가상 디바이스 네트워크상에서 불확실한 시간지연을 갖는 실시간 분산제어를 이용한 예지보전에 관한 연구

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Real-time Distributed Control in Virtual Device Network with Uncertain Time Delay for Predictive Maintenance (PM)

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Abstract : Uncertain time delay happens when the process reads the sensor data and sends the control input to the plant located at a remote site in distributed control system. As in the case of data network using TCP/IP, VDN that integrates both device network and data network has uncertain time delay. Uncertain time delay can cause degradation in performance and stability of distributed control system based on VDN. This paper first investigates the transmission characteristic of VDN and suggests a control scheme based on the Smith's predictor to minimize the effect of uncertain varying time delay. The validity of the proposed control scheme is demonstrated with real-time velocity control of DC servo motor located in remote site.

초록 : 원격지에 위치한 분산제어 시스템과 센서 데이터 또는 제어 명령을 주고 받을 때에는 불확실한 시간지연이 발생한다. TCP/IP 프로토콜을 이용한 데이터 네트워크와 마찬가지로 데이터 네트워크와 디바이스 네트워크를 결합한 가상 디자이스 네트워크도 불확실한 시간지연이 내재되어 있다. 이러한 시간지연은 분산제어시스템의 성능을 저하시키고 불안전성을 야기하는 원인이 된다. 본 논문에서는 이러한 네트워크상에 내재하는 시간지연을 평가하고 부정적인 효과를 최소화하기 위하여 Smith Predictor를 적용하였다. 제안된 제어 알고리즘은 실시간 서보제어를 통하여 효과를 입증하였으며 가상 디바이스 네트워크 개념에 근거한 분산제어 시스템을 이용하여 실시간 예지보전을 수행할 때 효과가 있음을 제시하였다.

Key Words : predictive maintenance, VDN(virtual device network), DCS(distributed control system), smith predictor

1. Introduction

Recently development in network and communication make remote system control possible. The trend in modern industrial and commercial systems is to integrate computing, communication and control into different levels of factory operations and information processes. For example, in many complex control systems, such as manufacturing plants, vehicles, aircraft, and spacecraft, serial communication networks are employed to exchange information and control signals between spatially distributed system components, like supervisory computers, controllers, and intelligent I/O devices (e.g., smart sensors and actuators).

Feedback control systems wherein the control loops are closed through a real time network are called networked control systems (NCSs)[1-2]. The defining feature of an NCS is that information (reference input, plant output, control input, etc.) is exchanged using a

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network among control system components (sensors, controller, actuators, etc.). The primary advantages of an NCS[1-2] are reduced system wiring, ease of system diagnosis and maintenance, and increased system agility. In result, NCS[1-2] is concerned primarily with the quality of real-time reliable service on the device network. But the change of communication architecture from point-to-point to common-bus introduces different forms of time delay uncertainty between sensors, actuators, and controllers. The characteristics of this time delay could be constant, bounded, or even random, depending on the network adopted and the chosen hardware. This type of time delay could potentially degrade a system's performance and possibly cause system instability. Consequently, in application of remote control using network and system to be demand accuracy and real-time control, real-time is embossed as an important problem.

Also recent trends require that access to the device network information be provided from several locations or anywhere in the enterprise. This causes the implementation of distributed control networks. And because of the ubiquity and cost structure of the Internet, it can be an attractive option for implementing distributed control system (DCS)[3] on wide area, different type network environments. Therefore device networks can take advantage of these capabilities by properly interconnecting the device network with data network components.

The network structure integrating device network to data network is called as virtual device network (VDN)[4]. VDN referenced in this work is an integrating form of LonWorks technology as device network and IP network as data network. VDN also has inherent uncertain time delay. To implement DCS on VDN[4], transmission characteristics on VDN need to be investigated.

In this paper, in a preliminary application of VDN to predictive maintenance, velocity control of DC servo motor across the VDN is investigated. The performance and the stability of DCS in VDN are analyzed and a control scheme augmented with the Smith's predictor to minimize the effect of uncertain time delay is suggested. The validity of the proposed control scheme is demonstrated experimentally.

2. Lonworks-Based Distributed Control Network

The concept and design of the distributed control networks (DCN) is based on sensors and actuators integrated into any on-line (real-time) control network. The requirements for the infrastructure and capabilities of DCN need to be carefully evaluated. Among many available fieldbus protocol, LonWorks[4] was chosen as the device control network for several reasons. LonWorks technology is the accepted standard in the semiconductor industry for implementing a distributed control system (DCS) as well as in the building automation industry.

Fig. 1 shows the typical implementation of DCS based on Lonworks over IP network architecture. LonWorks over IP gateway utilizes both an Ethernet capability and LonWorks compatibility. The Ethernet connection can support user to access IP network, and the LonTalk (LonWorks protocol) adapter can support user to access LonWorks network form any workstation with a TCP/IP connection.

In this (web) server-client model, a server will control and monitor LonWorks network locally and clients can control and monitor LonWorks network remotely. The server obtains the network variables (NVs) from LonWorks network. The server then sends it to IP network using Ethernet connection. In the client sites, the client will read it out and send back the related control command through network variables.

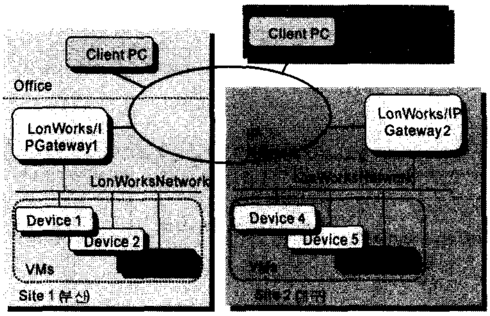

Fig. 1. Typical implementation of DCS based on LonWorks over IP network architecture

3. Modeling of a DC Servo Motor

A DC servo motor with relatively slow velocity response is used for experiment. The DC servo motor used in this study is driven by voltage command from the LonWorks analog output module. The dynamics of the DC servo motor experimentally identified is given in equation (1).

$$u = 0.3232\dot{x} + 1.0772x \tag{1}$$

where u is the torque command voltage, and x is the velocity. The transfer function (G) for DC servo motor is given by:

$$G(s) = \frac{X(s)}{U(s)} = \frac{1}{0.3232s+1.0772} \tag{2}$$

4. Distributed Control Network

In a network based system remote control time delay is always present. The important time delays that should be considered in a distributed control system analysis are the sensor to controller and controller to actuator end-to-end delays. In an NCS, time delay can be broken into two part: the device delay and the network delay. Device network time delay happens when device network accepts data read from sensor and when device network sends control data to plant. Data network time delay originates from communication through network.

Fig. 2 shows a distributed control network with time delay. The physical plant is a DC servo motor. The PI controller is implemented with JAVA Applet on the client web browser.

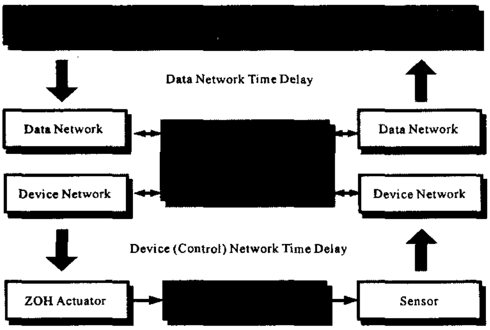

Fig. 2. Distributed control network with time delay

5. Experiments

The data packet undergoes uncertain time delays through the VDN. Sometimes longer time delay can make it impossible to guarantee the performance of the distributed control system. Walsh has studied the stability of the NCS[1-2]. The maximum allowable transmission interval (MATI) was introduced to guaranteeing the performance of the NCS. In his studies the MATI for the available performance and stability of the NCS is about less than 10 msec, which is very small for the VDN. Zhang et al. presented NCS models with networked induced delay on device network, and analyzed the stability of the NCS using stability regions and hybrid systems technique which includes discrete events and continuous dynamics.

On the VDN, the limitation of the MATI is too conservative to realize the real-time servo control. In this study it is assumed that the MATI is bounded by 3 *sec*. Fig. 3 shows that the experimental set up of the DCS on VDN where VDWorks' distributed control modules (LonWorks devices) DI-20, AI-20, AO-20 and IS-30 LonWorks/IP gateway were used. DC servo motor system by ED engineering was used as the plant.

The transmission delay in a data network is known to have a Gaussian distribution for transmission through long distances. For the cases of transmission through relatively short distances or transmission through many routers it is known to take the Gamma or exponential distribution[5]. The transmission delay in the VDN combines data network and device network should be more complex. There was a study on the transmission delay in the VDN through the round trip transmission experiment from the data network to the device network, and then back to the data network[6]. The trans-

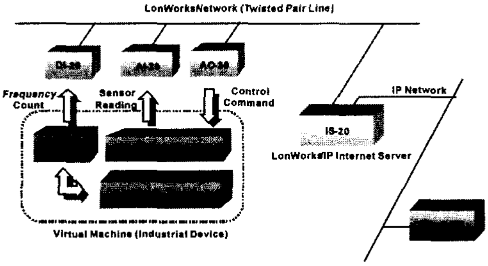

Fig. 3. The experimental set up of the DCS on VDN

mission is more likable to Gaussian distribution rather than gamma or exponential distribution. It seems to have both of the distributions because the transmission delay is not only due to the network channel but also due to the calculation time for protocol conversion on the web server/gateway. Fig. 4 shows the RTT from data network to device network, and then back to data network.

The transmission characteristics on internet and on VDN were investigated through the real time distributed control in[7]. Long transmission delays were intermittently observed due to the inherent transmission characteristics of the internet. It takes effects on the transmission characteristics of the VDN. In fact, the considerably long transmission delays of VDN sometimes observed is mainly due to the internet transmission characteristics.

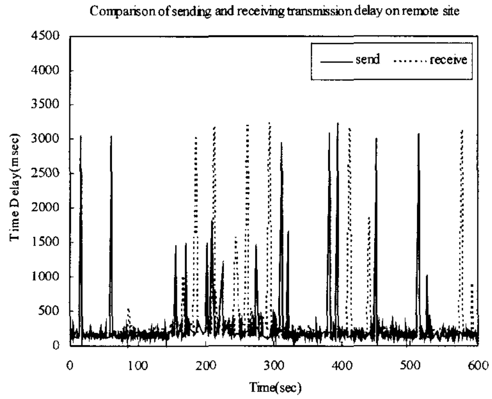

Fig. 4. Sending and receiving time delay at remote site

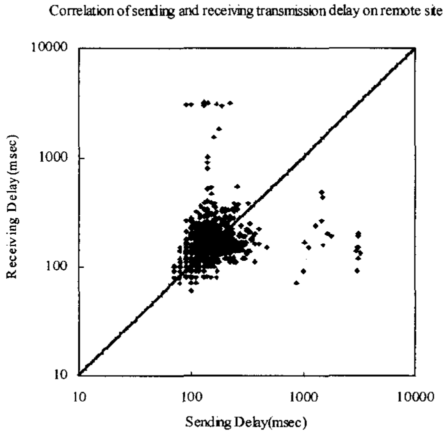

Fig. 5. Correlation of the sending and the receiving time delay on remote site

The correlation of the sending delay and the receiving delay is figured in Figs. 4 and 5. These show that the receiving delay is almost not dependent to the sending delay in especially relatively long time delay occurred. In the Table 1, the distribution of the transmission delay on the internet is described. The access delay of the client on the local site to the server is much smaller than that of the client on the remote site. It is quite natural.

Fig. 6 shows the block diagrams of DCS incorporated with the continuous time controller. A continuous time PI controller is designed with transfer function as equation (3). The discrete equivalent of the continuous time PI controller with the sampling time T_s has the transfer function as equation (4).

$$G_C(s) = 0.4 + \frac{0.15}{s} \tag{3}$$

$$G_C(z^{-1}) = 0.4 + \frac{0.15T_s}{2}\frac{1+z^{-1}}{1-z^{-1}} \tag{4}$$

The sampling interval of the discrete time PI controller on the data network and the velocity sensor node on the device network are not coincident with each other, and they are not synchronized with each other.

Table 1. Distribution of transmission delay on internet

Time Delay (ms)	Remote site (counts)	
	Send	Receive
< 100	101	70
100 - 1000	904	941
1000+	18	12

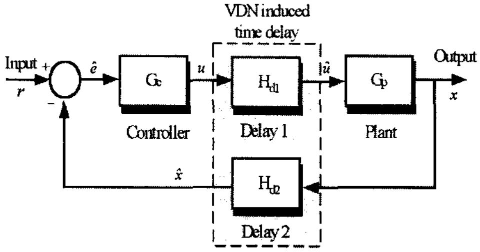

Fig. 6. Block diagram of proposed DCS with VDN induced time delay

6. DCS Based on Smith Predictor

For DCS with time delay, compensation of adverse effects coming from the time delay is necessary for successful implementation. In this study Smith's predictor was used[8,9]. Smith's predictor was proposed Smith in 1958. The main advantage of this technique is that the time delay can be eliminated from the characteristic equation of the closed loop system. Thus, the design problem for the process with delay can be transformed to the one without delay. Fig. 9 shows the block diagram of proposed control structure utilizing the Smith's predictor.

For the block diagram in Fig. 7, transfer function from the input to the output can be represented as equation (5), (6).

$$\frac{X(s)}{R(s)}=\frac{G_C G_P H_{d1}}{1+G_C G_{mo}-G_C G_P H_{d1} H_{d2}} \tag{5}$$

$$G(s)=H_{d1}(s)G_P(s)H_{d2}(s) \tag{6}$$

where

G_P : plant
G_{mo} : G_m without time delay,
H_d : time delay
G_m : nominal plant with time delay,
G_C : controller
G : actual plant with uncertain time delay.

In Fig. 7, H_{d1}, H_{d2} can be combined into a H_d since the delay H_{d1}, H_{d2} are induced by VDN. Consequently the transfer functions can be rewritten as in equation (7).

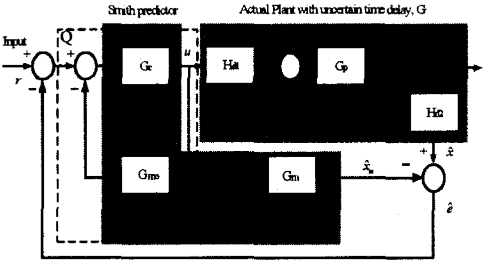

Fig. 7. Block diagram of the proposed control system based on Smith's Predictor

$$\begin{aligned}\frac{\hat{X}(s)}{R(s)}&=\frac{G_c G_p H_{d1} H_{d2}}{1+G_c G_{mo}-G_c G_m+G_c G_p H_{d1} H_{d2}}\\&=\frac{G_c G_p H_d}{1+G_c G_{mo}-G_c G_m+G_c G_p H_d}\end{aligned} \tag{7}$$

And G_{mo} and G_m can be described as in equation (8).

$$G_{mo}=\frac{1}{ms+b},G_m=G_{mo}\left(\frac{1}{1+\tau s}\right) \tag{8}$$

The controllers Q and G_c can be designed as in equation (9) and (10), respectively.

$$Q=\frac{ms+b}{\lambda s+1} \tag{9}$$

$$G_c=\frac{m}{\lambda}+\frac{b}{\lambda}\cdot\frac{1}{s} \tag{10}$$

Consequently, G_c takes the form of a PI controller. The smith controller is designed as in equation (11)

$$\frac{U}{E}=\frac{Q}{1-G_m Q}=\frac{m\tau s^2+(m+b\tau)s+b}{\tau\lambda s^2+(\tau+\lambda)s} \tag{11}$$

where τ is the time delay.

The parameter λ in the Smith's predictor is adjustable. When there is no model mismatch, λ is adjusted to achieve desired response. There are quantitative relationships between the parameter and the closed loop system performance, such as overshoot and rise time. When there exists a model mismatch, increasing λ will enhance the robustness of the system. The discrete equivalent of the continuous time Smith's predictor for a sampling time T_s has a transfer function as equation (12).

$$u(k)=\frac{1}{A}\begin{Bmatrix}Be(k)-Ce(k-1)+De(k-2)\\+Eu(k-1)-Fu(k-2)\end{Bmatrix} \tag{12}$$

where

$$A=\frac{\tau\lambda}{T_s^2}+\frac{\lambda+\tau}{T_s},\quad B=\frac{m\tau}{T_s^2}+\frac{(m+b\tau)}{T_s}+b$$

$$C=\frac{2m\tau}{T_s^2}+\frac{(m+b\tau)}{T_s},\quad D=\frac{m\tau}{T_s^2}$$

$$E=\frac{2\tau\lambda}{T_s^2}+\frac{(\tau+\lambda)}{T_s},\quad F=\frac{\tau\lambda}{T_s^2}$$

Figs. 8 and 9 compare the performances of the proposed control scheme based on Smith's predictor and that of PI control. In the figures, the time delay in the control system based on the Smith's predictor is shown to be smaller than that of the fine tuned PI control. Figures also show that the proposed control using Smith's predictor based control system can achieve better tracking performance. However, in those figures, frequent peaks in sending or receiving delays are responsible for the distorted shapes of the reference signals.

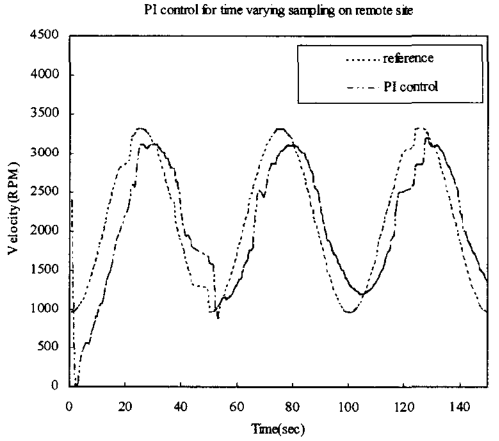

Fig. 8. Experimental results of the PI controller on remote site.

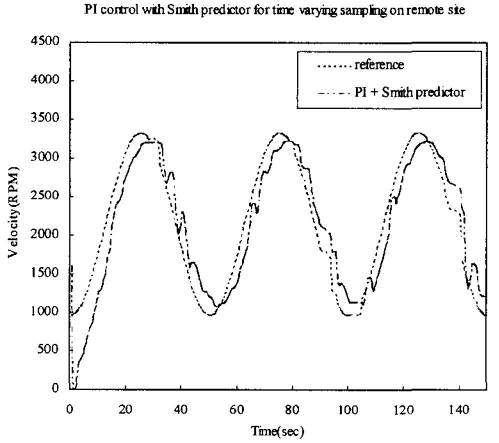

Fig. 9. Experimental results of the controller based on Smith's predictor on remote site.

7. Conclusion

In this paper the transmission characteristic of VDN is studied and a control scheme for dynamic systems based on the Smith's predictor to minimize the effect of network time delay is proposed and the validity of the proposed control scheme is experimentally studied through velocity control of a DC servo motor. The proposed controller proved to achieve a good tracking performance even under the uncertain network time delay. Incorporation of a rigorous model of the network time delay and the proper compensation is believed to bring in the better performance, particularly in an application to predictive maintenance. This is because rather timely response to the equipment abnormality is vital in predictive maintenance.

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References

1) M. S. Branicky, S. M. Phillips, and Wei Zhang, “Stability of Networked Control Systems: Explicit Analysis of Delay”, Proc. ACC, Chicargo, Illinois, pp. 2352~2357, June, 2000.
2) Wei Zhang, M. S. Branicky, and S. M. Phillips, “Stability of Networked Control Systems”, IEEE Control Systems Magazine, pp. 84~99, February 2001.
3) Feng-Li Lian, James Moyne, and Dawn Tilbury, “Network Design Consideration for Distributed Control Systems”, IEEE, pp. 297~307, March 2002.
4) G. H. Choi, G. S. Choi, and J. S. Kim, “LonWorks based

Virtual Device Network (VDN) for Predictive Maintenance", ICMIT'01, Yamaguchi Seminar Park, Japan, pp. 372~376, 2001.

5) G. H. Choi, "Transmission Characteristics in Lon Works/IP-based Virtual Device Network for Predictive Maintenance", J. KIIS, Vol. 18, No.4, pp

6) J. W. Park and J. M. Lee, "Design and Implementation of Internet-based Teleoperation Control System", ICCAS2001, pp. 452~455, 2001.

7) Ki Won Song, Gi Sang Choi, Gi Heung Choi, and Jung Soo Kim, "LonWorks-based Virtual Device Network (VDN) for Predictive Maintenance", International Journal of Applied Electromagnetics and Mechanics 11, pp. 1~13, November, 2000, JAE275 IOS Press.

8) Weidong Zhang and Xiaomong Xu, "Simple Predictor for Processes with Time Delay", Proc.AACC, San Diego, Califonia, pp. 822~826, June, 1999.

9) Saverio Mascolo, "Smith's Predictor for Congestion Control in High-Speed Data Networks", IEEE, pp. 358~364, February 2000.