시간영역 수동성 기법을 이용하여 시변 시간지연 하에서 안정성을 보장하는 양방향 원격제어기: 리셋 방법

Bilateral Control with Time Domain Passivity Approach under Time-varying Communication Delay: Resetting Scheme

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Abstract : Recently, two-port time-domain passivity approach was modified for time-varying communication delay. The newly proposed approach could achieve stable teleoperation even under the serious time-varying delay and packet loss communication condition. However, after some operation hour, the accumulated energy difference between the input energy from one port and the output energy at the other port caused unstable behavior until the passivity controller is activated. Resetting scheme is introduced for solving this problem, and stable bilateral teleoperation can be guaranteed without worrying about the accumulated energy difference.

Keywords : bilateral control, passivity controller, passivity observer, teleoperation, time-delay, 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[1,2] 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[3,4,7,10,12,22].

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.

However, the problem of previous approaches was the conservatism. The passivity was guaranteed with the expense of too much degradation of the system performance. For solving this performance and stability issue Hannaford and Ryu have proposed a new concept of energy based approach. They proposed "Passivity Observer" (PO) for a network system to check the passivity, and "Passivity Controller" (PC), which is a time-varying damping element, to make a network system passive by dissipating only the required amount of energy. This idea has been successfully applied for guaranteeing the passivity of haptic[6,15-17] and teleoperation systems with no communication time-delay[14]. Recently this idea has been extended for stable bilateral control of teleoperators including time-varying communication delay[18].

In our previous paper, teleoperation experiments with about 120 (msec) of time-varying delay each way have been performed, and the newly proposed controller has achieved stable teleoperaion in free motion and hard contact as well. However, we found a sort of unstable behavior when there is a big energy difference between the input energy at one port and the output energy at the other port until this energy difference is disappeared. In this paper, resetting scheme is introduced for escaping this big energy difference. The performance of the proposed resetting scheme is proved under serious time-varying delay and data packet loss communication condition.

II. TWO-PORT TIME DOMAIN PASSIVITY APPROACH CONSIDERING TIME-VARYING COMMUNICATION DELAY

In this Section, recently modified two-port time-domain passivity approach[18], considering time-varying communication delay, is reviewed.

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.

$$E_{obsv}(t_k) = E_{in}(k) - E_{out}(k) \qquad (1)$$

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. 1). The total input

(a) Energy flow into the network systems when $f \cdot v > 0$.

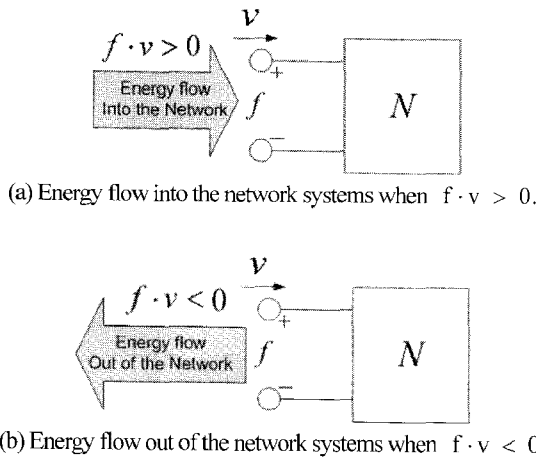(b) Energy flow out of the network systems when $f \cdot v < 0$.

그림 1. 그림 1. 힘과 속도의 부호에 따라 에너지가 원 포트 네트워크 시스템으로 흘러 들어가는지 흘러나오는지 를 알 수 있다.

Fig. 1. 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..

and output energy of the network system can be calculated by integrating the product for each cases.

$$E_{in}(k) = \begin{cases} E_{in}(k-1) + f(k)v(k) & if\ f(k)v(k) > 0 \\ E_{in}(k-1) & if\ f(k)v(k) \leq 0 \end{cases} \quad (2)$$

$$E_{out}(k) = \begin{cases} E_{out}(k-1) + f(k)v(k) & if\ f(k)v(k) < 0 \\ E_{out}(k-1) & if\ f(k)v(k) \geq 0 \end{cases} \quad (3)$$

With the above notation, the time-domain passivity condition for an one-port network[4] can be rewritten as follows:

$$E_{in}(k) \geq E_{out}(k) \quad (4)$$

For the bilateral controller two-port, input and output energy at each port can be calculated in a similar way as (2) and (3).

$$E_{in}^{M}(k) = \begin{cases} E_{in}^{M}(k-1) + f_{m}(k)v_{m}(k) & if\ f_{m}(k)v_{m}(k) < 0 \\ E_{in}^{M}(k-1) & if\ f_{m}(k)v_{m}(k) \geq 0 \end{cases} \quad (5)$$

$$E_{out}^{M}(k) = \begin{cases} E_{out}^{M}(k-1) - f_{m}(k)v_{m}(k) & if\ f_{m}(k)v_{m}(k) < 0 \\ E_{out}^{M}(k-1) & if\ f_{m}(k)v_{m}(k) \geq 0 \end{cases} \quad (6)$$

$$E_{in}^{S}(k) = \begin{cases} E_{in}^{S}(k-1) - f_{s}(k)v_{s}(k) & if\ f_{s}(k)v_{s}(k) < 0 \\ E_{in}^{S}(k-1) & if\ f_{s}(k)v_{s}(k) \geq 0 \end{cases} \quad (7)$$

$$E_{out}^{S}(k) = \begin{cases} E_{out}^{S}(k-1) + f_{s}(k)v_{s}(k) & if\ f_{s}(k)v_{s}(k) > 0 \\ E_{out}^{S}(k-1) & if\ f_{s}(k)v_{s}(k) \leq 0 \end{cases} \quad (8)$$

With the above notation, the time-domain passivity condition for two-port bilateral controller[10] can be rewritten as follows:

$$E_{in}^{M}(k) + E_{in}^{S}(k) \geq E_{out}^{M}(k) + E_{out}^{S}(k), \quad \forall k \geq 0 \quad (9)$$

In the previous approach, we adjusted $E_{out}^{M}(k)$ and $E_{out}^{S}(k)$ for satisfying the above single condition (9). However, if there is time-delay, the above condition (9) 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 $\left(E_{in}^{M}\right)$ 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 $\left(E_{out}^{M}\right)$ is always less than or equal to the transmitted input energy from the slave port $\left(E_{in}^{S}\right)$ with whatever amount of communication delay from slave to master $\left(D^{SM}\right)$ such that

$$E_{in}^{M}(k - D^{MS}) \geq E_{out}^{S}(k), \quad \forall k \geq 0 \quad (10)$$

$$E_{in}^{S}(k - D^{SM}) \geq E_{out}^{M}(k), \quad \forall k \geq 0 \quad (11)$$

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

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

Proof: By separating the time-domain passivity condition of the two-port bilateral controller (9), the following sufficient condition can be derived.
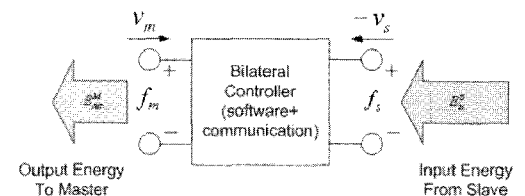
$$E_{in}^{M}(k) \geq E_{out}^{S}(k) \quad (13)$$

$$E_{in}^{S}(k) \geq E_{out}^{M}(k) \quad (14)$$

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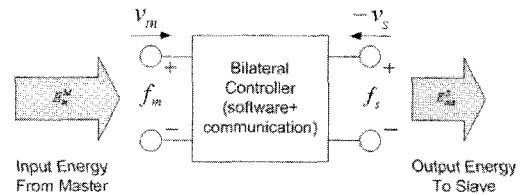
(a) Output energy to the slave should be less than the Input energy from the master for guaranteeing passivity.

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

그림 2. 양방향 원격조종 시스템에서 한 포트의 출력에너지 는 다른 한 포트의 입력에너지에 기인하며, 이 출력 에너지는 입력에너지보다 작은 값을 가져야 한다.

Fig. 2. 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.

note that similar condition has been used in [12] and [22], which were based on wave variable approach.

The above two conditions can be rewritten like,

$$E_{in}^{M}\left(k-D^{MS}\right)-E_{in}^{M}\left(k-D^{MS}\right)+E_{in}^{M}\left(k\right)\geq E_{out}^{S}\left(k\right) \quad (15)$$

$$E_{in}^{S}\left(k-D^{SM}\right)-E_{in}^{S}\left(k-D^{SM}\right)+E_{in}^{S}\left(k\right)\geq E_{out}^{M}\left(k\right) \quad (16)$$

and it is interesting to notice that

$$E_{in}^{M}\left(k\right)-E_{in}^{M}\left(k-D^{MS}\right)\geq 0 \quad (17)$$

$$E_{in}^{S}\left(k\right)-E_{in}^{S}\left(k-D^{SM}\right)\geq 0 \quad (18)$$

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 (5) and (7). Therefore, it is sufficient to satisfy (10) and (11) for guaranteeing the passivity of the teleoperator $\left(E_{obsv}(k)\geq 0\right)$. 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. 3). 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

$$\alpha_{2}\left(k\right)=\begin{cases}\dfrac{E_{out}^{S}\left(k\right)-E_{in}^{M}\left(k-D^{MS}\right)}{\Delta T v_{s}^{2}\left(k\right)} & if\ E_{out}^{S}\left(k\right)>E_{in}^{M}\left(k-D^{MS}\right)\\0 & if\ E_{out}^{S}\left(k\right)\leq E_{in}^{M}\left(k-D^{MS}\right)\end{cases} \quad (19)$$

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
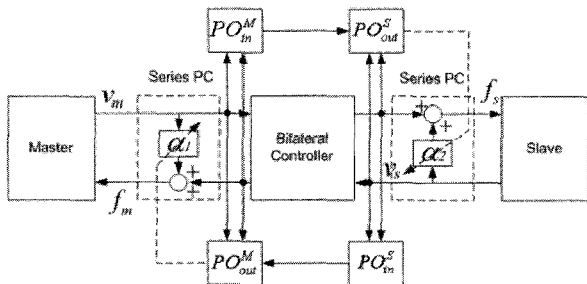

그림 3. 새로 제안된 PO/PC가 적용된 원격조종 시스템. 두 개의 직렬 PC가 양방향 원격제어기의 각 포트에 적 용되어 있다.

Fig. 3. Block diagram of a teleoperator with newly proposed PO/PC, considering time-delay. Two series PCs are attached at each port of bilateral controller.

the output energy at the master (E_{out}^{M}).

$$\alpha_{1}\left(k\right)=\begin{cases}\dfrac{E_{out}^{M}\left(k\right)-E_{in}^{S}\left(k-D^{SM}\right)}{\Delta T v_{m}^{2}\left(k\right)} & if\ E_{out}^{M}\left(k\right)>E_{in}^{S}\left(k-D^{SM}\right)\\0 & if\ E_{out}^{M}\left(k\right)\leq E_{in}^{S}\left(k-D^{SM}\right)\end{cases} \quad (20)$$

We can easily demonstrate that the sufficient condition for the passivity of the bilateral controller, (10) and (11) can be satisfied with the additional damping α_{1} and α_{2}, which is computed by (19) and (20). Please see[6] for more detailed proof.

III. A PROBLEM CAUSED BY THE ACCUMULATED ENERGY DIFFERENCE

In this Section, a problem in recent approach, which is about an unstable behavior due to the big energy difference between input energy at one port and the output energy at the other port, is discussed.

First, experimental condition is introduced. Fig. 4 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.

Fig. 5 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
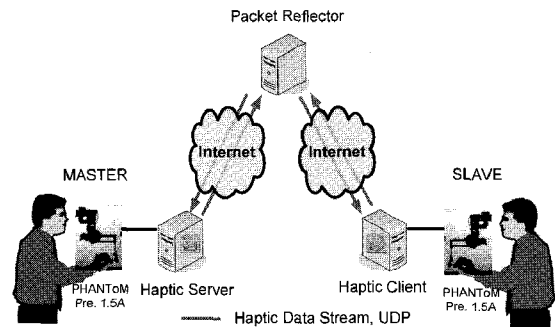

그림 4. 시간지연 원격조종 실험을 위한 셋업.

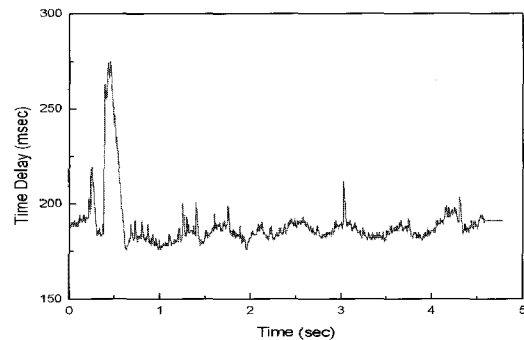Fig. 4. Experimental setup for the teleoperaiton with time-delay.

그림 5. 실험 동안 변화하는 시간지연의 양.

Fig. 5. Amount of time-varying delay of the teleoperation system during an experiment.
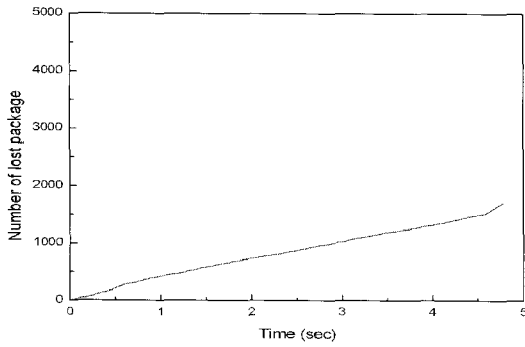
그림 6. 실험 동안 잃어버린 데이터의 양.

Fig.   6. Number of lost data packet during an experiment.

(msec) and 275(msec). Since we have used UDP connection for data communication, some data packet might be lost during the communication. Fig. 6 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.

Operator maneuvered the master manipulator in free space with the recently proposed PC. Operator tried to stay still after single sinusoidal motion. Position and force response of the master and slave manipulator showed stable behavior until 2.0 (sec), but went to unstable after that. (Fig. 7(a), 7(b)). Even though the behavior was unstable and there is excessive energy output at the master port (Fig. 7(c)) and the slave port (Fig. 7(d)), the PC was not activated since the transmitted input energy from the master $\left(E_{in}^M \left(t - T_d^{MS} \right) \right)$ and slave $\left(E_{in}^S \left(t - T_d^{SM} \right) \right)$ were still greater than the output energy at the slave $\left(E_{out}^S(t) \right)$ and at the master $\left(E_{out}^M(t) \right)$, respectively. After certain period of stable operation, the input and output energy will be accumulated, and the difference will be getting bigger and bigger. Since the PC can not be activated until the output energy is greater than the input energy even though there is unstable oscillation and big amount of active energy output, this accumulated energy difference might be a problem for a long period of operation.

IV. ENERGY RESETTING SCHEME

In this Section, a simple resetting scheme is proposed for removing the accumulated energy difference. If there is no active energy output for certain period of time at a port, we reset the accumulated energy output at the port as the transmitted input energy from the other port.

If $f_m(k)v_m(k) \geq 0$, for $N - M < k \leq N$

Then $E_{out}^M(N) = E_{in}^S \left(N - D^{SM} \right)$ (21)

If $f_s(k)v_s(k) \geq 0$, for $P - M < k \leq P$

Then $E_{out}^S(P) = E_{in}^M \left(P - D^{MS} \right)$ (22)

where M is the number of sampling time which the user need to design for resetting. If the output energy stays above zero, which means there is no active energy flow, during M sampling time, we reset the accumulated output energy to the delayed input energy.

Resetting the accumulated output energy is equal to add the accumulated energy difference. Therefore the sufficient condition (10) and (11) can be changed as follows:
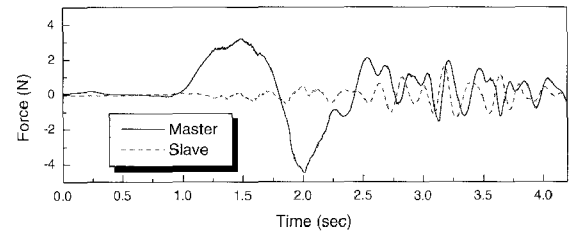
$$E_{in}^M \left(k - D^{MS} \right) - E_{in}^M \left(P - D^{MS} \right) + E_{out}^S(P) \geq E_{out}^S(k)$$

$$E_{in}^S \left(k - D^{SM} \right) - E_{in}^S \left(N - D^{SM} \right) + E_{out}^M(N) \geq E_{out}^M(k)$$
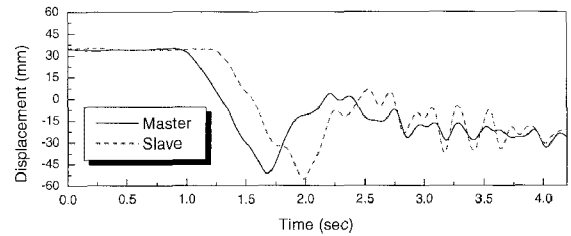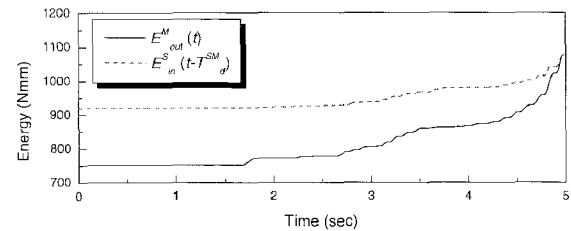

(a) 마스터와 슬레이브의 위치응답.

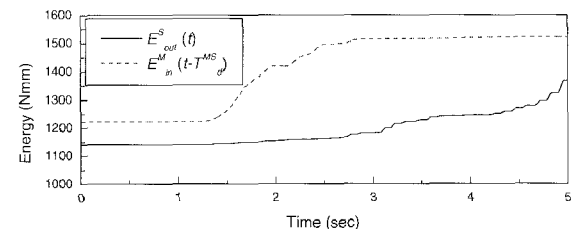(a) Position response of the master and slave.

(b) 마스터와 슬레이브의 제어 힘.

(b) Control force of the master and slave.

(c) 슬레이브로부터의 입력에너지와 마스터측의 출력에너지.

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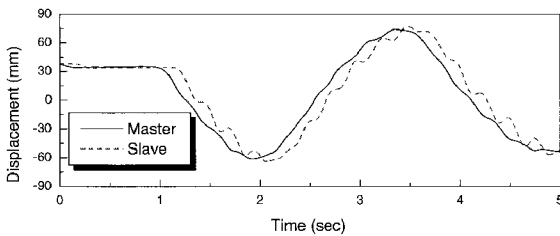

(d) 마스터로부터의 입력에너지와 슬레이브측의 출력에너지.

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

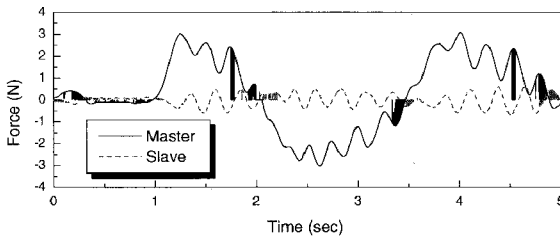그림 7. 시변 시간지연과 데이터 손실이 존재하는 경우 최근 제안된 PC 방법을 이용한 자유공간에서의 실험결과.

Fig.   7. Free motion with time-varying communication delay and packet loss with recently proposed PC.

where those added terms are negative. As a result, the resetting scheme allows the less active output energy, which makes the controller more conservatively guarantee the system passivity.
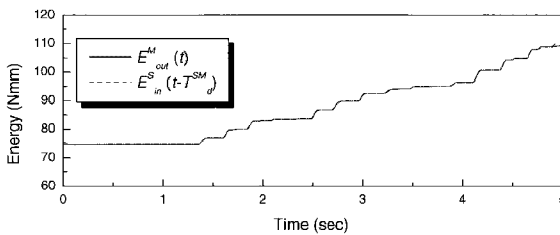
Same experiment as in Fig. 7 has been performed with the proposed resetting scheme. The accumulated energy difference was removed by resetting the output energy at each port based on (21) and (22). Thanks to the resetting scheme, position response of the master and slave manipulator showed stable behavior (Fig. 8) without worrying about accumulated energy difference. 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.

We made a contact with high stiffness environment about the same communication time-delay and with the proposed resetting scheme. The contact started about 2 (sec) and ended about 3.7 (sec). Position response of the master and slave manipulator was stable (Fig. 9(a)). However noisy behavior, which is worse than the most recent approach, is found during the contact (Fig. 9(b)). As we have already mentioned that the resetting scheme made the controller more
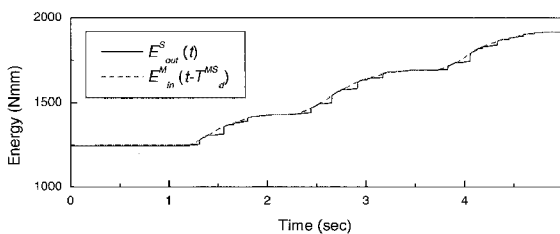

(a) 마스터와 슬레이브의 위치응답.

(a) Position response of the master and slave.

(b) 마스터와 슬레이브의 제어 힘.

(b) Control force of the master and slave.

(c) 슬레이브로부터의 입력에너지와 마스터측의 출력에너지.

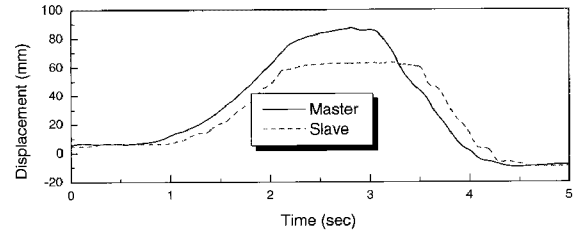(c) Output energy to the master and input energy from the slave with delay.

(d) 마스터로부터의 입력에너지와 슬레이브측의 출력에너지.

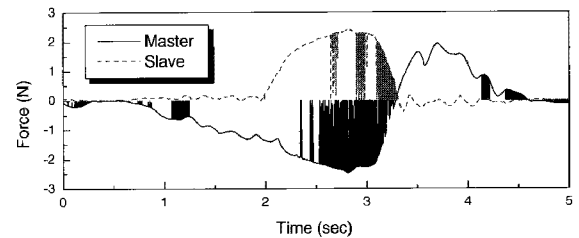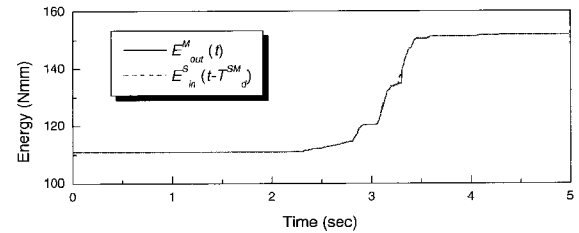(d) Output energy to the slave and input energy from the slave with delay.

그림 8. 시변 시간지연과 데이터 손실이 존재하는 경우 제안된 리셋방법을 이용한 자유공간에서의 실험결과.

Fig. 8. Free motion with time-varying communication delay and packet loss with resetting.
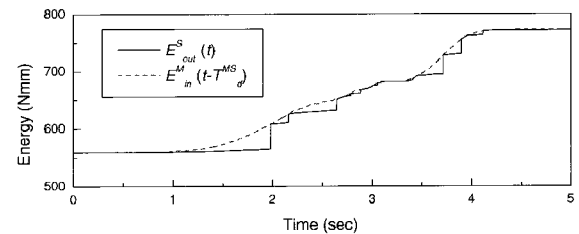

(a) 마스터와 슬레이브의 위치응답.

(a) Position response of the master and slave.

(b) 마스터와 슬레이브의 제어 힘.

(b) Control force of the master and slave.

(c) 슬레이브로부터의 입력에너지와 마스터측의 출력에너지.

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

(d) 마스터로부터의 입력에너지와 슬레이브측의 출력에너지.

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

그림 9. 시변 시간지연과 데이터 손실이 존재하는 경우 제안된 리셋방법을 이용한 강성이 강한 환경과의 충돌실험 결과.

Fig. 9. Hard contact with time-varying communication delay and packet loss with resetting.

conservative, this noisy behavior of the PC partly comes from the resetting scheme since the resetting scheme allows less active energy output.

V. CONCLUSIONS AND FUTURE WORKS

This paper improved the recently modified two-port time-domain passivity approach by solving the accumulated energy difference problem. Resetting scheme, which modify the output energy value, was introduced and solved the potentially unstable problem. Even though the proposed resetting scheme made the PO/PC more conservative, it can guarantee the system stability without worrying about the accumulated energy difference.

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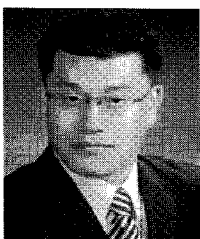
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