Design and Stability Analysis of Impedance Controller for Bilateral Teleoperation under a Time Delay

Hyun Chul Cho, Jong Hyeon Park*
School of Mechanical Engineering, Hanyang University, Haengdang-Dong, Sungdong-Ku, Seoul 133-791, Korea

A new impedance controller is proposed for bilateral teleoperation under a time delay. The proposed controller does not need to measure or estimate the time delay in the communication channel using the force loop-back. In designing a stable impedance controller, absolute stability is used as a stability analysis tool, which results in a less conservative controller than the passivity concept. Moreover, in order to remove the conservatism associated with the assumption of infinite port impedances, the boundaries of human and environment impedance are set to finite values. Based on this, this paper proposes a parameter design procedure for stable impedance controllers. The validity of the proposed control scheme is demonstrated by experiments with a 1-dof master/slave system.

Key Words : Bilateral Teleoperation, Impedance Control, Absolute Stability, Force Feedback, Time Delay

Nomenclature

T_1 : Time delay from the master to the slave
T_2 : Time delay from the slave to the master
$Z_{e,\max}$: Maximum of the environment impedance
$Z_{h,\max}$: Maximum of the human impedance
$Z_{h,\min}$: Minimum of the human impedance
$\bar{m}$, $\bar{b}$, $\bar{k}$: Mass, damping, and stiffness in the desired impedance
$f^*(w)$: Modified absolute stability criterion
f_e : Force exerted on the slave by its environment
f_h : Force applied at the master by the operator
k_f : Force scale factor
k_p : Position scale factor
m, b : Mass and viscous coefficient in dynamics
u : Input torque of the device
x : Position of the device

* Corresponding Author,
E-mail : jongpark@hanyang.ac.kr
TEL : +82-2-2290-0435; **FAX** : +82-2-2298-4634
School of Mechanical Engineering, Hanyang University, Haengdang-Dong, Sungdong-Ku, Seoul 133-791, Korea. (Manuscript **Received** November 25, 2003; **Revised** March 18, 2004)

1. Introduction

Impedance control (Hogan, 1985) adjusts the impedance of the manipulator, that is defined as $Z(s)=F(s)/V(s)$ where $F(s)$ denotes force and $V(s)$ denotes velocities in the Laplace transform ; and is determined typically by an inertia, a damper, and a spring. The desired impedance of the manipulator depends on the task that the manipulator performs.

In many telerobotic tasks, robot manipulators interact with their environments. Excessive contact force between the robot and the environment should be avoided to keep the stability of the controlled system and not to damage the system. Besides, the tracking ability in the freespace cannot be neglected for successful task performance. Since the impedance control can treat these situations effectively, it has many applications for teleoperation (Dubey et al., 1997 ; Park et al., 2000 ; Rubio et al., 1999). However, since these works do not consider a human and/or environment model in their stability analysis, the entire system stability cannot be guaranteed. The time delay in the communication channel is, moreover, not considered in the controller design.

In this paper, a new impedance controller for bilateral teleoperation is proposed considering the time delay and position/force scale factors. In the proposed controllers, the master impedance controller makes the master mimic a passive mechanical tool as well as provides a human operator with force-feedback. On the other hand, the slave tracks the master command and absorbs the contact forces with the impedance controller. In real implementations, these controllers do not need to measure or estimate the time delay imposed on the system since it just uses the force loop-back located in the slave controller, that sends the information on the contact force to and receives it from the master.

Many stability analysis tools, such as the passivity theory (Anderson and Spong, 1989; Lawrence, 1993; Niemeyer and Slotine, 1997; Raju et al., 1989), the Lyapunov stability theory (Dubey et al., 1997; Park et al., 2000), a Bode diagram (Rubio et al., 1999), the structured singular value (Colgate, 1993) or the absolute stability (Adams and Hannaford, 1999, 2002; Hashtrudi-Zaad and Salcudean, 2001), have been used for analyzing the stability of teleoperation. And the structured singular value and the absolute stability are known to yield less conservative controllers than the others. In this paper, the absolute stability is used as the stability analysis tool of the teleoperation system since it is less conservative and useful in the parametric representation of the stability criterion. Furthermore, we assume that human and environment impedances are rather limited by finite values in order to reduce the conservatism of the conventional absolute stability.

In tuning control parameters, it is important to know the relations between the parameters and the stability condition. We investigate the relations between the slave impedance parameter and the stability condition in order that a controller designer can guess how the changing parameters can affect the stability criteria in the frequency domain. Based on this, we propose a parameter-tuning procedure of the impedance controllers. Experiments with the impedance controllers designed by the suggested procedure show that the system can maintain stable behaviors even when it contacts with a wall and when a time delay exists in the communication channel.

Section 2 derives the impedance controllers for the master and the slave, and summarizes some definitions. Section 3 describes the stability analysis of suggested impedance-controlled teleoperation. The procedure to design parameter is explained in Sec. 4. Experiments with a 1-dof teleoperation system and their results are shown in Sec. 5, followed by conclusions in Sec. 6.

2. Impedance Control Laws for Teleoperation

2.1 Master and slave dynamics

In this paper, dynamics of the single dof master/slave system are modeled as a mass-damper system as follows:

$$m_m\ddot{x}_m(t)+b_m\dot{x}_m(t)=u_m(t)+f_h(t) \quad (1)$$

$$m_s\ddot{x}_s(t)+b_s\dot{x}_s(t)=u_s(t)-f_e(t) \quad (2)$$

where m and b denote mass and viscous coefficient; subscript 'm' and 's' denote the master and the slave, respectively.

2.2 Delayed signals and scale factors

For a bilateral teleoperation system, the position and force of the master are transmitted to the slave and the contact force of the slave is sent to the master through communication channels. When there is a time delay in the communication channel, the signals from and to the channel are related as:

$$x_m^d(t):=x_m(t-T_1),\ \dot{x}_m^d(t):=\dot{x}_m(t-T_1)$$

$$f_h^d(t):=f_h(t-T_1),\ f_e^d(t):=f_e(t-T_2)$$

These delayed signals out of the communication block are then scaled up or down with some factors depending on a teleoperation task such that

$$x_s=k_px_m^d,\ f_h=k_ff_e^d \quad (3)$$

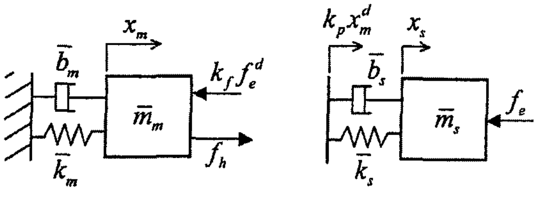


Fig. 1 Desired impedance models for the master and the slave

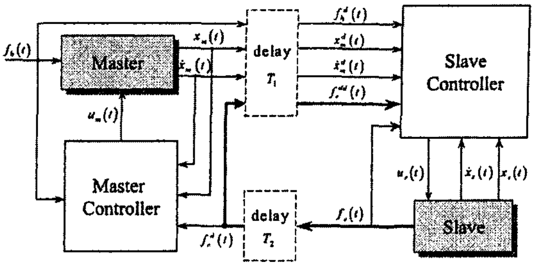


Fig. 2 The overall system block diagram

2.3 Impedance controllers for master and slave

Now, the impedance controllers for the maser and the slave are derived. These controllers are designed based on a force-position type teleoperation. The desired impedance models of the master and the slave are shown in Fig. 1.

The master can mimic a passive mechanical tool such as a racket or a hammer, and can provide force-feedback for a human operator with its desired impedance model. The slave tracks master commands in freespace and absorbs contact forces when it collides against a wall using the desired impedance model of the slave.

2.3.1 Master controller

Suppose that the desired impedance for the master is specified by

$$\begin{aligned}&\bar{m}_m\ddot{x}_m(t)+\bar{b}_m\dot{x}_m(t)+\bar{k}_m x_m(t)\\&=f_h(t)-k_f f_e^d(t)\end{aligned}\tag{4}$$

These parameters are selected for the maneuverability and the stability of the master device. Combining Eqs. (1) and (4) to remove acceleration $\ddot{x}_m$ results in the control input to the master :

$$\begin{aligned}u_m(t)=&\left(b_m-\frac{m_m}{\bar{m}_m}\bar{b}_m\right)\dot{x}_m(t)+\left(\frac{m_m}{\bar{m}_m}-1\right)f_h(t)\\&-\frac{m_m}{\bar{m}_m}(k_f f_e^d(t)+\bar{k}_m x_m(t))\end{aligned}\tag{5}$$

2.3.2 Slave controller

The desired impedance for the slave can be similarly defined as follows.

$$\begin{aligned}&\bar{m}_s\{\ddot{x}_s(t)-k_p\ddot{x}_m^d(t)\}+\bar{b}_s\{\dot{x}_s(t)-k_p\dot{x}_m^d(t)\}\\&+\bar{k}_s\{x_s(t)-k_p x_m^d(t)\}=-f_e(t)\end{aligned}\tag{6}$$

From Eqs. (2), (4) and (6), the control input for the slave can be found :

$$\begin{aligned}u_s(t)=&\left(b_s-\frac{m}{\bar{m}_s}\bar{b}_s\right)\dot{x}_s(t)-\frac{m_s}{\bar{m}_s}\bar{k}_s x_s(t)+\frac{m_s}{\bar{m}_m}k_p f_h^d(t)\\&+m_s k_p\left[\left(\frac{\bar{b}_s}{\bar{m}_s}-\frac{\bar{b}_m}{\bar{m}_m}\right)\dot{x}_m^d(t)+\left(\frac{\bar{k}_s}{\bar{m}_s}-\frac{\bar{k}_m}{\bar{m}_m}\right)x_m^d(t)\right]\\&+\frac{\bar{m}_m-m_s}{\bar{m}_m}f_e(t)-\frac{m_s}{\bar{m}_m}k_p k_f f_e^{dd}(t)\end{aligned}\tag{7}$$

where $f_e^{dd}(t):=f_e^d(t-T_1)=f_e(t-T_1-T_2)$. Note that $f_e^{dd}(t)$ can be obtained easily in real implementations by just sending signal $f_e(t)$ to and receiving it from the master. When the slave sends $f_e(t)$ to the master, $f_e(t-T_2)$, which is delayed by T_2, arrives at the master. Sending $f_e(t-T_2)$ from the master to the slave delays the signals again by T_1, and these signals are $f_e(t-T_1-T_2)$. Therefore, there is no need to measure a time delay in communication channel or store the external force data in a memory buffer in order to obtain the delayed signal.

The entire system structure including the controllers and the communication channel is shown in Fig. 2, where the thick line indicates the force loop used for the slave impedance controller. If there is no time delay in the communication channel, $f_e^{dd}(t)$ would be identical to $f_e(t)$, and the force loop-back for the slave control would not be required.

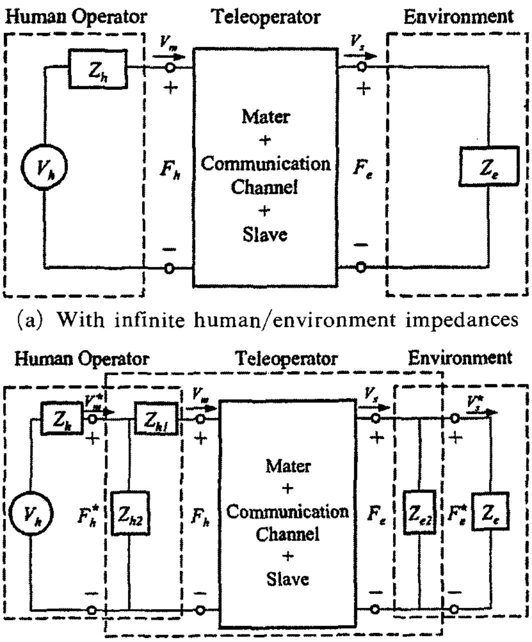
3. Stability Analysis

In this paper, absolute stability (Haykin, 1970) is used to analyze the stability of the teleoperation system. Since the absolute stability method provides a simple tool to analyze stability based only on input-output properties of the system, it is suitable for the stability analysis of a two-port teleoperation having unmodeled passive human operators and environments. Absolute stability has been widely used in the stability analysis of teleoperation systems owing to its less conservativeness than the one based on passivity (Adams and Hannaford, 1999 ; Cho et al., 2001 ; Hashtrudi-Zaad and Salcudean, 2001 ; Hwang et al., 2001).

3.1 Two-port model for the teleoperation system

Teleoperation systems should be represented in the form of a two-port network for the stability analysis based on absolute stability. Figure 3(a) shows a two-port network of the teleoperation system, where the operator-master interface is designated as the master port and the slave-environment interface as the slave port.

The relation between *efforts* (f_h, f_e) and *flows* ($\dot{x}_m$, $\dot{x}_s$) of the two ports can be described by the hybrid matrix obtained from the controlled master and slave behaviors of Eqs. (4) and (6) as follows.



(a) With infinite human/environment impedances

(b) With limited human/environment impedances ($Z_{h1}=Z_{h,\min}$, $Z_{h2}=Z_{h,\max}-Z_{h,\min}$ and $Z_{e2}=Z_{e,\max}$)

Fig. 3 A two-port model of teleoperation systems

$$\begin{bmatrix} F_h(s) \\ -V_s(s) \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} V_m(s) \\ F_e(s) \end{bmatrix} \quad (8)$$

where $F_h(s)$, $V_m(s)$, $V_s(s)$ and $F_e(s)$ are the Laplace transforms of $f_h(t)$, $\dot{x}_m(t)$, $\dot{x}_s(t)$, and $f_e(t)$, respectively, and h-parameters are :

$$\begin{aligned} h_{11} &:= \left.\frac{F_h(s)}{V_m(s)}\right|_{F_e=0} = \bar{m}_m s + \bar{b}_m + \frac{\bar{k}_m}{s} \\ h_{12} &:= \left.\frac{F_h(s)}{F_e(s)}\right|_{V_m=0} = k_f e^{-T_2 s} \\ h_{21} &:= \left.\frac{V_s(s)}{V_m(s)}\right|_{F_e=0} = -k_p e^{-T_1 s} \\ h_{22} &:= \left.\frac{-V_s(s)}{F_e(s)}\right|_{V_m=0} = \frac{s}{\bar{m}_s s^2 + \bar{b}_s s + \bar{k}_s} \end{aligned} \quad (9)$$

3.2 Conventional absolute stability of a two-port

The absolute stability is defined as follows (Haykin, 1970).

Definition : A linear two-port is said to be absolutely stable if there exists no set of passive terminating one-port impedances for which the system is unstable. If the network is not absolutely stable, it is potentially unstable.

A necessary and sufficient condition for the absolute stability of a two-port network is that one-port networks, resulting from any passive output and input termination, are themselves passive (Haykin, 1970). Llewellyn's stability criteria (Llewellyn, 1952) provides the necessary and sufficient conditions for the absolute stability :

(a) h_{11} and h_{22} have no poles in the right half plane ;

(b) Any poles of h_{11} and h_{22} on the imaginary axis are simple with real and positive residues ;

(c) For all real values of w,

$$\mathrm{Re}[h_{11}] \geq 0, \ \mathrm{Re}[h_{22}] \geq 0$$

$$2\mathrm{Re}[h_{11}]\mathrm{Re}[h_{22}] - \mathrm{Re}[h_{12}h_{21}] - |h_{12}h_{21}| \geq 0$$

If h-parameters of a hybrid matrix satisfy Llewellyn's stability criteria, the entire teleoperation system including the human and the environment is absolutely stable. In other words, the master and the slave device will be stable with any set of passive human operators and passive environments.

For the given two-port network of Eq. (8), conditions (a) and (b), together with the first and second conditions in (c) are satisfied with the positive parameters of the master and the slave. And combining the last of condition (c) with the h-parameters in Eq. (9) gives

$$[\cos(T_1+T_2)w-1]k_pk_f+\frac{2\bar{b}_m\bar{b}_sw^2}{(\bar{k}_s-\bar{m}_sw^2)^2+(\bar{b}_sw)^2}\geq 0 \quad (10)$$

3.3 Modified absolute stability for a two-port

The conventional absolute stability assumes the infinite port impedances. This assumption makes the stability criterion too tight and conservative since port impedances in teleoperation have actually finite values. This conservatism can be relaxed with limits imposed on the human/environment impedance as in (Adams and Hannaford, 2002; Hashtrudi-Zaad and Salcudean, 2001).

Figure 3(b) shows a two-port model of the teleoperation system with a limited human/environment impedance. If Z_h is $0(\infty)$, the human impedance becomes $Z_{h,\min}$ ($Z_{h,\max}$). So, the human impedance, which previously has an infinite range, is limited to $Z_{h,\min}\sim Z_{h,\max}$. Similarly, the environment impedance is bounded by $Z_{e,\max}$.

The hybrid matrix of the modified two-port model is

$$\begin{bmatrix} F_h^*(s) \\ -V_s^*(s)\end{bmatrix}=\begin{bmatrix} h_{11}^* & h_{12}^* \\ h_{21}^* & h_{22}^*\end{bmatrix}\begin{bmatrix} V_m^*(s) \\ F_e^*(s)\end{bmatrix} \quad (11)$$

where

$$h_{11}^*:=\frac{Z_{h2}(Z_{h1}+h_{11})}{Z_{h,\max}+h_{11}},\ h_{12}^*:=\frac{Z_{h2}h_{12}}{Z_{h,\max}+h_{11}}$$

$$h_{21}^*:=\frac{Z_{h2}h_{21}}{Z_{h,\max}+h_{11}},\ h_{22}^*:=h_{22}-\frac{h_{12}h_{21}}{Z_{h,\max}+h_{11}}+\frac{1}{Z_{e2}}$$

And the stability criterion of the modified two-port is

$$\begin{aligned} f^*(w)&:=-2\mathrm{Re}[h_{11}^*]\mathrm{Re}[h_{22}^*] \\ &+\mathrm{Re}[h_{12}^*h_{21}^*]+|h_{12}^*h_{21}^*|\leq 0 \end{aligned} \quad (12)$$

or

$$f^*(w)':=2\cos(\angle h_{12}^*h_{21}^*)+2\frac{\mathrm{Re}[h_{11}^*]\mathrm{Re}[h_{22}^*]}{|h_{12}^*h_{21}^*|}\geq 1$$

If the master impedance, h_{11} is small such that $h_{11}\ll Z_{h,\max}$, the hybrid matrix in Eq. (11) can be approximated as

$$H^*:=\begin{bmatrix} h_{11}^* & h_{12}^* \\ h_{21}^* & h_{22}^*\end{bmatrix}\approx\begin{bmatrix} h_{11}^* & h_{12}^* \\ h_{21}^* & h_{22}^*-\frac{h_{12}h_{21}}{Z_{h,\max}}+\frac{1}{Z_{e,\max}}\end{bmatrix}$$

and Llewellyn's stability criteria can be also approximated as follows:

$$\begin{aligned} f^*(w)'&\approx-\cos(\angle h_{12}h_{21})+2\frac{\mathrm{Re}[h_{11}]\mathrm{Re}[h_{22}]}{|h_{12}h_{21}|} \\ &+2\frac{\mathrm{Re}[h_{11}]}{|h_{12}h_{21}|}\mathrm{Re}\left[\frac{1}{Z_{e,\max}}-\frac{h_{12}h_{21}}{Z_{h,\max}}\right] \end{aligned} \quad (13)$$

The first two terms of Eq. (13) are Llewellyn's stability criteria with the infinite port impedance. The above equation shows that a relaxed stability criterion can be obtained if the last term on the right side of Eq. (13) is positive. Suppose that $Z_{e,\max}=m_{ex}s+b_{ex}+\frac{k_{ex}}{s}$ and $Z_{h,\max}=m_{hx}s+b_{hx}+\frac{k_{hx}}{s}$,

$$\begin{aligned} &\mathrm{Re}\left[\frac{1}{Z_{e,\max}}-\frac{h_{12}h_{21}}{Z_{h,\max}}\right]=\mathrm{Re}\left[\frac{1}{Z_{e,\max}}\right]-\mathrm{Re}\left[\frac{h_{12}h_{21}}{Z_{h,\max}}\right] \\ &=\frac{b_{ex}w^2}{(b_{ex}w)^2+(m_{ex}w^2-k_{ex})^2}-k_pk_f\frac{w\sin((T_1+T_2)w+\phi)}{\sqrt{(b_{hx}w)^2+(m_{hx}w^2-k_{hx})^2}}\geq 0 \end{aligned}$$

which is satisfied only if

$$\frac{b_{ex}w^2}{(b_{ex}w)^2+(m_{ex}w^2-k_{ex})^2}\geq\frac{k_pk_fw}{\sqrt{(b_{hx}w)^2+(m_{hx}w^2-k_{hx})^2}} \quad (14)$$

where $\phi=\cos^{-1}\frac{m_{hx}w^2-k_{hx}}{\sqrt{(b_{hx}w)^2+(m_{hx}w^2-k_{hx})^2}}$.

Since $\mathrm{Re}[h_{11}]>0$, a more relaxed stability condition is obtained if Eq. (14) is satisfied.

4. Impedance Parameter Design

Since the criteria for absolute stability depend solely on the h-parameters having impedance parameters, we can use these criteria to design impedance parameters. Before proceeding to the design of impedance parameter, the relations between the slave impedance parameter and the system stability are investigated.

4.1 Relations between slave impedance and absolute stability criterion

The following equations are the partial derivatives of $f^*(w)$ with respect to each slave impedance parameter. Using these equations, we can guess how $f^*(w)$ varies with the changing slave impedance.

$$\frac{\partial f^*(w)}{\partial \bar{m}_s} = -4\mathrm{Re}[h_{11}^*]\frac{\bar{b}_s w^4(\bar{k}_s - \bar{m}_s w^2)}{(\bar{b}_s^2 w^2 + (\bar{k}_s - \bar{m}_s w^2)^2)^2}$$

$$\frac{\partial f^*(w)}{\partial \bar{b}_s} = 2\mathrm{Re}[h_{11}^*]\frac{w^2(\bar{b}_s^2 w^2 - (\bar{k}_s - \bar{m}_s w^2)^2)}{(\bar{b}_s^2 w^2 + (\bar{k}_s - \bar{m}_s w^2)^2)^2} \quad (15)$$

$$\frac{\partial f^*(w)}{\partial \bar{k}_s} = 4\mathrm{Re}[h_{11}^*]\frac{\bar{b}_s w^2(\bar{k}_s - \bar{m}_s w^2)}{(\bar{b}_s^2 w^2 + (\bar{k}_s - \bar{m}_s w^2)^2)^2}$$

In Eq. (15), if the equation is negative, f^* becomes smaller as the slave impedance increases and vice versa. The frequency regions satisfying $\partial f^*/\partial z_s < 0$ are summarized in Table 1, where z_s is the slave impedance parameter. This table shows that an increasing $\bar{m}_s$ makes f^* smaller at $0 < w < \sqrt{\bar{k}_s/\bar{m}_s}$. Similarly, an increasing $\bar{k}_s$ makes f^* smaller at $w > \sqrt{\bar{k}_s/\bar{m}_s}$. Since $|\partial f^*/\partial \bar{m}_s| = w^2 |\partial f^*/\partial \bar{k}_s|$, the changes in $\bar{k}_s$ affect f^* more dominantly than $\bar{m}_s$ at low frequencies and vice versa at high frequencies. And the increase in $\bar{b}_s$ guarantees smaller f^* except in $(-\bar{b}_s + \sqrt{\bar{b}_s^2 + 4\bar{k}_s\bar{m}_s})/(2\bar{m}_s) \le w \le (\bar{b}_s + \sqrt{\bar{b}_s^2 + 4\bar{k}_s\bar{m}_s})/(2\bar{m}_s)$.

4.2 Parameter selection procedure

Firstly, the position/force scale factors are determined depending on a device type and an application. The scale factors affect, of course, on the system stability, but these are designed regardless of the stability for convenience.

At the master controller, the control objective is not to achieve ideal transparency of teleoperation (Kim et al., 2003; Lawrence, 1993), which means that environment impedance is precisely transferred to the human operator, but to make the master device mimic a passive mechanical tool. The dynamic characteristic of the passive tool is realized by the desired master impedance model, Eq. (4), and is designed according to the task at hand. Too large master impedance makes the device heavy and sluggish, while it is difficult to operate the device precisely with too small impedance.

For the slave impedance, the tracking performance and the contact behavior of the slave are considered. The slave impedance is a second-order system, and it can be described by ζ and w_n such as $s^2 + \frac{\bar{b}_s}{\bar{m}_s}s + \frac{\bar{k}}{\bar{m}_s} = s^2 + 2\zeta w_n s + w_n^2$. The transient response of the slave is designed by ζ and w_n, and then the slave impedance can be calculated using the coefficient comparison.

Now, the absolute stability of the system with the designed parameters is investigated by $f^*(w)$ evaluating in Eq. (12). Before calculating $f^*(w)$, the bounds of port impedances and the allowable maximum round-trip time, $T_{\max}$ should be determined. If the calculated $f^*(w)$ does not satisfy Eq. (12) at high (low) frequencies, reduce $\bar{m}_s$ ($\bar{k}_s$) with an increased $\bar{b}_s$ until Eq. (12) is satisfied for all frequencies.

The proposed design procedure is summarized below.

(1) Select k_p and k_f considering a device and a task.

(2) Design $\bar{m}_m$, $\bar{b}_m$ and $\bar{k}_m$ in order that the master can mimic a desired passive mechanical tool.

(3) Select $\bar{k}_s$ to have the slave a desired tracking ability.

(4) Determine ζ and w_n and then calculate $\bar{m}_s = \bar{k}_s/w_n^2$ (or $\bar{k} = w_n^2\bar{m}_s$) and $\bar{b}_s = 2\zeta w_n \bar{m}_s$.

(5) Check the absolute stability by evaluating $f^*(w) \le 0$.

(6) Reduce $\bar{m}_s$ ($\bar{k}_s$) with an increased $\bar{b}_s$ if

Table 1 The frequency regions satisfying $\partial f^*/\partial z_s < 0$, where z_s is each slave impedance parameter

	Frequencies where $\partial f^*/\partial z_s < 0$
$\bar{m}_s$	$0 < w < \sqrt{\frac{\bar{k}_s}{\bar{m}_s}}$
$\bar{b}_s$	$0 < w < \frac{-\bar{b}_s + \sqrt{\bar{b}_s^2 + 4\bar{k}_s\bar{m}_s}}{2\bar{m}_s}$, $w > \frac{\bar{b}_s^2 + 4\bar{k}_s\bar{m}_s}{2\bar{m}_s}$
$\bar{k}_s$	$w > \sqrt{\frac{\bar{k}_s}{\bar{m}_s}}$

the condition of Eq. (12) is not satisfied at high (low) frequencies.

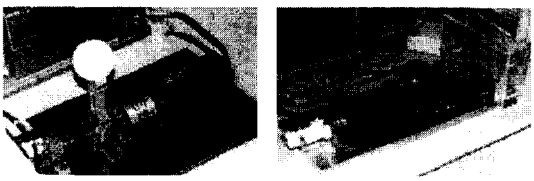
(7) Go to step 5) until Eq. (12) is satisfied.

(8) If step 7) fails or better tracking performance is required, go to step 2) with the increased master impedance.

5. Experiments

In this section, the validity of the proposed control scheme is investigated through the experiments with the 1-dof bilateral teleoperation system shown in Fig. 4. The master and the slave are connected each other by the TCP/IP. A memory buffer is used to generate various sizes of time delays. The data to be exchanged between the master and the slave are written to the buffer, and they are sent to their intended destination only when the buffer is full. Thus, the time delay depends on the buffer size.

Impedance parameters are designed based on the proposed procedure. At first, the scale factors are determined considering the size and configuration of the device. Then, the master impedance is adjusted by trial and error accordingly as the impedance-controlled master is easy to drive and is suitable for a precise motion. The stiffness of the slave, $\bar{k}_s$ is selected to be 80 [N/m] as a first try considering the tracking performance in a freespace. And $\bar{m}_s$ and $\bar{b}_s$ are designed as 0.09 [kg] and 3.73 [Ns/m], respectively, corresponding to $\zeta=0.7$ and $w_n=30$ [rad/s]. It is then tested with $T_{\max}=1.5$ [sec] whether these parameters satisfy Eq. (12). As the maximum impedance, $Z_{h,\max}=6.75$ [Nms]$+22.5/s$ [Nm], which is from (Adams and Hannaford, 2002), and $Z_{e,\max}=10^6/s$ [N/m] are used. And we assumed that the operator maintains over 10% of $Z_{h,\max}$ during the operation for convenience ($Z_{h,\min}=0.1Z_{h,\max}$). It also means that the human operator does not release the master device during the operation.



(a) Master (b) Slave

Fig. 4 The master and slave systems used in the experiments

Figure 5 shows that the condition of Eq. (12) is not satisfied with the designed parameters at low frequencies. To resolve this, $\bar{k}_s$ is reduced to 45 [N/m] and is increased to 5.5 [Ns/m]. Then Eq. (12) is checked again with the revised parameters, and now is satisfied for all the frequencies. Though an increase in the master impedance has an effect on the stability enhancement, only the slave impedance is changed at this stage.

The performance with the above two parameter sets, summarized in Table 2, is investigated by a series of experiments. For this, the slave is commanded to follow an alternating motion of the master, and it contacts with the wall during the motion. For the performance comparison, the tracking ability and contact stability of the slave are considered. The wall stiffness used in the experiments is about 3×10^4 [N/m].

The first experiment is performed with the unstable set in Table 2. In this case, the slave tracks well the master commands in a freespace due to relatively large stiffness in the slave impedance. But when the slave contacts with the wall, it shows unstable behaviors as shown in Fig. 6(a). This is because when the teleoperation is mani-

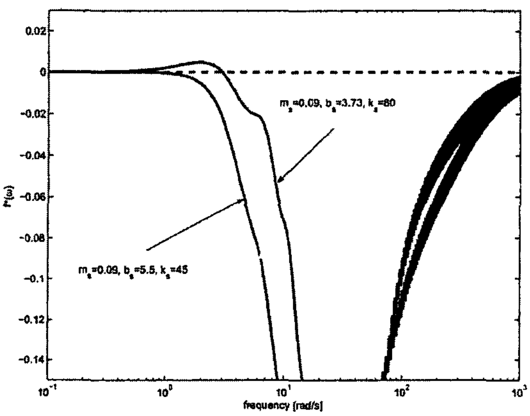
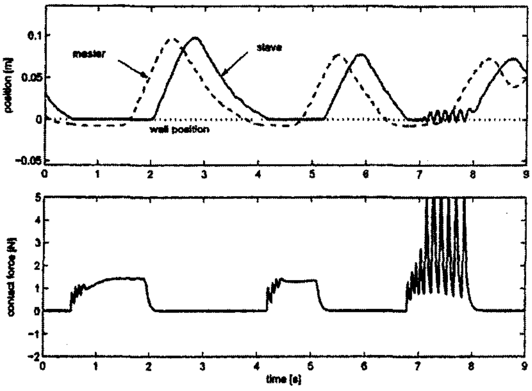


Fig. 5 $f^*(w)$ with 1st and 2nd impedance set when RTT=1.5s

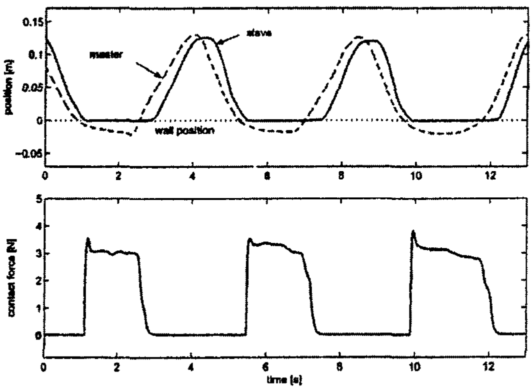
pulated in a bilateral fashion under a time delay, it loses its passivity and becomes potentially unstable. Since the human operator has an ability to damp out the oscillating contact forces with the human impedance, the unstable behaviors can be observed only at the slave side.

Table 2 The parameters used in the experiments

Scale factors and maximum RTT		Master impedance	
k_p	0.1 [m/rad]	$\bar{m}_m$	0.02 [kgm^2]
k_f	0.05 [m]	$\bar{b}_m$	0.05 [Nms]
T_{max}	1.5 [s]	$\bar{k}_m$	0.04 [Nm]
Slave impedance (unstable set)		Slave impedance (stable set)	
$\bar{m}_s$	0.09 [kg]	$\bar{m}_s$	0.09 [kg]
$\bar{b}_s$	3.73 [Ns/m]	$\bar{b}_s$	5.50 [Ns/m]
$\bar{k}_s$	80 [N/m]	$\bar{k}_s$	45 [N/m]
J	0.9344 [m]	J	10.0632 [m]



(a) With the unstable impedance set in Table 2



(b) With the stable impedance set in Table 2

Fig. 6 Master/slave position and contact force at the slave

The next one is with the stable set in Table 2. In Fig. 6(b), though the reduced stiffness degrades the tracking performance of the slave, the slave can keep the stable contacts even when there exists the time delay. In order to quantitatively measure the tracking performance of the slave, the performance index, $J := \mathrm{std}(x_s(t) - k_p x_m^d(t))$ is considered, where std $(\cdot)$ is the standard deviation of the argument. This index can be used in step 8) in Sec. 4.2 to determine whether the tracking performance of the slave is satisfactory or not. The smaller J is, the better the slave tracks the master commands. The calculated J for each case is in Table 2. For the case of the unstable set, the position data in $2 \leq t \leq 4$ of Fig. 6(a) are used, and for the stable case, the data in $1.2 \leq t \leq 3.2$ of Fig. 6(b) are used.

6. Conclusions

In this paper, a new impedance controller for bilateral teleoperation is proposed. The proposed controller considers a time delay imposed on the system and the position/force scale factors. Using the force loop-back located at the slave controller, it can be implemented without a measurement or an estimation of a time delay. For a stable impedance controller, the impedance parameters are designed using the absolute stability. In this paper, bounds for the human/environment impedances are introduced to avoid the conservatism of absolute stability.

Though the proposed procedure requires a maximum RTT in the communication line, it is intuitive and easy to be applied for designing impedance controllers for a stable teleoperation under a time delay. In the experiments, it can be observed that the impedance set not satisfying the condition of Eq. (12) shows non-passive behaviors when the slave contacts the wall. On the other hand, the impedance set designed through the proposed guideline guarantees that the impedance-controlled teleoperation is absolutely stable with time delay boundary, T_{max}.

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