MULTI-RATE CONTROL IN INTERNET BASED CONTROL SYSTEMS

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Abstract

One of the major challenges in Internet based control systems is how to overcome the Internet transmission delay. In this paper we investigate the potential of using the multi-rate control scheme to overcome the Internet transmission delay. Only the feedback transmission delay is considered in the paper under the assumption that the feed-forward channel obtains the high bandwidth in the Asymmetrical Digital Subscriber Lines (ADSL). A two level hierarchy is used for the Internet-based control systems. At the lower level a local controller is implemented to control the plant at a higher frequency. At the higher level a remote controller is employed to remotely regulate the desirable setpoint at a lower frequency for the local controller. A compensator located at the feedback channel is designed for the remote controller at the higher level. The simulation results illustrate that the multi-rate control scheme has the potential to overcome the Internet time delay.

1 Introduction

The Internet based control systems constitute a new class of control systems including specific problems such as Internet time delay, loss of information and data, security and safety. Figure 1 shows a two channel delay closed-loop networked control system. The sensor, actuator and plant are assumed to be remotely commissioned by a controller that interchange measurements and control signals through a communication network. If the communication network is the Internet it is called Internet-based control system.

When time delay and data loss occur in the network the network switch is open. During this period, the plant is controlled by the open loop, and all the measurements were generated by the plant model. When the network communication is recovered the network switch is closed. The plant is controlled by the closed loop. The problem is that the plant model must be able to accurately describe the behaviour of the plant, otherwise the open loop control will never work for a long period.

Our approach incorporates a two level control architecture, the lower level of which guarantees the plant being under control even the network communication is lost for a long time. The higher level of the control architecture implements the global control function. The two levels are running at different frequencies. The lower level is running at a higher frequency to stabilize the plant, the higher level at a lower frequency to reduce the communication load and increase the possibility of receiving data on time. The delayed data is compensated once the transmission is recovered.
This paper is organised as follows: in Section 2 the two level control architecture is described. Section 3 discusses the single-rate scheme in which the lower level and higher level control loops are running in a same rate. Section 4 extends the system into the multi-rate scheme, in which the lower level control loop is running at a higher frequency and the higher level control loop at a lower frequency. The compensation of the feedback delay is presented in Section 5. Simulation results are given in Section 6. Conclusions are presented in Section 7.

2 Two Level Hierarchy In Process Control

Any plantwide process control system involves four levels of control. From bottom to up the four levels are process protection level, basic regulatory control level, advanced control level, and overall plant optimisation level. Our recent work [7] introduced the Internet as an extra level and suggested the Internet can be connected to any level according to the control requirements. If the Internet is connected with the regulatory control level and the advanced control level is located at the remote side to cooperate with other plants the control system will have a two level hierarchy as shown in Figure 3, in which one controller located in the local side, another in the remote side, and linked through the Internet. Usually the controller in the local side is responsible for the regulation of the normal situations. Once the performance of the controller is degraded due to the disturbance from the environment or the change of the production situation, the controller in the remote side is put in use for tuning the parameters and/or changing the desired input for the controller in the local side. This two level control structure has been widely used in robotic tele-operation [8], which uses the controller in the local side to control the slave device, and uses the one in the remote side to control the master device.

Figure 4 illustrates the control structure for this scenario. $T_{\text{local}}$ and $T_{\text{remote}}$ are the sampling intervals for the local controller and the remote controller respectively. The transmission delay at the feedback channel referees to the Internet time delay, which is denoted as the random access time in the SC link.

The Internet time delay exists at both the feed-forward and feedback channels for the symmetrical communication. In order to simplify the scenario studied here we only investigate the Asymmetrical Digital Subscriber Lines (ADSL) communication where the feed-forward channel obtains the high bandwidth, therefore the Internet time delay only exists at the feedback channel. This scenario is also denoted as the access time in the controller-actuator (CA) link being zero and the one in the sensor-controller (SC) link being random.

Uncertain transmission time delay and data loss problems are not avoidable for any Internet-based application. The reasons why the variable time delay occurs are as follows [3]:

- Network traffic changes all the time because multiple users share the same computer network.
- Routes or paths of data transmission decided by Internet Protocol (IP) are not certain. Data is delivered through different paths, gateways, and networks whose distances vary.
- Large data is separated into smaller units such as packets. Moreover, data may also be compressed and extracted before sending and after receiving.
- Using TCP/IP protocols, when error in data transmission occurs, data will be retransmitted until the correct data is received.

3 Single-rate Control Scheme

The single-rate control scheme normally assumes that there is no time skew between the sensor data sampling instant, the control calculation instant, and the control application instant [2]. For the control structure shown in Figure 4 a single sampling interval $T_s$ is chosen.
\[ T_{\text{local}} = T_{\text{remote}} = T_s \]  

A: the instant at which the sensor sends data to the controllers;  
B: the instant at which the local controller receives the data;  
C: the instant at which the remote controller receives the data;  
D: the instant at which the control action is calculated and sent out by both the controllers.

Figure 5: Time scheme for single-rate control

Figure 5 shows a time scheme for the single-rate control system. \( T_{\text{delay}} \) is the Internet transmission delay. As can be observed in Figure 5, if \( T_{\text{delay}} \) is greater than the sampling interval, the remote controller can’t calculate the control action based on the current measurement; if \( T_{\text{delay}} \) is less than the sampling interval, the latest measurement is not used until the next control instant. To avoid the influence of the Internet transmission delay on the control performance, the sampling interval should be greater than the delay time.

\[ T_{\text{delay}} < T_s \]  

Obviously, the greater this delay is, the lower control frequency will be used. This can be a serious problem for those process and dynamic specifications which need high frequencies. In the next section we investigate multi-rate control scheme.

4 Multi-rate Control Scheme

As described in Equation 2, in order to avoid the loss of data, the sampling interval has to be greater than the delay time even in the worst case for the single-rate control scheme. This involves a low control frequency, which will degrade the control performance. In this section we discuss that the local and remote controllers are running at different frequencies. The local controller at the lower level in the hierarchy is running at a higher frequency to stabilize the plant, the remote controller at the higher level at a lower frequency to reduce the communication load and increase the possibility of receiving data on time. We denoted the local controller as the fast controller and the remote controller as the slow controller. The structure of a dual-rate control is illustrated in Figure 6. The two sampling intervals for the fast and slow controllers are chosen as:

\[ T_{\text{remote}} = nT_{\text{local}} \]
\[ n \in \{2,3,4,...\} \]

There are two cases which are involved in the dual-rate control scheme.

Case 1: \( T_{\text{delay}} < T_{\text{remote}} \)

The time scheme of the case 1 is illustrated in Figure 7. Because the transmission delay \( T_{\text{delay}} \) is less than the control period of the slow controller \( T_{\text{remote}} \) there is no data loss during each sampling interval. Therefore the transmission delay has no influence on the slow controller.

Case 2: \( T_{\text{delay}} \geq T_{\text{remote}} \)

A: the instant at which the sensor sends data to the controllers;  
B: the instant at which the fast controller receives the data;  
C: the instant at which the fast controller sent out the control action;  
D: the instant at which the slow controller receives the data;  
E: the instant at which the control action is calculated and sent out by the slow controller.

Figure 7: Time scheme of dual-rate control with the transmission delay less than the sampling interval

Figure 6: Dual-rate control loop

As described in Equation 2, in order to avoid the loss of data, the sampling interval has to be greater than the delay time even in the worst case for the single-rate control scheme. This involves a low control frequency, which will degrade the
B: the instant at which the fast controller receives the data;
C: the instant at which the fast controller sent out the control action;
D: the instant at which the slow controller receives the data;
E: the instant at which the control action is calculated by and sent out from the slow controller.

Figure 8: Time scheme of dual-rate control with the transmission delay greater than the sampling interval

The time scheme of the case 2 is illustrated in Figure 8. Since the transmission delay is greater than the sampling interval the sample will be delayed to arrive at the slow controller after the next control instant A compensator must be employed in this case, which is designed in the following section.

5 Compensation For Feedback Delay

The Dynamic Matrix Controller (DMC), which is widely accepted in the industries, is used in this study. Supposed the fast controlled closed loop is described in the step response model as follows:

\[ y(t) = \sum_{i=1}^{\infty} g_i \Delta u(t-i) \]  

where \( y \) is the process output variable; \( \Delta u \) is the increment of the control action; \( g_i \) is the coefficient of the step response; \( t \) is the current time instant. The DMC general control law can be given as [1]:

\[ u = (G^T G + \lambda I)^{-1} G^T (w - f) \]  

in which \( \lambda \) is the penalization factor for the control costs; \( I \) is the unit matrix; the superscript \( T \) means the transfer of the vector; \( G \) is the system dynamic matrix.

The element of the reference trajectory vector \( w \) is computed as:

\[ w(t) = y_m(t), \quad w(t+k) = \alpha w(t+k-1) + (1-\alpha)r(t+k) \]  

where \( y_m(t) \) is the process output variable; \( \alpha \) is a parameter between 0 and 1; \( r(t+k) \) is the set-point of the controller; \( N \) is the process horizon.

The time delay occurring in the feedback transmission channel causes the DMC controller in the remote site being not able to receive the feedback signal \( y_m(t) \) on time. Once the time delay occurs \( y_m(t) \) in the equations (8) and (9) will be replaced with the predictive value \( \hat{y}(t) \) obtained from the step response model in the equation (1). The latest measurement value of the process output, denoted as \( y_m(t-l) \), and the corresponding predictive value, denoted as \( \hat{y}(t-l \mid t-l \} \), are used to correct the predictive value \( \hat{y}(t) \) as follows.

\[ f(t+k) = \hat{y}(t \mid t) + \beta (y_m(t-l) - \hat{y}(t-l \mid t-l)) \]  

\[ + \sum_{i=1}^{N} (g_{k+i} - g_i) \Delta u(t-i) \]  

\[ w(t) = \hat{y}(t \mid t) + y_m(t-l) - \hat{y}(t-l \mid t-l) \]  

\[ w(t+k) = \alpha w(t+k-1) + (1-\alpha)r(t+k) \]  

\[ k = 1, ..., N \]

\( \beta \) is an adjustable parameter between 0 and 1; \( y_m(t-l) \) is the latest measurement value.

6 Simulation Results

Simulation has been carried out for single-rate and dual-rate control schemes. The process is represented as a discrete transfer function \( 0.3/(z-1) \). The fast controller is designed as a PID controller with the parameters \( K_p=5 \), \( K_i=1.2 \), \( K_o=0.001 \). The slow controller is designed using the control law shown in the equations (7) and (10) with the parameters \( N=12, \lambda=0.8, \alpha=0.5, \beta=1 \). The sampling intervals of the two controllers \( T_{local} \) and \( T_{remote} \) are chosen as 1 or 10 for different situations.

Figure 9 illustrates the response to the remote set-point change for the single-rate control scheme with a constant transmission delay \( T_{delay}=5 \). The sampling interval \( T_s \) is 1 and 10 for respectively. A quite big delay has been shown in the response if taking a lower control frequency. Obviously the greater the control interval is, the poor the control performance will be.

Figure 10 shows the simulation result for the dual-rate control scheme with a lager constant transmission delay \( T_{delay}=18 \), and two sampling intervals \( T_{local}=1 \), and \( T_{remote}=10 \). The setpoint is compared with the responses with and without compensations. If no compensation is implemented the delayed feedback is directly used as a current measurement of the process output. Obvious delay in the response has been illustrated. If compensation is used, the predictive output based on the process model is used as the current measurement. Concerning the mismatch between the process model and the actual process the available delayed feedback and the predictive output at that delayed instant are used to correct the predictive output at the current instant. The simulation result shown in Figure 10 clearly presents that the compensation has reduced the delay in the response and the dynamic performance is much better than the one without the compensation.

7 Conclusions

The majority of the existing solutions of overcoming the Internet transmission delay in Internet based control systems adopt the model based output feedback control approaches. In this paper we have investigated the potential of using the
multi-rate control scheme to overcome the Internet transmission delay. A two level control hierarchy is used here, the fast controller is located at the lower level, and the slow controller at the higher level. Only the transmission delay at the feedback channel is considered in this study. Starting from the single-rate control scheme, the time scheme has been investigated. The delay time must be less than the sampling interval, otherwise the control frequency might not be big enough to satisfy the need of the processes with the fast dynamic specifications. In the dual-rate control scheme the remote controller is running at a lower frequency to reduce the data loss and the Internet transmission load, and the local controller is running at a higher frequency to stabilise the process. If the Internet transmission delay is less than the sampling interval for the slow controller there will be no data loss; otherwise compensation is required. The predictive measurement of the process output with the correction based on the available delayed measurement is used as the current measurement once the delay is greater than the sampling interval. Our simulation results have illustrated all the above findings and show that the multi-rate control scheme has potential to overcome the Internet time delay.

Figure 9: Single-rate control with $T_s=1$ and $T_s=10$

Figure 10: Dual-rate control with and without feedback delay compensation

References