



Haptic Interface Technique in Large-Scale Virtual Environment

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ABSTRACT

The CAD modeling system based on virtual reality (VR) techniques enables the user to create, modify and manipulate 3D CAD models intuitively, and at the same time allows the user to visualize CAD models immersively. This paper presents the research work on the development of haptic interface in the large-scale virtual environment and the integration of such a haptic interface in the VR based CAD modeling system. The haptic device has limited physical workspace compared to the large stereoscopic screen of the virtual environment. There is a mismatch between the workspace of the haptic device and the large-scale virtual environment. The haptic rendering algorithm presented in this paper consists of three parts: haptic workspace moving algorithm, collision detection, and collision response.

Keywords: CAD, virtual reality, haptics

1. INTRODUCTION

The techniques of digital freeform model generation have been developed and used in virtual product design, digital prototyping, NC simulation, surgery simulation, human model simulation, etc. [1], [10], [11]. Freeform models are widely employed in the aerospace, automobile, mold/die making, toy design, and many other industries. The shapes of those models are order of magnitude more complex than the product components used in most engineering systems. The design and modeling of a product component with freeform shape are beyond the capability of current Computer-Aided Design (CAD) systems such as NX, CATIA, and Pro-Engineer. For the past few decades, many investigators have been conducting researches on developing techniques which enable the creation of digital freeform model directly in a computer system. Such a freeform modeling system will shorten the product development cycle.

Most recently, freeform modeling system has been augmented by virtual reality (VR) techniques which enables the user to create, modify and manipulate 3D CAD models intuitively, and at the same time allows the user to visualize CAD models immersively. Haptic interface has become an important component in such a freeform modeling system based on VR environment. Haptic interface uses an electro-mechanical feedback device which enables a user to touch, feel, and manipulate virtual objects. Incorporating haptic

interface into the CAD modeling system provides the user with more realistic experience. Force feedback enables the user to feel the model creation process like actual interaction with physical materials. To continuously provide a stable sensation of touch, an update rate of at least 1,000 Hz is required for the haptic rendering [13]. Less than 1 kHz update rate will result in uncomfortable perception of friction, ridges, and general roughness.

The authors have developed a freeform modeling system integrated with large-scale virtual environment [11]. The limitation of the small physical size of the PC monitor has significantly impaired the realistic experience for the user to visualize the large scale models. With the implementation of stereoscopic visual feedback and haptic force feedback in an immersive large-scale virtual environment, the designer would appreciate a much better understanding of the 3D shape geometry and can explore through the 3D scene like he/she can do in the real world. However, the haptic device has limited physical workspace compared to the large stereoscopic screen of the virtual environment. There is a mismatch between the workspace of the haptic device and the large-scale virtual environment. This paper presents the research work on the development of haptic interface in the large-scale virtual environment and the integration of such a haptic interface in the freeform modeling system.



The rest of the paper is organized as follows. In Section 2, related works are reviewed. Section 3 presents the schematic structure of the large-scale virtual reality CAD modeling system. Haptic rendering algorithm is discussed in Section 4. Implementation and results are presented in Section 5. Conclusions are described in Section 6.

2. RELATED WORK

A haptic rendering algorithm consists of using information about the virtual environment to assign forces to be displayed, given the position, velocity, etc. of the operational point of a haptic interface. The operational point is the physical location on the haptic interface where position, velocity, acceleration, and force are measured. If a collision is detected between the operational point and the virtual environment, the interaction forces are computed using preprogrammed rules for collision response.

Based on the type of haptic interaction, the existing haptic rendering techniques can be divided into three kinds: point-based, ray-based, and 3D-based. The point-based haptic interaction algorithm simply models the haptic interface as a point [12], [15]. Zilles and Salisbury [15] used the term *haptic interface point* (HIP) to describe the operational point of the haptic interface. They proposed to use the god-object, also known as the Ideal Haptic Interface Point (IHIP), to represent to location of the surface point. The god-object's location is subject to the constraint that it is on the currently contacted surface (known as the active surface) and that the distance between the god-object and the HIP is minimum. For the ray-based algorithm, the haptic interface is modeled as a line segment [1], [6]. Many efforts have focused on rendering haptic interactions between two 3D models [5], [8].

Some research works have been done on integrating force feedback with CAD modeling. Swarup [14] developed a model to represent the dynamic behavior of visco-elastic objects, where virtual objects are modeled as a discrete network of masses connected by mechanical elements such as springs and dampers. Haptic interactions such as stroking, palpation, and plucking were demonstrated using this model. Dachille et al. [2] developed an algorithm to model the deformation of B-spline surfaces with haptic feedback. Point, normal, and curvature constraints could be specified interactively and modified intuitively with haptic feedback. They devised a dual representation of B-spline surfaces where the physics-based mass-spring model is mathematically constrained by a B-spline surface throughout the sculpting session. McDonnell et al. [9] proposed a real-time sculpting system with haptic toolkits. Based on subdivision of solids and physics-based modeling, the sculpting system gave the feeling of manipulating semi-elastic virtual clay.

The haptic device has limited physical workspace compared to the large stereoscopic screen of the virtual environment. Some solutions have been developed to address the mismatch between the workspace of the haptic device and the large-scale virtual environment. Scaling technique developed by Fischer and Vance [4] maps the haptic workspace to the workspace of virtual environment by amplifying the motion of PHANTOM with a scaling factor. The method has low precision. It becomes difficult if someone wants to edit a small portion of the large model. Clutching technique [7] works like a 2D mouse. When reaching the limit of PHANTOM workspace, the user may declutch and freeze the virtual cursor by pressing a button. Then the user can move the haptic device to a comfortable position, and then clutch the haptic device with the virtual cursor. This technique has higher precision yet low efficiency. The Bubble technique developed by Dominjon et al. [3] is based on position/rate control. A bubble (sphere) is defined and display as the boundary between the position-control zone and the rate-control zone. When the cursor is inside the bubble, the motion of cursor is fine controlled by the PHANTOM. When the cursor is outside, it will reach any location of the VE quickly. This method can achieve both high precision and high efficiency.

The technical contributions of the work described in this paper are described as following. The haptic workspace moving algorithm was developed to solve the workspace mismatch problem. Compared to the methods abovementioned, our method is easy to operate and has high efficiency. In our method, the user can move the haptic workspace by two convenient ways. The user can drag the haptic workspace to the desired location by holding the stylus button on haptic device. The user can also keep pressing then releasing the button, so the haptic workspace will "jump" to the destination. Our method provides fine and precise control to reach and touch the virtual object in virtual environment. The haptic rendering in our system also includes fast and accurate collision detection and force generation algorithms. By using the bounding box, only small amount of geometry data is searched for collision detection and active triangle generation purposes. The 1000 Hz update rate stringent requirement of haptic rendering can be achieved.

3. STRUCTURE OF LARGE-SCALE VIRTUAL REALITY CAD MODELING SYSTEM

The PowerWall system used in this work is a large-scale virtual reality system. As illustrated in Fig. 1., the PowerWall system consists of active stereo PowerWall, stereo eyewear and emitters, computer system, PHANTOM Omni, and tracking system. The PowerWall is a single, flat, large-scale (10 ft by 7.5 ft) stereoscopic screen illuminated from the rear by a video projector.

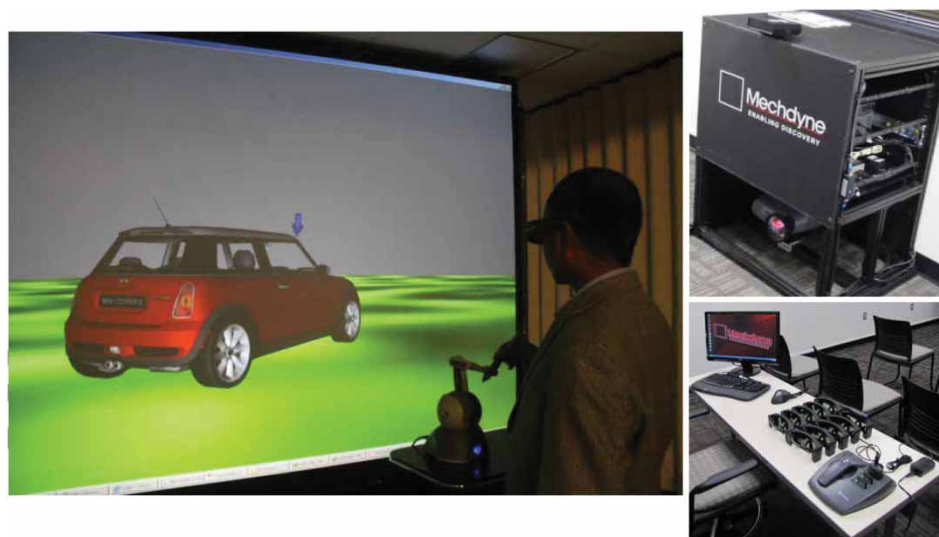


Fig. 1: The large-scale PowerWall virtual environment.

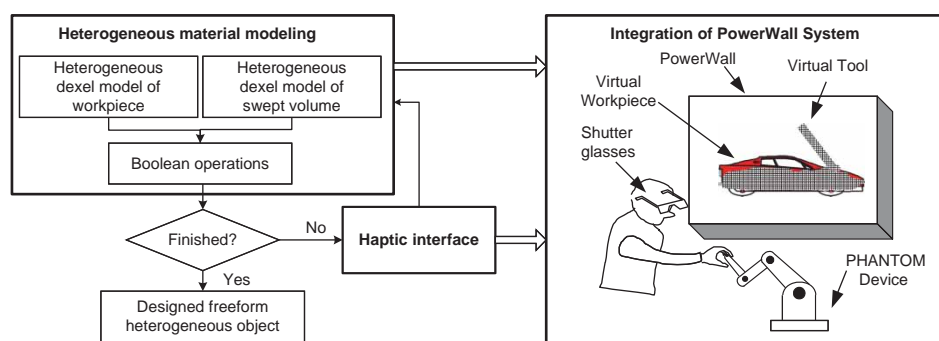


Fig. 2: Schematic of the system configuration.

When applications are reviewed in stereo-graphics, realistic 1:1 scale models and environments can be presented in highly accurate detail in sizes up to floor-to-ceiling. The Active Stereo Projector offers full active 3D stereoscopic display on PowerWall at 120 fps refresh rates at all resolutions up to 1080p inputs. The tracking system consists of a Tracker and a Wand. The tracker is a sensor that provides the position and orientation of the object that the tracker is mounted on and maps it to the object's relative position in the VE. The Wand is an input device which allows the user to move, rotate, and manipulate the 3D scene in the virtual environment. PHANTOM Omni is the haptic force feedback device used in this work. This device has three motors and six encoders to enable 6-DOF motion tracking and 3-DOF force feedback. Its workspace is 6.4 W x 4.8H x 2.8D in.

The schematic of the large-scale CAD modeling system is shown in Fig. 2. The research approach is to apply virtual sculpting method by interactively carving a workpiece using a virtual tool. A virtual tool controlled by a haptic device capable of 6-DOF positioning/orienting is used to carve a virtual workpiece to obtain the design model based on the designer's

intent. Boolean operations between the model and the tool are executed to change the geometry and materials of the design model simultaneously. Haptic interface is incorporated to reflect the interaction between the tool and the model during sculpting process. The virtual sculpting process is then integrated into the large scale PowerWall virtual environment. The solid modeling component of the system includes a triple-dixel generation module and a Boolean operation module. The solid modeling engine represents the volume of the sculpting tool for each segment of tool by 1) generating the triple-dixel representations of the tool and the workpiece by scan-converting their boundary representations, and 2) performing Boolean operations between the dixel representation of the workpiece and that of the tool [10], [11].

4. HAPTIC INTERFACE

As illustrated in Fig. 3., the haptic rendering algorithm in our system consists of three parts: (a) haptic workspace moving algorithm, (b) collision detection, and (c) collision response. First, the haptic workspace

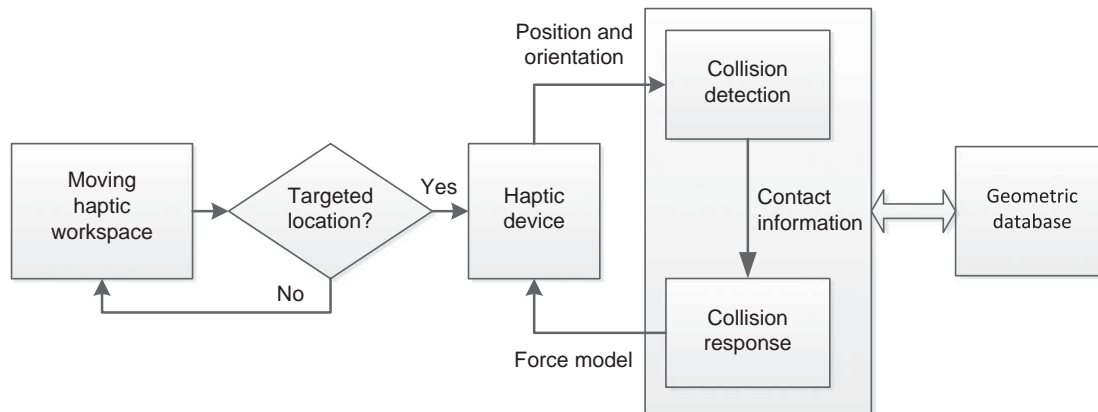


Fig. 3: The haptic rendering algorithm of the system.

moving algorithm allows the user to move the haptic workspace within the much larger virtual environment workspace. Once the haptic workspace is moved to the targeted location, the user can start the modeling process. As the user manipulates the stylus of the haptic device, the new position and orientation of the stylus are obtained. Then the position and orientation of the tool are input to the collision detection process. If a collision is detected between the haptic stylus and virtual workpiece, the contact force is calculated using a force model for collision response. The force is then conveyed through the haptic device to provide the force feedback.

4.1. Haptic Workspace Moving Algorithm

The PHANTOM Omni used as haptic device in the system has the workspace of 6.4 W x 4.8 H x 2.8 D in. The PowerWall is a single, flat, large-scale stereoscopic screen with the size of 10 ft by 7.5 ft. There is a mismatch between the workspace of the haptic device and the large size of PowerWall virtual environment. The haptic workspace moving algorithm has been developed to provide fine and precise control to reach and touch the virtual object in PowerWall virtual environment.

In this haptic workspace moving algorithm, the haptic workspace can be moved within the Virtual Environment as shown in Fig. 4. The VE workspace and haptic workspace are represented as boxes. The VE workspace is much larger than the haptic workspace. The detailed step by step procedures of the haptic workspace moving algorithm are described below:

- (I) In the beginning (Step One), the user can move the virtual tool inside the haptic workspace. When the user reaches the boundary of the haptic workspace, he/she presses the stylus button on PHANTOM. The modeling process is paused. The haptic workspace moving process starts. The center of the transparent box

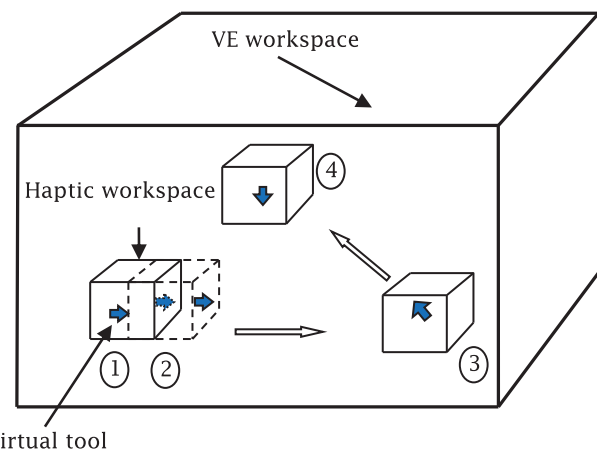


Fig. 4: Haptic workspace moving algorithm.

coincides with the virtual tool (Step Two). When the user releases the button, the haptic workspace coincides with the transparent box. The haptic workspace is moved. The virtual tool is now free to move inside the haptic workspace;

- (II) When the user keeps pressing then releasing the stylus button, the haptic workspace jumps in the direction of movement of virtual tool. The user can also drag haptic workspace while keeping holding the stylus button to reach any position (Step Three);
- (III) Once the haptic workspace reaches the destination (Step Four), the user will stop pressing the button. The haptic workspace will stop moving. The user can start editing the virtual object;
- (IV) Once the job is done, the process can be repeated.

4.2. Force Generation

After the haptic workspace is moved to the targeted location within the large-scale virtual environment,

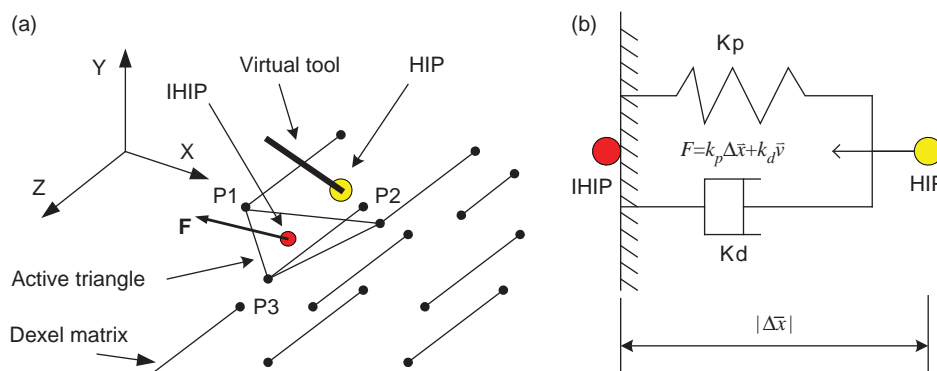


Fig. 5: Force generation algorithm.

the modeling process will be resumed. The next step in haptic rendering process is to find if the virtual tool is touching the object. After a collision is detected, forces are then determined and displayed as haptic feedback to the user.

The god-object concept suggested by Zilles and Salisbury [15] is adopted to haptically render the 3D model in the modeling system. Simply the virtual tool tracked by haptic device is simulated as a single point called the Haptic Interface Point (HIP). The ideal haptic interface point (IHIP) is considered to follow the trace of the HIP. The HIP can penetrate the object and the IHIP is constrained such that it doesn't penetrate any object.

When a collision is detected, the first step of the force generation algorithm is to extract a virtual boundary surface which will be utilized to interact with the virtual tool. Due to the stringent requirement of 1 K Hz update rate, it is impossible to construct the surface for the whole design model. The x and y position of the HIP can be tracked from the haptic device. As illustrated in Fig. 5(a), the dexel points P1, P2 and P3 which contain the HIP can be located so that they form a triangle. The HIP is enclosed in this triangle called "active triangle". As illustrated in Fig. 5(b), a virtual surface can be modeled as an elastic element. Then the reaction force acting on the tool during the interaction will be:

$$F = k_p \Delta \bar{x} + k_d \bar{v} \quad (4.1)$$

where k_p is the stiffness coefficient, k_d is the damping coefficient, $\Delta \bar{x}$ is displacement and \bar{v} is velocity. For frictionless interactions, the reaction force F is normal to surface of the object that the sculpting tool collides with. Keeping the stiffness coefficient low would make the surface perceived soft. If the virtual tool penetrates the object, the active triangle is constructed as shown in Fig. 5(a). The Ideal Haptic Interface Point (IHIP) stays on this surface. Then the nearest distance from the current HIP to the contacted surface is calculated. As long as the tool moves out the covering range of the contacted triangles, a new triangle is formed as the new active triangle.

5. IMPLEMENTATION AND RESULTS

Our system is implemented and tested on a Microsoft Windows XP workstation with a Xeon 2.4G Hz CPU, 6GB RAM, and NVidia Quadro FX5800 graphics card. The system is developed using Vizard. The haptics interface is implemented using the PHANTOM Omni Device and the OpenHaptics Toolkit software available from Sensable Technologies. The OpenHaptics is a software toolkit that enables application developers to interact with the haptic device and create a haptic environment at the object level.

Figure 6. demonstrates the haptic workspace moving process. The haptic workspace (represented by a transparent box) moves along with the virtual tool (represented by the marker). In the beginning, the virtual tool is free to move inside the haptic workspace. When the user moves stylus at six degrees of freedom, the virtual tool moves with it. The Fig. 6(a). shows the initial position of the haptic workspace. The user brings the virtual tool at the boundary of the haptic workspace as shown in Fig. 6(b). Here the user wants to modify the color of the soccer ball. The user presses the stylus button and the center of the transparent box coincides with the virtual tool as shown in Fig. 6(c). When the user releases the stylus button, the haptic workspace coincides with the transparent box. As a result, the haptic workspace moves with the virtual tool as shown in the Fig. 6(d). The user can drag the haptic workspace while pressing the button or keep on press/release the stylus button to reach the destination as shown in Fig. 6(e). The virtual tool touches the soccer ball and the color of the ball is changed as shown in Fig. 6(f).

The haptic force is calculated at 1,000 Hz rate and transmitted to the haptic device where the force values are converted into motor torques. The force output is displayed in Fig. 7(a). It shows the x, y and z components of the force vector. Because the velocity data are obtained by differentiating the measured displacements, chattering (high-frequency vibration) of the stylus occurs. Filtering is used to reduce the noise component of a measured signal. The Exponentially Weighted Moving Average Filter has been

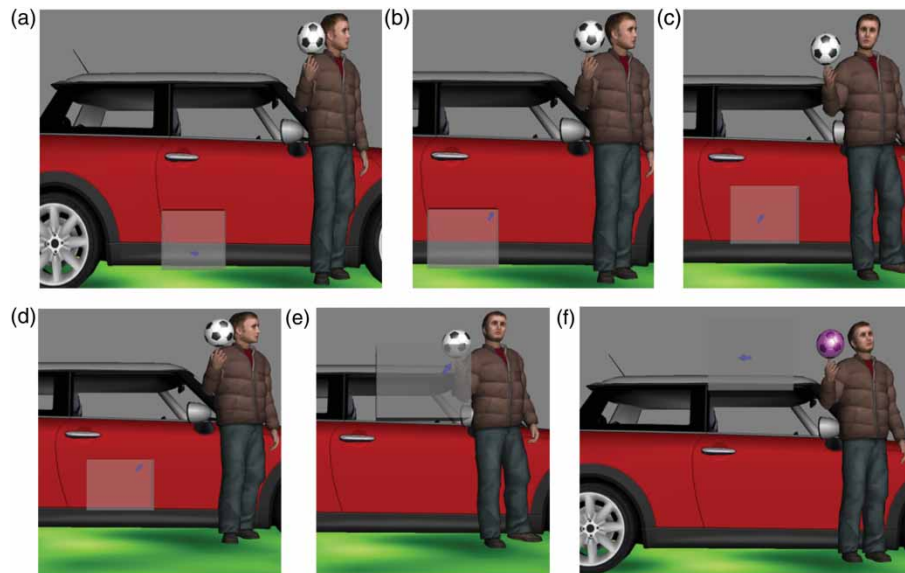


Fig. 6: An example of haptic workspace moving process.

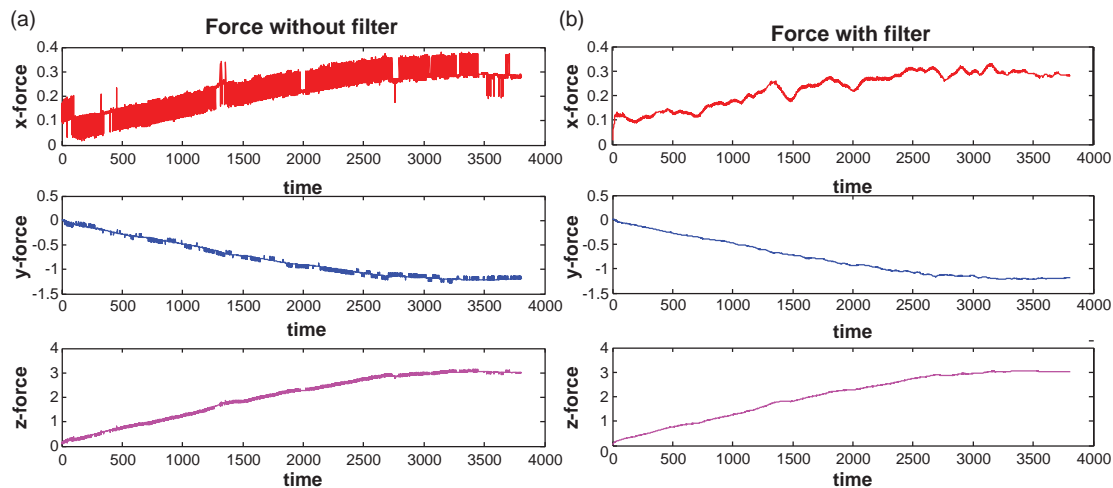


Fig. 7: (a) shows the force without filtering, (b) shows the force with filtering ($\alpha = 0.9$).

demonstrated to show the desirable characteristics of smoothing the force function. The underlying mathematics of this filtering can be stated as

$$F_i = E_i(1 - \alpha) + F_{i-1}\alpha \quad (5.1)$$

where F_i is the expected force value at time step i , α is the smoothing factor and its value is between 0 and 1, and E_i is the value of the sampled function at time step i .

The force output with filtering is displayed in Fig. 7(b). for $\alpha = 0.9$. The noise has been dramatically reduced in the case of filtering and the user can hardly feel the vibration. We can see how this works by expanding F_i on the right hand side as

$$F_i = E_i(1 - \alpha) + E_{i-1}(1 - \alpha)\alpha + E_{i-2}(1 - \alpha)\alpha^2 + E_{i-3}(1 - \alpha)\alpha^3 + \dots + F_0\alpha^i \quad (5.2)$$

The contribution of older values of E_i are weighted by increasing the power of α . Since α is less than 1, the contribution of older values of E_i becomes progressively smaller. What this means is that in calculating the filtered value, larger weights are given to more recent measurements. The noise attenuation is better when α is set to a high value, but this is at the expense of larger lags on the filtered signal. From our experiment, a value of $\alpha = 0.9$ gives a good performance in the described application.

6. CONCLUSIONS

Haptic interface has become an important component in the virtual reality based CAD modeling system. Incorporating a haptic interface to the modeling system provides the user with a more realistic

experience. Due to the limited physical workspace compared to the large screen of the virtual environment, there is a mismatch between the workspace of the haptic device and the large-scale virtual environment. The haptic workspace moving algorithm has been developed and demonstrated to provide fine and precise control to reach and touch the virtual object in PowerWall virtual environment. The haptic force generation algorithm was integrated in the modeling process to provide user the force feedback. An exponentially weighted moving average filter was implemented in the force model to reduce the vibration on the haptic device.

ACKNOWLEDGEMENTS

The work is supported by the National Science Foundation under HRD Grant Number 1137578. Any opinions, findings, conclusions, or recommendations presented are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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