

# Realistic and Stability Performances of Haptic System with Adaptive Virtual Coupling

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## Abstract

A high performance haptic system should provide both stable and realistic interaction to users. In order to improve system stability, virtual couplings have been used in order to separate the haptic display from virtual environment simulations. A static virtual coupling can improve system stability but unfortunately degrades realistic performance of the system. This improved concept named adaptive virtual coupling is designed such that its parameters can be adjusted to maximize realistic performance while ensuring stability. The experimental result indicated that with adaptive virtual coupling users could feel more realistic interaction than the existing static virtual coupling method.

**Keywords:** Haptic System, Realistic Performance, Virtual Reality

## 1. Introduction

Visual-based interaction, a VR interaction modality, while very useful for many applications, is sometimes insufficient to give the user a sense of immersion in the virtual environment. Many simulations, especially ones that involve manual dexterity, require haptic sensation to allow user to understand the digital information. Not only the correspondence of force and visual interface, but also the safety of the interaction should be seriously concerned. For these reasons, the main objective of haptic interface is to provide realistic feeling to users while maintaining stability.

Many researches have been explored the aspect of stability in haptic system for ensuring haptic system stability. Colgate and his colleague [1] proposed a linear two-port network named virtual coupling in order to guarantee system stability. Such component is used to couple simulation of a virtual environment and haptic device. These parameters are necessary for achieving system stability. Hannaford and Adams [3][4][5] also implemented a virtual coupling in their system. When each end of this coupling is connected with passive environment and human, necessary and sufficient conditions of the virtual coupling which guarantee system stability could be determined. Ryu and Hannaford [6] used a time domain passivity control in order to regulate the excess energy and perform a real-time dissipation. However, while enhancing the system stability, such a virtual coupling affects the realism of haptic simulation due to coupling impedance.

A high performance haptic interface should allow users to feel like he or she interacts with real environment while, in fact, interacting with virtual environment.

Hence, the transparency defined as a quality of force and velocity transformation of haptic systems is a very crucial property in the required performance. Colgate and Brown [7] used a dynamic range of achievable impedance so called "Z-Width" to measure the performance of force reflecting interfaces. Furthermore, Lawrence [8] proposed a concept of "Ideal-Equivalent" which considers the limitation of human sensation. By knowing this limitation, an impedance objective, a range of realistic interaction impedance sufficiently convincing users, could be determined.

## 2. Virtual Coupling

Consider a linear one-degree of freedom impedance display haptic system as shown in figure 1

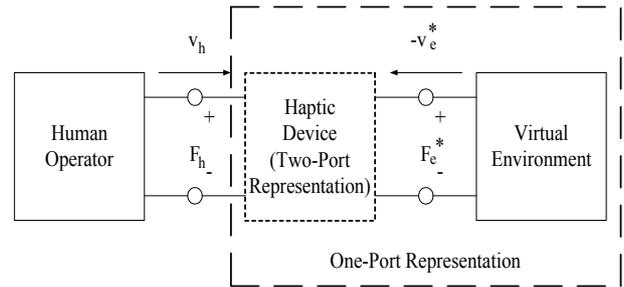


Figure 1 Impedance Display Haptic System

From figure 1,  $F_h$ ,  $v_h$ ,  $F_e$  and  $v_e$  represent human force, human velocity, virtual environment force and virtual environment velocity, respectively. The parameters with "\*" are in discrete form. The haptic system can be modeled in form of Two-port representation as

$$\begin{bmatrix} F_h \\ -v_e^* \end{bmatrix} = \begin{bmatrix} Z_d(z) & ZOH(z) \\ -1 & 0 \end{bmatrix} \begin{bmatrix} v_h \\ F_e^* \end{bmatrix} \quad (1)$$

In order to find the unconditionally stability criteria of a two-port network haptic system, the human operator and the virtual environment should be assumed to be passive operators. From Llewellyn's stability criteria [6], typical haptic system would not be unconditional stable. However, it does not mean that the system will always unstable. Therefore, Colgate and his colleague [2] proposed a virtual coupling which is a synthetic coupling. This coupling, which will be described in the next subsection, is used as a complementary component in order to make the system satisfy unconditionally stability criteria.

A virtual coupling, a synthetic coupling which is shown in figure 2, is used for connecting between the haptic device and the virtual environment in order to improve the stability of haptic interface system.

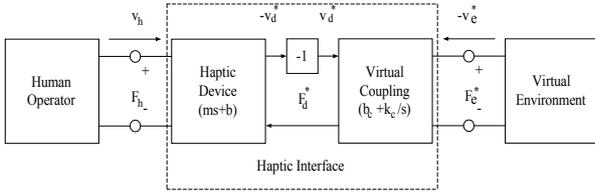


Figure 2. Schematic Diagram of a Haptic System with a Virtual Coupling

This coupling could be modeled as any arbitrary structure. As shown in figure 2, a spring/damper model is used as our coupling. The impedance of the virtual coupling is

$$Z_c(z) = \left( b_c + \frac{k_c}{s} \right) \Bigg|_{s \rightarrow \frac{z-1}{Tz}} \quad (2)$$

The two-port representation of the haptic system with a virtual coupling can be written as

$$\begin{bmatrix} F_h \\ -v_e^* \end{bmatrix} = \begin{bmatrix} Z_d(z) & \text{ZOH}(z) \\ -1 & 1/Z_c(z) \end{bmatrix} \begin{bmatrix} v_h \\ F_e^* \end{bmatrix} \quad (3)$$

Based on Llewellyn's stability criteria [6], this haptic system with a virtual coupling would be an unconditionally stable system if

$$\text{Re}(Z_d(z)) \geq 0, \quad (4)$$

$$\text{Re}(1/Z_c(z)) \geq 0, \quad (5)$$

$$\text{Re}(1/Z_c(z)) \geq \frac{1 - \text{COS} \angle \text{ZOH}(z)}{2 \text{Re}(Z_d(z))} |\text{ZOH}(z)| \quad (6)$$

From equation (6), the virtual coupling could be designed to satisfy the unconditionally stability criteria.

### 3. Adaptive Virtual Coupling

Even though the use of the pre-calculated virtual coupling can ensure system stability when the human operator and the virtual environment are passive, but at the same time the realistic performance is affected. Thus, the compromising solution between stability and realistic performance of haptic system can be found by adapting the virtual coupling parameters. The adaptive virtual coupling has parameters that are adapted according to interaction frequency to satisfy both stability condition and realistic performance during operation.

The realistic performance boundaries, proposed by Lertpolpairaj and his colleagues [10], represent variation of human perceived impedance ( $Z_h(z)$ ) while stably interacting with the reference environment through a haptic interface without virtual coupling.

These boundaries depend on impedance of an adjustable virtual environment. They could be delineated from an experimental data. The upper and lower values of this range are substituted into the human perceived impedance equation, equation (1), and the plot of realistic performance boundaries can be

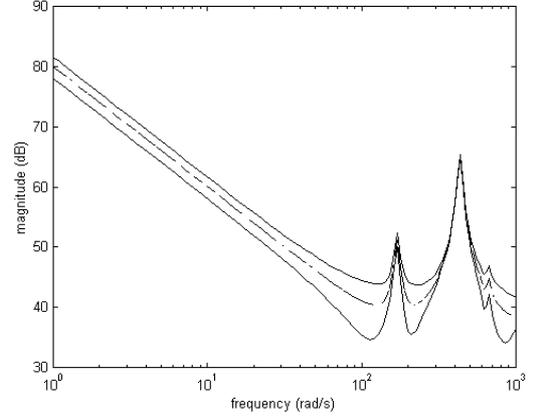


Figure 3. Realistic Performance Boundaries of a Haptic Interaction

impedance while interacting with a reference virtual environment. Two solid-lines above and under the dash-line are the upper boundary and lower boundary of the realistic performance boundaries respectively.

### 3.1 An Algorithm for Determining Parameters of an Adaptive Virtual Coupling

adaptive virtual coupling is

$$Z_{avc}(z) = \left( b_{avc}(z) + \frac{k_{avc}(z)}{s} \right) \Bigg|_{s \rightarrow \frac{z-1}{Tz}} \quad (7)$$

Thus, the human perceived impedance of haptic system with an adaptive virtual coupling ( $Z_{h\_avc}(z)$ ) can

$$Z_{h\_avc}(z) = Z_d(z) + \text{ZOH}(z)Z_{e\_avc}(z) \quad (8)$$

$$\text{,where } Z_{e\_avc}(z) = \frac{Z_e(z)Z_{avc}(z)}{Z_e(z) + Z_{avc}(z)} \quad (9)$$

Suppose that we want to find an adaptive virtual coupling of a virtual environment. The first set of parameters that should be determined are the parameters of the realistic performance boundaries such as the damping and stiffness of the upper bound ( $b_{e\_UCI}$  and  $k_{e\_UCI}$ ) and the damping and stiffness of the lower bound ( $b_{e\_LCI}$  and  $k_{e\_LCI}$ ). The desired human perceived impedance

( $Z_{h\_ds}(z)$ ), which represents these boundaries as shown in equation (10), can be formulated.

$$Z_{h\_ds}(z) = Z_d(z) + ZOH(z)Z_{ds}(z) \quad (10)$$

, where the desired impedance is

$$Z_{ds} = \left( \frac{(b_{e\_UCI} + b_{e\_LCI})}{2} + \frac{(k_{e\_UCI} + k_{e\_LCI})}{2s} \right) \Bigg|_{s \rightarrow \frac{T(z-1)}{2(z+1)}}$$

The desired impedance is defined as the impedance, which its magnitude is laying in the middle between the upper bound and the lower bound. Thus, the parameters of  $Z_{ds}$  are the average parameters between the parameters of these two bounds. Reminding that the goal of the adaptive virtual coupling is to maximize the realistic performance while ensuring system stability. Hence, this goal can be mathematically formulated as: To minimize:

$$\left( \left| Z_{h\_ds}(z) \right| - \left| Z_{h\_avc}(z) \right| \right)^2 \quad (11)$$

Subject to constraint:

$$\text{Re}(Z_{h\_avc}(z)) \geq 0, \quad \forall \omega \in \mathbb{R} \quad (12)$$

However, it is not easy to use  $b_{avc}$  and  $k_{avc}$  as the optimized variables because the impedance equations, i.e. human perceived impedance of haptic system with adaptive virtual coupling ( $Z_{h\_avc}(z)$ ) and

$Z_{h\_ds}(z)$ , are all complex functions. Moreover, our constraint, which is described in form of

$\text{Re}(Z_{h\_avc}(z))$ , cannot be easily represented in

$b_{avc}$  and  $k_{avc}$ . The feasible region of the solution (feasible  $b_{avc}$  and  $k_{avc}$  that satisfy the objective function and the constraint) is possibly a complicated contour and difficult to be determined. Therefore, in order to simplify our problem we use real part of  $Z_{h\_avc}(z)$  ( $\text{Re}(Z_{h\_avc}(z))$ ) and imaginary-part of  $Z_{h\_avc}(z)$  ( $\text{Im}(Z_{h\_avc}(z))$ ) instead of  $b_{avc}$  and  $k_{avc}$ .

$$J = \frac{1}{2} \left[ \left( \frac{\text{Re}(Z_{h\_ds}(z)) - \text{Re}(Z_{h\_avc}(z))}{\text{Re}(Z_{h\_ds}(z)) - \text{Re}(Z_{h\_avc\_max}(z))} \right)^2 + \left( \frac{\text{Im}(Z_{h\_ds}(z)) - \text{Im}(Z_{h\_avc}(z))}{\text{Im}(Z_{h\_ds}(z)) - \text{Im}(Z_{h\_avc\_max}(z))} \right)^2 \right] \quad (13)$$

where the constraint is the same as constraint equation (12). The terms  $\text{Re}(Z_{h\_avc\_max}(z))$  and

$\text{Im}(Z_{h\_avc\_max}(z))$  are the maximum real part and imaginary part of the searching space, respectively. Meanwhile, two conditions, i.e.

$\text{Re}(Z_{h\_avc\_max}(z)) \geq \text{Re}(Z_{h\_ds}(z))$  and

$\text{Im}(Z_{h\_avc\_max}(z)) \geq \text{Im}(Z_{h\_ds}(z))$  must be satisfied in order to ensure that the minimum point is located in the searching area. Instead of finding the minimum difference between  $\left| Z_{h\_ds}(z) \right|$  and

$\left| Z_{h\_avc}(z) \right|$ , the new objective is to find the

minimum difference between  $\text{Re}(Z_{h\_ds}(z))$  and

$\text{Re}(Z_{h\_avc}(z))$ , and between  $\text{Im}(Z_{h\_ds}(z))$

and  $\text{Im}(Z_{h\_avc}(z))$ . This objective function,

plotted in figure 5, is a quadratic function which has only one minimum point at

$$[\text{Re}(Z_{h\_avc}(z)), \text{Im}(Z_{h\_avc}(z))] = [\text{Re}(Z_{h\_ds}(z)), \text{Im}(Z_{h\_ds}(z))]$$

From equation (25), the constraint is an inequality

linear constraint, thus the feasible region can be

directly drawn on the contour of the objective function.

Such that, there are only two possible cases which are

$\text{Re}(Z_{h\_avc}(z)) \geq 0$  and  $\text{Re}(Z_{h\_avc}(z)) < 0$ .

Case 1:  $\text{Re}(Z_{h\_avc}(z)) \geq 0$

The minimum point which is the solution is

$$[\text{Re}(Z_{h\_avc}(z)), \text{Im}(Z_{h\_avc}(z))] = [\text{Re}(Z_{h\_ds}(z)), \text{Im}(Z_{h\_ds}(z))]$$

Case 2:  $\text{Re}(Z_{h\_avc}(z)) < 0$

The minimum point which is the solution is

$$[\text{Re}(Z_{h\_avc}(z)), \text{Im}(Z_{h\_avc}(z))] = [0, \text{Im}(Z_{h\_ds}(z))]$$

After  $\text{Re}(Z_{h\_avc}(z))$  and

$\text{Im}(Z_{h\_avc}(z))$  are determined,  $b_{avc}$  and  $k_{avc}$

which are the actual variables that we want to

determine can be easily derived by follow these steps.

Step1:

$$Z_{h\_avc}(z) = \text{Re}(Z_{h\_avc}(z)) + j\text{Im}(Z_{h\_avc}(z)) \quad (14)$$

Step 2:

$$Z_{e\_avc}(z) = \frac{Z_{h\_avc}(z) - Z_d(z)}{ZOH(z)} \quad (15)$$

Step 3:

$$Z_{avc}(z) = \frac{Z_e(z)Z_{e\_avc}(z)}{Z_e(z) - Z_{e\_avc}(z)} \quad (16)$$

Step 4:

$$b_{avc} = \left[ \text{Re}(Z_{avc}(z)) - \frac{k_{avc} \text{Re}(s)}{(\text{Re}(s)^2 + \text{Im}(s)^2)} \right] \Bigg|_{s \rightarrow \frac{T(z-1)}{2(z+1)}} \quad (17)$$

### 3.2 Implementation of adaptive virtual coupling

In order to implement the adaptive virtual coupling, there are two components, i.e. the interacting frequency estimator and the adaptation procedure, added in the system as illustrated in figure 4. The parameters of the



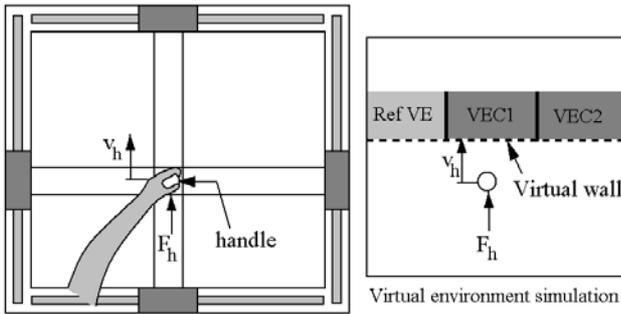


Figure 6 A Simulation Used as an Evaluation of Realistic Performance (Note that: Ref VE, VEC1 and VEC2 are Referenced Virtual Environment, Referenced Virtual Environment with Virtual Coupling (Number One) and Referenced Virtual Environment with Virtual Coupling (Number Two))

Table 1 Experimental Results on the Matching of the Virtual

VEs	No VC		Static virtual coupling			Adaptive virtual coupling		Unable to match
	Stability	Stability	Realistic performance	Stability	Realistic performance			
						Stable	Stable	
VE 2	10	10	10	10	3	10	3	4
VE 3	10	10	10	10	3	10	5	2
VE 4	10	10	10	10	6	10	4	0
VE 5	4	10	10	10	1	10	9	0
VE 6	0	10	10	10	1	10	9	0
VE 7	0	10	10	10	2	10	8	0

In the high stiffness virtual environments, such as VE5, VE6 and VE7, the realistic performance of the haptic system with adaptive virtual coupling is considerably increased as shown in Table 1. On the other hand, in the medium stiffness virtual environment, VE3 and VE4, user cannot distinguish the difference between two types of virtual coupling. Furthermore, in case of low stiffness: VE2, human could not even perceive the difference between the two simulations. These results show that the realistic performance of the haptic system with an adaptive virtual coupling is enhanced comparing with the haptic system with a static virtual coupling. However, the degree in improvement of the realistic performance depends on the impedance of the virtual environment. The adaptive virtual coupling enhances the realistic performance when it is used with the high stiffness virtual environment. However, the adaptive virtual coupling does not increase the performance when it is used with very low impedance environment.

### 5. Conclusions

In this research, a method of adapting the parameters of the virtual coupling according to the virtual environment which can enhance the realistic performance of haptic systems was proposed. A desired impedance based on realistic performance boundary is proposed in order to be used as our objective impedance. The parameters of the virtual coupling can be determined with respect to frequency. Therefore, each defined virtual environment has its

own set of parameters of virtual coupling that both ensure system stability and increase the realistic performance of system. The experimental results showed that the realistic performance of haptic system can be increased by using the adaptive virtual coupling especially with the high stiffness virtual environment.

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