

A Heuristic Rule for the Performance Improvement in Time Domain Passivity Control of Haptic Interfaces

Yoon Sang Kim and Blake Hannaford

Abstract: A practical issue is studied to improve the performance of a new energy based method of achieving stable, high performance haptic interface control. The issue is related to resetting the amount of energy accumulated in the Passivity Observer for faster operation. A heuristic method is derived and experimentally tested for the resetting and it is shown to help the PC to operate sooner when the system gets active. Experimental results are presented for the "Excalibur" haptic device.

Keywords: haptic interface, passivity observer, passivity controller, heuristic rule

I. 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 can damage the hardware and 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 especially it difficult to analyze haptic systems in terms of known parameters and linear control theories. One fruitful avenue to ensure stable operation is to use the idea of passivity. Hogan [1] showed that the human operator is passive at frequencies of interest. Colgate et. al. [2] and Zilles and Salisbury [3] 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. Adams and Hannaford [4][5] derived a method of virtual coupling design from two-port network theory which was applied to all causality combinations and was less conservative than the passivity based design. Miller et. al.[6][7] has derived another design procedure which extends the analysis to non-linear environments and extracts a damping parameter to guarantee a stable operation. Even though the passivity idea has many attractive features in terms of creating the sufficient stability, the major problem in using passivity to design haptic interaction systems is that it is too conservative. Therefore, in many cases performance can be poor if a fixed damping value is used to guarantee passivity under all operating conditions. Hannaford and Ryu [8] proposed an energy based method, which is defined as the "Passivity Observer" (PO) and "Passivity Controller" (PC), for controlling a haptic interface system to ensure a stable contact under a wide variety of operating conditions in place of fixed-parameter virtual couplings. In this paper, a

practical issue is studied to improve the performance of the PO/PC method. The issue is related to resetting the amount of energy accumulated in the PO for the faster PC operation. A heuristic rule is derived and experimentally evaluated how it works in the PO/PC of haptic interface systems.

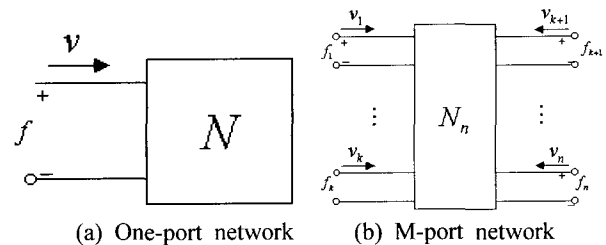


Fig.1. One-port and M-port networks.

II. Time domain passivity control of haptic interface systems

In this section the definitions of the passivity observer and controller are reviewed [8][9]. Force (' f ') and velocity (' v ') 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,

$$\int_t^0 (f_1(\tau)v_1(\tau) + \dots + f_M(\tau)v_M(\tau))d\tau + E(0) \geq 0, \quad \forall t \geq 0 \quad (1)$$

for all admissible forces (f_1, \dots, f_M) and velocities (v_1, \dots, v_M). Equation (1) states that the energy applied to a passive network must exceed $-E(0)$ for all time[5]. In haptic interface systems, the relevant forces and velocities can be measured by the computer and (1) can be computed in real time by appropriate software. This software is very simple in principle because at each time step, (1) can be evaluated with few mathematical operations.

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

Manuscript received: Jan. 1, 2001., Accepted: Feb. 14, 2001.

Yoon Sang Kim, Blake Hannaford: Department of Electrical Engineering, University of Washington, Box 352500, Seattle, WA, USA.(yoonsang@u.washington.edu, blake@u.washington.edu)

*This work was supported by postdoctoral fellowships program of the corresponding author from Korea Science & Engineering Foundation.(KOSEF)

the following "Passivity Observer," (PO)

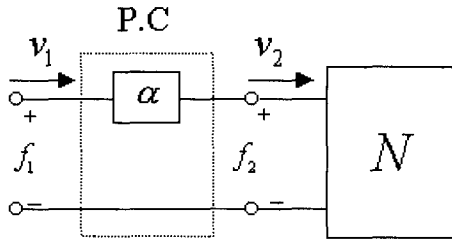


Fig. 2. Configuration of Passivity Controller for one-port networks(case of Series or velocity conserving Passivity Controller).

$$E_{obsv}(n) = (\sum_{k=1}^n [f_1(k)v_1(k) + \dots + f_M(k)v_M(k)]) \times \Delta T \quad (2)$$

where, ΔT is a 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. 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 dissipative element in a series or parallel configuration (Fig. 2). This obeys the constitutive equation.

$$f = av \quad (3)$$

Specifically,

$$f_1 = f_2 + av \quad (4)$$

For a series PC with impedance causality, we compute a 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.

$$3) \quad E_{obsv}(n) = E_{obsv}(n-1) + (v_2(n)f_2(n) + a(n-1)v_2(n-1)^2) \Delta T$$

$$4) \quad a(n) = \begin{cases} \frac{-E_{obsv}(n)}{\Delta T v_2(n)^2} & \text{if } E_{obsv}(n) < 0 \\ 0 & \text{if } E_{obsv}(n) \geq 0 \end{cases}$$

$$5) \quad f_1(n) = f_2(n) + av_2(n) \rightarrow \text{output}$$

For a proof of stability and extension to the case of dissipative loads, see [8][9].

III. Derivation of a heuristic rule : Resetting

1. Problems statement

The PC begins to operate based on the PO monitoring whether the system is passive or not. This means that if the PO has a "build-up" of dissipated energy, then the PC does not work until all "built-up" energy is dissipated. For example, consider the cases of a virtual environment may interact extensively with a very dissipative object. In this case, the PO will accumulate a large positive value. A second case occurs locally, when non-linear behavior of the environment can cause dissipative behavior closely followed by active behavior. In both cases, if the energy accumulated in the PO can be reset to zero properly, then the 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.

2. Force threshold and duration time

The value of the force threshold is very important because it is directly related with the haptic interface performance which distinguishes the free regime from the contact 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 (Table 1). In free motion, $f = 0$ by constraint of the virtual environment..

Table 1. ε and τ ($T=1msec$, $F_{MAX}=200N$), "..." means no experiment.

	$10^{-7} \times F_{MAX}$	$10^{-3} \times F_{MAX}$	$10^{-1} \times F_{MAX}$
$1 \times T$	viscous feeling and PC on in free motion: Case 1	...	too much resetting : Case 4
$10 \times T$...	good performance	...
$100 \times T$	viscous feeling and PC on in free motion: Case 2	...	too much resetting : Case 3

Case 1: (small force threshold ($10^{-7} \times F_{MAX}$) and short duration ($1 \times T$): When $10^{-7} \times F_{MAX}$ was chosen for the force threshold and τ was $1 \times T$, we found a very sluggish feeling in free motion : the resetting was continuous and the PC was operating all the time.

Case 2: (small force threshold ($10^{-7} \times F_{MAX}$) and long duration ($100 \times T$): We found a very sluggish feeling in free motion, too.

Case 3: (big force threshold ($10^{-1} \times F_{MAX}$) and long duration ($100 \times T$): 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.

Case 4: (big force threshold ($10^{-1} \times F_{MAX}$) and short duration ($1 \times T$): Assume the extremely short case that the duration equals the sampling time ($1 \times T_{sec}$). In the case of $\epsilon = 10^{-1} \times F_{MAX}$ with such a short duration, resetting is being done when even a single noisy signal is less than the force threshold, as the PC operates too much. But faster stable contact was not achieved.

Finally, we determined $\epsilon = 0.2N$, ($10^{-3} \times F_{MAX}$) and $\tau = 0.01sec$, ($10 \times T$) were useful values for the resetting. Note that as the heuristic rule for the resetting is derived in our haptic interface system, its formulation can be different in other haptic interface systems.

IV. Experiment results

The experiments were performed using our "Excalibur" 3-axis, high force output, haptic interface system in the laboratory [10] (Fig 3) in the same manner as the previous work (for more details, see [8]). This system consists of the following elements: 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 $300 \times 300 \times 200mm$ workspace. The virtual environment consists of virtual Lego-like blocks. In the experiments, the PO accounted for energy flow in the HC, PC, and VE. The virtual object parameter had very high stiffness ($k = 90 kN/m$). The operator approached the object at about 200mm/s. Note that the high stiffness means unstable system. In other words, $k=90kN/m$ used in the experiments are so high that the haptic system becomes very unstable, as it is out of the range which the stability is guaranteed in the haptic interface system (in our case, $k < 70kN/m$ guarantees the stable interaction, see [11]). Therefore, we will show how the PO/PC work first, and then how the resetting can improve the performance on the PO/PC in the system with high stiffness.

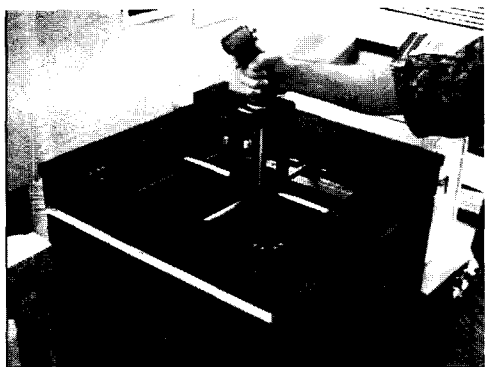


Fig. 3. The "Excalibur", 3-axis, high force output haptic interface device developed by University of Washington and HTI Inc.

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. 4b) ; the passivity observer (Fig. 4c) 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.

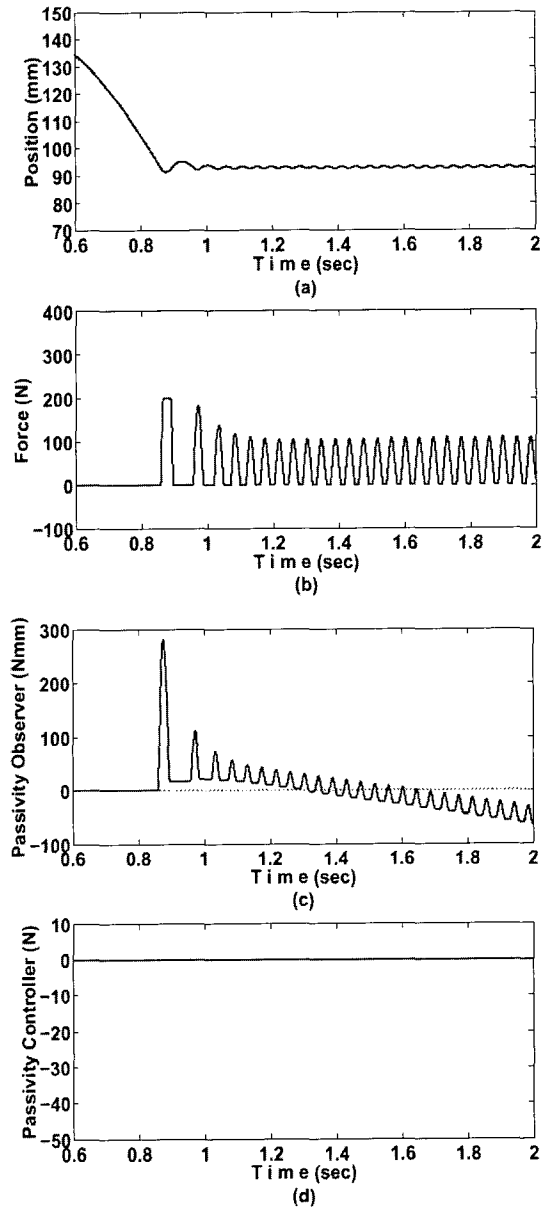


Fig. 4. Experimental result without PC in contact with high stiffness ($k = 90kN/m$): the PO grows more negative with each contact. (a) position (v) force (c) PO energy (d) PC force.

2. Operation of the basic PO/PC

In the second experiment, with the PC turned on, the operator approached the virtual object at the same velocity (Fig. 5a), but a stable contact was achieved with about 13 bounces (Fig. 5b). Again the first bounce can be seen to behave passively, but the subsequent bounces are smaller (Fig. 5c). After eight bounces, the PC began to operate (Fig. 5d), and eliminated the oscillation.

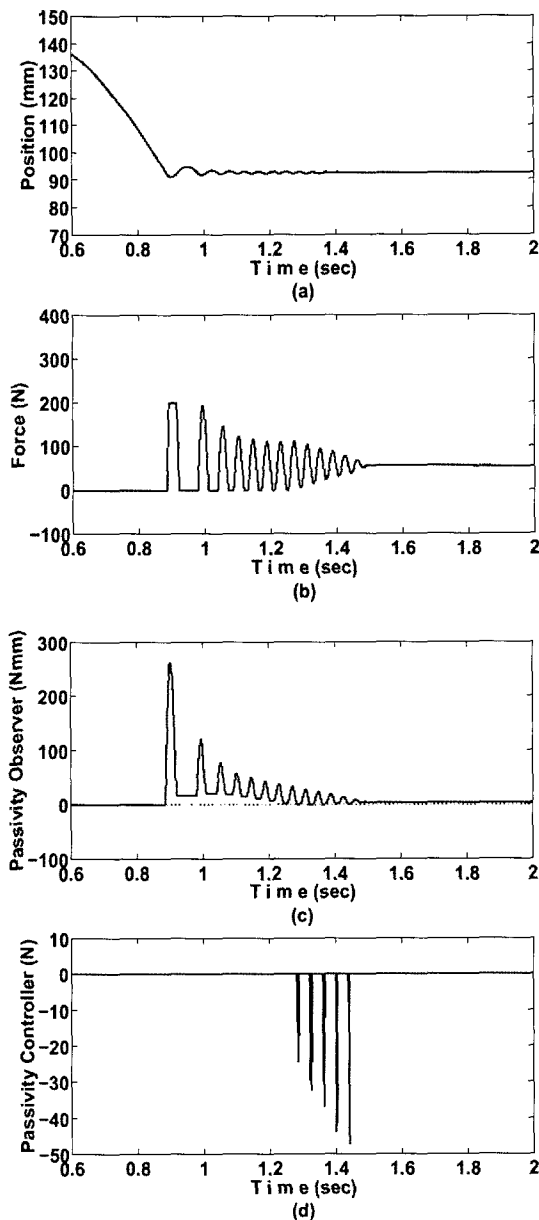


Fig. 5. Experimental result with only PC in contact with high stiffness ($k=90kN/m$): the PC began to operate eliminated the oscillation after eight bounces when all the energy accumulated in the PO was dissipated. Note that it was after the third bounce when the system got active. ((a) position (v) force (c) PO energy (d) PC force).

3. Resetting operation

We added resetting to the experimental system under the conditions of previous subsection. With the PC and resetting turned on, a stable contact is achieved with about 8 bounces (Fig. 6b). Compared to the case without resetting (Fig. 5), the contact transient is shorter (8 vs 13 bounces) because the PC operates about 200msec sooner after the initial contact. Resetting helps the PC to operate exactly and immediately when the system becomes active without changing the stability, just proposed.

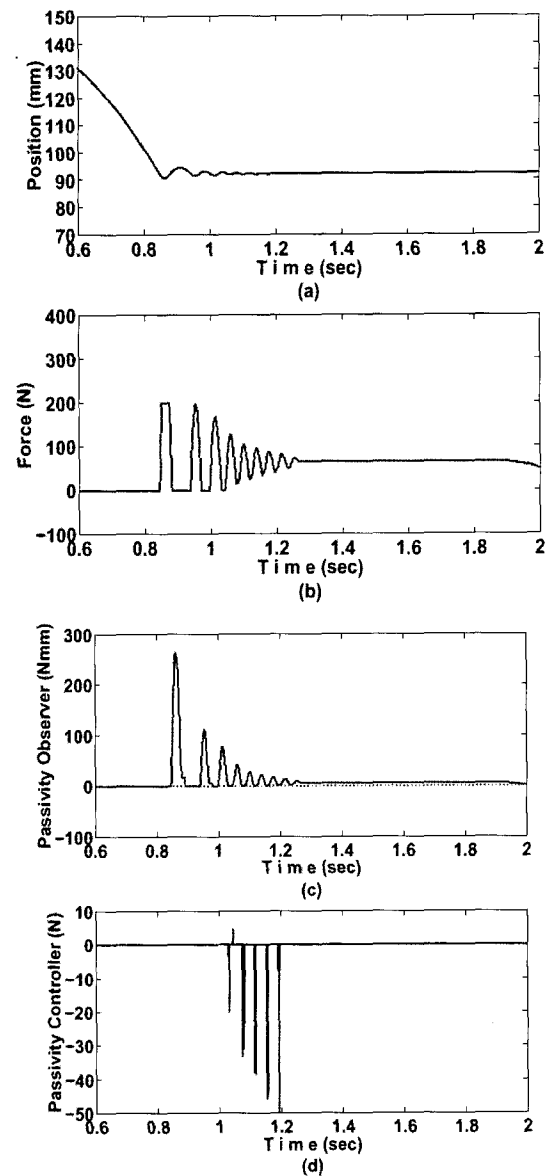


Fig. 6. Experimental result by the resetting (with $\epsilon=0.2N$ and $\tau=0.01sec$): added to basic PO/PC operation in contact with high stiffness ($k=90kN/m$): compared to Fig 5, the contact transient is shorter by resetting the energy accumulated in the PO after the first and second bounce. ((a) position (v) force (c) PO energy (d) PC force).

V. Conclusion

Relating to the performance of haptic control, a heuristic rule to reset the stored energy in the PO based on the detection of a free motion state is derived, and it is verified by experiment how exactly and immediately this resetting helps the PC to operate when the system gets active without changing the stability. Finally, it is validated that the faster stable contact can be achieved with smaller bounces.

References

[1] N. Hogan, "Controlling impedance at the man/machine," *Proc. IEEE Int. Conf. Robot. Automat.*,

Scottsdale, AZ, pp. 1626-1631, 1989.

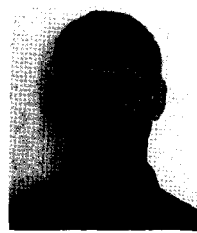
- [2] J. E. Colgate, M. C. Stanley and J. M. Brown, "Issues in the Haptic Display of tool use," *Proc. IEEE/RSJ Int. Conf. on Intelligent Robotics and Systems, Pittsburgh, PA*, pp. 140-145, 1995.
- [3] C. B. Zilles and J. K. Salisbury, "A Constraint-based god-object method for Haptic Display," *Proc. IEEE/RSJ Int. Conf. on Intelligent Robotics and Systems, Pittsburgh, PA*, pp. 146-151, 1995.
- [4] R. J. Adams, D. Klowden and B. Hannaford, "Stable Haptic Interaction using the excalibur force display," *Proc. IEEE Int. Conf. Robot. Automat., San Francisco, CA*, pp. 770-775, 2000.
- [5] R. J. Adams and B. Hannaford, "Stable Haptic interaction with virtual environments," *IEEE Trans. Robot. Automat.*, vol. 15, no. 3, pp. 465-474, 1999.
- [6] B. E. Miller, J. E. Colgate and R. A. Freeman, "Computational delay and free mode environment design for haptic display," *Proc. ASME Dyn. Syst. Cont. Div.*, pp. 229-236, 1999.
- [7] B. E. Miller, J. E. Colgate and R. A. Freeman, "Environment delay in haptic systems," *Proc. IEEE Int. Conf. Robot. Automat., San Francisco, CA*, pp. 2434-2439, 2000.
- [8] B. Hannaford, J. H. Ryu, "Time domain passivity control of haptic interfaces," *Proc. IEEE Int. Conf. Robot. Automat., Seoul, Korea*, pp. 1863-1869, 2001.
- [9] Hannaford, J. H. Ryu, "Time domain passivity control of haptic interfaces," Accepted to *IEEE Trans. Robot. Automat.* (To be published).
- [10] R. J. Adams, M. R. Moreyra and B. Hannaford, "Excalibur, A Three-Axis force display," *ASME Winter Annual Meeting Haptics Symposium, Nashville, TN*, November, 1999.
- [11] R. J. Adams, "Stable haptic interaction with virtual environments," Ph.D. Thesis, University of Washington, Department of Electrical Engineering, September, 1999.



Yoon Sang Kim

Yoon Sang Kim received the B.S. degree in Electrical Engineering from SungKyunKwan University, Korea in 1993, and the M.S. and Ph.D. degrees in Electrical Engineering from SungKyunKwan University, Korea, in 1995 and 1999 respectively. From

1999 to 2000 he worked on the teleoperation of the humanoid robot, CENTAUR in the Humanoid Robotics Research Center of Korea Institute of Science and Technology (KIST), Seoul, Korea. Since September 2000, he has been at University of Washington in Seattle, where he has been Research Associate of Electrical Engineering (Biorobotics Laboratory). He was awarded Korea Science & Engineering Foundation's (KOSEF) Oversea Postdoctoral Fellow. His currently active interests include haptic control, surgical simulation, telesurgery and mechatronics/control applications.



Blake Hannaford

Blake Hannaford received the B.S. degree in Engineering and Applied Science from Yale University in 1977, and the M.S. and Ph.D. degrees in Electrical Engineering from the University of California, Berkeley, in 1982 and 1985 respectively. Before

graduate study, he held engineering positions in digital hardware and software design, office automation, and medical image processing. At Berkeley he pursued thesis research in multiple target tracking in medical images and the control of time-optimal voluntary human movement. From 1986 to 1989 he worked on the remote control of robot manipulators in the Man-Machine Systems Group in the Automated Systems Section of the NASA Jet Propulsion Laboratory, Caltech. He supervised that group from 1988 to 1989. Since September 1989, he has been at the University of Washington in Seattle, where he has been Associate Professor of Electrical Engineering since 1993. He was awarded the National Science Foundation's Presidential Young Investigator Award and the Early Career Achievement Award from the IEEE Engineering in Medicine and Biology Society. His currently active interests include haptic displays on the internet, surgical biomechanics, and biologically based design of robot manipulators. He is the founding editor of Haptics-e, The Electronic Journal of Haptics Research. (www.haptics-e.org)