Fuzzy Virtual Coupling Design for High Performance Haptic Display

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Abstract. Conventional virtual coupling is designed mainly for stabilizing the virtual environment (VE) and it thus may have poor performances. This paper proposes a novel adaptive virtual coupling design approach for haptic display in passive or time-delayed non-passive virtual environment. According to the performance errors, the virtual coupling can be adaptively tuned through some fuzzy logic based law. The designed haptic controller can improve the "operating feel" in virtual environments, while the system's stability condition can still be satisfied. Experimental results demonstrate the effectiveness of this novel virtual coupling design approach.

1 Introduction

Haptic feedback is a way of conveying information between human and computer [1], [2], [3]. As with most control problems, there are two conflicting goals for haptic display designs, performance and stability. Earlier research focused more on stability than fidelity issues. The stability of haptic system was first addressed by Minsky et al. [4]. In their paper, a continuous time, time-delayed model approximated the effects of sample-and-hold. Colgate et al. [5] used a simple benchmark problem to derive conditions under which a haptic display would exhibit passive behavior. A more general haptic display system design method to guarantee stable operation-- "virtual coupling" structure was introduced by Colgate et al. [6] and Zilles et al. [7] by connecting the virtual environment with the haptic device. The proposed virtual coupling was a virtual mechanical system interposed between the haptic interface and the virtual environment to limit the maximum or minimum impedance presented by the virtual environment in such a way as to guarantee stability.

Correct selection of virtual coupling parameters can guarantee stable haptic display in virtual environments. The virtual coupling parameters can be set empirically or by some theoretical design procedure. One fruitful approach is to use the idea of passivity to design the virtual coupling, as passivity is a sufficient condition for system stability. The major problem with using passivity theory for designing virtual coupling parameters is that it is too conservative. To improve the performance, Adams et al [8] derived

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a new virtual coupling design approach, by applying impedance or admittance based haptic display, which is less conservative than the passivity based design method. Miller et al. [9] extended the analysis to nonlinear non-passive virtual environments and designed the virtual coupling by considering the whole passivity condition of both the virtual environment and the haptic interface, so that the excessive passivity can be reduced by extracting some constant damping from the haptic interface. Hannaford et al. [10] moved a step further by designing a virtual coupling with adaptively changing parameter value, which was calculated in real time through the virtual environment "passivity observer". A disadvantage of these methods is that they cannot improve the haptic interface performance if the virtual environment is passive.

In this paper, we propose a new virtual coupling design method: two-port network model based adaptive virtual coupling for stable and accurate haptic display. Different from constant-parameter virtual coupling, the parameter values of this two-port network model based virtual coupling can be adaptively tuned according to fuzzy logic algorithm [11], [12]. Due to its simple structure, fuzzy logic algorithm is relatively easy to use and is well understood by a great majority of industrial practitioners and automatic control designers [12], [13]. Comparing with traditional virtual coupling, this two-port network based virtual coupling can increase the performance of haptic interface in addition to stabilizing the whole haptic display system. The adaptive tuning of the virtual coupling can improve the system's response time, increase the haptic display accuracy.

This paper is organized as follows: in Section 2, we briefly review the network based haptic display system and traditional virtual coupling. In section 3, the adaptive nonlinear virtual coupling for haptic display is presented. In section 4, we present some case studies using this fuzzy logic based haptic controller in experiments. Finally the conclusions are drawn in section 5.

2 Network Based Haptic Display

Network models, common in circuit theory, where they are used to characterize the effects of different loading conditions on two terminal electrical networks, are a natural way of describing stability and performance in bilateral teleoperation [2], [14], and in the field of control for haptic display [8], [10]. Haptic display methods can be divided into two categories: Admittance based and Impedance based haptic display. For admittance based haptic display, the operator applies force to the haptic interface, the haptic interface produce a kinematic movement to the operator, whereas the impedance based haptic display works the other way around.

Fig. 1 shows a typical structure of the network based haptic controller for admittance based display. In Fig. 1, the human operator, virtual coupling and virtual environment are modeled as a one-port network model, whereas the haptic interface is modeled as a two-port network model. The human operator contacts the haptic interface with the velocity v_h and force f_h. The virtual environment modulates the angular velocity v_r and force f_r according to the physical law in the virtual world. For impedance based haptic display, the directions of the arrows are inverted.

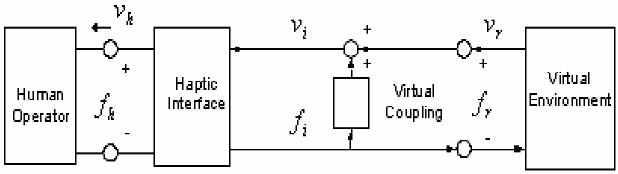

Fig. 1. Typical network based admittance haptic display system

3 Adaptive Virtual Coupling Design for Haptic Display

In most prior research work, the virtual coupling is designed as a damping element connecting the haptic interface and the virtual environment to stabilize the nonlinear VR. It is difficult to achieve at the same time a high performance for the haptic display with such an approach. To overcome such a limitation and to improve the performance of the haptic display, we develop an adaptive nonlinear virtual coupling based on two-port network model and fuzzy logic. By adaptively tuning the parameters of the nonlinear virtual coupling, the fuzzy logic based virtual coupling can result in a stable and high performance haptic display. In what follows, we first introduce the two-port network based virtual coupling. Then we present the design method using fuzzy logic theory. The following derivation is based on the admittance based haptic display.

The proposed two-port network based virtual coupling is different from the traditional virtual coupling structure. As shown in Fig. 2, the two-port network model based virtual coupling is designed as follows: f_r equals the measured interaction force f_h, v_i is the measured velocity from the haptic device, v_r is VE output. Here f_i is the virtual coupling output to the haptic device and its parameter k as shown in equation (1) is adaptively tuned by the fuzzy logic based law. Here only this parameter is tuned, because general fuzzy based PID parameter tuning method has proved its validity and easy to use [11].

From Fig. 2, f_i can be represented in a new form:

$$f_i(t) = K\Delta x(t) + K_i \int \Delta x(t)dt + B\Delta \dot{x}(t) \tag{1}$$

where $\Delta x(t) = x_r(t) - x_i(t)$, is the displacement error between the controller haptic interface output $x_i = \int v_i dt$ and the reference virtual environment displacement output $x_r = \int v_r dt$, $f_i(t)$ is the controller input to the haptic interface. K, B, K_i areconstant gains that can be determined by Ziegler-Nichols formula respectively.

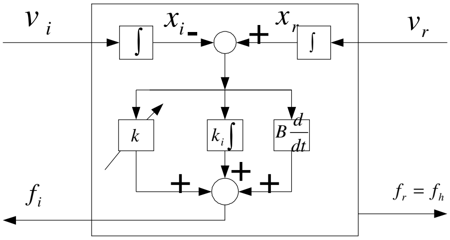

Fig. 2. Adaptive virtual coupling design for haptic display

Converting equation (1) into frequency domain, we have

$$F_i(s) = K\Delta X(s) + K_i \frac{\Delta X(s)}{s} + Bs\Delta X(s) \tag{2}$$

Using backward difference and the trapezoidal approximation for the derivative and the integral respectively, the discrete-time realization of (2) is

$$\begin{aligned} F_i(z) = {} & K\Delta X(z) + K_i \frac{T}{2}\frac{1+z^{-1}}{1-z^{-1}}\Delta X(z) + \\ & B\frac{1}{T}\left(1-z^{-1}\right)\Delta X(z) \end{aligned} \tag{3}$$

where $T > 0$ is the sampling period. Here we extended the fuzzy set-point weighting based technique [11] and derive our algorithm called the extended fuzzy set-point weighting technique which is described in the following formulation. Equation (3) can be rewritten as:

$$\begin{aligned} & F_i(nT) = K(\delta(nT)x_r(nT) - x_i(nT)) + \\ & K_i \frac{T}{2}\frac{1+z^{-1}}{1-z^{-1}}\Delta x(nT) + B\frac{1}{T}\left(1-z^{-1}\right)\Delta x(nT) \\ & \delta(nT) = 1 + f(nT) \end{aligned} \tag{4}$$

Where $f(nT)$ is the output of a fuzzy inference system consisting of triangular and trapezoidal membership functions for the two inputs $\Delta x, \Delta\dot{x}$, and nine triangular functions for the output. The fuzzy rules are listed in Fig. 3.

In Table 1, the definitions of the linguistic variables in the fuzzy inference system are given.

Through the designed controller, we can see, by tuning $f(nT)$, the controller parameter K can be tuned accordingly. While $f(nT)$is the fuzzy inference of two inputs $\Delta x, \Delta\dot{x}$ according to the fuzzy rule.

The fuzzy based virtual coupling must keep system stable in nonlinear virtual environments. This can be realized by tuning the dead zone width $d > 0$ of the membership function as seen in Fig. 4. In general, the dead zone width can be different. Here we let them be same to simplify the design and notation in the following discussions.

				$\Delta\dot{x}$		
		NB	*NS*	*Z*	*PS*	*PB*
	NB	*NVB*	*NB*	*NM*	*NS*	*Z*
	NS	*NB*	*NM*	*NS*	*Z*	*PS*
Δx	*Z*	*NM*	*NS*	*Z*	*PS*	*PM*
	PS	*NS*	*Z*	*PS*	*PM*	*PB*
	PB	*Z*	*PS*	*PM*	*PB*	*PVB*

				$\Delta\dot{x}$		
		NB	*NS*	*Z*	*PS*	*PB*
	NB	*PVB*	*PB*	*PM*	*PS*	*Z*
	NS	*PB*	*PM*	*PS*	*Z*	*NS*
Δx	*Z*	*PM*	*PS*	*Z*	*NS*	*NM*
	PS	*PS*	*Z*	*NS*	*NM*	*NB*
	PB	*Z*	*NS*	*NM*	*NB*	*NVB*

Fig. 3. Basic rules for the fuzzy inference (upper: when $x_r > 0$, lower: when $x_r < 0$)

Table 1. Definition of the linguistic variables

NVB	Negative very big
NB	Negative big
NM	Negative medium
NS	Negative small
Z	Zero
PS	Positive small
PM	Positive medium
PB	Positive big
PVB	Positive very big

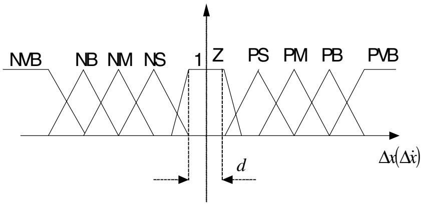

Fig. 4. Stabilizing the haptic interface by tuning the fuzzy dead zone width

4 Implementations

4.1 Experimental Setup

Fig. 5 illustrates the schematic diagram of our experimental test bed. The haptic device is a planar 1-DOF rotating link with a vertical joint connected to a DC motor through a gearbox with a ratio 1:80. The mass of the moment inertial of the link is $I = 2.438\times 10^{-2} kgm^2$. An optical encoder, with a resolution of 500 pulses per revolution, measures the joint angular displacement. A finger type three-dimensional force sensor is installed on the end of the link. This force sensor has a resolution of $0.005N$ for the force measurement in each direction. A DSP (PS1103 PPC) controller board is used on a host PC for the haptic display control. The PC based virtual environment is connected to the controller for real-time information change.

The first experiment conducted is the performance comparison between the traditional virtual coupling and our adaptive virtual coupling for the case of a virtual wall. The second experiment repeats the first but with the computational time delay and feedback signal time delay incorporated respectively. To obtaining objective results, a point-mass of 0.1 kg is installed on top of the three-dimensional force sensor to replace the human operator.

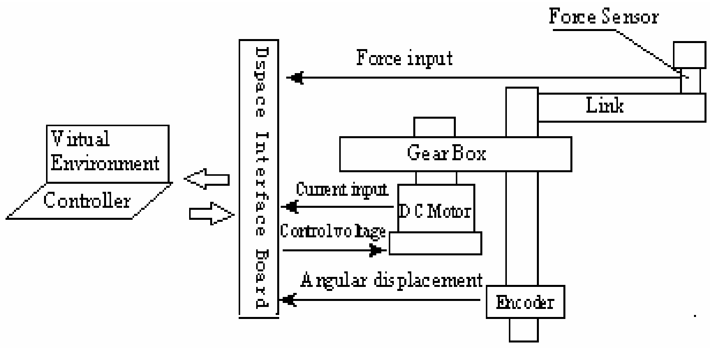

Fig. 5. Schematic diagram of the experimental test bed

4.2 Experimental Results

The first experiment displays a virtual wall without considering any time delay. The virtual finger driven by the haptic device met the virtual wall at $\theta = 1.744$ from its initial position. For admittance based haptic display, we model this ideal "virtual wall contact" behavior as a displacement step function output. Fig. 6 shows the experimental result by using the traditional virtual coupling and our adaptive virtual coupling scheme. The dashed line shows the interaction displacement response of the haptic display system using the adaptive virtual coupling. The dash-dotted line shows the experimental results using the traditional virtual coupling. Comparing the results of the two controllers, we can see that with the adaptive virtual coupling scheme, very little overshoot or fluctuation is observable in the displacement when meeting the virtual wall. Here the initial fuzzy logic based virtual coupling parameters were selected using IAE principle as $K = 3.5, B = 0.12$.

In the next experiment, we considered in the display of a virtual wall with time delay of 0.1s as the disturbance from the feedback signal. The initial virtual coupling parameter values were set at $K = 0.5, B = 0.12$. Fig. 7 shows the corresponding results. The dash-dotted line shows the experimental results using the traditional virtual coupling. The dashed line shows the display result using our adaptive virtual coupling in which case a fast response in the displacement is clearly observable.

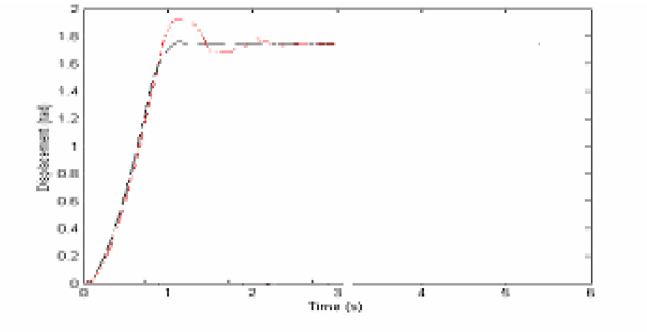

Fig. 6. Interaction with no time delay

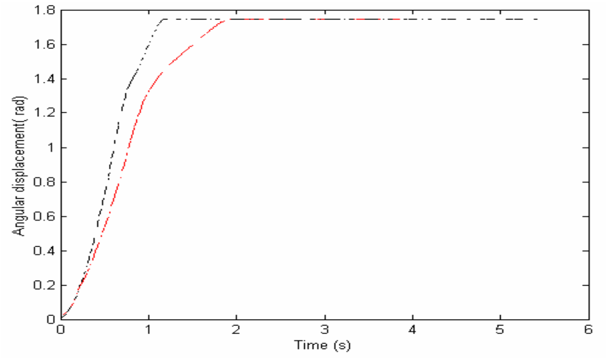

Fig. 7. Interaction with 0.1s delay

Table 2. The IAE values using adaptive virtual coupling and constant virtual coupling

	Adaptive virtual coupling	Constant virtual coupling
Haptic display with no time delay	0.918	1.213
Haptic display with 0.1s delay	1.003	1.308

Table 2 shows the quantitative comparison of the IAE values of the experimental results using the adaptive virtual coupling and traditional virtual coupling approach. From the comparison, we can see that the performance is improved in all the cases when using the adaptive virtual coupling as compared against using the traditional virtual coupling.

5 Conclusions

The conventional virtual coupling design for haptic display is concerned mainly with stability, which usually makes performance conservative. This paper presents an adaptive virtual coupling design approach for haptic display which takes into account both the stability and performance in its design. The studies show that with the adaptive haptic coupling design, improved performance in the haptic display can be achieved, while at the same time the stability can be guaranteed by tuning the parameters when VE is bounded output.

The implementation proved the validity of the developed adaptive virtual coupling design method. The Fuzzy logic based adaptive virtual coupling can increase the system's speed of response and the haptic display accuracy in addition to stabilizing the human-haptic interface interaction. Further explorations in the work include the how to select initial parameters for stable and accurate haptic display.

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