Multirate 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 multirate control scheme and the time-delay compensation to overcome the Internet transmission delay. 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 set-point at a lower frequency for the local controller. A compensator located at the feedback channel is designed to overcome the time delay occurring in the transmission from the local site to a remote site. Another compensator in the feedforward channel is designed to compensate the time-delay occurring in the control action transmission. The simulation and experimental application results illustrate that the multirate control scheme with the time delay compensation offers a promising way to efficiently reduce the effect of Internet time delay on control performance.**

***Index Terms*—Compensation, delay systems, Internet, predictive control, process control.**

I. Introduction

THE internet-based control system is a new concept, which has recently received much attention [1]–[5]. This new type of control system allows remote monitoring and control of process plants over the Internet. With the ubiquitous nature of the Internet, benefits can be achieved by retrieving data and reacting to plant fluctuations from anywhere around the world at any time. The objective of establishing an Internet-based control system is to enhance rather than to replace an ordinary computer-based control system by adding an extra Internet level to the control system. A block diagram of an Internet-based control system is shown in Fig. 1. Advantages include the following:

1) global access to the monitoring and control functionality;
2) use of zero cost software (standard web browsers) on the client site to access information;
3) allowing collaboration among skilled plant managers situated in geographically diverse locations.

There are a number of new features in the design of Internet-based control systems, such as requirement specification, architecture design, interface design, and safety and security analysis. The problem studied in this paper concerns time-delay overcoming. A rich literature [7]–[11] exists in this area.

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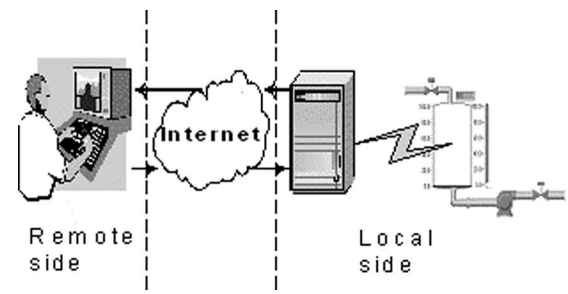

Fig. 1. Block diagram of an Internet-based control system [6].

The majority of them [7], [8] adopt the model-based output feedback control approaches. Some of them [10], [11] focus on how to design a model-based time-delay compensator or a state observer to reduce the effect of transmission time delay. These approaches hold a process model in the remote site to approximate the plant behavior during the time periods when the time delay or data package loss causes sensor data being not available. The process model is incorporated in the controller and might be updated regularly. When time delay and data loss occur in data transmission, the plant is controlled in an open loop, and all the measurements are generated by the plant model. When the network communication is recovered, the plant is controlled by a closed loop. The difficulty is that the plant model must be able to accurately describe the behavior of the plant; otherwise, the open loop control will never work for a long period. It is somewhat unreasonable to model the Internet time delay for accurate prediction at every instant.

The approach proposed here incorporates 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 a long time. The higher level of the control architecture implements the global control function. The two levels run at different frequencies. The lower level runs at a higher frequency to stabilize the plant, while 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 organized as follows. In Section II, the two-level control architecture is described. Section III discusses the multirate control scheme, where the lower level control loop runs at a higher frequency and the higher level control loop at a lower frequency. The compensation of feedback and feedforward delay is presented in Section IV. Simulation and experimental results are given in Sections V and VI. The conclusion is presented in Section VII.

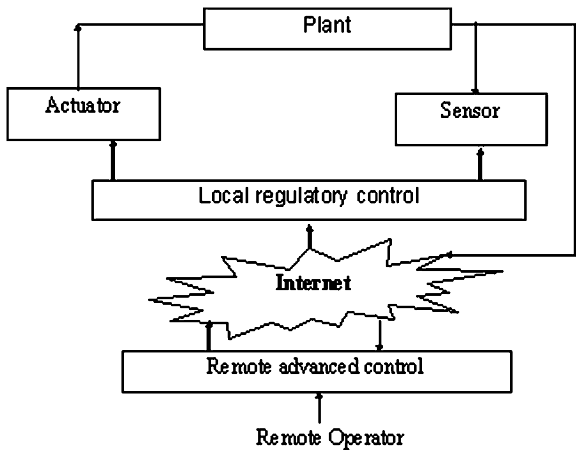

Fig. 2. Two-level hierarchy of process control.

II. Two-Level Hierarchy in Process Control

Any plantwide process control system involves four levels of control. The four levels are, from bottom to top, process protection level, basic regulatory control level, advanced control level, and overall plant optimization level. Our recent work [6] introduced the Internet as an extra level and suggested that 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 site to cooperate with other plants, the control system will have a two-level hierarchy, as shown in Fig. 2, where one controller is located at the local site and another at the remote site, which are linked through the Internet. Usually, the controller at the local site is responsible for the regulation of normal situations. Once the performance of the controller is degraded due to disturbance from the environment or change of the production situation, the controller at the remote site is put in use for tuning the parameters and/or changing the desired input for the controller at the local site. This two-level control structure originally derives from the robotic teleoperation [12]–[14], in which one controller controls a slave device at the local site and another controls the master device at the remote site. The slave device may be a mathematical model or a simple physical model of the master device. These two controllers work independently and irregularly exchange control commands. One of the obvious advantages of using the two-level hierarchy in Internet-based control over the single level one, which most of the existing networked control systems use, is that in case the network communication collapses for a period of time the plant is still under control through the local regulatory control system. The advantages over the robotic teleoperation is that the local and the remote controllers in the two-level control structure closely work together to achieve an agreed control objective.

As described in the Introduction, Internet time delay is one of the major obstacles in bringing Internet-based process control systems into a reality. It can destabilize the control system. Luo and Chen [13] have repeatedly tested the transmission efficiency of the Internet by sending 64-byte data each time from their Web server to different remote Web servers. The resulting statistics of the experiments show that the Internet contains a serious and uncertain time-delay problem. A block diagram of the Internet-based control system is shown in Fig. 1. The total time for performing an operation (a control action) per cycle consists of four parts.

1) $T_{\mathrm{delay\_re}}$. Time delay for making control decision by a remote operator.
2) $T_{\mathrm{delay\_ff}}$. Time delay for transmitting a control command from the remote operator to the local system (the Web server).
3) $T_{\mathrm{delay\_lo}}$. Execution time of the local system to perform the control action.
4) $T_{\mathrm{delay\_fb}}$. Time delay for transmitting the control information from the local system to the remote operator.

When the control system is in an automatic mode, the time delay for making a control decision by a remote operator $T_{\mathrm{delay\_re}}$ does not need to be considered. The execution time of the local system to perform the control action $T_{\mathrm{delay\_lo}}$ can also be excluded from consideration because it was inherited from the local system and can be overcome in a traditional way. Therefore, if those feed-forward and feedback time delays, $T_{\mathrm{delay\_ff}}$ and $T_{\mathrm{delay\_fb}}$, that appear in the information transmission over the Internet are always constants, then the Internet-based control has a constant transmission time delay. Unfortunately, as shown in [13], this is not the case. The Internet time delays, i.e., $T_{\mathrm{delay\_ff}}$ and $T_{\mathrm{delay\_fb}}$, increase with distance, and also depend on the number of nodes traversed and the Internet load [14]. The reasons for the occurance of variable time delays are as follows.

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

The network communication delay means that remote operators can no longer rely on their reflexes to detect and correct problems that happen to the controlled object. In the aeronautical and space industries such as the National Aeronantics and Space Administration, intelligent autonomy control, which follows the principle of the two-level hierarchy, as shown in Fig. 2, has been widely employed [15]. The sufficient intelligence of the local control system enables it to react to problems immediately by itself. The local control system is normally designed as a fast controller. The communication between remote operators and the controlled object is only carried out at a more abstract level, rather than at a detail command level. Therefore, the remote operation can be at a lower frequency and perform via a delayed low-bandwidth communication link.

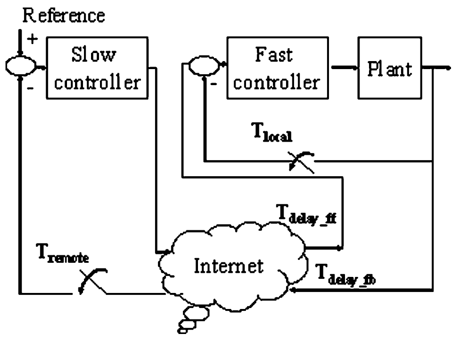

Fig. 3. Dual-rate control scheme.

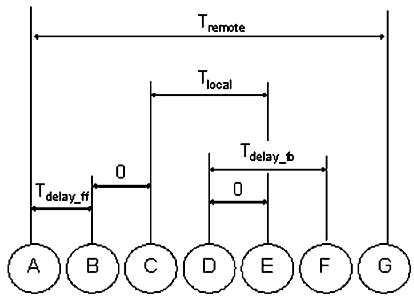

Fig. 4. Time scheme of dual-rate control with the total transmission delay less than the sampling interval. The instant at which (A) the control action is sent out by the slow controller from the remote site; (B) the fast controller receives the control command from the slow controller; (C) the fast controller sent out the control action; (D) the sensors send data to the controllers; (E) the fast controller receives the data from the sensors; (F) the slow controller receives the data from the sensors; (G) the slow controller is ready to send out the next control command.

III. Multirate Control Scheme

Being distinguished from the existing approaches of networked control, the multirate control scheme, proposed in this section, investigates overcoming the Internet time delay from the control system architectural point of view by taking the intelligence of the local control system. The multirate control scheme incorporates the earlier described two-level control architecture, the lower level of which runs at a higher frequency to stabilize the plant, and guarantees that the plant is under control even when the network communication is lost for a long time. The higher level of the control architecture implements the global control function and runs at a lower frequency to reduce the communication load and increase the possibility of receiving data on time. We denote 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 Fig. 3. The two sampling intervals for the fast and slow controllers, T_{remote} and T_{local}, are chosen as: $T_{\text{remote}} = nT_{\text{local}}, n \in \{2, 3, \ldots\}$.

The slow controller is linked with the fast controller and the plant via the Internet. The total Internet-induced transmission delay T_{delay} is equal to the sum of the transmission delays occurring in the feedback and feed-forward channels, i.e., $T_{\text{delay}} = T_{\text{delay\_fb}} + T_{\text{delay\_ff}}$. There are two cases involved in the dual-rate control scheme.

Case 1. $T_{\text{delay}} + T_{\text{local}} < T_{\text{remote}}$: The time scheme of Case 1 is illustrated in Fig. 4. The transmission delay occurring in the local control system has been omitted, i.e., the transmission time between nodes D and E is 0. If the sum of the total transmission delay T_{delay} and the sampling interval of the fast controller T_{local} is less than the sampling interval of the slow controller T_{remote}, there is no data loss during each sampling interval. Therefore, the transmission delay has no influence on the slow controller.

Case 2. $T_{\text{delay}} + T_{\text{local}} \geq T_{\text{remote}}$: The time scheme of Case 2 is illustrated in Fig. 5. Since the sum of the transmission delay T_{delay} and the sampling interval of the fast controller T_{local} is greater than the sampling interval of the slow controller T_{remote}, the sample is delayed to arrive at the slow controller after the next control instant. A compensator must be employed in this case to compensate the effect caused by the transmission delay. The detail will be discussed in the following section.

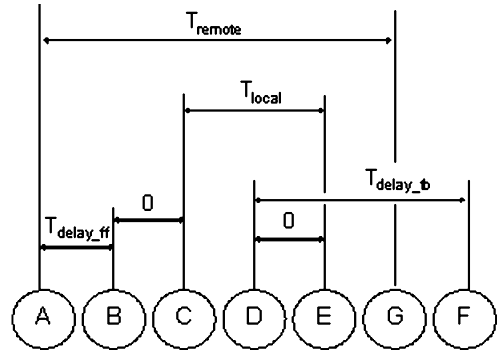

Fig. 5. Time scheme of dual-rate control with the transmission delay greater than the sampling interval. The instant at which (A) the control action is sent out by the slow controller from the remote site; (B) the fast controller receives the control command from the slow controller; (C) the fast controller sent out the control action; (D) the sensors send data to the controllers; (E) the fast controller receives the data from the sensors; (F) the low controller receives the data from the sensors; (G) the slow controller is ready to send out the next control command.

IV. Time-Delay Compensation

Even though any type of controller, including proportional integral differential (PID) controllers, can be implemented in the dual-rate control structure proposed earlier, the dynamic matrix controller (DMC) is chosen for the design of time-delay compensation because DMC is widely accepted in industry [16]. Two compensators are designed, one in the feedback channel and another in the feed-forward channel. The compensator in the feedback channel is designed to overcome the time delay occurring in the transmission from the local site to a remote site, while the compensator in the feed-forward channel is designed to overcome the time delay occurring in the transmission from a remote site to the local site. All data are sent over the Internet with a time stamp generated by a global timer in the Internet-based control system. The receiving time is compared with the time stamp for each data to justify whether a delay has occurred or the transmission is normal.

Treat the plant and the fast controller as an extended process for the remote slow controller and assume that the extended process is described in the step-response model as follows:

$$y(t) = \sum_{i=1}^{\infty} g_i \, \Delta u(t-i) \tag{1}$$

where y is the process output variable, Δu is the increment of the control action, g_i is the coefficient of the step response, and t is the current time instant. The general DMC control law can be given as [16]

$$\boldsymbol{u} = (\mathbf{G}^T\mathbf{G} + \lambda\mathbf{I})^{-1}\mathbf{G}^T(\boldsymbol{w} - \boldsymbol{f}) \tag{2}$$

in which λ is the penalization factor for the control costs, $\mathbf{I}$ is the unit matrix, the superscript "T" is the transpose of the vector, and $\mathbf{G}$ is the system dynamic matrix defined as

$$\mathrm{G} = \begin{bmatrix} g_1 & 0 & \cdots & & 0 \\ g_2 & g_1 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & & \vdots \\ g_m & g_{m-1} & \cdots & g_2 & g_1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ g_p & g_{p-1} & \cdots & g_{p-m+2} & g_{p-m+1} \end{bmatrix}_{p\times m}$$

where m is the control horizon and p is the prediction horizon. The control action $\boldsymbol{u}$ is defined as

$$\boldsymbol{u} = [\Delta u(t)\,\Delta u(t+1)\,\cdots\,\Delta u(t+m-2)\,\Delta u(t+m-1)]^T. \tag{3}$$

The reference trajectory vector $\boldsymbol{w}$ is defined as

$$\boldsymbol{w} = [w(t+1)\; w(t+2)\;\cdots\; w(t+p)]^T.$$

The free response vector $\boldsymbol{f}$ is defined as

$$\boldsymbol{f} = [f(t+1)\; f(t+2)\;\cdots\; f(t+p)]^T.$$

The element of the reference trajectory vector $\boldsymbol{w}$ is computed as

$$\begin{aligned} w(t) &= y_m(t) \\ w(t+k) &= \alpha w(t+k-1) + (1-\alpha)\times r(t+k), k = 1,\ldots,N \end{aligned} \tag{4}$$

The element of the free response vector $\boldsymbol{f}$ is computed as

$$f(t+k) = y_m(t) + \sum_{i=1}^{N}(g_{k+i} - g_i)\,\Delta u(t-i) \tag{5}$$

where $y_m(t)$ is the measurement value of the process output variable, α is a parameter between 0 and 1, $r(t+k)$ is the set point of the remote controller, and N is the process horizon.

A. Compensation at the Feedback Channel

The time delay occurring at the feedback channel causes the slow controller at 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 (4) and (5) is replaced by the predictive value $\widehat{y}(t|t)$ obtained from the step-response model in (1). The latest available measurement value of the process output, denoted as $y_m(t-l)$, and the corresponding predictive value, denoted as $\hat{y}(t-l|t-l)$, are used to correct the predictive value $\widehat{y}(t|t)$ as in (6), shown at the bottom of the page, where β is an adjustable parameter between 0 and 1.

If the time delay at the feedback channel does not occur, the remote slow controller simply takes the forms shown in (4) and (5) for the computation of the control law.

B. Compensation at the Feedforward Channel

The objective of the compensation at the feed-forward channel is to reduce the effect of control signal blanks caused by the transmission delay. In (3), $\boldsymbol{u}$ is a vector composed of the current control increment and the $m-1$ future control increments. Normally, only the one at the current instant, $\Delta u(t)$, is taken into action, the future control increments from $\Delta u(t+1)$ to $\Delta u(t+m-1)$ are simply not in use. Therefore, it is possible to use these available future control increments in the situation where the time delay occurs at the feed-forward channel.

When the time delay occurs at the feed-forward channel, the elements in the control vector $\boldsymbol{u}$ in (3) are shifted one step forward at every sampling interval. Equation (3) becomes (7), in which the first element is $\Delta u(t+1)$, and the last element is replaced by zero. If the time delay is longer than $m-1$, $\boldsymbol{u}$ will be a zero vector after delaying $m-1$ steps, and the extended process will be in an open-control mode.

$$\boldsymbol{u} = [\Delta u(t+1)\;\Delta u(t+2)\;\cdots\;\Delta u(t+m-1)\;0]^T \tag{7}$$

V. Simulation Results

Simulation has been carried out for the dual-rate control scheme. 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 $K_p = 5$, $K_I = 1.2$, and $K_D = 0.001$. The slow controller is designed using the control law, as given in (2)–(6). The maximum transmission delay is set as $T_{\text{delay}} = 18$. The prediction horizon p is chosen as 10; the control horizon m is 5; the process horizon N is 12; the reference trajectory parameter α is 0.5; the parameter β is 1; and the parameter λ is 0.8. The square changes are made by switching between 15 and 35. The sampling intervals of the fast and slow controllers are chosen as $T_{\text{local}} = 1$ and $T_{\text{remote}} = 10$. The time unit in the simulation study is the number of the simulation instant. The output unit is percentage.

Fig. 6 shows the simulation results for the dual-rate control scheme. The square wave set point 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. An obvious delay in the response is illustrated as the cycle line in Fig. 6. If compensation

$$\begin{cases} f(t+k) = \hat{y}(t|t) + \beta(y_m(t-l) - \hat{y}(t-l|t-l)) + \sum_{i=1}^{N}(g_{k+i} - g_i)\Delta u(t-i) \\ w(t) = \hat{y}(t|t) + y_m(t-l) - \hat{y}(t-l|t-l) \\ w(t+k) = \alpha w(t+k-1) + (1-\alpha) r(t+k) \end{cases} \quad k = 1,\ldots,N \tag{6}$$

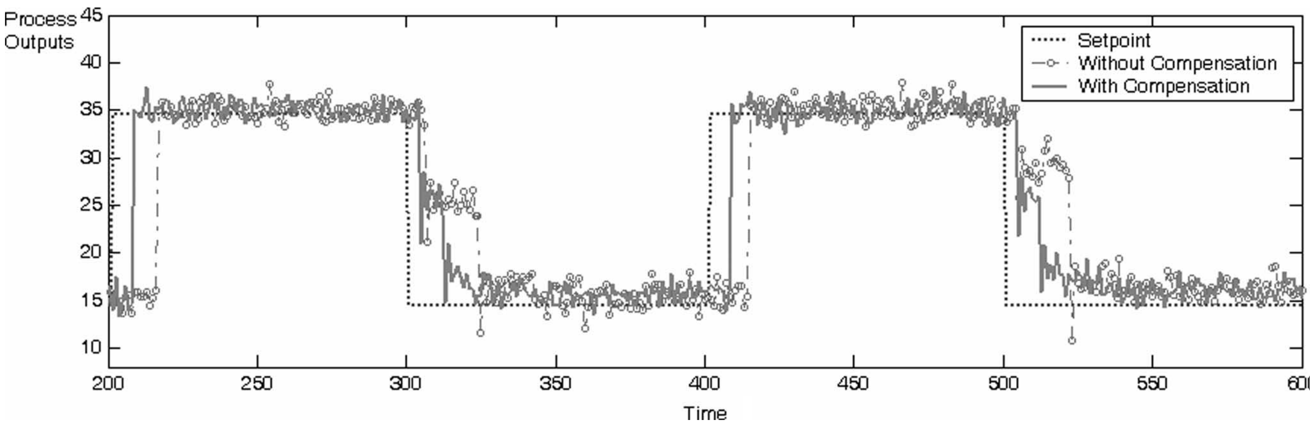

Fig. 6. Dual-rate control with and without feedback delay compensation.

is used, the predictive output based on the process model is used as the current measurement. Concerning the mismatch between the process model in the form of the system dynamic matrix and the actual process represented as $0.3/(z-1)$, the latest available delayed feedback and the predictive output at that delayed instant are used to correct the predictive output at the current instant. Fig. 6 clearly presents that the compensation reduces the delay in the response, and the dynamic performance with the compensation is much better than the one without the compensation.

VI. Experimental Application Results

To illustrate the validity of the proposed multirate control scheme and to evaluate how well the proposed time-delay compensation copes with the Internet communication features, a water tank teaching rig is used as an example in our process control laboratory. An Internet-based predictive control system for the water tank is implemented. Experiments with and without the time-delay compensation are carried out with similar Internet transmission conditions.

A. System Architecture

The process to be controlled through the Internet is a water tank in the Process Control Laboratory located in the Department of Chemical Engineering at Loughborough University. The control target is to maintain the liquid level of the water tank at a desired value. The experimental system layout is shown in Fig. 7. The tank is filled through an inlet flow controlled by a hand valve and is emptied into a drainage tank through a connecting pipe and a pump. The outlet flow is controlled by a local PID control system to maintain the liquid level of the tank at a desired value. The predictive controller is located at the remote control system, which is deployed on a laptop computer. Its function is to change the set point of the local PID controller. The data acquisition (DAQ) instrument is used to gather the liquid level signal from the water tank and send a control command to it. The local control system of the tank and the DAQ instrument are connected and wired through a RS-232c serial port. The real-time data are exchanged between the local control system and the instrument through the serial cable. The local

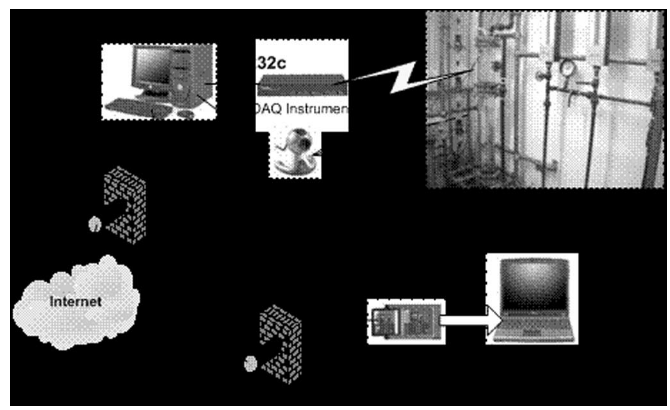

Fig. 7. Physical layout of the Internet-based DMC/PID dual-rate control system.

control system acts as a Web server and a video server as well. A Web camera provides visual information to users. Because the Web camera is independent of the DAQ, it is considered to be an extra sensor. The web server provides the Internet services (IIS 5.0) and establishes connections between the remote control system and the local control system. The remote control system is connected to the Internet through a telephone modem providing 33.6-kB bandwidth. Due to the limited transmission capability of the modem, Internet congestion is often encountered. The time delay, which is the experimental circumstance that we expected for the remote predictive controller with the time-delay compensation, is also observed.

The block diagram of the above experimental system with the feedback and feed-forward compensators is shown in Fig. 8. In practice, the dual-rate control scheme is more realistic and safer than the one in which a direct remote control over the Internet is exercised. As described in the Introduction, the Internet-based process control system is intended to enhance rather than replace ordinary control systems by adding an extra Internet level to the control system hierarchy. The local control system ensures that at any situation including an Internet crash, the process is still under control and safe. Another more important factor of embedding a local control system in the Internet-based control

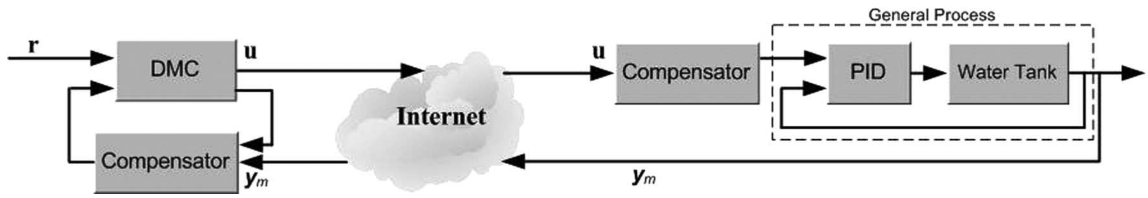

Fig. 8. DMC/PIC dual-rate control system of the water tank.

system structure is that it is very hard for process industries to accept the idea of complete remote control over the Internet.

B. Experimental Results and Analysis

Three categories of the experiments have been conducted from two different locations, 5 (in the same city) and 50 km (in the same country) away from the water tank process, respectively. The first category of experiments locates the DMC controller with the local PID controller at the local site when only local network communication is involved. The second category of experiments locates the DMC controller at a remote site when Internet communication is involved, but no time delay compensation is employed. The third category of experiments is the same as the second one, but the proposed time-delay compensation is applied. The experiments in the first category are used as a standard reference for comparison, in which the local network communication effect is completely ignored.

The step response model is obtained by applying a step change in the set point of the local PID controller, which is the model of the extended process, i.e., the water tank plus the local PID control loop. In order to evaluate the controller's performance, the set point (reference) of the remote DMC controller is driven by a square wave with the wave centre at 50%, which is the desired value of the liquid level of the water tank. For the control parameter, the prediction horizon p is 10, the control horizon m is 5, and the reference trajectory parameter α is 0.7. The sampling intervals of the local PID controller and the remote DMC controller are 50 and 500 ms, respectively.

The TCP/IP communication protocol is used to implement the remote communication over the Internet. The TCP/IP link between the remote DMC controller and the local PID controller has been used for the whole period of the experiments. For symmetrical communication network, the feedback and feedforward channels possess an equal bandwidth and have a similar latency. Only the time delay in the feedback channel during the experiments carried out from 5 km away from the water tank, illustrated in Fig. 9, in order to show the uncertainty of the Internet latency. There are some, but not significant, differences in the time delays between the experiments carried out from 5- and 50-km distances. The reason for this might be that the amount of information actually exchanged over the Internet is small, only a few variables are communicated over the Internet, and the TCP/IP communication protocol is employed.

The experimental results are summarized in Table I. Parts of them are illustrated in Fig. 10. In order to compare the experimental results obtained under different network communication conditions and at different locations, all the experiments listed

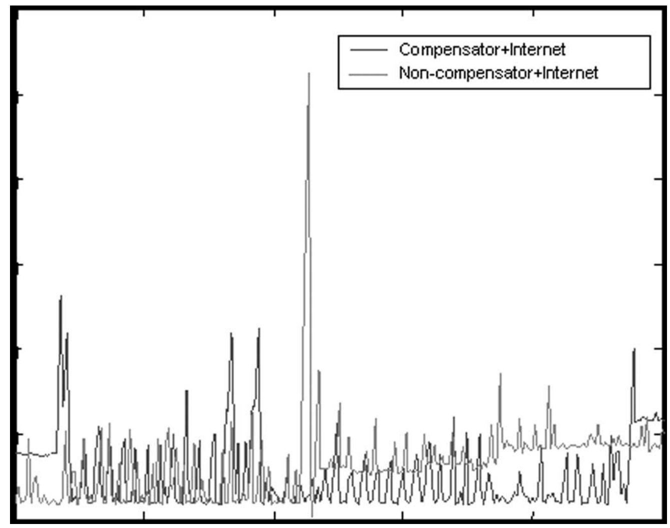

Fig. 9. Feedback transmission delays in experiments 2 and 3.

are carried out by introducing an identical set-point change, driven by the square wave, as shown in Fig. 10 as a solid line. Three elements for each category of the experiments are recorded in Table I: average feedback transmission time, standard deviation, and data loss. The average feedback transmission time indicates the data transmission time from the local site to the remote site, the standard deviation represents the dispersant degree of the transmission time, and data loss records the number of transmission failure out of a total number of transmissions. Data loss could be caused by the transmission data loss and/or the transmission timeout. There are a number of criteria that can be used for controller performance evaluation. Only the integral square error (ISE) criterion is employed in Table I.

Concerning the experiments carried out at a 5-km distance from the water tank, the total Internet time delay is about 1 s, which is double of the average feedback transmission time for experiments 2 and 3, 494.32 and 555.60 ms, respectively. The total Internet time delay is greater than the sampling interval of the remote DMC controller (500 ms in these experiments). The compensation shown in (6) and (7) is required. The high standard deviation values, 327.17 and 377.92 ms, respectively, illustrate the existence of the unpredictability of the Internet transmission. The feedback transmissions in experiments 2 and 3 over the Internet have 13 out of 217 and 20 out of 205 data loss events, respectively. It can be viewed that the Internet circumstance for experiment 3 is worse than the one for experiment 2. Investigating the ISE values of experiments 1–3, the ISE value increases from 9561.9 to 10923 because of the Internet time

TABLE I
SUMMARY OF THE EXPERIMENTAL RESULTS

Experiment order number	Results / Conditions	Control transmission: Average feedback transmission time (ms)	Control transmission: Standard deviation (ms)	Control transmission: Data package loss number / total package number	Control result (ISE)
Experiments carried out locally					
1	Traditional controller + local network communication	11.95	23.85	0/250	9561.9
Experiments carried out from a 5 km distance					
2	Non-compensation controller + Internet communication	494.32	327.17	13/217	10923
3	Compensation controller + Internet communication	555.60	377.92	20/205	9957.7
Experiments carried out from a 50 km distance					
4	Non-compensation controller + Internet communication	553.06	357.62	16/210	11012
5	Compensation controller + Internet communication	582.36	460.75	26/194	9980.8

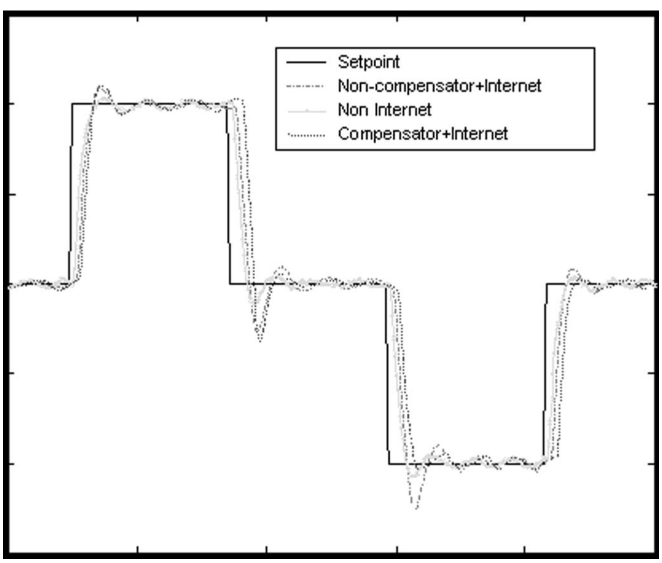

Fig. 10. Control performance of experiments 1–3.

delay if the compensation is not employed, but from 9561.9 to 9957.7 if the compensation is employed in experiment 3. However, experiment 3 shows that even in the worse circumstance compared with experiment 2, the ISE value of the experiment with the compensation, 9957.7, is still less than the one of the experiment without the compensation. Therefore, it empirically shows the efficiency of the compensation technique.

Concerning experiments 4 and 5 carried out at a 50-km distance from the water tank, very similar results to experiments 2 and 3 are obtained. There are some minor differences between experiments 2 and 3, and 4 and 5 in Internet circumstance, such as the average feedback transmission time, standard deviation, and data package loss times. The control performance index ISEs for experiments 4 and 5 are very close to the ones for experiments 2 and 3 as well. A similar phenomenon can be observed: even though the Internet circumstance for the experiment with the compensation (experiment 5) is worse than the one without the compensation (experiment 4), the control performance of experiment 5 is still slightly better than the one of experiment 4.

Two findings can be observed while comparing the results of experiments 2 and 3 with the ones of experiments 4 and 5: 1) the performance of the Internet-based control system would be independent of its physical location if the Internet circumstance has not had a significant change and 2) the control performance with the time-delay compensation is better than the one without the compensation even in a worse Internet circumstance.

Fig. 10 gives the graphical presentation of the experimental results for experiments 1–3. Experiment 1 is carried out in the local network and is used as a standard reference for comparison, in which the network communication effect is completely ignored. It is observed that the experimental results with the compensation over the Internet have less overshoot and more quickly approach the desired set point than the ones without the compensation.

VII. CONCLUSION

Internet time delay is one of the biggest obstacles in the design of Internet-based process control systems. Since the Internet time delay is affected by the number of nodes and the Internet load, it is variable and unpredictable. 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 investigated the potential of using the multirate control scheme and the model-based compensation 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. The remote controller runs at a lower frequency to reduce the influence of the data loss and the Internet transmission load, and the local controller runs at a higher frequency to stabilize the process. The predictive measurement of the process output with the correction based on the available delayed measurement is used as the current measurement in the compensation. Our simulation and comprehensive experimental results have illustrated all the above findings and show that the multirate control scheme with the time-delay compensation offers a promising way to efficiently reduce the effect of Internet time delay on control performance.

Internet-based control systems have great potential applications for widely geographically distributed devices and processes, such as windmill power stations, small-scale hydroelectric power stations, food manufacturer warehouses, food retailers, and logistics operators. For example, small-scale hydroelectric power stations are widely geographically distributed among countrysides. Centralized remote control technologies delivered via the Internet might be the best solution for them.

Today the high-speed Ethernet, also a nondeterministic communication medium, is being adopted for process automation. Industries are beginning to implement networked control systems through this high-speed communication medium. Given the potential development of the next-generation Internet and other enhancements to the World Wide Web infrastructure, the speed of the next-generation Internet might be sufficiently fast to be able to dramatically reduce the transmission delay and data loss. Therefore, it is possible that Internet latency and data loss might become less important issues in future Internet applications.

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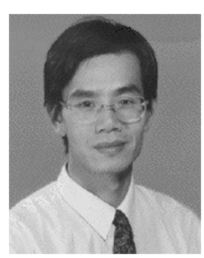

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