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Virtual Sculpting and Multi-axis Polyhedral Machining Planning Methodology with 5-DOF Haptic Interface

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Abstract. This paper presents techniques of integrating haptic device into computer-aided design and manufacturing. The methodology is proposed as three steps: 1) develop the virtual sculpting system for aiding product design; 2) convert the product design into acceptable form for downstream manufacturing or rapid prototyping; 3) develop multi-axis polyhedral machining planning system with haptic input. Experiment and examples are presented to illustrate the workflow. The presented techniques can be used for haptic virtual prototyping, computer-aided design and manufacturing, and multi-axis machining planning.

1 Introduction

How haptic interface can be contributed to the design and manufacturing has been of great interest for CAD/CAM (Computer-aided Design / Manufacturing) and haptics researchers in the recent years. It can be foreseen that with the rapid advance of haptics and graphics technology, haptic interface will play an important role in compressing the time to market of new products. While the hardware barrier is gradually being cleared, general methodology research is called for to facilitate the integration of haptic interface into product design and manufacturing. This research project aims to explore this kind of methodology.

Haptic interface has been used for free-form design. Commercial volume model based on free-form modeling system has been developed in which the tool is defined as regular or simple shapes such as spheres. The collision detection has mostly been limited to single point collision detection and force feedback calculation. Earlier work in virtual sculpting based on Voxel modeling had been successfully done as in [1]. A dexel modeling dynamic sculpting system integrated with commercial haptic device was reported in [2]. Haptic interface has rarely been used for manufacturing machining planning. A haptic rendering methodology for milling process was presented in [3]. A 5-axis tool path generation application integrated with haptic interface was presented in [4]. Earlier results of this project have been reported in [5,6,7,8].

This paper reports the latest advance of the research project. The remaining of this paper is organized as follows. Section 2 briefly introduces the haptic device development involved in the project. Section 3 narrates an analytical methodology for real-time haptic dexel-based volume model updating for free-form design with rotational symmetric tools. Section 4 briefly described a newly proposed method of constructing triangulated mesh polyhedral surface model from the dexel volume model. Section 5 presented the methodology of utilizing haptic interface in the multi-axis manufacturing machining planning. The experiment and examples are presented in Section 6. Conclusions are in Section 7.

2 Haptic Interface Development

As shown in Figure 1, the haptic device is a lab-built 5-DOF (degree of freedom) pen-based electro-mechanical device made by Suzuki, *Inc.*, Japan. It can detect 6-DOF of haptic probe movement and gives 5-DOF force feedback, with both force and torque feedback. Figure 1 shows our lab setup with the haptic device located in the middle. In Figure 1, the left hand side is its controller, which is built in our lab, and the right hand side shows the dual-CPU 2.4GHz workstation.

3 An Analytical Methodology for Haptic Virtual Sculpting

Virtual sculpting can be classified as two types: one is based on deformable object modeling; the other one is similar to NC simulation process, where stock material is removed whenever a virtual tool sweeps a stock. The latter type of virtual sculpting is usually based on Voxel or Dexel models. Dexel model requires less memory than Voxel model. Based on Dexel model, an analytical methodology is developed and presented in details in our papers [7]. Figure 2(a) shows the Dexel models, which represents an object with packed columns. In the data structure, a Dexel volume model is recorded as a regular 2D grid, with each grid point associated with a linked list of Dexel elements. During the haptic virtual sculpting, as a tool collides with any part of the object represented with Dexels, it removes the material away from the object. This process, if translated in the modeling, is the Dexel-updating process. In the *Dexel-updating process*, each Dexel is treated as a vector as in Figure 2(b).

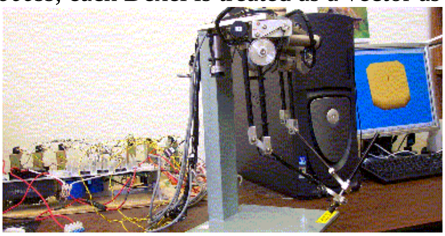
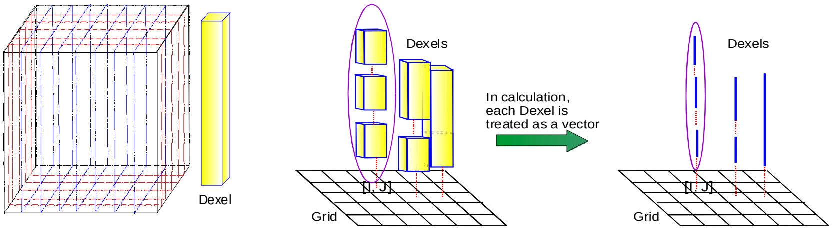


Fig. 1. Lab setup of 5-DOF haptic device with a haptic controller and a dual-CPU workstation

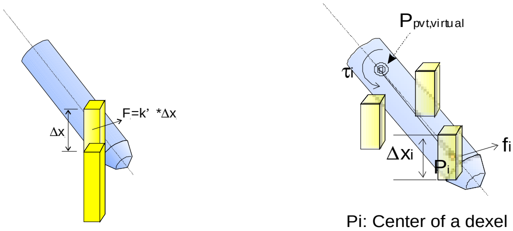
Besides the designed the object modeling, the other critical element of the haptic virtual sculpting system is the tool definition. To simulate the practical machining process, the sculpting tools are defined as rotational symmetric. The detailed algorithms for the *Dexel-updating process* have been described as in [7]. In the haptic rendering method, a *Dexel Removal Rate* (DRR) approach is used to analyze the haptic sculpting force-torque feedbacks. MRR can be considered to be proportional to the dexel volume removed accumulatively per unit time, which is defined by us as *Dexel Removal Rate* (DRR). The haptic force response is calculated based on the DRR. Based on the analysis from the previous section, the DRR can be calculated during the *Dexel-updating process*.



(a) Dexel model

(b) In the Dexel-updating process, each Dexel is treated as a vector

Fig. 2. Dexel model and its updating process



(a) Force is proportional to the removed Dexel height

(b) The calculation of torque based on the force and pivot point

Fig. 3. Calculation of force and torque

As shown in Figure 3(a), a component force magnitude $f_{i,mag}$ can be defined as proportional to the removed dexel volume and is given by the following formula:

$$f_{i,mag} = k \cdot (\Delta x_i \cdot Dx_{area}) = (k \cdot Dx_{area}) \cdot \Delta x_i = k' \cdot \Delta x_i \quad \textbf{(1)}$$

where Δx_i is the height of the dexel segment, Dx_{area} is the cross section of the Dexel elements, k is the pre-defined cross-section dependent force coefficient, k' is the cross-section independent force coefficient. Although similar in form, this is NOT *Hooke*'s law. It is based on the assumption that the force is proportional to the removed dexel volume. The force feedback direction $\vec{f}_{i,dir}$ is opposite to the 'tool-approaching direction' to each removed dexel volume.

The torque calculation method is shown as in Figure 3(b) and $\vec{\tau}_i$ is calculated by the following formula:

$$\vec{\tau}_i = f_{i,mag} \cdot (\vec{f}_{i,dir} \times (\overrightarrow{P_i P_{pvt}})) \quad \textbf{(2)}$$

where $\vec{f}_{i,dir}$ is the direction of a component force, P_i is the center of the removed dexel, P_{pvt} is the virtual tool pivot point, $\overrightarrow{P_i P_{pvt}}$ is the vector from P_i to P_{pvt}. It is noted that the force and torque calculated on each removed dexel are accumulated and fed back to a user through haptic interface.

4 Convert Dexel Model to Polyhedral Model

While Dexel model is good for real-time haptic sculpting calculation, common machining planning is usually done on surface model. Polyhedral model is a special kind of surface model that has gradually attracted the attention of industry, and consequently academia. While at first sight it may not seem difficult, the conversion from Dexel model to polyhedral model turns out to be an interesting and challenging problem. A top-down approach is presented in analyzing the conversion problem [9]. The proposed visibility sphere marching algorithm is composed of 3 sub-algorithms: roof and floor covering, wall-building and hole-filling algorithms. The stock material represented in Dexel volume model is sculpted into a designed model using the developed haptic sculpting system. The sculpted Dexel volume model can then be converted to polyhedral surface model in STL format by the visibility sphere marching algorithm proposed in [9]. Polyhedral surface model can then be input to and processed by available CAM (Computer-aided Manufacturing) or RP (Rapid Prototyping) systems.

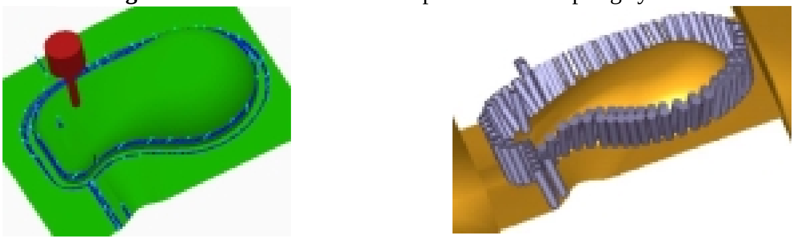
5 Haptic-aided Multi-axis Polyhedral Model Machining Planning

The polyhedral surface model converted from the haptic sculpting system can be further processed by the machining planning system. The challenging problem in multi-axis machining planning includes two critical tasks: the tool path geometry and the tool orientation. Both of them contribute to the better machining surface finish (quality) and required machining time. In our previous research, we have done a lot in both tasks [10,11]. However, the tool orientation control is still an open problem in computer-aided manufacturing. In this research, haptic interface is utilized to help determine the tool orientation.

In the following description, we take 5-axis pencil-cut as illustrative sub-modules for the machining planning system. Pencil-cut is a special kind of machining strategy. Its purpose is to use a relatively small too to remove the material at the sharp edges or corners on the designed surface model. During the operation process, the pencil-cut region is first identified by using the revised *Rolling-ball method* developed in our earlier work presented in [10, 11]. Tool locations (CC points: cutter contact points) are then computed based on the pencil-cut region. In the next step, the haptic device helps to determine the tool orientations corresponding to these CC points. Only the tool orientations of those critical CC points need to be specified and the other CC points' tool orientations are to be defined by interpolation. This is analogous to animation creation, where key animation frames are defined and interim animation frames are automatically created by interpolation. Details of the Two-phase haptic rendering for the machining planning can be found in our earlier work presented in [8].

(a) Bird dexel model | (b) Cat dexel model

Fig. 4. Dexel models from the haptic virtual sculpting system



(a) computing pencil-cut tool orientations (b) tool orientation selection in a complex machining environment

Fig. 5. Using haptic interface to help determine 5-axis tool orientation in a complex machining environment

6 Experiments and examples

The proposed techniques and the haptic hardware have been implanted at our lab. Figure 4 shows some Dexel models from the haptic virtual sculpting system. Figure 5 illustrates the machining planning process. Figure 6 shows the some NC simulation results based on the NC code generated from the machining planning system. Figure 6(a) shows the surface finish before the pencil-cut machining. Figure 6(b) shows that material at the edges and corners are removed after the 5-axis pencil-cut operation.

(a) Mouse model after finishing without pencil-cut (b) Mouse model during pencil-cut

Fig. 6. 5-axis pencil-cut machining of the computer mouse model

7 Conclusions

This paper summarizes our research project whose purpose is to explore the methodology of integrating haptic device into computer-aided design and manufacturing. The methodology is proposed as three steps: 1) develop the virtual sculpting system for aiding product design; 2) convert the product design into acceptable form for downstream manufacturing or rapid prototyping; 3) develop multi-axis polyhedral machining planning system with haptic input. Experiment and examples are presented to illustrate the workflow.

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