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An Application of Robust Control for Force Communication Systems over Inferior Quality Network

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1. Introduction

The developments of computer and network technologies have provided a virtual reality environment and ubiquitous network systems. Especially audio-visual devices play an important role in communication. For example, voice communication by telephone, audio-visual communication, streaming technology, digital television system and so on. However, we know that the human makes communication not only by audio-visual information but also by using all five-senses (touch, taste, hearing, eyesight, and smell). The realization of the five-senses communication system is one of the prospected technologies. Especially force communication is a hopeful application in the coming e-world. Several kinds of gimmicks can be considered for transmitting or exchanging the sense of touch, haptic, tactile, force and kinesthetic. In the area of the wearable computing technologies some force-like communication system is realized by using pressure, tension, bending, stress sensors and vibration or pressure actuators, which give the illusion of force communication. On the other hand, robotic researchers have discussed on bilateral tele-operation systems, which realizes remote-manipulations with the sense of reaction forces caused by collision or touching of remote objects and environments. An aim of the technology is that the communication channel between two terminals simulates as if a rigid rod or tight rope. In this article, we consider the bilateral tele-operation systems as a force communication device. It is a well-known that the computer network has inevitable time-delay and jitter in the transmission of the data. And in control engineering deterioration of the stability and performance of the closed loop systems is a well-known fact. Control researchers have proposed several kinds of approaches to overcome the problems. The rest of the chapter is composed as follows. In Section 2, a characterization of the computer network from the view point of transmission delay is discussed. In Section 3, control systems of force sensorless bilateral tele-operation system and the problems caused by transmission delay are examined with a brief historical review. Section 4 presents a procedure how to design a robust control system over the uncertain time-delay network. In section 5 a simulation result is introduced, and some discussions are presented. In section 6 experimental results over the real broadband computer network are introduced. And the results of experiments and investigation are explained in detail. Section 6 concludes the article.

2. Communication network and time delay

Fusion of computer and tele-communication technologies has provided the revolution of the computer network such as the Internet. Before the revolution usual tele-communication is established in two steps. Firstly, according to the request from the sender the system searches the receiver and establishes a communication channel by reserving network resources exclusively. Secondly, the session starts on the reserved real communication channel. After the end of the session, the reserved resources are released. In this case, the time-delay over the communication channel is so small as can be ignored.

On the other hand, communication on the computer network between two terminal nodes is realized as a set of the exchange process of datagrams (frame, packet, cell, Ac). For example, the information is converted into digital data and divided into datagrams. These datagrams are put on the node and travel along the path while looking for appropriate next node until they reach to the destination. In general the data exchange process includes the huge number of data processing such as encoding, storing and (route) switching. And the length of the processing time depends on the size of datagram and transmitting rate the busyness of the equipments. Especially the network routers are shared by multi-users. Since the practically implemented algorithm is almost trying and error type, the data buffer sometimes overflowed and fails data(packet loss). In order to ensure the reproducibility of the data several kinds of data processing algorithms are implemented according to transmission protocols. TCP/IP(Transmission Control Protocol/Internet Protocol) provides confirming of receiving data (acknowledge), control of window size, and data retransmission and so on. Because of the complexity of the mechanism and sharing of the resource of the network the time-delay is greater than the circuit channel type communications. And the jitter, variation of the time delay occurs frequently.

Fig.1 shows an example of time delay during a day between two campuses(Kumamoto and Fukuoka) in 1998. The left graph (a) indicates the time series from midnight to midnight, and the right(b) is the histogram of the number of packets with respect to transmission delay. It is too difficult to construct the prediction model of time-delay because of the randomness and chaos. Here we adopt a statistical model as a rectangular distribution as follows.

$$0 < L \leq L_{max} \quad (1)$$

In practice it is possible to set L_{max} such that 95% of packets are travels in the time interval $[0, L_{max}]$.

3. Historical review of tele-operation systems

3.1 Master slave system

Suppose the situation in which an operator manipulates (push/ pull/ lift/ put on and so on) some object through the communication network. Such a kind of system is called a master slave system or *tele-operation system*. Usually the terminals for the operator and the object are called the *master* and the *slave* equipment each other. Operators motion is converted to the motion data by the master mechanism, transmitted to the slave side and realized as a motion of the slave equipment. If the system can transmit the force information caused in the slave side to the master side it called *bilateral tele-operation systems*. Several kind of mechanisms are proposed for the control of bilateral tele-operation systems.

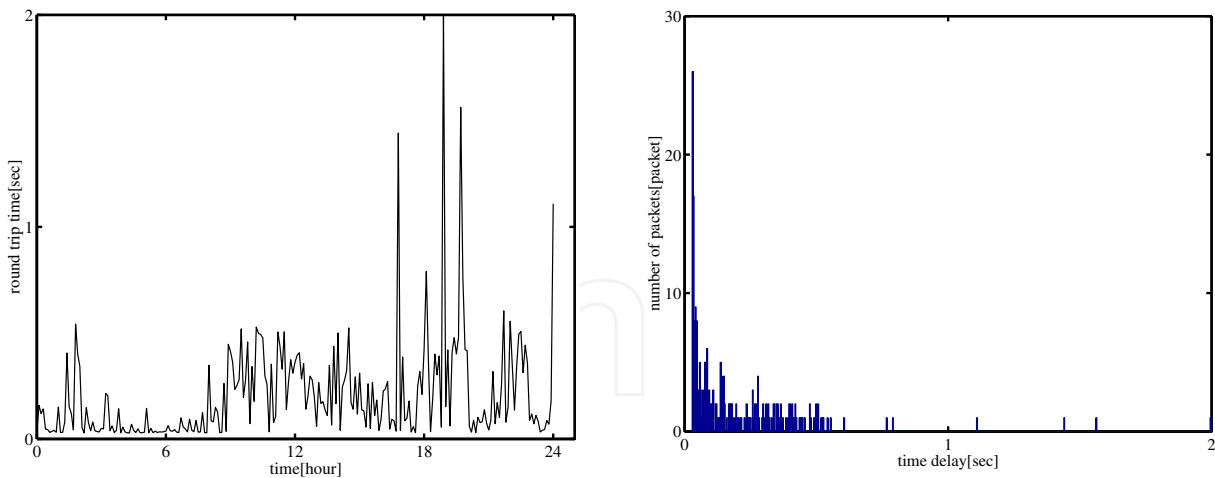


Fig. 1. An example of transmission delay of the Internet: (left)time history(time vs. delay), (right) Histogram (delay vs. frequency)

PE(position error) type is the most simple one. Master and slave exchange the position data each other. Both controllers compensate the deviation of the positions independently. It means that the system is a combination of two position feedback control systems. When the master and the slave equipments have the same characteristics the structure of the system is completely symmetric. In FR(Force reflection) type, master equipment transmits the position data and receives the force data from the slave equipment. On the other hand FRP(Force reflection with passivity) type exchanges the velocity data and the force data respectively.

3.2 Delay and instability

It is well-known that the time delay in the loop deteriorates the stability, performance and robustness of the feedback systems. Fig.2(b) shows a demonstration of the trade-off of gain K and time-delay L . If (L, K) is chosen in the range of *stable* region the closed loop system depicted in Fig. 2(a) becomes stable, and vice versa. This trade-off curve is identical to the contour of the H_∞ norm of the transfer function

$$\gamma := \left\| \frac{K}{s^2 + K} (1 - e^{-Ls}) \right\|_\infty \quad (2)$$

with $\gamma = 1$. It is easy to calculate that the transfer function matches to one at the cutting point a in Fig.2.

This plot says the following facts.

- (1) If $L = 0$ then the gain margin is infinite.
- (2) The gain margin decreases rapidly as the time-delay grows, that is, the robustness to time-delay deteriorate as the time-delay grows.

According to the considerations the necessity of careful investigation to time-delay is required.

3.3 Scattering and wave variable method

Anderson and Spong (6) introduced a new communication architecture for tele-operation over the network with time-delay. Their method is based on the passivity and scattering representation of the network. Thus the strictly passivity of master and slave systems

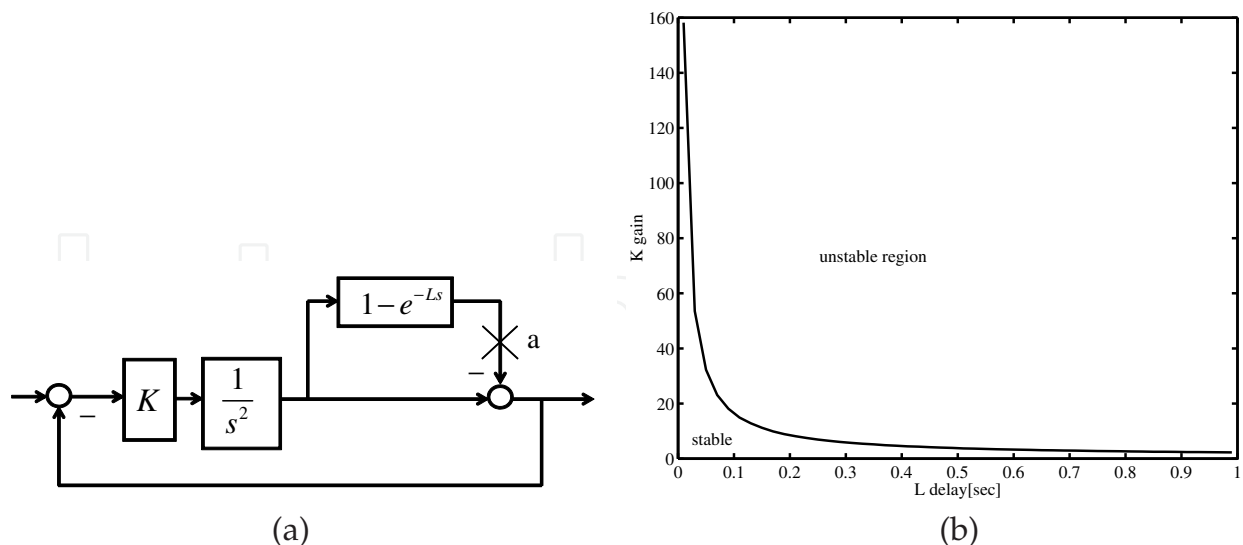


Fig. 2. Trade-off between time-delay and loop gain (delay vs. loop gain)

and stationary time-delay are assumed, which are strong constraints for design. Moreover Niemeyer and Slotine (7) extended their method by using wave variables. Since it is a generalization of Anderson-Spong method, it has the same constraints and difficulties in practice. On the other hand Leung, Francis and Apkarian (8) proposed a controller designed via μ -Synthesis. The proposed method based on robust control theory can deal fluctuation of time-delay and has strong practicability. But all the above methods have the same configuration in which the master and slave system exchanges the velocity and the force variables (v, f) through the network. This means that the position, integral of velocity v , of the master and the slave systems are depend on the initial conditions, and the stability is ensured not in the sense of position but velocity. Moreover the necessity of force sensors makes the systems configuration sophisticated. The more simple architecture is prefer for the practical application.

4. Robust control approach

4.1 Paradigm of robust control

There are several kind of strategies to overcome the problem of time delay. Assuming the rectangular (uniform) distribution of time delay H_∞ control theory can be applied as follows. Fig.4 shows the correspondence between time-delay and multiplicative uncertainty. Now let define a 1-st order high-pass filter $W_D(s; L)$ as

$$W_D(s; L) = \frac{As}{s + \frac{1}{L}} \quad (3)$$

where $A = 2.102904074495\dots$ It is easy to verify that the norm of $(e^{-Ls} - 1)$ holds the following inequality for any frequency (on the imaginary axis) and any time delay L with $0 < L \leq L_{max}$

$$|1 - e^{-j\omega L}| < W_D(j\omega; L) \leq W_D(j\omega; L_{max}), \quad \forall j\omega \in j\mathbf{R}, \quad (4)$$

where L_{max} is the upper bound of the estimated time-delay. This means that the uncertainty caused by the variation of time-delay between $[0, L_{max}]$ can be covered by the weighting function $W_D(s; L_{max})$ as a high-pass filter with cut-off frequency $1/L_{max}$ [rad/sec]

$$W_D(s, L_{max}) = \frac{2.1s}{s + \frac{1}{L_{max}}} \tag{5}$$

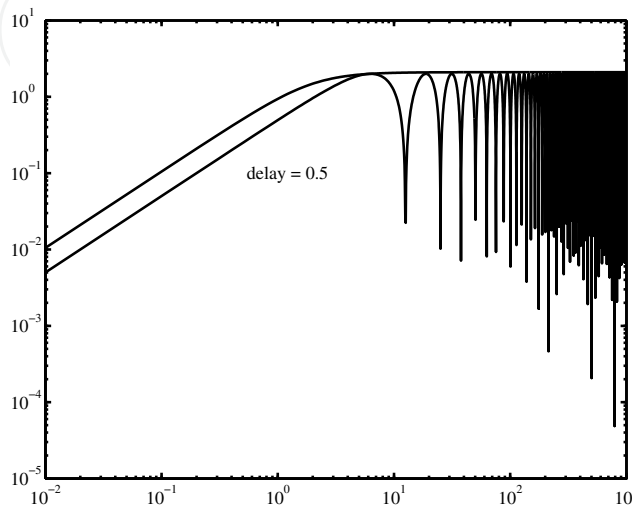


Fig. 3. variation of the gain casued by time delay and inequality in (4)

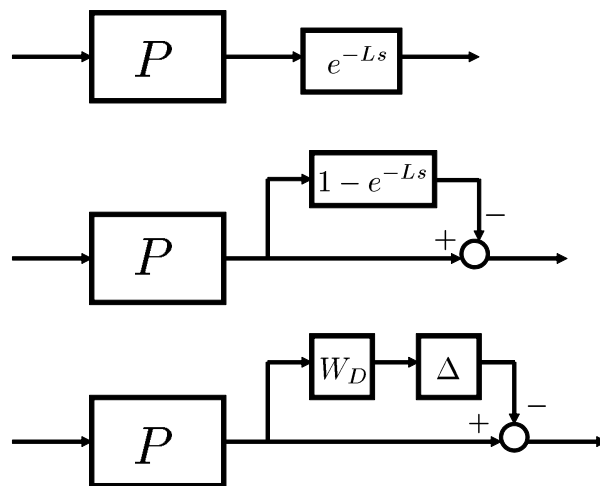


Fig. 4. correspondence between time-delay and multiplicative uncertainty

By using the function $W_D(s; L_{max})$ and uncertain bounded function Δ ($|\Delta| < 1$) the inequality 4 can be replaced as

$$e^{-Ls} = 1 + W_D(s; L_{max})\Delta. \tag{6}$$

4.2 PE type bilateral tele-operation system

Here we introduce a simple PE type bilateral tele-operation system designed with robust control technique. Two joystick mechanisms, corresponds to master and slave, are considered.

Each joystick has a DC-servo motor for torque generation and a position sensor for measurement of the angle of the joy-stick. Force sensors attached to the joysticks are not for use of the control but for the performance evaluation of force communications. They are controlled by computers which are connected to the computer network (see Fig.5). These joysticks are assumed to be modeled as

$$J_m \ddot{x}_m(t) + D_m \dot{x}_m(t) = K_m u_m(t) + f_m(t) \quad (7)$$

$$J_s \ddot{x}_s(t) + D_s \dot{x}_s(t) = K_s u_s(t) - f_s(t) \quad (8)$$

where x , f and u indicate the variables of position of the joystick, external force and input voltage for motor torque generator each other. J and D indicate the physical parameters of inertia and friction each other. The suffixes m, s indicate the master and the slave respectively.

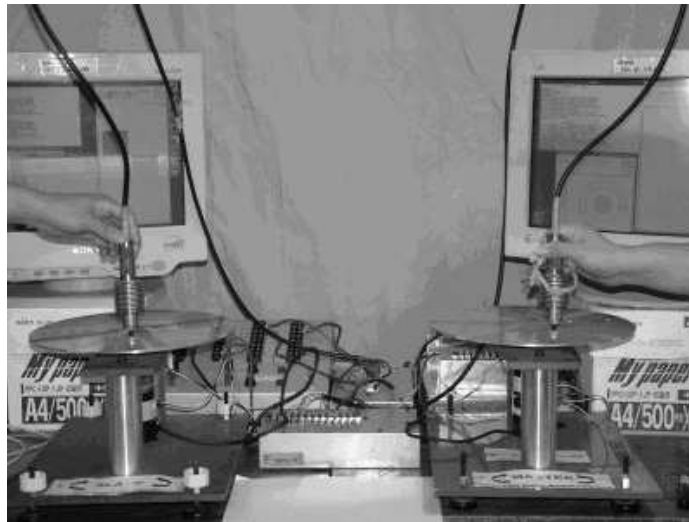


Fig. 5. A view of experimental equipments: Two joysticks controlled by computers connected to the network

J_m	0.0140	[Kgm ²]
J_s	0.0379	[Kgm ²]
D_m	0.0110	[Nms]
D_s	0.0250	[Nms]
K_m	0.2557	[Nm/V]
K_s	0.2557	[Nm/V]

Table 1. Parameters of master and slave joysticks

If there is no time delay between master and slave sides the deviations of the joysticks are evaluated as

$$e_{m0}(t) = x_m(t) - x_s(t) \quad (9)$$

$$e_{s0}(t) = x_s(t) - x_m(t) = -e_{m0}(t). \quad (10)$$

When the master and the slave controllers exchange the information through the network, as stated in the previous section, the time-delay must be considered. Let us assume that the

time-delay $L > 0$ exists between master and slave controllers symmetrically. The evaluated deviations (9)(10) at each controller might be computed as follows.

$$e_{mL}(t) = x_m(t) - x_s(t - L) \tag{11}$$

$$e_{sL}(t) = x_s(t) - x_m(t - L) \tag{12}$$

In the rest of the chapter $e_{m0}, e_{s0}(e_{mL}, e_{sL})$ are called as errors in ideal (computed) deviation. The Laplace transform of computed deviation e_{mL} (11) is written as

$$\begin{aligned} E_{mL}(s) &= X_m(s) - e^{-Ls} X_s(s) \\ &= X_m(s) - X_s(s) + X_s(s) - e^{-Ls} X_s(s) \\ &= E_{m0}(s) + (1 - e^{-Ls}) X_s(s). \end{aligned} \tag{13}$$

In the same way the Laplace transform of e_{sL} can be written as

$$E_{sL}(s) = E_{s0}(s) + (1 - e^{-Ls}) X_m(s). \tag{14}$$

This means that the minimization of computed deviations ($E_{mL}(s), E_{sL}(s)$) is accomplished by the simultaneous minimization of $E_{m0}(s)(= -E_{s0}(s)), (1 - e^{-Ls}) X_s(s)$ and $(1 - e^{-Ls}) X_m(s)$ from the inequality as

$$\begin{aligned} |E_{mL}(j\omega)| &\leq |E_{m0}(j\omega)| + |(1 - e^{-j\omega L}) X_s(j\omega)| \\ &\leq |E_{m0}(j\omega)| + |W_D(j\omega; L) X_s(j\omega)|. \\ &\leq |E_{m0}(j\omega)| + |W_D(j\omega; L_{max}) X_s(j\omega)|. \end{aligned} \tag{15}$$

$$|E_{sL}(j\omega)| \leq |E_{s0}(j\omega)| + |W_D(j\omega; L_{max}) X_m(j\omega)|. \tag{16}$$

As mentioned in previous section the time delay L includes uncertainty. But if the upper bound of L is obtained as L_{max} according to 4 and 5 the minimization problem can be accomplished by the minimization of $E_{m0}(s), W_D(s; L_{max}) X_s(s)$ and $W_D(s; L_{max}) X_m(s)$.

H_∞ theory gives a design method to obtain an appropriate feedback gain to keep stability and robustness against the type of model uncertainty.

4.3 Plant model

Let us consider the two joystick mechanisms as a system with two inputs and two outputs plant

$$\begin{bmatrix} X_m(s) \\ X_s(s) \end{bmatrix} = \begin{bmatrix} P_m(s) & 0 \\ 0 & P_s(s) \end{bmatrix} \begin{bmatrix} U_m(s) \\ U_s(s) \end{bmatrix}. \tag{17}$$

where,

$$P_m(s) = \frac{K_m}{s(J_m s + D_m)}, \quad P_s(s) = \frac{K_s}{s(J_s s + D_s)}. \tag{18}$$

The purpose is the design of a controller

$$\begin{bmatrix} U_m(s) \\ U_s(s) \end{bmatrix} = \begin{bmatrix} C_{mm}(s) & C_{ms}(s) \\ C_{sm}(s) & C_{ss}(s) \end{bmatrix} \begin{bmatrix} X_m(s) \\ X_s(s) \end{bmatrix} \tag{19}$$

which satisfies the requirements specified as follows. The schematic diagram is depicted in Fig.6

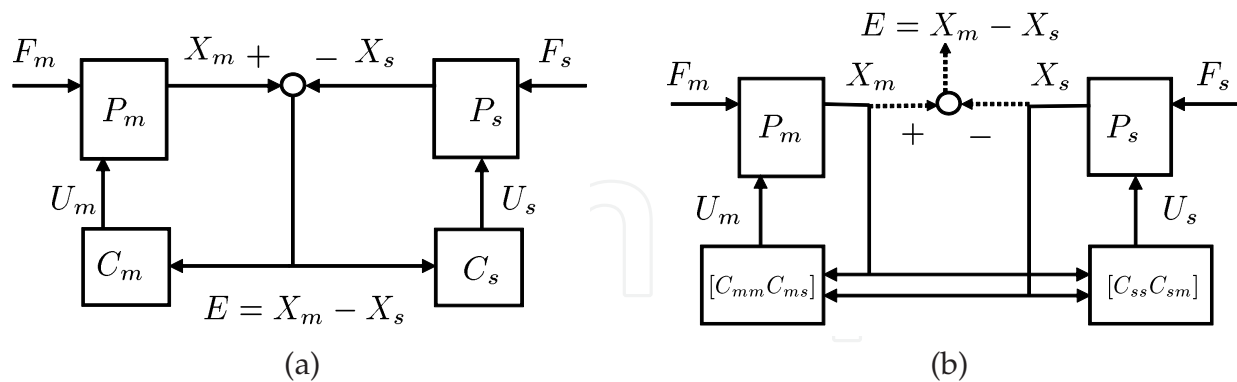


Fig. 6. scheme of PE type master-slave system (a)ideal (non time-delay) scheme,(b) practical(implementable) scheme

tracking performance

The closed loop system is a kind of regulator which makes the deviation $e = X_m - X_s \rightarrow 0$ as time goes. For the robust control systems design the deviation e is generalized to a criteria for tracking performance as

$$z_1 = W_{11}e, \quad e = x_m - x_s. \quad (20)$$

In general W_{11} has to be chosen as high gain at low frequency and low gain at high frequency.

stability augmentation

More over in order to obtain a adequate local feedback gain which improves the stability and robustness of closed loop system, the criteria for stability is formulated as

$$z_2 = W_{12}x_m, \quad z_3 = W_{13}x_s. \quad (21)$$

properness of controller

In order to ensure the properness of the controller $C(s)$ in (19) the input variables for the plant are added to the criteria for design as

$$z_4 = W_{21}(w_1 + u_1), \quad z_5 = W_{22}(w_2 + u_2) \quad (22)$$

where w_1, w_2 are exogenous inputs or exerted external forces(torques) as in Fig.7.

robust stability against time-delay

As mentioned in the previous section the robustness corresponds to the minimization of $W_D(s; L_{max})X_s(s)$ and $W_D(s; L_{max})X_m(s)$. Thus we introduce new two output variables

$$z_6 = W_D x_m, \quad z_7 = W_D x_s. \quad (23)$$

with two more variables w_3, w_4 which come from the uncertainty (6) as

$$w_3 = \Delta z_6, w_4 = \Delta z_7. \tag{24}$$

4.4 Construction of generalized plant

Let's define the exogenous input w and evaluated output z as

$$w = [w_1 w_2 w_3 w_4]^T \tag{25}$$

$$z = [z_1 z_2 z_3 z_4 z_5 z_6 z_7]^T. \tag{26}$$

Moreover defining the following vectors

$$U = [U_m U_s]^T \tag{27}$$

$$X = [X_m X_s]^T \tag{28}$$

the generalized plant is obtained as follows (see Fig.7).

$$\begin{bmatrix} z \\ X \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} w \\ U \end{bmatrix} \tag{29}$$

$$\begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} = \left[\begin{array}{cccc|cc} W_{11}P_m & -W_{11}P_s & W_{11} & -W_{11} & W_{11}P_m & -W_{11}P_s \\ W_{12}P_m & 0 & W_{12} & 0 & W_{12}P_m & 0 \\ 0 & W_{13}P_s & 0 & W_{13} & 0 & W_{13}P_s \\ W_{21} & 0 & 0 & 0 & W_{21} & 0 \\ 0 & W_{22} & 0 & 0 & 0 & W_{22} \\ W_{D1}P_m & 0 & 0 & 0 & W_{D1}P_m & 0 \\ 0 & W_{D2}P_s & 0 & 0 & 0 & W_{D2}P_s \\ \hline P_m & 0 & 0 & 0 & P_m & 0 \\ 0 & P_s & 0 & 0 & 0 & P_s \end{array} \right] \tag{30}$$

By applying the controller (19) to the above system a transfer function matrix from w to z

$$G_{zw}(s) = G_{11} + G_{12}(I - CG_{22})^{-1}CG_{21} \tag{31}$$

can be obtained. By using the design procedure based on the H_∞ control theory a controller is obtained such that

$$\|G_{zw}(s)\|_\infty < \gamma \tag{32}$$

where γ is a design parameter chosen as small as possible (5).

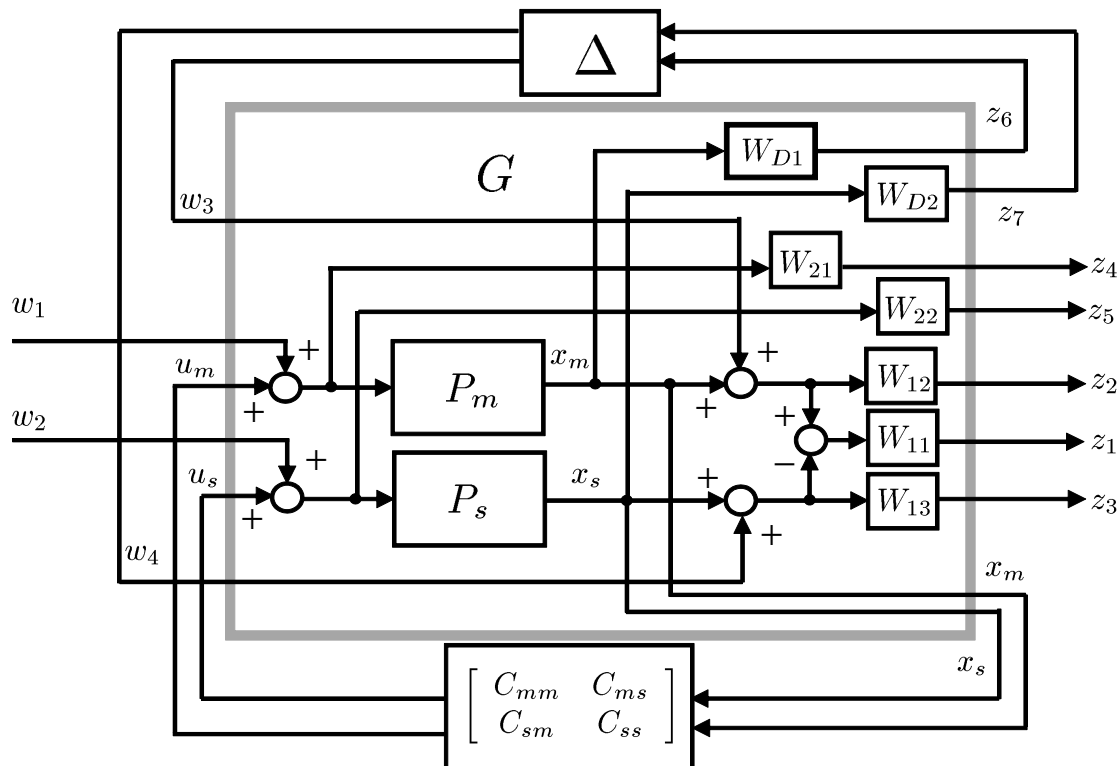


Fig. 7. generalized plant for master-slave systems

5. Simulation and estimates of robustness

In order to demonstrate the robustness w.r.t. time delay computer simulations on the stability and tracking analysis are shown here. The time-delay is assumed as $L_{max} = 0.1[\text{sec}]$. According to the specifications discussed above weighting functions $\{W_i\}, i = 1, 2, 3$ are set as follows.

$$W_{D1}(s) = W_{D2}(s) = \frac{2.1s}{s + 10} \quad (33)$$

$$W_{11}(s) = \frac{1.0 \times 10^5 s + 2.0 \times 10^5}{1.0 \times 10^4 s + 1.0} \quad (34)$$

$$W_{12}(s) = W_{13}(s) = \frac{0.01s + 1}{0.1s + 1} \quad (35)$$

$$W_{21}(s) = W_{22}(s) = 10 \quad (36)$$

Fig.8 shows the bode diagrams of the transfer functions.

Table 2 shows simulation results for analysis of stability and tracking performance.

The values in the left column indicate actual time-delay L_{act} in simulation. When the actual time-delay is not greater than the assumed maximum one, that is $L_{act} \leq L_{max}$, the stability and tracking performance are kept well. On the other hand if the time-delay exceeds estimated value, $L_{act} > L_{max}$, the performance of the system becomes worse. It points that the importance of the estimate of maximum time delay L_{max} .

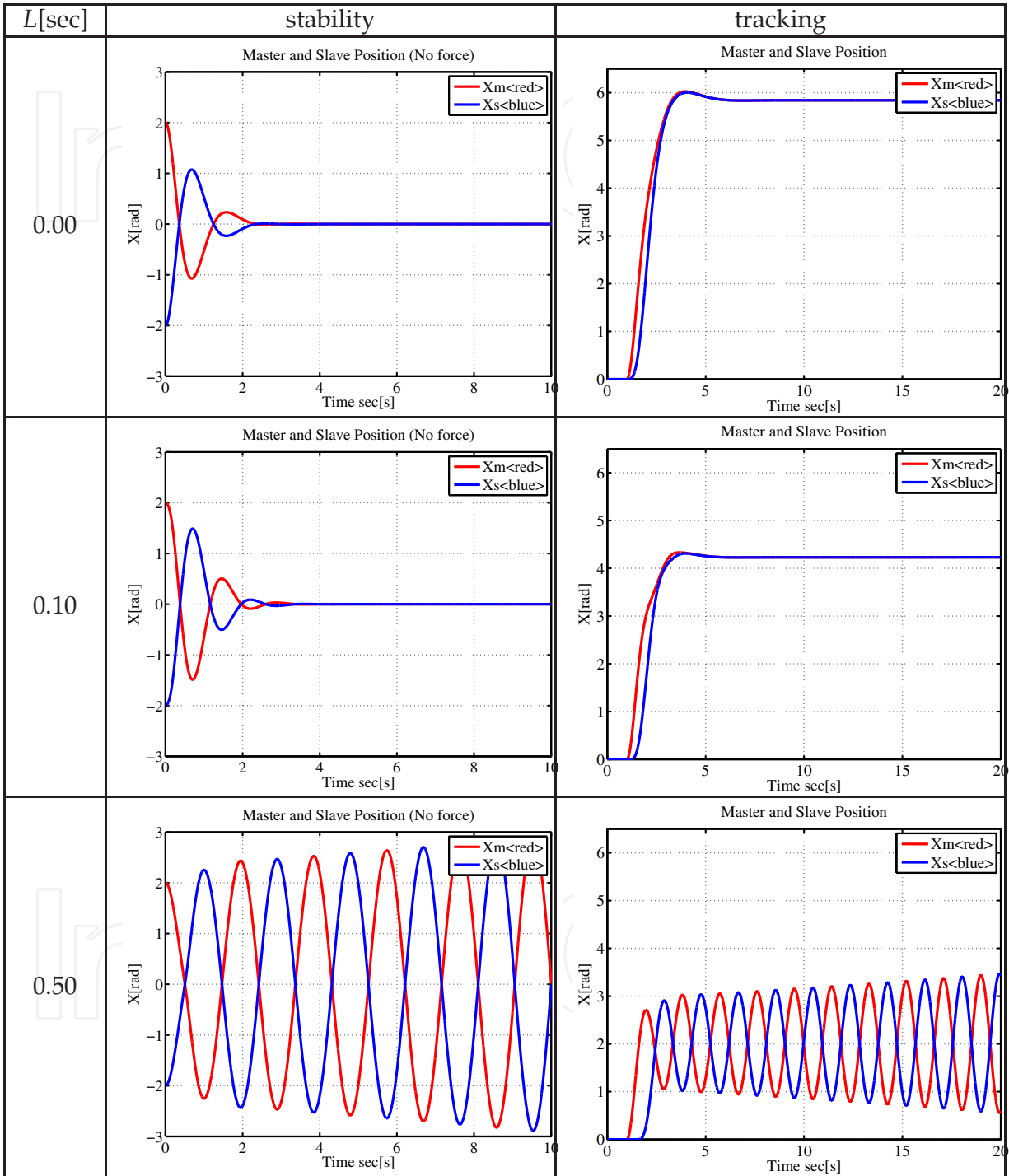


Table 2. Analysis of stability and tracking performance w.r.t. time-delay

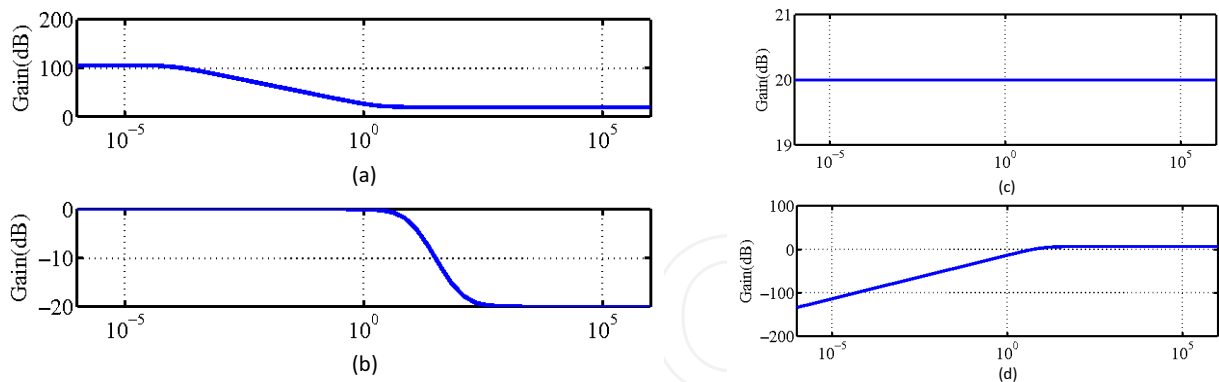


Fig. 8. Bode (gain) diagrams (a) W_{11} , (b) W_{12}, W_{13} , (c) W_{21}, W_{22} , (d) W_{D1}, W_{D2}

Analysis of designed controller

Fig. 9 shows bode diagrams of controller $C(s)$. It can be observed that roughly seeing of the controller is a kind of integrator, but it works constant gain in the middle range $1 \sim 10^3$ [rad/sec].

5.1 Analysis via hybrid matrix

In order to investigate the force communication ability and transparency of master-slave system hybrid matrix is defined as

$$\begin{bmatrix} F_s \\ X_m \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} X_s \\ F_m \end{bmatrix}. \quad (37)$$

Table 10 shows the bode daigram of hybrid matrix. $h_{12} = F_s/F_m$ and $h_{21} = X_m/X_s$ indicate that the tracking ability of position and force communication are expected to work in the range from DC upto 1 rad/sec.

6. Experiments over the network with time-delay

In order to demonstrate the robustness of the proposed control systems a networked control system is constructed as in Figure 11.

Master and slave mechanisms and their local controllers (C_m, C_s) are located on the same cite (at Kumamoto city), and another computer (C_T) is located beyond the network (at Kitakyushu city, 150km far from Kumamoto city). These three computers are connected to the network JGN, which was Japanese broadband network as an experimental testbed administrated by TAO¹. The controllers C_m and C_s can communicate each other by way of relay computer C_T , but not admitted to communicate directly. The transmission capacity of the network is about 100Mbps. The control period at C_m and C_s is 5[msec] and that of communication period between C_m and C_s is 10[msec]. The communication protocol UDP/IP is adopted.

¹ Telecommunications Advancement Organization of Japan; reorganized to NICT(National Institute of Information and Communications Technology) in 2004 (<http://www.nict.go.jp/>)

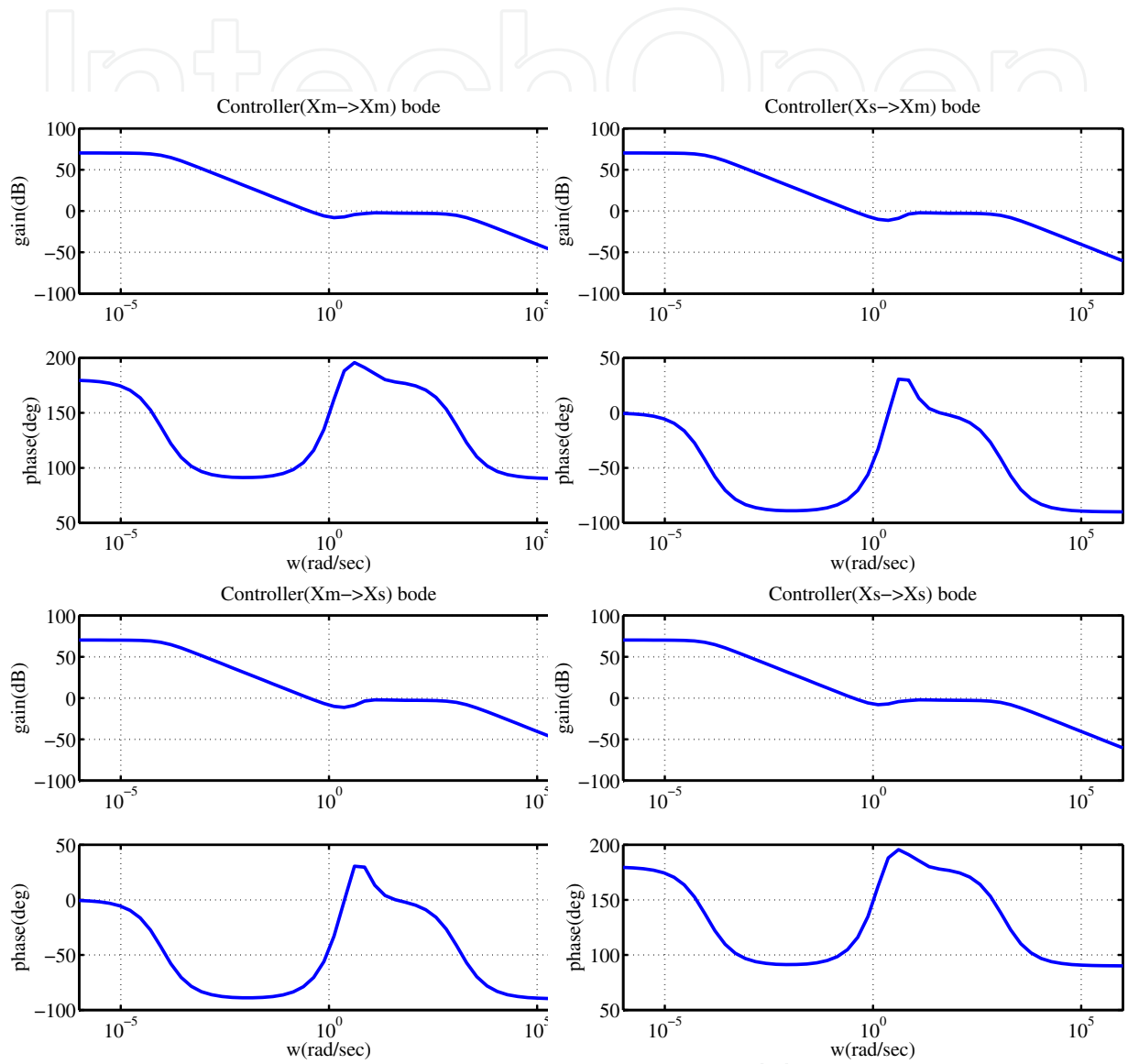


Fig. 9. Bode diagram of the controller $C(s)$

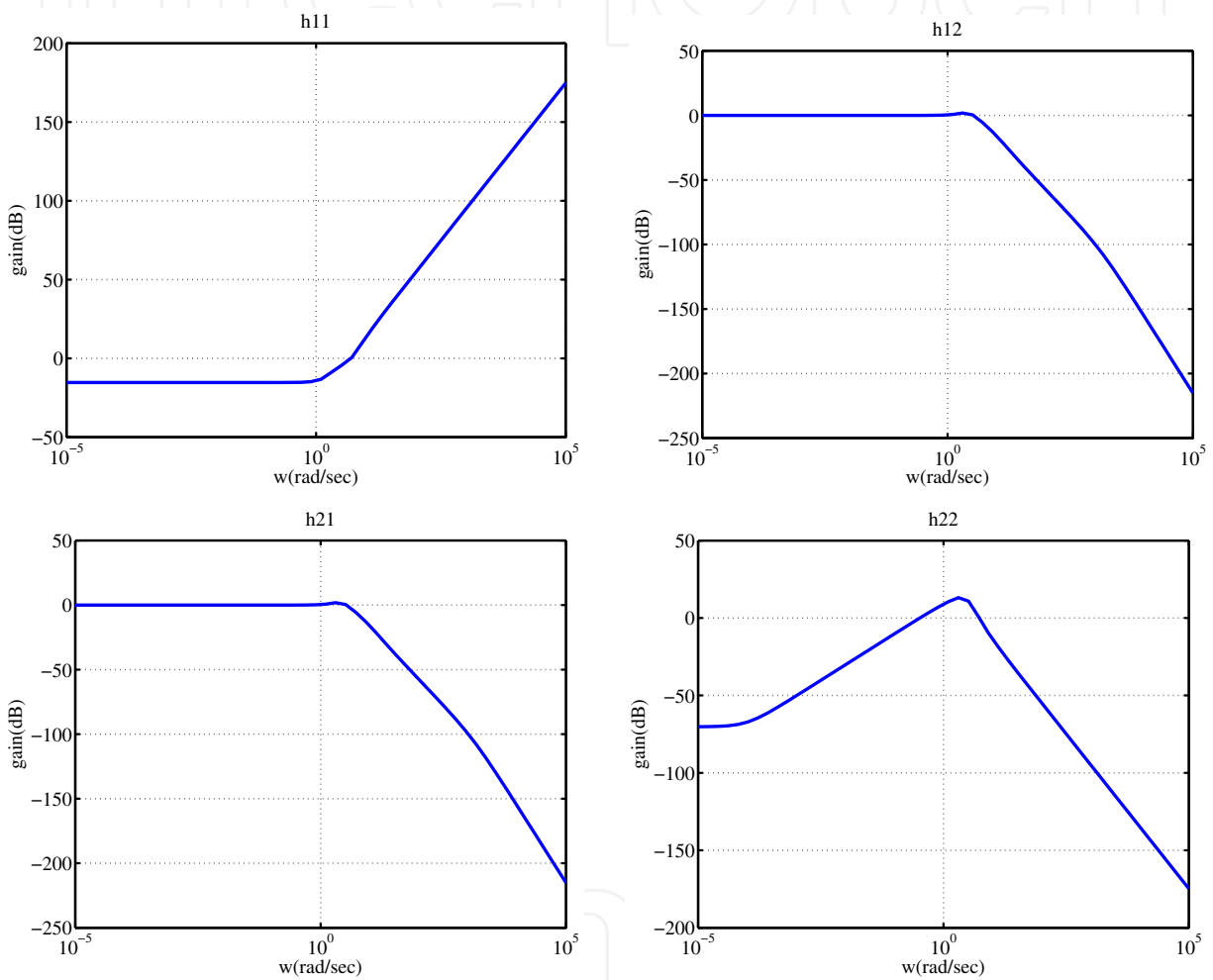


Fig. 10. Bode (gain) diagram of hybrid matrix (37)

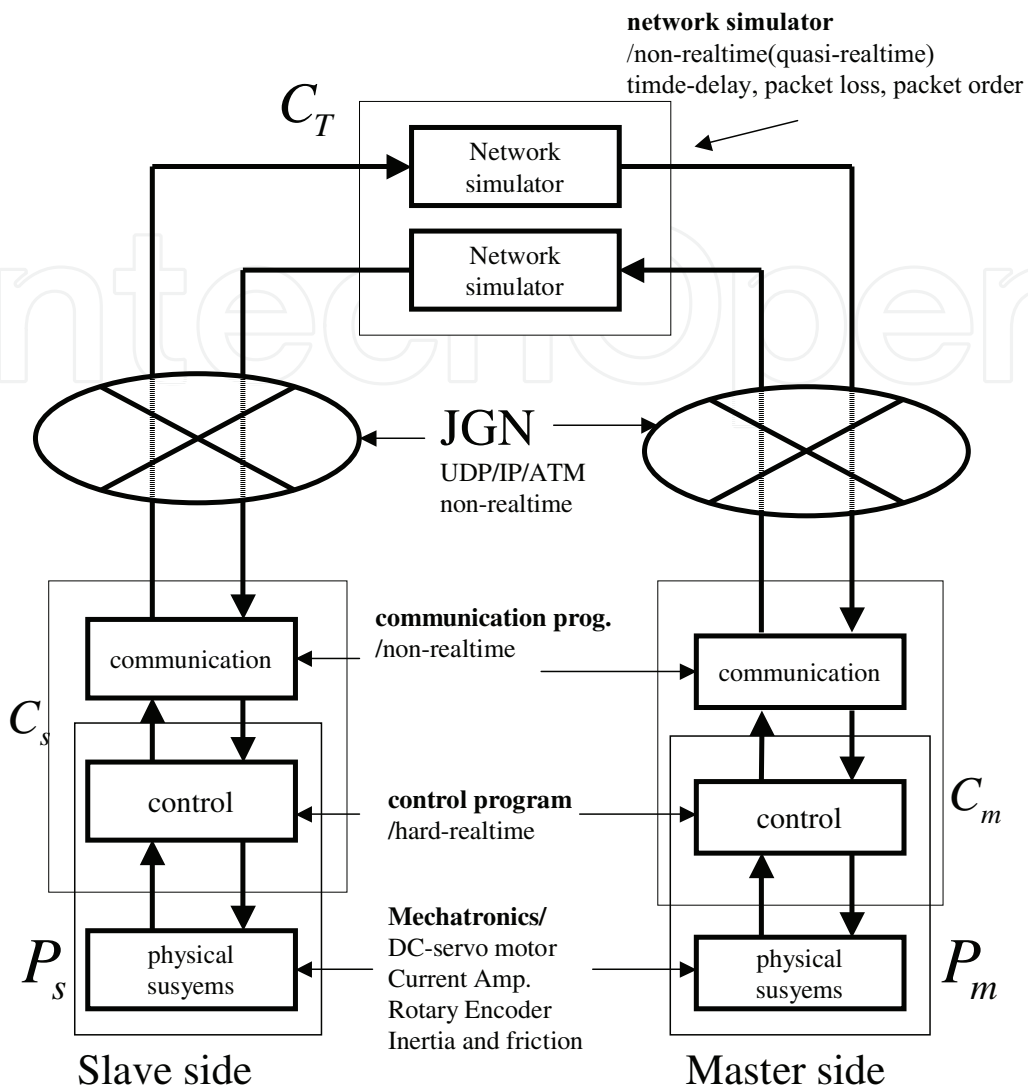


Fig. 11. experimental network system for robust control on JGN

design parameters

Weighting functions in generalized plant (29) are specified as

$$W_{11} = \frac{0.3s + 20 \times 10^7}{3.9 \times 10^6s + 10^5}, \tag{38}$$

$$W_{12} = W_{13} = \frac{1}{1.5}, \tag{39}$$

$$W_{21} = W_{22} = 0.2, \tag{40}$$

$$W_D = \frac{2.1s + \epsilon}{s + \frac{1}{L_{max}}} \tag{41}$$

By specifying the allowable time-delay L_{max} and upper bound of H_∞ norm γ in (32) the controller $C(s)$ is obtained by using MATLAB².

² MATLAB is a product of The MathWorks, Inc.

implementation issues

The controllers are implemented in personal computers. The algorithms are coded by C-language with RT-Linux formats and embedded as a kernel modules of Linux system. The control period is set at 5 [msec] and data exchange rate is set at 10 [msec]. Thus the data processing sequences must be synchronized.

Fig.12 shows a sequence diagram. The time goes from left to right and the datagram travels from master side(top) to slave side(bottom) through the network(middle). Because of the control period is a half of the communication period a copied value of the oposit side is used once every two control calculation. The right half part of the diagram assumes the case of long time-delay. In this case copied value is used over and over again until the new datagram reaches again.

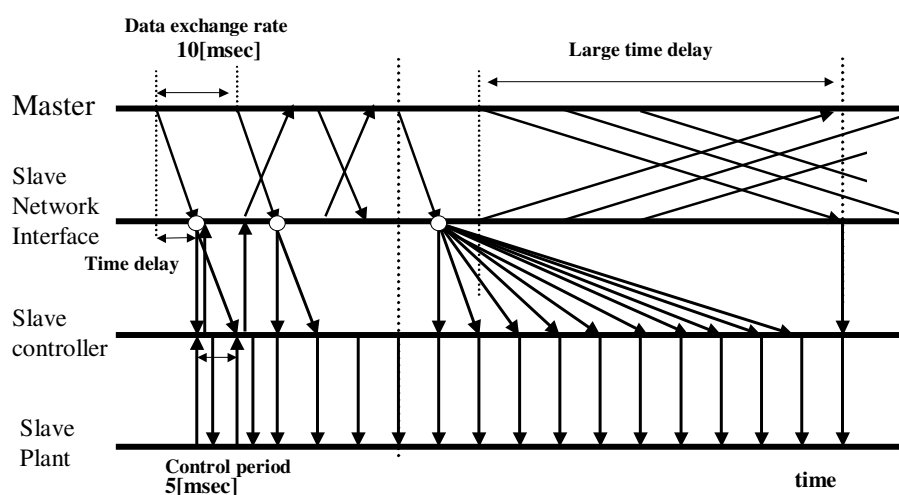


Fig. 12. Sequence diagram of data exchanges between master and slave

MASTER	CPU AMD Duron 600MHz NIC 100/10 Base T OS RT-Linux 3.1 on Linux 2.2.19
SLAVE	CPU Pentium 75+ 166MHz NIC 100/10 Base T OS RT-Linux 2.2 on Linux 2.2.14
RELAY	CPU Pentium 600MHz NIC 100/10 Base T OS Linux 2.2.14

Table 3. Parameters of master and slave controllers

emulation of network with poor quality

C_T is a computer located beyond the network to emulate various kind of qualities. It can emulate various kind of probability distribution of transmission delay, packet loss, packet shuffling and so on. Here we set the maximum time delay 1.0[sec] and the jitter in the Pareto distribution. The design parameter for robustness w.r.t. time-delay is set at $L_{max} = 1.5[\text{sec}]$ and $\epsilon = 6.6 \times 10^{-3}$ Here the $\epsilon > 0$ is selected to reduce the effects of integrator.

experimental result

Fig. 13 indicates an experimental result for evaluation of tracking performance. In the first half master(solid line) leads to the slave(dashed line). And last half slave leads to the master. This means that the master-slave tele-operation system works symmetrically well.

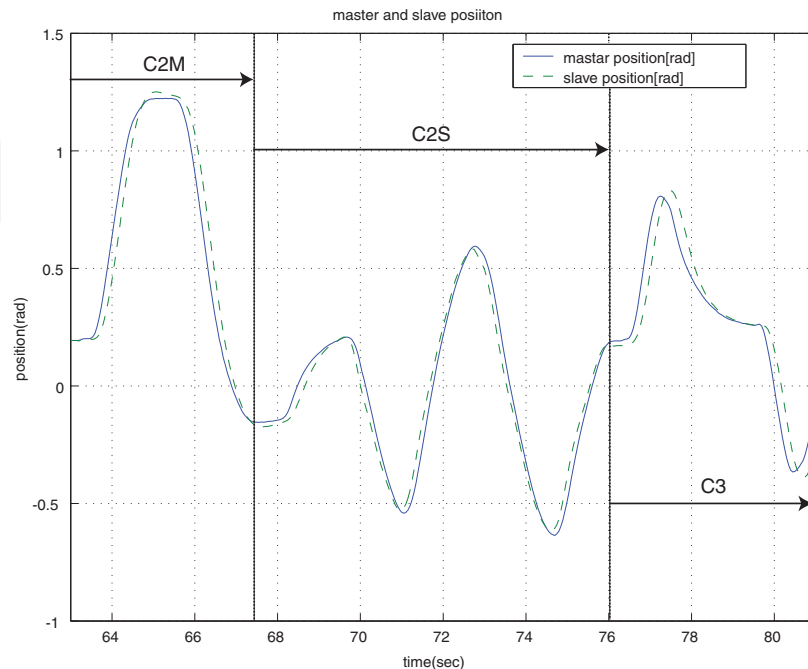


Fig. 13. experimental result of position tracking: master (solid line), slave (dashed line)

7. Summary

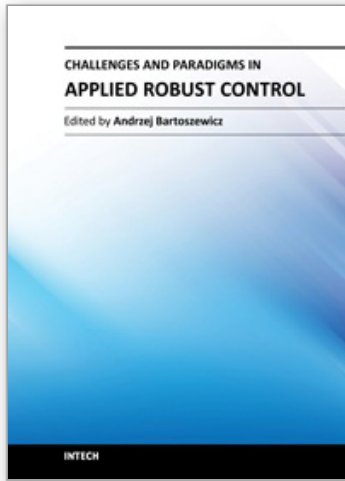
In this chapter we discussed on an application of robust control for force communication systems over inferior quality network. According to the investigation of the experiments the effectiveness of bilateral tele-operation system for force communication is confirmed. Especially the most important problem of the robustness w.r.t. time-delay is improved by H_∞ control systems theory.

8. References

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The main objective of this book is to present important challenges and paradigms in the field of applied robust control design and implementation. Book contains a broad range of well worked out, recent application studies which include but are not limited to H-infinity, sliding mode, robust PID and fault tolerant based control systems. The contributions enrich the current state of the art, and encourage new applications of robust control techniques in various engineering and non-engineering systems.

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