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A Transparency-optimized Control for a 6-DOF parallel-structured Haptic Device

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Abstract

This paper presents a design method of transparency optimized feedback controller with robustness for a parallel 6-DOF haptic system. A disturbance observer is employed to eliminate coupling effects that exist in a mechanically coupled structure. A performance index for the transparency is defined by admittance matching, and by solving H_2 optimal problem, the optimal solution that minimizes the performance index is obtained.

1 Introduction

Haptic interface is a kinesthetic link between a human operator and computer-generated virtual world. Up to now, human-computer interaction has taken place through uni-directional channel of information such as mouse, keyboard, etc. But, haptic interaction is fundamentally different from those kinesthetic information flows from and to the operator. As with other control problems, there are two conflicting goals in haptic control; performance and stability. Performance can be characterized by transparency. Perfect transparency implies that forces and velocities experienced by operator are identical to those generated by the virtual reality software. Also, since the haptic device actively generates physical energy, instability can damage hardware and even pose a threat to the human.

A number of researchers have considered stability in haptic simulation. Colgate *et.al.* proposed the passivity conditions for haptic system including virtual wall, haptic device and feedback controller[1]. In the system including this work, the dynamic range of achievable impedance, Z-width, is defined as a measure of performance and several factors affecting Z-width have been discussed[2]. However, the result is restricted to the case that virtual wall dynamics employed as the closed-loop controller. And there was not discussed design method of feedback controller. Adams and Hannaford have modeled the haptic interface as a linear two-port network, and derived an unconditionally stable condition. They also proposed a design procedure using virtual coupling to guarantee the stability[3, 4]. Their approach has the advantage in the sense that the design problem can be decoupled from the design of virtual environment. However, because the passivity condition depends on the dynamics of haptic device as well as numerical integration algorithm, the design problem may not be directly applied to the multi-axis parallel-structured haptic system whose dynamics are changing according to the configuration of haptic system.

This paper begins with a description on the disturbance observer-based 6-DOF haptic system modeling, and is followed by an outline of the transparency-optimized haptic system. The haptic interface control and its implementation are then described and evaluated experimentally.

2 Disturbance Observer-based 6-DOF Haptic System Modeling

Haptic display can be considered as a multi-axis robot mainpulator depicted in Fig.1. Consider dynamics of an n link robot manipulator given by a set of highly nonlinear and coupled differential equations as

$$\tau = M(q)\ddot{q} + V(q,\dot{q}) + G(q) + B\dot{q} + H(\dot{q}), \qquad (1)$$

where $M(q)$ and B are $n \times n$ inertia matrix and viscous friction constant matrix, respectively. And $V(q, \dot{q})$, $G(q)$, and $H(\dot{q})$ are $n \times 1$ vectors of the Coriolis and centrifugal forces, the gravity loading and Coulomb friction force, respectively. τ is the $n \times 1$ torque vector applied to the joint of robot manipulator. q, $\dot{q}$, $\ddot{q}$ are $n \times 1$ vectors representing angular position, velocity and acceleration, respectively. The robot dynamics of

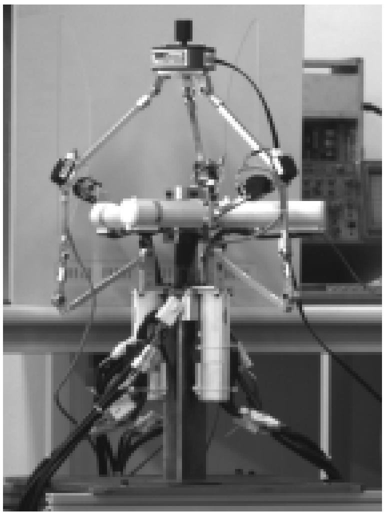


Figure 1: A 6-DOF haptic display

Eq.(1) in Cartesian space using Jacobian matrix can be written as

$$F = M_x(q)\ddot{x} + V_x(q, \dot{q}) + G_x(q) + B_x\dot{x} + H_x(\dot{q}), \quad (2)$$

where x, $\dot{x}$, $\ddot{x}$ are $m \times 1$ vectors representing position, velocity and acceleration in Cartesian space, respectively. The robot dynamics in Eq.(2) can be rewritten as a fixed mass and viscous friction plus an equivalent disturbance force given by

$$F = \bar{M}_x\ddot{x} + \bar{B}_x\dot{x} + F_{xd}(q, \dot{q}), \quad (3)$$

where $\bar{M}_x \triangleq diag\{\bar{M}_{11} \cdots \bar{M}_{mm}\}$ is $m \times m$ diagonal matrix. $\bar{M}_{ii}$ is the constant value of nominal mass of the ith axis, and it can be measured approximately from the frequency response.

A frequency response for the ith axis can be obtained by locking all other axis except the ith axis. Assume that the dynamics of the ith axis can be treated as $F_i = \bar{M}_{ii}\ddot{x}_i + \bar{B}_{ii}\dot{x}_i$, then $\bar{M}_{ii}$ and $\bar{B}_{ii}$ can be measured experimentally by using a frequency response for the force input and the velocity output. In Eq.(3), $F_{xd}(q, \dot{q}) \triangleq [F_{1xd}, \cdots, F_{mxd}]^T$ is $m \times 1$ vector implying equivalent disturbance including all the unmodeled dynamics, such as nonlinearity and coupling effect. F_{xd} can be rewritten as

$$F_{xd} = (M_x(q) - \bar{M}_x)\ddot{x} + V_x(q, \dot{q}) + G_x(q) + H_x(\dot{q}). \quad (4)$$

If the equivalent disturbance in Eq.(4) can be obtained, dynamics of each axis can be decoupled by eliminating the equivalent disturbance. Fortunately, the equivalent disturbance can be estimated by disturbance observer [5, 6], and thus can be suppressed by adding the estimated disturbance signal to the control input. Fig.2 shows a structure of the disturbance ob-

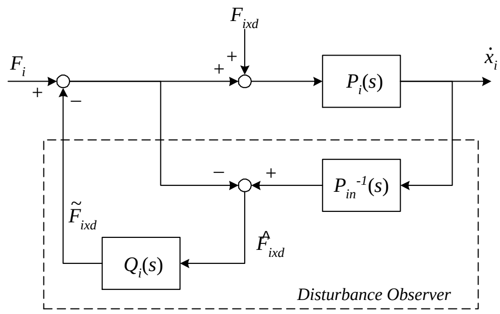


Figure 2: A structure of disturbance observer

server for the ith single axis which is based on inverse model of nominal plant. In Fig.2, P_{in} is the nominal plant of the real system $P_i(s)$ where P_{in} is given as $1/(\bar{M}_{ii}s + \bar{B}_{ii})$, and $Q_i(s)$ is a low pass filter which is employed to realize $P_{in}^{-1}(s)$ and to reduce the effect of measurement noise. From the relationship between input and output in Fig.2, if the magnitude of $Q_i(s)$ is approximately equal to one, the real plant acts as the nominal plant, otherwise as real plant. This implies that for a disturbance signal whose maximum frequency is lower than cut-off frequency of $Q_i(s)$, the disturbance signal is effectively rejected and the real plant behaves as a nominal plant. Therefore, if such a disturbance observer is employed for every axis, the robot dynamics in Cartesian space can be treated as the simple equivalent dynamic system[8] given by

$$F = \bar{M}_x\ddot{x} + \bar{B}_x\dot{x}. \quad (5)$$

From Eq.(5), the 6-DOF haptic display in Fig.1 can be simply modeled to several 1-DOF haptic device model sketched in Fig.3.

General haptic system model is presented in Fig.4, where $P(s)$ is a dynamic model of haptic device, ZOH is a zero order holder and $V(s)$ is a virtual environment. The dynamics of human operator can be represented as a time-varying nonlinear model. However,

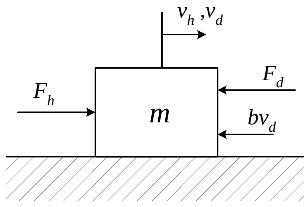


Figure 3: 1-DOF haptic device model

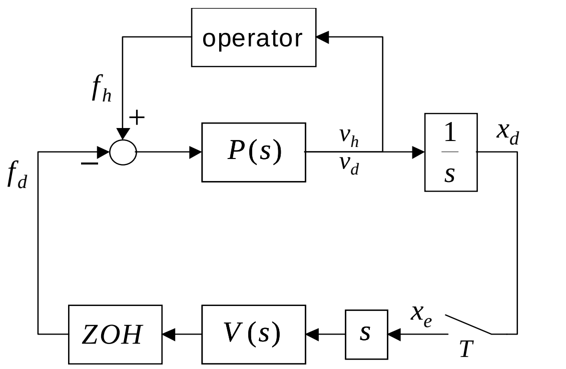


Figure 4: Block diagram of general haptic interface

by the fact that operator interacting with robot manipulator is passive, it can be assumed that the dynamics of operator does not affect the stability of haptic system.

Consider a 1-DOF rigid manipulator as haptic device whose dynamics is given by

$$m\dot{v}_d + bv_d = F_h - F_d, \quad v_d = v_h, \tag{6}$$

where v_h and v_d are the velocity of the human operator at the point of contact with the device and the velocity of the device at the point of actuation, respectively. F_h is the force applied to/by human operator at the point of contact and F_d is the force applied by/to the device at the point of acutation. For impedance model of haptic interaction where the force are applied to the human operator in response to measured displacement, the continuous time transfer function from f_h to v_h can be found by taking the Laplace transform of Eq.(6)

$$P(s) = \frac{1}{ms + b}. \tag{7}$$

The force commands should be sent to actuator through D/A converter modeled by putting the transfer function in Eq.(7) in series with a zero-order holder. The effect of zero-order holder can be approximated as a low pass filter with unity gain and 90 degrees phase lag at the Nyquist frequency.

The spring-damper model is typically employed as a virtual wall and the transfer function from the velocity at the contact point to the command force is given by

$$V(s) = \frac{K + Bs}{s}. \tag{8}$$

where K and B are the spring and damping coefficient of virtual wall, respectively. The feedback controller, $V(s)$, is generally implemented by using virtual wall dynamics, and the transmitted admittance of the closed loop haptic system in Fig.4 can be derived as

$$Y_t(s) = \frac{P(s)}{1 + ZOH(s)P(s)V(s)}. \tag{9}$$

3 Transparency-Optimized Haptic Interface Control

Colgate and Brown[1] proposed the performance measure, Z-width, for haptic system. It is defined as the dynamic range of achievable impedances. However, when the virtual environment is out of the range, stability as well as transparency cannot be guaranteed. Fig.5 is the admittance plot of the unstable haptic system.

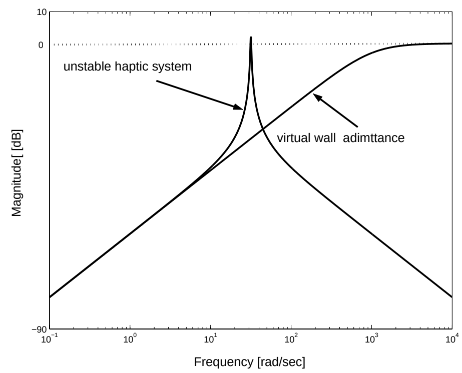


Figure 5: Typical admittance plot

The admittance plot for virtual wall has high pass filter dynamics and the unstable haptic system has the same response in low frequency region. However, the overall system has chattering or unstable characteristic due to the peak resonance. In this case, it is desirable to design the haptic feedback controller, $V(s)$, such that the peak resonance is excluded. Adams[3] introduced a virtual coupling network between the haptic device and the virtual environment that guarantees the stability of the combined haptic interface for arbitrary passive human operator and environmental immittances. The haptic interface block

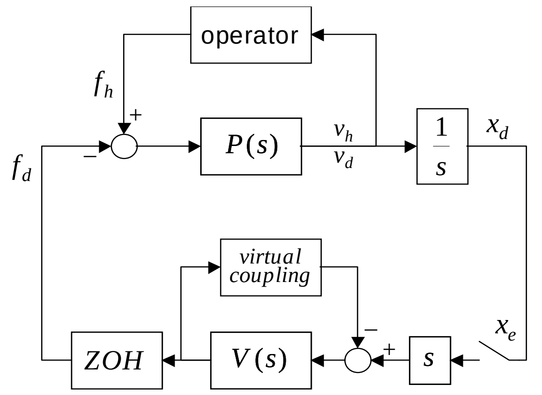


Figure 6: Block diagram of haptic interface using virtual coupling

diagram using virtual coupling is depicted in Fig.6. Virtual coupling could satisfy a stable condition for passive virtual environment, and enabled us to get a stable haptic interface for all virtual environment satisfying passivity. However, the stability condition based on passivity may be conservative. And, virtual coupling may not preserve the transparency, though no uncertainties exist in the virtual environment dynamics given by user.

In this paper, we propose a design method of haptic controller that maximizes transparency for a given dynamics of virtual environment.

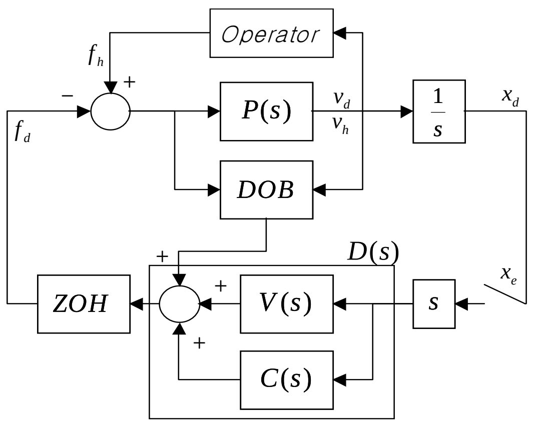


Figure 7: Block diagram of proposed haptic interface

Fig.7 shows the structure of the proposed haptic interface conroller, and our transmitted admittance function can be obtained as

$$Y_t = \frac{P(s)}{1 + ZOH(s)P(s)(V(s) + C(s))}. \quad (10)$$

The objective of our haptic controller design is to find $C(s)$, not only stabilizing the haptic feedback system, but minimizing the admittance error between virtual wall and haptic feedback system. The performance index for the transparency can be defined as an integral of the squared output error between the virtual wall and haptic feedback system for the same input force. And it can be transformed to frequency domain by Parseval's theorem;

$$J = \int_0^\infty (v_v(t) - v_h(t))^2 dt, \quad (11)$$

or

$$\begin{aligned} J &= \|w_1(Y_v - Y_t)\|_2^2 \quad (12) \\ &= \frac{1}{2\pi}\int_{-\infty}^{\infty} |w_1(jw)(Y_v(jw) - Y_t(jw))|^2 dw, \end{aligned}$$

where $Y_v(s)$ is the admittance function of virtual wall given as $s/(B_c s + K_c)$. $w_1(s)$ is an weight function which can be properly determined according to input signal[7]. Because the input force signal exerted by human operator, f_h, is a frequency limited signal, whose range is from 12Hz to 25Hz, $w_1(s)$ may be chosen as a low pass filter ranging from 40Hz to 80Hz[9].

The design problem of the optimal controller minimizing performance measure in Eq.(12) is to find H_2 optimal solution. If the feedback controller has the same form as the dynamics of the virtual wall, $C(s)$ can be written as

$$C(s) = B_c + \frac{K_c}{s}, \quad (13)$$

where K_c and B_c are the feedback gains for position and velocity, respectively. When the position feedback gain, K_c, is equal to zero, the steady state error between the position of haptic feedback system and virtual wall goes to zero. Thus, K_c should be set to be zero. It implies that if K_c is not equal to zero, the performance measure defined in Eq.(12) is not bounded and the H_2 optimal solution is meaningless. As a result, the H_2 optimal controller design problem can be reduced to a simple parameter optimization problem to find B_c minimizing the performance index.

4 Experimental Results

Proposed control algorithm was implemented on a 6-DOF parallel type haptic device depicted in Fig.1. The control algorithm is implemented using C language in our prototype controller, where a industrial PC board embedded Windows NT are used as sketched in Fig.8. The nominal values of mass and

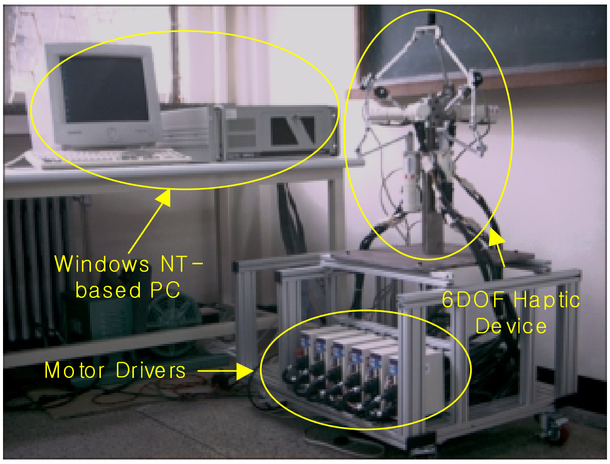


Figure 8: Experimental setup

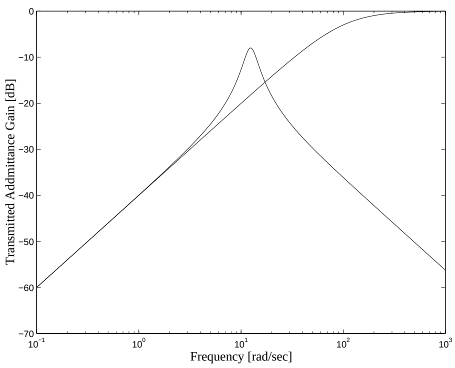
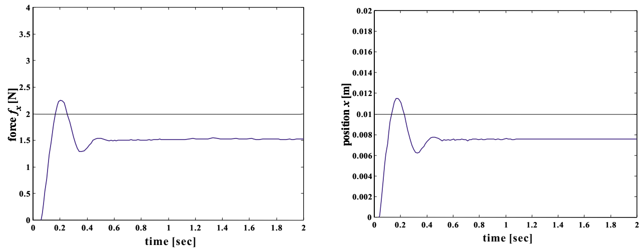


Figure 9: Admittance plot of typical haptic interface method

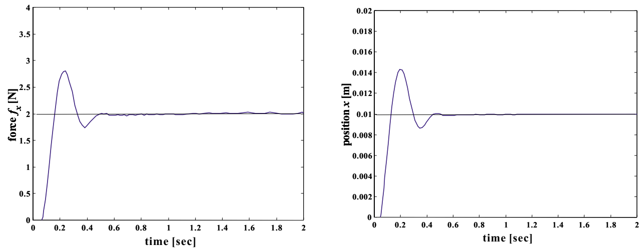
viscous friction of the haptic device are obtained by the frequency response in Cartesian space as $m = 0.6576[Kg]$ and $b = 1.566[Nsec/m]$, respectively. The stiffness and damping factors of the virtual wall are given by $K = 200[N/m]$ and $B = 1[Nsec/m]$, respectively. Force command of $2[N]$ is exerted in the +x direction.

Fig.9 is the admittance plot and Fig.10 represents the force and position response of typical haptic control method depicted in Fig.4. In Fig.9, peak resonance exists around $10[rad/sec]$, where causes the oscillation in transient response. Also, the displayed force should be 2[N], but actually measured force is 1.5[N] because of the dynamic effect such as gravity. The force and position response employing disturbance observer is presented in Fig.11 The oscillation in transient response still exists, but the gravity force treated as a disturbance is removed by disturbance observer. So, force error does not exist.



(a) Force response (b) Position response

Figure 10: Force and position response of typical haptic interface method



(a) Force response (b) Position response

Figure 11: Force and position response of disturbance observer method

In order to apply the proposed algorithm, determine the optimal gain B_c in the viewpoint of transparency for given virtual wall. The weighted performance measure defined in Eq.(11) for variation of B_c is plotted in Fig.12. From Fig.12, when B_c is set to $3[Nsec/m]$, the admittance error is minimized and the operator can feel the similar admittance under the given environment.

The force and position responses for the admittance matching solution is depicted in Fig.13. The admittance in frequency domain is shown in Fig.14, and it

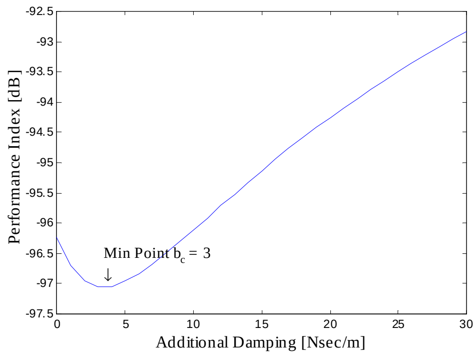
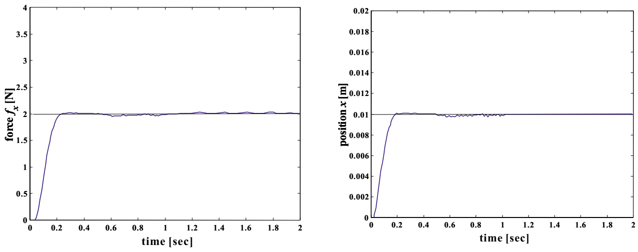


Figure 12: Performance index of proposed method



(a) Force Response (b) Position Response

Figure 13: Force and Position response of the proposed haptic controller

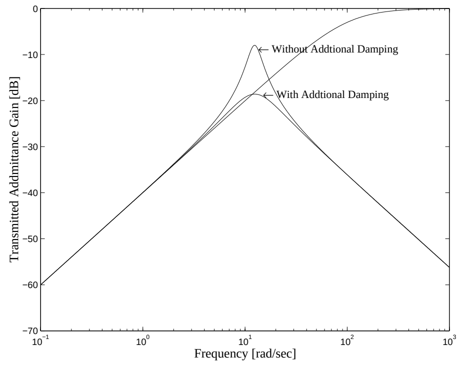


Figure 14: Admittance response of proposed method

can be observed that the peak resonance affecting the chattering or unstable characteristic has disappeared.

5 Concluding Remarks

A controller design methodology was presented for 6-DOF haptic display considering transparency and robust stability. To exclude the coupling effect existing in multi-axis haptic display, the equivalent disturbance in Cartesian space including modeling uncertainties and coupling effect was derived and can be effectively removed using disturbance observer. Thus, haptic model employing disturbance observer could be simplified to several one DOF haptic device model.

A performance index for the transparency-optimized haptic interface was defined in a viewpoint of admittance matching, and the optimal solution minimizing the performance index was obtained by solving H_2 optimal problem.

Acknowledgement
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References

[1] J. E. Colgate and G. Schenkel, “Passivity of a Class of Sampled-Data System : Application to Haptic Interface,” *Proc. of American Control Conference*, Baltimore, pp.3236-3240, 1994

[2] J. E. Colgate and J. M. Brown, “Factors Affecting the Z-width of a Haptic Display ,” *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp.3205-3210, 1994

[3] R. J. Adams and B. Hannaford, “A two-port Framework for the Design of Unconditionally Stable Haptic Interface,” *Proc. of 1998 IEEE/RSJ Int. Conf. on Intelligent Robotics and System*, pp.1254-1259, 1998

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

[5] T. Umeno and Y. Hori, “Robust speed control of dc servomotors using modem two degrees-of-freedom controller design,” *IEEE Trans. on Industrial Electronics*, vol.38, no.5, pp.363-368, 1991.

[6] H. S. Lee, “Robust Digital Tracking Controllers for High-Speed/High-Accuracy Positioning System,” *Ph.D. Dissertation*, U.C Berkeley, 1994

[7] M. Morari and E. Zafiriou, *Robust Process Control*, Prentics Hall, 1989

[8] K. S. Eom, I. H. Suh, W. K. Chung and S. -R. Oh, "Disturbance Observer based Force Control of Robot Manipulator without Force Sensor,” *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp.3012-3017, 1998

[9] R. E. Ellis, O. M. Ismaeil and M. G. Lipsett, “Design and Evaluation of a High-Performance Haptic Interface,” *Robotica*, vol.4, pp.321-327, 1996