A Perceptually-Inspired Force Model for Haptic Texture Rendering

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Abstract

One of the most salient haptic characteristics of objects is surface texture. Psychophysics studies have identified several key factors that affect perception of roughness during exploration of surface textures. Inspired by these recent findings, we develop the first force model for haptic display of interaction between two textured objects. We describe how our force model accounts for important elements identified by psychophysics studies. We then analyze and validate our model by comparing our simulation results against actual perceptual studies. We show that our model captures similar effects to those observed in the earlier experiments on roughness perception.

1 Introduction

Surface texture, one of the most salient haptic characteristics of objects, can be a compelling cue to object identity and can strongly influence dexterous manipulation [Klatzky and Lederman 2002]. Recently haptic texture rendering has received increasing attention, both from the perceptual and computational perspectives. However, up to date, techniques for haptic rendering of interaction between two objects, known as six-degree-of-freedom (6-DoF) haptics, have not been able to capture roughness effects rising from two textured surfaces.

Recently Klatzky and Lederman (see [Klatzky and Lederman 2002] for a summary of their work) have presented several important findings on perception of roughness through an intermediate object. Inspired by these findings, we have developed a new force model for haptic texture rendering between two surfaces. We have also successfully incorporated our force model in a haptic rendering framework based on approximate object representations and texture images. Our force model enables, for the first time, haptic display of forces and torques resulting from interaction between *two textured objects* [Otaduy et al. 2004].

In this paper, we present the synthesis and analysis of a perceptually-inspired force model for haptic texture rendering. Force and torque are computed based on the gradient of directional penetration depth between two textured models. We analyze the influence of factors highlighted in perceptual studies on the vibratory motion induced by our force model. Our experiments demonstrate a qualitative match with roughness perception observed in earlier experiments.

The rest of the paper is organized as follows. In Sec. 2 we discuss related work. Sec. 3 presents the synthesis of the force model. We describe our experiments and results in Sec. 4, and conclude with a discussion of future research directions in Sec. 5.

2 Related Work

In this section we summarize previous work on haptic perception and rendering of textures.

2.1 Psychophysics of Texture Perception

Existing research on the psychophysics of texture perception indicates a clear dichotomy in terms of exploratory procedures: (a) perception of texture with the bare skin, and (b) perception through an intermediate (rigid) object, a probe. Katz [1989] suggested that roughness is perceived through a combination of spatial and vibratory codes during direct interaction with the skin. More recent evidence demonstrates that static pressure distribution plays a dominant role in perception of coarse textures (features larger than 1mm), but motion-induced vibration is necessary to perceive very fine textures [Hollins and Risner 2000].

Our driving problem is the computation and rendering of texture forces occurring during interaction of two objects. As pointed out by Klatzky and Lederman [2002], in this case roughness is encoded in vibratory motion transmitted to the subject. In the last few years, Klatzky and Lederman have directed experiments that analyze the influence of several factors on roughness perception through a rigid probe. For the design of a force model for haptic texture rendering, we are mostly interested on factors related to the physical interaction between objects: object geometry [Lederman et al. 2000; Klatzky et al. 2003], applied force [Lederman et al. 2000] and exploratory speed [Lederman et al. 1999; Klatzky et al. 2003]. In Sec. 3.1 we summarize results relevant to our force model.

2.2 Haptic Texture Rendering

Most of the existing work in haptic texture rendering has focused on tracing a textured surface with a single contact point. Geometry-dependent high frequency forces are computed based on the position of the contact point, resulting in a feel of "roughness". Minsky [1995] proposed the computation of texture-induced forces proportional to the gradient of a 2D height field stored in a texture map. Ho et al. [1999] also suggested altering the magnitude and direction of 3D normal force based on height field gradient. These techniques exploit the fact that, for point-object contacts, a pair of texture coordinates can be well defined, and this is used to query height fields stored in texture maps. Siira and Pai [1996] used a stochastic approach, where texture forces were synthesized according to a Gaussian distribution to generate a sensation of roughness. Choi and Tan [2003] have analyzed stability problems in point-based texture rendering.

Point-based techniques are limited to capturing only geometric effects of one object and cannot render effects caused by rotational motion. For rendering forces and torques occurring during the interaction of *two surfaces*, the geometric interaction often cannot be represented by a single pair of contact points and thus cannot be captured by point-based techniques.

Up to date, techniques for 6-DoF haptic rendering [McNeely et al. 1999; Kim et al. 2003; Johnson and Willemsen 2003] have not captured roughness effects rising from exploration of surface texture, due to sampling limitations. Otaduy and Lin [2003] proposed a technique to overcome sampling problems by selecting object resolution adaptively at each contact. However, this approach filtered high-frequency geometric detail, thereby removing texture effects.

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[*] http://gamma.cs.unc.edu/HTextures

3 Synthesis of the Force Model

In this section we describe our force model for haptic texture rendering. We first summarize results of psychophysics studies on roughness perception through a rigid probe, and then describe how our force model accounts for the factors identified in the studies.

3.1 Summary of Psychophysics Results

The experiments conducted by Klatzky and Lederman to characterize roughness perception follow a common pattern: subjects explore a textured plate with a probe with a spherical tip, and then they report a subjective measure of roughness. Plates of jittered raised dots are used, and the mean frequency of dot distribution is one of the variables in the experiments. Resulting data is analyzed by plotting subjective roughness values vs. inter-dot spacing in logarithmic graphs, as shown in Figs. 1-3 of the color plate.

Klatzky and Lederman [1999] compared graphs of roughness vs. texture spacing (a) with finger exploration and (b) with a rigid probe. They concluded that, in the range of their data, roughness functions were best fit by linear approximations in finger exploration, and by quadratic approximations in probe-based exploration. In other words, when perceived through a rigid spherical probe, roughness initially increases as texture spacing increases, but, after reaching a maximum roughness value, it decreases again. Based on this finding, the influence of other factors on roughness perception can be characterized by the maximum value of roughness and the value of texture spacing at which this maximum takes place.

Lederman et al. [2000] demonstrated that the diameter of the spherical probe plays a crucial role in the maximum value of perceived roughness and the location of the maximum. The roughness peak is higher for smaller probes, and it occurs at smaller texture spacing values (See Fig. 1 in the color plate).

Lederman et al. [2000] also studied the influence of the applied normal force during exploration. Roughness is higher for larger force, but the influence on the location of the peak is negligible (See Fig. 2 in the color plate).

The effect of exploratory speed was studied by Lederman et al. [1999]. They found that the peak of roughness occurs at larger texture spacing for higher speed (See Fig. 3 in the color plate). Also, with higher speed, textured plates feel smoother at small texture spacing, but they feel rougher at large spacing values. The studies reflected that speed has a stronger effect in passive interaction than in active interaction.

3.2 Offset Surfaces and Penetration Depth

Klatzky et al. [2003] stated that the perception of roughness is intimately related to the trajectory traced by the probe. In particular, they identified the value of texture spacing at which the probe can exactly fall between two texture dots as *drop point*. The peak of roughness perception occurs approximately at the drop point, and it depends on geometric (i.e. probe diameter) and dynamic factors (i.e. speed).

For a spherical probe, and in the absence of dynamic effects, the surface traced by the probe during exploration constitutes an offset surface, as shown in Fig. 1. The oscillation of the offset surface produces the vibratory motion that encodes roughness. The idea of offset surfaces has also been used by Okamura and Cutkosky [2001] to model interaction between robotic fingers and textured surfaces.

In the design of a force model for haptic texture rendering, we face the question: How can we generalize the concept of offset surface to the interaction between two arbitrary surfaces? To answer this question, we consider the case of a spherical probe whose center moves along a textured surface, as depicted in Fig. 1. In this situation, the probe penetrates the textured surface. The *vertical penetration depth* δ is the vertical translation required to separate the probe from the textured surface. Vertical penetration depth equals the height of the offset surface.

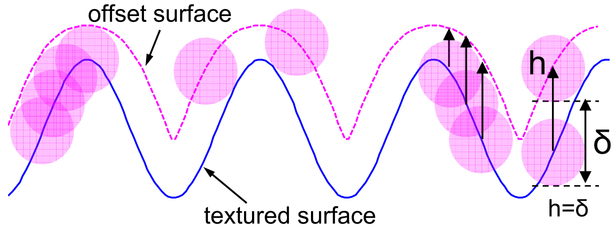

Figure 1: **Offset Surfaces.** *Left: offset surface computed as the convolution of a surface with a sphere; Center: sphere whose trajectory traces an offset surface; Right: correspondence between penetration depth (δ) and height of the offset surface (h).*

The concept of directional penetration depth is also applicable to the interaction between arbitrary surfaces. Using the contact normal between low-resolution approximations of the surfaces, we can define a directional penetration depth between the full-resolution surfaces. The variation of the penetration depth (i.e. the gradient) can be interpreted as texture-induced motion. The validity of the gradient of penetration depth as a descriptor for texture-induced forces has already been proved by point-based rendering methods [Minsky 1995; Ho et al. 1999].

3.3 Force Model

An ideal solution to 6-DoF haptic rendering would be to compute the motion of virtual objects using full-resolution models and constraint-based simulation, and render contact forces directly to the user. However, as explained in Sec. 2.2, this approach would be computationally prohibitive with complex textured models. Instead, we propose a force model that produces effective texture forces using approximate geometric representations. We also adopt the penalty method that computes contact forces proportional to penetration depth, thus reducing the cost of dynamic simulation.

A second consideration for the synthesis of the force model is that it need not account for certain dynamic effects. The influence of exploratory speed highlighted in perceptual studies is mainly determined by the motion and impedance characteristics of the subject. Haptic simulation is a human-in-the-loop system, therefore dynamic effects associated with grasping factors should not be modeled explicitly.

For two virtual objects A and B, penetrating a distance δ, we define a penalty-based potential field U with stiffness k as:

$$U = \frac{1}{2} k \delta^2 \tag{1}$$

Based on this energy and the gradient ∇ in 6-DoF configuration space, we define force $\mathbf{F}$ and torque $\mathbf{T}$ as:

$$\begin{pmatrix} \mathbf{F} \\ \mathbf{T} \end{pmatrix} = -\nabla U = -k\delta\left(\nabla\delta\right) \tag{2}$$

At each contact location between objects A and B we can define a penetration direction $\mathbf{n}$ based on the contact normal between low-resolution (texture-less) approximations of the objects. We assume that, locally, the penetration depth can be approximated by the directional penetration depth $\delta_{\mathbf{n}}$ along $\mathbf{n}$. We rewrite Eq. 2 for $\delta_{\mathbf{n}}$ in a reference system $\{\mathbf{u},\mathbf{v},\mathbf{n}\}$[1]. In this case, Eq. 2 reduces to:

$$\begin{pmatrix} F_u & F_v & F_n & T_u & T_v & T_n \end{pmatrix}^T = -k\delta_{\mathbf{n}} \begin{pmatrix} \frac{\partial\delta_{\mathbf{n}}}{\partial u} & \frac{\partial\delta_{\mathbf{n}}}{\partial v} & 1 & \frac{\partial\delta_{\mathbf{n}}}{\partial\theta_u} & \frac{\partial\delta_{\mathbf{n}}}{\partial\theta_v} & \frac{\partial\delta_{\mathbf{n}}}{\partial\theta_n} \end{pmatrix}^T \tag{3}$$

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[1] $\mathbf{u}$ and $\mathbf{v}$ may be selected arbitrarily as long as they form an orthonormal basis with $\mathbf{n}$.

where θ_u, θ_v and θ_n are the rotation angles around the axes **u**, **v** and **n** respectively.

As it can be inferred from Eq. 3, the normal force F_n is the typical normal force of penalty-based methods. However, our force model also considers forces and torques in the other axes. These forces and torques depend on the gradient of penetration depth, therefore they are very sensitive to geometric perturbations and crucial to conveying roughness information. Although similar in spirit, our model is quite different from point-based techniques [Minsky 1995; Ho et al. 1999], because we compute the gradient of *object interpenetration* instead of the gradient of a *height field*. This difference is inspired and supported by the influence of probe geometry, highlighted by perceptual studies, and which cannot be captured by point-based techniques. Also, notice that the torque and the tangential force are proportional to the normal force in our model. This dependence is consistent with the qualitative relation found by Lederman et al. [2000].

Other effects, such as friction, can be easily incorporated to our force model using existing techniques at each contact location.

4 Analysis of the Force Model

In order to analyze the force model, we have performed two types of experiments. First, we describe offline experiments where we analyze the influence of the factors highlighted by perceptual studies on the vibratory motion induced by our force model. And, second, we present actual haptic simulations where we have tested the effectiveness of the force model and the performance of its implementation.

4.1 Description of Offline Experiments

As mentioned in Sec. 3.1, Klatzky and Lederman conducted experiments where users explored textured plates with spherical probes, and they reported subjective values of perceived roughness. We have created simulated replicas of these experiments, and we have analyzed the vibratory motion induced by our force model. Our virtual experiments required the simulation of probe-plate interaction, as well as human dynamics.

We model the spherical probe as a circular disk of diameter D, and the textured plate as a sinusoidal curve, as shown in Fig. 2. We move the circular disk along a horizontal line, which represents the low resolution approximation of the sinusoidal curve. At each position of the disk we compute the vertical penetration depth $\delta_{\mathbf{n}}$ with respect to the sinusoidal curve.

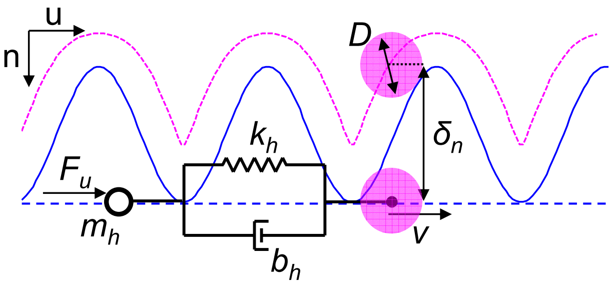

Figure 2: **Model of Probe-Surface Interaction and Grasping Dynamics.** *A disk moves on a sinusoidal texture at constant speed v, while dragging a mass m_h. A texture force F_u, based on penetration depth $\delta_{\mathbf{n}}$, is applied on the mass.*

Following our force model for haptic texture rendering, we define texture-induced normal and tangential forces as:

$$F_n = -k\delta_{\mathbf{n}} \tag{4}$$

$$F_u = -k\delta_{\mathbf{n}} \frac{d\delta_{\mathbf{n}}}{du} \tag{5}$$

The normal force F_n is one of the factors studied by Lederman et al. [2000]. We will consider it as an input in our experiments. Then, we can rewrite:

$$F_u = F_n \frac{d\delta_{\mathbf{n}}}{du} \tag{6}$$

We have modeled human dynamics as a system composed of mass m_h, spring k_h and damper b_h [Hasser and Cutkosky 2002]. The mass is linked through the spring and damper to a point moving at constant speed v on the textured surface. The dragging force imposed by the point accounts for the influence of exploration speed, which is a factor analyzed by Lederman et al. [1999]. Figure 2 shows a diagram of the dynamic system that we have simulated.

The texture force F_u also acts on the mass that models the human hand. In the presence of a textured surface, F_u will be an oscillatory force that will induce a vibratory motion on the mass. The motion of the mass is described by the following differential equation:

$$m_h \frac{d^2u}{dt^2} = k_h (vt - u) + b_h \left(v - \frac{du}{dt} \right) - F_u \tag{7}$$

4.2 Comparison with Perceptual Studies

The experiments summarized by Klatzky and Lederman [2002] reflect graphs of perceived roughness vs. texture spacing, both in logarithmic scale. We have simulated the motion of the hand model in Matlab, based on Eq. 7. In our simulations we cannot estimate subjective roughness values. Instead, knowing that roughness is perceived through vibration, we have quantified the vibration during simulated interactions by measuring maximum tangential acceleration values. More specifically, we have measured $max(\frac{d^2u}{dt^2})$ once the motion of the mass reaches a periodic state.

Effects of Probe Diameter:

In Fig. 1 of the color plate we compare the effects of probe diameter on perceived roughness and maximum simulated acceleration. The first conclusion is that the graph of acceleration vs. texture spacing can be well approximated by a quadratic function in a logarithmic scale. The second conclusion is that the peaks of acceleration and roughness functions behave in the same way as a result of varying probe diameter: both peaks of roughness and acceleration are higher and occur at smaller texture spacing values for smaller diameters.

Effects of Applied Force:

The graphs in Fig. 2 of the color plate compare the effect of applied force on perceived roughness and simulated acceleration. In both cases the magnitude under study grows monotonically with applied force, and the location of the peak is almost insensitive to the amount of force.

Effects of Exploratory Speed:

In Fig. 3 of the color plate we compare the effects of exploratory speed on perceived roughness and simulated acceleration. At large values of texture spacing, both perceived roughness and simulated acceleration increase as speed increases. However, the effects do not match at small values of texture spacing. We would expect simulated acceleration to be larger at lower speeds, but it remains almost constant.

To summarize, the effects of probe diameter and applied force on the motion induced by our force model for texture rendering match in a qualitative way the effects of these factors on perceived roughness of real textures. Our experiments exhibit some differences on the effects of exploratory speed. These differences may be due to limitations of the force model or the dynamic hand model employed in the simulations.

4.3 Performance Tests with Complex Models

We have integrated our force model in a novel algorithm for haptic rendering of interaction between textured models. Similar to graphic texture mapping, we represent objects as low-resolution polygonal models along with texture images storing fine geometric detail.

As a first step in force computation, we perform collision detection between low-resolution approximations of the models, identifying contact locations and penetration directions. We estimate the directional penetration depth and its gradient at each contact, using information from texture images. The algorithm for penetration depth computation is efficiently implemented on graphics hardware. Finally, we compute texture force and torque at each contact using the force model presented in this paper, and we apply them to the probe object held by the user.

The algorithm for haptic rendering using texture images, along with its efficient hardware-based implementation, enables high force update rates on complex textured models such as the ones shown in Figs. 4-6 of the color plate. We are able to perform force computation at frequencies as high as 500Hz in scenes such as a probe exploring a textured plate (shown in Fig. 4 of the color plate). The force update rate is as high as 100 to 200Hz in very challenging scenarios such as a complex textured hammer interacting with striped blocks (shown in Fig. 5 of the color plate), and a file scrubbing a CAD part (shown in Fig. 6 of the color plate). The experiments with complex models have proved that our perceptually-inspired texture force model allows successful conveyance of roughness in haptic rendering of interaction between complex textured models. A detailed description of the algorithm for haptic texture rendering, its implementation, and performance results are presented in a technical report [Otaduy et al. 2004].

5 Discussion and Conclusion

We have presented a force model for haptic rendering that addresses geometric and dynamic factors associated with roughness perception. This force model creates virtual texture stimuli by computing forces and torques proportional to the gradient of penetration depth. This model can be regarded as a generalization of previous point-based techniques for haptic texture rendering. To the best of our knowledge, it is the first force model for 6-DoF haptic texture rendering.

An analysis of the vibratory motion induced by the force model demonstrates that it presents important qualitative correspondences with human roughness perception. In particular, if we consider simulated hand acceleration as a function of texture spacing, this function presents a peak whose magnitude and location depend on probe diameter and applied force very similarly to the behavior of perceived roughness. In the case where exploratory speed is a variable factor, we have also found some behavioral similarities. We conclude that our texture force model is capable of producing virtual roughness stimuli that resemble qualitatively physical roughness stimuli transmitted through rigid objects.

The connection between physical parameters, such as forces and motion, and a subjective metric of roughness is still unknown. In our experiments we have used acceleration to quantify vibratory motion, but we do not know if perceived roughness is directly or solely dependent on acceleration. Nevertheless, our analysis has been based on qualitative comparisons of location and values of function maxima. This approach relaxes the need for a known relationship between acceleration and roughness. For example, if perceived roughness depends monotonically on acceleration in the interval of study, the maxima of roughness and acceleration will occur at the same values of texture spacing. This correlation is basically what we have found in our experiments.

We plan to extend our work by enriching the types of surfaces and properties rendered, such as higher frequency textures and deformable textured surfaces, and by applying our texture force model to applications in assisted technology, surgical training and virtual prototyping. We believe that the future refinement of our model can benefit tremendously from further research on the psychophysics of roughness perception.

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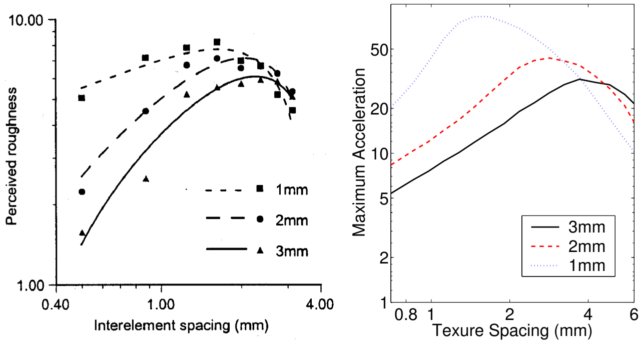

Figure 1: **Effects of Probe Diameter.** Left: results of psychophysics studies by Lederman et al. [2000] *(printed with permission of ASME and authors)*; Right: simulation results using our force model.

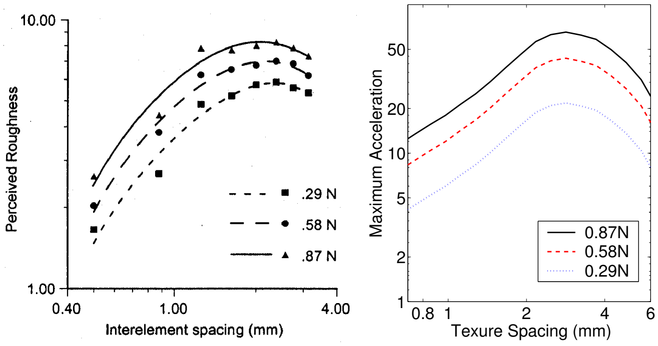

Figure 2: **Effects of Applied Force.** Left: results of psychophysics studies by Lederman et al. [2000] *(printed with permission of ASME and authors)*; Right: simulation results using our force model.

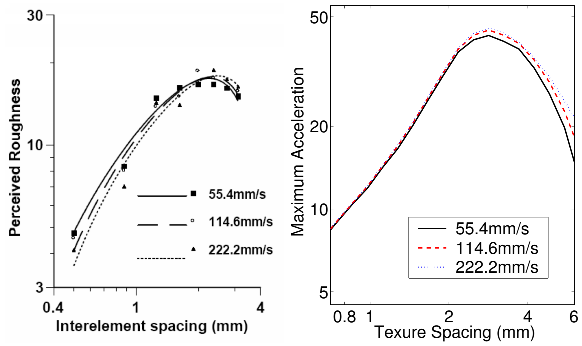

Figure 3: **Effects of Exploratory Speed.** Left: results of psychophysics studies by Lederman et al. [1999] *(printed with permission of Haptics-e and authors)*; Right: simulation results using our force model.

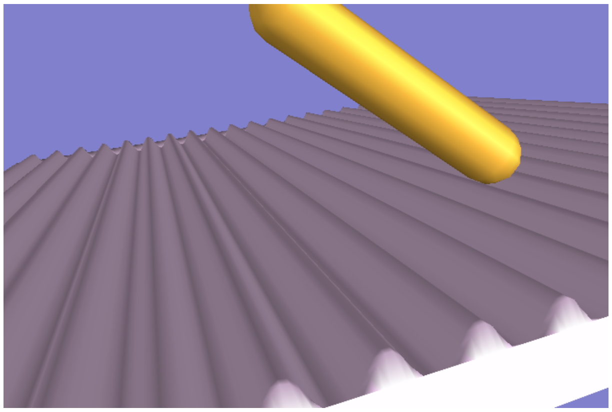

Figure 4: **Haptic Simulation of Probe and Plate:** A subject virtually explores a textured plate using a probe with a spherical tip. This haptic simulation resembles experiments carried out as part of perceptual studies.

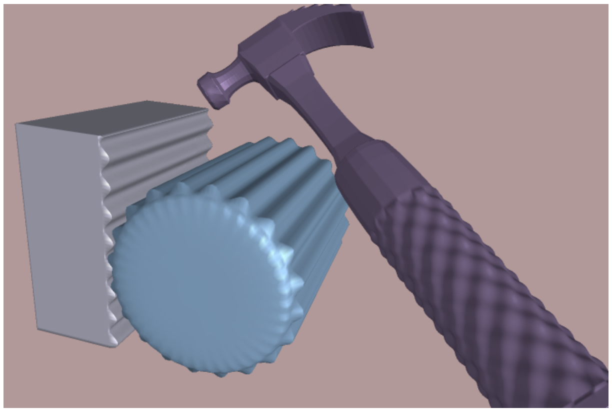

Figure 5: **Haptic Simulation of Hammer and Blocks:** Virtual haptic interaction between a textured hammer and striped blocks.

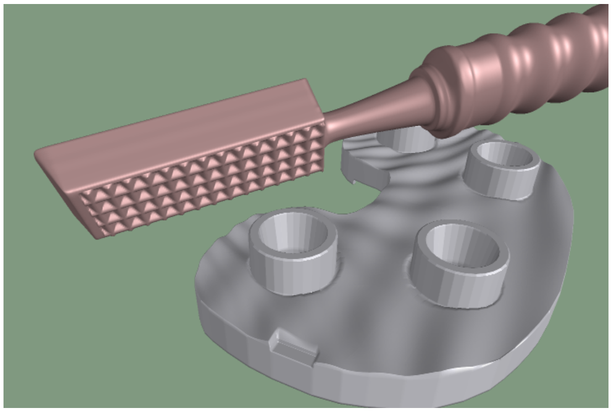

Figure 6: **Haptic Simulation of File and CAD Part:** Scrubbing a CAD part with a virtual file in a highly challenging simulation.