Abstract—In this paper, a hybrid stabilization approach involving both passivity observer/passivity controller and wave variables is addressed to stabilize a teleoperation system with fixed time delay. To guarantee the stability of master or slave side, passivity observer/passivity controller are applied. But, passivity observer/passivity controller cannot deal with communication delay, and thus even small communication delay cause the system to be unstable. To cope with this problem, wave variables are additionally employed to have robustness to fixed communication delays. To show the validity of our proposed approach, several computer simulation and experimental results are illustrated.

Index Terms—teleoperation, wave variables, passivity controller

I. INTRODUCTION

A bilateral teleoperation system may be described by means of the block diagram as shown in Figure 1. The main components of teleoperation system are master, slave, and communication channel. A master robot takes the motions of an operator and generates desired motion commands which a slave robot should follow. While following the desired motion command transmitted from a master side, a slave sends force information measured at the environment to the master robot.

Fig. 1. Two port network model of bilateral teleoperation system

Many research works have been done on the analysis of stability and performance of teleoperation system. Zaad and Salcudean classified operating mode of teleoperation by specifying the transmitted data pair and analyzed the stability conditions and performances for each operating mode [2], [3]. Hannaford and Ryu proposed the time domain passivity observer and passivity controller [4], [5]. The passivity observer checks whether a system is passive or not by measuring energy flows. When the system is detected to be active by a negative value of the passivity observer, the passivity controller makes the system passive by dissipating the generated energy output. However, their method cannot deal with the instability caused by communication time delay.

Niemeyer and Slotine proposed a physically motivated, passivity-based formalism to provide energy conservation and to ensure stability in the presence of time delay [6], [7]. By transmitting wave variables in place of the power variables (velocity and force), the passivity of time-delayed teleoperation system is guaranteed. Although the concept of characteristic impedance of waves was introduced and an analogy was drawn, there was no research work on the relationship between characteristic impedance and the performance of teleoperation system.

In this paper, a hybrid stabilization approach involving both passivity observer/controller and wave variables is addressed to stabilize the teleoperation system with time delay. To guarantee the stability of a master or slave side, passivity observer/controller are applied. Wave variables are additionally employed to have robustness to communication delay. And, the performance of wave-based teleoperation system is analyzed by using the minimum value of transmitted impedance from a slave to an operator.

II. WAVE VARIABLES

A. Definition

Wave variables are defined by encoding power variables \( (\mathbf{x}, \mathbf{F}) \) as

\[
\mathbf{u} = \frac{b\mathbf{x} + \mathbf{F}}{\sqrt{2b}}, \quad \mathbf{v} = \frac{b\mathbf{x} - \mathbf{F}}{\sqrt{2b}},
\]

where \( \mathbf{u}, \mathbf{v} \), and \( b \) denote the right moving wave, the left moving wave, and the characteristic wave impedance which is a positive constant or a symmetric positive definite matrix, respectively.

This transformation is bijective, so that it is always unique and invertible. No information is lost or gained in this encoding. And, the transformation can be used to determine any combination of power and wave variables. This means that any two of the four variables can be chosen as input or output. For example, when we choose the measured velocity \( \dot{x}_m \) and the left moving wave \( \mathbf{v}_m \) at the master side as input, the right moving wave \( \mathbf{u}_m \) and the feedback force \( \mathbf{F}_m \) are determined as

\[
\mathbf{u}_m = \sqrt{2b}\dot{x}_m - \mathbf{v}_m, \quad \mathbf{F}_m = b\dot{x}_m - \sqrt{2b}\mathbf{v}_m
\]
Together with the observed slave force $F_s$, the right moving wave $u_s$ is decoded into a velocity command $\dot{x}_s$ and the feedback wave $v_s$.

$$v_s = u_s - \frac{1}{b}F_s; \quad \dot{x}_s = \sqrt{\frac{2}{b}}u_s - \frac{1}{b}F_s$$  \hspace{1cm} (3)

Figure 2 shows the wave transformation at each side.

![Fig. 2. Structure of wave transform](image)

In (1), the wave impedance $b$ is a tuning parameter which trades off the speed of motion and level of force. When the wave impedance is increased, this places a larger weight on the velocities as compared to the forces. In other words, an increase of wave impedance will raise force levels while reducing velocity for the same wave value. Thus, the system will be more damped. The opposite is true when the wave impedance is decreased. The system associates a larger weight on the forces as compared to the velocities. Therefore, the system will be less damped.

![Fig. 3. One port network](image)

B. Passivity of wave variables

The power flow to a one-port network in Figure 3 can be calculated as

$$P_{in} = \dot{x}^TF$$  \hspace{1cm} (4)

where power flowing into the network is considered positive. One-port system is passive if the total energy delivered to the system is non-negative [9]

$$E(t) = \int_0^t P_{in}d\tau + E_{store}(0) \geq 0, \ \forall t \geq 0$$  \hspace{1cm} (5)

where $E_{store}(0)$ denotes the initial stored energy.

The power input to a one-port system can be computed as following wave form

$$P_{in} = \dot{x}^TF = \frac{1}{2}u^Tu - \frac{1}{2}v^Tv$$  \hspace{1cm} (6)

where $\frac{1}{2}u^Tu$ is the power flowing into the system and $\frac{1}{2}v^Tv$ is the power flowing back.

In the wave domain, the passivity condition (5) becomes

$$\int_0^t \frac{1}{2}v^Tv d\tau \leq \int_0^t \frac{1}{2}u^Tu + E_{store}(0), \ \forall t \geq 0$$  \hspace{1cm} (7)

and the system is passive if the energy in the outgoing wave($v$) is limited to the energy provided by the incoming wave($u$) or stored energy. So all systems, which were passive in the power variable notation, still remain passive after transformation into wave domain.

For the communication channel, the total power input at any point in time is given by

$$P_{in} = \dot{x}_m^TF_m - \dot{x}_s^TF_s$$  \hspace{1cm} (8)

where the minus sign appears because power is considered positive while flowing in the main direction from left to right.

Using wave transform, power input can be expressed as

$$P_{in} = \frac{1}{2}u_m^Tu_m - \frac{1}{2}v_m^Tv_m - \frac{1}{2}u_s^Tu_s + \frac{1}{2}v_s^Tv_s$$  \hspace{1cm} (9)

where all variables are measured at the current time $t$.

When the time delay exists in communication channel, wave variables are transmitted via

$$u_s(t) = u_m(t - T), \quad v_m(t) = v_s(t - T)$$  \hspace{1cm} (10)

Substituting (10) into (9), power input becomes

$$P_{in} = \frac{1}{2}u_m^Tu_m(t) - \frac{1}{2}u_s^Tu_s(t - T) + \frac{1}{2}v_m^Tv_m(t) - \frac{1}{2}v_s^Tv_s(t - T)$$  \hspace{1cm} (11)

Integrating (11), all input power is stored according to

$$E_{store}(t) = \int_0^t P_{in}d\tau = \int_0^t \left(\frac{1}{2}u_m^Tu_m + \frac{1}{2}v_m^Tv_m\right)d\tau$$  \hspace{1cm} (12)

assuming zero initial conditions. Should the returning wave get delayed then energy is only temporarily stored in the communication channel and released later, still satisfying the passivity condition. In addition, time delays are now also passive elements in wave variable notation, systems expressed in wave form become completely robust to time delay of any amount. Furthermore, it does not require knowledge of the delay nor equal delays in forward and reverse paths.
III. PERFORMANCE ANALYSIS OF WAVE-BASED TELEOPERATION

In the wave-based teleoperation system as depicted in Figure 4, the output from the master side is a velocity and the input to the master side is a feedback force. This input-output relation can be matched with four channel architecture, where channel 3 and 4 are not used in Figure 5 [1]. The only difference between two architectures is that velocity and force information are transmitted via independent channel in four channel architecture. However, communication channels are coupled each other in wave-based architecture, performance analysis is relatively difficult.

![Fig. 5. Block diagram of a four channel teleoperation architecture](image)

In this paper, two port network theory is used to analyze the effect of wave impedance \( b \) on the performance of wave-based teleoperation architecture. If \((V_h, F_h)\) and \((F_e, -V_e)\) are chosen as the input and output of communication channel, two port network can be represented as a hybrid model [9]

\[
\begin{pmatrix}
    F_h \\
    -V_e
\end{pmatrix} =
\begin{pmatrix}
    h_{11} & h_{12} \\
    h_{21} & h_{22}
\end{pmatrix}
\begin{pmatrix}
    V_h \\
    F_e
\end{pmatrix}
\] (13)

When the velocity channel from master to slave and the force channel from slave to master are used, hybrid parameters can be calculated as

\[
\begin{align*}
    h_{11:4Ch} &= Z_{cm} \\
    h_{12:4Ch} &= C_s e^{-2\pi T} \\
    h_{21:4Ch} &= -C_s e^{-\pi T}/Z_{cs} \\
    h_{22:4Ch} &= 1/Z_{cs}
\end{align*}
\] (14)

The hybrid parameters of wave-based two port network can be derived as

\[
\begin{align*}
    h_{11:W} &= Z_{cm} + \frac{(2\Gamma - 1)\{bC_s Z_s(2\Gamma - 1) - b^2 Z_{cs}\}}{bZ_{cs} - C_s Z_s(2\Gamma - 1)} \\
    h_{12:W} &= 2e^{-\pi T} \frac{bZ_{cs} - C_s Z_s(2\Gamma - 1)}{1 + e^{-2\pi T} - bZ_{cs} - C_s Z_s(2\Gamma - 1)} \\
    h_{21:W} &= -2bC_s(1 - \Gamma)e^{-\pi T} \\
    h_{22:W} &= \frac{bZ_{cs} - C_s Z_s(2\Gamma - 1)}{b - C_s(2\Gamma - 1)}
\end{align*}
\] (15)

where \( Z_{cm} = Z_m + C_m, Z_{cs} = Z_s + C_s \), and \( \Gamma = e^{-2\pi T}(1 + e^{-2\pi T})^{-1} \).

The performance of teleoperation system can be evaluated as transparency, which is a match between environment impedance \( Z_e \) and the transmitted impedance to the operator \( Z_{to} \). In ideal case, perfect transparency means that the transmitted impedance is equal to the environment impedance.

\[
Z_{to} = \frac{F_h}{V_h} \bigg|_{F_s^* = 0} = h_{11} + (h_{11}h_{22} - h_{12}h_{21})Z_{se} \\
1 + h_{22}Z_{se}
\] (16)

The minimum value of transmitted impedance can be defined as (17), when slave moves freely without any contact with environment.

\[
Z_{to.min} = Z_{to} \bigg|_{Z_e = 0} = h_{11}
\] (17)

Substituting (15), (16) into (17) and after some manipulation, the minimum values of \( Z_{to} \) become

\[
Z_{to.min} : 4Ch = Z_{cm}
\] (18)

\[
Z_{to.min} : W = Z_{cm} + \frac{(2\Gamma - 1)\{bC_s Z_s(2\Gamma - 1) - b^2 Z_{cs}\}}{bZ_{cs} - C_s Z_s(2\Gamma - 1)}
\] (19)

Two minimum values of \( Z_{to} \) differ by

\[
\frac{(2\Gamma - 1)\{bC_s Z_s(2\Gamma - 1) - b^2 Z_{cs}\}}{bZ_{cs} - C_s Z_s(2\Gamma - 1)}
\]

(a) velocity-force mode of 4 channel structure

(b) wave-based structure

![Fig. 6. Plot of \( Z_{to.min} \) minimum](image)

Figure 6(a) shows the \( Z_{to.min} \) plot of four channel architecture, where velocity-force mode is used, and Figure 6(b) shows the \( Z_{to.min} \) plot when the wave variables are applied in teleoperation system with different \( b \). When the value of \( b \) is 1, the performances of four channel and wave-based system look similar. When the value of \( b \) is 100, the
minimum value of $Z_{to}$ is increased by 50 times. Thus, the performance of wave-based teleoperation system will be degraded if $b$ grows, which cause the growth of $Z_{to}$ minimum value at high frequency range over 10[rad/sec].

IV. PASSIVITY OBSERVER AND CONTROLLER

As another passivity-based stabilizing control method, Hannaford and Ryu proposed time-domain passivity observer(PO)/passivity controller(PC) [4]. In their work, analysis was confined to systems having sampling rate substantially faster than the dynamics of device and human operator, so that the change in force and velocity at each sample is small.

For one-port network, where the sign convention of the product of force and velocity is positive when power enters the port, delivered energy in discrete-time domain can be calculated as

$$E_{obsv}(n) = \left( \sum_{k=0}^{n} f(k)v(k) \right) \Delta T + E(0) \quad (20)$$

where $\Delta T$ is a sampling time.

If $E_{obsv}(n) \geq 0$ for every $n$, the system dissipates energy. If $E_{obsv}(n) < 0$ at any time, the system generates energy and the total amount of generated energy is $-E_{obsv}(n)$. Passivity observer checks whether a system is passive or not by using (20). When the system detected to be active by a negative value of the passivity observer, a passivity controller makes the system passive by dissipating the generated energy.

The passivity controller takes the form of a dissipative element. It can be connected in a series or parallel configuration and we used a series configuration.

V. HYBRID STABILIZING CONTROL METHOD FOR TELEOPERATION

Figure 7 shows the structure of proposed hybrid stabilizing method. Wave variables are applied at communication channel to guarantee the stability of time-delayed teleoperation system and the PC is applied at the environment to guarantee the passivity of a slave. Note that the series passivity controller is connected in parallel, this is an artifact of switching block diagram for the connection between the device and environment.

![Fig. 7. Structure of the proposed hybrid stabilization approach](image)

The control commands to master and slave manipulators are given as (21) and (22), respectively.

**master** : $U_m = F_h - (b + C_m)V_h + \sqrt{2b}v_m$ \quad (21)

**slave** : $U_s = \frac{\sqrt{2b}}{b}u_s - F'_e - (\alpha + C_s) Ve - \frac{C_s}{b}F_s$ \quad (22)

where $F'_e$ is a measured force at the environment and a PD controller is used at the slave.

VI. SIMULATION AND EXPERIMENTAL RESULTS

Figures from 8 to 12 show simulation results of proposed hybrid method. The parameters used in simulation given as

$$Z_m = 0.7s, \quad C_m = 16.8 + 630/s$$

$$Z_s = 0.7s, \quad C_s = 50.4 + 630/s \quad (23)$$

and all simulations were performed with Simulink.

As shown in Figure 8, the slave followed the master motion exactly and the monitored energy at environment satisfied the passivity condition. The position difference between master and slave at steady state was caused by the fact that slave contacted the virtual wall located at 5cm.

To show the effectiveness of the passivity controller when the master or slave was unstable, 30msec time delay was assumed at the slave in the following simulation. The position response of master and slave and monitored energy at the slave are shown in Figure 9. The energy monitored at the slave is negative, which violates the passivity condition, system is unstable and as a result master and slave robot oscillate severely.

![Fig. 8. Position responses and monitored energy for the case without time delay in the communication channel](image)

![Fig. 9. Position responses and monitored energy for the case with 30msec delay in the virtual environment](image)

Simulation result when the passivity controller is applied to the above situation is shown in Figure 10. One can find that the passivity controller stabilize the system by consuming the generated energy. Next simulation is to check whether wave variable method can stabilize the teleoperation system with time delay in communication channel. Communication time delay is assumed 50msec and the passivity controller is applied to the slave side.
As shown in Figure 11, the position of master and slave oscillate and the passivity controller which is applied at slave cannot deal with the communication delay. Finally, Figure 12 shows the simulation result when the proposed hybrid stabilization method is applied. It can be seen that the position responses of the master and slave are settled down, even 50msec time delay exists in communication channel.

In every experiment, two manipulators were allowed to fall under the influence of gravity. Human operator released the master manipulator and did not contact again during the experiment. This is an extreme case of instability. Figure 14 shows the result when the slave manipulator contacted the stiff wall. The reaction force was so large that the master and slave manipulator showed oscillatory behavior. And, monitored energy at the environment grew to more and more negative. In the second experiment, PC was applied at the environment to dissipate the generated energy. After the first bounce, master and slave manipulator achieved stable contact as shown in Figure 15. On the first bounce, PC began to operate and monitored energy, which was negative on the first bounce, became positive. Thus, the oscillation was eliminated. To show the effectiveness of the PC when a virtual environment is slow computing environments. These slow virtual environments are characteristic of complex simulations such as deformable objects for surgery. Figure 16 shows the experimental results when 10msec delay is included in virtual environment with no PC. The output force of the virtual environment is held for 10 samples and replaced with new force value. Even with 10msec delay, the position of haptic device is fluctuated. When the PC is employed at the delayed virtual environment, the master device contacts stably at the virtual wall whose location is 20° as shown in Figure 17. In the next experiment, time delay of 30msec was included at the communication channel when the PC was applied at the environment. Although monitored energy at the environment was positive, master and slave manipulator oscillated severely as shown in Figure 18. This shows that the PC cannot deal with communication channel delay. In the final experiment, both wave variables and PC were applied at the communication channel and the environment, respectively. Time delay of 200msec was included on the communication channel. Although there was position difference between master and slave manipulator, slave followed achieved stable contact with environment as shown in Figure 19.

VII. CONCLUSION

A hybrid stabilization technique involving both passivity controller and wave variables was proposed to stabilize the bilateral teleoperation system with time delay. To stabilize
a master or slave side, the passivity controller was applied and wave variables were additionally employed to guarantee the stability of the teleoperation system with communication delay. By use of two port network theory and the minimum value of transmitted impedance, the performance of wave-based teleoperation system were also evaluated qualitatively. And, the effectiveness of proposed method was verified by several simulation and experiments.

REFERENCES


