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Haptic sculpting of multi-resolution B-spline surfaces with shaped tools

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Abstract

In this paper, we first propose an implicit surface to B-spline surface haptic interface, which provides both force and torque feedback. We then present a new haptic sculpting system for B-spline surfaces with shaped tools of implicit surface. In the physical world, people touch or sculpt with their fingers or tools, instead of just manipulating points. Shaped virtual sculpting tools help users to relate the virtual modeling process to physical-world experience. Various novel haptic sculpting operations are developed to make the sculpting of B-spline surfaces more intuitive. Wavelet-based multi-resolution tools are provided to let modelers adjust the resolution of sculpture surfaces and thus the scale of deformation can be easily controlled. Moreover, sweep editing and 3D texture have been implemented by taking advantage of both the wavelet technique and haptic sculpting tools.

Keywords: Geometric design; Haptic sculpting; Haptic rendering; Multi-resolution

1. Introduction

In CAD/CAM systems, B-spline has become the de facto standard for surface representation. Much work has been done to facilitate design using B-spline surfaces. Several editing operations, such as control point manipulation, direct manipulation, free form deformation (FFD) and variational modeling, can be employed to generate surface models. However, with traditional two-dimensional (2D) based human–computer interfaces, it is still difficult to create and edit complex freeform CAD surface models. The fast developing haptic technology provides new potential by allowing human operators to interact with digital models using a sense of touch [13]. Haptic sculpting is a modeling technique for sculpting virtual models while simultaneously providing haptic feedback. The sense of touch adds a new modality to virtual sculpting.

In spite of the power of haptic interfaces, modelers may still suffer similar problems to using the traditional keyboard and mouse interface. Sometimes, the modeler may need the control point mesh of the surface to be dense enough for adding further details, but for other situations, the modeler may want a sparse control point mesh, which deforms more globally. A multi-resolution framework is valuable and useful in CAD because both the higher resolution details and the lower resolution sweep are simultaneously available. Therefore, a model can be edited at different resolution levels for different purposes. Although multi-resolution B-spline surfaces can deal with global details and fine local details, traditional 2D interfaces or 3D non-haptic virtual interfaces cannot fully exploit the advantages of the multi-resolution nature of B-spline surfaces because it is difficult and time-consuming to process and modify fine details with traditional human computer interfaces.

By trying to combine the advantages of a haptic interface with a multi-resolution framework, we propose a haptic sculpting system, which features a new tool–model haptic interaction and a multi-resolution B-spline surface sculpting technique. The final shape of the model not only depends on the material property of the model and the moving path of the tool, but also on the shape and size of the tool. This can be compared with the commercial FreeForm haptic modeling system, which provides arrays of modeling tools of different shapes and sizes to help modelers relate the virtual sculpting with their experiences of sculpting in the physical world [27]. The shapes of tools also serve as visual hints that correlate the desired deformation on models with the shape of selected tool. In our system, we have developed shaped probe/tools with that purpose so that modelers can anticipate some result before action.

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2. Related work

2.1. B-spline surface design

B-spline or NURBS surface models are widely used in CAD applications. Various techniques have been developed to improve the modeling and editing process. Sederberg and Parry demonstrated a deformation method called free-form deformation (FFD) for global editing [24]. Coquillart extended this method for more general deformations [6]. Celniker applied finite element method (FEM) to generate continuous deformable shapes [4]. Welch and Witkin present a variational surface modeling technique, allowing the user to define a set of constraints and then finding the solution by minimizing the surface area [32].

2.2. Haptic interface

A haptic interface includes hardware and software components. Our focus is on the software. The software of a haptic interface includes a haptic rendering unit and application units.

Haptic rendering is the process of applying forces to give the operators a sense of touch and interaction with physical objects [33]. The existing techniques for haptic rendering can be categorized according to the way the probing object is modeled: (1) a point, (2) a line segment, or (3) a 3D object made of groups of points, line segments and polygons [3].

The point-object haptic rendering paradigm assumes that we interact with the virtual world with a single point probe, therefore only the three Euclidean interaction force components can be fed back. Various point–object style approaches for haptically rendering triangular mesh virtual objects can be found in [22,30,33]. Because use of implicit surface is convenient for collision detection, some researchers have managed to present point-based haptic rendering techniques with implicit surface. Salisbury and Tarr introduced an algorithm for virtual objects based on implicit surfaces with an analytical representation [23]. Kim introduced a haptic algorithm, which is for a non-analytical implicit surface [16].

Although the point–object interaction metaphor has proven to be convincingly useful and efficient, it has limitations of being unable to provide torques and hence cannot offer sufficient dexterity and control. Basdogan et al. implemented a ray-based haptic rendering method, which can provide 5-DOF interaction between a line segment probe and virtual objects [2]. However, line segments are unsuitable to represent sculpting tools in this research. The object–object haptic interface can introduce a much more complex haptic cursor into the haptic simulation, thus improving the degree of realism and hence is desirable for many applications. Although a number of object–object 6-DOF haptic rendering methods are available, their applications have been limited mainly due to computational complexity and restoring forces that must be computed at the desired force updates (typically 1000 Hz). Gregory et al. presented an algorithm for haptic display of moderately complex polygonal models with a polygonal haptic cursor [11]. Their method features applicability to dynamic environments and accurate contact determination. However, this method requires that each object must be convex or must be decomposed into convex primitives. This is undesirable in haptic sculpting systems because it entails real-time decomposition of deformable objects into convex primitives. McNeely et al. put forward a simple, fast, and approximate voxel-based approach. This approach enables the manipulation of a modestly complex haptic cursor within an arbitrarily complex environment of rigid objects [20]. However, McNeely's method is not suitable for deformable surface or B-Rep modeling because virtual objects have to be voxelized with this method and this would be too expensive. This method would be highly efficient when dealing with static objects or volumetric sculpting. Balasubramaniam et al. presented a 5-DOF haptic machining interface by using combinations of spheres and cylinders to represent a milling tool while point clouds represent contact models [1]. This haptic interface is quite close to our approach. However, geometric shape for sculpting tools provided in this method is too simple for haptic sculpting, although they are good at simulating ball-head milling tools.

One application for a haptic interface is haptic sculpting. Haptic sculpting is a modeling technique based on the notion of sculpting a solid material with tools. Polygonal mesh is a common model representation in haptic systems. In the haptic sculpting system called *inTouch* [10], users can interactively edit and paint subdivision-based polygonal meshes. Volume sculpting is widely used in virtual sculpting because it is capable of modeling objects in arbitrary topology, examples include [5,15]. The *FreeForm* haptic modeling system, from SensAble Ltd, is the first commercially successful computer aided industrial design (CAID) tool which lets designers sculpt and form virtual clay using similar tools and techniques that are employed in the physical world [26]. The FreeForm system is also based on volumetric modeling techniques. The research group led by Qin at State University of New York developed several novel haptic sculpting methods based on some other geometric model representations, such as subdivision solids [19], volumetric implicit functions [14] and point set models [12].

Although geometric representations like polygonal mesh, volumetric model, subdivision solids or volumetric implicit function have certain advantages, these model representations are unsuitable for mainstream CAD applications. Models from these sculpting systems are difficult, if not impossible, to transfer to CAD applications, such as Solidworks or UG [18]. In [25], Sener investigated how industrial designers use FreeForm and emphasized the importance of file exchange. Therefore, haptic sculpting directly on NURBS surface or B-Rep model is desirable. Dachille and Qin put forward a novel haptic interface and presented a physics-based B-spline surface modeling approach [7]. Their work demonstrates the feasibility of using haptic interface to manipulate B-spline surface models and hence is considered as a breakthrough in both CAD and computer haptics field. In this research, we adapt their technique of transform mass-spring mesh into B-spline surface. Liu et al. also developed a haptic design system for CAD