Extending the Z-Width of a Haptic Device Using Acceleration Feedback

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Abstract. This paper proposes a nonlinear controller to extend the Z-width of a haptic device. A time-domain passivity analysis of the Z-width diagram leads to the new haptic controller, which employs acceleration feedback. The passivity condition for one degree of freedom (1DOF) haptic interaction with a virtual wall via the proposed controller is derived using passivity theory in the frequency domain. The perfomance of the proposed controller is validated experimentally on a PHANTOM Omni haptic device. The experiments illustrate that the new controller considerably extends the Z-witdh of the haptic interface.

Keywords: Z-width, virtual damping, passivity, time-domain passivity, acceleration feedback.

1 Introduction

The haptic rendering of a virtual wall is a key building block for haptic simulations of rigid virtual environments. Yet, displaying rigidity via high stiffness control of impedance haptic interfaces is challenging. Various factors limit the maximum stiffness that a manipulandum can display. They include the friction and the damping of the haptic device, the resolution of its encoders, the zero-order hold inherent in the control and the simulation algorithms, the limited bandwidth of the device amplifiers. The effect of these factors on stability has been the focus of much haptics research, alongside control strategies aiming to improve performance.

The role of the zero-order hold in the generation of unphysical energy (termed “energy leaks” [1]) by the virtual environment has been elucidated in [1]. In [2], passivity of linear time invariant networks and frequency domain tools are used to derive the passivity condition for a haptic interaction system. This condition is a general condition that depends on the Z-transform of the virtual environment. As an example, the passivity condition for the specific case of a virtual wall modeled as a linear spring-damper system has also been derived in [2].

Haptic systems have also been studied using passivity analysis in the time domain. In [3], the effect of physical damping, Coulomb friction, sampling and

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quantization on the passivity of haptic interaction with a virtual spring has been investigated. The passivity condition has been derived via analyzing the time-domain balance between the energy generated by sampling and quantization, and the energy dissipated through Coulomb friction and physical damping. Because the virtual wall is a pure stiffness, the derived passivity condition does not consider virtual damping. A similar analysis has been performed in [4], where the effect of quantization and sampling rate on the stability of the interaction with a pure stiffness has been clarified.

Passivity analysis in the time domain has led to nonlinear control in [5]. In this work, the energy leak caused by the zero-order hold is counteracted via suitable control. The control entails a passivity observer and a passivity controller. The observer keeps track of the generation and the dissipation of energy in the system. When the generated energy exceeds the dissipated energy, a control force is calculated to dissipate the excess energy over a single control step. Since the control force is applied over a single time step, it may be very large and may cause actuator saturation or may excite the high frequency modes of the haptic interface. To overcome these problems, a modified passivity observer and passivity controller that avail of a reference energy have been introduced in [6].

Classical control tools have also been utilized to derive stability conditions for the haptic rendering of virtual walls. In [7], the Z-width diagram has been derived by considering the closed loop characteristic equation and ignoring the human operator. A discrete time spring-damper represents the virtual wall in this work. A similar approach has been used in [8] to study a device with physical damping. The Ruth-Hurwitz criterion has provided the stability boundary for haptic interaction with a spring-damper virtual wall without considering time delays and physical damping in [9], and including time delays and physical damping in [10].

The present paper proposes a nonlinear control method for extending the Z-width of a haptic device, with one degree of freedom [2]. In Section 2, it presents a time-domain passivity analysis which leads to the new controller in Section 3. The performance of the new controller and the Z-width of a PHANTOM Omni haptic interface with and without this controller are verified experimentally in Section 4. Concluding remarks are presented in Section 5.

2 Energy Analysis of the Haptic System Including Virtual Damping

The energy analysis of the haptic interaction with a virtual wall presented in this section is based on passivity concepts and focuses on energy balance during one time step. Following the approach in [3], it can be shown that for haptic interaction with no initial eneregy and with a virtual wall modeled as a linear spring-damper system, the passivity condition is:

$$-\frac{1}{2}KT\,|\Delta y|\,|v(\xi)| + (B+b)\,|\Delta y|\,|v(\xi)| + B\int_{kT}^{(k+1)T}(v^{*}-v)v\,dt \geq 0. \quad (1)$$

In Eq. (1), y and v are the position and the velocity of the haptic device, $|\Delta y|$ is the device displacement during one time step, b is the device (physical) damping, K and B are the stiffness and the damping of the virtual wall, k is the time step and $\xi \in [kT, (k+1)T]$. The last term in Eq. 1, $E_v = B\int_{kT}^{(k+1)T}(v^* - v)vdt$, is the effect of virtual damping and discussed in the next section.

3 Alleviating the Negative Effect of E_v

3.1 Acceleration Feedback

Because E_v may be positive or negative, it may increase or decrease the energy dissipated by the system, i.e., it may have a positive or a negative effect on passivity. The negative influence of E_v on passivity can be alleviated via changing the expression to be integrated such that it is positive.

The sign of E_v depends on the rate of change of velocity, i.e., on the acceleration of the device a, and on the sign of the velocity of the haptic interface. Indeed, when $av \geq 0$, $(v^* - v)$ and v have opposite signs and $E_v \leq 0$. When $av \leq 0$, $(v^* - v)$ and v have the same sign and $E_v \geq 0$. Hence, a suitable algorithm to eliminate the negative effect of E_v is:

- if $av \geq 0$, change v^* to change the sign of $(v^* - v)$. This change of sign can be achieved via adding nTa^* to v^* when $a^*v \geq 0$, where a^* is the sampled acceleration of the haptic device, and n is a constant.

In the following section, the passivity condition of the haptic interaction system with the proposed controller is determined using the approach presented in [2], and a suitable n is identified.

3.2 Passivity Condition with Proposed Controller

Consider the following passivity condition [2]:

$$\int_0^t (Ky^* + Bv^* + bv)vd\tau \geq 0. \tag{2}$$

By defining a class of truncated signals $v_\theta(\tau)$:

$$v_\theta(\tau) = \begin{cases} v(|\tau|) & |\tau| \leq \theta \\ 0 & |\tau| \geq \theta \end{cases}, \tag{3}$$

Eq. (2) can be written as:

$$\int_{-\infty}^{+\infty} (Ky_t^* + Bv_t^* + bv_t)v_t d\tau \geq 0. \tag{4}$$

Parseval's theorem gives an equivalent inequality [2]:

$$\int_{-\infty}^{+\infty} (KY^{**}(j\omega) + BV^{**}(j\omega) + bV(j\omega))V^*(j\omega)d\omega \geq 0, \tag{5}$$

where $Y^{**}(j\omega)$, $V^{**}(j\omega)$, and $V(j\omega)$ are the Fourier transforms of y_t^*, v_t^* and v_t, respectively, and $V^*(j\omega)$ is the conjugation of $V(j\omega)$. It is shown in [2] that Eq. (5) is equivalent to:

$$\int_{-\infty}^{+\infty} \left(-\frac{KT}{2} + Bcos(T\omega) + b \right) V(j\omega)V^*(j\omega)d\omega \geq 0. \tag{6}$$

Because the proposed controller is nonlinear, the Describing Function method [11] is used to find a linear approximation of the controller for use in the analysis. The controller can be described as:

$$c(t) = \begin{cases} nTa & \text{if} \quad av \leq 0 \\ 0 & \text{if} \quad av \geq 0 \end{cases}. \tag{7}$$

By considering the input as $v(t) = Acos(\omega t)$ and neglecting higher order terms in the Fourier series:

$$c(t) = \frac{2nT|\omega|}{\pi} v(t), \tag{8}$$

and the Fourier transfer function of the linear approximation of the controller becomes:

$$C(j\omega) = \frac{2nT|\omega|}{\pi} V(j\omega). \tag{9}$$

Furthermore, considering the sampling effect equivalent to that of a time delay T, the Fourier transform function of the proposed controller becomes:

$$C(j\omega) = e^{-Tj\omega} \frac{2nT|\omega|}{\pi} V(j\omega). \tag{10}$$

After addition of Eq. (10) to Eq. (6), the passivity condition becomes:

$$\int_{-\infty}^{+\infty} \left(-\frac{KT}{2} + Bcos(T\omega) + b + e^{-Tj\omega} \frac{2nT|\omega|}{\pi} V(j\omega) \right) V(j\omega)V^*(j\omega)d\omega \geq 0. \tag{11}$$

Since $v_\theta(t)$ is a purely real and even function, its Fourier transform is real and even. Hence, Eq. (11) becomes:

$$\int_{-\infty}^{+\infty} \left(-\frac{KT}{2} + Bcos(T\omega) + b + Bcos(T\omega) \frac{2nT|\omega|}{\pi} \right) V(j\omega)V^*(j\omega)d\omega \geq 0. \tag{12}$$

Eq. (12) will be satisfied for all admissible $V(jw)$ iff the expression in brackets is positive at all frequencies, i.e.,:

$$-\frac{KT}{2} + Bcos(T\omega) + b + Bcos(T\omega) \frac{2nT\omega}{\pi} \geq 0 \quad \forall \omega \geq 0, \tag{13}$$

or, after addition and subtraction of B:

$$-\frac{KT}{2} + B + b - 2Bsin^2 \left(\frac{T\omega}{2} \right) + Bcos(T\omega) \frac{2nT\omega}{\pi} \geq 0 \quad \forall \omega \geq 0. \tag{14}$$

In Eq. (14), the $-2Bsin^2\left(\frac{T\omega}{2}\right)$ term shows the difference between the effect of physical damping and of virtual damping on the passivity of the haptic interaction system. The effect of the proposed controller is embodied in the $Bcos(T\omega)\frac{2nT\omega}{\pi}$ term. Indeed the controller alleviates the negative effect of ZOH on the virtual damping, i.e., $-2Bsin^2\left(\frac{T\omega}{2}\right)$ term, and enhances passivity when $\omega \leq \frac{\omega_N}{2}$, ω_N is Nyquist frequency. Therefore, n is computed such that the term:

$$-2Bsin^2\left(\frac{T\omega}{2}\right) + Bcos(T\omega)\frac{2nT\omega}{\pi} \geq 0 \tag{15}$$

is positive in a broader frequency range. The performance of the proposed controller is validated experimentally in the following section.

4 Experimental Validation

The experimental setup consists of a PHANTOM Omni haptic device with motion restricted along the vertical direction. The experiments are performed without touching the manipulandum. Rather, gravity is used as a constant user-applied force. The Z-width of the haptic device with and without the proposed nonlinear controller is identified experimentally in Fig. 1. This figure illustrates the extended Z-width of a PHANTOM Omni under the new control.

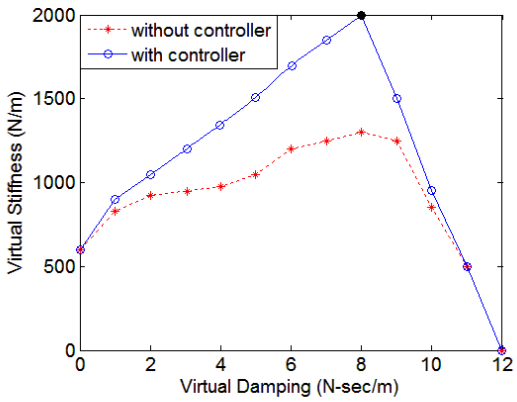

Fig. 1. Experimental Z-width of the PHANTOM Omni: with the proposed controller (continuous line); and via direct coupling to the virtual wall (dotted line)

5 Conclusions

This paper has investigated the effect of virtual damping on the stability of 1DOF haptic interaction with a virtual wall. Based on passivity arguments, it has proposed a nonlinear controller to enhance the positive effect of virtual damping. A new passivity condition for interaction with a virtual wall via the proposed controller has predicted the stable haptic display of larger virtual stiffnesses. The theoretical developments have been validated via experiments performed using a PHANTOM Omni device.

References

1. Gillespie, R., Cutkosky, M.: Stable user-specific haptic rendering of the virtual wall. In: Proceedings of the ASME Dynamic Systems and Control Division, Atlanta, GA, pp. 397–406 (1996)
2. Colgate, J., Schenkel, G.: Passivity of a class of sampled-data systems: application to haptic interfaces. Journal of Robotic Systems 14(1), 37–47 (1997)
3. Diolaiti, N., Niemeyer, G., Barbagli, F., Salisbury, J.: Stability of Haptic Rendering: Discretization,Quantization, Time-Delay and Coulomb Effects. IEEE Transactions on Robotics and Automation 22(2), 256–268 (2006)
4. Abbott, J., Okamura, A.: Effects of Position Quantization and Sampling Rate on Virtual-Wall Passivity. IEEE Transactions on Robotics 21(5), 952–964 (2005)
5. Hannaford, B., Ryu, J.: Time-Domain Passivity Control of Haptic Interfaces. IEEE Transactions on Control Systems Technology 13(5), 737–742 (2005)
6. Ryu, J., Preusche, C., Hanford, B., Hirzinger, G.: Time Domain Passivity Control With Reference Energy Following. IEEE Transactions on Robotics and Automation 18(1), 1–10 (2002)
7. Salcudean, S., Vlaar, T.: On the emulation of stiff walls and static friction with a magnetically levitated input/output device. ASME Journal of Dynamic Systems, Measurement and Control 119, 127–132 (1997)
8. Hulin, T., Preusche, C., Hirzinger, G.: Stability Boundary for Haptic Rendering: Influence of Physical Damping. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China, pp. 1570–1575 (2006)
9. Gil, J., Avello, A., Rubio, A., Flórez, J.: Stability Analysis of a 1 DOF Haptic Interface Using the Routh-Hurwitz Criterion. IEEE Transactions on Control Systems Technology 12(4), 583–588 (2004)
10. Gil, J., Sanchez, E., Hulin, T., Preusche, C., Hirzinger, G.: Stability Boundary for Haptic Rendering: Influence of Damping and Delay. In: Proceedings of the IEEE International Conference on Robotics and Automation, Roma, Italy, pp. 124–129 (2007)
11. Gelb, A., Van der Velde, W.E.: Multiple-Input Describing Functions and Nonlinear System Design. McGraw-Hill Book Company, New York (2001)