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# Robust Network Motion Control System Based on Disturbance Observer

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**Original scientific paper**

The aim of this paper is to realize robust network motion control system. One of the most significant issues for network motion control realization is time delay during transmission. Obviously, most time delay systems are unstable. Additionally, time delay may cause control performance degradation in motion control system. In this paper, a modified disturbance observer with Smith predictor is proposed to compensate time delay. This modification realizes a robust two-degree-of-freedom control system ower network. The serial compensation of Smith predictor is utilized to compensate time delay. The validity of the proposed method is confirmed by the position control of linear motor over network experimentally. Experimental results show that the proposed control system has robustness against transmission delay fluctuation over network and external force.

**Key words:** motion control, network control systems, observers, linear motors

## 1 INTRODUCTION

Motion control technology is very useful and essential for industrial application. Particularly, this technology is a key technology for mechatronics and robotics. In addition, motion control realizes precise positioning control and vibration control in manufacturing system.

Generally, the purpose of motion control is to improve motion quality. Various motions, such as positioning and pushing, are realized by motion control. The criterion of motion quality is represented as control stiffness that changes based on the task reference. Basically, the realization of robust control requires high control stiffness. However, the robustness and control stiffness can be set by controling the acceleration independently. Hence, the control of acceleration will keep robustness and realize various motion according to the task reference [1].

Most motion control system has been applied to closed environment system such as industrial application. Recently, welfare and medical fields require motion control technology where open and remote environment system such as mobility system and network system applied [2]. The aim of this paper is to realize motion control system in open environment or remote environment system over network. In these environments, one of the most significant issues for the realization of motion control is time delay on transmission. Obviosly, in closed-loop control system, most of time delay systems are unstable. Additionaly, time dalay may cause control performance degradation. Particularly, a slight time delay may lead to critical problem in motion control.

Recently, network control system has received tremendous interest in the last decade. Especially, teleoperation control system as an example of network control system has been utilized in practice [3, 4]. Here, data communication in network control system realizes open and remote control system. However, data communication over network causes time delay, and data loss. Especially, closed control system over network is unstable due to time delay. Hence, the most considering technical issue of network control system is to keep its stability.

Smith predictor [5] is a well known technique to compensate time delay and to keep stability. Smith predictor removes the impact of time delay from closed control system through the prediction of controlled object's output. However, it has been shown earlier [6, 7] that Smith predictor could not make the steady error to zero due to step disturbance. To overcome this problem, a modified Smith predictor has been suggested by Astron, et al. [8]. A subsequent article by Zhang, et al. [9] has proposed a modified Smith predictor with two-degree-of-freedom control system where the disturbance response is decoupled from the setpoint response. However, the application of these methods is used only for process control with time delay. It can not be adjusted to motion control system directly.

Generally, a disturbance observer is usually adopted to realize robust acceleration control system [10, 11]. Disturbance observer estimatees and compensates disturbance force by the comparing controller's output and controlled object's output. Disturbance observer is one of the two-degree-of-freedom control system with rejection to disturbance force. However, it can not be applied directly to time delay system, since it requires an inverse model of controlled objects.

In this paper, disturbance observer based on network motion control system is proposed to control time delay system such as network system. Here, a disturbance force is estimated by modified disturbance observer based on minimum phase system without time delay element. Hence, the modified disturbance observer realizes a rejection of disturbance force. Moreover, in the proposed system, the serial compensation of Smith predictor to controller is adapted to keep stability. By using this method, it is possible to realize the rejection of disturbance force while keeping the stability.

To confirm the validity of the proposed control system, the realization of motion control with network is performed experimently. Real-time data communication is applied over local area network. In the experiments, this control scheme is applied to linear motor positioning control, and the effectiveness is clarified.

## 2 NETWORK CONTROLLED OBJECT MODEL

In this section, the network motion control system is described. Figure 1 shows the framework of network motion control system. The network represented by local area network, links the controller and the controlled object such as a linear motor. The controller's output and the controlled object's output is transmitted over the network.

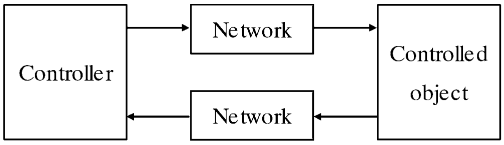


*Fig. 1 Network motion control system*

The mechanical dynamics of a linear motor is expressed as follows.

$$M\ddot{x} + F_l = F_m \tag{1}$$

$$F_m = K_t i_a \tag{2}$$

where

| | |
|---|---|
| $F_l$ | load force, N |
| $F_m$ | generated force by linear motor, N |
| $M$ | thrust rod mass, kg |
| $x$ | position, m |
| $i_a$ | current input, A |
| $K_t$ | thrust constant, N/A |

The representative of linear motor's load forces is friction force and external force. The linear motor generates the thrust force proportionately as current increases. Generally, the actuator current $i_a$ corresponds to the current reference $i_a^{ref}$ due to the current minor loop which is usually equipped with.

The current reference value $i_a^{ref}$ and position information $x$ are transmitted over network. However, time delay and lack of information such as packet loss exists due to network transmission. These informations can not be transmitted over network accurately. Hence, the network transmission models are represented as follows.

$$\bar{i}_a^{ref} = e^{-sT_0} i_a^{ref} - d_0 \tag{3}$$

$$\bar{x} = e^{-sT_1} x - d_1 \tag{4}$$

where $T_0$, $T_1$ are time delay over network, and $d_0$, $d_1$ are information error due to lack of information.

Consequently, the controlled object with network is represented as Figure 2.

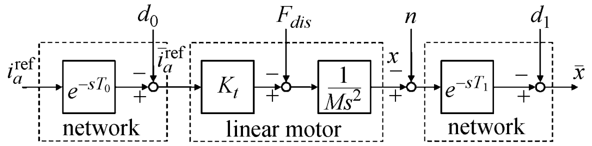


*Fig. 2 Network controlled object model*

## 3 PROPOSED CONTROL SYSTEM

### A. Modified Disturbance observer

At first, this section describes the realization of robust motion control. Recently, a disturbance observer is used to realize motion control. The control system based on disturbance observer is shown in Figure 3. Here, $r$ is command input, $u$ is the controller's output, $y$ is controlled object's output, $d'$ is the load force, and $\xi$ is the observation noise. Subscription »$n$« means nominal model. A low-pass filter is adopted as $Q(s)$ to the reduce observation noise. In this structure, disturbance observer estimates and compensates the disturbance force. The disturbance force including the difference between real and nominal model is defined as follows.

$$d \equiv d' - \left(\frac{1}{P} - \frac{1}{P_n}\right)y. \tag{5}$$

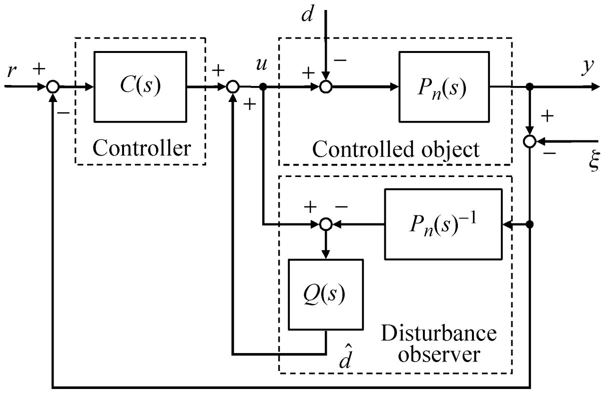


*Fig. 3 Disturbance observer*

In Figure 3, the command input response $G_{ry}(s)$ and sensitivity function $S(s)$ are represented as follows.

$$G_{ry}(s) = \frac{y(s)}{r(s)} \tag{6}$$

$$= \frac{C(s)P_n(s)}{1+C(s)P_n(s)} \tag{7}$$

$$S(s) \equiv \frac{\dfrac{\partial G_{ry}(s)}{G_{ry}(s)}}{\dfrac{\partial P(s)}{P_n(s)}} \tag{8}$$

$$= \frac{1-Q(s)}{1+C(s)P_n(s)}. \tag{9}$$

Having disturbance observer, the command input response and the disturbance response can be set independently from each other. Hence, two-degree-of-freedom control system is realized by disturbance observer. However, disturbance observer can not be adapted to time delay system since it requires the inverse controlled object's model.

In this paper, a modified disturbance observer is proposed to adapt the network controlled object (Figure 2). The modified disturbance observer is represented as Figure 4. Here, the controlled object, the disturbance force and the observation noise are defined as follows respectively.

$$P_n(s) = \frac{K_{tn}}{M_n s^2} \tag{10}$$

$$d \equiv \frac{1}{K_{tn}}\Big[(F_{dis} + K_t d_0) + \\ + (K_t e^{-sT_0} - K_{tn} e^{-sT_{0n}}) i_a^{ref} - (M - M_n)s^2 x\Big] \tag{11}$$

$$\xi \equiv e^{-sT_{1n}} + d - (e^{-sT_1} - e^{-sT_{1n}})x. \tag{12}$$

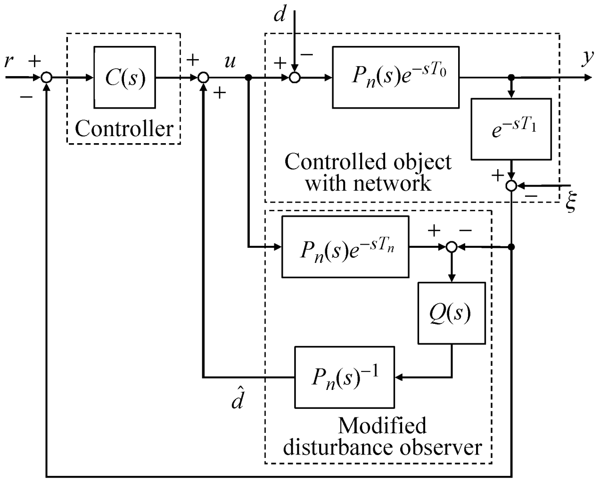


*Fig. 4 Modified disturbance observer*

This paper assumes that the fluctuation of transmission delay over network (jitter) is included in the disturbance force and in the observation noise as well.

In Figure 4, the command input response $G_{ry}(s)$ and sensitivity function $S(s)$ are represented as follows respectively.

$$G_{ry}(s) = \frac{C(s)P_n(s)e^{-sT_0}}{1+C(s)P_n(s)e^{-sT_n}} \tag{13}$$

$$S(s) = \frac{1-Q(s)e^{-sT_n}}{1+C(s)P_n(s)e^{-sT_n}}. \tag{14}$$

The modified disturbance observer also enables the command input response and sensitivity function to be set independently. Therefore, it is possible to reject disturbance force and realize robust acceleration control system. However, modified disturbance observer is likely to be unstable due to time delay. Therefore, the recovery method is described in the next section to compensate the transmission delay.

### B. The compensation of Smith predictor

Smith predictor, a common method to compensate time delay, is shown in Figure 5. It can remove the effect of time delay that causes instability. Hence, this paper considers to the modified disturbance observer to recover the stability.

Figure 6 shows the proposed control system. The serial compensation of Smith predictor is adapted to modified disturbance observer to keep its stability. In Figure 6, the command input response $G_{ry}(s)$ and sensitivity function $S(s)$ are represented as follows respectively.

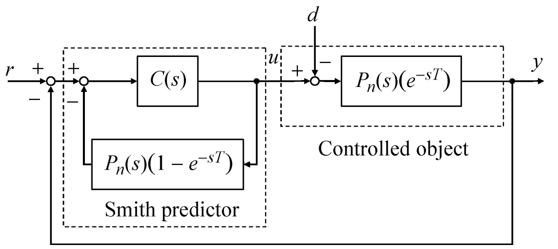


*Fig. 5 Smith predictor*

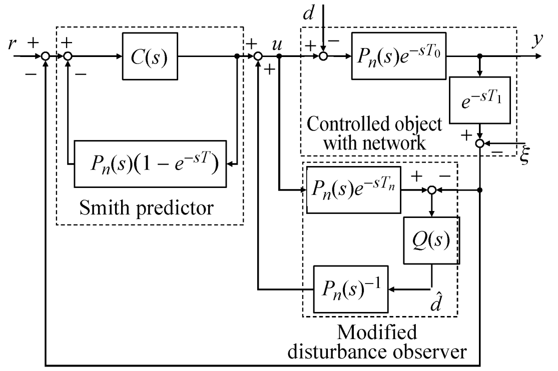


*Fig. 6 Proposed control system*

$$G_{ry}(s)=\frac{C(s)P_n(s)}{1+C(s)P_n(s)}e^{-sT_0} \tag{15}$$

$$S(s)=\frac{1+C(s)P_n(s)(1-e^{-sT_n})(1-Q(s)e^{-sT_n})}{1+C(s)P_n(s)} \tag{16}$$

where, $T_n$ is nominal round trip time, and the round trip time means total transmission delay which is expressed as $T=T_0+T_1$.

Hence, the proposed control system is a two-degree-of-freedom control system. The characteristic of the command input response is determined by $C(s)$ regardless of sensitivity function and time delay. Where $C(s)$ can be set at a desirable command input response.

The rejection of disturbance is expressed as sensitivity function. Hence, the rejection of disturbance is determined by round trip time and $Q(s)$. Since $Q(s)$ is low pass filter,

$$\lim_{s\to 0} S(s)\to 0. \tag{17}$$

Consequently, the proposed control system will make the steady error to zero due to step disturbance. Additionally, the compensation with Smith predictor removes the impact of time delay from closed control system through the prediction of controlled object's output. Hence, the compensation can make it stable.

## 4 EXPERIMENT RESULTS

The proposed control system is applied to network system to confirm the validity of the proposed control system. In the experiments, two PCs (Pentium 4: 2.8 GHz) are used at 0.1 ms sampling time. The overview of experiment system is shown in Figure 7. The network links the controller and a linear motor as the controlled object. The linear motor is shown in Figure 8. Table 1 shows the linear motor parameters. The linear motor is controlled by the motor driver. Its position is estimated by the position encoder with 0.1 μm resolution.

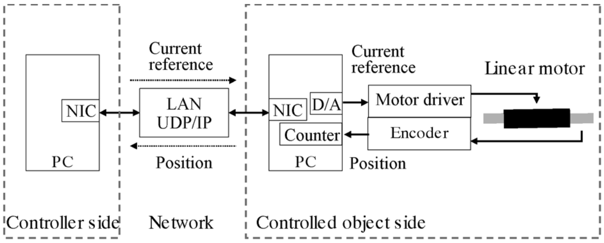


*Fig. 7 Network linear motor motion control system for experiments*

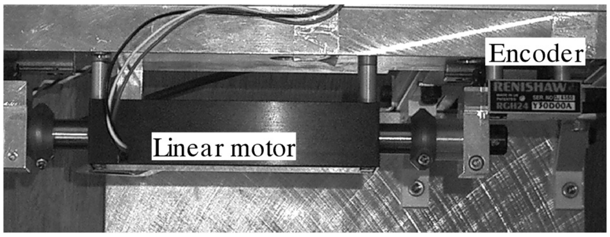


*Fig. 8 Experimental system*

Table 1 **Linear motor parameters**

| | | |
|---|---|---|
| $K_t$ | thrust constant, N/A | 22.0 |
| $M$ | mass, kg | 0.2 |

It is well-known that hard real time system is required to realize motion control. RT Linux which is the hard real time extension for Linux is utilized to realize hard real time system in this experiment system. Here, network motion control system involves real time data communication. In this paper, the real time communication network with RT-Socket is utilized. RT-Socket is a real time communication package included in RT Linux and is based on UDP/IP protocol. Thus, it is possible to realize real time network system. The performance of the real time communication based on RT-socket was evaluated by [12]. The real time network system of this experiment system transmits and receives transmission data at 0.1 ms sampling time respectively.

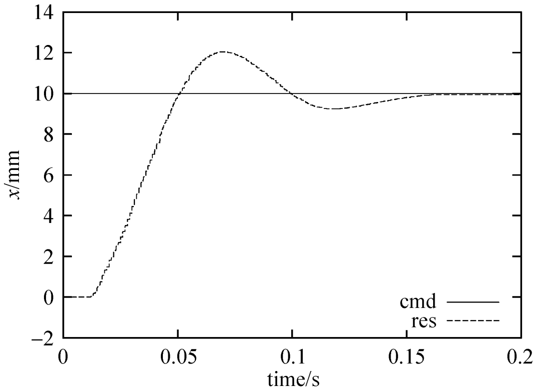
In the experiments, PD control system is adapted to $C(s)$ which determines the command input response of the proposed system. In the PD control system, a one order low pass filter is adopted to the approximate differentiation as noise reduction. A second order low pass filter is adopted as $Q(s)$. Table 2 shows control parameters of the proposed control system.

$$C(s) = K_p + K_v \frac{s g_v}{s + g_v} \tag{18}$$

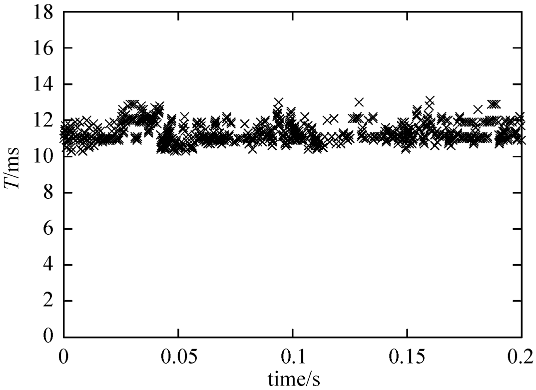
$$Q(s) = \left( \frac{g_d}{s + g_d} \right)^2 . \tag{19}$$

Table 2 **Controller parameters**

| | |
|---|---|
| Position gain $K_p$, rad/s | 1440 |
| Velocity gain $K_v$, rad/s | 120 |
| Differential gain $g_v$, rad/s | 100 |
| Observer gain $g_d$, rad/s | 100 |
| Nominal time delay $T_n$, ms | 10 |



(a) position response

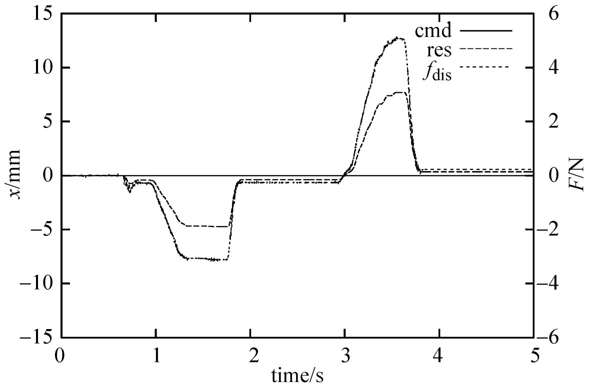


(b) round trip time

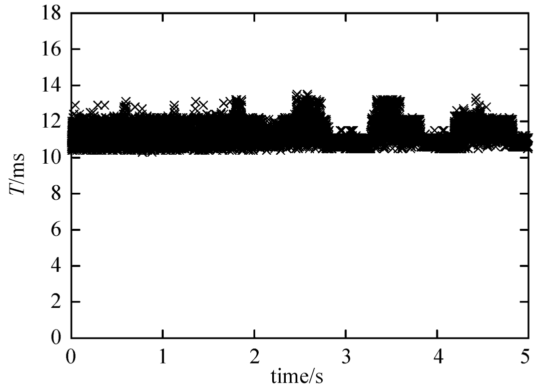
*Fig. 9 Experimental result of step response under jitter*

Figure 9 shows the experimental result of step response. It describes the robustness to transmission delay which includes time delay, jitter, and packet loss. 2000 packets were transmitted from controlled object's PC and the controller's PC received 629 packets for 0.2 s. Here, 68.6 % packet was lost. Moreover, Figure 9(b) shows round trip time and jitter. However, the response converged to the step command in Figure 9(a). The steady error is 0.05 mm and the settling time is 0.135 ms.

The position response is shown in Figure 10(a), where the external force is applied to the linear motor in position control. Applied external force is denoted in Figure 10(a). Figure 10(b) shows transmission delay with jitter. The control parameters is the same as the previous experiment. Figure 10 reveals that proposed control system has the robustness to external force.



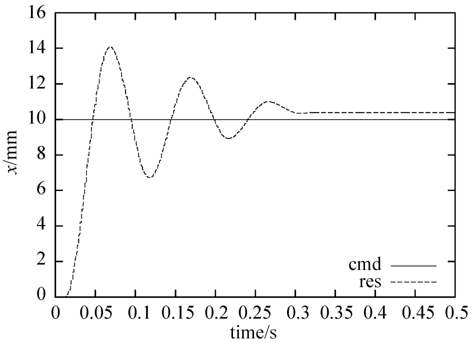
(a) position response



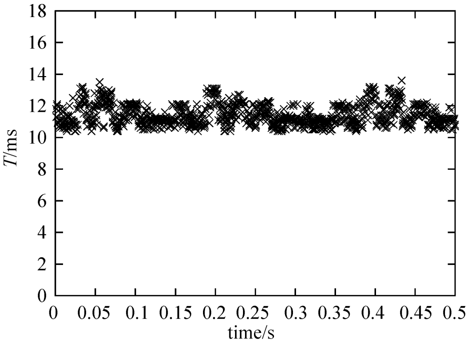
(b) round trip time

*Fig. 10 Experimental result of applied external force*

Finally, robustness to parameter mismatch is investigated. It is assumed that $M_n = M/3.0$ in this experiment. The position response is shown in the Figure 11. Figure 11(a) shows that the position response is converged to the command in spite of the degradation of control performance. Hence, it is revealed that proposed control system has the robustness to parameter mismatch.



(a) position response



(b) round trip time

*Fig. 11 Experimental result of step response under mass mismatch*

## 5 CONCLUSION

This paper presents network motion controls system. The technical issue to realize this system is time delay on transmission. Hence, this paper proposed modified disturbance observer with Smith predictor to compensate time delay. The proposed method is two-degree-of-freedom control system. The command input response and the disturbance response can be set independently from each other. In addition, the robust stability of the proposed control system is confirmed experimentally. The experimental results show the robustness against transmission delay, which includes jitter and packet loss, external force and the mismatch of linear motor model. Consequently, this paper shows a method to realize network motion control system.

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**Robusni sustav upravljanja gibanjem preko komunikacijske mreže zasnovan na rekonstrukciji poremećaja.** Cilj je ovoga članka realizacija sustava upravljanja gibanjem preko komunikacijske mreže. Jedan od najvećih problema u realizaciji sustava upravljanja gibanjem preko komunikacijske mreže jest kašnjenje u prijenosu podataka. To kašnjenje dovodi do narušavanja svojstava sustava upravljanja gibanjem, a može ga učiniti i nestabilnim. Za kompenzaciju kašnjenja u radu se predlaže modificirani rekonstruktor poremećaja zasnovan na Smithovu prediktoru. Predloženi rekonstruktor omogućuje izvedbu robusnog sustava upravljanja gibanjem s dva stupnja slobode. Valjanost predloženog sustava potvrđena je eksperimentalno na sustavu upravljanja pozicijom linearnog motora preko komunikacijske mreže. Dobiveni rezultati pokazuju robusno vladanje predloženog sustava u uvjetima promjenjivog kašnjenja prijenosa podataka preko mreže i pri djelovanju vanjske sile.

**Ključne riječi:** upravljanje gibanjem, sustavi upravljanja preko mreže, rekonstrukcija signala, linearni motori

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