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시변 시간지연 하에서 안정성을 보장하는 양방향 원격제어기: 시간영역 수동성 기법

Bilateral Controller for Time-varying Communication Delay: Time Domain Passivity Approach

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Abstract : In this paper, modified two-port time-domain passivity approach is proposed for stable bilateral control of teleoperators under time-varying communication delay. We separate input and output energy at each port of a bilateral controller, and propose a sufficient condition for satisfying the passivity of the bilateral controller including time-delay. Output energy at the master port should be less than the transmitted input energy from the slave port with time-delay, and output energy at the slave port should be less than the transmitted input energy from the master port with time-delay. For satisfying above two conditions, two passivity controllers are attached at each port of the bilateral controller. A packet reflector with wireless internet connection is used to introduce serious time-varying communication delay of teleoperators. Average amount of time-delay was about 190(msec) for round trip, and varying between 175(msec) and 275(msec). Moreover some data packet was lost during the communication due to UDP data communication. Even under the serious time-varying delay and packet loss communication condition, the proposed approach can achieve stable teleoperation in free motion and hard contact as well.

Keywords : teleoperation, bilateral control, time-delay, passivity controller, passivity observer, time-domain passivity.

I. Introduction

Teleoperation is one of the first domain of robotics and has been one of the most challenging issue [21]. In teleoperation, a human operator conducts a task in a remote environment via master and slave manipulators. With the progress of computer network, teleoperation is getting considerable attention again [5] because of its potential applications including tele-surgery, tele-maintenance and welfare.

When a robot is operated remotely by use of a teleoperator, force feedback can considerably improve an operator's ability to perform complex tasks by kinesthetically coupling the operator to the environment. However, any data communication over the computer network has communication time-delay. In the presence of communication time-delay, even though it is small, force feedback has strong destabilizing effect [20].

There have been numerous research for solving the time-delay problem in bilateral control of teleoperators. Based on the scattering theory, Anderson and Spong [1] proposed a bilateral control law that maintains stability under the communication time-delay. Niemeyer and Slotine [11] extended this idea, and introduced the notion of "wave variable". Even the wave variable method was successful, it assumed constant time-delay. Several approaches extended the original wave variable method to the case when there is time-varying communication delay [3,4,7,10,12,24].

There were also several other approaches. Leung [9] proposed a bilateral controller for time-delay based on the H_∞ optimal controller and μ-synthesis frameworks. Oboe and Fiorini [13] and Lee [8] dealt with the time delay problem over the internet by using a simple PD-type controller. Sano [19] proposed a gain-scheduled H_∞ controller using measured time-delay.

Recently, the author have proposed a new concept of energy based approach for guaranteeing the passivity of haptic [6] and teleoperation systems with no communication time-delay [14]. In this paper, previously proposed two-port time-domain passivity approach is modified for stable bilateral control of teleoperators including time-varying communication delay.

II. Review of the Time Domain Passivity Approach

1. Time Domain Passivity Observer and Controller

The following widely known definition of passivity was used.

Definition 1: The one-port network (Fig. 1), N, with initial energy storage $E(0) = 0$ is passive if and only if,

$$\int_0^t f(\tau)v(\tau) \ge 0, \qquad \forall t \ge 0 \tag{1}$$

holds for admissible forces (f) and velocities (v), where their product is defined to be positive when power enters the system port. Eqn(1) states that the energy supplied to a passive network must be positive for all time [22,23].

The conjugate variables that define power flow in such a network system are discrete-time values, and the analysis was confined to systems having a sampling rate substantially faster

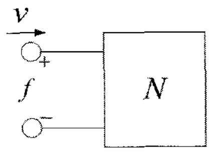

그림 1. 원포트 네트워크 시스템.

Fig. 1. One-port network system representing components.

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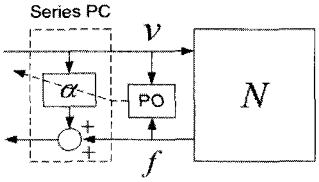


그림 2. 직렬구조를 가지는 원포트 네트워크 시스템의 수동성 제어기.

Fig. 2. Series configuration of passivity controller for an one-port network system.

than the dynamics of the system. Thus, we could easily "instrument" one or more blocks in the system with the following "Passivity Observer," (PO) for a one-port network to check the passivity (1).

$$E_{obsv}(t_k) = \Delta T \sum_{j=0}^{k} f(t_j)v(t_j) \tag{2}$$

where ΔT is the sampling period, and $t_j = j \times \Delta T$. If $E_{obsv}(t_k) \geq 0$ for every k, this means the system does not generate energy. If there is an instance when $E_{obsv}(t_k) < 0$, this means the system generates energy and the amount of generated energy is $-E_{obsv}(t_k)$.

Consider a one-port system which may be active. Depending on operating conditions and the specifics of the one-port element's dynamics, the PO may or may not be negative at a particular time. However, if it is negative at anytime, we know that the one-port may then be contributing to instability. Moreover, since we know the exact amount of the generated energy, we can design a time-varying damping element to dissipate only the required amount of energy. We call this element a "Passivity Controller" (PC). The PC takes the form of a dissipative element in a series or parallel configuration depending on the input causality [6]. Fig. 2 shows the series configuration of the PC for an one-port network system. α is an adjustable damping elements at the port. Choice of configuration depends on input/output causality of model underlying each port.

2. Time Domain Passivity Approach for Teleoperation Systems Without Time-delay

Fig. 3 shows a network model of a teleoperation system, where v_h and v_e denote the velocities at the interacting points of the human/master and environment/slave, respectively, and f_h and f_e represents the force that the operator applies to the master manipulator and the slave manipulator applies to the environment, respectively.

It is well known fact that the teleoperator two-port should be passive for guaranteeing the stability of the teleoperation system [2,25]. In the previous work [14], following two ports PO was designed for monitoring the energy flow of the bilateral controller,

$$E_{obsv}(t_k) = \Delta T \sum_{j=0}^{k} (f_m(t_j)v_m(t_j) + f_s(t_j)v_s(t_j)) \tag{3}$$

and two series PCs are attached at each port of the bilateral controller (Fig. 4) for dissipating active energy flow at each port by adjusting the damping elements α_1 and α_2. Please see

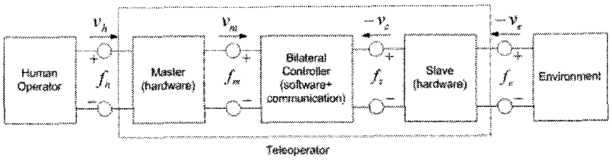


그림 3. 원격조종시스템의 블록다이어그램.

Fig. 3. Block diagram of a complete teleoperation system.

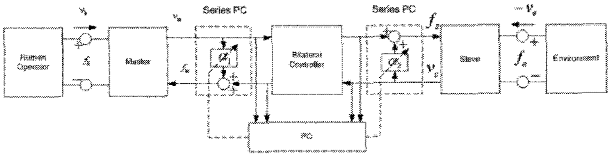


그림 4. 수동성제어기가 적용된 원격조종시스템의 블록다이어그램.

Fig. 4. Block diagram of a teleoperator with PC. Two series PCs are attached at each port of the bilateral controller.

[6,14,15,17,18] for more detail about the time-domain passivity approach.

When there was no time-delay, the previous two-port time-domain passivity approach showed satisfiable performance while guaranteeing the passivity [14]. However, once time-delay is introduced, the passivity condition cannot be satisfied anymore with the previous approach. The main reason was on the fact that the PO should integrate the power flow at each port of the bilateral controller at the same sampling time.

III. Two-Port Time Domain Passivity Approach Considering Time-Varying Communication Delay

In this Section, a modified two-port time-domain passivity approach is proposed, considering time-varying communication delay.

The basic idea of the modified approach is that we can separate the input and output energy at each port based on the sign of the product of the force and velocity at each port.

$$E_{obsv}(t_k) = E_{in}(k) - E_{out}(k) \tag{4}$$

Note that k means the k'*th* step sampling time (t_k).

If the sign of the product at a port is positive, that means energy is flowing into the network system. If the sign is negative, that means energy is flowing out of the network system. (Fig. 5). The total input and output energy of the network system can be calculated by integrating the product for each cases.

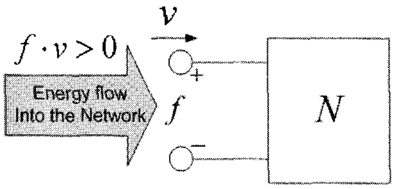
$$E_{in}(k) = \begin{cases} E_{in}(k-1) + f(k)v(k) & if\ f(k)v(k) > 0 \\ E_{in}(k-1) & if\ f(k)v(k) \leq 0 \end{cases} \tag{5}$$

$$E_{out}(k) = \begin{cases} E_{out}(k-1) + f(k)v(k) & if\ f(k)v(k) < 0 \\ E_{out}(k-1) & if\ f(k)v(k) \geq 0 \end{cases} \tag{6}$$

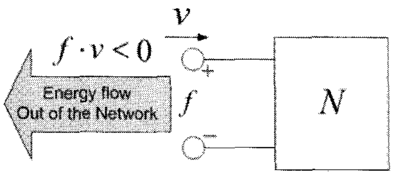
With the above notation, the time-domain passivity condition for an one-port network (2) can be rewritten as follows:

$$E_{in}(k) \geq E_{out}(k) \tag{7}$$

For the bilateral controller two-port, input and output energy at each port can be calculated in a similar way as (5) and (6).



(a) Energy flow into the network systems when f · v > 0.



(b) Energy flow out of the network systems when f · v < 0.

그림 5. 각 포트에서 속도와 힘의 곱이 가지는 부호를 근거로 에너지의 흐름을 판별할 수 있다.

Fig. 5. Based on the sign of the product of force and velocity at a port, it is possible to differentiate whether energy is flowing into the network system or flowing out of the network system.

$$E_{in}^{M}(k)=\begin{cases}E_{in}^{M}(k-1)+f_m(k)v_m(k) & if\ f_m(k)v_m(k)<0\\ E_{in}^{M}(k-1) & if\ f_m(k)v_m(k)\geq 0\end{cases} \tag{8}$$

$$E_{out}^{M}(k)=\begin{cases}E_{out}^{M}(k-1)-f_m(k)v_m(k) & if\ f_m(k)v_m(k)<0\\ E_{out}^{M}(k-1) & if\ f_m(k)v_m(k)\geq 0\end{cases} \tag{9}$$

$$E_{in}^{S}(k)=\begin{cases}E_{in}^{S}(k-1)-f_s(k)v_s(k) & if\ f_s(k)v_s(k)<0\\ E_{in}^{S}(k-1) & if\ f_s(k)v_s(k)\geq 0\end{cases} \tag{10}$$

$$E_{out}^{S}(k)=\begin{cases}E_{out}^{S}(k-1)+f_s(k)v_s(k) & if\ f_s(k)v_s(k)>0\\ E_{out}^{S}(k-1) & if\ f_s(k)v_s(k)\leq 0\end{cases} \tag{11}$$

With the above notation, the time-domain passivity condition for two-port bilateral controller (3) can be rewritten as follows:

$$E_{in}^{M}(k)+E_{in}^{S}(k)\geq E_{out}^{M}(k)+E_{out}^{S}(k), \quad \forall k\geq 0 \tag{12}$$

In the previous approach, we adjusted $E_{out}^{M}(k)$ and $E_{out}^{S}(k)$ for satisfying the above single condition (12). However, if there is time-delay, the above condition (12) cannot be checked in real-time anymore.

Theorem 1: If the output energy at the slave port (E_{out}^{S}) is always less than or equal to the transmitted input energy from the master port (E_{in}^{M}) with whatever amount of communication delay from master to slave (D^{MS}, which is the number of delayed sampling step) and the output energy at the master port (E_{out}^{M}) is always less than or equal to the transmitted input energy from the slave port (E_{in}^{S}) with whatever amount of communication delay from slave to master (D^{SM}) such that

$$E_{in}^{M}(k-D^{MS})\geq E_{out}^{S}(k),\ \forall k\geq 0 \tag{13}$$

$$E_{in}^{S}(k-D^{SM})\geq E_{out}^{M}(k),\ \forall k\geq 0 \tag{14}$$

where $E_{in}^{M}(n)=E_{in}^{S}(n)=0$ when $n<0$, then the two-port bilateral controller can be passive as follows:

$$E_{in}^{M}(k)+E_{in}^{S}(k)\geq E_{out}^{M}(k)+E_{out}^{S}(k),\ \forall k\geq 0 \tag{15}$$

Proof: By separating the time-domain passivity condition of the two-port bilateral controller (12), the following sufficient condition can be derived.

$$E_{in}^{M}(k)\geq E_{out}^{S}(k) \tag{16}$$

$$E_{in}^{S}(k)\geq E_{out}^{M}(k) \tag{17}$$

The output energy at the slave port should be less than the input energy at the master port, and the output energy at the master port should be less than the input energy at the slave port. It is interesting to note that similar condition has been used in [12] and [24], which were based on wave variable approach.

The above two conditions can be rewritten like,

$$E_{in}^{M}(k-D^{MS})-E_{in}^{M}(k-D^{MS})+E_{in}^{M}(k)\geq E_{out}^{S}(k) \tag{18}$$

$$E_{in}^{S}(k-D^{SM})-E_{in}^{S}(k-D^{SM})+E_{in}^{S}(k)\geq E_{out}^{M}(k) \tag{19}$$

and it is interesting to notice that

$$E_{in}^{M}(k)-E_{in}^{M}(k-D^{MS})\geq 0 \tag{20}$$

$$E_{in}^{S}(k)-E_{in}^{S}(k-D^{SM})\geq 0 \tag{21}$$

since the input energy at time step k is always greater than or equal to the input energy at the previous time step whatever amount of delay there is. Please see (8) and (10). Therefore, it is sufficient to satisfy (13) and (14) for guaranteeing the passivity of the teleoperator $(E_{obsv}(k)\geq 0)$. Note that the great thing on the above sufficient condition is that this is still valid sufficient condition even for the case when there is time-varying communication delay.

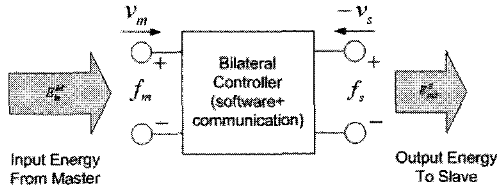
This sufficient condition can be satisfied by modifying each output energy $E_{out}^{S}(k)$ and $E_{out}^{M}(k)$, which can be accessible in real-time by adding adaptive damping elements at each port (Fig. 7). Two series PCs are attached at each port of the bilateral controller. Two POs at each port are monitoring the input energy and output energy, separately. Input energy from the master (E_{in}^{M}) is monitored by PO_{in}^{M} and transmitted to the P_{out}^{S}, which monitor the output energy at the slave (E_{out}^{S}), and adjusting the damping elements α_2 for bounding the output energy at the slave (E_{out}^{S}) according to

$$\alpha_2(k)=\begin{cases}\dfrac{E_{out}^{S}(k)-E_{in}^{M}(k-D^{MS})}{\Delta T v_s^2(k)} & if\ E_{out}^{S}(k)>E_{in}^{M}(k-D^{MS})\\ 0 & if\ E_{out}^{S}(k)\leq E_{in}^{M}(k-D^{MS})\end{cases} \tag{22}$$

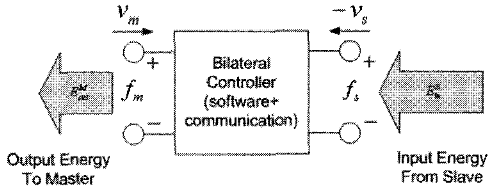
Input energy from the slave (E_{in}^{S}) is monitored by PO_{in}^{S} and transmitted to the PO_{out}^{M}, which monitor the output energy at the master (E_{out}^{M}), and adjusting the damping elements α_1 for bounding the output energy at the master (E_{out}^{M}).

$$\alpha_1(k)=\begin{cases}\dfrac{E_{out}^{M}(k)-E_{in}^{S}(k-D^{SM})}{\Delta T v_m^2(k)} & if\ E_{out}^{M}(k)>E_{in}^{S}(k-D^{SM})\\ 0 & if\ E_{out}^{M}(k)\leq E_{in}^{S}(k-D^{SM})\end{cases} \tag{23}$$

We can easily demonstrate that the sufficient condition for the



(a) Output energy to the slave should be less than the Input energy from the master for guaranteeing passivity.



(b) Output energy to the master should to be less than the Input energy from the slave for guaranteeing passivity.

그림 6. 양방향 제어기를 가지는 원격조종시스템에서, 한 포트의 출력에너지의 소스는 다른 포트의 입력에너지이며, 그 출력에너지는 입력에너지보다 작아야 한다.

Fig. 6. In teleoperation systems with bilateral control law, the main source of the output energy at one port is the input energy at the other port, and the output energy should be less than the input energy.

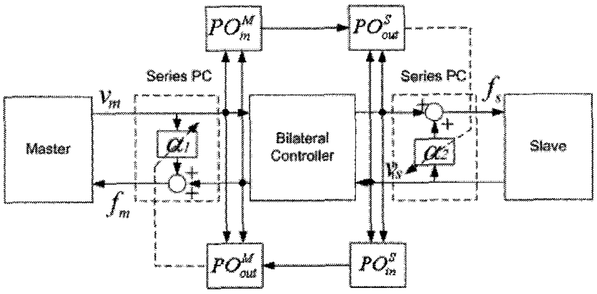


그림 7. 제안된 수동성 제어기가 적용된 원격조종시스템의 블록다이어그램. 두 개의 직렬형 수동성 제어기가 양방향 제어기의 각 포트에 적용 되어 있다.

Fig. 7. Block diagram of a teleoperator with newly proposed PO/PC, considering time-delay. Two series PCs are attached at each port of bilateral controller.

passivity of the bilateral controller, (13) and (14) can be satisfied with the additional damping α_1 and α_2, which is computed by (22) and (23). Please see [6] for more detailed proof.

IV. Experimental Results

Fig. 8 shows the experimental setup for the teleopertaion with time delay. PHANToM was used for master and slave manipulator, and UDP connection was used for a data communication. A packet reflector at local site was introduced to make the experimental system experience a time-varying internet delay. The packet reflector has wireless internet connection to the both haptic server and haptic client.

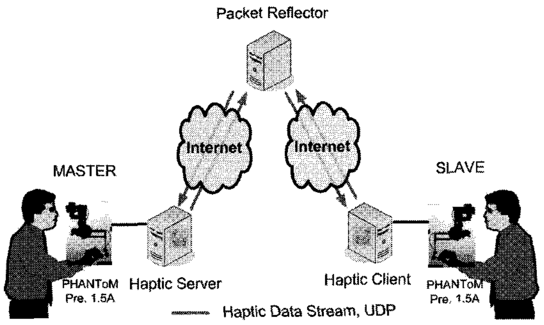


그림 8. 시간지연이 적용된 원격조종 시스템의 실험장치.

Fig. 8. Experimental setup for the teleoperaiton with time-delay.

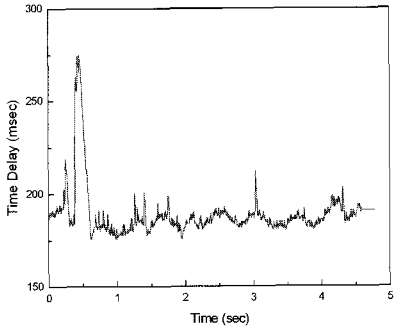


그림 9. 실험과정 중 발생한 시간지연의 양.

Fig. 9. Amount of time-varying delay of the teleoperation system during an experiment.

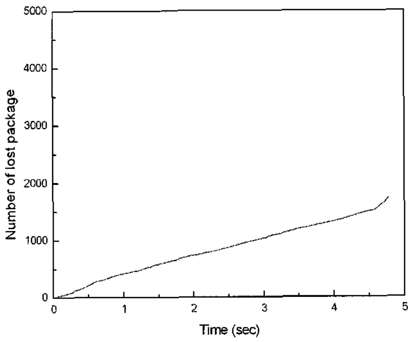


그림 10. 실험과정 중 발생한 데이터 손실 양.

Fig. 10. Number of lost data packet during an experiment.

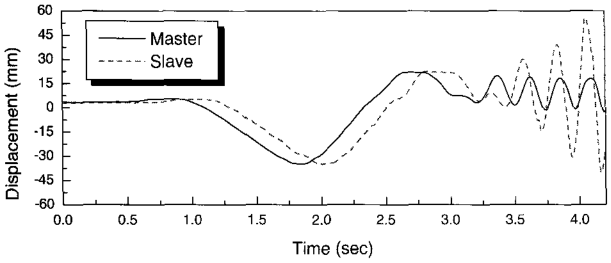
Fig. 9 shows the amount of time-varying delay of the teleoperation system during an experiment. The communication had about 190 (msec) average time-delay for round trip, and varying between 175 (msec) and 275(msec). Since we have used UDP connection for data communication, some data packet might be lost during the communication. Fig. 10 shows the number of lost data packet during a communication experiment. Note that each packet was sent for every single millisecond.

Following position-position bilateral control architecture was used,

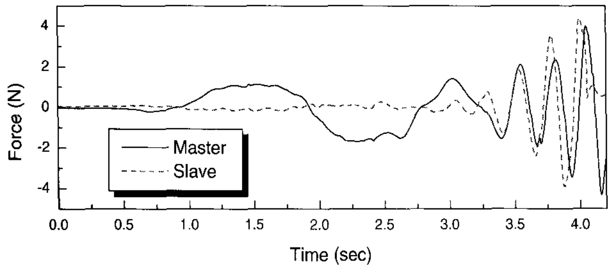
$$f_m(t) = K_P\left(X_s\left(t - T_D^{SM}\right) - X_m(t)\right)$$
$$f_s(t) = K_P\left(X_m\left(t - T_D^{MS}\right) - X_S(t)\right)$$

where $K_P = 100(N/m)$ and T_D^{SM} and T_D^{MS} are time-varying communication delay from slave to master and master to slave, respectively.

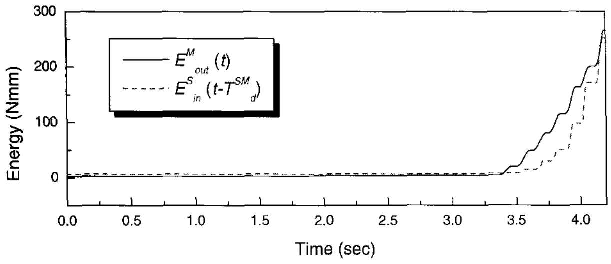
First, operator maneuvered the master manipulator in free space without the PC. Position and force response of the master and slave manipulator showed unstable behavior (Fig. 11(a), 11(b)). Due to the excessive energy output at the master port (Fig. 11(c)), which is greater than the energy input from the slave port, master manipulator was oscillating. Before 3(sec) slave was seems like following the position command from the master. However the position of the slave manipulator started to diverge since when the output energy at the slave port became greater than the input energy from the master (Fig. 11(d)) (after 3.7 (sec)).



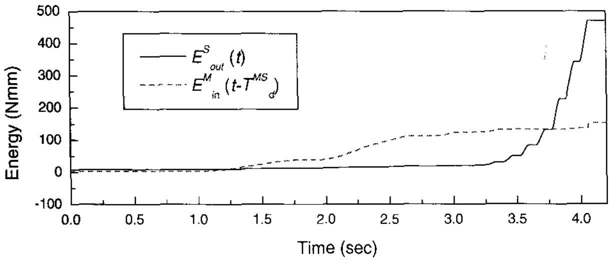
(a) Position response of the master and slave



(b) Control force of the master and slave



(c) Output energy to the master and input energy from the slave with delay

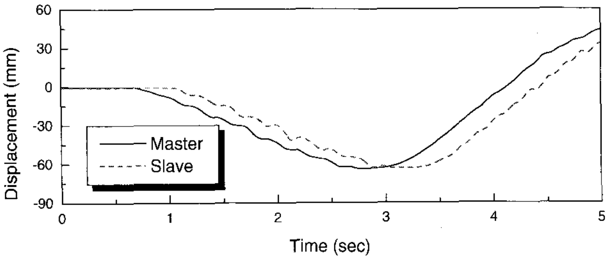


(d) Output energy to the slave and input energy from the slave with delay.

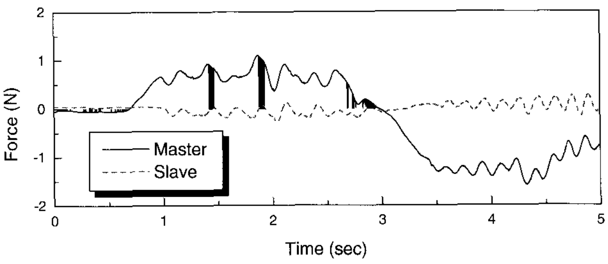
그림 11. 수동성 제어기가 적용되지 않고, 단 방향으로 각각 120msec의 시간이 존재하는 실험환경에서의 비구속 모션.

Fig. 11. Free motion with time-varying communication delay and packet loss without PC.

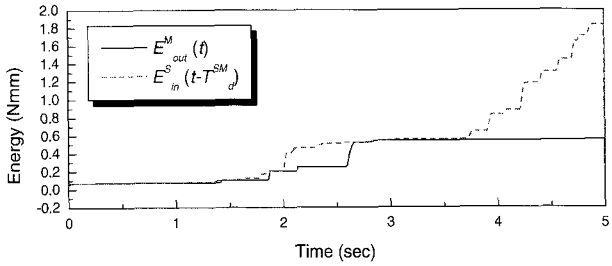
Same experiment as in Fig. 11 has been performed with the proposed PC. Position response of the master and slave manipulator showed stable behavior (Fig. 12(a)). The proposed PC made the bilateral controller passive by making the output energy at the master port stay below the input energy from the slave port (Fig. 12(c)), and the output energy at the slave port stay below the input energy from the master port as well (Fig. 12(d)). When the output energy at the master port was about to be greater than the input energy from the slave port (before 2 (sec) and around 3 (sec) in Fig. 12(c)), the PC was activated and modified



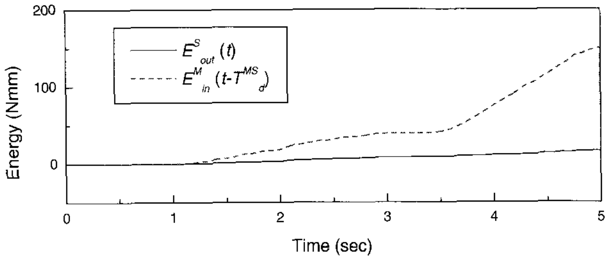
(a) Position response of the master and slave



(b) Control force of the master and slave



(c) Output energy to the master and input energy from the slave with delay



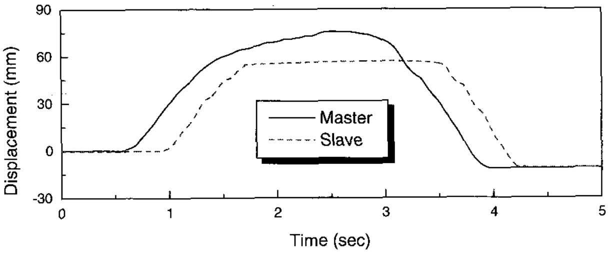
(d) Output energy to the slave and input energy from the slave with delay

그림 12. 수동성 제어기가 적용되고, 단 방향으로 각각 120msec의 시간이 존재하는 실험환경에서의 비구속 모션.

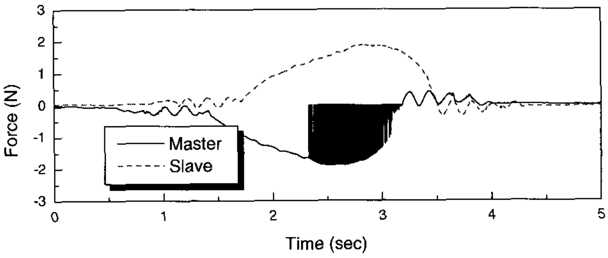
Fig. 12. Free motion with time-varying communication delay and packet loss with PC.

the control force of the master when it is necessary (Fig. 12(b)).

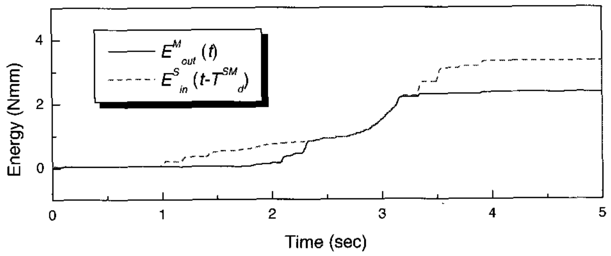
We made a hard contact with about the same communication time-delay and with the proposed PC. Position response of the master and slave manipulator was stable (Fig. 13(a)). The proposed PC made the output energy at the master port staying below the input energy from the slave port (Fig. 13(c)). The contact started about 1.7 (sec) and ended about 3.7 (sec). At the end of the contact, the bilateral controller was about to produce active energy at the master port, which is larger than the input energy from the slave port. (Fig. 13(c)), so the PC at the master port was activated to dissipate the active energy output (Fig. 13(b)). At the end of the contact, there was a noisy behavior on the force to the master. The reason could be found on low velocity during the contact. Especially, sudden sign change and zero value of velocity. In our previous work [16], noisy behavior of the PC, due to the low velocity, has been studied. This noisy behavior obviously lower the control performance, however please be note that it did not break the passivity condition.



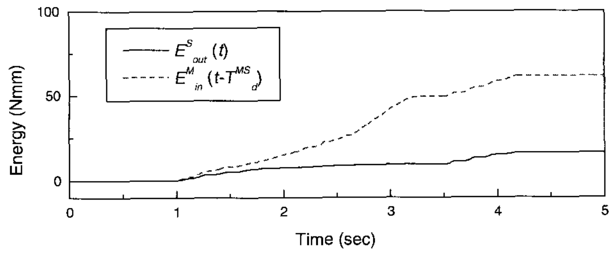
(a) Position response of the master and slave



(b) Control force of the master and slave



(c) Output energy to the master and input energy from the slave with delay



(d) Output energy to the slave and input energy from the slave with delay

그림 13. 수동성 제어기가 적용되고, 단 방향으로 각각 120 msec의 시간이 존재하는 실험환경에서의 구속 모션.

Fig. 13. Hard contact with time-varying communication delay and packet loss with PC.

V. Conclusions and Future Works

This paper extended the previously proposed two-port time-domain passivity approach including time-varying communication delay. The key idea of this paper is separating the input and the output energy at each master and slave port of the bilateral controller, and bounding each output energy of one port to the input energy at the other port. The feasibility of the proposed approach was proved with the master/slave dual PHANToM teleoperation system under very serious communication condition, about 190(msec) average time-delay for round trip, variation range was in between 175 (msec) and 275(msec), and almost one over third of the data packet was lost. There are sill some issues about the performance, such as noisy behavior of the PC. However, the proposed approach has its own contribution on the fact that it can at least guarantee the passivity of a teleoperator even under time-varying communication delay.

If the proposed approach is compared with other previous approaches, like modified wave variable methods for time-varying delay, it is expected that the proposed approach will show better performance for short time delay, and will have more noisy behavior for long time delay while passivity is maintained on both approaches. At the current state, it is hard to directly compare both methods without analytic and environmental evaluations at the same condition. As our further work, we are now carefully approaching this.

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