Transparency Oriented Virtual Coupling Design: New Approach and Application to a Novel Admittance Haptic Device

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Abstract. A novel admittance haptic device which has low inertia and high speed to guarantee the high force bandwidth for the haptic interaction system is presented. Friction wheel is used to implement a rapid adjustment of the velocity loop. According to the admittance character of the haptic interface, PI velocity feedback control is utilized in the haptic interaction system. By introducing the virtual coupling into the system, Llewellyn's stability criteria in circuit theory is used to derive the constraint conditions to guarantee the system's absolute stability. Furthermore the parameters of the virtual coupling are optimized oriented to high transparency of the system. Man-machine haptic interaction system is established with the novel admittance interface. The experimental results indicate that optimized virtual coupling guarantees the large range stability, as well as improving the transparency effectively.

Keywords: Admittance device; Two-port network; Virtual coupling; Stability; Transparency.

1 Introduction

As well as visual and audio capabilities, the sensation of force and touch is also the essential information passage for human being's perception of the external world. Human-machine haptic interface system is composed of operator, the haptic interface devices, and virtual environment. Stability and transparency of the system depend on the complicated interaction between each one of the three. In Virtual Reality and tele-operated system, the simulation and recreation of the sense of touch is the key way to strengthen the genuine feeling of the system, to create the effect of indulgence. Hence, the related research has already been focused on , and evolved into a completely new field for studying[1]. Since haptic interface devices can release energy, unstable state may result in not only the destruction of the hardware, but also the threat to the safety of the operator. Stability is prior to all the problems to be concerned when it comes to system-controller design. In general, stable state depends on many factors such as operator, hardware (Motors, sensors, controllers, etc), virtual environment and the complicated interaction between each individual of the

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previously mentioned three. Initial hard work to solve the problem proposed virtual coupling of the virtual environment and haptic device. Virtual Coupling is a kind of virtual mechanical system including combination of components which are connected in series or in parallel. These components between haptic interface and virtual environment can constrain the maximum or minimum impedance of the virtual environment, and guarantee the stability of the system. Firstly introduced by colgate[2] , the method was used to solve the problem of non-continuity in environment appearing in collision. Besides, Zilles and Salisbury[3] have promoted a similar approach called "god-object", which utilized a virtual spring damper between force-feedback device and virtual environment. Meanwhile, Adams and Hannaford have deduced the means of designing virtual coupling parameters using two-terminal network theory, concerning every combinations of the relationship of reason and result, which has less conservation than passive design.

In this paper, a novel 1-DOF admittance haptic device has been designed, and algorithm for controlling to ensure system stability and transparency through visual coupling optimization method has been studied, which has the assumption of passivity of virtual environment.

2 Novel 1-DOF Admittance Haptic Interface

The 1-DOF haptic interface is shown as Fig.1,made up of three parts: 1)power, including motor and digital RC motor, 2)transmission mechanism, including driving-wheel and directing-wheel, 3)sensors, including collinear displacement sensor and six-dimension force sensor.

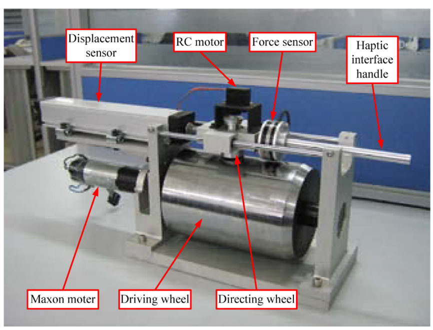


Fig. 1. The 1-DOF admittance haptic device

Two round surfaces have been used for transmission with the help of friction. Initially, the axis of the directing wheel is parallel to that of the driving wheel, which is obvious in Fig.2. At this time, there is no relative displacement between the two wheels. When the directing-wheel rotates along its axis Z1 for a certain degree θ, since the two axis are not parallel to each other, helical movement can be created, thus leading to linear movement. The advantage of such realization lies in rapid conversion of movement direction, for traditional transmission method makes sure that when moving part moves inversely, mostly motors will rotate in a different direction. In this way, processes for motor-speed deduction and increment have to be enhanced.

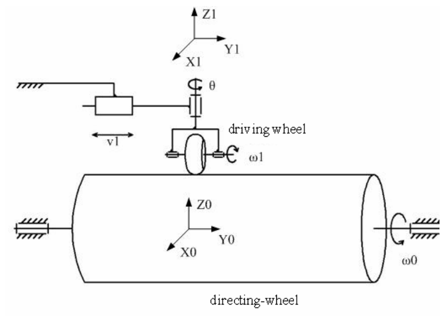


Fig. 2. Transmission diagram of the haptic device

3 Modeling of Admittance Haptic Interface System

3.1 Simplified Dynamic Model of the Haptic Device

Up to now modeling available for the operator comes in mainly two forms: 1)regarding the operator equivalently as passive impedance[4,5] 2)treating the operator as the equal linear combination of mass, spring, and damper[6,7,8], which is limited with particular operator and operating style concerned. In this paper the previous method will be used.

Taking 1-DOF haptic interface devices into consideration , corresponding dynamic model is depicted as Fig.3.

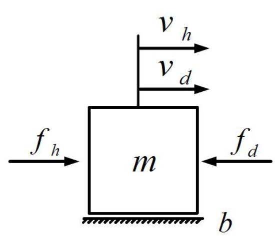


Fig. 3. Simplified dynamic model of the haptic deive

m is the total mass of the driving motor and the supplementary connecting parts, b is the damping of the device, f_h and v_h are the force and velocity of the driving point of the operator, f_d and v_d are the force and velocity of the driving point of the motor.

Dynamic equations of the device can be listed as follows:

$$\begin{cases} f_h - f_d = ms^2 x_d + bsx_d \\ x_h = x_d \end{cases} \tag{1}$$

For virtual environment, a reasonable dynamic model can be a combination of spring, damp and mass:

$$\begin{cases} f_e = m_e s^2 x_e + b_e s x_e + k_e x_e \\ f_h = f_e \end{cases} \tag{2}$$

In which f_e is the virtual force, m_e, b_e, k_e are virtual mass, virtual damping coefficient and virtual elastic factor, respectively.

3.2 Closed-Loop Control Model for the System

Haptic device discussed in this paper belongs to admittance type device. Its control model with speed closed-loop is shown in Fig.4.

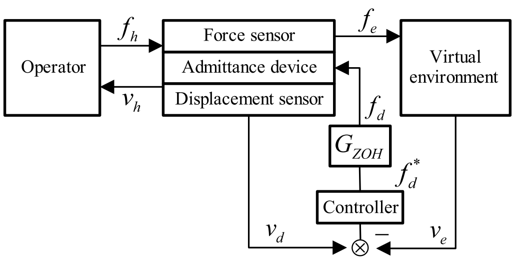


Fig. 4. The control model with speed closed-loop

A kind of internal speed closed-loop control strategy has been introduced, as Fig.4 illustrated, the control strategy is :

$$f_d^* = K_v(v_d - v_e) + K_p(x_d - x_e) \tag{3}$$

In which K_v is speed gain, K_p is position gain, v_e is the velocity in the virtual environment, the asterisk on the right upper position indicates discrete quantity. Velocity and position signals of the virtual environment are the inputs to the controller, considering phase-delay of the zero-order holder, obtained:

$$f_d = f_d^* G_{ZOH} \tag{4}$$

Based on the equivalent effect of mechanical system and electrical system, i.e. , force is equivalent to voltage, velocity is the counterpart to current, analysis of the relationship between force and velocity can be accomplished on the base of analyzing two-terminal network circuit. Equations (1)～(4) is converted to:

$$\begin{cases} f_h - f_d = msv_d + bv_d \\ v_h = v_d \end{cases} \tag{5}$$

$$\begin{cases} f_e = msv_e + bv_e + kv_e/s \\ f_h = f_e \end{cases} \tag{6}$$

$$f_d = [K_v(v_d - v_e) + K_p \frac{1}{s}(v_d - v_e)] \cdot G_{ZOH} \tag{7}$$

Utilizing equations (5)～(7),the following is got:

$$\begin{pmatrix} v_h(s) \\ f_e(s) \end{pmatrix} = \begin{pmatrix} G_{hh}(s) & -G_{he}(s) \\ 1 & 0 \end{pmatrix} \begin{pmatrix} f_h(s) \\ -v_e(s) \end{pmatrix} \tag{8}$$

In which

$$G_{ZOH} = 1 - e^{-sT}/s \approx 2/2 + Ts \tag{9}$$

$$G_{hh}(s) = 1/ms + b + (K_v + K_p/s) \cdot G_{ZOH} \tag{10}$$

$$G_{he}(s) = (K_v + \frac{K_p}{s}) \cdot G_{ZOH} \Big/ ms + b + (K_v + \frac{K_p}{s}) \cdot G_{ZOH} \tag{11}$$

4 Transparency Oriented Virtual Coupling Design

4.1 Stability Analysis for the Admittance Haptic System

For any two-terminal network system, the mapping relationship between input and output can be described by the admittance matrix $P_{2\times 2}$ of the system, i.e. , y=Pu. According to Llewellyn's criterion, absolute stability of two-terminal network does exist on and only on the condition that:

$$\begin{aligned} &\mathrm{Re}(p_{11}) \geq 0 \,\&\, \mathrm{Re}(p_{22}) \geq 0 \\ &2\,\mathrm{Re}(p_{11})\mathrm{Re}(p_{22}) \geq |p_{12}p_{21}| + \mathrm{Re}(p_{12}p_{21}), \forall \omega \geq 0 \end{aligned} \tag{12}$$

Consulting to the research of Hogan[9], operator is passive. Meanwhile, virtual environment is assumed to be passive, thus the stability of the haptic interface system depends on the absolute stability of the haptic interface. Therefore, the mapping relationship between two-terminal network can be shown as equation (8), absolute stability rely on and only on:

$$\begin{aligned}&\mathrm{Re}(G_{hh}(s)) \geq 0\\&\mathrm{Re}(G_{he}(s)) \geq |G_{he}(s)|, \forall \omega \geq 0\end{aligned} \tag{13}$$

In which the following can be easily found:

$$\frac{\mathrm{Re}(G_{he}(s))}{|G_{he}(s)|} = \cos(\angle G_{he}(s)) \geq 1 \tag{14}$$

For a system with sampling and holding, the lag or delay of phase ensures $\cos(\angle G_{he}(s)) < 1$, which means the haptic interface is not absolutely stable.

4.2 System Stability Conditions with Virtual Coupling Introduced

For such system, to guarantee that haptic interface is absolutely stable, the method preferred is to introduce the virtual coupling path, and for admittance-recreation approach, it means to add virtual mass-damping willingly unit between haptic interface and virtual environment. The two-terminal network is shown in Fig.5:

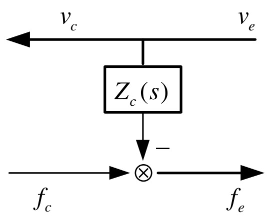


Fig. 5. Virtual coupling network composed of mass-damping

The relationship of the parameters in the virtual coupling is shown as following:

$$\begin{pmatrix} v_c(s) \\ f_e(s) \end{pmatrix} = \begin{pmatrix} 0 & -1 \\ 1 & Z_c \end{pmatrix} \begin{pmatrix} f_c(s) \\ -v_e(s) \end{pmatrix} \tag{15}$$

$$f_c = f_h \tag{16}$$

$$Z_c = \frac{b_c \cdot m_c s}{b_c + m_c s} \tag{17}$$

Substituting （15）, （16）, （17）into（8）,we can obtain:

$$\begin{pmatrix} v_h(s) \\ f_e(s) \end{pmatrix} = \begin{pmatrix} G_{hh}(s) & -G_{he}(s) \\ 1 & Z_c(s) \end{pmatrix} \begin{pmatrix} f_h(s) \\ -v_e(s) \end{pmatrix} \tag{18}$$

Hence, for admittance-recreation approach, with virtual coupling path introduced, the stability of the system can be got through（12）:

$$\begin{aligned}&\mathrm{Re}(G_{hh}(s)) \geq 0 \,\&\, \mathrm{Re}(Z_c(s)) \geq 0\\&\mathrm{Re}(Z_c(s)) \geq \frac{|-G_{he}(s)| + \mathrm{Re}(-G_{he}(s))}{2\,\mathrm{Re}(G_{hh}(s))}\end{aligned} \tag{19}$$

From which we see that to make sure of the absolute stability of system, there are two steps: 1)choose appropriate speed closed-loop controller to get $G_{hh}(s)$ all positively real; 2)using the function of frequency to find proper virtual coupling path $Z_c(s)$ to ensure that the second description in equation （19） is true.

4.3 Transparency Oriented Virtual Coupling Optimization

Performance of the haptic interface system can be measured on the degree of transparency. For an ideal system, position of the main hand and force should be exactly corresponding to position and force in virtual environment. For the two-terminal network system we described, the mixture mapping matrix should satisfy:

$$\begin{pmatrix} v_h \\ f_e \end{pmatrix} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} f_h \\ -v_e \end{pmatrix} \tag{20}$$

According to (20), to realize the thorough transparency in haptic interface system, the following should be satisfied:

$$\begin{aligned}&G_{hh} = \frac{1}{ms + b + (K_v + \frac{K_p}{s}) \cdot G_{ZOH}} = 0\\&G_{he} = \frac{(K_v + \frac{K_p}{s}) \cdot G_{ZOH}}{ms + b + (K_v + \frac{K_p}{s}) \cdot G_{ZOH}} = 1\\&Z_c = \frac{b_c \cdot m_c s}{b_c + m_c s} = 0\end{aligned} \tag{21}$$

To achieve the total transparency of the system, speed closed-loop gain should be increased as much as possible. At the same time, impedance of the virtual coupling path should be decreased as much as possible. However, the realization of the stability of haptic interface system should simultaneously satisfy the stability conditions listed by equation （19）, and this calls for us to find an equilibrium point between stability and transparency of the system. The is a multi-variable related, multi-goal, non-linear, complicated process.

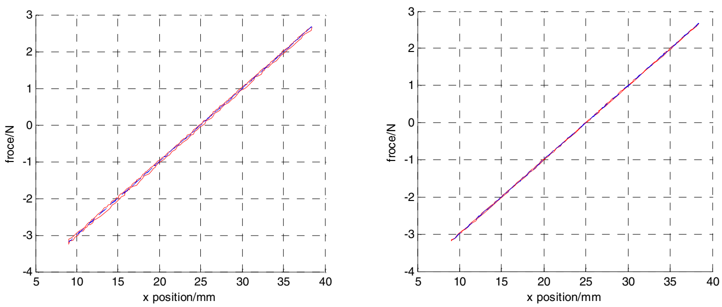
The four parameters K_v， K_p， b_c， m_c in equation （21） can be used as design parameters for optimization, equation （19） can be used as constraint conditions for optimization, the three parameters G_{hh}， G_{he}， Z_c can be used as goal of optimization. Computation with the optimizing toolbox of MATLAB, utilizing linear search algorithm by Quasi-Newton, optimized velocity loop gain parameter and virtual coupling parameter can be achieved.

5 Experimental Research

Using the virtual coupling parameters obtained through optimization, the experiment of simulation and recreation of the virtual spring force and damping is done.

5.1 Spring Force Simulation

Assuming the stiffness of virtual environment is 200N/m, operator takes hold of the handle and move at a certain speed(approximately 10mm/s) along x-axis back and forth, the zero-force-position of the spring is at x=25mm,the tested result of the mapping relationship is illustrated in Fig.6.



a) b)

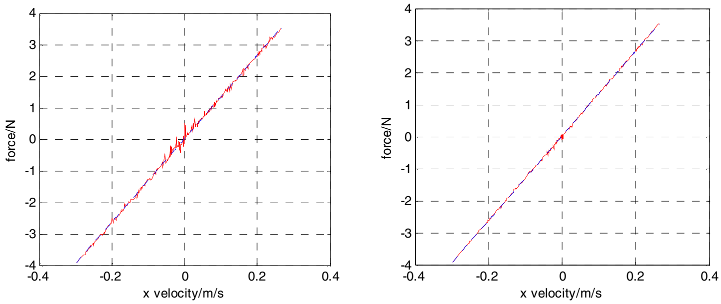
Fig. 6. Experimental curve of the spring force simulation. a) with regular PID controller. b) with virtual coupling optimized controller.

It is obvious that force and displacement in Fig.6b) are related to each other in a more linear way than the one in Fig.6a), and during repetitive movement, the degree of non-overlapping of the loaded curve is less than 0.05N, indicating that optimized virtual coupling path has overcome the influenced caused by the damping and inertia of the hardware in a better way.

5.2 Damping-Force Simulation

Assuming the elastic coefficient of the virtual environment is 14N.s/m, and operator holds the handle, moving along the x-axis, the experiment result is shown in Fig.7:

In which the dashed line means the linear least square of the result point. As shown in Fig.7a), At approximately zero point, the working of the hardware transpose from static friction and dynamic friction, resulting in additional random interruption ,thus causing relatively larger force fluctuation at zero-speed area. In Fig.7b), it is easily seen that with the virtual coupling path under way, system keep stable, and the strengthening of transparency does good to the linear relationship of force and velocity.



a) b)

Fig. 7. Experimental curve of the damping force simulation. a) with regular PID controller. b) with virtual coupling optimized controller.

6 Conclusion

A novel low-inertia, high bandwidth admittance haptic interface device is designed, the introduction of port network theory guarantees the absolute stability of new admittance haptic system. Moreover, through the optimization of the virtual coupling parameters and speed closed-loop gain parameters, higher transparency of the system is derived. By utilizing the new approach into the haptic system, experiments results have shown apparent improvement of transparency within the stable control domain. This paper has formed a basis for the transparency and stability oriented design and analysis for multi-degrees-of-freedom admittance haptic interface system.

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