

# Tracking Position Control of DC Servo Motor in LonWorks/IP Network

Ki-Won Song, Gi-Sang Choi, and Gi-Heung Choi

**Abstract:** The Internet's low cost and ubiquity present an attractive option for real-time distributed control of processes on the factory floor. When integrated with the Internet, the LonWorks open control network can give ubiquitous accessibility with the distributed control nature of information on the factory floor. One of the most important points in real-time distributed control of processes is timely response. There are many processes on the factory floor that require timely response. However, the uncertain time delay inherent in the network makes it difficult to guarantee timely response in many cases. Especially, the transmission characteristics of the LonWorks/IP network show a highly stochastic nature. Therefore, the time delay problem has to be resolved to achieve high performance and quality of the real-time distributed control of the process in the LonWorks/IP Virtual Device Network (VDN). It should be properly predicted and compensated. In this paper, a new distributed control scheme that can compensate for the effects of the time delay in the network is proposed. It is based on the PID controller augmented with the Smith predictor and disturbance observer. Designing methods for output feedback filter and disturbance observer are also proposed. Tracking position control experiment of a geared DC Servo motor is performed using the proposed control method. The performance of the proposed controller is compared with that of the Internal Model Controller (IMC) with the Smith predictor. The result shows that the performance is improved and guaranteed by augmenting a PID controller with both the Smith predictor and disturbance observer under the stochastic time delay in the LonWorks/IP VDN.

**Keywords:** Disturbance observer, internal model controller, LonWorks/IP virtual device network, Smith predictor, time delay.

## 1. INTRODUCTION

Recent developments in network and communication technology on the Internet and the device network (also called the control network or the field-bus network) have made remote system control possible. It means that 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 such as supervisory computers, controllers, and intelligent I/O devices (e.g., smart sensors and actuators).

The ubiquity and low cost structure of an IP network makes the 'ubiquitous' accessibility of information possible. This makes the implementation of distributed control network on the IP network possible to offer 'ubiquitous' accessibility of information from factory operations. It can be an attractive option for implementing distributed control system (DCS) on a wide area and on different types of network environments. Device network (or control network) can take advantage of these capabilities and offer 'ubiquitous' accessibility by properly interconnecting the device network with data network components.

Timely response is essential in real-time control related to the manufacturing process on the network [1,2]. Time delay is a major problem to be resolved, and estimation, prediction, and compensation of such a delay are particularly needed for real-time servo application. Time delay has been a tough problem in

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many engineering applications and a tremendous amount of efforts has been directed towards solving such a problem. In radar or sonar applications, time delay is caused by the multi-path signal transmission or the noise interference from the sender to the receiver [3,4]. In the control of the chemical process, large time constant and delay dead band in the response cause time delay [5].

Smith predictor has been widely used since Otto J. Smith devised a predictor to compensate for static time delay in control systems [5]. The Smith predictor-based controllers are usually called Internal Model Controllers (IMCs). It is known that Smith predictor-based controllers exhibit a good performance for systems with static time delay, provided that the system model is precisely known a priori. In the 1980s, some industrial controllers embedded with IMC based on the Smith predictor have been supplied for servo control systems on the factory floor [5].

Control problems subject to uncertain time delay have been less investigated than those of static time delay. With uncertain time delay, stability cannot be guaranteed and the level of control performance is usually low. In the networked distributed control system in the LonWorks/IP VDN, the time delay from the controller to the actuator can be significantly different from what one can expect from the sensor to the controller [1,2]. In order to guarantee stability and to achieve a high performance of the networked distributed control system, the time delay has to be predicted and compensated.

In this paper, a new servo control scheme that works on the network structure integrating the device network to the data network (LonWorks/IP VDN) is proposed. It includes a predictor for time delay, a disturbance observer, and a compensator. To show the effectiveness of the proposed control scheme, the performance of the proposed control scheme is compared with that of the modified Smith predictor-based IMC of a loaded DC servomotor. In Section 2, the time delay in LonWorks/IP VDN is estimated and its effect on the performance of the control system is investigated. In Section 3, the control scheme for the prediction and compensation of intermittently long time-varying delay is proposed. In Section 4, the effectiveness of the proposed control scheme is compared with that of the Smith predictor-based IMC through experiments of the DC motor.

## 2. EFFECTS OF TIME DELAY

For ubiquitous access to the information on the factory floor, the integration of device network and IP network such as LonWorks/IP VDN appears to be very useful [6]. LonWorks/IP VDN is composed of smart sensors and actuators integrated into online

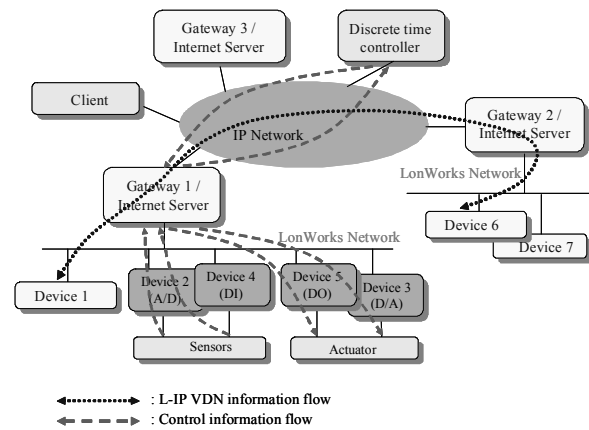


Fig. 1. DCS based on LonWorks/IP VDN structure.

(real-time) distributed control network, and characterized by peer-to-peer communication over an IP network. Fig. 1 shows the typical implementation of DCS based on LonWork/IP VDN structure. LonWorks/IP gateway (or Internet server) makes it possible to utilize the compatibilities of both the Ethernet and LonWorks networks. The Ethernet connection can support the user to access the IP network, and the LonWorks connection can support users to access LonWorks network from any workstation connected to a TCP/IP network.

Transmission characteristics of many different kinds of networks have been investigated in the past. Transmission characteristics of integrated networks such as LonWorks-IP VDN, however, drew relatively less attention. Transmission characteristics of both IP network and LonWorks-IP VDN were investigated in previous studies [1,2]. Depending on the direction of communication packets, time delay in a networked distributed control system can be conveniently categorized into two groups, one group from sensors to controllers and the other group from controllers to actuators. In view of the location, the time delay takes place during the computation in protocol conversion and network transmission in a networked distributed control system as shown in Fig. 2.

The network transmission delay in LonWorks/IP VDN is simply the sum of the delay in the device network and the delay in the data network. The delay in the device network happens when the LonWorks/IP gateway/Internet server accepts data from the sensor node on the LonWorks network or when it sends control data to the actuator node of the plant. The delay in data network originates from communications among the nodes on the IP network. The transmission delay in a data network is known to have a Gaussian distribution for transmission through long distances. Transmission through relatively short distances or transmission through many routers is known to have the Gamma or exponential distribution [7]. The transmission delay in the LonWorks/IP network is

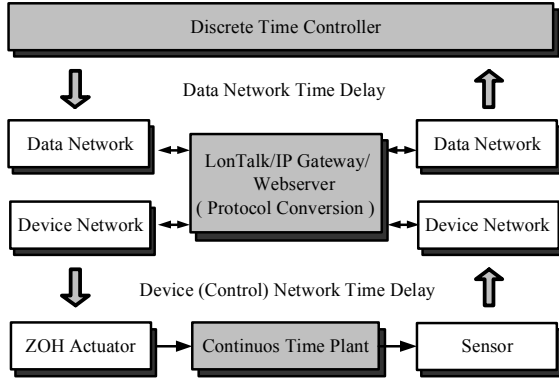


Fig. 2. Time delay in distributed control system based on LonWorks/IP VDN.

expected to have a more complex form. The delay in the round-trip transmission from the data network to the device network, and then back to the data network in the LonWorks/IP VDN was studied in [1,2] where the characteristics of both distributions were experimentally observed. This is because the delay is due to the network transmission as well as the calculation time for protocol conversion in the LonWorks/IP gateway/Internet server.

If the time delay is static, it can be identified and compensated effectively. If there is no model mismatch, the IMC based on the Smith predictor can perform better than the PID controller. In many cases, however, the delay is time varying and uncertain, and the model mismatch is almost always present due to the unknown dynamics and nonlinearities of the plant, among other factors. There have been some research studies on networked control systems (NCS) subject to time delay. Most of those studies focused on the stability of the NCS [8-12]. However, relatively less research has been carried out on control systems subject to time-varying delay in LonWorks/IP VDN. The time-varying delay is inherent in the networked distributed control system operating on LonWorks/IP VDN. Compensation for the transmission delay is necessary for real-time servo control applications.

### 3. CONTROLLER DESIGN

#### 3.1. Internal model control based on smith predictor

Fig. 3 shows the block diagram of the modified Smith predictor-based IMC for distributed control systems with time delay. The IMC based on the Smith predictor was implemented with a JAVA applet on the client web browser. The sampling interval of the discrete time controller on the data network is different from that of the velocity sensor node on the device network, and they are not synchronized. For compensation of the time delay, the Smith predictor controller was used. Using this technique, the time delay term can be completely eliminated from the

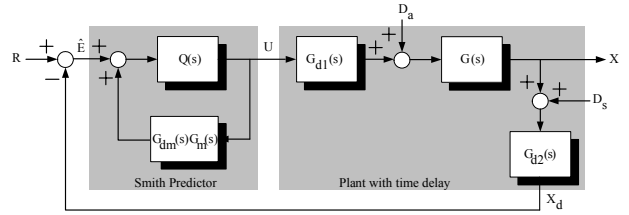


Fig. 3. Block diagram of IMC scheme of distributed control system based on modified Smith's Predictor.

characteristic equation of the closed loop system. Thus, the controller design for the process with delay can be reduced to one without delay.

In the block diagram in Fig. 3, the transfer function from the input to the output can be represented as:

$$\frac{X(s)}{R(s)} = \frac{G_c G_p G_{d1}}{1 + G_c G_{pm} - G_c G_m + G_c G_p G_{d1} G_{d2}}, \quad (1)$$

$$G(s) = G_{d1}(s) G_p(s) G_{d2}(s), \quad (2)$$

where

- $G_p$ : Plant
- $G_{pm}$ : Nominal plant without time delay
- $G_d$ : Time delay
- $G_{dm}$ : Modeled time delay
- $G_m$ : Nominal plant with time delay
- $G_c$ : Controller
- $G$ : Plant with time delay.

The transfer functions for time delay  $G_{d1}, G_{d2}$  can be combined into  $G_d$  as both of them are induced by LonWorks/IP VDN. Consequently, the transfer function in (1) can be rewritten as:

$$\frac{X_d(s)}{R(s)} = \frac{G_c G_p G_d}{1 + G_c G_{pm} - G_c G_m + G_c G_p G_d}. \quad (3)$$

Zero-order Pade approximation of the time delay  $\tau$  can be justified if  $|\tau s|_{s=j\omega}$  is small enough. If it is the case,  $G_{pm}$  and  $G_m$  can be described as:

$$G_{pm} = \frac{B(s)}{A(s)}, \quad G_m = G_{pm} \left( \frac{1}{1 + \tau s} \right). \quad (4)$$

If the plant is of the minimum phase system, the IMC controllers  $Q$  and  $G_c$  for step inputs can be designed respectively as [5]:

$$Q = \frac{1}{\lambda s + 1} \cdot \frac{A(s)}{B(s)}, \quad (5)$$

$$G_c = \frac{1}{\lambda s} \cdot G_{pm}^{-1}(s). \quad (6)$$

If  $G_{pm}(s)$  in (4) has the first-order dynamics and has no zeros,  $G_c(s)$  in (6) will be the integral-proportional and derivative (I-PD) controller. When there is no model mismatch, the parameter  $\lambda$  in the Smith predictor can be adjusted to achieve the desired response. The quantitative relationship between  $\lambda$  and the closed loop system performance is reflected in the overshoot and the rise time. In case of a model mismatch, increasing  $\lambda$  will improve the robustness of the system. Although the IMC based on the Smith predictor outperforms the PI controller, it is not enough for compensation of the time-varying delay in the LonWorks/IP VDN. For the prediction of the time-varying delay and its compensation, a new control scheme needs to be devised.

In (6), the controller  $G_c$  is composed of pure integrator, the gain of  $1/\lambda$  and the inverse of the plant model without the time delay  $G_{pm}^{-1}$ . If the plant without the delay is not the minimum phase, the internal controller in (6) cannot be designed.

Assume that the plant  $G_p$  can be written as:

$$G_p = \frac{B(s)}{A(s)} = \frac{B^+(s)B^-(s)}{A(s)}, \quad (7)$$

where  $B^+(s)$  is composed of stable zeroes and  $B^-(s)$  is composed of unstable zeroes. Then, the internal controller  $Q$  and  $G_c$  can be designed, respectively, as:

$$Q = \frac{1}{\lambda s + 1} \cdot \frac{A(s)B^-(s)}{B^+(s)\psi}, \quad (8)$$

$$G_c = \frac{A(s)B^-(s)}{B^+(s) \left[ \lambda \psi s + (\psi - |B^-(s)|^2) \right]}, \quad (9)$$

where  $\psi = \max |B^-(j\omega)|^2$ ,  $\omega \in [0, \pi/T_s]$  and  $T_s$  is the sampling time.

If the prediction model  $G_{pm}$  perfectly matches the plant with time delay, the approximate relationship between the input and the output can be written as

$$\frac{X}{R} = QG_{d1}G_p = \frac{1}{\lambda s + 1} \cdot \frac{1}{\tau_1 s + 1} \cdot \frac{|B^-(s)|^2}{\psi}, \quad (10)$$

where  $\tau_1$  is the time delay from the controller to the actuator.

The tracking performance and the robustness of the IMC based on the Smith predictor are heavily dependent on parameter  $\lambda$ . Equation (10) shows that the amplitude of the output is always less than or equal to the reference, with added phase delay.

### 3.2. Feedback compensator

The effects of the sensor noise or disturbance  $D_s$  also need to be studied. If there is no model mismatch in the plant and in the time delay, the transfer function between  $D_s$  and the delayed output  $X_d$  can be described as

$$\frac{X_d}{D_s} = \frac{G_{d2}}{1 + G_c G_{pm}}, \quad (11)$$

whereas the relationship between the disturbance  $D_s$  and the plant output  $X$  is given by

$$\frac{X}{D_s} = \frac{G_c G_{pm} G_{d1} G_{d2}}{1 + G_c G_{pm}}. \quad (12)$$

In (11) and (12),  $D_s$  directly influences the delayed output  $X_d$  and the plant output  $X$ . In order to achieve a higher performance, the robustness of the control system to the disturbance  $D_s$  and the model mismatch must be assured and the time delay's prediction error must be kept sufficiently small. Assume that the transfer function of the plant can be described with the nominal plant and the multiplicative modeling error as

$$G_p = G_{pm} (1 + G_\delta), \quad (13)$$

where  $G_\delta$  is the modeling error. Also assume that the prediction error of time delay can be written as:

$$G_d = G_{d1} G_{d2} = e^{-(\tau_1 + \tau_2)s} = e^{-\tau s} \cong \frac{1}{(\tau s + 1)}, \quad (14)$$

$$G_{dm} = e^{-\tau_m s} \cong \frac{1}{\tau_m s + 1}, \quad (15)$$

$$G_d = G_{dm} \cdot e^{-\tau_\delta s} \cong \frac{1}{(\tau_m s + 1)} \cdot \left( 1 - \frac{\tau_\delta s}{\tau_\delta s + 1} \right), \quad (16)$$

where  $\tau = \tau_m + \tau_\delta$ .

Then the difference between the delayed plant output and the predicted output,  $\Delta X(s)$  in Fig. 3 is given by:

$$\Delta X \equiv (G - G_m)U = \frac{G_{pm} G_{dm}}{\tau_\delta s + 1} (G_\delta - \tau_\delta s)U. \quad (17)$$

Equation (17) implies that the effects of the model mismatch and the prediction error of time delay appear in the plant output even after filtering by the internal model controller  $G_c$ . It is due to the fact that the polynomial  $(G_\delta - \tau_\delta s)$  is bounded but not converged to zero, whereas the function  $\tau_\delta s / (\tau_\delta s + 1)$  works as a high pass filter and makes the margin of the controller  $Q$  small. Any high-frequency noise or disturbance added at sampling instances by sensors is directly sent to the controller

and deteriorates the performance and stability of the control system. A disturbance observer is needed in order to compensate for the model mismatch and the prediction error of time delay. Also, a feedback compensation filter is necessary to cancel out the effect of the high pass filter characteristic of  $\tau_\delta s / (\tau_\delta s + 1)$ . Thus, the controller needs to be integrated with the feedback compensation filter and the disturbance observer. The proposed control scheme is shown in Fig. 4.

After the disturbance observer is adopted, the difference between the delayed plant output  $X_d$  and the predicted output of the plant  $X_p$  can be defined as:

$$\Delta X(s) \equiv X_d - X_p = GU - G_m \hat{U}. \quad (18)$$

Referring to Fig. 4, if the proper filter  $H$  is the same as the disturbance observer  $K$ , then the relationship between  $Q$ ,  $R$ ,  $H$ ,  $U$ ,  $\Delta X$ ,  $X_d$ , and  $X$  can be written as:

$$\hat{U} = Q(R - H \cdot \Delta X), \quad (19)$$

$$U = \hat{U} + H \cdot \Delta X = QR + H(1 - Q)\Delta X, \quad (20)$$

$$X_d = G_d G_p U = G_d G_p QR + G_d G_p H(1 - Q)\Delta X, \quad (21)$$

$$X = G_{d1} G_p U = G_{d1} G_p QR + G_{d1} G_p H(1 - Q)\Delta X. \quad (22)$$

Substituting (14) through (16) into equation (21), one can have:

$$X_d = (1 + G_\delta) \left( 1 - \frac{\tau_\delta s}{1 + \tau_\delta s} \right) G_m QR + (1 + G_\delta) G_m H(1 - Q)\Delta X. \quad (23)$$

In order to characterize the effect of the model mismatch and the prediction error of the delay, the undesired output can be defined as

$$\Phi_d(s) \equiv G_\delta G_m QR - \tau_\delta s(1 + G_\delta)e^{-\tau_\delta s} G_m QR + (1 + G_\delta)e^{-\tau_\delta s} G_m H(1 - Q)\Delta X. \quad (24)$$

The norm of  $\Phi_d(s)$  has to converge to zero in the

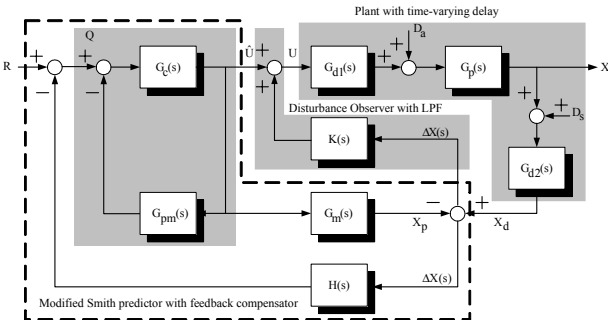


Fig. 4. Block diagram of the proposed control scheme.

wide frequency ranges. In order to achieve that, the low pass filter  $H(s)$  can be designed as:

$$\|H(j\omega)\| = \left[ \frac{\|(G_\delta - \tau_\delta s(1 + G_\delta)e^{-\tau_\delta s})QR\|}{\|(1 + G_\delta)e^{-\tau_\delta s}(1 - Q)\Delta X\|} \right]. \quad (25)$$

It was already shown in the design of the IMC  $Q(s)$  in equations (1) through (10) that there is no pole-zero cancellation in  $Q(s)$ . For a better response of the proper filter, the actual output  $x$  needs to be implemented. However, only the time-delayed version of output  $x_d$  can be transmitted on the network channel. The output  $X(s)$  and the undesired output  $\Phi(s)$  can be defined respectively as:

$$X \equiv G_{pm}QR - \tau_1 s(1 + G_\delta)e^{-\tau_1 s} G_{pm}QR + G_\delta G_{pm}QR + (1 + G_\delta)e^{-\tau_1 s} G_{pm}H(1 - Q)\Delta X, \quad (26)$$

$$\Phi \equiv e^{-\tau_1 s} G_{pm} [(G_\delta - \tau_1 s)QR + (1 + G_\delta)H(1 - Q)\Delta X]. \quad (27)$$

The norm of  $\Phi(s)$  should be close to zero in the wide frequency ranges as in the case of  $\Phi_d(s)$ . Then the relationship between  $Q$ ,  $R$ ,  $H$ , and  $\Delta X$  are given by:

$$\|H(j\omega)\| = \left[ \frac{\|(G_\delta - \tau_1 s)QR\|}{\|(1 + G_\delta)(1 - Q)\Delta X\|} \right], \quad (28)$$

$$\|H \cdot \Delta X\| = \left[ \frac{\|(G_\delta - \tau_1 s)QR\|}{\|(1 + G_\delta)(1 - Q)\|} \right]_{s=j\omega}, \quad (29)$$

$$\left\| \frac{\Delta X}{R} \right\| = \left[ \frac{\|(G_\delta - \tau_1 s)QH^{-1}\|}{\|(1 + G_\delta)(1 - Q)\|} \right]_{s=j\omega}, \quad (30)$$

$$\|\Delta X\| = \left[ \frac{\|(G_\delta - \tau_1 s)QH^{-1}R\|}{\|(1 + G_\delta)(1 - Q)\|} \right]_{s=j\omega}. \quad (31)$$

In (28), the larger amplitude of  $\Delta X(s)$  implies a smaller magnitude of  $H(s)$ . According to (29), the norm of  $H(s)\Delta X(s)$  has to be bounded. Equations (30) and (31) indicate that the amplitude of the prediction error  $\Delta X(s)$  can be suppressed if the amplitude of  $H(s)$  is larger in the low-frequency range of the reference signal and smaller in the high-frequency range of the noise signal. If the plant could be described by the first-order system model such as  $1/(1 + \tau s)$ , a proper filter can be a low pass filter, for example  $(1 + \tau_m s) / (1 + 2\zeta\omega s + \omega^2 s^2)$ . If the plant is to be the second-order system, such as  $1/s(1 + \tau s) = 1/s - \tau/(1 + \tau s)$ , then the above phase lag compensated low pass filter is not proper anymore.

Model mismatches due to non-linear friction and un-modeled dynamics have to be carefully considered in designing a proper feedback compensation filter. If the nominal plant model is the second-order system with a pure integrator and the controller type is IMC, a proper feedback compensation filter can be a second-order low-pass filter designed by (32). On the other hand, if the controller is of the PID type, a proper filter can be a second-order band pass filter designed by (33).

$$H(s) = \frac{1}{1 + 2\zeta\tau_{\max}s + \tau_{\max}^2s^2}, \quad (32)$$

$$H(s) = \frac{s}{1 + 2\zeta\tau_{\max}s + \tau_{\max}^2s^2}, \quad (33)$$

where  $\zeta$  is the damping ratio and frequency selectivity of  $H$ , and  $\tau_{\max}$  is the maximum allowable transmission interval [9,10]. The values of  $\zeta$  and  $\tau_{\max}$  can be determined by the frequency of the reference signal.

### 3.3. Disturbance observer

Aside from model mismatches, there is also a time-varying delay on the network channel. So the disturbance observer should be incorporated into the controller to compensate for non-periodic and uncertain disturbance due to the prediction error in time delay. In order to design the disturbance observer, let us define  $\hat{Q}$  and  $\hat{G}$ , respectively, as:

$$\hat{Q} \equiv \frac{G_c}{1 + G_c G_{pm}(1 - G_{dm}H)}, \quad (34)$$

$$\hat{G} \equiv \frac{G_d G_p}{1 - G_d G_p K}. \quad (35)$$

Then the proposed control scheme can be expressed as in Fig. 5, and the input-output relationship can be given by:

$$\frac{X}{R} = \frac{\hat{Q}\hat{G}(1 - G_{dm}G_{pm}K)G_d^{-1}}{1 + \hat{Q}\hat{G}H(1 - G_{dm}G_{pm}K)}. \quad (36)$$

Referring to (36),  $G_{dm}G_{pm}K \neq 1$  should hold. Let (36) to be defined as:

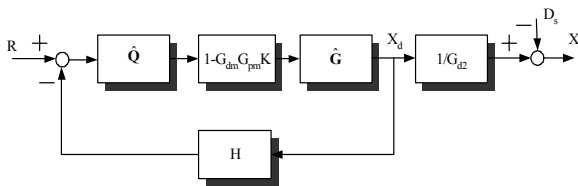


Fig. 5. Block diagram of the modified control scheme.

$$\frac{X}{R} \equiv \frac{N(s)}{L(s)} \equiv \frac{N_1(s)N_2(s)}{L_1(s) + L_2(s)}. \quad (37)$$

Then

$$N_1(s) = G_c G_{pm}, \quad (38)$$

$$N_2(s) = (1 + G_\delta)G_{d1}(1 - G_{dm}G_{pm}K), \quad (39)$$

$$L_1(s) = 1 + G_c G_{pm}, \quad (40)$$

$$L_2(s) = G_c G_d G_p H - G_c G_{dm} G_{pm} H - G_d G_p K. \quad (41)$$

In order to describe (37) only with (38) and (40),  $\|G_{dm}G_{pm}K\|_{s=j\omega}$  and  $\|L_2(j\omega)\|$  should be close to zero. Then the disturbance observer can be designed as:

$$K(s) = kG_c(s)H(s), \quad (42)$$

where  $k \leq \max\|1 - (1 + G_\delta)e^{\tau\delta s}\|_{s=j\omega}$ ,  $k \neq 0$  can be determined within the maximum absolute value of the modeling error of the plant. If the modeling error could be as small as to be negligible, then the gain  $k$  can be zero. This means that only the proper feedback filter is needed to stabilize the control system.

As a result of implementing a proper filter and disturbance observer, the proposed control scheme can be stabilized and desirable performance may be achieved. The LonWorks/IP network transmission characteristics limit the control bandwidth. Tracking control of high-frequency reference could not be easily implemented. So, in the low-frequency ranges, the proposed control scheme can make the system more robust to the time-varying delay.

## 4. EXPERIMENTS

### 4.1. Plant model

A PWM-driven geared DC servomotor is chosen as the physical plant to be controlled. For the purpose of controller design, the motor's dynamics was identified by curve-fitting the experimental step response data to that of the second-order linear systems. It is characterized by

$$u = 0.150\ddot{x} + 1.042\dot{x}, \quad (43)$$

where  $u$  is torque command, and  $\dot{x}$  is velocity. Then, the transfer function between the input voltage and the output position can be written as

$$G_{pm}(s) = \frac{1}{s(0.150s + 1.042)}. \quad (44)$$

A more realistic model that incorporates the effect of friction and compliances is adopted for the motor dynamics. However, the motor-driven system also has saturation, dead band, and other nonlinearities. In fact,

the motor dynamics was set with around 10% model mismatch to (43), incorporating the friction model that includes the effect of the static friction and the Coulomb friction but ignores the memory effect [13]. The plant dynamics adopted in the experiments was

$$u = 0.165\ddot{x} + 1.042\dot{x} + f(\dot{x}, u),$$

$$f(\dot{x}, u) = \begin{cases} F_s \operatorname{sgn}(u), & \text{if } \dot{x} = 0 \\ F_c \operatorname{sgn}(\dot{x}), & \text{else if } |\dot{x}| > \dot{x}_s \\ (F_c + (F_v - F_c)e^{-\beta\dot{x}^2}) \operatorname{sgn}(\dot{x}), & \text{else} \end{cases} \quad (45)$$

where  $F_s$  is stick friction,  $F_c$  is Coulomb friction,  $F_v$  is viscous friction, and  $\beta$  is stick-slip coefficient. In the experiments, the above coefficients are set to  $F_s = 400$ ,  $F_c = 1$ ,  $F_v = 200$ , and  $\beta = 0.001$ .

4.2. Results of experiments

The experiments were performed with a Texas Instrument DSP2406A processor, a PWM motor driver and a geared DC motor. The time delay in the LonWorks/IP VDN randomly varies, making prediction difficult. In the experiments, the time delay was assumed to be varied between 0.1 and 1.5 sec. The sampling interval sequence and the time delay sequence used in the experiments are shown in Fig. 6.

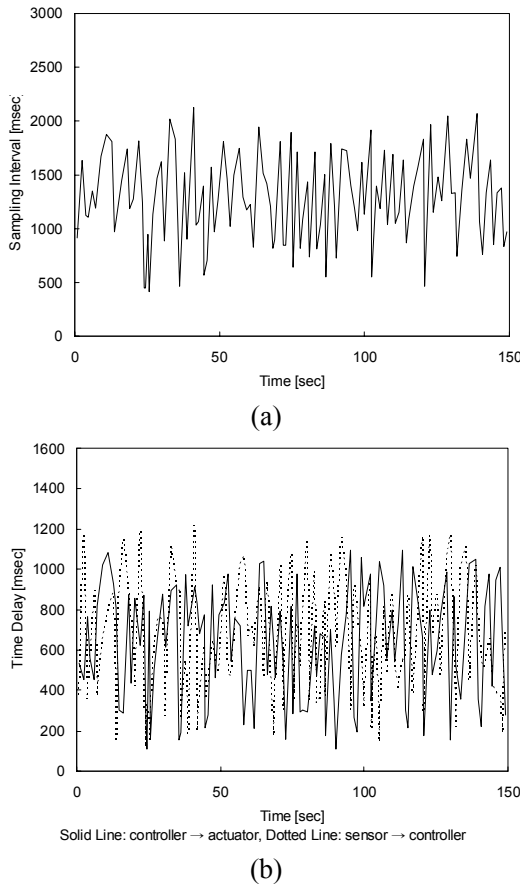


Fig. 6. (a) Sampling interval and (b) time delay.

The time delay in the Smith predictor was set at 0.1, 0.5, or 1 sec, whereas the sampling interval  $T_s$  for the controller was fixed at 0.5 sec. In the experiments, the control command from the controller is calculated, and delayed in accordance with the experimental time delay sequence as shown in Fig. 6.

Figs. 7-9 compare the tracking control performances of the IMC based on the Smith predictor, and the proposed controller based on the Smith predictor and the disturbance observer. It is shown in Figs. 7-9 that the Smith predictor-based IMC is robust enough to stabilize the networked distributed control system. It is also shown that the position error of the Smith predictor-based IMC becomes much larger than that

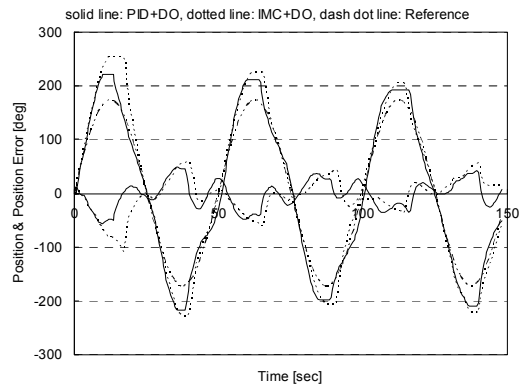


Fig. 7. Results while  $\tau_m$  is set to 0.1sec.

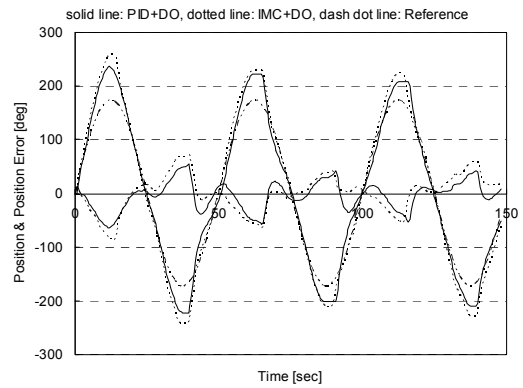


Fig. 8. Results while  $\tau_m$  is set to 0.5sec.

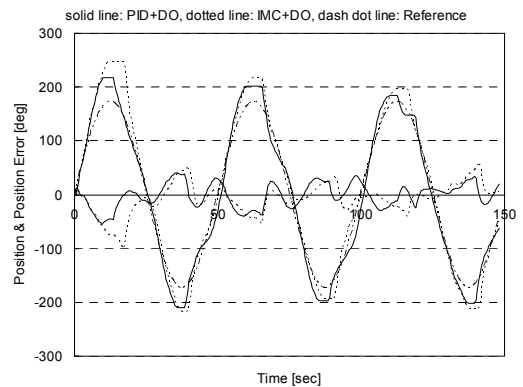


Fig. 9. Results while  $\tau_m$  is set to 1sec.

of the proposed control scheme.

## 5. CONCLUSIONS

In this paper a new control scheme for the real-time distributed control on the LonWorks/IP VDN was proposed. It is based on IMC based on modified Smith predictor, model based disturbance observer, and feedback compensator for the cancellation of the high frequency noise and disturbance. The proposed control scheme proved to be robust even under the model mismatch and the prediction error in the time-varying delay. The proposed control scheme is, therefore, expected to improve the quality and reliability of real-time distributed control of the process on the factory floor.

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