Testing Time Domain Passivity Control of Haptic Enabled Systems

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Abstract

Much recent work has studied the means of achieving stable yet high performance control of haptic interfaces. Such interfaces provide compelling force feedback in virtual reality simulations for medical training, advanced computer aided design (CAD), entertainment, and other applications. This paper reports experimental testing of a new method of stable haptic interface control, the Passivity Observer (PO) and Passivity Controller (PC). Experimental results from three different laboratories confirm basic operation of the PO/PC. The PO/PC method is applied to high stiffness haptic interaction, to a 2-degree-of-freedom (DOF) system with coupled kinematics and dynamics, and to a bi-lateral telemanipulation system controlling metal-to-metal contact. (An abridged version of this report will be published in Proceedings of the International Symposium on Experimental Robotics 2002 (ISER-02), *Experimental Robotics 2002*, B. Siciliano and P. Dario eds. *Series in Advanced Robotics*, Springer Verlag.)

1 Introduction

One of the most important issues in haptic interface design is to achieve stable interaction between the haptic display and the virtual environment for any operating conditions and for any virtual environment parameters. Vibration or divergent behavior caused by the instabilities is very distracting, can damage the hardware, and in large systems, may even pose a physical threat to the human operator. The facts that virtual environments of interest are always non-linear and dynamic properties of a human operator are always involved, can make it especially difficult to analyze haptic systems in terms of known parameters and linear control theories. Colgate et. al. [1] and Zilles and Salisbury [2] introduced the "virtual coupling" between haptic display and virtual environment, which is a practical way to increase the stability of a haptic interface independent of human grasp impedance and of the details of virtual environment design. One fruitful avenue to ensure stable operation is to use the idea of passivity[3, 4, 5, 6, 7, 8, 9].

Recently, Hannaford and Ryu [10, 11, 16] proposed an energy based method, whose components are termed the "Passivity Observer" (PO) and "Passivity Controller" (PC). The PO measures the total amount of energy dissipated in the haptic interface system and identifies time samples in which this energy becomes negative (indicating active behavior). The PC adds a calculated amount of damping to constrain $PO \geq 0$. This paper explores some implementation issues in the PO/PC method. In particular, we will explain and experimentally test features added to the method to: 1) take care of the case where excessive build-up of energy in the PO might prevent or delay the PC from promptly operating to stabilize the system, 2) explore the applicability to a planar robot with coupled degrees of freedom, and 3) test the method in a master-slave teleoperation system with bi-lateral kinesthetic coupling.

2 Time Domain Passivity Control

In this section we review our passivity observer and controller. For more details, and the stability proof, see [10, 11]. Force and velocity are the key variables which define the nature of haptic contact. 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). We also assume that the system has initial stored energy at $t = 0$ of $E(0)$. We then use the following widely known definition of passivity.

Definition 1*: The M-port network, N_M, with initial energy storage $E(0)$ is passive if and only if,*

$$\int_0^t \left(f_1(\tau)\,v_1(\tau) + \cdots + f_M(\tau)\,v_M(\tau)\right) d\tau + E(0) \geq 0, \forall t \geq 0 \tag{1}$$

for all admissible forces $(f_1, \cdots, f_M)$ and velocities $(v_1, \cdots, v_M)$. Equation (1) states that the energy applied to a passive network must exceed $-E(0)$ for all time[5],[13].

2.1 Passivity Observer

The conjugate variables which define power flow in such a computer system are discrete-time values. Thus, we can easily "instrument" one or more blocks in the system with the following "Passivity Observer," (PO)

$$E_{obsv}(n) = \left(\sum_{k=1}^{n} \left[f_1(k)v_1(k) + \cdots + f_M(k)v_M(k)\right]\right) \times \triangle T \tag{2}$$

where, $\triangle T$ is the sampling time.

If $E_{obsv}(n) \geq 0$ for every n, this means the system dissipates energy. If there is an instance that $E_{obsv}(n) < 0$, this means the system generates energy and the amount of generated energy is $-E_{obsv}(n)$.

2.2 Passivity Controller

Consider a one-port system which may be active. Depending on operating conditions and the specifics of the one-port element's dynamics, the Passivity Observer 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 will call this element a "Passivity Controller" (PC). The Passivity Controller takes the form of a virtual dissipative element controlled in real time. The exact form of the PC depends on the causality (impedance or admittance) of the system[10, 11]. In this paper we concentrate exclusively on the impedance case since that type of system was used in our experiments. The PC obeys the constitutive equation

$$f = \alpha(n)v \tag{3}$$

And its force is combined with that of the VE (Fig 2a):

$$f_1 = f_2 + \alpha v \tag{4}$$

We compute $\alpha(n)$ in real time as follows:

1. $v_1(n) = v_2(n)$
2. $f_2(n) = F_{VE}(v_2(n))$
   where $F_{VE}()$ is the output of the virtual environment.
3. $E_{obsv}(n) = E_{obsv}(n-1) + \left(v_2(n)f_2(n) + \alpha(n-1)v_2(n-1)^2\right) \times \triangle T$
4. $$\alpha(n) = \begin{cases} \frac{-E_{obsv}(n)}{\triangle T \times v_2(n)^2} & \text{if } E_{obsv}(n) < 0 \\ 0 & E_{obsv}(n) \geq 0 \end{cases} \tag{5}$$
5. $f_1(n) = f_2(n) + \alpha(n)v_2(n) \rightarrow$ output.

Note that $\triangle T$ can be canceled from above equations 5-3) and 5-4) for brevity and to reduce computation. Thus, we can also express the PO as:

$$W(n) = \sum_{k=1}^{n} f_2(k)v_2(k) + \sum_{k=1}^{n-1} \alpha(k)v_2(k)^2 \tag{6}$$

where, $W(n) = 1/\triangle T \times E_{obsv}(n)$.

3 Basic PO/PC operation

The PO/PC was tested experimentally on our "Excalibur," 3-axis, high force output, haptic interface system in the laboratory [12, 10] (Fig 3(a)). This system consists of the following elements (Fig 4) : human operator (HO), Haptic Interface (HI), haptic controller (HC) having feed forward gravity compensation and friction compensation, the passivity controller (PC), and the virtual environment (VE). The system is entirely synchronous at $1000Hz$. The HI senses position in $0.008mm$ increments, and can display $200N$ force inside a 300x300x200mm workspace. The virtual environment consists of virtual $LEGO^{TM}$ blocks (Fig 3(b)). In the experiments, the PO accounted for energy flow in the HC, PC, and VE. The virtual object parameter had very high stiffness ($k = 90kN/m$). The operator approached the object at about $200mm/s$.

3.1 Unstable operation and behavior of PO

In the first experiment, without the PC, the contact was unstable, resulting in an oscillation observable as force pulses (Fig 6b) ; the passivity observer (Fig 6c) was initially positive, but grew to more and more negative values with each contact. Note that the initial two bounces were passive, but after the third bounce the system gets active.

3.2 Stabilization of contact via PC

In the second experiment, with the PC turned on, the operator approached the virtual object at the same velocity (Figure 7a), but a stable contact was achieved with about 13 bounces (Fig 7b). Again the first bounce can be seen to behave passively, but the subsequent bounces were active (Figure 7c). After eight bounces, the PC began to operate (Figure 7d), and eliminated the oscillation.

4 Implementation Issues

4.1 "Resetting"

A virtual environment typically contains different properties in different regions of space. One issue which can be significant for the PO/PC is that one portion of the VE may be passive while another is active. If the user interacts for a long time with the passive portion, the PO acquires a "build-up" of dissipated energy. If the user now moves and interacts with the active region, the PC will not work until total active behavior equals the accumulated energy value in the PO. A second case occurs locally, when non-linear behavior of the environment can cause dissipative behavior closely followed by active behavior (Figures 6 & 7). In both cases, if the energy accumulated in the PO can be reset to zero properly, then faster stable contact can be achieved with smaller bounces. With this motivation, we want to derive a heuristic rule, called "resetting" throughout this paper, and based on the detection of free motion state.

The rule is as follows. *If* $|f| < \varepsilon$ *for* τ *sec, then Reset the* ***PO*** *to zero.* where we call ε the force threshold, and τ the duration. The idea is that this rule can detect free motion and that problems of active behavior do not persist from one contact state to the next. Thus it might be appropriate to reset the PO in between contacts with virtual surfaces. We experimented with the force threshold ε and duration τ to get values for correct detection of the free motion regime. A wide variety of values were studied and explored in the experiment. We expressed the force threshold as a fraction of the maximum force output of the device and the duration as multiples of the sampling time, $T = 0.001$sec. In free motion, f is exactly zero without any noise because it is computed by the virtual environment.

4.2 Coupled Degrees of Freedom

Most of the initial development of the PO/PC has taken place in a single degree of freedom, or on devices with decoupled degrees of freedom. Theoretically there should be no difference in passivity of a system introduced by the transformation of force and velocity between Cartesian Space and joint space. Note that the textbook derivation of the Jacobian matrix using the principle of virtual work *assumes* that the incremental kinematics are passive.

To verify the ability of the PO/PC method to work with non-linear kinematics and coupling between degrees of freedom, the PO and PC were implemented in a 2 DOF version of a 5 DOF haptic arm master developed at Korea University (Fig. 9). To create this experimental system, 3 of the 5 DOF were immobilized. The controller sampling period was set to 1msec, and the resolution of angular displacement and velocity at the joints were 0.0024 radians and

τ \ ε	$10^{-7} \times F_{MAX}$	$10^{-3} \times F_{MAX}$	$10^{-1} \times F_{MAX}$
$1 \times T$	viscous feeling in free motion	...	too much resetting
$10 \times T$	...	good performance	...
$100 \times T$	viscous feeling in free motion	...	no resetting

Table 1: Results of varying the parameters, ε (the force threshold) and τ (the duration) of the Passivity Observer resetting rule $(T = 1msec, F_{MAX} = 200N)$.

0.00027 $\mathrm{rad/sec}$, respectively A virtual wall of 45 kN/m stiffness was placed parallel to and 300mm below the X-axis as shown in Fig 9(b). The manipulator was released from the initial position and came into contact with the virtual wall. Without the PO and PC, the responses showed oscillatory (and unstable) behavior, and the endpoint bounced about 10mm above the virtual wall after the first contact. Experiments with the PO/PC were performed in both joint space and Cartesian space. The relationship between the endpoint velocity $V = [V_x \quad V_y]^T$ and the joint velocity $\theta = [\theta_1 \quad \theta_2]^T$ is described by $J(\theta)$, where J is the Jacobian matrix.

4.3 Bi-lateral System

Figure 5 shows a network model of a teleoperation system which can be represented as a two-port network terminated by two one-ports, the human operator and the environment. v_m and v_s denote the velocity of the master and slave manipulator, respectively. f_h represents the force that the operator applies to the master manipulator, and f_e denotes the force that the slave manipulator applies to the environment. Details of the two-port PO/PC implementation can be found in [16]. The PO computation is easily derived from 2. Although the PC may be placed at either port, it is advantageous to put one at each of the two ports[16]. When the two-port is active, (i.e. equation 2 < 0) three cases must be considered:

1. Energy flows *out* the human operator (master) port.
2. Energy flows out the slave port.
3. Energy flows out both ports.

Our method places the dissipation at the port where energy is produced during active behavior and allocates the dissipation energy between the two ports for case three.

5 Experimental results

5.1 Resetting

We added resetting to the experimental system as described in section 4.1. The results obtained (Table 1) are summarized as follows:

- When $10^{-7} \times F_{MAX}$ was chosen for the force threshold and τ was $1 \times T$ or $100 \times T$, we found a very sluggish feeling in free motion : the resetting was continuous and the PC was operating all the time.
- When a big value ($10^{-1} \times F_{MAX}$) was chosen as the force threshold with $\tau = 100 \times T$, we found no resetting even during the contact. The PC could not operate and instability was not prevented until the PO was dissipated.
- When the duration equals the sampling time ($1 \times Tsec$), there was too much resetting. In the case of $\varepsilon = 10^{-1} \times F_{MAX}$ with such a short duration, resetting was done when even a single noisy signal is less than the force threshold, and the PC operates too much. Faster stable contact was not achieved.
- Finally, we determined $\varepsilon = 0.2N, (10^{-3} \times F_{MAX})$ and $\tau = 0.01sec, (10 \times T)$ were best values.

With the PC and resetting turned on ($\varepsilon = 0.2N$ and $\tau = 0.01sec$), a stable contact was achieved with about 8 bounces (Fig 8b). Compared to 13 bounces with no resetting (Fig 7), the contact transient was shorter because the PC operated about $200msec$ sooner after the initial contact. Resetting helped the PC to operate immediately as soon as the system becomes active without changing the stability, just as proposed.

5.2 Coupled Degrees of Freedom

We now consider experimentation at Korea University on the 2-DOF system with coupled kinematics and dynamics described in section 4.2. Basic operation of the PO/PC was assessed with virtual wall contact experiments in which the manipulator was allowed to fall under the influence of earth gravity until it made virtual contact. Note that the human operator released the device and was not in contact during the experiment — an extreme case for instability.

With the PC operating in Cartesian space, the phase plane response of the system rapidly reached the equilibrium point representing stable contact (Y = -300mm, 0m/s, Figure 10). Without the PC, the otherwise identical system encountered limit cycles (not shown here) around the equilibrium point. The response in the Y direction settled in the final position with only a little oscillation (i.e., a maximum bounce of 2mm), and the passivity level was maintained positive except for the instant just after the first contact. Only the response in the Y direction is shown in the figure, but the X-direction response showed a similar trend.

Figure 11 illustrates the 2-DOF system with the PO/PC activated in joint space. As in the case of the Cartesian space scheme, the responses of both joints provide satisfactory behavior in terms of stability. In the joint space scheme, the PO and PC were implemented for both joints separately in such a way that the PCs maintain positive passivity levels at both joints.

5.3 Bi-lateral System

In this section we describe experiments conducted at the Korean Advanced Institute of Science and Technology (KAIST), Taejon Korea, on the teleoperation system with force-feedback described in section 4.3. In these experiments, the PO and PC were added to a teleoperation system consisting of a two-DOF master and slave manipulator (Figure 12). A steel wall was placed parallel to the Y-Axis. A position/force control architecture was used for the bilateral controller. The control system was entirely synchronous at 1000 Hz. Each axis of the master and slave sensed position in increments of 1.7×10^{-4} rad. Resetting was not used.

In the first experiment, without the PC, the operator maneuvered the master to make the slave contact the hard wall at about 23.3 mm/s. Since the operator made contact at relatively low velocity and gradually increased the interaction force after contact (Figure 13), stable contact was achieved even though the wall was very stiff (at least 150 kN/m). Only X-direction signals are plotted since the main interaction occurs on the X-Axis. Note that the energy in Fig. 13c (and the following figures) means net supplied energy to the bilateral controller and the PC, and this energy equals the sum of the value of the PO and the dissipation amount of the PC,

$$E_{obsv}(n) + \alpha_1(n)v_m(n)^2 + \alpha_2(n)v_s(n)^2$$

When the operator maneuvered the master to contact at higher velocity of about 120 mm/s, contact was unstable. This resulted in an oscillation observable as force and position pulses (Figure 14); the value of the PO was initially positive, but became increasingly negative with each contact. As in our haptic interface experiments (Figures 6 & 7), the initial bounce was passive, but from the second bounce the system became active. In the next experiment, with the PC turned on, the operator approached the contact point at the same velocity (Figure 15), but stable contact was achieved with about 7 bounces. Again the first bounce behaved passively, but subsequent smaller bounces were active (Figure 15c). On the second bounce, the PC at the master port began to operate and eliminated the oscillation by briefly modifying the transmitted force to the operator. On the other hand, the PC at the slave port only operated on the second bounce.

Finally, we studied the behavior of the bi-lateral system during a low velocity experiment, in which the operator maneuvered the master to make the slave contact a diagonal hard wall at about 30 mm/s, and made sliding contact. Without the PC (not shown) the contact became unstable after t = 1.5 sec, resulting in an increasing oscillation observable as position and force pulses. The PO became increasingly negative with each contact. With the PC turned on, the operator maneuvered the teleoperator in the same way, but stable surface following was achieved (Figure 16). The small force bounces before t = 1.2 sec behaved passively, but the following small force bounces were active. After t = 1.7 sec, the PC at the master and slave port began to operate, and eliminated the oscillation by modifying the transmitted force to the operator. However, the PC output consisted of a noise-like signal during the surface following (after t = 1.7 sec). The noisy behavior of the PC coincides with a period of low velocity.

6 Conclusion

In this report, some practical issues relating to the performance of the PO/PC method were experimentally studied. First, a heuristic rule to reset stored energy in the PO based on the detection of a free motion state is derived, and experiments verified that this resetting helps the PC to operate quickly when the system gets active without changing the stability. Further experimentation demonstrated effects of parameters outside their optimum ranges. The heuristic resetting rule adds built-in assumptions to the stabilizing Passivity Controller. This heuristic rule may not be suitable for all virtual environments. Extensive experimental testing will be required to fully verify the method for a given application.

The system was also applied to a 2-DOF planar mechanism with coupled kinematics and dynamics. The PO/PC successfully stabilized contact with a virtual wall in both Cartesian and joint spaces. By generalizing the method to two energy ports, the PO/PC was applied to a bi-lateral teleoperation system, and successfully stabilized controlled static and sliding contact with a hard surface. The PO/PC system is a promising method to address many stability issues associated with force feedback systems. Experimental evaluation on a wide variety of hardware systems is giving us a better idea of its strengths and limitations.

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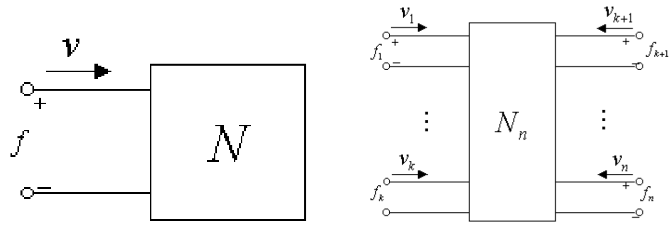
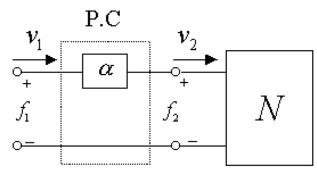


(a) (b)

Figure 1: One-port (a) and M-port networks (b)



(a)

Figure 2: Configuration of Passivity Controller for one-port networks with impedance causality.

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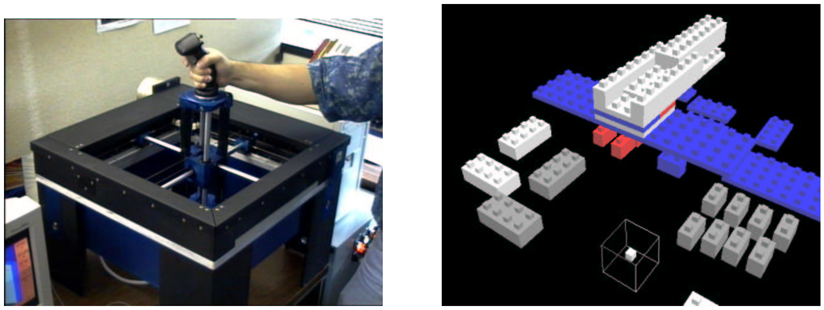


(a) (b)

Figure 3: "*Excalibur*", high force output haptic device (a) and virtual LEGO (TM) blocks (b)

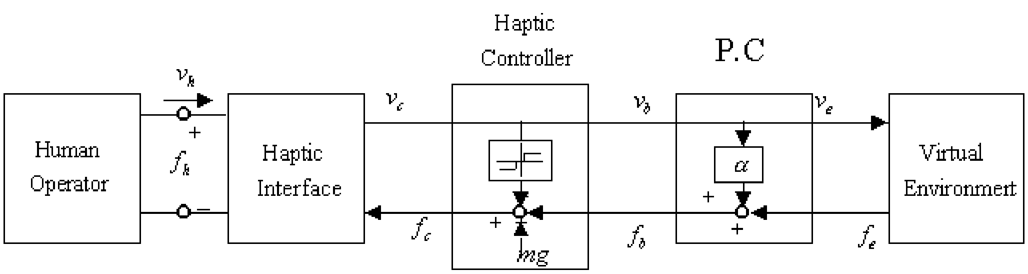


Figure 4: Network diagram of haptic interface system as implemented in the "*Excalibur*" 3-axis, high force output, device. System consists of human operator (HO), Haptic Interface (HI), haptic controller (HC) with feed forward gravity compensation and friction compensation, passivity controller (PC), and the virtual environment (VE).

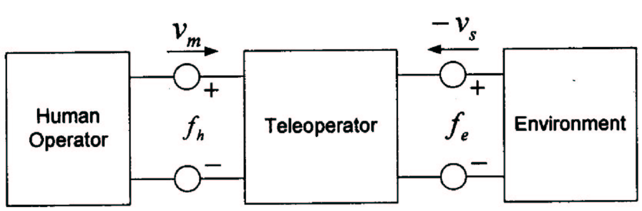


Figure 5: Network representation of bi-lateral teleoperator as two-port network. (00030.eps)

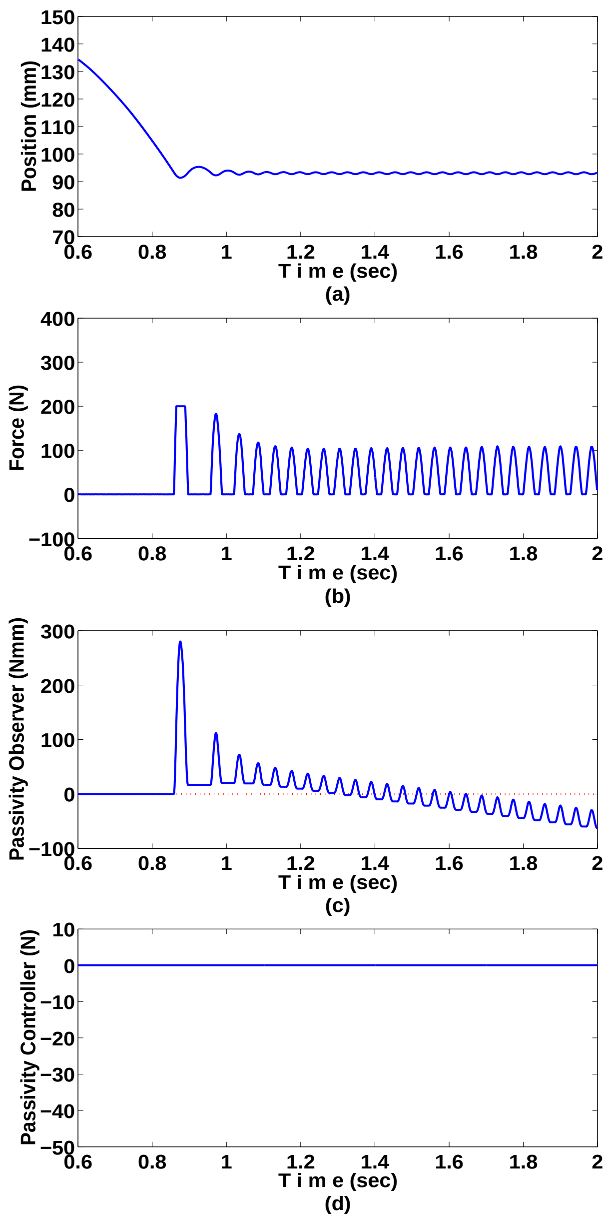


Figure 6: Unstable contact with high stiffness ($k = 90kN/m$) virtual wall without Passivity Controller (PC). During oscillation, the Passivity Observer (PO) grows more negative with each contact. ((a) position (b) force (c) PO energy (d) PC force)

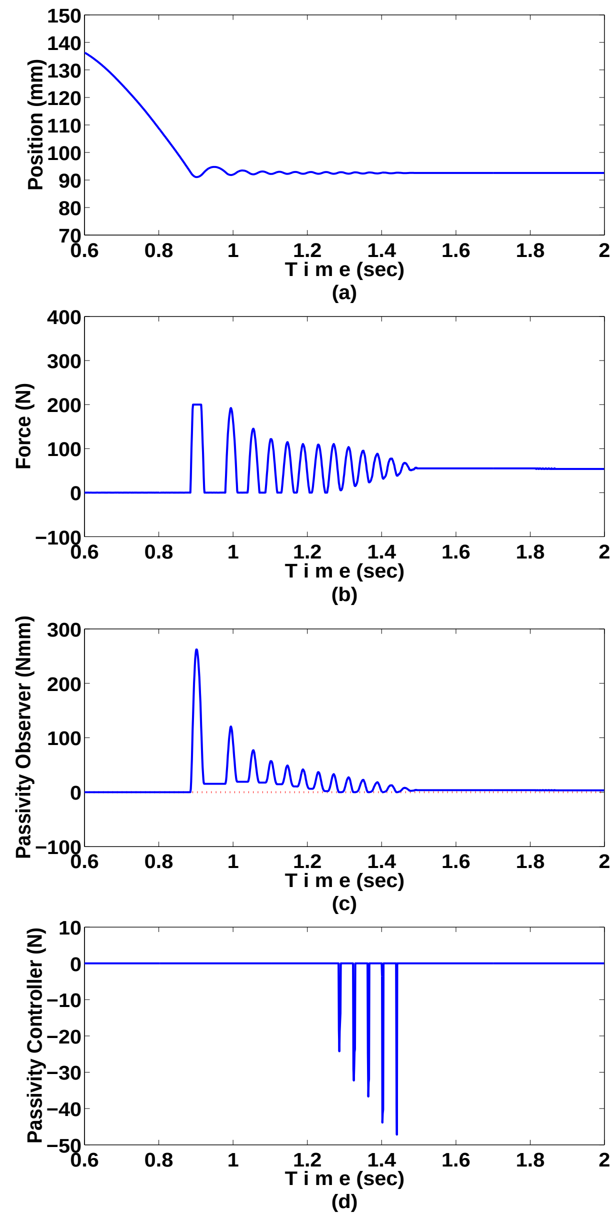


Figure 7: Virtual wall under same conditions as Figure 6 but with the PC turned on. The PC began to operate and eliminated the oscillation after eight bounces when all the energy accumulated in the PO was dissipated. Note that it was after the third bounce when the system became active. ((a) position (b) force (c) PO energy (d) PC force)

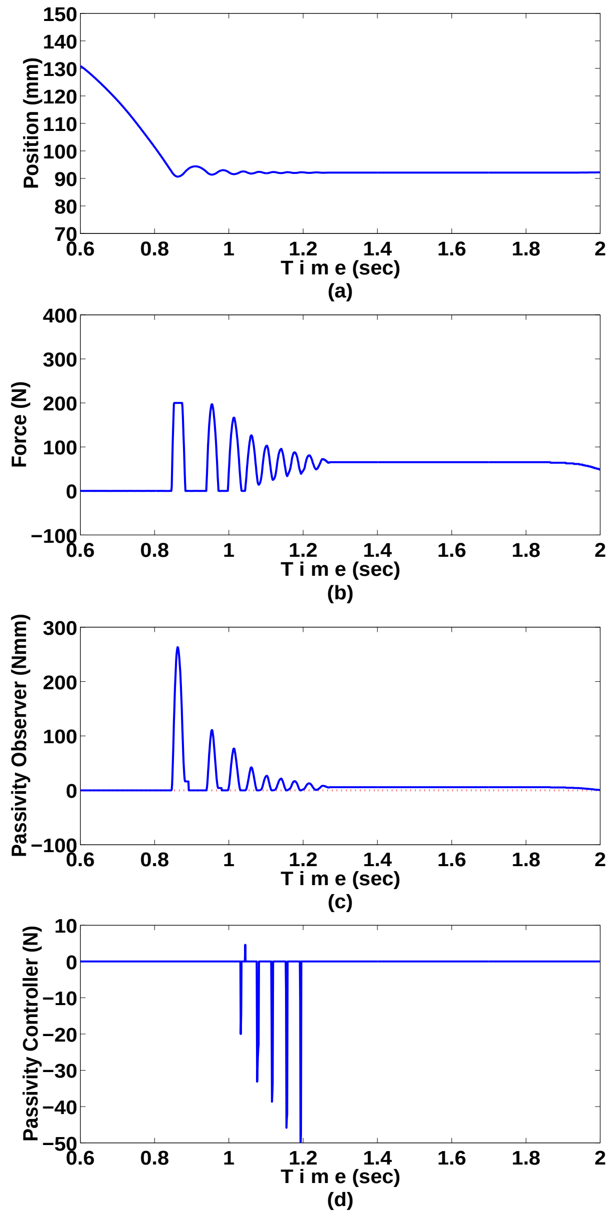


Figure 8: Virtual wall contact with resetting function added to basic PO/PC operation ($k = 90kN/m$). Resetting parameters: $\varepsilon = 0.2N$ and $\tau = 0.01sec$. Compared to the case without resetting (Fig 7), contact transient is shorter (8 vs 13 bounces) because PC operates about $200msec$ sooner after third bounce when the system becomes active. ((a) position (b) force (c) PO energy (d) PC force)

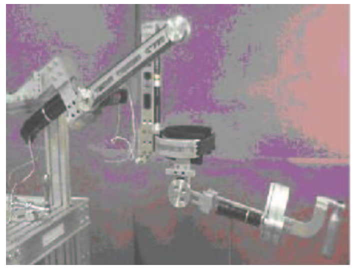


Figure 9: PO/PC control was evaluated with a 2-DOF version of the Haptic arm master manipulator developed at Korea University. The device was interfaced to a virtual wall of stiffness 45 kN/m

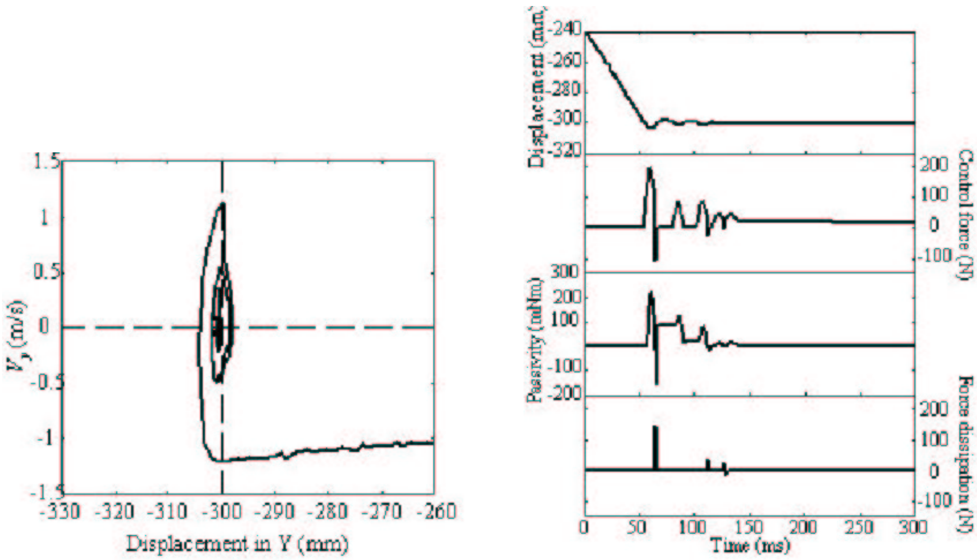


Figure 10: Contact with stiff virtual wall with PO/PC activated in Cartesian space (2 DOF experiment) (a) Phase portrait (b) Responses of Y axis

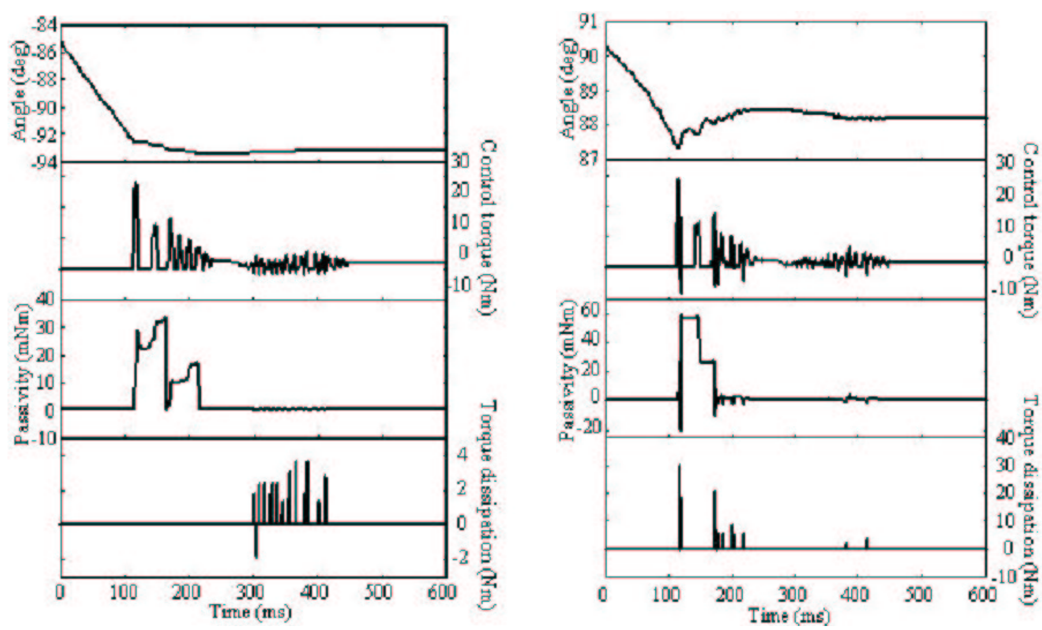
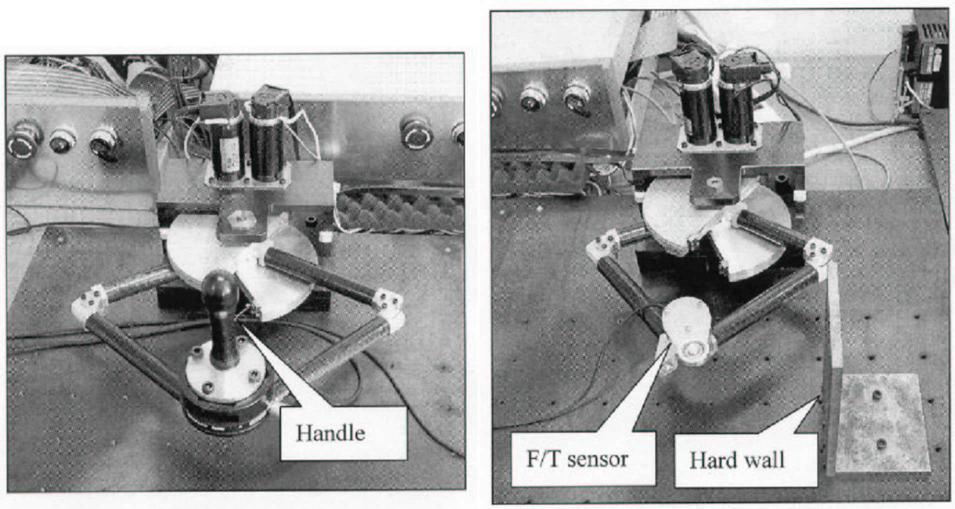


Figure 11: 2-DOF PO/PC control evaluated in joint space. (a) Responses of joint 1. (b) Responses of joint 2.



(a) Master manipulator (b) Slave manipulator

Figure 12: Experimental two DOF bi-lateral teleoperation system.

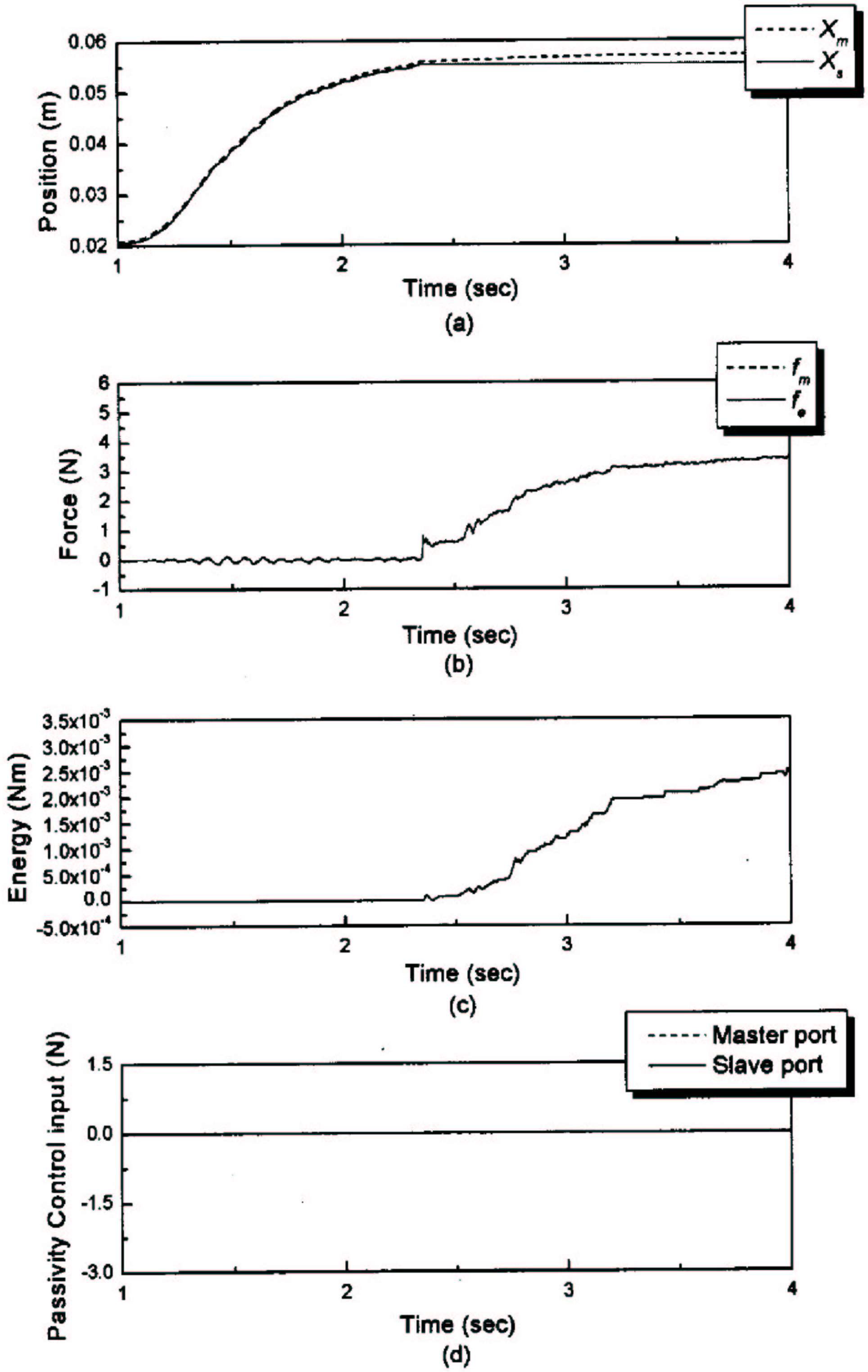


Figure 13: Hard contact made with the 2-DOF teleoperation system at low velocity was stable, even without the PO/PC.

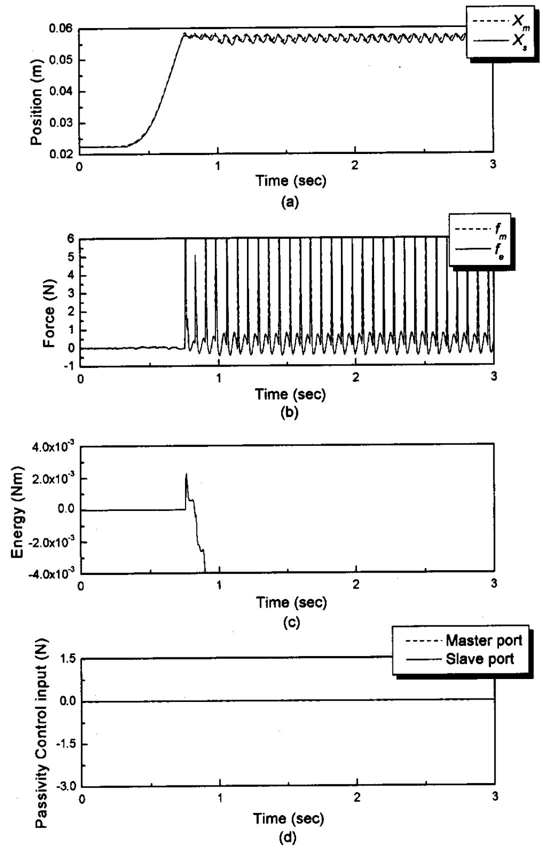


Figure 14: At higher velocity (relative to Figure 13) teleoperated contact was highly unstable.

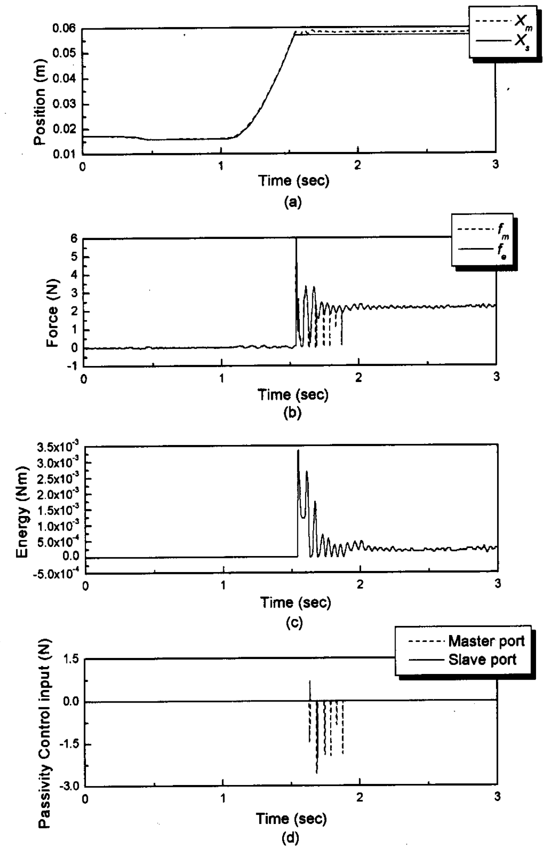


Figure 15: High velocity contact with the PO/PC enabled was stablized within about 3 bounces. Remaining transient contact forces are typical of stable metal-to-metal contact.

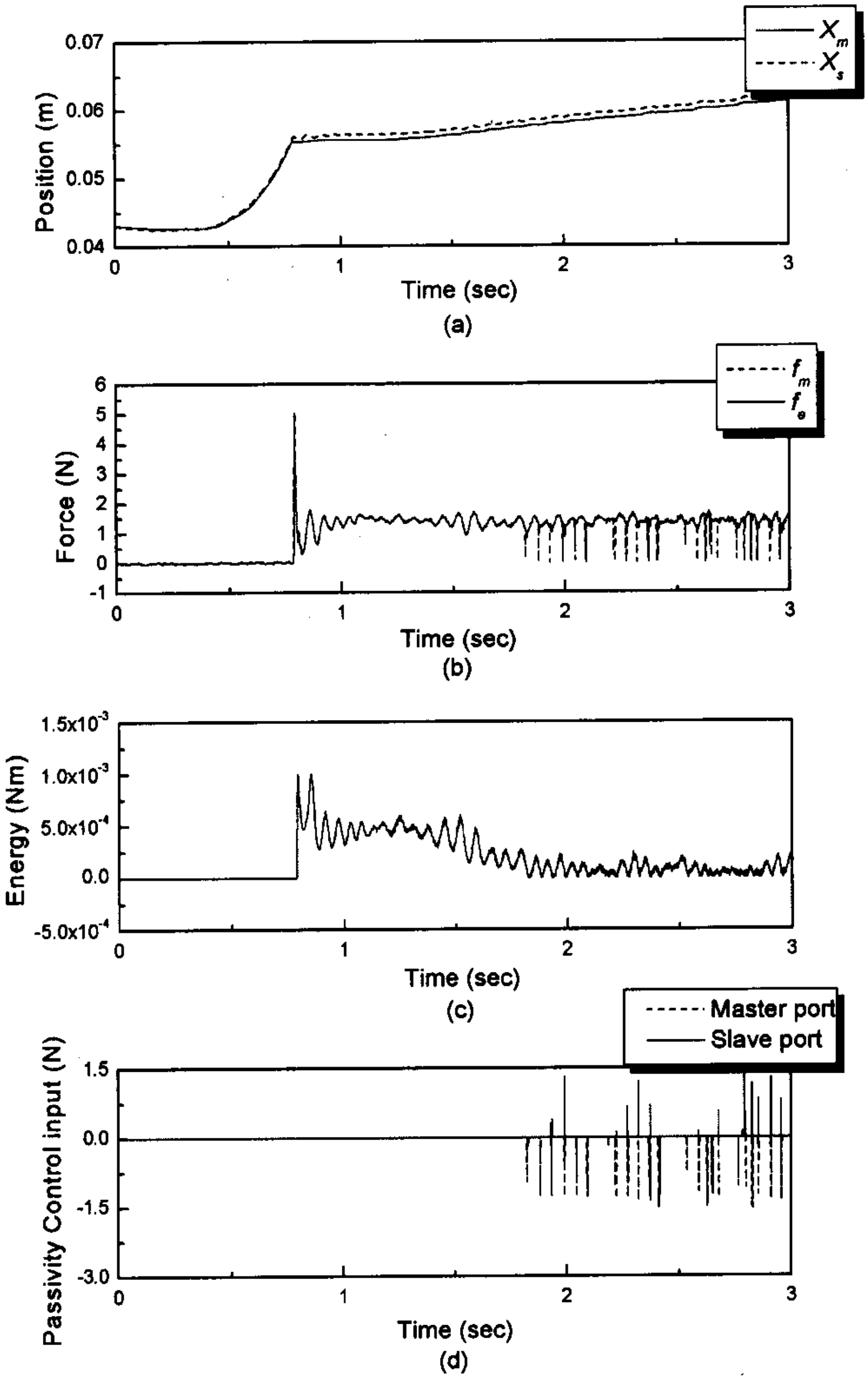


Figure 16: PO/PC enabled stable contact with slanted wall. Some PO/PC noise was observed (t= 1.8 – 3.0 seconds).