should be kept as small as possible; in other words, the sampling time of the remote controller should be kept as big as possible. Therefore, there is a need to work out a way which meets the control performance requirements subject to load minimization on the Internet.

This paper proposes such a load minimization design method for the Internet-based control systems with dynamic performance specifications. It resolves the stability problems with a dual-rate configuration. As illustrated in Figure 1, the dual-rate control system, see L. Yang et al. [2007], is a two-level control architecture, the lower level of which guarantees that the plant is under control even when the network communication is lost for along time. The higher level of the control architecture implements the global control function. The two levels run at different sampling times. The lower level runs at a small sampling time(higher frequency) to stabilize the plant, while the higher level at a big sampling time (lower frequency) to reduce the communication load and increase the possibility of receiving data on time. With the local system stable and the inputs of the remote controller bounded, the overall control system would remain stable. The PID controller is used for the remote control loop for simplicity and ease of tuning. The requirements on control performances, such as overshoot and settling time of step response, are represented a pair of conjugate poles. With the dominant pole placement method we work out the upper bounds of the remote control system's sampling time and design the remote PID controller. The novelty of this paper is focused on guaranteeing both control performance and stability of Internet-based control systems and minimizing the data transmission load over the Internet simultaneously by maximizing the remote controller sampling time.

2. PROBLEM FORMULATION

Consider an Internet-based control system as shown in Figure 1. It is a discrete-time control system by nature. The dual-rate scheme is used here, which basically means the local control loop has a smaller sampling time than the remote loop. The local controller stabilizes the plant and also meets the performance requirements on the local control system. The PID controller, located over the other side of the Internet, remotely regulates the output according to the desired reference. The control input from the remote controller comes to the local control system via the Internet. The feedback signal from the local control system is sent to the remote controller through the Internet.

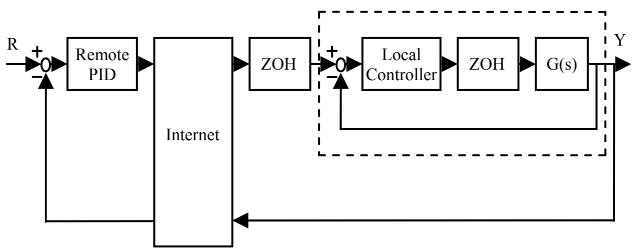

Fig. 1. Control Scheme

The transmission via the Internet brings time delay inevitably. Suppose the time delay of feedback via the Internet is T_b and time delay of feedforward is T_f . We can replace the Internet block with two blocks of time delays, e^{-T_b} and e^{-T_f} . Both T_b and T_f are random variables, which is considered as the prime cause of instability and difficulty in control. However, in reality, the ranges of the time delays are approximately known. It means

$$0 < T_b \le \overline{T_b}, 0 < T_f \le \overline{T_f}$$

Where, $\overline{T_b}$ and $\overline{T_f}$ are upper bounds for the time delay of feedback and feedforward respectively.

To assess the performance of a discrete-time system is difficult since there is no handy formula or method which could be used. We need to transform the original discrete-time system into continuous-time through some approximations so that the second-order model and dominant pole placement method can be used.

Denote the sampling time of the local loop by T_l and that of the remote loop by T_r . Approximate the Zero-Order-Hold as a time delay of half the sampling time, and transform the Internet-based control system into a conventional continuous-time system. The two ZOHs shown in Figure 1 are essentially another two blocks of time delays, $e^{-0.5T_l}$ and $e^{-0.5T_r}$. For the sake of simplicity, the continuous-time block diagram is redrawn in Figure 2.

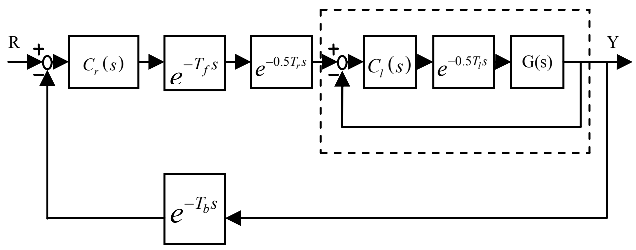

Fig. 2. Block Diagram

The remote sampling time is used as a measurement of load on the Internet. Load minimization for the Internet is to maximize the remote sampling time. The overshoot and settling time of step response are chosen as the index of dynamic performance. Our problem at hand is to design the local controller and remote PID controller so as to minimize the load on the Internet subject to these dynamic performance specifications.

3. PROPOSED METHOD

As the type of controller to use for a given plant in the local control system is not limited and a fast sampling time is possible, there are many methods to design the local controller. Throughout this paper, the plant would not be studied directly for simplicity. It is assumed that the local control system is already stable and fulfils the control specifications. The model of the local control system can be obtained from the step response method, or model reduction methods like the one presented in M. Liu et al. [2007]. Thereby, we have a new and simpler block diagram as shown in Figure 3, in which $G_l(s)$ is the transfer function of the local control system. From the dead time, overshoot, and settling time of the step response, the local system is modelled as first or second order with time delay. If the step response of $G_l(s)$ has certain overshoot, it is approximated as a second-order transfer function:

$$G_l(s) = \frac{1}{as^2 + bs + c} e^{-sL}$$

If there is no overshoot, it would be approximated as first-order:

$$G_l(s) = \frac{1}{Ts + 1} e^{-sL}$$

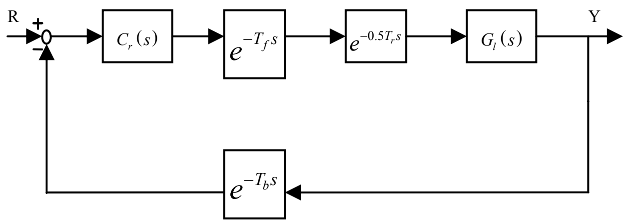

Fig. 3. Simplified Block Diagram

We use the method presented in Q.G. Wang et al. [1999] in tuning of the remote PID or PI controller. The reason is that it cancels out the denominator of $G_l(s)$ with the nominator of $C_r(s)$ and transfers our problem to a simple one-variable one. Write the transfer function of $C_r(s)$ as

$$C_r(s) = k\frac{as^2 + bs + c}{s} \tag{1}$$

if $G_l(s)$ is second-order, or

$$C_r(s) = k\frac{Ts + 1}{s} \tag{2}$$

if $G_l(s)$ is first-order. In both cases the open-loop transfer function becomes

$$Q(s) = G_l(s)C_r(s)e^{-(T_f + T_b + 0.5T_r)s} = \frac{k}{s}e^{-(T_f + T_b + L + 0.5T_r)s}$$

The only variable left to determine for the controller is k. k affects both the stability and performance of the closed-loop system.

Firstly it is necessary to study the stability of the overall closed-loop transfer function with respect to k. An equivalent case is found when a pure integral process with time delay is controlled by a simple P controller. That has been studied in X. Lu [2007] and the stabilizing range of k is found to be

$$0 < k < \frac{\pi}{2(T_f + T_b + L + 0.5T_r)} \tag{3}$$

We use the method of dominant pole placement to find a suitable k. Suppose the requirements on the overshoot and settling time of step response are represented by a pair of the poles, $p_{1,2} = -\omega\zeta \pm j\omega\sqrt{1-\zeta^2}$, where ζ is the closed-loop damping ratio. Substituting them into the closed-loop characteristic equation

$$1 + Q(p_1) = 0$$

gives

$$k = \omega e^{-\omega\zeta(T_f + T_b + L + 0.5T_r)} \tag{4}$$

Where $\omega = \dfrac{\cos^{-1}\zeta}{\sqrt{1-\zeta^2}(T_f + T_b + L + 0.5T_r)}$ Suppose these two poles, $p_{1,2} = -\omega\zeta \pm j\omega\sqrt{1-\zeta^2}$, are dominant, the settling time of step response can be roughly represented as K.J. Astrom et al. [1995],

$$t_s \approx \frac{4}{\omega\zeta} + (T_f + L + 0.5T_r)$$

With the value of ω in (4) the above equation becomes,

$$t_s \approx \frac{4\sqrt{1-\zeta^2}(T_f + T_b + L + 0.5T_r)}{\zeta\cos^{-1}\zeta} + (T_f + L + 0.5T_r)$$

Given a performance requirement on settling time,

$$t_s \le \overline{t_s}$$

where $\overline{t_s}$ is the largest allowable settling time. The range of T_r should be

$$T_r \le \frac{\overline{t_s} - \dfrac{4\sqrt{1-\zeta^2}}{\zeta\cos^{-1}\zeta}(T_f + T_b + L) - T_f - L}{\dfrac{2\sqrt{1-\zeta^2}}{\zeta\cos^{-1}\zeta} + 0.5} \tag{5}$$

Because T_f and T_b are random with certain ranges and it is impossible to find the exact value, the most conservative upper bounds of T_f and T_b, denoted as $\overline{T_f}$ and $\overline{T_b}$ respectively, are chosen to recalculate the range of k ensuring stability, so (3) becomes

$$0 < k < \frac{\pi}{2(\overline{T_f} + \overline{T_b} + L + 0.5T_r)} \tag{6}$$

Applying the upper bounds of T_f and T_b into (4) gives

$$k = \omega e^{-\omega\zeta\left(\overline{T_f}+\overline{T_b}+L+0.5T_r\right)} \quad (7)$$

where $\omega = \dfrac{\cos^{-1}\zeta}{\sqrt{1-\zeta^2}\left(T_f + T_b + L + 0.5T_r\right)}$. And (5) becomes

$$T_r \le \frac{\overline{t_s} - \dfrac{4\sqrt{1-\zeta^2}}{\zeta\cos^{-1}\zeta}\left(\overline{T_f}+\overline{T_b}+L\right) - \overline{T_f} - L}{\dfrac{2\sqrt{1-\zeta^2}}{\zeta\cos^{-1}\zeta} + 0.5} \quad (8)$$

Experiences show that satisfactory responses are obtained if closed-loop poles of damping ratio $\zeta = 0.7071$ are chosen. By (8) the range of T_r becomes

$$T_r \le \frac{\overline{t_s} - 5.1\overline{T_b} - 6.1\overline{T_f} - 6.1L}{3.05} \quad (9)$$

And substituting $\zeta = 0.7071$ into (7) yields

$$k = \frac{0.5}{\overline{T_f} + \overline{T_b} + L + 0.5T_r} \quad (10)$$

Since this value is within the range provided by (6), the resulted system is stable. The largest allowable T_r based on (9) is taken to calculate k in (10) and design the remote PID controller.

4. SIMULATION EXAMPLE

Let us look at an example and demonstrate the use of our proposed method. Consider the local system $G_l(s)$ and use the step response method to determine its transfer function. It has a step response with a dead time 2 seconds, overshoot 10% and settling time 7 seconds. The transfer function is approximated as

$$G_l(s) = \frac{1}{0.546s^2 + 0.8737s + 1}e^{-2s}$$

Suppose the largest possible time delay caused by the Internet is 1 second, which means $\overline{T_b} = \overline{T_f} = 0.5$.

By (1) the remote PID controller is

$$C_r(s) = k\frac{0.546s^2 + 0.8737s + 1}{s}$$

The next step is to determine k according to the largest allowable settling time. If the largest allowable settling time is 30 seconds, according to (9) the range of the sampling time should be

$$T_r \le 4$$

When the sampling time is taken to be 2 seconds and 6 seconds respectively, and k is calculated based on (10), so the controller is designed as

$$C_r(s) = \begin{cases} \dfrac{0.0683s^2 + 0.1092s + 0.125}{s}, (k_{(a)} = 0.125) \\ \dfrac{0.0453s^2 + 0.0725s + 0.083}{s}, (k_{(b)} = 0.083) \end{cases}$$

Likewise, when $\overline{T_b} = \overline{T_f} = 1$, according to (9), the range of the sampling time should be

$$T_r \le 2.23$$

When T_r is set to be 2 seconds and 6 seconds respectively, based on (10) , the controller should be designed as

$$C_r(s) = \begin{cases} \dfrac{0.0546s^2 + 0.0874s + 0.1}{s}, (k_{(c)} = 0.1) \\ \dfrac{0.039s^2 + 0.0624s + 0.0714}{s}, (k_{(d)} = 0.0714) \end{cases}$$

The step responses of these four circumstances are shown in Figure 4. The obtained settling times are smaller than 30 seconds and the responses are satisfactory when T_r are smaller than the thresholds.

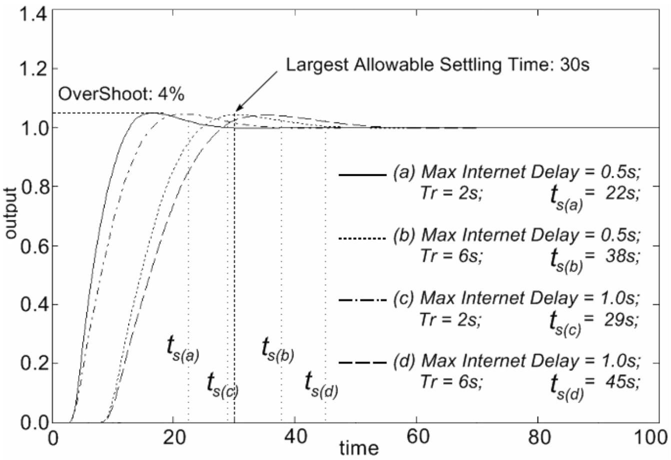

Fig. 4. Step Response in Simulation

5. REAL-TIME IMPLEMENTATION

In order to show the applicability and effectiveness of the proposed method, read-time experiments have been carried out on a real-time Process Control Unit (PCU) in the Network and Control Laboratory at Loughborough University, UK. Figure 5 shows the layout of the experimental system, which includes the PCU and the remote control system. Inside the PCU, there are the local control system and a water tank rig. The water tank rig consists of a process tank, sump, pump, cooler and several drain valves. Based on the measurements of the liquid level of the water tank and flow rate of the pump, the objective is to control the liquid level or the inlet flow rate of the water tank by regulating the flow rate of the pump. The local controller parameters and sampling interval are chosen by the local operator through an operation interface. The remote control system is connected to the PCU via the Internet. More details on this experimental system can be found in S.H. Yang et al. [2007]. We have conducted a flow rate control experiment.

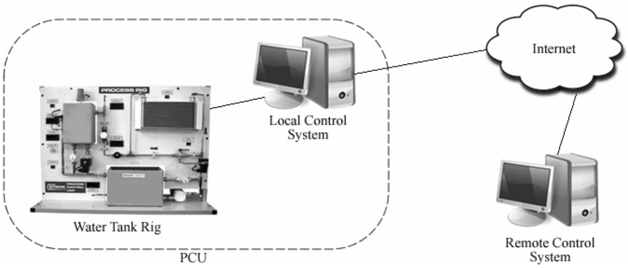

Fig. 5. Experimental System Layout

The first step is to get the model of the local control system using the step response method. A step change in the setpoint of the flow rate has been introduced into the local flow rate control system. The step response is with 14.9% overshoot and 9.9 seconds settling time. The dead time is 0.5 second in average. Therefore, the local close-loop control system is modelled as a second-order object with a transfer function:

$$G_l(s) = \frac{1}{2.922s^2 + 1.771s + 1} e^{-0.5s}$$

The largest possible time delay caused by the Internet between the local and remote controllers is 0.5 second, which means

$$\overline{T_b} = \overline{T_f} = 0.5$$

By (1) the remote PID controller is

$$C_r(s) = k \frac{2.922s^2 + 1.771s + 1}{s}$$

If the largest allowable settling time is set as 15 seconds, when the dead time is L=0.5, the range of the remote sampling time according to (9) should be

$$T_r \le 2.082$$

When the remote sampling time is taken to be 2.082 seconds, the largest value in order to minimize the data transmission load, and k is calculated based on (10)

$$k = 0.197$$

The remote flow rate controller is designed as

$$C_r(s) = 0.348 + \frac{0.197}{s} + 0.576$$

A step response of the remote controller has overshoot 12% and 11.4 seconds settling time as shown in Figure 6. The unit of the flow rate is litre per minute (L/min). The performance is satisfactory.

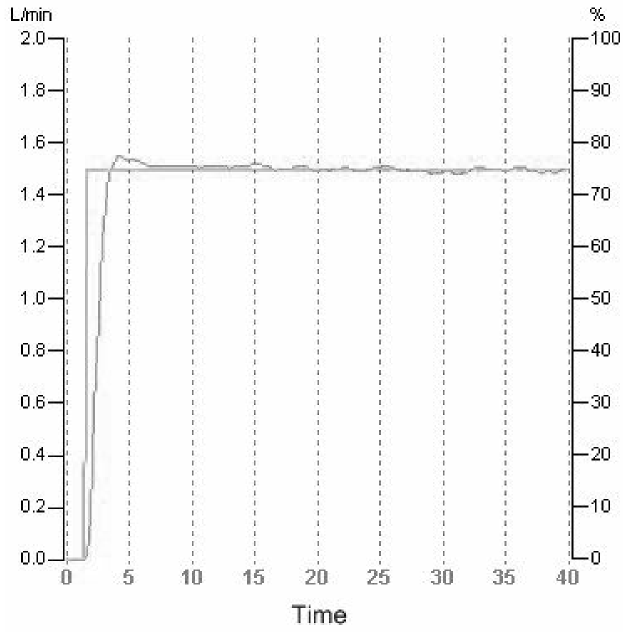

Fig. 6. Step response of the remote flow rate controller when $Tr = 1s$.

If the remote sampling time is taken to be 4 seconds, which is out of the range of (0, 2.082], then k is calculated based on

$$k = 0.143$$

The remote flow rate controller is designed as

$$C_r(s) = 0.253 + \frac{0.143}{s} + 0.418$$

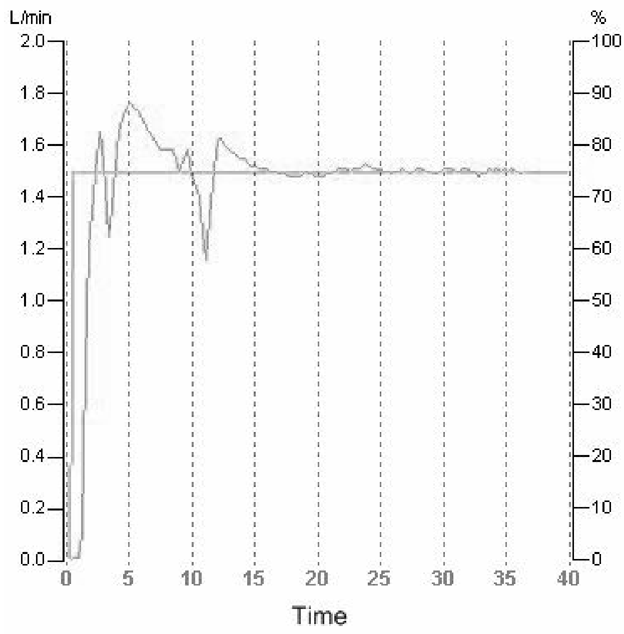

Fig. 7. Step response of the remote flow rate controller when $Tr = 4s$.

A step response of the remote controller has overshoot 14% and 15.2 seconds settling time as shown in Figure 7. The performance is unsatisfactory as the settling time is great than the desirable value 15 seconds.

6. CONCLUSIONS

In this paper a method to meet performance requirements and minimize load on the network for Internet-based control systems is presented. The relationship between the sampling time and settling time of the system step response is worked out. The remote PID controller is tuned to fulfil the requirement on the settling time of step response and maximize the sampling time. Good responses in simulation examples and real-time implementation are obtained.

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