변형 가능한 작업환경에 대한 시간영역 수동제어 방법

Time Domain Passivity Approach for Soft and Deformable Environments

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Abstract : Recently proposed control scheme for a stable teleoperation, which was based on two-port time-domain passivity approach [21], has been successful for a contact with high stiffness environments. However, we found several conservatisms during the contact with deformable environments and unconstrained motion. The two-port time-domain passivity controller was excessively dissipating energy even though it was not necessary for some cases of an unconstrained motion and soft contact. The main reason of those conservatisms was on the fact that the two-port time-domain passivity controller was activated without considering the amount of energy dissipation at the master and slave manipulators. Especially, the exclusion of the slave manipulator from the two-port was the dominant reason of the conservatisms. In this paper, we consider the amount of energy dissipation at slave manipulator for designing the time-domain passivity observer and controller. The measured interaction force between slave manipulator and environment allow the time-domain passivity observer to include the amount of energy dissipation at the slave manipulator. Based on the modified passivity observer, reference energy following method [24] is applied to satisfy the passivity condition in real-time. The feasibility of the developed methods is proved with experiments. Improved performance is obtained for an interaction with deformable environments and an unconstrained motion.

Keywords : teleoperation, bileteral control, time-domain passivity control

I. Introduction

The goal of teleoperation system control is to achieve transparency while maintaining stability (i.e., such that the system does not exhibit vibration or divergent behavior) under any operating conditions and for any environments. To this end, several bilateral control architectures have thus far been developed [6,9,11,12,25,26,31].

In designing the bilateral controller, a classic engineering trade-off between transparency and stability has been an important issue, since transparency must often be reduced in order to guarantee stable operation in the wide range of environment impedances (for example, in terms of stiffness of "free space" and "hard contact"). This has necessitated investigating into methods to increase transparency without introducing instability. Several previous studies have sought out theoretical design methods for control parameters based on linear circuit theory [1,10] or linear robust control theory [4,16,30].

However, the teleoperation systems of our interest are non-linear and the dynamic properties of a human operator are always involved. These factors make it difficult to analyze teleoperation systems in terms of known parameters and linear control theory. To cope with the non-linearity and uncertain parameters of the teleoperation system, several researchers have used non-linear control laws such as adaptive control to design the bilateral controller [8,15,19,33]. However, this approach requires, at the very least, system dynamic equations, and the system uncertainty should be captured with a few unknown parameters. Generally, it is very difficult to obtain an exact dynamic model of the teleoperation system. Furthermore, the dynamic structure of a teleoperation system is too complicated to capture with just a few parameters. Thus it becomes very complicated to apply this model-based approach when the teleoperation system has high Degrees of Freedom (DOF).

One promising approach is the use of the idea of passivity to guarantee stable operation without exact knowledge of model information. Anderson and Spong [3] and Niemeyer and Slotine [18] have used passivity concepts for stable teleoperation when a time delay exists. Yokokohji et al. [32] have introduced an energy monitoring method to satisfy passivity under time-varying communication delay. Lozano et al. [17] also presented an idea to solve the time-varying delay problem based on passivity. Lee and Li [13,14] proposed a method to make the teleoperation system passive using fictitious energy storage. Colgate and Schenkel [5] have used passivity to derive fixed parameter virtual coupling (i.e., haptic interface controllers). Anderson [2] has implemented passive module idea to teleoperation systems. However, the use of the passivity for designing teleoperation systems has resulted in an overly conservative controller since they have analyzed system passivity in frequency domain which could not avoid fixed damping design. Thus, in many cases, performance can be poor since a fixed damping value is derived for guaranteeing passivity under all operating conditions.

Recently, Hannaford and Ryu [7] have proposed a new energy based method for stable haptic interaction, and have extended this idea to a teleoperation two-port network [21]. This method has been tested with two-DOF master/slave teleoperation system, and stable operation has been achieved with hard wall contact and hard surface following. However, we have found several conservatisms during the contact with

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deformable environments and unconstrained motion. A certain amount of energy for moving the slave robot was dissipated by the two-port time-domain passivity controller even though it was not necessary. In this paper, a method for removing these conservatisms is proposed by applying the newly proposed reference energy following scheme [24].

II. Review of the time domain passivity approach

1. One-port approach

In this section, we briefly review the time-domain passivity approach. First, we define the sign convention for all forces and velocities so that their product is positive when power enters the system port (Fig. 1). Also, the system is assumed to have initial stored energy $E(0)=0$ at $t = 0$. The following widely known definition of passivity is used.

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

$$\int_0^t f(\tau)\dot{x}(\tau)d\tau \geq 0, \quad \forall t \geq 0 \qquad (1)$$

for forces (f) and velocities $(\dot{x})$. Eqn. 1 states that the energy supplied to a passive network must be positive for all time [28,29].

The conjugate variables that define power flow in such a system are discrete-time values, and the analysis is confined to systems having a sampling rate substantially faster than the dynamics of the system. We assumed that there is no change in force and velocity during one sample time. Thus, we can 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).

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

where ΔT is the sampling period. If $E_{obsv}(k) \geq 0$ for every k, this means the system dissipates energy. If there is an instance when $E_{obsv}(k) < 0$, this means the system generates energy and the amount of generated energy is $-E_{obsv}(k)$. Recently, other research has allowed this constant force and velocity assumption to be relaxed [22,27] and a more accurate PO was proposed for the case of impedance causality [22].

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 any time, we know that the one-port may then be contributing to instability. Moreover, we know the exact amount of energy generated and we can design a time-varying 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 [7].

2. Two-port approach

Similar to the one-port case, the PO can be designed for a two-port network (Fig. 2).

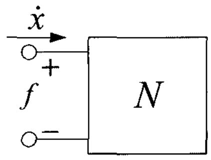

그림 1. 원포트 네트워크.

Fig. 1. One-port network.

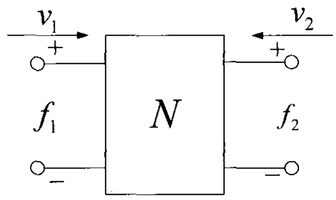

그림 2. 투포트 네트워크.

Fig. 2. Two-port network.

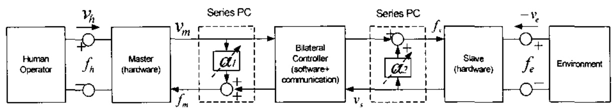

그림 3. 원격조종 시스템에 직렬형 PC가 적용된 구조.

Fig. 3. Configuration of the series PC for the teleoperation system (two-port).

$$E_{obsv}(k) = \Delta T \sum_{j=0}^{k} \left(f_1(t_j)v_1(t_j) + f_2(t_j)v_2(t_j) \right) \qquad (3)$$

However, unlike in the one-port case, there are two gateways through which the generated energy flows out. Theoretically, the two-port network can be made passive by placing the PC at either port. However, there might be some instance where the two-port network generates energy $(E_{obsv}(k) < 0)$, even though the input signal (velocity for impedance causality and force for admittance causality) of a port where the PC is placed is zero. Consequently, another PC should be placed at the other port.

In addition, we have to consider how to activate the PC at each port to make the two-port passive. Mathematically, there are two ways to make the two-port network passive (the total sum of energy is greater than zero). The first way is to make the produced energy less than the absorbed energy. The other way is to make the absorbed energy greater than the produced energy. However, it is more feasible way to make the produced energy less than the absorbed energy by monitoring the conjugate signal pair (f_1v_1 and f_2v_2) of each port in real time, when the two-port network becomes active. Fig. 3 shows the teleoperation system with the PC.

3. Reference energy following scheme

A method to use a time-varying desired energy threshold has been proposed instead of fixed zero energy threshold for the PO. It made the actual energy input follow the time-varying energy threshold. With the time-varying energy threshold, the PC control action became smooth without sudden impulsive behavior by distributing the dissipation. Please see [7,20,21-24] for more detail about the time-domain passivity approach.

III. Conservatisms of the two-port approach

Even though the proposed two-port approach has been successful for guaranteeing the stability in contacting with high stiffness environments, there were several conservatisms which need to be removed for increasing the transparency during the contact with deformable environments and unconstrained motion

In this paper, control schemes are tested in a teleoperation system that has a two-DOF master and a two-DOF slave manipulator, which has been used in [21]. As a deformable environment, soft sponge is placed in parallel to Y-Axis. Position/force control architecture is used for bilateral controller. This system is entirely synchronous at 1000 Hz. Each axis of the master and slave senses position in 1.6716e-4 rad and 1.6519e-4 rad increments, respectively.

1. Excessive energy dissipation

In [20], a conservatism of the two-port PO/PC approach during the contact with a deformable environment has been already mentioned. When the operator made a contact with a soft sponge with high velocity and without the PC, the PO value showed that the two-port bilateral controller was active even though the contact was stable (Fig. 4).

Fig. 5 shows the same experiment as in Fig. 4 with the PC. Both PCs at the master and slave port were activated (Fig. 5d) for making the bilateral controller two-port passive (Fig. 5c) even though it was not actually necessary based on Fig. 4. Therefore, the transmitted force to the master was radically modified (Fig. 5b), and operator felt distorted impedance of the environment.

2. Discrimination between constrained and unconstrained motion

When operator maneuvered the master while the slave was in unconstrained space, the slave well followed the position command from the master, and both positions remained stable Fig. 6. However, the PO value was kept falling down to more negative value (Fig. 6c), which means the bilateral controller two-port was producing energy.

The main source of the produced energy is the position controller of the slave manipulator. Certain amount of active energy was generated to make the slave follow the position command from the master while there was no energy input from the master. If the PC was activated based on this negative PO value, the slave would not follows the position command from the master anymore since the PC would dissipate the energy output for moving the slave. It shows that the two-port approach in [21] could make the bilateral controller conservative in unconstrained motion. Therefore, it was required to discriminate constrained and unconstrained motions to make the integration of the PO value on and off for removing the nonnecessary PC activation. In our previous two-port approach [21], user defined force threshold has been used for discriminating the constrained and unconstrained motion. However, this method is heuristic and depends too much on system dynamics.

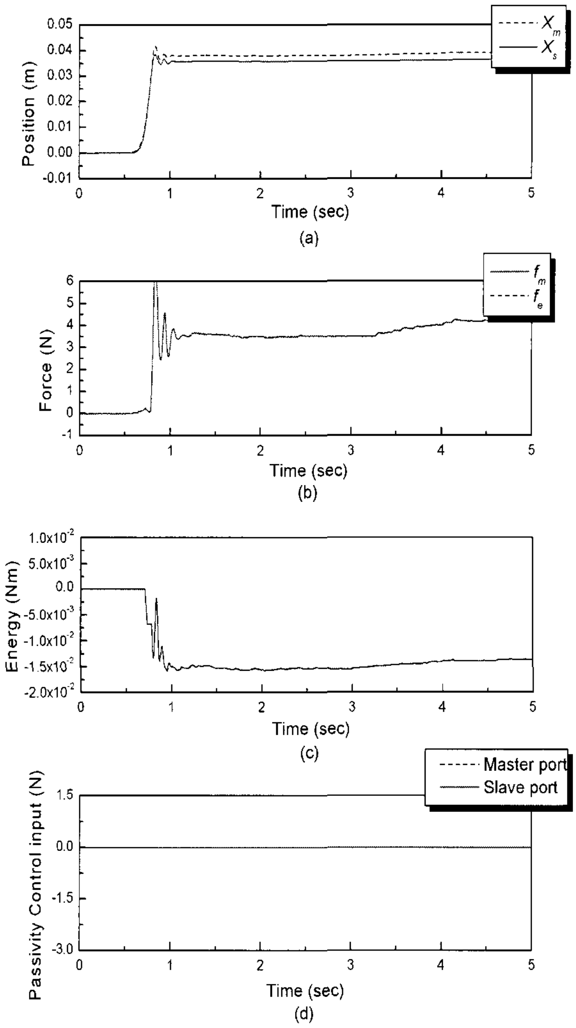

그림 4. 작업자가 마스터를 구동하여 슬레이브가 스펀지와 접촉하게끔 한 실험. PC를 사용하지 않았으며, 접촉이 안정적이었음에도 불구하고 PO값이 음을 나타내고 있다.

Fig. 4. Operator maneuvered the master to make the slave contact with a soft sponge without the PC. The PO value crossed to negative values even though the contact response was stable.

IV. Main reason of the conservatisms

The dominant reason of those conservatisms during the contact with deformable environments and unconstrained motion were from the fact that the ability of energy dissipation at the external elements, especially slave manipulator, have not been considered. The force, only for moving the slave manipulator, should be excluded from the PO integration since some part of produced energy from the two-port bilateral controller is supposed to be used for moving the slave manipulator. If there is no position displacement during the contact (ex., contact with high stiffenss environments), the energy dissipation at the slave manipulator is ignorable due to zero velocity $\left(\sum f_s v_s = 0\right)$. However, when there is some position displacement (ex., contact with deformable environments and unconstrained motion), it is required to consider the amount of energy dissipation at the slave manipulator.

V. Considering the external energy dissipation elements

The passivity of the bilateral controller two-port was a sufficient condition for the passivity of the teleoperation system since the mechanical parts of the master/slave manipulator were excluded in designing the PO/PC for the real-time energy modification, as we mentioned in [20,21]. When the bilateral controller is active, the generated energy flows into the master and slave through the both port. If the mechanism of the master/slave manipulators (intrinsically passive external energy dissipation elements) are capable of dissipating the produced active amount of energy, the overall teleoperation system can be remaining passive without any energy modification.

In this paper, we only consider the mechanism of the slave since it was the dominant reason of the above conservatisms. If the measured interaction force (f_e) between the slave and environment and the velocity of the slave (v_e) can be measured in real-time, it is usually possible to construct the PO including the amount of energy dissipation of the slave manipulator.

$$\begin{aligned} E_{obsv}(k) &= \Delta T\sum_{j=0}^{k}\left(f_m(t_j)v_m(t_j)+f_s(t_j)v_s(t_j)\right) \\ &\quad+\Delta T\sum_{j=0}^{k}\left(-f_s(t_j)v_s(t_j)-f_e(t_j)v_e(t_j)\right) \\ &= \Delta T\sum_{j=0}^{k}\left(f_m(t_j)v_m(t_j)-f_e(t_j)v_e(t_j)\right) \end{aligned} \quad (4)$$

The first line of the right side of (4) is the dissipated energy at the bilateral controller, and the second line is the dissipated energy at the slave manipulator.

However, it cause a question that how we could dissipate the produced energy at the slave/environment port based on the two-port time domain passivity approach [21], since these are responses of a physical interaction between the environment and the slave manipulator, both signals (f_e, v_e) are hard to be modified in real-time.

The only option for keeping the PO value positive $(E_{obsv}(k) \geq 0)$ in real-time is placing the PC in-between master

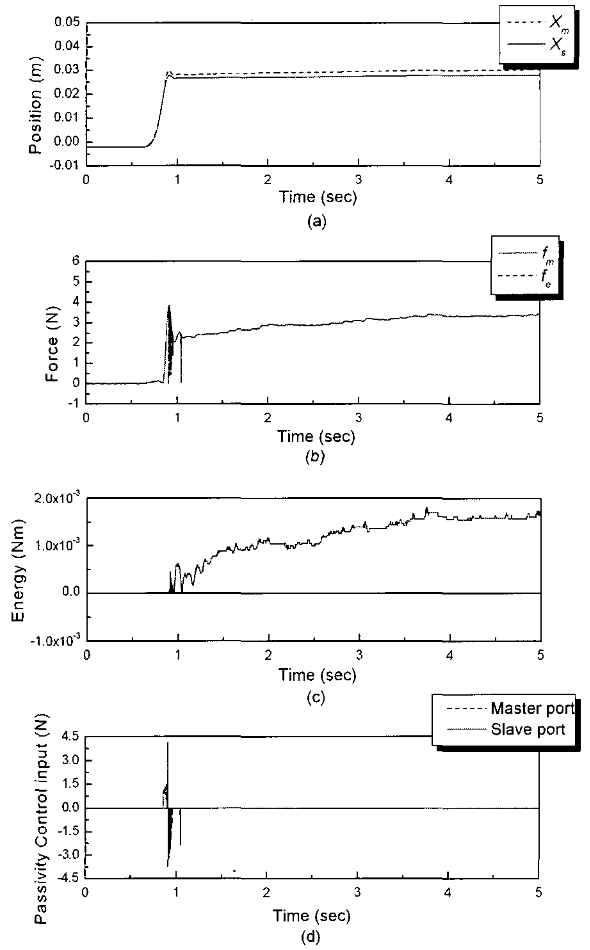

그림 5. 작업자가 마스터를 구동하여 슬레이브가 스펀지와 접촉하게끔 한 실험. PC를 사용하였으며, PC의 과도한 에너지 소비가 작업자로 전달되는 힘을 왜곡시켰다.

Fig. 5. Operator maneuvered the master to make the slave contact with a soft sponge with the PC. Excessive energy dissipation of the PC distorted the transmitted force to the operator.

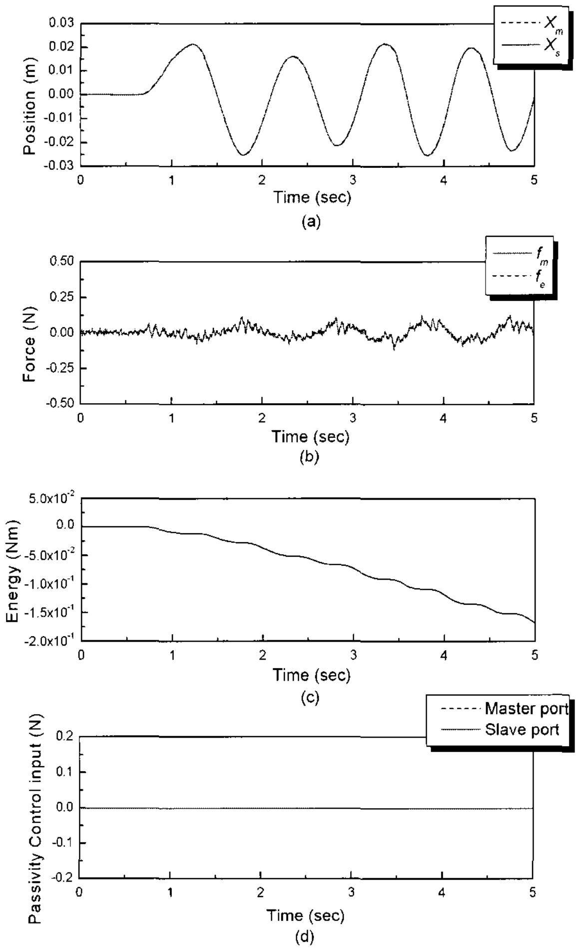

그림 6. 자유공간에서의 원격조종. PC를 사용하지 않았으며, 안정성을 유지함에도 불구하고, PO값이 계속 음으로 떨어지고 있다.

Fig. 6 Unconstrained motion of the master and slave teleoperation system without the PC. The PO value was kept falling down to more negative value even though the response was stable.

and bilateral controller, and making the energy behavior at the master port follows the energy behavior at slave/environment port. In this case, previously proposed reference energy following idea [24] is applied. The energy behavior at the port between slave and environment can be reference energy since this energy behavior is actually what we want to transfer to human operator. Following is the time varying reference energy constraint,

$$\Delta T\sum_{j=0}^{k} f_m(t_j)v_m(t_j) \ge \Delta T\sum_{j=0}^{k} f_e(t_j)v_e(t_j), \quad \forall t_k \ge 0. \qquad (5)$$

Please see [24] for more detailed reference energy following PC algorithm.

One possible problem is that the internal states (such as, slave position and force) could be unstable even though the master port remains passive with the PC. However those internal states can be stable as long as the slave controller (in this paper, position tracking controller) is designed to be stable.

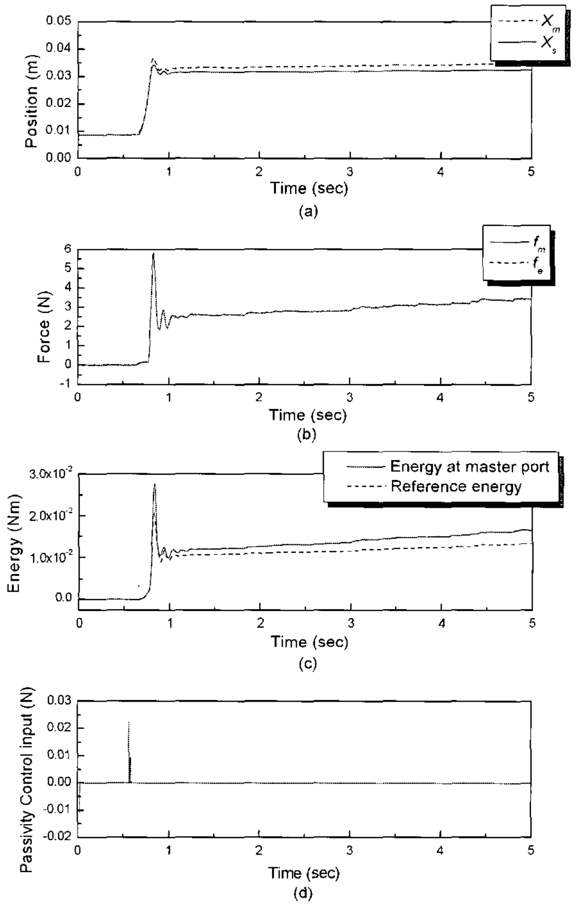

그림 7. 작업자가 마스터를 구동하여 슬레이브가 스펀지와 접촉하게끔 한 실험. 제안된 에너지 추종방법이 사용되었으며, 작업자로 전달되는 힘의 왜곡이 그림 5에 비하여 현저히 줄었다.

Fig. 7. Operator maneuvered the master to make the slave contact with a soft sponge with the proposed reference energy following scheme with the PC. Force distortion was significantly removed, compared to Fig. 5.

There could be numerous control methods to make a single manipulator stable, and the generalized time domain passivity approach [23] can also be applied.

1. Contact with a deformable environment

Based on the above studies, the modified PO and PC is implemented in the same teleoperation system as in Fig. 5, and the operator maneuvers the master for making a contact with the soft sponge. Contact was stable (Fig. 7), and the energy behavior at the master port was well following the reference energy behavior, and even greater than the reference value with the significantly small PC force at the master port (Fig. 7cd). Therefore, operator could feel smooth contact force by removing the unnecessary PC operation.

2. Unconstrained motion

In the same teleoperation system as in Fig. 6, the operator maneuvered the master in unconstrained space with about 1 Hz sinusoidal manner. The slave well followed the position command of the master, and the transmitted force was remained within noise level (Fig. 8). Fig. 8c shows that the energy behavior at the master port $\left(\sum f_m v_m\right)$ was following

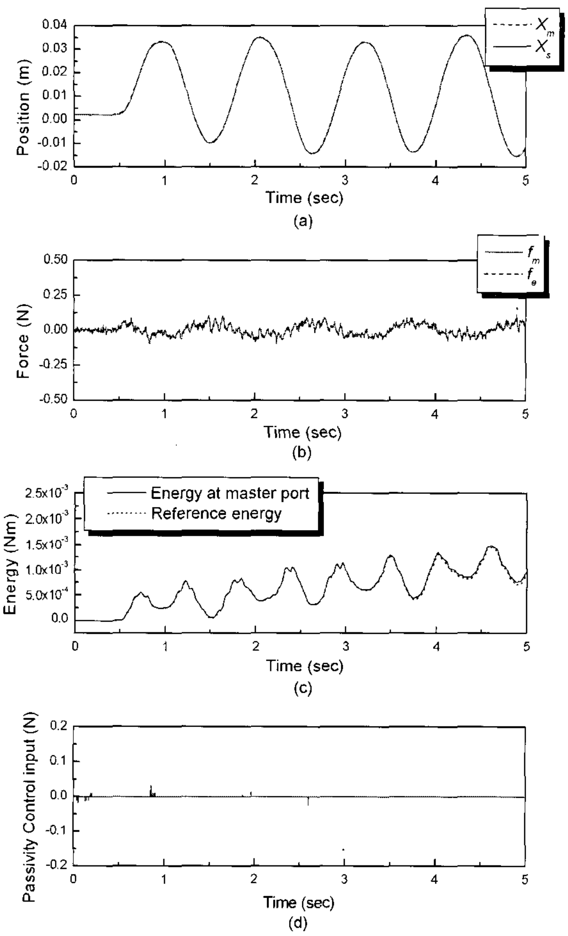

그림 8. 자유공간에서의 원격조종. 제안된 에너지 추종방법이 사용되었음. PO 값이 기준에너지를 추종하며 양으로 계속 증가함.

Fig. 8. Unconstrained motion of master/slave teleoperation system with the proposed reference energy following scheme with the PC.

the reference energy behavior $\left(\sum f_e v_e\right)$ with significantly small PC force (Fig. 8d). As a result, it is not required to discriminate constrained and unconstrained motion anymore. The reason why the reference energy was growing to positive value is because the attached tool-tip on the F/T sensor of the slave acted like a load.

VI. Conclusions

In this paper, several conservatisms in previous two-port time-domain passivity approach were introduced. Nonnecessary PC operation was found when a teleoperation system was making a contact with deformable environments. And, it was required to discriminate constrained and unconstrained motion for making the slave move in unconstrained space. For solving these conservatisms, reference energy following idea, introduced in [24], is applied. As a result, unnecessary PC operation was significantly reduced, and it was not required to discriminate constrained and unconstrained motion anymore. The modified approach makes the time-domain passivity approach more practically useful.

However, there is sill an issue on the internal states as we have discussed in Section V. This is required to be investigated as our future works.

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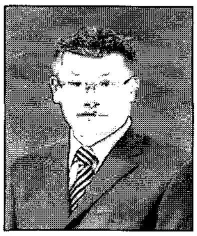

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