# Development of a High Definition Haptic Rendering for Stability and Fidelity

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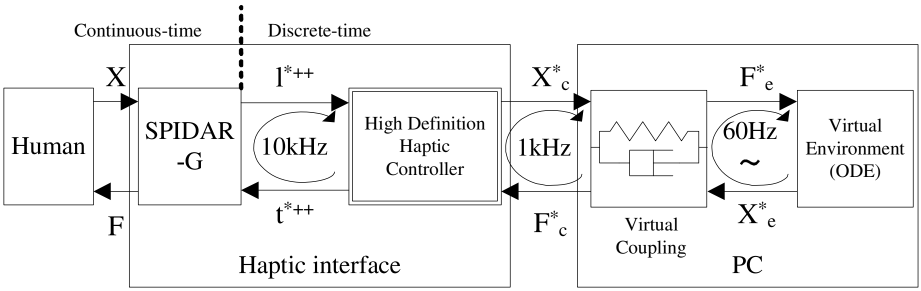
**Abstract.** In this study, we developed and evaluated a 10kHz high definition haptic rendering system which could display at real-time video-rate (60Hz) for general VR applications. Our proposal required both fidelity and stability in a multi-rate system, with a frequency ratio of approximately 160 times. To satisfy these two criteria, there were some problems to be resolved. To achieve only stability, we could use a virtual coupling method to link a haptic display and a virtual object. However, due to its low coupling impedance, this method is not good for realization of fidelity and quality of manipulation. Therefore, we developed a multi-rate system with two level up-samplings for both fidelity and stability of haptic sensation. The first level up-sampling achieved stability by the virtual coupling, and the second level achieved fidelity by 10kHz haptic rendering to compensate for the haptic quality lost from the coupling process. We confirmed that, with our proposed system, we could achieve both stability and fidelity of haptic rendering through a computer simulation and a 6DOF haptic interface (SPIDAR-G) with a rigid object simulation engine.

**Keywords:** Haptic interface, High definition haptic and SPIDAR.

## 1 Introduction

Over the past few decades, a considerable number of studies have been conducted on haptic interfaces. Interest in VR (Virtual Reality) applications that have physics simulators with haptic interfaces have, in particular, been growing. Generally, it is thought that a haptic interfaces should be controlled at approximately 1kHz frequency to achieve stable haptic sensation. However, there seems not to be enough haptic quality in the 1kHz haptic rendering to display hard surfaces with high fidelity. It is also difficult to accurately maintain the 1kHz frequency on a general PC (personal computer) environment where VR applications need a large amount of resources, depending on the scale of the application. We developed a special haptic controller that achieved a 10kHz high definition haptic rendering in a 3DOF (Degree Of Freedom) haptic interface [11].

J.A. Jacko (Ed.): Human-Computer Interaction, Part II, HCII 2011, LNCS 6762, pp. 3–12, 2011.




| | |
|---|---|
| $X$ : Grip position | $X^*_c$ : Grip position |
| $F$ : Displaying force | $F^*_c$ : Displaying force |
| $l^{*++}$ : Wire length | $X^*_e$ : Object position |
| $t^{*++}$ : Wire tense | $F^*_e$ : Displaying force to object |

**Fig. 1.** System configuration

The results of the study indicated that the haptic ability (Z-width) was approximately ten times as large as the ability of a traditional 1kHz haptic rendering. It was possible to stably display a hard surface with high fidelity in a VR application with a penalty based method. While we'd like to use an analytical based method [3] [16] [17] which allows a video-rate control frequency (60Hz) for visual sensation in a VR application, the frequency difference between the systems (60Hz to 10kHz) is approximately 160 times. One of the most important issues in this study was how to interpolate the large difference in satisfying both stability and fidelity. We describe these issues in following sections.

## 2 Achieving Stability and Fidelity

We aimed for achieving both stability and fidelity in manipulating a virtual rigid-object. The purposes of this study are given below.
The purposes of this study at visual sensation

- To avoid penetration between rigid-objects (fidelity of visual sensation).
- To maintain stability against a haptic device.
- To use a VR application frequency over video-rate(60Hz–).

The purposes of this study at haptic sensation

- To display the extra-stiffness of a virtual rigid-object.
- To maintain stability against a video-rate VR application.
- To use a haptic rendering frequency over 10kHz.

It is important to define an objective criterion for fidelity. Contact feeling is one of the most important factors in manipulation of a virtual rigid-object. When virtual rigid-objects collided with each other, a haptic device needs to display a life-like force. In this study, fidelity of manipulation of a virtual rigid object was evaluated by the stiffness of the object surface at the contact point. When we chose a penalty based method [19] [18] for a VR application in order to use an impedance haptic display, we could not avoid penetration between colliding objects when calculating the interaction force. From the viewpoint of visual sensation, such penetration influence is unreasonable because penetration between rigid-objects does not occur in the real world. On the other hand, with an analytical based method, such penetration does not occur and a video-rate frequency while conducting the interaction of objects can be stably maintained. Therefore, an analytical based method for VR application was the proper choice to achieve the purposes in this study. We adopted an analytical based method despite it having some problems with usage in an impedance haptic display.

## 3 Haptic Display

In this study, we focused on an impedance haptic display. There are several studies about controlling a haptic display for stability. Generally, it is thought that a high control frequency is necessary to achieve stable haptic sensation [15] [6] [14]. Colgate et al. [6] obtained a relationship (1) among the virtual wall's impedance (K and B), a haptic device inherent viscosity (b) and a control sampling time (T) to display haptic sensation for stability with a passivity method.

$$b > \frac{KT}{2} + B \tag{1}$$

According to the relationship (1), when trying to display a high impedance virtual wall, we need to decrease sampling time (T) (increase sampling frequency) or increase the inherent device dumper (b). When we increase the inherent device viscosity, it decreases the transparency between the device and user. Therefore, to increase sampling frequency, it is important to achieve stability and fidelity at the device level.

## 4 Virtual Coupling

When we use an impedance display in an analytical VR application, we cannot connect the two systems directly. Colgate et al. [7] proposed a coupling between a haptic device and a VR application with a virtual spring and dumper. The structure linking the two systems is called a virtual coupling [7] [8] [20]. Fig. 2 shows the connection of an impedance haptic display and an analytical VR application with virtual coupling. In this study, this coupling process allowed up sampling from video-rate (approximately 60Hz) to transmission frequency (approximately 1kHz) between a PC and a haptic controller. The force ($F_e$) inputted into the VR application was adopted to the average along time ($\overline{F_h}$) of the force ($F_h$) inputted into the haptic device.

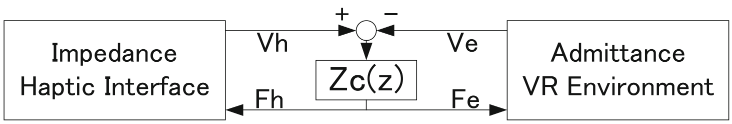



**Fig. 2.** Virtual coupling

$$F_h = Z_c(V_h - V_e) \tag{2}$$

$$F_e = \overline{F_h} \tag{3}$$

In this coupling structure, the stability and fidelity of the coupling depends on the coupling impedance ($Z_c$). To increase the fidelity, coupling impedance must also be increased. However, with VR applications running at video-rate, it is impossible to increase the impedance to maintain stability because of the loss of passivity of the virtual impedance causing severe oscillations in the haptic end-effecter for the user. In actuality, the coupling impedance must be set to a low value when using this coupling, though fidelity of manipulation of the virtual object suffers. In this study, to compensate for the loss of quality in the coupling process, a high definition haptic rendering with interpolation from information of a displaying wall was adopted.

# 5 High Definition Haptic Rendering

Most research about multi rate simulations in haptic sensation are directed for 1kHz frequency [1] [9] [10] [5] [4]. To achieve 10kHz frequency, an interpolating algorithm needs to be as simple as possible [11]. Especially in a 6DOF haptic rendering, we need the shape and dynamics of a virtual object which are connected to a haptic end-effecter to calculate displaying force accurately. In the case of 10kHz rendering, the difference of the position of the haptic end-effecter is small. We can make the accuracy of interpolation simpler with the basis of two assumptions during an interpolation. First, the dynamics of a virtual object linked to a haptic end-effecter are static. Second, the rendering surface of the virtual object is constant.

## 5.1 6DOF 10kHz Haptic Interpolation

We proposed a 6DOF interpolating algorithm for the 10kHz high definition haptic rendering. This interpolating haptic rendering (IHR) did not need a shape of a virtual object to calculate displaying force. The interpolating force was calculated by the force of the rendering surface and an impedance of the rendering surface. Fig. 3 indicates the interpolating haptic rendering in a 3DOF translation force. For a 3DOF rotation force, an analogy of the 3DOF translation was adopted.

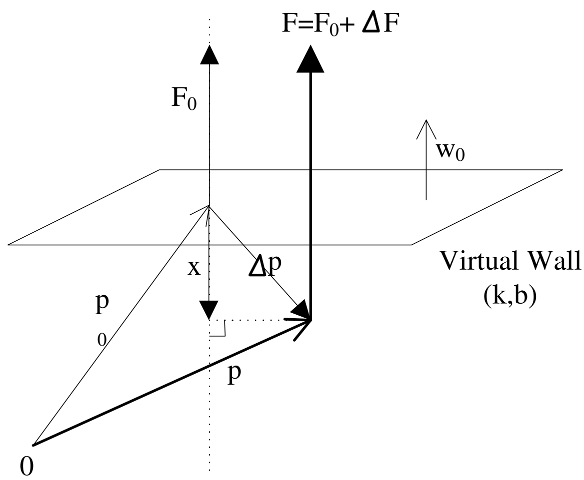



**Fig. 3.** Interpolating haptic rendering (IHR)

### 5.2 High Definition Haptic Controller

As described in previous sections, a high definition haptic controller (HDHC) was developed [11]. The controller has an SH4 micro-processor (SH7750@200MHz) made by Renesas Technology and a USB2.0 (universal serial bus) interface. The processor conducts haptic device inherent calculations such as measuring a position of the haptic end-effecter from the encoders count and distributing a force to the actuators. In order to achieve a high control frequency (10kHz), it was important to reduce overhead time in calling interrupt functions. Instead of using an OS (operating system) or RTOS (real time operating system) on the processor, the source code programming was implemented as the native programming. In particular, the time critical functions were written in assembler code. For the development environment, the implementation was used with HEW3 (Renesas Technology) which consists of a C/C++ compiler assembler (SuperH RISC engine tool-chain 7.1.3.0).

## 6 System Configuration

To summarize the system configuration (Fig. 4), a VR application based on an analytical method was carried out at video-rate (60Hz). A 6DOF haptic device based on an impedance display was performed at 10kHz with HDHC. The whole system was conducted as a multi rate system with two level up-samplings with a frequency ratio of approximately 160 times (60Hz over 10kHz). The first up-sampling process with a frequency ratio of 60Hz (video-rate) over 1kHz (USB transmission speed) consisted of the virtual coupling which connects the different input-output systems between the VR application and the haptic device. This process allowed for stable manipulation of a virtual object with a low coupling impedance. The second up-sampling process with a frequency ratio of 1kHz over 10kHz consisted of the high

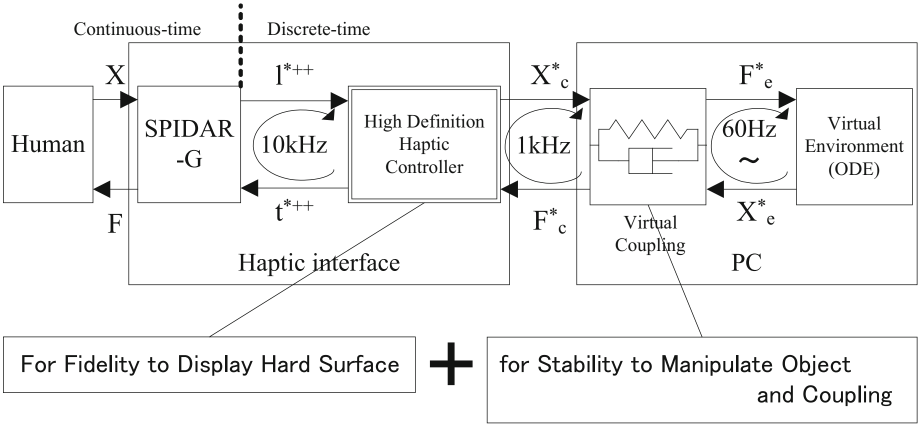



**Fig. 4.** System configuration

definition haptic rendering with the interpolation from information of the displaying wall. This process allowed for manipulation of a virtual object with high fidelity.

# 7 Evaluation

In this section, we describe an evaluation of our proposed system. We examined it with a computer simulation and an application with a rigid object simulation engine.

## 7.1 Computer Simulation

We performed a computer simulation to compare the proposed system with an ideal system (whole system control frequency of 10kHz) (Fig. 5). It is supposed that a haptic end-effecter displays force against a virtual wall in simulation. We examined the force trajectory with changes in the coupling impedance and the 10kHz haptic interpolating parameters (IHR) according to Table 1.

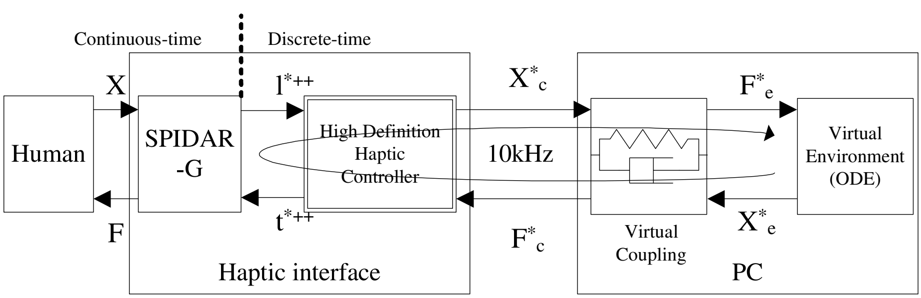



**Fig. 5.** System configuration of 10kHz ideal simulation

### 7.2 Simulation Results

In this simulation, the position of the haptic end-effector, as an input signal in this simulation, is shown in Fig. 6-(1), and the force trajectories A to C and D to F are shown in Fig. 6-(2) and Fig. 6-(3) respectively.

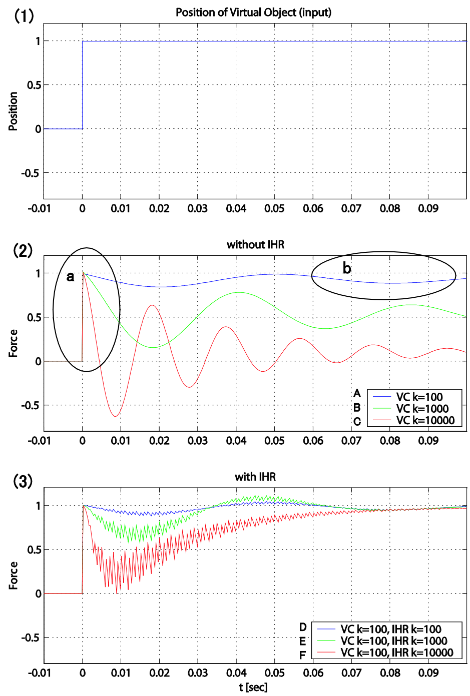



**Fig. 6.** Simulation Results

To compare the force in Fig. 6-(2) and (3), the trajectory is normalized to when the contact occurred. Fig. 6-(2) is the result of the ideal system. This result indicates that increasing a coupling impedance (Kc) makes the falling edge at the contact point (Fig. 6-(2)a) steep. This movement corresponds to the characteristics of the trajectory in [12] [2]. From the results of [12] [2], the stiffness of a real object becomes higher, and then the falling edge at contact point becomes steeper when we tap an object on the table in the real world. The trajectory after contact is restored to its normal state (Fig. 6-(2)b), depending on the coupling impedance (Kc). In comparison, Fig. 6-(3) shows the result of the proposed approach. This result indicates that in spite of the low coupling impedance, the IHR impedance was equal to that of a high coupling impedance at the contact point. At steady state, the trajectories with IHR ware restored to the convergent trajectory of low coupling impedance. At the contact point, a haptic end-effecter was coupled strongly to a virtual object, resulting in high fidelity. In the other manipulation of a virtual object, the coupling impedance became inherently low, creating high stability of manipulation. Therefore, this proposed

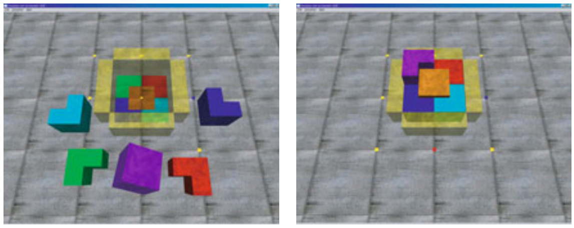


**Fig. 7.** 3D-puzzle

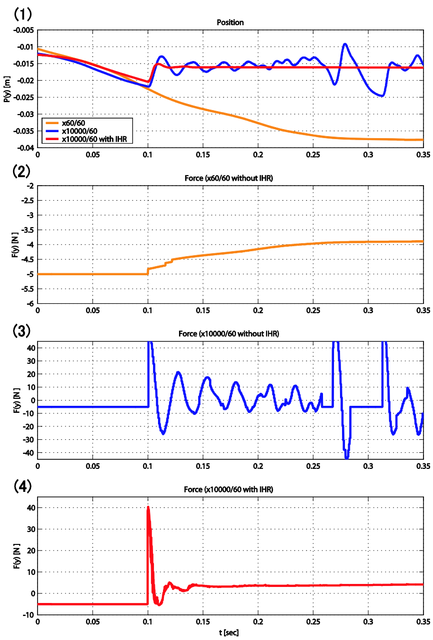



**Fig. 8.** Result of displaying virtual wall

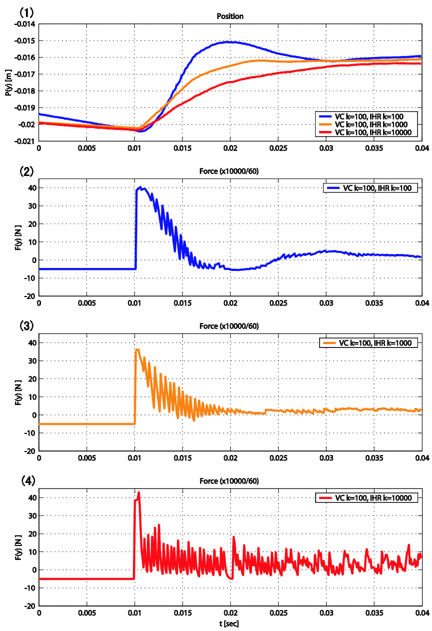



**Fig. 9.** Result of displaying virtual wall (high impedance)

system achieved both stability and fidelity in manipulation of a rigid virtual object. There was some noise until steady state increasing the interpolation stiffness. The noise, which did not occur with high coupling impedance in the ideal system configuration, seemed to have been caused by an error of the interpolation. However, the noise is very effective in replicating hard surfaces, yet does not induce severe vibrations. In [12] [2], the noise is one of the most important factors in displaying a hard surface, when recording a pulse signal or effective vibration from a haptic end-effecter, resulting in high fidelity.

### 7.3 Measurement of Displaying Force

We confirm stability and fidelity on the 3D-puzzle VR application(Fig.7). We measured position and force trajectories of tapping a virtual wall with a virtual object connected to the haptic interface. Fig. 8-(2)(3) are the results of the traditional haptic system with only virtual coupling(2) and with virtual coupling and without IHR(3) respectively. Traditional haptic systems cannot achieve a sharp surface or a stable surface like real one. Fig. 8-(4), Fig. 9 are the results of the proposed system with 10kHz IHR. The characteristics of the force trajectory in Fig. 8-(4) are very close to the ideal result when tapping an object surface in the real world [12] [2]. These results showed that applying our proposed system eliminates the problems of stability and fidelity in displaying virtual objects.

## 8 Conclusion

In this study, we proposed and implemented a new system configuration which achieved both stability and fidelity in a video-rate VR application using the 10kHz high definition haptic rendering whose frequency ratio is approximately 160 times. We confirmed that our proposed system could achieve the stability and fidelity of haptic rendering through a computer simulation and 3D-puzzle application. Results showed that this system provided both stability, achieved by the virtual coupling with a low coupling impedance, and fidelity, achieved by the 10kHz high definition haptic rendering with a high interpolating impedance, in manipulation of a virtual object.

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