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Predictive and Preventive Maintenance using Distributed Control on LonWorks/IP Network

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Abstract : The time delay in servo control on LonWorks/IP Virtual Device Network (VDN) is highly stochastic in nature. LonWorks/IP VDN induced time delay deteriorates the performance and stability of the real-time distributed control system and hinders an effective preventive and predictive maintenance. Especially in real-time distributed servo applications on the factory floor, timely response is essential for predictive and preventive maintenance. In order to guarantee the stability and performance of the system for effective preventive and predictive maintenance, LonWorks/IP VDN induced time delay needs to be predicted and compensated for. In this paper position control simulation of DC servo motor using Zero Phase Error Tracking Controller (ZPETC) as a feedforward controller, and Internal Model Controllers (IMC) based on Smith predictor with disturbance observer as a feedback controller is performed. The validity of the proposed control scheme is demonstrated by comparing the IMC based on Smith predictor with disturbance observer.

Key Words : Internal Model Controller(IMC), LonWorks/IP Virtual Device Network(VDN), predictive and preventive maintenance, time delay, Zero Phase Error Tracking Controller(ZPETC)

1. Introduction

The availability and extendibility of the Internet access is increased day after day, and the backbone of modern enterprise data networks is along with the "internet". Recently, access to the information of the devices and equipments from several locations, any time, and anywhere in the enterprise is being implemented. One example can be the intelligent building system. Another example can be the intelligent manufacturing system needs for flexibility and modularity of the smart devices and equipments. The above mentioned systems are generally equipped with smart sensors, actuators, and controllers which provide very useful information if utilized properly[1], and need to be properly monitored and controlled. For this predictive and preventive maintenance including monitoring and control for diagnosis and remedy action should be performed. These activities can be performed by web-based predictive and preventive maintenance using ubiquitous accessibility[2].

Web-based predictive and preventive maintenance inevitably involves the distributed monitoring and control network. LonWorks/IP Virtual Device Network (VDN) is composed of smart sensors, actuators, and controllers which provide interoperability in variety of manufactures. Therefore, LonWorks/IP VDN can be an attractive option for implementing the web-based predictive and preventive maintenance on the factory floor[3, 4].

Feedback systems wherein the control loops are closed through a real time network are called networked control systems (NCSs). The defining feature of an NCS is that control information is exchanged using a network among control system components such as sensors, controllers, actuators, etc. An NCS has the advantages of reduced system wiring, ease of system diagnosis and maintenance, and increased system agility. In result, NCS is concerned primarily with the quality of real-time reliable service on the device network. But based on the communication architecture and the chosen hardware, the characteristics of time delay between sensors, actuators, and controllers could be bounded and constant, or bounded but random. This type of time delay could degrade a system's performance and possibly cause system instability.

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The effective and efficient predictive and preventive maintenance on the factory floor is also related to the time delay. LonWorks/IP VDN structure can offer the web-based real-time predictive and preventive maintenance on the factory floor. Time delay on the distributed control network such as LonWorks/IP VDN can makes the web-based real-time predictive and preventive maintenance impossible.

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. Consequently in applications of remote control using network and system to be demand accuracy and real-time control, real-time and timely response is embossed as an important problem[3].

In a preliminary application of VDN to predictive and preventive maintenance on the factory floor, some studies were performed[2~6]. In[6], a control scheme based on Smith predictor, feedback compensator, and disturbance observer is suggested to minimize the effect of uncertain time delay and the modeled mismatch. In this paper, position control of DC servo motor having hard nolinearities across the VDN is investigated. The performance and the stability of distributed control system in VDN are analyzed and a control scheme incorporating zero phase error tracking controller (ZPETC) [9] into the control structure suggested in [6] is suggested to compensate for the phase lag of the closed loop system. The validity of the proposed control scheme is demonstrated through computer simulation.

2. LonWorks/IP VDN for Distributed Control

The concept and design of the distributed control networks is based on sensors and actuators integrated into any on-line control network. Carefully evaluated the requirements for the infrastructures and capabilities, LonWorks/IP VDN architecture can be a good option for implementing the seamless wide area distributed control systems as well as in the building automation industry.

Fig. 1 shows the typical implementation of the distributed control systems based on LonWorks/IP VDN architecture. LonWorks/IP gateway utilizes both an Ethernet capability and LonWorks capability. the ethernet connection can support user to access IP network, and the LonTalk (LonWorks protocol) adapter can support user to access LonWorks network from any workstation with a TCP/IP connection. In this server-client model, a server will control and monitor LonWorks network locally and clients can control and monitor LonWorks network remotely. The control information can be exchanged by the binding between the input network variables and the output network variables.

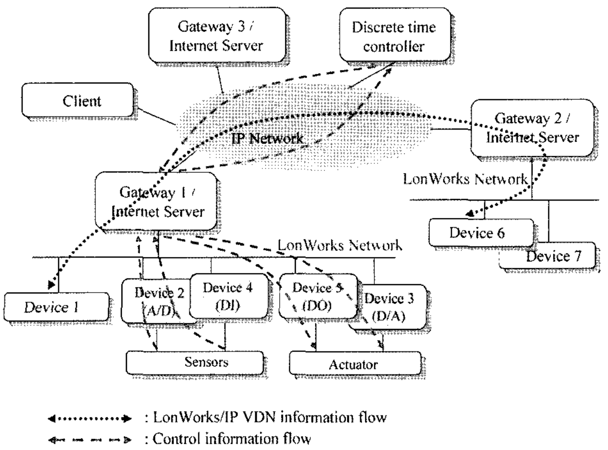


Fig. 1. Distributed Control Systems on LonWorks/IP Virtual Device Network.

In a network based remote control system 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 composed of two parts: 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 block diagram of the distributed control on LonWorks/IP VDN with time delay. The discrete time controller can be implemented with JAVA applet

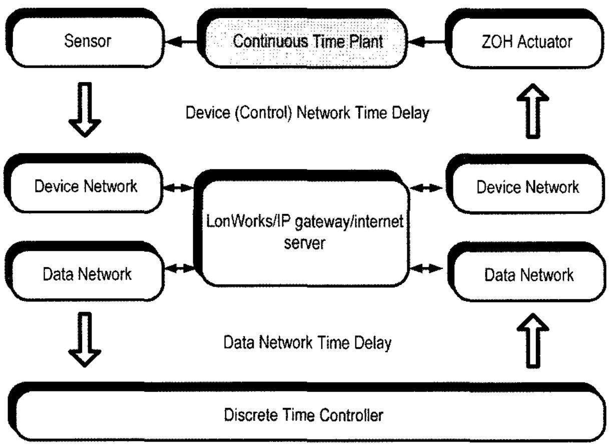


Fig. 2. Block diagram of the distributed control on LonWorks/IP VDN with time delay.

on the client web browser. 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 stidied the stability of the NCS [7, 8]. 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 [9, 10]. For the cases of transmission in VDN it is more likeable to Gaussian distribution rather than Gamma or exponential distribution, but both distributions were experimentally observed [5]. 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.

Many sensors and actuators supporting various types of manufacturing processes can be integrated into LonWorks/IP VDN by virtue of the features of each node (interoperability in variety of manufactures, peer-to-peer communication, and coverage from the bit-level sensors/actuators to the control level). Any servo application can be included in the processes of factory automation. In any servo application real-time and timely response is very crucial. For the effective and efficient predictive and preventive maintenance, a lot of sensors and actuators have to be able to measure actual data and operate correct actions on time. In this sense DC motor control as a preliminary application on LonWorks/IP VDN needs to be investigated.

3. Distributed Control of DC Motor

3.1 Plant Modeling

A voltage-driven DC servomotor with relatively slow velocity response is chosen as the physical plant to be controlled. Fig. 3 shows a virtual experimental setup for computer simulation. For the purpose of controller design the dynamics of the motor was identified by curve-fitting the experimental step response data to that of the 2^{nd} order linear systems. It is characterized by

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

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

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

More realistic model that incorporates the effect of friction and compliances is adopted for simulation of the motor dynamics. In fact the motor dynamics was set with around 10% model mismatch to the Eq. (2), and the friction model that includes the effect of the static friction and the Coulomb friction but ignores the memory effect was incorporated [11]. The plant dynamics adopted in the computer simulation was

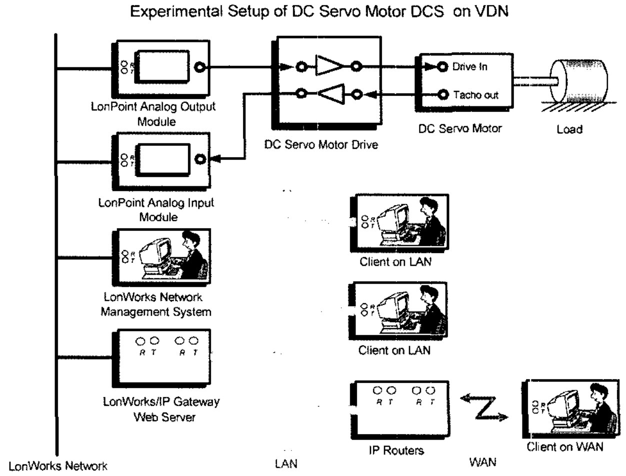


Fig. 3. Virtual experimental setup for computer simulation.

$$\begin{aligned} u &= 0.2938\ddot{x} + 1.0772\dot{x} + f(\dot{x}, u) \\ f &= \begin{cases} F_s sgn(u), \text{if } \dot{x} = 0 \\ F_c sgn(\dot{x}), \mathit{elsei\ f}|\dot{x}| > |\dot{x}_s| \\ (F_c + (F_v - F_c)e^{-\beta\dot{x}^2})sgn(\dot{x}), \mathit{others} \end{cases} \end{aligned} \tag{3}$$

where F_s is stick friction, F_c is Coulomb friction, F_v is viscous friction, and β is stick-slip coefficient. In the computer simulation they are set to F_s=0.5463, F_c=0.25, F_s=0.5, and β=9.0 respectively.

3.2 Controller Design

In the previous studies a stabilizing controller based on Smith predictor [12], output feedback filter, and disturbance observer was developed and tested through the distributed control on LonWorks-IP VDN with uncertain time delay [6]. Fig. 4 shows a block diagram of modified Smith's Predictor based control scheme with output feedback filter and disturbance observer to compensate for the prediction error of time delay and the modeled mismatch.

In Fig. 4, a stabilizing controller $G_c(s)$ can take the form of IMC or PID [6]. If there is no modeled mismatch (G_{pm}=G_p) and no prediction error of time delay (G_{dm}=G_d), the transfer function from the input to the

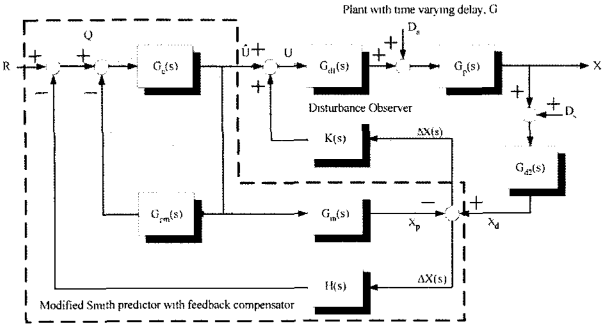


Fig. 4. Smith predictor based control with disturbance observer.

output can be represented as:

$$\frac{X(s)}{R(s)} = \frac{G_cG_{pm}G_{dm1}}{1+G_cG_{pm}} \tag{4}$$

where

G_p: Plant

G_{pm}: Nominal plant without time delay

G_d: Time delay ($G_d=G_{d1}G_{d2}$)

G_{dm}: Modeled time delay ($G_{dm}=G_{dm1}G_{dm2}$)

G: Plant with time delay ($G=G_pG_d$)

G_m: Nominal plant with time delay ($G_m=G_{pm}G_{dm}$)

G_c: Controller

H: Output feedback filter

K: Disturbance observer.

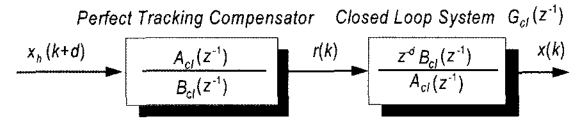
If the controller $G_c(s)$ takes the IMC form, the output feedback filter and the disturbance observer take the proper forms, the resulting input and output relationship can be approximated as:

$$G_{cl}(s) \equiv \frac{X(s)}{R(s)} \simeq \frac{G_cG_{pm}G_{dm1}}{1+G_cG_{pm}} = \frac{e^{-\tau_{m1}s}}{\lambda s+1} \tag{5}$$

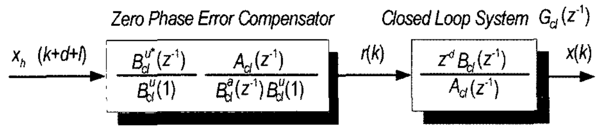
where λ is the parameter related to the performance and robustness, τ_{m1} is the average of the time delay and affected by prediction error of the time delay.

Eq. (5) shows that the tracking error is likely to depend on the parameter λ and the prediction error of the time delay, and results in phase delay. In order to compensate for the phase delay, Tomizuka [13] proposed a feedforward controller based on perfect tracking controller (PTC) or zero phase error tracking controller (ZPETC) by combinations of pole/zero cancellation and phase cancellation. In [13] the feedback loop was designed for regulation purposes, and a feedforward controller was placed for tracking purposes. For the design of a feedforward controller in discrete time domain, zero-order-hold effect has to be considered.

(a) Perfect Tracking Controller



(b) Zero Phase Error Tracking Controller



$B_{cl}^{u}(1)$: *the sum of the coefficients of the polynomial of unstable zeros*

$B_{cl}^{a}(z^{-1})$: *the polynomial of stable zeros,* $B_{cl}^{u}(z^{-1})$: *the polynomial of unstable zeros*

$B_{cl}^{u*}(z^{-1}) = z^{-l}B_{cl}^{u}(z)$, *l: the number of unstable zeros of* $G_{cl}(z^{-1})$

Fig. 5. Block diagram of PTC and ZPETC.

Then, Eq. (5) can be described by:

$$G_{cl}(z^{-1}) \equiv \frac{X(z^{-1})}{R(z^{-1})} = \frac{(T/\lambda)z^{-d}}{1-e^{-T/\lambda}z^{-1}} \tag{6}$$

where $T \simeq (1-e^{-sT})/s$ is the sampling interval provided that it is small enough, and $d \simeq \tau_{m1}/T$ is the number of samples of delay, and varied with the τ_{dm}.

Fig. 5 shows the block diagram of the feedforward controllers. If the zeros of the plant transfer function are all in the stable region, the feedforward controller is designed to be perfect tracking controller (PTC). On the other hand, if there is at least one unstable zero, the feedforward controller is designed to be ZPETC. There is no unstable zeros in Eq. (6). Then the resulting feedforward controller can be designed by:

$$r(k) = \frac{1-e^{-T/\lambda}z^{-1}}{T/\lambda}x_h(k+d) \tag{7}$$

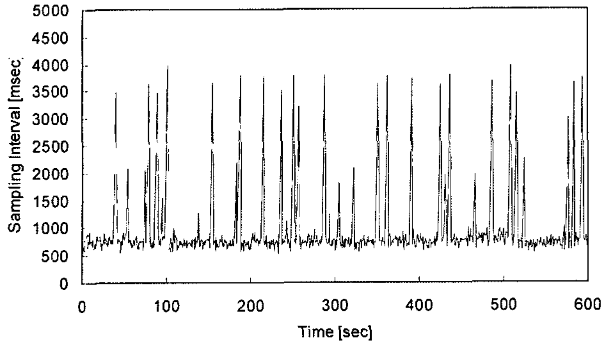
where $r(k)$ is the reference input, and $x_h(k)$ is the desired output.

The sampling interval sequence and the time delay sequence used in the computer simulation are shown in Fig. 6. The time delay on the LonWorks/IP VDN varies in a random manner so that it is not easy to predict. Time delays can make the effective and efficient preventive and predictive maintenance impossible. Time delay needs to be compensated for the effective preventive and predictive maintenance.

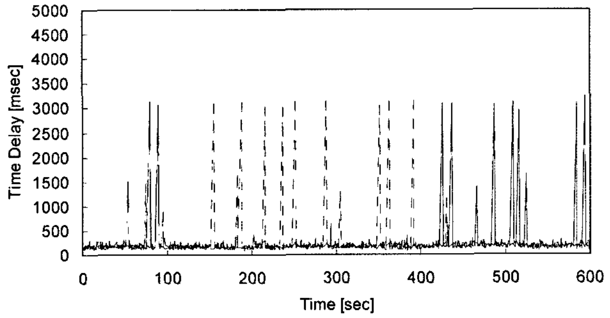
4. Result of Simulation and Analysis

4.1. Result of Simulation

In the simulation the time delay in the Smith predictor of the closed loop system was set at 0.1, 0.5, 1, or 3 sec, while the sampling interval for the controller was



(a) Sampling Time Sequences

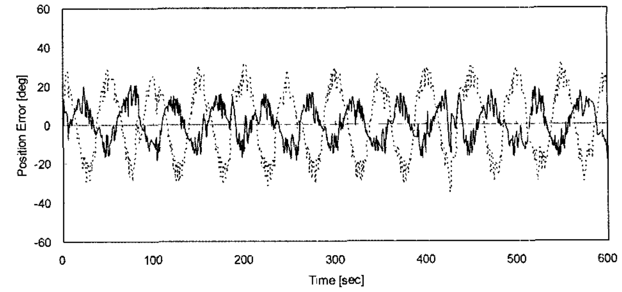


Solid line: controller → actuator, Dotted line: sensor → controller

(b) Time Delay Sequences

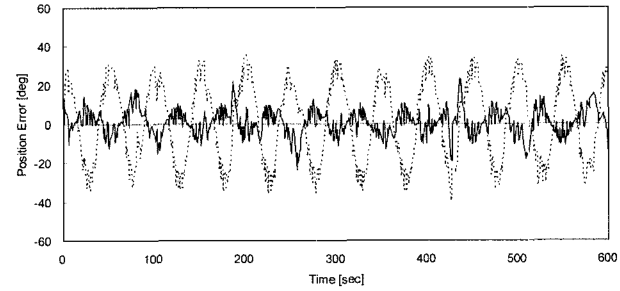
Fig. 6. (a) Sampling interval, and (b) time delay.

fixed at 0.5 sec. The control command from the controller is calculated, and delayed in accordance with the experimental time delay sequence as shown in Fig. 6. The plant output was updated every 2 msec through the 4th order Runge-Kutta integration [14]. In order to get better performance, T/λ has to be adjusted on account of the approximation error ($T \simeq (1-e^{-sT})/s$) and the variable number of samples of delay ($d \simeq \tau_{m1}/T$) in Eq. (6).



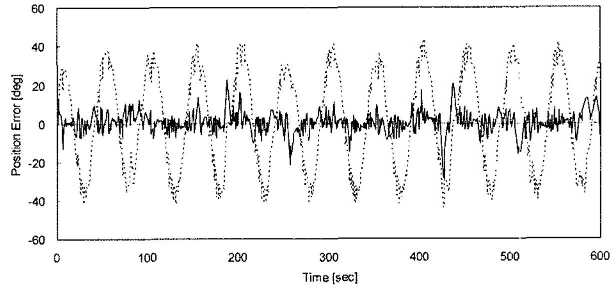
Solid Line: Phase Lag Compensator + IMC with Disturbance Observer
Dashed Line: IMC with Disturbance Observer

Fig. 7. Simulation results when τ_{dm} is set to 0.5 sec.



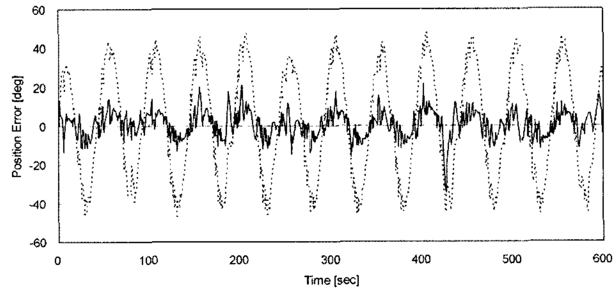
Solid Line: Phase Lag Compensator + IMC with Disturbance Observer
Dashed Line: IMC with Disturbance Observer

Fig. 8. Simulation results when τ_{dm} is set to 1.0 sec.



Solid Line: Phase Lag Compensator + IMC with Disturbance Observer
Dashed Line: IMC with Disturbance Observer

Fig. 9. Simulation results when τ_{dm} is set to 2.0 sec.



Solid Line: Phase Lag Compensator + IMC with Disturbance Observer
Dashed Line: IMC with Disturbance Observer

Fig. 10. Simulation results when τ_{dm} is set to 3.0 sec.

Figs. 7~10 compare the tracking control performances of the IMC control scheme based on the Smith predictor, output feedback filter and disturbance observer in Fig. 4, and the proposed controller in Fig. 5. The simulation results show that as the predicted time delay gets smaller the tracking error also gets smaller. It is shown in the Figs. 7~10 that the Smith predictor based IMC in Fig. 4 is enough to stabilize the networked distributed control system if the predicted time delay is small. It is also shown that the position error of the Smith predictor based IMC in Fig. 4 becomes larger as the predicted time delay gets larger. Furthermore, the magnitude of position error of the Smith predictor based IMC in Fig. 4 is directly related to the prediction error of the time delay. On the other hands the proposed control composed of a feedback controller (Smith predictor based IMC in Fig. 4) and a feedforward controller(PTC/ZPETC in Fig. 5) compensates for the phase error effectively, and gets the tracking error smaller than the control in Fig. 4.

4.2. Analysis of the result

However the proposed control compensates for the phase error effectively, and gets the tracking error smaller than the control in Fig. 4, the glitch and the abrupt phase inversion of the tracking error were shown between 420 sec and 430 sec in the Figs. 7-10. It is considered owing to the fact that the relatively long time delays over 1 sec take place in order from controller to actuator, from sensor to controller and from controller to actuator in Fig. 6. Except for the case the proposed control proved to be effect and efficient for the tracking position control on the LonWorks/IP VDN with time delay.

5. Conclusion

In this paper, as a preliminary step to the application of the LonWorks/IP VDN for the predictive and preventive maintenance of the manufacturing processes, the real-time distributed control simulation of the DC servo motor was performed. The proposed control scheme proved to be efficient at cancelling the phase error, and therefore is expected to improve the quality and reliability of real-time distributed control of processes on the factory floor.

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