

Virtual Prototyping System Based on Haptic Interactive Sensors

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Abstract: This paper presents a Virtual Prototyping System (VPS), which can be used in virtual environments generated with the help of computer to simulate the process of real product model that the modelers sculpt product profile. With this system, designers can use the combination of haptic technologies and virtual prototyping method to increase real sense of Human Computer Interaction (HCI) during different steps of design process. The operation of cutting, pasting, and compensating is accomplished by a haptic sensor device, PHANToM Desktop. The virtual mechanics simulation model of the feedback force is proposed to solve the real-time force feedback simulation problem of haptic-based virtual prototyping method. Furthermore, a novel haptic rendering technology that enables users to perceive tactile feedback from virtual 3-dimensional models is studied. Finally, VPS with real-time force feedback interactive technology is completed by using sensing technologies of haptic sensor devices. The study reported in the article adopted an actual case to examine these sensory responses to virtual model that may deeply influence user judgment and decision.

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Keywords: Virtual prototyping system, Human computer interaction, Haptic interactive sensors.

1. Introduction

Today's virtual prototyping environments are capable of simulating visual realism to a very high level. The next big challenge for the virtual prototyping community is simulating realistic interaction. Virtual prototyping, sometimes referred to as digital prototyping, is widely adopted by industry to simulate visual appearance and functionalities of production. Unfortunately, conventional virtual prototyping techniques lack the simulation of the physical properties of a real interaction between user and product. Force feedback, also called sensible feeling, is best envisaged as an evolution of virtual prototyping. Prototyping methods based on strict physical

disciplines need much time to deform objects, which are not suitable for interactive applications.

2. Related Works

The sense of touch is often called the proximal sense in contrast to vision, smell and hearing, which can operate at a distance and through the air. Touch can be subdivided into two senses, cutaneous and kinesthetic [1]. The cutaneous system refers to stimulation of the skin. The kinesthetic system refers to signaling from muscles, tendons and joints. In general, the sense of touch can only perceive one input at a time, whereas some other senses such as vision can simultaneously perceive a wide array of information [2].

Haptics is an evolving technology that offers a revolutionary approach to realistic interaction. Haptics means both force feedback and tactile feedback. Research has shown that the addition of haptics to virtual environments can result in improved task efficiency times [3]. Force cues provided by haptics technology can help designers feel and better understand the virtual objects by supplementing visual and auditory cues and creating an improved sense of presence in the virtual environment [4-6].

Various approaches for providing haptic feedback for modeling have been presented in the past which focused on developing new methods for providing tactile [7], visual perception [8], collision [9, 10] and gravitational force feedback [11]. The high update rate (*1 kHz) requirement for effective haptics has always been a challenge in integrating this technology [12]. As stated earlier, most physics-based algorithms used highly coarse model representations to maintain the update rate requirements. The resulting lack of part shape accuracy of such approaches presents problems when detailed contact information is necessary. Maintaining update rates for haptic interaction (*1 kHz) while performing highly accurate collision/physics computations in complex interactive simulations such modeling remains a challenge for the community. In addition, there are several limitations of the haptics technology currently available.

The application field for the sensor will also expand in future [13-15]. Computational technology gives us a very rich material to express interaction design form. Consequently, the need to design and deploy new HCI for the computer aided industrial design (CAID) system is evident, especially in support of conceptual design. In addition, the use of CAID in conceptual design should allow designers to concentrate on the creative design aspects rather than applying themselves to the interaction constraints [16-19]. Modeling methods based on strict physical disciplines need much time to deform objects, which are not suitable for interactive applications [20].

3. Approach Overview

3.1 Haptic Process

Highly efficient physics-based methods that are capable of maintaining high update rates are generally used for implementing haptic feedback in virtual prototyping simulations.

In this paper, we introduced force feedback with SensAble Phantom Desktop and Open Haptics API to improve HCI operations, cutting, pasting and compensating. In VPS, a user can virtually cut or paste a raw stock to get an intuitive design by using a haptic interface. And we also described the Dixel-based haptic rendering (force feedback)

programming, illustrating the integrated software and hardware developed in the haptic interface system based on material removal rate. The main operation process and key technology are listed in Fig. 1.

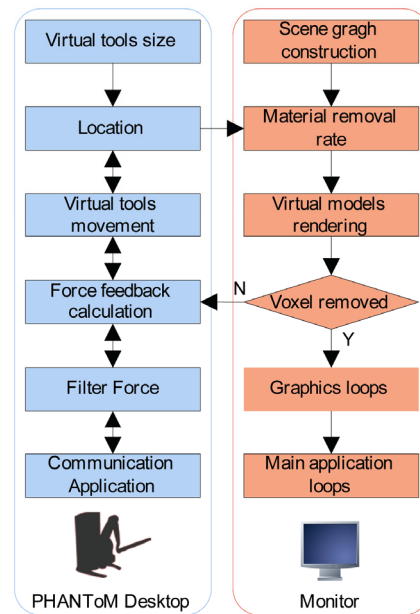


Fig. 1. The main operation and technology in VPS.

3.2. Haptic Operation

Kabbash et al. [21] pointed out that the felicitous allocation tasks could effectively improve the efficiency, otherwise it might lead to greater burdens, and the deficiency was lower than one-hand's situations. Delporte Baptiste et al., [22] proposed two methods based on quaternions to compute the angles of inclination and the angular velocity with 6 degrees of freedom using the measurements of a 3-axis accelerometer and a 3-axis magnetometer. YAN et al., [23] pointed out that there were three universal interactive tasks in virtual environment: selection/operation (also known as translation/rotation), roaming, and control system. Generally, the three tasks are alternative and cooperatively work together. In VPS, prototyping operations such as cutting, pasting and compensating are continuous actions. In order to assign two-handed tasks rationally, effectively and avoid tired for using keyboard and mouse continually, we must take into account the following situations:

- Suitable HCI sensors and devices;
- Appropriate difficulty for achieving interactive task simultaneously;
- Rational task distribution for left and right hands' interactive tasks;
- Cutting, pasting and compensating are mainly interactive tasks with virtual prototyping method.

Table 1 shows their basal functions during prototyping process. In real life, the operations of two

hands are divided into 3 types when users complete all kinds of tasks: one hand task, symmetric and non-symmetric behavior task for two hands. In human-computer interactive science, two non-symmetric hands occupy the mostly cases, it is mostly used and feel most harmonious. Similarly, designers drag virtual tools (translation/rotation) with mouse and change modeling states with keyboard (modeling or not) to achieve prototyping operations in VPS. Therefore, they can be treated as a non-symmetric two-handed interactive actions, it will be more effectively in enhancing efficiency when we use different devices to achieve different tasks.

Table 1. Three Basic Operations in VPS.

Operation	Description	Flag
Cutting	Scrape away virtual materials	T
Pasting	Add virtual materials	P
Compensating	Scrape and add virtual materials	M

3.3. Haptic Devices

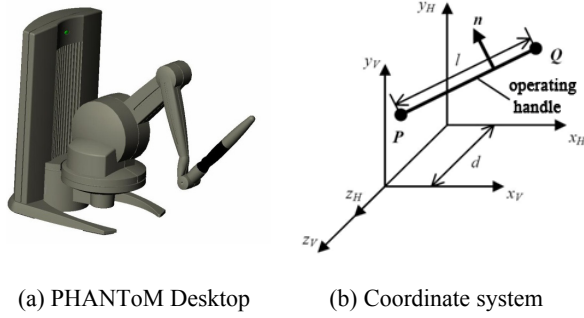


Fig. 2. 6-DOF PHANToM Desktop and Coordinate.

Haptic feedback device from SensAble Technologies Incorporation, PHANToM Desktop, has a lot of merits, such as light-weight design and compact structure, as shown in Fig. 2(a). The device can produce three translational and two rotational degree-of-freedom components, and can produce equipment coordinate system and graphics space coordinate system sketch map. These directions can be figured by a 4×4 homogeneous coordinate transformation matrix M .

In Fig. 2 (b), PQ is a stylus in the device, n is normal vector of stylus; l is the length of the stylus. X_H, Y_H, Z_H is device coordinate system of PHANToM Desktop, X_V, Y_V, Z_V is user's coordinate system, if axis of X_H, Y_H, Z_H and X_V, Y_V, Z_V is consistent, d is the distance between two axis. Coordinates of stylus' head P and tail are (P_{Hx}, P_{Hy}, P_{Hz}) and (Q_{Hx}, Q_{Hy}, Q_{Hz}) in device coordinate system, are (P_x, P_y, P_z) and (Q_x, Q_y, Q_z) in word coordinate system, and view transformation matrix is M_{view} , their relation is as following.

$$\begin{bmatrix} P_{Hx} \\ P_{Hy} \\ P_{Hz} \\ 1 \end{bmatrix} = M \cdot \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} M_{03} \\ M_{13} \\ M_{23} \\ 1 \end{bmatrix}, \quad \begin{bmatrix} Q_{Hx} \\ Q_{Hy} \\ Q_{Hz} \\ 1 \end{bmatrix} = M \cdot \begin{bmatrix} 0 \\ 0 \\ l \\ 1 \end{bmatrix} = \begin{bmatrix} lM_{02} + M_{03} \\ lM_{12} + M_{13} \\ lM_{22} + M_{23} \\ 1 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} P_x \\ P_y \\ P_z \\ 1 \end{bmatrix} = M_{view}^{-1} \cdot \begin{bmatrix} P_{Hx} \\ P_{Hy} \\ P_{Hz} - d \\ 1 \end{bmatrix}, \quad \begin{bmatrix} Q_x \\ Q_y \\ Q_z \\ 1 \end{bmatrix} = M_{view}^{-1} \cdot \begin{bmatrix} Q_{Hx} \\ Q_{Hy} \\ Q_{Hz} - d \\ 1 \end{bmatrix} \quad (2)$$

By the same token, to stylus PQ 's normal vector N , if its coordinate is (N_{Hx}, N_{Hy}, N_{Hz}) and (N_x, N_y, N_z) in device coordinate system, so it is

$$\begin{bmatrix} N_{Hx} \\ N_{Hy} \\ N_{Hz} \\ 0 \end{bmatrix} = M \cdot \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} M_{01} \\ M_{11} \\ M_{21} \\ 0 \end{bmatrix}, \quad \begin{bmatrix} N_x \\ N_y \\ N_z \\ 0 \end{bmatrix} = M_{view}^T \cdot \begin{bmatrix} N_{Hx} \\ N_{Hy} \\ N_{Hz} \\ 0 \end{bmatrix} \quad (3)$$

SpaceBall 5000 [24] transformate or rotate a point $P_{(x_p, y_p, z_p)}$ in space, if $P^*_{(x_p, y_p, z_p)}$ have been switched, P^* 's coordinate switch can be expressed as:

$$\begin{bmatrix} x_p^* \\ y_p^* \\ z_p^* \\ 1 \end{bmatrix} = \begin{bmatrix} x_p \\ y_p \\ z_p \\ 1 \end{bmatrix} \cdot M \quad (4)$$

We make the formula (1), (2) into the equation (4), then the stylus can be moved front and rear, left and right, upper and lower translation in scene graph; we make equation (3) into (4), then the rotation of object will be came true.

3.4. Mapping Model of Virtual Haptic System

Virtual haptic occurs in a digital environment with the processing being similar to how manual modelling takes places with physical model. The process of virtual prototyping is highly procedural and systematic. And as a number of computational processes are involved, current systems are still limited in terms of integrating these actions that take place at hardware and software level. In an attempt to resolve the issue of force feedback control in a virtual prototyping system, a mapping relationship between virtual sculpting (cutting and pasting operations) must first be established.

In order to define the cutting and pasting activity through a mathematical approach, the authors first denote that the operations in a conventional sculpting is Set W . According to different modeling methods in virtual systems, Set W can be divided into multiple non-disjoined sub-sets T . If the computer state sequence is expressed by Set C , the device of HCI is expressed by Set E . For device $e \in E$, $S(e)$ is the status sequence of Set e . The mapping relationship

of any selection operation see between W and T can thus be expressed as:

$$see: W \rightarrow T \quad (5)$$

The method of conventional manual kneading is expressed by function sim , which can map the traditional method sequence Set T to the computer state sequence of Set $P(C)$:

$$sim: T \rightarrow P(C) \quad (6)$$

In formula (6), $P(C)$ is the power set of Set C .

The characterization of virtual objects is expressed by emulation function $show$, which can map computer state sequence Set $P(C)$ to HCI sensor device state sequence of Set $D(E)$:

$$show: P(C) \rightarrow D(E) \quad (7)$$

Assume do is the control function with which the user is able to control the computer simulation within the interactive operation between human and sensor device, then the computer state sequence collection is Set C .

$$do: C \times D(E) \rightarrow C \quad (8)$$

According to the formula (5), the traditional method collection status can be mapped to computer state sequence, that is to say, each step that operated by the traditional modeling method can be achieved in the computerized system. So, an eight-tuple can be defined by the mapping between conventional manual kneading methods is set W and the computer state sequence collection Set C .

$$\langle W, T, C, E, see, sim, show, do \rangle \quad (9)$$

In formula (9), functions $sim, show, do$ are the three categories in a virtual environment.

Function sim reflects the modeling simulation in computerized system, it can be an algorithm or axiomatic system, and also represents a structured input process of computation.

Function $show$ is used to describe the simulated objects in computerized system. It can be an algorithm, a data conversion or a structured data output flow.

Function do is a structured flow of input whereby users can control the virtual model in the digital environment, and is closely related to the interactive sensor device.

During the process of conventional sculpting, the operation of cutting and pasting is the main method of modeling. These two modes of operation can be further extended into the third operative mode – compensating.

The cutting operation on the model surface can be represented by sim_{cut} , as shown in Fig. 3 (a).

The add operation using styling tools can be represented by sim_{pst} , as shown in Fig. 3 (b).

The operation of scraping the convex surface and filling hollow at the same time can be represented by sim_{cmp} , as shown in Fig. 3(c).

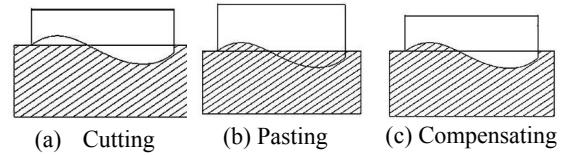


Fig. 3. Mapping operation in Virtual Clay Prototyping System.

Assume function E represents the modeling tools, function W represents the operation of cutting, pasting and compensating, as shown in Fig. 3. Three kinds of operating mode can be mapped by functions $see_{cut}, see_{pst}, see_{cmp}$ and simulated by functions $sim_{cut}, sim_{pst}, sim_{cmp}$. Furthermore, in the virtual computerized environment, the execution state sequence for these three kinds of operating mode can be represented by functions: $C_{cut}, C_{pst}, C_{cmp}$, the characterization results can be represented by functions: $show_{cut}, show_{pst}, show_{cmp}$.

According to the formula (9), the eight-tuple can be defined by the mapping between the operation of cutting, pasting and compensating using conventional sculpting methods and the three kinds of operating modes in virtual environment. The simulated mapping of cutting operation is shown in formula (10), the simulated mapping of pasting operation is shown in formula (11), the simulated mapping of compensating operation is shown in formula (12). Through the above mapping method, the operation of cutting, pasting and compensating with conventional manual kneading methods can be mapped to the computerized virtual space.

$$\langle W, T_{cut}, C_{cut}, E, see_{cut}, sim_{cut}, show_{cut}, do_{cut} \rangle \quad (10)$$

$$\langle W, T_{pst}, C_{pst}, E, see_{pst}, sim_{pst}, show_{pst}, do_{pst} \rangle \quad (11)$$

$$\langle W, T_{cmp}, C_{cmp}, E, see_{cmp}, sim_{cmp}, show_{cmp}, do_{cmp} \rangle \quad (12)$$

3.5. Implementation of Virtual Haptic System

The sensor object provides access to the 3D motion data of the 3D connexion device [25]. In a C++ COM application the sensor object can be obtained from the device object.

The integrated development environment of VPS is MS VC 2005, graphical kernel library is Open Inventor, the user interface using Qt application programme framework, and calculate of haptic feedback force is used function library of Open Haptics. The VPS has been developed with Open Inventor and Qt framework to demonstrate the feasibility of the proposed new method.

Fig. 4 gives the scene structure sketch map which was managed by Open Inventor scene manager in the VPS, and which is conducive system maintenance and expand in the latter; At the same time, because the Open Inventor is based on the development of OpenGL, making the VPS also have a good compatibility and the ability to run cross-platform.

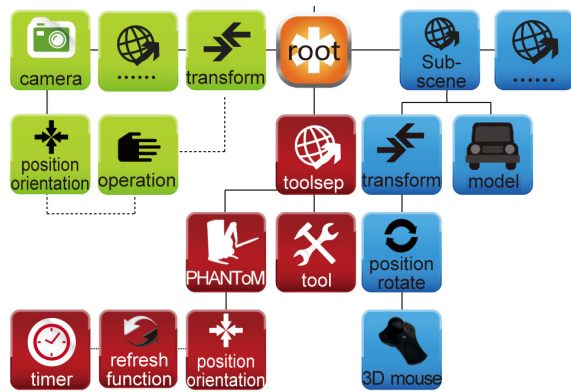


Fig. 4. Open Inventor Scene Structure of VPS.

The default value of Open Inventor Transform modes as follows:

```

Transform {translation    0 0 0
Rotation                0 0 1 0
ScaleFactor             1 1 1
ScaleOrientation        0 0 1 0
Center                  0 0 0}

```

In addition, there are many simple function in these nodes can be user-friendly settings operation. The PHANToM Desktop can also be form rotate control of modeling tools by the formula (3), the other operation realized by using Spaceball 5000.

While manipulating the virtual model, users watch what is emerging on the monitor and feel the feedback force from the haptic sensors synchronously.

4. Experiments

In previous studies, we demonstrated that the virtual methods could increase students' effective haptics and found that 85 % of the respondents had utilized force-feedback to gain a better tactile understanding of surfaces [26]. The actual stimulus could play an important role in data collection

because its visual and tactual properties would be presented more effectively.

A total of 4 final year undergraduate students from Northwestern Polytechnical University were recruited for the experiment involving a product design activity. As the students were finalists, they were familiar with the NPD process and were competent in the use of computer aided industrial design software. All of them were aware of haptic devices and had experience in the use of such systems for design projects.

Each student was given two tasks. The four participants were asked to recognize two different cubes and under two different conditions, haptic sensors (Spaceball 5000 and PHANToM) and traditional devices (keyboard and 3D mouse). In order to aid clarity, all students were given a handbook that explained the user interface and its functionality of the virtual prototyping tools. Fig. 5 gave their average time of operation with different conditions.

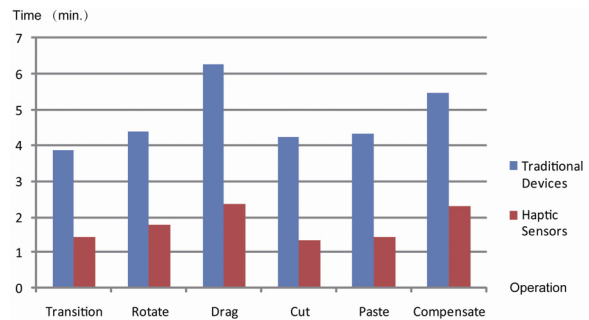


Fig. 5. Operation time between two different conditions.

From this study, the results from the data analysis were classified into two categories, namely (1) the operation by traditional devices; (2) the operation by haptic sensor devices.

The results showed that the traditional devices casted two to three times than the haptic sensors. When the participants operated with traditional devices, they operated and interacted by watching the interface of graphics simulate, for example, dragger and manipulator of Open Inventor. Completing a simple operation, such as move and rotate, need lots of complex actions, furthermore too much actions would be likely to increase the inaccuracy of operation. However, Haptic sensors could help the operators complete these basic operations easily with the sense of visual and tactile. Through the observation and interaction, participants were able to visualize and experience how haptic sensors might contribute to prototype object and interact with the virtual model.

5. Conclusions

This paper introduced 6 degree of freedom haptic sensors, Spaceball 5000 and PHANToM Desktop,

established the combination of equipments and interactive assignment with both left and right hands, calculated the feedback force of 6 degree freedom controlling sensors. Detailed techniques of multi-sensory virtual prototyping, material removal rate force rendering and haptic design were proposed in Virtual Prototyping System, which supported the 6 degrees of freedom haptic feedback will further push practicality of haptic-based sensing technology. With the proposed methodology, users can virtually sculpt a stock volume to get an intuitive design by using the developed force feedback haptic interface.

The further development of the system is focused on increasing the usability and improving the realism of sensations. To increase the usability is to combine haptic rendering and haptic algorithm model modification to speed up the modeling process. As to the increasing of the realism of the implemented haptic rendering system, a combination of real and virtual worlds could be used. This would embed new and interacting technologies to the latent needs of diverse users.

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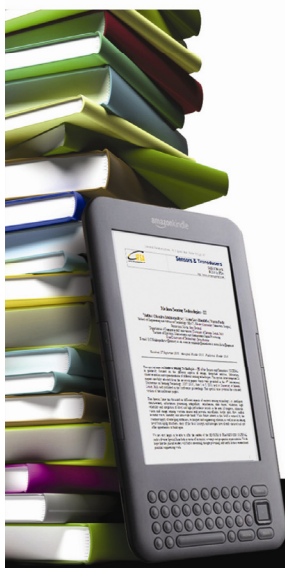
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