Using Deformation Map Painting for Bimanual, Haptic Sculpting of 3D Digital Models

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ABSTRACT

We explore a novel interaction technique using force-feedback devices for creative manipulation of 3D models that combines interactive mesh deformation with painting a deformation property map. Painting a deformation map permits the artist to easily assign different values of “malleability” to specific areas of the model in order to locally manipulate the deformation behavior during interactive sculpting. The technique uses Phantom force-feedback devices for direct 3D interactions with the 3D object and to provide the artist with immediate haptic and visual feedback. Using a second haptic device allows us to explore complex bimanual interactions in which both hands contribute to the sculpting process. One example of this bimanual interaction is painting the malleability value onto the model with one hand while simultaneously deforming it with the second hand. These complex multi-sensory interactions are an important step towards empowering digital 3D artists with efficient and easy-to-use 3D tools.

Author Keywords
Digital 3D shapes, geometric modeling, real-time, bimanual, interaction, interactive deformation, haptic

ACM Classification Keywords
I.3.6 Methodology and Techniques - Interaction techniques; I.3.4 Graphics Utilities - Graphic Editors; H.5.2 Haptic I/O;

INTRODUCTION AND RELATED WORK

Digital 3D artists typically use professional 3D modeling applications, such as Autodesk’s Maya [1] or Pixologic’s ZBrush [2], to create and manipulate the geometry and appearance of 3D models. These applications provide a vast array of sophisticated functionality and tools, but typically only support traditional interaction devices, such as a mouse, keyboards or graphics tablets. The goal of these digital tools is to facilitate the expression of the artist’s imagination in a form that can be shared. However, many types of direct interactions with 3D models, such as freeform sculpting, are fundamentally limited by the nature of these devices. Interaction devices that track the artist’s hand movements within 3D space are one step towards providing the digital equivalent of real-world clay sculpting [3]. The addition of the sense of touch and the flexibility to use two hands, shown in Figure 1, may provide digital artists with an even richer interaction experience and may further improve their abilities to manipulate 3D shapes in an intuitive way.

Figure 1: Using two Phantom haptic devices to manipulate 3D digital models.

Figure 2: Different degrees of malleability, shown as different colors, lead to different results when performing interactive deformations (eyes). A low malleability (black) can be used to preserve internal structure during deformation of the nose.

Deformation map painting extends 3D artistic interaction beyond what is possible with clay sculpting by enabling the
direct manipulation of both the deformation and the model’s local deformation properties. This technique allows the artist to directly paint a malleability value onto a deformation map of the model’s surface. Subsequent deformation of the model results in locally different deformation behavior, depending on the malleability painted onto the model (Figure 2). This interaction technique is part of a larger proof-of-concept system that supports bimanual interactions with meshes, such as cutting and freeform sculpting, and provides visual, haptic visual and auditory feedback.

SensAble’s family of Phantom force feedback devices offer one method of combining 3D interaction with touch. These grounded haptic devices provide the artist with active, kinesthetic feedback at the tip of a stylus. Although the overall haptic experience conveyed by the Phantom is a reduction of a real-world haptic experience, it is well suited as an augmentation for 3D graphics. To the user, the Phantom’s stylus appears as a force-enabled 3D mouse, which tracks the stylus’ position and rotation within a 2’ –4’ workspace and projects small forces of up to 10 Newtons to the hand grasping the stylus. These forces are used to convey the shape, stiffness, friction, and other haptic properties of virtual 3-D objects; these can be mapped to the geometry of a 3D object similar to color in visual rendering. Dynamic force effects, such as attraction or repulsion, can be used to create sophisticated 3D user interactions.

The Phantom is a component of haptic interfaces in a variety of contexts, including in the areas of art and design. Foskey et al. [4] and Gregory et al. [5] outline techniques for painting and deformation of 3D meshes. McDonnell et al. explore a volumetric framework based around subdivision solids, and one interaction within their framework is “stiffness painting,” which allows the user to paint stiffness values onto the nodes of a control lattice [6]. Cani et al. also present several approaches to manipulating virtual clay [7], and suggest that some approaches would benefit from more than a single device. However, although bimanual 3D interactions and their benefits have been investigated [8], art-related 3D interactions with two haptic devices remain largely unexplored.

INTERACTIONS BASED ON DEFORMATION MAPS

Using a paint metaphor with visual texture maps for color texturing a 3D model is a common function in artistic software; our interaction technique is based on a) using texture maps as a metaphor for deformation properties (“stiff” or “malleable”) and b) painting these deformation properties instead of colors into a deformation texture map. A 3D brush performs the deformation map painting and allows the artist to locally assign inhomogeneous deformation properties to different parts of the model. The painting metaphor provides the artist with an intuitive interface to directly modify the deformation properties of the mesh at the vertex granularity. The Phantom’s stylus acts as the virtual 3D brush, its haptic feedback allows the artist to feel the geometry of the surface mesh and greatly increases the speed and ease of painting a 3D object.

Figure 3 shows a deformation map painted onto a 3D model. While most of the areas of the mesh have been painted to be very malleable (white color), the areas around each ear have been stiffened with different shades of red, and the area around the top part has been set rigid with black. The brush’s color can be varied along a black-red-yellow-white color scale by touching the brush tip to the heat map on the right side of Figure 3. This heat metaphor provides the artists with a visual connection between the implied malleability and color. Black, for cold iron, signifies the lack of malleability; warmer shades of reds, oranges, yellows, and bright white signify increasing degrees of malleability.

Grabbing a point on the mesh surface with a pair of virtual tweezers and moving it in 3D space initiates a real-time deformation of the mesh originating at that contact point. The artist can observe the visual effect of the deformation and feel a resistance force equivalent to the magnitude of deformation. This form of interactive deformation not only honors the topology of the mesh (Figure 4), but is also directly affected by the malleability values in the deformation map. An area with lower values, represented by colder colors on the heat map will offer a higher resistance force, and exhibit a lower degree of deformation than areas with higher values (warm colors).

Deformation map painting provides the artist with a greater amount of control over the outcome of a deformation on the model than traditional approaches. It allows the artist the creative license to experiment with deformation in localized portions of the model, to fine-tune details of its 3D shape and to lock/unlock critical areas with regard to deformation.

Bimanual Deformation Map Painting and Deforming

When using one Phantom for painting or for deforming, the second Phantom can be used to grab the object and to reorient it during the painting or deformation process. In this asymmetric bimanual interaction, the second hand plays a
supporting role by creating a frame of reference for the first hand. In addition to sequentially switching between the deformation map painting and deformation tasks, it is also possible to perform both tasks together. This allows the user to have one hand painting to the deformation map while the other hand simultaneously deforms this area. Figure 3 shows the deformer tool (tweezers) grasping a point of contact in the black (hard) area, and the paintbrush poised to apply white to the area. While one of the tools is likely to play a more active role, this type of bimanual interaction is closer to being symmetric and both tools may alternate between the active role.

Performing both tasks together enables the artists to create complex shapes. For example, painting malleability values that are softer than the surrounding area may be used to increase the displacement of an area and to create a spike-shaped deformation, while painting a stiffer value causes more points to absorb the displacement, creating a rounder displacement. The user may also create a deformation that propagates laterally along the surface of the model by painting a stiff value in a path across the surface, and surrounding it with a more malleable region.

Painting
In addition to painting into a deformation map, the system provides a brush tool for painting the model with visual colors and permits the artist to switch between them. Each of these maps can be blended with additional textures that were loaded as part of the appearance of the 3D model; both forms of painting are layered nondestructively onto the original texture. Because the deformation algorithm requires three parameters, the transfer function converts the one-channel malleability values to three property values used in the deformation algorithm: stretch, shear, and compression. The transfer function, shown in Figure 5, shows a simple configuration of linear functions for these three properties (red, green and blue lines). However, the shape of these functions can be altered to create a different interpretation of malleability that may be better suited to a specific artistic application. Artists may gain finer control over deformation map painting through direct access to these functions as part of the 3D user interface.

IMPLEMENTATION
The overall system infrastructure implements a more general framework for manipulating the topology of triangle meshes, deforming its geometry in real-time, and for texturing and defining surface properties. The user manipulates the model through the functions of virtual tools, which interact with the environment through the Phantom’s stylus. For example, separate tools exist for cutting the mesh and painting texture maps on the mesh surface. Deformation map painting uses a combination of texture painting and an advanced form of deformation based on the Generalized ChainMail algorithm [9], which also handles complex mesh topology alterations created by cutting the 3D model.

Generalized ChainMail Deformation
The Generalized ChainMail algorithm provides fast mesh deformations that approximate the active deformation of certain types of materials. The interactive speed allows the deformation to be calculated each frame, which gives the user the ability to reverse the severity of the deformation by reducing the displacement of the contact point. The algorithm operates directly on vertices of the mesh, and translates a malleability value to deformation parameters for each vertex. From the point of contact with the stylus tip, the deformation spreads outward, with each displaced point sponsoring the analysis of its neighbors, ignoring points that have already moved. This means that each point is only analyzed once, and the complexity of the algorithm is proportional only to the number of affected points.

Figure 6 illustrates principle behind the Generalized ChainMail algorithm by depicting the box, or valid region,
around a candidate for deformation. The sponsoring point creates a box centered on the original offset from the sponsor to its neighbor on the left. The dimensions of the box are given by the material parameters defined for this point; stretch elongates the box, compression reduces the length of the box, and shear determines the width and height of the box. As the sponsor moves, the center of box moves the same distance; if the neighbor then lies outside of this box, it is moved to the closest position inside the box.

**Malleability Gradient Deformation**

The problem that arises when using the Generalized ChainMail algorithm to perform a deformation on a vertex set with varying malleability values is that it allows a more malleable point to control the displacement of a stiffer point. Since the deformation propagates outward from the contact point, malleable points near the contact point sponsor the displacement of neighboring stiffer points. In Figure 7, the light gray malleable points absorb the deformation of the point on the right, and that causes the stiffer dark gray stiffer to move closer together and out of alignment. The stiff point calculates its displacement relative to the malleable point, which may cause it to move to an invalid position relative to any neighboring points with higher stiffness values that might exist. This can cause undesired ripples throughout the stiffer region of the mesh.

Schill solves this problem by calculating the distance each neighbor must move as a result of the displacement of the sponsor, the constraint violation, and prioritizing the neighbor with the highest constraint violation [10]. Another method for solving this problem is to use a gradient of malleability values stored in the deformation map. With the malleability gradient, a point may only sponsor the movement of a neighbor if the neighboring point is equally or more malleable. The exception to this rule is that a malleable point should be allowed to displace a neighboring stiff point if the malleable point has the highest stiffness among the active candidates for deformation; otherwise the malleable points along a stiffer boundary would stretch infinitely.

This allows a deformation to propagate faster through stiffer regions before spreading to more malleable areas. It also respects the exception where a deformation begins in a malleable area and expands into a stiff region; the first point in the stiff region would then propagate the displacement to the rest of the stiff region. This solution preserves the move-once approach of the ChainMail algorithm, and reduces the calculation required to determine the order in which the deformation spreads to neighboring points.

**SUMMARY & CONCLUSIONS**

We present an innovative interaction technique for shaping the geometry of 3D digital objects. The method is based on the combination of a deformation tool and a brush tool that changes the mesh’s malleability contained in a deformation map. A specialized version of the Generalized ChainMail algorithm uses this deformation map to calculate locally varying degrees of deformation. This method has been implemented as part of a larger system that explores bimanual interactions with digital 3D models via haptic force feedback devices.

An initial pilot user study indicates that this system, with its bimanual interaction methods, has the potential to significantly enhance the artistic process of sculpting complex 3D shapes. A larger user study is in progress to evaluate the bimanual haptic interface against a comparable single device interface for speed, error rate and workload while performing typical 3D model manipulation tasks.

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