Time Domain Passivity Approach for Soft and Deformable Environments

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Abstract: Recently proposed stable teleoperation control scheme, base on time domain passivity, is modified to remove several conservatisms. During unconstrained motion and contacting with soft and deformable environments, the two-port time domain passivity approach [21] was excessively dissipating energy even though it was stable without any energy dissipation. The main reason of this conservatism is on the fact that the time domain passivity controller does not include the external energy dissipation elements at the slave manipulator. The measured interaction force between slave and environment allow the time domain passivity observer to include the amount of energy dissipation of the slave manipulator to the monitored energy. With the modified passivity observer, reference energy following idea [24] is applied to satisfy the passivity condition. The feasibility of the developed methods is proved with experiments. Improved performance is obtained in unconstrained motion and contacting with a soft environment.

Keywords: Teleoperation, bilateral control, time-domain passivity control.

1. 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 Neimeyer 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 2-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 unconstrained motion and contacting with soft and deformable environments since we have not considered the external energy dissipation elements.

In this paper, a method for removing these conservatisms is propsed by applying the newly proposed reference energy

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following scheme [24].

2. Review of the Time Domain Passivity Control

2.1. One-port Network

In this section, we briefly review time-domain passivity control. 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 $E(0)$ is *passive* if and only if,

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

for forces (f) and velocities ($\dot{x}$). Eqn. (1) states that the energy supplied to a passive network must be greater than negative $E(0)$ for all time [28], [29].

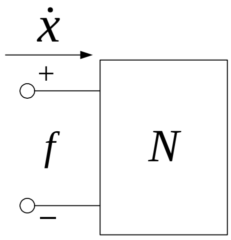

Fig. 1. 1-port network

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).

$$E_{obsv}(k) = \Delta T \sum_{j=0}^{k} f(t_j)v(t_j) + E(t_0) \qquad (2)$$

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],

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].

2.2. Two-port Network

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

$$E_{obsv}(k) = \Delta T \sum_{j=0}^{k} (f_1(t_j)v_1(t_j) + f_2(t_j)v_2(t_j)) + E(t_0). \quad (3)$$

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.

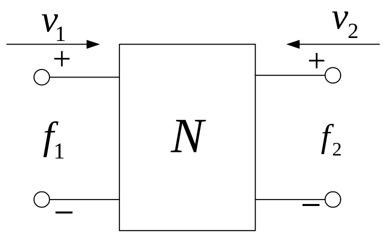

Fig. 2. 2-port network

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 2-port network becomes active. Fig. 3 shows the teleoperation system with the PC. Please see [7], [20], [21–24] for more detail about time-domain passivity control approach.

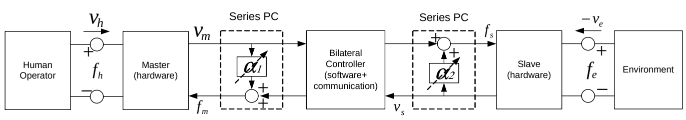

Fig. 3. Configuration of the series PC for the teleoperation system. Two-port approach.

3. Conservatisms of Previous Two-port Approach

Even though the proposed two-port approach has succeeded in implementing the idea to a real master/slave teleoperation system and obtined satisfiable results, we found several conservatisms which need to be removed for increasing the transparency during unconstrined motion and contacting with soft and deformable environments.

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 soft environment, soft sponge wall 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.

3.1. Unconstrained Motion

When operator maneuvers the master while the slave is in unconstrined space, there is no reason the teleoperation system become unstable unless the position controller of the slave is designed unstable. Fig. 4 shows the experimental result of the unconstrained motion of the teleoperation system. The slave well followed the position command from the master, and both positions remained stable. However, the PO value was kept falling down to more negative value, which means the bilateral controller was producing energy.

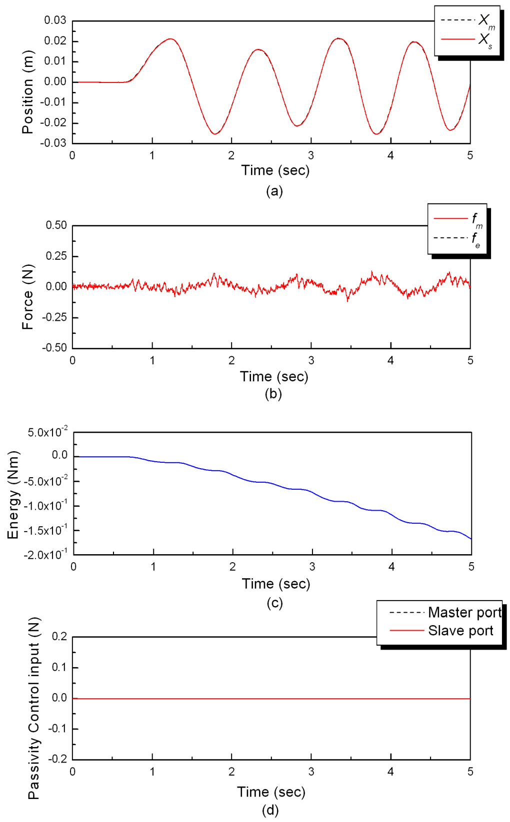

Fig. 4. Experimental result: unconstrained motion of the master and slave teleoperation system without the PC. The PO value was kept falling down to more negative value even though the response was stable.

In this case, the main source of the produced energy is the position controller of the slave. Certain amount of active energy was generated to make the slave manipulator follows the position command from the master while there was no energy input from the master. The teleoperation system remained stable since this produced energy was fully dissipated or restored at the slave mechanism, such as, damping, friction and inertia of the slave manipulator. Therefore, if the PC is activated based on this negative PO value, the slave can not follows the master position command anymore since the PC will 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 is required to differentiate constrained and unconstrained motion to make the integration of the PO value on and off for removing the nonnecessary PC activation. In our previous paper [21], user defined force threshold of a force sensor at the end of slave manipulator was used to differentiate the constrined and unconstrained motion. However, this method is huristic and depends too much on system parameters.

3.2. Contact with Soft and Deformable Environments

In [20], a problem of the two-port PO/PC approach during soft contact has been already mentioned. Even though the predefined force threshold of the measured force signal can discriminate the constrained and unconstrained motion and make the PO integration only effective during the constrained motion, there still some amount of consevatism is remained .

When the operator made a contact with a soft sponge with high velocity (Fig. 5) without the PC, contact was stable even though the PO crossed to negative values (Fig. 5c). This was because the passivity of the teleoperator is a sufficient condition for stability, and the mechanical parts of the master/slave manipulators were excluded for designing the PO/PC, as mentioned in [20, 21]. When the bilateral controller is active, the generated energy flows into the human/master and the environment/slave through the both port. If these external energy dissipation elements (the human/master and the environment/slave) are capable of dissipating the active amount of energy, the overall teleoperation system can remain passive without activating the PC. Thus, if we activate the PC in the above cases, the PC may give a certain amount of conservatism with excessive energy dissipation.

Fig. 6 shows the case when the PC was activated for the same experiment as in Fig. 5. Both PCs of master and slave port were activated (Fig. 6d) to make the PO value passive (Fig. 6c), and the transmitted force to the master was radically modified (Fig. 6b). As a result, operator felt distorted impedance of environment even though the response was stable without the PC.

4. Reference Energy Following Scheme

One of the dominant reason of those conservatisms during unconstrained motion and soft contct were from the fact that the dissipation of the slave manipulator has not been considered, that is, the force only to move the slave manipulator should be excluded for the PO calculation. Some part of produced energy from the slave port of the bilateral controller is used for moving the slave manipulator. If there is no position displacement during the contact (ex., hard contact),

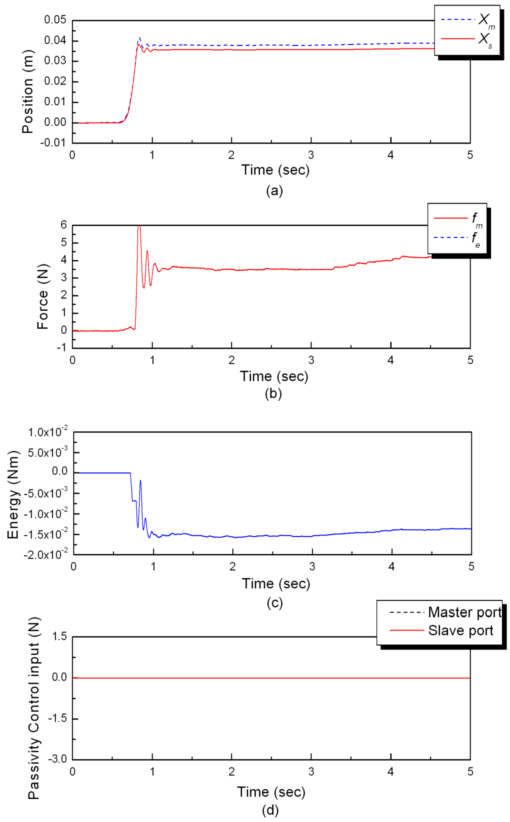

Fig. 5. Experimental result: Operator maneuvered the master to make the slave contact with a soft sponge without the PC. The PO value crossed to negative values even though the contact response was stable.

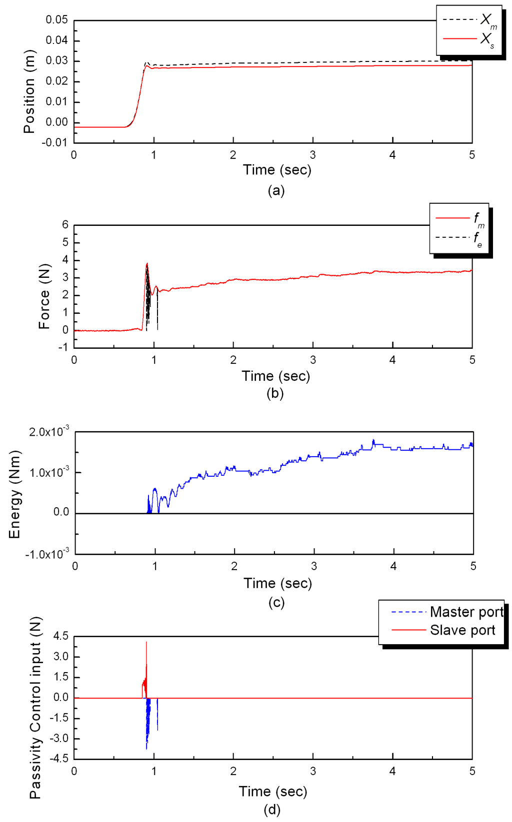

Fig. 6. Experimental result: Operator maneuvered the master to make the slave contact with a soft sponge with the PC. Excessive energy dissipation of the PC distorted the transmitted force to the operator

the energy dissipation at the slave manipulator is ignorable. However, when there is some position displacement (ex., soft contact), it is required to consider the energy dissipation at the slave manipulator.

By using the measured interaction force (f_e) between the slave and environment, we can include the amount of energy dissipation of the slave into the PO integration.

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

The first half of the right side of (4) is the dissipated energy of the bilateral controller, and the last half is dissipated energy of the slave manipulator.

However, it cause a question that how we could dissipate the produced energy through the slave/environment port, based on the two-port time domain passivity approach [21], since both signals (f_e, v_e) are hard to be modified in real-time. In this case, previously proposed reference energy following idea [24] can be applied. The energy behavior at the port between slave/environment can be a reference energy since this energy behavior is actually what we want to transmit to human operator. Following is the time varying reference energy constraint,

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

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

4.1. Unconstrained Motion

Based on the above studies, the modified PO and PC is implemented in the same teleoperation system as in Fig. 4. The operator maneuvers 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. 7). Fig. 7c shows that the energy behavior at the master port ($\sum f_m v_m$) was following the reference energy behavior ($\sum f_e v_e$) with significantly small PC force (Fig. 7d). The conservatism in unconstrained motion was radically removed with the proposed approach. The reason why the reference energy was growing to positive value is becasue the attached tool-tip on the F/T sensor of the slave acted like a load.

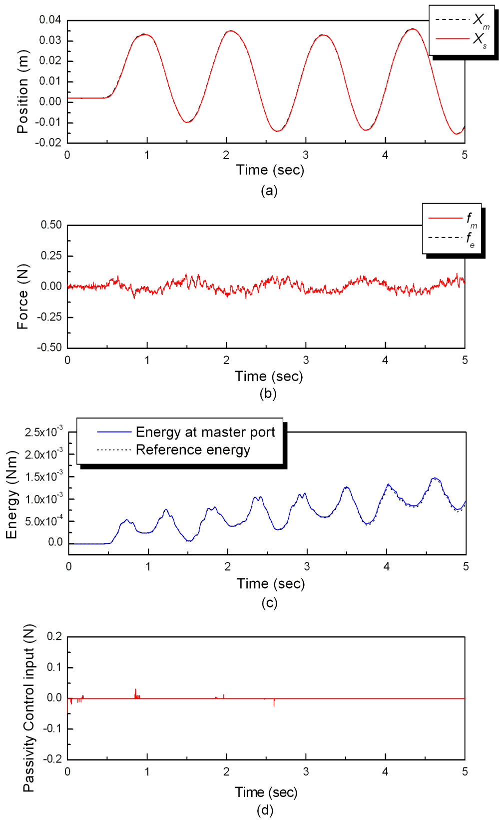

Fig. 7. Experimental result: unconstrained motion of master/slave teleoperation system with the proposed reference energy following scheme with the PC.

4.2. Contact with Soft and Deformable Environments

In the same experimental condition as in Fig. 6, soft contact had been done with the proposed PC. Contact was stable (Fig. 8), and the energy behavior at the master port was well following and even greater than the reference energy behavior with the significantly small PC force modification at the master port (Fig. 8cd).

5. Conclusions

In this paper, reference energy following idea, introduced in [24], is applied to the previous two-port time domain passivity teleoperation control scheme. The proposed approach improves the performance of the teleoperation by removing several conservatisms significantly. During unconstrained motion and contacting with soft environments, the unnecessary PC operation is radically reduced while guaranteeing the passivity. The modified approach makes the time domain passivity control scheme more practically useful.

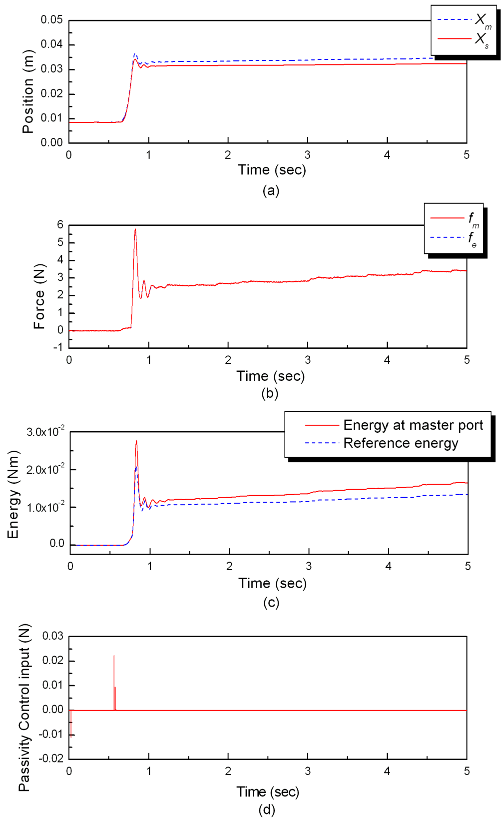

Fig. 8. Experimental result: Operator maneuvered the master to make the slave contact with a soft sponge with the proposed reference energy following scheme with the PC. Force distortion was significantly removed, compared to Fig. 6

References

[1] R. J. Adams and B. Hannaford, "Stable Haptic Interaction with Virtual Environments," *IEEE Trans. on Robotics and Automation*, vol. 15, no. 3, pp. 465-474, 1999.

[2] R. J. Anderson, "Autonomous, Teleoperated, and Shared Control of Robot Systems," *IEEE Int. Conf. on Robotics and Automation*, Minneapolis, MN, 1996, pp. 2025-2032.

[3] R. J. Anderson and M. W. Spong, "Asymptotic Stability for Force Reflecting Teleoperators with Time Delay," *Int. Journal of Robotics Research*, vol. 11, no. 2, pp. 135-149, 1992.

[4] J. E. Colgate, "Robust Impedance Shaping Telemanipulation," *IEEE Trans. Robotics and Automation,* vol. 9, no. 4, pp. 374-384, 1993.

[5] J. E. Colgate, and G. Schenkel, "Passivity of a Class of Sampled Data Systems: Application to Haptic Interfaces," *American Control Conference, Baltimore*, MD, 1994, pp. 3236-3240.

[6] B. Hannaford, "Design Framework for Teleoperators with Kinesthetic Feedback," *IEEE Trans. Robotics and Automation,* vol. 5, no. 4, pp. 426-434, 1989.

[7] B. Hannaford, and J. H. Ryu, "Time Domain Passivity Control of Haptic Interfaces," *IEEE Trans. on Robotics and Automation*, vol. 18, no. 1, pp. 1-10, 2002.

[8] K. Hashtrudi-Zaad and S. E. Salcudean, "Adaptive Transparent Impedance Reflecting Teleoperation," *IEEE Int. Conf. Robotics and Automation,* 1996, pp. 1369-1374.

[9] K. Hashtrudi-Zaad and S. E. Salcudean, "On the use of Local Force Feedback for Teleoperation," *IEEE Int. Conf. Robotics and Automation,* pp. 1863-1869, 1999.

[10] K. Hashtrudi-Zaad and S. E. Salcudean, "Analysis of Control Architectures for Teleoperation Systems with Impedance/Admittance Master and Slave Manipulators," *Int. Journal of Robotics Research,* vol. 20, no. 6, pp. 419-445, 2001.

[11] H. Kazerooni and C. L. Moore, "An Approach to Telerobotic Manipulations," *ASME Journal of Dynamic Systems, Measurement, and Control,* vol. 119, pp. 431-438, 1997.

[12] D. A. Lawrence, "Stability and transparency in bilateral teleoperation," *IEEE Trans. Robotics and Automation,* vol. 9, no. 5, pp. 624-637, 1993.

[13] D. Lee and P. Li, "Passive Coordination Control for Nonlinear Bilateral Teleoperated Manipulators," *IEEE Int. Conf. Robotics and Automation,* pp. 3278-3283, 2002.

[14] D. Lee and P. Li, "Passive Feedforward Approach to the Control of Bilateral Teleoperated Manipulators," *ASME Haptics Symposium at IMECE* 2000.

[15] H. Lee and M. J. Chung, "Adaptive Controller of a Master-Slave System for Transparent Teleoperation," *Journal of Robotic Systems,* vol. 15, no. 8, pp. 465-475, 1998.

[16] G. M. H. Leung, B. A. Francis, and J. Apkarian, "Bilateral Controller for Teleoperators with Time delay via Mu-Synthesis," *IEEE Trans. Robotics and Automation,* vol. 11, no. 1, pp. 105-116, 1995.

[17] R. Lozano, N. Chopra, and M. W.Spong, "Passivation of Force Reflecting Bilateral Teleoperators with Time Varying Delay," *Mechatronics'02,* Entschede, Netherlands, June pp. 24-26, 2002.

[18] G. Niemeyer and J. J. Slotine, "Stable Adaptive Teleoperation," *IEEE Journal of Oceanic Engineering*, vol. 16, pp. 152-162, 1991.

[19] J. H. Ryu and D. S. Kwon, "A Novel Adaptive Bilateral Control Scheme using Similar Closed-loop Dynamic Characteristics of Master/Slave Manipulators," *Journal of Robotic Systems,* vol. 18, no. 9, pp. 533-543, 2001.

[20] J. H. Ryu, D. S. Kwon and B. Hannaford, "Stable Teleoperation with Time Domain Passivity Control," *IEEE Int. Conf. Robot. Automat*, Washington DC, USA, pp. 3260-3265, 2002.

[21] J. H. Ryu, D. S. Kwon and B. Hannaford, "Stable Teleoperation with Time Domain Passivity Control," *IEEE Trans. on Robotics and Automation*, vol. 20, no. 2, pp. 365-373, 2004.

[22] J. H. Ryu, Y. S. Kim, and B. Hannaford, "Sampled and Continuous Time Passivity and Stability of Virtual Environments," *IEEE Trans. on Robotics*, vol. 20, no. 4, pp. 772-776, 2004.

[23] J. H. Ryu, D. S. Kwon and B. Hannaford, "Stability Guaranteed Control: Time Domain Passivity Approach," *IEEE Trans. on Control Systems Technology,* Vol. 12, No. 6, pp. 860-868, 2004.

[24] J. H. Ryu, B. Hannaford, C. Preusche, and G. Hirzinger "Time Domain Passivity Control with Reference Energy Behavior," *Poc. IEEE/RSJ Int. Conf. on Intelligent Robotics and Systems*, Las Vegas, USA, 2003, pp. 2932-2937.

[25] S. E. Salcudean, "Control for Teleoperation and Haptic Interfaces", *Control Problems in Robotics and Automation,* B. Siciliano and K.P. Valavanis (Eds), Springer-Verlag Lecture Notes in Control and Information Sciences, vol. 230, pp. 50-66, 1997.

[26] S. E. Salcudean, K. Hashtrudi-Zaad, S. Tafazoli, S. P. DiMaio, and C. Reboulet, "Bilateral Matched-Impedance Teleoperation with Application to Excavator Control," *IEEE Control Systems Magazine,* vol. 19, no. 6, pp. 29-37, 1999.

[27] S. Stramigioli, C. Secchi and A. J. van der Schaft, "A Novel Theory for Sampled Data System Passivity," *IEEE/RSJ Int. Conf. on Intelligent Robotics and Systems*, Switzerland, 2002, pp. 1936-1941.

[28] A.J. van der Schaft, "L2-Gain and Passivity Techniques in Nonlinear Control," Springer, Communications and Control Engineering Series, 2000.

[29] J. C. Willems, "Dissipative Dynamical Systems, Part I: General Theory," *Arch. Rat. Mech. An.*, vol. 45, pp. 321-351, 1972.

[30] J. Yan and S. E. Salcudean, "Teleoperation Controller Design using H_{inf}-optimization with Application to Motion-scaling," *IEEE Trans. Control Systems Technology,* vol. 4, no. 3, pp. 244-258, 1996.

[31] Y. Yokokohji and T. Yoshikawa, "Bilateral Control of Master-slave Manipulators for Ideal Kinesthetic Coupling-Formulation and Experiment," *IEEE Trans. Robotics and Automation,* vol. 10, no. 5, pp. 605-620, 1994.

[32] Y. Yokokohji, T. Imaida and T. Yoshikawa, "Bilateral Control with Energy Balance Monitoring Under Time-Varying Communication Delay," *IEEE Int. Conf. Robotics and Automation,* San Francisco, CA, 2000, pp. 2684-2689.

[33] W. Zhu and S. E. Salcudean, "Stability Guaranteed Teleoperation: An Adaptive Motion/Force Control Approach," *IEEE Trans. Automatic Control,* vol. 45, no. 11, pp. 1951-1969, 2000.