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Achieving Position Synchronization in Passive Bilateral Teleoperation

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***Abstract*—When wave-variable-based methods is used in passivity-based bilateral teleoperation, the systems are often subject to a position drift. During carrying out interaction tasks in such master-slave teleoperation systems, the size of this position drift may be prominent notable. In this study, we propose a passivity-based method to patch piece up such position drift problems in delayed master-slave robot system, which arises during carrying out the tele-manipulation tasks. As a result, the operator perception on the force information to the remote environment is improved. Simulations and experiments are carried out on a self-made one degree-of-freedom master-slave platform. Stable trajectory and force-tracking performance are demonstrated.**

***Index Terms*—Passivity-based teleoperation, position drift, delayed tele-manipulation, passive system.**

I. Introduction

TELEOPERATION is one of the most challenging domains of robotics, due to the inherent conflict between stability and transparency. A stable system is required with respect to a lot of uncertainties in teleoperation systems, which may be introduced by the human operator, teleoperation channel, environment, and installed sensors. This requirement leads to the examination of the performance of bilateral teleoperation systems. Transparency is the measure of such performance requirements.

A breakthrough to the bilateral teleoperation problem was achieved by introducing passivity theory into tele-manipulation control schemes to maintain stability with system uncertainty or time delays [1]. The most popular passive methods for time delay compensation can be divided into two groups: *Wave variable-based methods* [2][3]and *time domain passivity control methods*[11][12][13]. The wave-variable method is the most classical method in teleoperation system with time delay. However, when using such classical wave-variable-based channels, only force and velocities are exchanged in local and remote sides, in the position drift between master and slave robots arised [6]. Until now, position drift compensation methods for wave-variable-based controllers were categorized into two approaches. The first approach is wave integrals, which contain both position and momentum information. This can be directly carried out from robot position measurements [6][9][10].The second approach for position drift compensation adds a correcting term tothe actual wave command in response to the observed position drift between the two robots [4][5][6][8].In [4], Chopra presented a method by adding an outer position loop to the traditional wave-variable approach to decrease the position errors between the master and slave robots. Ching and Book [5] introduced a robust position drift control algorithm that addressed position errors caused by wave predictor modeling errors. Ye and Liu [6] proposed an augmented approach to eliminate the distortion due to the bias term introduced by the wave transmission by adding a modification term on the wave path channel. Recently, to achieve both a stable movement and force tracking for wave-variable-based teleoperations, Li and Kawashima [8] improved the transparency of the teleoperation system by adding both forward and backward wave paths to the impedance-matched wave-variable transmission.

The above frequency-domain wave-variable approach has fixed controller parameters. In the worst-case scenario, this method is suitable for teleoperation system by dissipating the active energy, which is generated by the delayed channel. As a result, this approach leads to an over-conservative control system. Though the passivity of the teleoperation system was guaranteed, the performance of the system is degraded too much. To solve the stability and performance problem, Hannaford and Ryu [11][12]formulated an energy-based time-domain passivity controller using time-varying controller parameter schemes. In this approach, a passivity observer (PO)was proposed to monitor the system passivity in real time, and the system energy was adaptively turned through a passivity controller(PC) to enforce system passivity. However, such system passivity controller suffers from force chattering when the time-domain passivity condition is breached [13]. As

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the desired position of the slave robot must be integrated by the desired velocity (similar to the wave-variable-based approach), this time-domain approach also has the weakness of position drift between the master and slave robots [14][15].In [14], Artigas et al. proposed a compensation method by injecting extra system energy into the remote slave controller to alleviate position errors between the master and slave robots. The compensation energy was bounded by the magnitude of the passivity gap. As a result, the system passivity was not violated. Chawda [15] extended Artigas's compensation method to solve the position drift problem by introducing a virtual dependent energy source. However, all experimental results of this method were obtained under constant communication delays.

Most recently, in order to achieve synchronization, Chawda and O'Malley [7] proposed a passivity-based control approach using feedback signals in bilateral teleoperation systems using a power-based time-domain passivity approach. To attain stable position tracking, robot position information was encoded with the velocity to construct a composite signal for transmitting through the communication channel.

From the aforementioned passive control methods, the position drift is a common problem of passivity-based teleoperation system with time delay. Modifications in the desired velocity signal from the master robot to passivity controller are additive over time causing in position drift. Though several techniques [7][13][14] have been proposed to address such position drift problem for passivity-based controllers in teleoperation system, not much work has been done to solve the position drift problem. Meanwhile, the system transparency remains high.

To solve such position drift problem of the master-slave teleoperation robot while enforcing high transparency, this study advances a novel adaptive impedance control using a feedback r-passivity controller. The damping coefficient of the master robot is changed depending on the output of the power observer for absorbing the extra-generated energy by the non-passive part during teleoperation.

In this paper, the performance of the proposed controller is analyzed, considering practical implementation considerations. The passivity of delayed teleoperation systems using our proposed approach is analyzed theoretically. The remainder of this paper is organized as follows: In section II, the traditional time domain passivity control method is briefly introduced, and the commonly used teleoperation system structure and a new bilateral controller are proposed. Section III presents the simulations and experiments to evaluate the performance of the system. Finally, a summary and concluding remarks are presented in section IV

II. Passivate Communication Channel With Power-Based Teleoperation

A. *Passivity in Teleoperators*

For the stability of a two-port network, passivity is a sufficient condition. Therefore, most of the stabilization schemes based on passivity are rather conservative due to the use of over-damping to effectuate system passivity. The following theorem establishes the relationship between system stability and passivity. Let E_i denote the initial energy of a system. Following Theorem 1, a teleoperation system is passive and stable if:

$$E(\mathrm{t}) = \int_0^t P d\tau + E_i \geq 0 \qquad (1)$$

where $E(t)$ is the whole system energy at time t. P is the net power at the input and output ports. Assuming the initial energy of the system is zero, we can obtained an expression for energy of the system as

$$E(\mathrm{t}) = \int_0^t P d\tau = \int_0^t \vec{u}^T \vec{y} d\tau \geq 0 \qquad (2)$$

where $\vec{u}$ and $\vec{y}$ represent system input and output vectors, respectively. In the case of teleoperation systems, they are usually the causal pair $\vec{f}$ (force) and $\vec{v}$ (velocity). For a two-port network, (2) changes to:

$$E(\mathrm{t}) = \int_0^t P d\tau = \int_0^t \left(f_1(\tau) v_1(\tau) - f_2(\tau) v_2(\tau) \right) d\tau \geq 0 \qquad (3)$$

Depending on the energy flow, signs should be carefully selected in this expression and they should be kept consistent throughout the calculation of the system energy. Here, f_1, v_1 are considered the input; whereas f_2, v_2 are output variables. Equation (3) stands for that a passive system must not generate energy by itself. It can only dissipate the input system energy or in ideal conditions, it can function as a lossless channel [in which case $E(t) = 0$].

Passivity can be thought as a tool that is utilized various ways to guarantee the stability of dynamics systems. The idea utilized a PO to monitor energy $E(t)$ in real time. Lie on the operating conditions and specifics of the dynamics of the element, the PO may or may not be negative at a particular time. If such value is negative all the time, then such certain condition of the system may be contributing to instability. Refer to [11], [12] for more details about this method.

B. *Passivity Analysis of Power Based Passivity Control*

It is not necessary that power variables should be transformed into wave variables in time domain passivity controller. However, this approach suffers from force chattering when the passivity condition is violated [13][16]. This noisy problem of the passivity controller is the results of the see-and-action essence of such method [17]. To solve this problem, Jafari [18] added a force error term to the conventional passivity architecture to improve the system passivity. Recently, Ye et.al [20] proposed a passivity based controller to solve sudden force change problems.

Fig.1 shows a network model of a teleoperation system, where $\dot{x}_h$ and $\dot{x}_e$ are the velocities of the haptic devices at the interacting positions and slave device/environment, respectively. f_h and f_e represents the operator applied force to the haptic device and the force which the slave device applies to the environment, respectively. The power flow into the teleoperation network is

$$P = P_m - P_s$$

$$= f_m(t)\dot{x}_m(t) - f_s(t)\dot{x}_s(t) \tag{4}$$

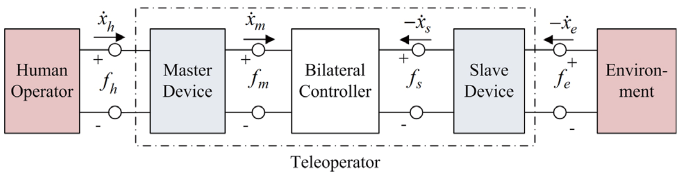


Fig.1. Block diagram of a complete teleoperation system.

where $P_m = \dot{x}_m{}^T f_m$ and $f_m(t)$, $\dot{x}_m(t)$ are the power correlated effort and flow signals at the system left port, and $P_s = \dot{x}_s{}^T f_s$ and $f_s(t)$, $\dot{x}_s(t)$ is the power relating to the signals at the sytem right port. Signs of forces and velocities represent the power flow into the delayed network and represents power flow out of the delayed network. Here, to relate the units of the system force and velocity signals (Fig.2(a)), a positive constant parmater b is introduced and the system power flow can be written as:

$$u_m(t) = \frac{b\dot{x}_m + f_m}{\sqrt{2b}}, \quad v_m(t) = \frac{b\dot{x}_m - f_m}{\sqrt{2b}} \tag{5}$$

The power flow at the master side is

$$P_m = \frac{1}{2}u_m{}^T u_m - \frac{1}{2}v_m{}^T v_m \tag{6}$$

$$= \frac{1}{2}\left(\frac{b\dot{x}_m + f_m}{\sqrt{2b}}\right)^T \left(\frac{b\dot{x}_m + f_m}{\sqrt{2b}}\right)$$

$$-\frac{1}{2}\left(\frac{b\dot{x}_m - f_m}{\sqrt{2b}}\right)^T \left(\frac{b\dot{x}_m - f_m}{\sqrt{2b}}\right)$$

$$\Leftrightarrow 2P_m = \frac{b\dot{x}_m{}^2}{2} + \frac{f_m{}^2}{2b} + \dot{x}_m f_m - \frac{(b\dot{x}_m - f_m)^2}{2b} \tag{7}$$

Note that $P_m = \dot{x}_m{}^T f_m$, and (7) is

$$P_m = \frac{b\dot{x}_m{}^2}{2} + \frac{f_m{}^2}{2b} - \frac{(b\dot{x}_m - f_m)^2}{2b} \tag{8}$$

Similarly, the wave transformation on the slave side is:

$$v_s(t) = \frac{b\dot{x}_s + f_s}{\sqrt{2b}}, \quad u_s(t) = \frac{f_s - b\dot{x}_s}{\sqrt{2b}} \tag{9}$$

And the power flow at the slave side is

$$P_s = \frac{1}{2}u_s{}^T u_s - \frac{1}{2}v_s{}^T v_s$$

$$= -\frac{f_m{}^2}{2b} - \frac{b\dot{x}_s{}^2}{2b} + \frac{(f_s + b\dot{x}_s)^2}{2b} \tag{10}$$

Combining equation (8) and (10), the power flow in (7) can be rewritten as

$$P = P_m - P_s$$

$$= \frac{b\dot{x}_m{}^2}{2} + \frac{f_m{}^2}{2b} - \frac{(b\dot{x}_m - f_m)^2}{2b} - \left[-\frac{f_m{}^2}{2b} - \frac{b^2\dot{x}_s{}^2}{2b} + \frac{(f_s + b\dot{x}_s)^2}{2b}\right]$$

$$= \frac{1}{b}f_m{}^2 - \frac{1}{2b}(f_m - b\dot{x}_m)^2 + b\dot{x}_s{}^2 - \frac{1}{2b}(f_s + b\dot{x}_s)^2$$

$$+\frac{1}{2b}f_s{}^2 - \frac{1}{2b}f_m{}^2 + \frac{b}{2}\dot{x}_m{}^2 - \frac{b}{2}\dot{x}_s{}^2 \tag{11}$$

Using the signal transmission relations

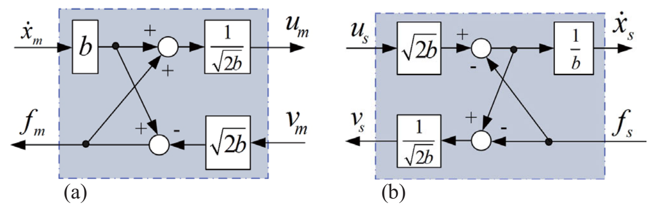


Fig.2. Wave transformation. (a) master side. (b) slave side.

$$f_m(t) = f_s(t - T_2)$$

$$\dot{x}_s(t) = \dot{x}_m(t - T_1) \tag{12}$$

where last part of (11) can be written as

$$\frac{1}{2b}f_s{}^2 - \frac{1}{2b}f_m{}^2 + \frac{b}{2}\dot{x}_m{}^2 - \frac{b}{2}\dot{x}_s{}^2$$

$$= \frac{1}{2b}f_s(t)^2 - \frac{1}{2b}f_s(t-T_2)^2 + \frac{b}{2}\dot{x}_m(t)^2 - \frac{b}{2}\dot{x}_s(t-T_1)^2$$

$$= \frac{d}{dt}\int_{t-T_2}^{t}\left(\frac{1}{2b}f_s{}^2(\tau)\right)d\tau - \frac{1}{2b}\dot{T}_2(t)f_s^2(t - T_2(t))$$

$$+\frac{d}{dt}\int_{t-T_1}^{t}\left(\frac{b}{2}\dot{x}_m{}^2(\tau)\right)d\tau - \frac{b}{2}\dot{T}_1(t)\dot{x}_m{}^2(t - T_1(t)) \tag{13}$$

As a result, the power flow given by (11) can be rewritten as

$$P = \frac{1}{b}f_m{}^2(t) - \frac{1}{2b}(f_m(t) - b\dot{x}_m(t))^2$$

$$+b\dot{x}_s(t)^2 - \frac{1}{2b}(f_s(t) + b\dot{x}_s(t))^2$$

$$-\frac{1}{2b}\dot{T}_2(t)f_s^2(t - T_2(t)) - \frac{b}{2}\dot{T}_1(t)\dot{x}_s{}^2(t - T_1(t)) + \frac{dE}{dt} \tag{14}$$

where $E = \int_{t-T_2}^{t}\left(\frac{1}{2b}f_s^2(\tau)\right)d\tau + \int_{t-T_1}^{t}\left(\frac{b}{2}\dot{x}_m{}^2(\tau)\right)d\tau$ (15)

is the stored energy. The remaining parts in (14) can be viewed as

$$P_{diss} = \frac{1}{b}f_m{}^2(t) - \frac{1}{2b}(f_m(t) - b\dot{x}_m(t))^2$$

$$+b\dot{x}_s(t)^2 - \frac{1}{2b}\left(f_s(t) + b\dot{x}_s(t)\right)^2$$

$$-\frac{1}{2b}\dot{T}_2(t)f_s^2(t - T_2(t)) - \frac{b}{2}\dot{T}_1(t)\dot{x}_s{}^2(t - T_1(t)) \tag{16}$$

where P_{diss} is the dissipated energy. For the network passivity, the energy flow in the net must be positive. Using the system passivity definition as,

$$E_{flow}(t) = \int_0^t P(\tau)d\tau$$

$$= \int_0^t \left(\frac{dE}{dt} + P_{diss}\right)(\tau)d\tau$$

$$= E(t) - E(0) + \int_0^t P_{diss}(\tau)d\tau$$

$$\geq -E(0) + \int_0^t P_{diss}(\tau)d\tau \tag{17}$$

Assuming the original stored energy $E(0)=0$, then

$$E_{flow}(t) \ge \int_0^t P_{diss}(\tau)d\tau \tag{18}$$

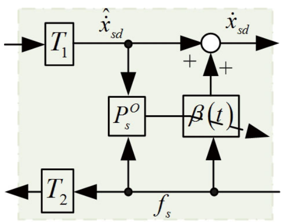


Fig.3 Passivated time domain passivity network with the PO/PC in admittance configuration.

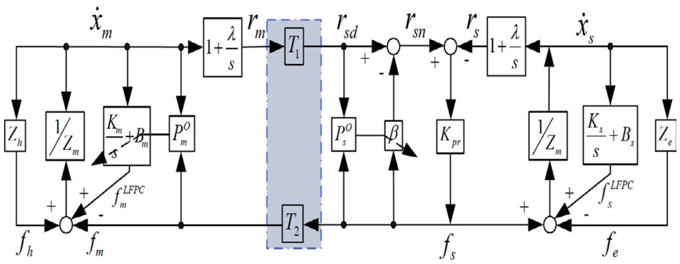


Fig.4. The proposed passive bilateral control system.

As a result, if the condition $P_{diss} \ge 0$ is true, then we get $E_{flow} \ge 0$, and the system is passive.

C. r-Passivity and Position Synchronization

The position signal from the master x_{sd} is obtained by integrating transmitted velocity as

$$x_{sd}(\tau) = \int_0^t \dot{x}_{sd}(\tau)d\tau \tag{19}$$

The modified position signal for the controller of the slave robot with drift x_{err}, given as

$$x_{err}(n) = \int_0^t \dot{x}_{sd}(\tau)d\tau - \int_0^t \hat{\dot{x}}_{sd}(\tau)d\tau$$
$$= \int_0^t \beta(\tau) f_s(\tau)d\tau \tag{20}$$

$\hat{\dot{x}}_{sd}$ is the delayed velocity from the master robot and β is the dissipative element on the slave side as shown in Fig.3. A new transmitted signal $r(t)$ to alleviate the problem of position drift was used. The r signal combines both position and velocity information, and this signal is transmitted through the network channel instead of velocity alone.

$$r(t) = \dot{x}(t) + \lambda x(t) \tag{21}$$

where λ is a positive constant value. Hereafter, the system passivity with respect to the signal $r(t)$ is referred as "*r-passivity*". The master and slave devices are modeled as

$$m_i \ddot{x}_i(t) + b_i \dot{x}_i(t) = f_i^{con} + f_i^{ext}, i = m, s \tag{22}$$

where f_i^{ext} is the operator applied force to the devices by the or the forces applied to the remote environment by slave robot, and f_i^{con} is the controller force, given as

$$f_i^{con} = f_i^{LFPC} + f_i, i = m, s \tag{23}$$

where f_i is the control force from the master or slave controllers, and f_i^{LFPC} is the contribution from the local feedback passivity controller, given as

$$f_i^{LFPC} = -B_i \dot{x}_i - K_i x_i, i = m, s \tag{24}$$

Using $r(t)$ as the transmitted signal instead of velocity, the slave controller, which was a proportional derivative (PD) controller acting on the position error between the delayed master robot position and current slave robot position, is replaced by an equivalent proportional controller, given as

$$f_s(t) = K_{pr}(r_{sd}(t) - r_s(t))$$
$$= K_{pr}(\dot{x}_{sd}(t) - \dot{x}_s(t)) + K_{pr}\lambda(x_{sd}(t) - x_s(t)) \tag{25}$$

which is similar to the position error controller.

D. Proposed Controller

For the two-port network system, $P_{diss}(t)$ is not observable in real time at any single port of the system network. Therefore, to facilitate real-time monitoring of system passivity, (19) is rewritten as

$$P_{diss}(t) = P_m^O(t) + P_s^O(t) \tag{26}$$

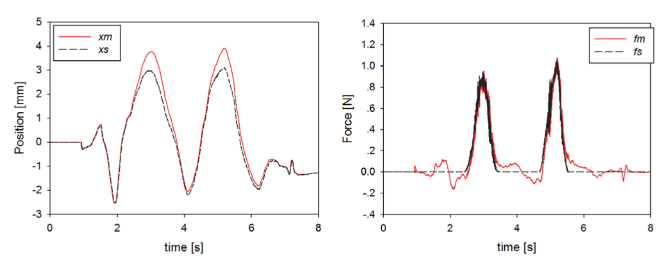
where $P_m^O(t)$ and $P_s^O(t)$ are the power observer at the left and right ports, respectively, which are given as

$$P_m^O(t) = \frac{1}{b} f_m^2(t) - \frac{1}{2b}(f_m(t) - b\dot{x}_m(t))^2 - \frac{1}{2b}\dot{T}_2 f_m^2(t) \tag{27}$$

$$P_s^O(t) = br_{sd}(t)^2 - \frac{1}{2b}(f_s(t) + br_{sd}(t))^2 - \frac{b}{2}\dot{T}_1 r_{sd}^2(t) \tag{28}$$

It is shown that both $P_m^O(t)$ and $P_s^O(t)$ are only composed of signals that are observable at the left and right ports, respectively. The passivity condition for the delayed passivity network was derived as $P_{diss} \ge 0$. By increasing the damping of the system, the system energy can be absorbed by the non-passive communication channel during contact motion[19] [20]. This provides the motivation for changing the damping of the the master robot to variations according to the output of the system power observer. As a result, the master velocity $\dot{x}_m(t)$ is

$$\dot{x}_m(s) = \frac{f_h - f_s e^{-T_2 s}}{M_m s + B_m + K_m/s + B_{act}} \tag{29}$$



(a) (b)

TABLE I
EXPERIMENT PARAMETERS

Parameters	Quantity	Value
M_m	mass of the master device	0.01 kg
B_m	viscosity of the master device	0.01 Ns/mm
M_s	mass of the master device	0.01 kg
B_s	viscosity of the master device	0.01 Ns/mm
K_m	proportional control gain on master side	0.25 N/mm
K_s	proportional control gain on slave side	0.25 N/mm
B_s	derivative control gain on slave side	0.031 Ns/m
K_{pr}	proportional gain of *r*- passivity	0.032Ns/m
λ	constant positive value	2 s^{-1}

Fig.5. Simulation results of the *r*-passivity controller without the PO/PC controller. (a) Position tracking of the master slave robot and (b) Force tracking performance of the teleoperator.

where B_{act} is a variable value, which is computed from the output of the system power observer. As a result, the master robot damping coefficient is modified by this variable. We utilize the following relationship to calculate such damping coefficient B_{act} in real time

$$B_{act} = \begin{cases} P_m^O / \zeta, P_m^O < 0 \\ const., P_m^O \geq 0 \end{cases} \quad (30)$$

where ξ is a parameter that turns the rate at how much the system power is used as the damping coefficient for the master device.

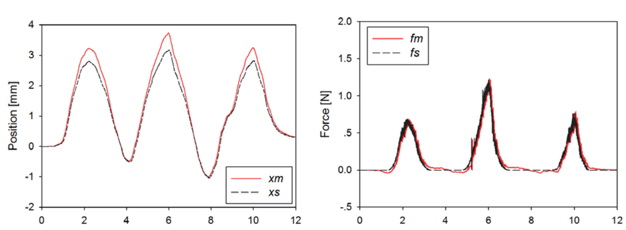
On the slave side, the PC modifies the velocity signals depending on the causality of the port to enforce this passivity condition. In an admittance configuration, the PC is given as

$$r_{sn}(t) = r_{sd}(t) + \beta(t) f_s(t) \quad (31)$$

where r_{sd} is the *r*-signal out of the delayed port and r_{sd} is the *r*-signal after modification by the PC. The coefficient $\beta(t)$ is given as

$$\beta(t) = \begin{cases} 0, \quad if \quad P_s^O(t) > 0 \\ \dfrac{P_s^O(t)}{f_s^2(t)} \quad else \quad if \left| f_s(t) \right| > 0 \end{cases} \quad (32)$$

The overall block diagram of the proposed control method is shown in Fig.4.



(a) (b)

Fig.6.Simulation results using the new proposed controller. (a) Position tracking of the master slave robot and (b) Force tracking performance of the teleoperator.

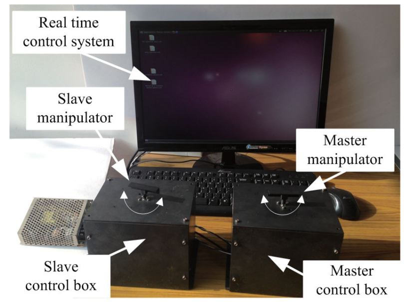


Fig.7. Experiment setup of one DOF teleoperation system.

III. EXPERIMENTAL RESULTS

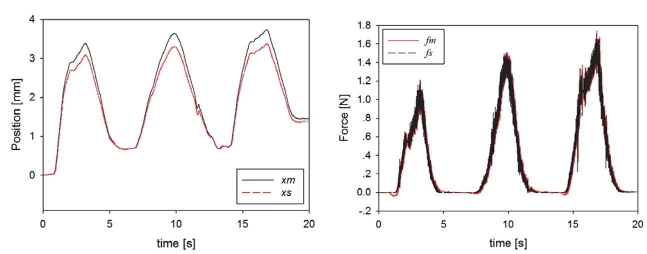
In this section, we compare and discuss the results obtained from the simulation and experiments that were conducted on both the proposed and benchmark controllers. To validate and assess the performance of the proposed power based teleoperation control scheme presented in the previous section, two experimental evaluation methods are carried out.

A. Simulation Results

The simulation is carried out based on a basic haptic interface which consists of the human operator, haptic interface and slave side robot. The slave side robot is virtually installed in the computer. A pulley with R =13 mm on the slave side was utilized for transforming the rotation position of the driving DC motor to rectilinear motion. A DC motor provided by Maxon motor Inc. is employed as the master robot equipped with an encoder (provided by Microtech Laboratory Inc. MEH-12-2000PST16) with a resolution of 32,000 PPR.

First, the traditional power-based passivity controller was applied to the simulation. The simulation results corresponded to an ideal response, which is shown in Fig.5. It was clear that position correspondence for the bench mark power-based passivity controller was obtained. The position tracking of the master and slave robot show stable interaction performance (Fig.5 (a)).

Fig.5 (b) shows that the feedback force to the human operator has the largest spiking signal at approximately 0.2N. This spiking force may significantly deteriorate the human operator's real perception of environment on the slave side. From Fig.5 (b), most of these force spikes occure at the free space motion.



(a) (b)

Fig.8. Actual experimental results of *r*-passivity using the PO/PC controller for time delay. (a) Position tracking of the master slave robot and (b) Force tracking performance of the teleoperator.

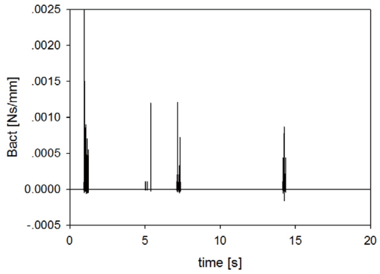


Fig.9.The modified value of the damping coefficient added to the master controller.

Second, a similar simulation was conducted by applying the new proposed adaptive passivity controller. Simulation results are shown in Fig.6. The position and force signal of the simulated master and slave robots show a stable interaction performance (Fig. 6 (a) and (b)). It is evident from these results that the spiking force in the feedback force signal was eliminated. The operator has a real and stable perception of the stable feedback forces even during free motion of the teleoperation system.

From the above simulation results, it is verified that the proposed adaptive passivity controller provides the teleoperation system high transparency while the system passivity is satisfied.

B. Experimental Results

The adaptive passivity controller approach presented in section III was applied to the one DOF master slave manipulator (as shown in Fig.7). The teleoperation experiment was conducted to evaluate the performance of the controller with random time delay in the communication line. The master slave device parameters and control parameters are shown in Table I.

The experimental results are shown in Fig.8. The position response of the master and slave were shown in Fig. 8 (a). The master and slave manipulators all begin at the initial position of 0 mm. At 2.5s, 88.6s, and 14s, the slave manipulator was in contact with the environment. The delayed reflecting force to the master is shown in Fig.8 (b). At this time, the human operator can feel a reliable force from the environment.

In the proposed method, instead of directly modifying the reflected contact force according to the PO output, the master haptic damping coefficient is modified. From Fig.9, the propsed method of (30) is used to activate the calcualtion of parameter B_{act}. Comparing Fig. 5 (b) with Fig.8 (b), it is concluded that the proposed controller offers enhanced poistion performance while providing reliable feedback force to the human operator under time delay.

IV. Conclusion

A novel method by modifying the impedance parameters of a master-slave teleoperaiton system is presented. The impedance adaption algorithm is based on a calculation of the system power. A method for encoding and transmission of the system position and velocity is described. Stable trajectory tracking in master-slave system is achieved, and the contact force on the remote slave side is accurately displayed to the human operator. As a result, the master-slave system behaves a high transparency. As the same time, the passivity of the delayed teleoperation system is kept and the spiking feedback force in the system can also be effectively eliminated through modifying of the master viscosity.

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