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A STUDY ON TELEOPERATION OF FLUID POWER SYSTEM OVER INTERNET

Shuyi JING*, Ato KITAGAWA*, Pingdong WU**

* Department of Mechanical and Control Engineering, Tokyo Institute of Technology
Tokyo, 152-8550 JAPAN
(E-mail: jsy@cm.ctrl.titech.ac.jp)
**Mechatronics Center, Beijing Institute of Technology
Beijing, 100081 CHINA

ABSTRACT

The main objective of this research is to demonstrate experimentally the feasibility of teleoperating a hydraulic system over Internet in real time. The teleoperation is based on the client/server architecture. Time delay caused by Internet is the main problem of the teleoperation system. After discussing the characteristic of uncertain time delay and the format of communication protocol, this paper introduces a control algorithm with prediction. Combining with the characteristic of time delay and TCP/IP protocol, this method can compensate the time delay existing in forward and feedback path. Moreover, the operator can operate transparently the master just as operating the remote object. A hydraulic master slave system is developed as a test rig and experimental results verify the feasibility of the compensator.

KEY WORDS

Teleoperation, Impedance, Time delay, Master slave, Fluid power

NOMENCLATURE

B : viscous coefficient (Ns/m)
F_m : operating force of the operator on the master (N)
F_s : contact force of the slave (N)
K : stiffness (N/m)
M : inertia (kg)
t : time (s)
U : actuator-driving force (N)
V : (reference) velocity (m/s)
Z : impedance (Ns/m)

Subscripts
e : object
m : master
o : target
s : slave

1 INTRODUCTION

The main purpose of teleoperation system is to extend the distance between an operator and an object. If an operator can operate a remote object smoothly, it will become reality that an experiential doctor conducts a telesurgery, or an engineer telecontrols a robot to work in some dangerous place, etc. For these significant aspects, many researchers have focused their attentions on the related works [1], and presented several examples of successful control over Internet in both theory and application. Anderson and Spong proposed a control law for Master-slave system with any non-varying time-delay based on passivity and scattering theory for the first time [2]. Adriana Vilchis presented a slave robot in new architecture for tele-echographic examination [3]. Tachi reported the master slave system by telexistence with advanced presence [4].

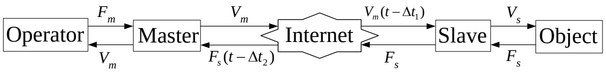


Figure 1 A master slave teleoperation system over Internet

A simplified sketch of this research is given in figure 1. The master slave teleoperation system takes on the precise job to operate a remote object over Internet. The slave consists of a hydraulic robot. Because the utilization of hydraulic actuators is attractive in several situations, due to their standard, safety and high load capacity, as well as their reliable performance. Hydraulic systems are, however, complex and nonlinear which may pose problems when applying control laws. For example, the fact that oil is compressible under high pressure, along with high load inertia may reduce the natural frequency. Furthermore, the performance of hydraulic valves is highly sensitive to payload. Finally, external and internal leakage, Coulomb friction, fluid flow dead band all result in parameters change of the system. These practical considerations make the successful implementation of control strategies rather difficult. Moreover, the hydraulic system is teleoperated. In this research, we will integrate an internal closed-loop position control on cylinder of hydraulic system with a much higher frequency than the external open-loop control. The teleoperation system aims at making the operator teleoperate the hydraulic system with high transparency.

2 A MASTER SLAVE TELEOPERATION SYSTEM

2.1 The Bilateral Impedance Control Method

A teleoperation system consists of a master, a slave, an operator and an object. In order to make equations derivation more intuitive [5], one degree of freedom (DOF) teleoperation system is considered. Before the Internet is introduced, there is no time delay in the communication. Assuming that the slave may not depart from the object, the dynamics of the master and the slave are modeled as follows in the form of impedance:

$$F_m - U_m = Z_m(s)V_m \tag{1}$$

$$U_s - F_s = Z_s(s)V_s \tag{2}$$

where

$$Z_m(s) = M_m s + B_m + \frac{K_m}{s} \tag{3}$$

$$Z_s(s) = M_s s + B_s + \frac{K_s}{s} \tag{4}$$

If the internal control input of master $U_m = F_s$ and $V_s = V_m = V_o$ is assumed, the system block diagram of impedance control becomes figure 2. The input and output relation between the master and the slave is expressed with the Eq. (5) and (6).

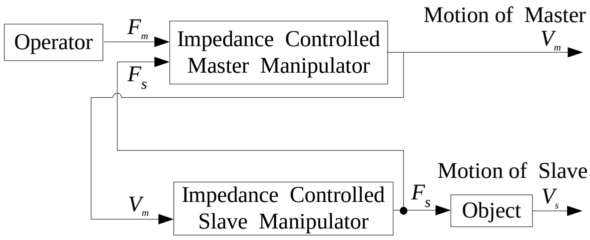


Figure 2 Schematic diagram of impedance control method

$$F_m - F_s = Z_o(s)V_o \tag{5}$$

$$U_s - F_s = Z_o(s)V_o \tag{6}$$

Here, the slave follows the master at the same speed. If target impedance $Z_o(s)$ is set small enough, then $F_m = F_s$ can be obtained. This indicates that the operator can operate the object transparently.

2.2 The Control Technique over Internet

This research aims at realization of teleoperation of the master and the slave over Internet. The control block diagram is shown in figure 3, and the following Eq. (7) and Eq. (8) can be obtained from figure 3.

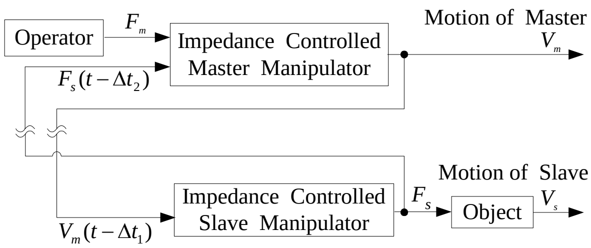


Figure 3 Schematic diagram of impedance control method over Internet

$$F_m - F_s(t-\Delta t_2) = Z_o(s)V_m \tag{7}$$

$$U_s - F_s = Z_o(s)V_m(t-\Delta t_1) \tag{8}$$

The forward time delay of a communication course is shown as Δt_1, and the backward time delay of a course is shown as Δt_2. Therefore, it is different from the ideal Eq. (5) and (6) in the case of real time.

3 EXPERIMENT SETUP

In this paper, experiment setup of the teleoperation system over Internet is depicted in figure 4.

The teleoperation system allows the operator to operate the master handle in one degree of freedom (DOF) in a line of 10cm with a maximum force of 200N. The master controller gathers force from the operator and then transmits it to the slave controller continuously every 10ms. The slave robot is consisted of a hydraulic system. Measured force from the object is also transmitted every 10 ms to the master controller.

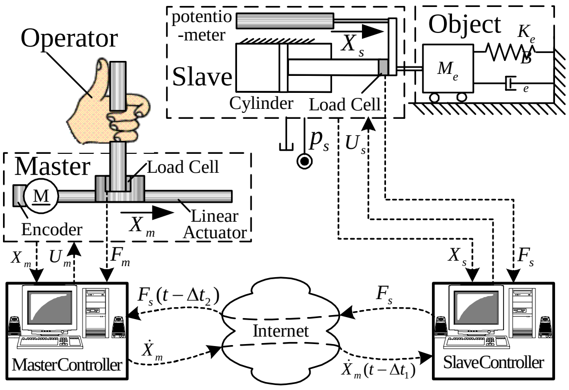


Figure 4 Schematic diagram of experiment setup

An external open-loop position-force control integrated with an internal closed-loop position control on cylinder of hydraulic system was implemented.

4 INTERNET

4.1 Characteristic of Time Delay

Considering the reliability and credibility of network [6, 7], TCP/IP protocol is adopted in this paper.

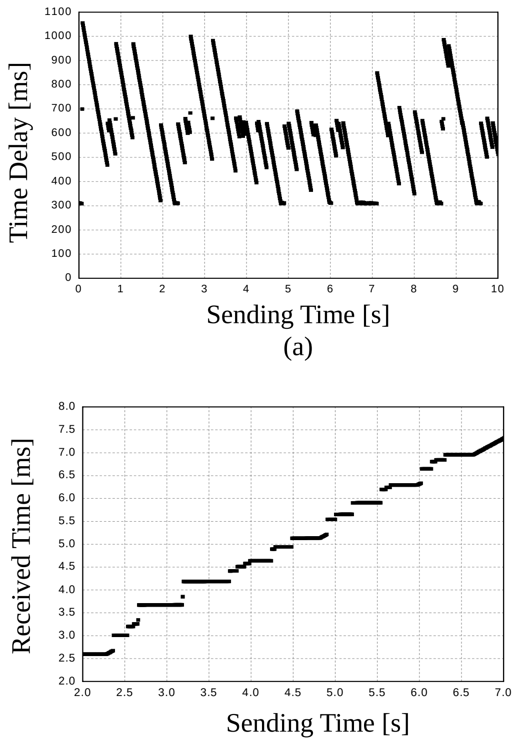
Figure 5 (a) is one example of the results of Internet-induced time delay between Kitagawa lab in Tokyo of Japan and Beijing of China. From figure 5 (a) (b), the Internet-induced time delay and its uncertainty is clear. In almost all of receiving time, packets are dropped off completely.

4.2 Format of Datagram

The teleoperation is based on the client/server architecture. Figure 6 shows the format of communication datagram. The unit of datagram is byte. In the forward path, master controller writes control signal and timestamp into datagram. On the other hand, in the feedback path, slave controller writes feedback signal, timestamp that remote computer received, and timestamp that remote computer send into datagram.

4.3 Simulation about Internet

To make results more convictive, we use the same time delay pattern with every result in this paper. However, time delay is uncertainly changing in the real communication process because of Internet routing or congestion etc. Therefore, we simulate Internet as figure 1 by making the time delay between the master and slave the same as typical data of time delay over Internet. The front part with 10s in a set of typical data with 30s is shown in figure 5.



(b)

Figure 5 Internet-induced time delay between Tokyo and Beijing

Sequence number	Control signal	Feedback signal	Timestamp sent by local computer
Timestamp received by remote computer	Timestamp sent by remote computer		

Figure 6 Format of communication datagram

5 EXPERIMENT RESULTS WITHOUT PREDICTITION

In this paper, the parameters are set as followings.

$$M_o = 0.05[\text{kg}],\ B_o = 0.4[\text{Ns/m}],\ K_o = 0$$
$$M_e = 0,\quad B_e = 0,\quad K_e = 1500[\text{N/m}]$$

Here, we just take a spring as the object.

5.1 Experiment Result without Internet

In the case of direct communication between the master and the slave, the signal is transmitted as figure 7. The experimental result by the setup in figure 4 without Internet is shown in figure 8. Figure 8 (a) describes displacements of the master and the slave. In the figures of displacement in this paper, "master" expresses the displacement X_m of the master and "slave" expresses the displacement X_s of the slave, or the displacement of the object. The figure shows that the slave robot follows the master well.

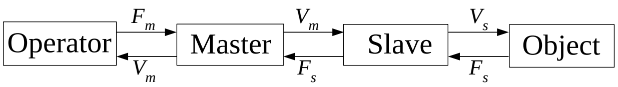
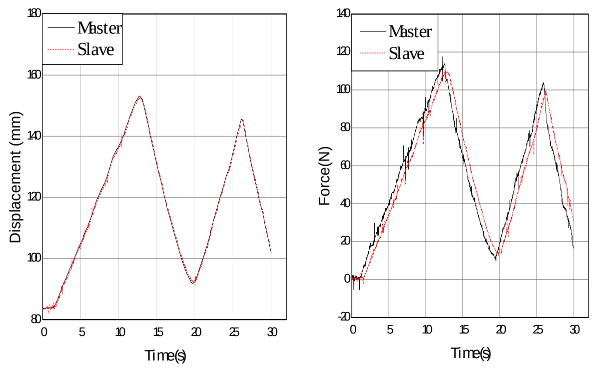


Figure 7 A master slave system without Internet

Figure 8 (b) shows force of the master and the slave. In the figure of force in this paper, "master" expresses the force F_m applied by the operator, and "slave" expresses the reaction force F_s from the object. The figure shows that the force from the operator and the reaction force from an object are almost the same. Therefore, it shows that the master slave system works well in figure 8.



Displacement of master and slave (a)

Force of master and slave (b)

Figure 8 The result without Internet

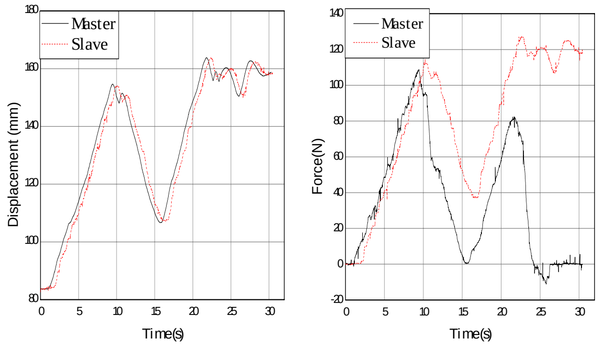
5.2 Experiment Result over Internet

If the signal is transmitted over Internet as figure 1 and figure 3, the experiment result is shown as figure 9.

Figure 9 (a) indicates that system becomes unstable, but the slave still follows the master well.

Figure 9 (b) shows that the system becomes unstable and operator cannot continue operation any more.

Because of the existence of Δt_1 and Δt_2 in Eq. (7) and (8), the diffrence of force between master and slave becomes larger and larger. This is the reason why the system becomes unstable and it is impossible for the operator to operate the object over Internet. Due to time delay from Internet, the teleoperation system even cannot retain stability. Therefore, some special compensator is necessary.



Displacement of master and slave (a)

Force of Master and slave (b)

Figure 9 The result over Internet

6 DYNAMIC PREDICTOR

6.1 Teleoperation with Predictor

The analysis above indicates that Internet-induced time delay is changing uncertainly. Thus, compensator should compensate the changes of Internet-induced time delay, to ensure the dynamic characteristic and stability of system. In this paper, we utilize the prediction control theory, which corrects an object model in the master side with history information, and schematic block diagram of the system is shown as figure 10. Where, $\overline{F}_s$ is the reaction force from the object model.

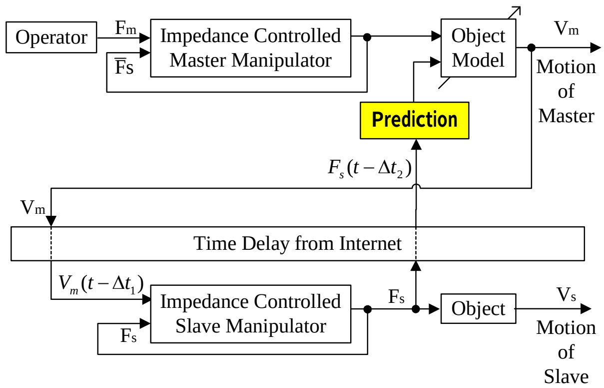


Figure 10 The schematic diagram of prediction control

6.2 Dynamic Principle of Prediction

The operator teleoperates an object by a master slave system over Internet. For system stability, this research compensates suitably by designing a dynamic predictor. The strategy exploits a particular kind of linear plant model called the 'controlled autoregressive integrated moving average' (CARIMA) model

$$A(q^{-1})y(t) = B(q^{-1})u(t-1) + \frac{\xi(t)}{1-q^{-1}} \qquad (9)$$

Where $A(q^{-1})$ and $B(q^{-1})$ are polynomials of degrees n_a and n_b in the backward shift operator q^{-1} and $\xi(t)$ is an uncorrelated random noise, $u(t)$ and $y(t)$ represent the input and the output, respectively. Since the noise filter, represented by the last term in Eq. (9), has a pole at z =1, a nonzero mean disturbance is produced in the CARIMA model.
As the primary of this research, we assume that the object persist one parameter of its rigidity, or its viscosity, e.g. viscosity. Here introduces $b(t)$ as the spring constant, and the j-step ahead prediction of $b(t)$ and $F_s(t)$, i.e. $\hat{b}(t)$, $\hat{F}_s(t)$, are obtained from Eq. 10 and Eq. 11.

$$\hat{b}(t) = \frac{1}{n_2 - n_1 + 1} \sum_{j=n_1}^{n_2} \frac{F_s(t-j)}{X(t-j)} \qquad (10)$$

$$\hat{F}_s(t) = \frac{1}{n_2 - n_1 + 1} \sum_{j=n_1}^{n_2} F_s(t-j) + [\hat{b}(t) * (\sum_{j=0}^{\frac{(n_1+n_2)}{2}} X_j)] \qquad (11)$$

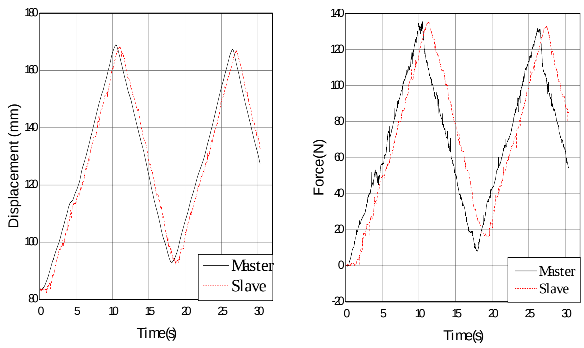
Where n_1 is the minimum output horizon and n_2 is the maximum output horizon. The objective of predictive control law is to determine future control signals, based on future predicted plant outputs and a given sequence of future set points. Because 30 steps is a little further, to reduce the calculation, we define n_1 and n_2 as below. From the time delay, we define n_1 as the last one of $F_s(t)$ that we have gotten. Because of the sliding-window protocol of TCP, and the characteristic of figure 5, so we define n_2 as (n_1+50).
Moreover, we use the following cost function:

$$J(n_1, n_2) = E\{\sum_{j=n_1}^{n_2} [\hat{F}_s(t) - F_s(t)]^2\} \qquad (12)$$

If $J(n_1, n_2)$ is bigger than the threshold value, it indicates that predicted $\hat{F}_s(t)$ is too different from $F_s(t)$. In this situation, the slave cannot follow the master, so the system will be obliged to stop to avoid danger.

6.3 The result with Prediction

The result with prediction is given in figure 11. Compared with the figure 8 (a), figure 11 (a) shows although there is time delay in displacements between the master and the slave, the system has become stable. This figure shows that the slave robot follows the master well. Compared with figure 8 (b) , figure 11 (b) shows although there is time delay in force between the master and the slave, the force from the operator and the force to the object are almost the same. It just means that operator can operate remote hydraulic system transparently.



Displacement of master and slave (a) | Force of Master and slave (b)

Figure 11 The result over Internet with dynamic compensator

As the result of the experiment, figure 12-figure 14 shows the force of the operator. Without Internet, figure 12 shows that the master system is in so good situation that the force of the operator is nearly the same as the object reaction force in the operation process. The difference of two cures depends on the master dynamic characteristic, and nonlinear hydraulic systems, which is not objective of this research. However, under communicating over Internet without compensator, figure 13 shows that operator cannot feel the object as a spring any more. With prediction, figure 14 shows that operator move the master over Internet, just like moving object directly.

7 CONCLUSIONS

This paper presented a research on teleoperation of a hydraulic robot with time delay over Internet. After describing the control mechanism of master slave system, the characteristic of uncertain time delay caused by Internet, and the format of communication protocol are discussed. Another emphasis is the designation of the compensator to solve the instability caused by time-delay. The control algorithm on line with prediction brought out in this paper can guarantee the stability of the system effectively. Moreover, this paper demonstrated experimentally the feasibility of operating the remote object by the hydraulic setup over Internet in real time.

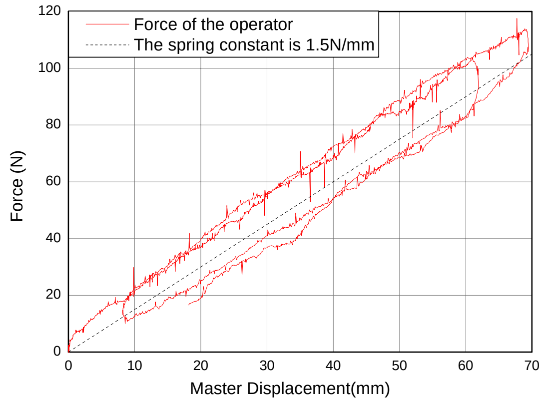


Figure 12 Force of the operator without Internet

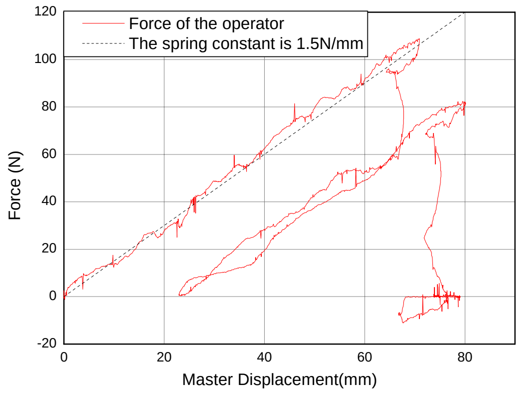


Figure 13 Force of the operator over Internet without predictor

Figure 14 Force of the operator over Internet with predictor

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