Haptic Display of Multiple Scalar Fields on a Surface

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Abstract

We present here the outlines of a system for simultaneous presentation of several related data sets to users by means of a multidimensional haptic display. Such a display is preferable to a visual display in some situations, for example when (as in our lab) a nanometer-scale real surface is being both examined and modified by the user, and rapid local feedback from the modifications is needed. We propose that each data set (e.g. each property of the nanosurface) be represented by a different haptic dimension, and that equal increments in the property be represented by *perceptually* equal increments on the corresponding dimension. Fortunately for this scaling requirement, the results reported here reveal that the "power law," a simple mathematical function which sensory scientists have found to describe the subjective intensity of many types of real stimuli (Stevens, 1961; Gescheider, 1997), applies to virtual ones as well.

Introduction

The scientists with whom we collaborate need to analyze what is happening to a sample during the course of an experiment using an Atomic Force Microscope (AFM). While graphical techniques for displaying simultaneous data sets are quite useful to them once they have collected the data from their experiments, such techniques are not as useful during an experiment, while they are modifying a sample in the microscope. We believe that our strategy of mapping a different haptic dimension to each data set under consideration has the potential to be useful to them during interactive control of the microscope.

We present here our work in haptic display of data on a surface. We describe our implementations of four haptic stimuli (stiffness, friction, surface vibration, and small-scale surface bumps). We have also begun a series of psychophysical experiments to try to understand the user's perception of haptic stimuli composed of these surface features. We want to understand the user's perception of the differences in the magnitude of a given surface feature when presented with different combinations of these features. We present a linear scaling with perception of each of the four surface effects we discuss.

Related Work and Contributions

Many people have studied the problem of implementing realistic haptic stimuli for use in virtual environments. Friction appears to be the most-studied of the stimuli we implemented, followed closely by surface texture.

Our work builds on the surface and friction model described by Zilles (Zilles, 1995) and implemented by SensAble Technologies Inc. as part of the GHOST haptic toolkit. We have extended the god-object model described by Zilles to implement a form of haptic texture mapping.

In her dissertation work (Minsky, 1995), Margaret Minsky presents results of texturing surfaces using grates and grids. Her implementation of surface texture was notable because it demonstrated that with only forces in two dimensions, it was possible to create a compelling simulation of forces from a probe interacting with a textured surface.

William Mark, et al. (Mark, 1996) demonstrate adding friction and surface texture to a graphics system. They discuss the problem of preventing discontinuities in haptic stimuli when the slope of the surface changes rapidly.

Among others who have used non-visual techniques for information visualization, Mitsuishi et al. (Mitsuishi, 1993), map information to both force feedback stimuli and to sound. They especially use sound to catch the user's attention and emphasize information. We expect our implementation of surface vibration may be useful for similar purposes.

Jason Fritz's work (Fritz, 1996a) discusses implementations of friction and surface texture and states that these properties are useful for haptic exploration. He has also implemented haptic graphing (Fritz, 1996b), a method allowing a user to feel curves and surfaces from scientific data. Our work focuses on the visualization of multiple scalar fields defined on a two-dimensional lattice.

Application

The techniques we present have been developed in the context of the nanoManipulator application, a virtual-environment interface to an Atomic Force Microscope (AFM). To scan a sample, the AFM moves its (nanometer-scale) tip across the surface of the sample in a raster pattern, collecting data at regular intervals as it moves. The microscope tip maintains a constant force on the sample while it is scanning, so the vertical movement of the tip gives us topography information. Other scalar data fields (adhesion, lateral force, electrical resistance, etc.) can also be measured during the scan.

The user of the nanoManipulator interacts with the surface (scaled up by a factor of about a million) using a SensAble Technologies PHANTOM force feedback device. This device allows the user to directly control the tip of the microscope to modify the sample being scanned; motors in the device allow the user to directly "feel" the surface.

There is only one tip on the microscope, which can either be scanning or modifying the surface, but not both at once. Graphical display techniques (color maps, contours, etc.) are used to visualize the automatically scanned data; they allow identification of areas of interest and overlap between data sets on the surface. These methods are not as useful when the user is touching (or modifying) the surface interactively because the data is only collected locally wherever the tip is currently positioned (at a point instead of over an area). In real time during an experiment, we instead use multivariate haptic display to enable the user to *feel* what is happening at each point on the surface as the tip moves across or through objects. Haptic data display is being used to let the user know what is happening *during* the experiment.

Implementation of Haptic Stimuli

Our implementation is based on a local plane approximation to the virtual surface. The user contacts the surface through a virtual point of contact anchored to the PHANTOM stylus (the user's position in this environment). At any point during the surface simulation, we assume that we know the local planar surface approximation at the point at which the user is contacting the surface. This assumption is particularly well-suited to our application because our virtual surface is a height field. When the user's position goes below the current plane (inside the surface), the user is treated as being in contact with the surface. The surface contact point (SCP) is found by projecting the user's position onto the plane. The surface stiffness (which forms the basis for all other surface forces) is simulated by constraining the user's position to the SCP by a linear spring force.

Stiffness. This is the most straightforward of our haptic stimuli. We simply vary the spring constant so that the surface feels stiffer for high data values and less stiff for lower values. (See Figure 1.)

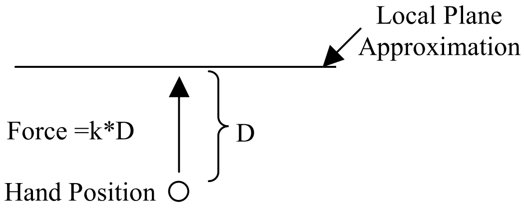

Figure 1: Stiffness Model

Friction. In each iteration of the force update cycle, we supply the GHOST haptic toolkit with a position and a normal vector which are easily calculated as the normal projection of the user's position onto the current plane and the plane normal. The GHOST software simulates friction based on consecutive hand positions by allowing the SCP to lag behind by a set distance that depends on the amount of friction and the penetration distance into the surface (See Figure 2.). This algorithm is described in more detail in (Zilles, 1995).

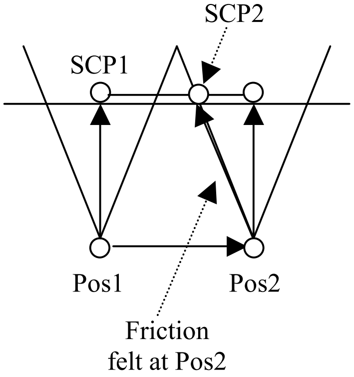

Figure 2: Friction Model

Bumpiness. This is the most complex stimulus we implemented. The bumps are formed from a locally-defined texture which is dynamically mapped to the surface in a way that depends on the user's path. Unlike graphical textures, haptic textures do not need have a globally-defined mapping onto a surface. A simple analogy to our simulation is a bumpy wheel mounted on the end of the stylus as shown in figure 3.

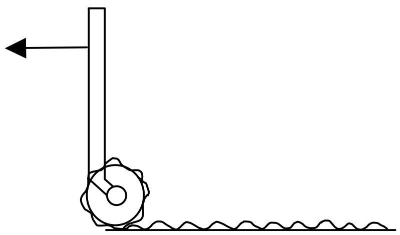

Figure 3: Texture Model

At any point in the simulation, the projection of the user's position onto the surface falls within a circular area which defines the current bump. As soon as the user exits that circle, a new circle is layed down onto the surface with its perimeter lying on the center of the previous one and its center at the position at which the user exited the previous circle. The bump that is felt is a surface of revolution formed by revolving one period of a cosine wave about the origin (mapped to the center of the current circle) (see Figure 4).

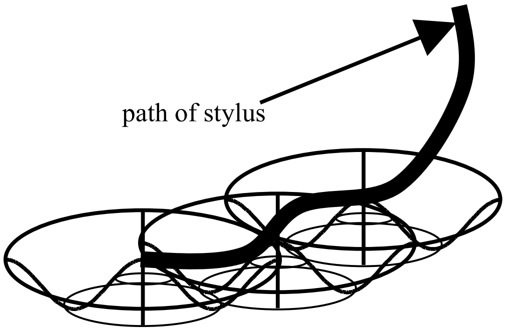

Figure 4: Dynamic mapping of texture along user's path

The implementation of the sinusoidal bump texture is relatively simple for a single plane but as the user's hand moves, the local plane approximation changes and some adjustment of the bump location must be made to ensure continuity of the surface forces.

When the plane is updated, the coordinate system for the plane is rotated about the hand position at the time of the plane update. In this way, the user's hand gets mapped to the same part of the bump texture as it was before the plane was updated. The axis of rotation is calculated as the line passing through the hand position with direction given by the intersection of the previous plane with the new plane. The bumpy profile gets wrapped along the polygonal surface like a sticky string trailed behind the user. (See Figure 5.)

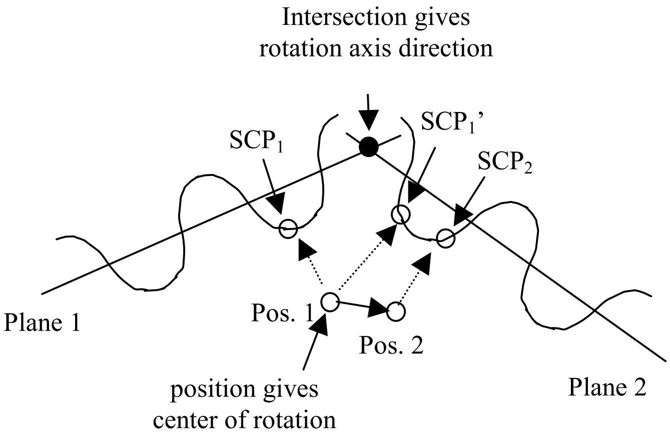

Figure 5: Computation of the coordinate rotation to keep textured surface force continuous when plane changes

This method works well unless the bumps are too small or the user's hand is moving too quickly. If this is the case then temporal aliasing can occur, and the user will perceive a lower spatial frequency than the one intended. The speed of the moving cursor in the psychophysical experiments (See User Studies section.) was well below this Nyquist rate.

Note that the addition of these bumps to a surface can cause significant confusion with surface topography if the surface has features near the scale of the bumps.

Vibration Intensity. To implement vibration, we keep the position of the surface fixed and add a sinusoidal modulating force with an amplitude equal to the force amplitude if the surface height was oscillating in a sinusoidal pattern. There are three cases for what the user should feel from a vibrating surface, depending upon the user's hand height relative to the modulated surface height.

If the user's hand position is completely above the modulated surface (above the original height plus height modulation amplitude), then the user will not feel the effects of vibration because the hand is never in contact with the surface. If instead the hand position is completely below the modulated surface, the user will be in contact with the surface through the entire period of the sine wave. (See Figure 6.) However, if the hand position is not far enough below the surface, then the user will feel a clipped version of the vibration signal. He or she will feel vibration intensity for the part of the sine wave's period that causes the modulated surface to be above the hand position but not when the position of the modulated surface is below the hand position. (See Figure 7.) For this, we apply a force with magnitude equal to the calculated spring force, but in the opposite direction, so the user does not feel force due to vibration when the position on the sine wave is below the hand position.

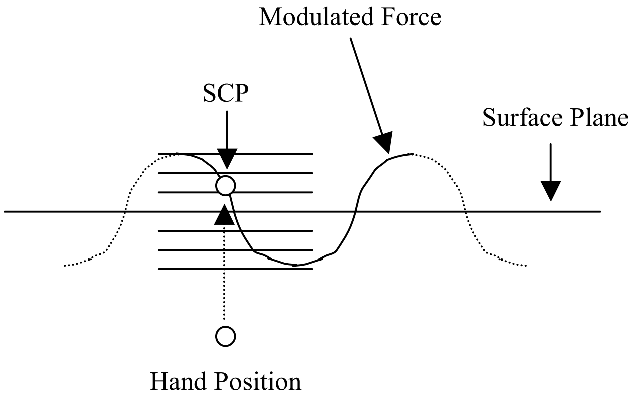

Figure 6: Vibration intensity model. In this case the user's hand position is completely below the sinusoid causing the user to experience the full vibration.

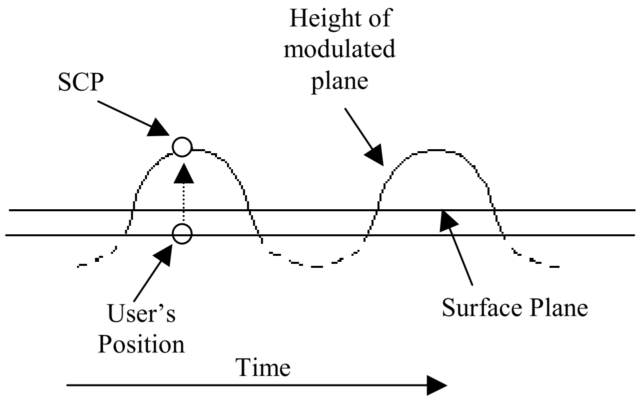

Figure 7: Clipped vibration intensity when the user is near the surface. The dashed lines in the sinusoid indicate when the user will *not* feel the surface.

User Studies

We are in the process of performing a series of user studies (1) to determine the linear perceptual mapping for each stimulus to allow correct mapping of data sets and (2) to determine the interference effects when multiple stimuli are presented on the same surface. We present here the early results of our linear perceptual scaling study, which we used to linearize the presented data sets.

Background. A central focus of our research is to create a virtual haptic surface that is compelling in its own right, and that can effectively communicate to the user information about a real, but nanometer-scale, surface. One of the most important components of this effort is to represent properties of the real surface by means of tangible properties of the virtual surface. The relationship between real properties and the virtual properties onto which they are mapped may be one of conceptual similarity (e.g. bumpiness of the two surfaces), or may be completely arbitrary (e.g. adhesion on the real surface and vibration of the virtual surface). Once pairings have been assigned, another set of decisions has to do with quantitative aspects of the mapping—should friction of the virtual surface be a linear function of charge density of the real surface, for example? The answer of course depends on the specific information about the real surface that the user is most interested in, and also on the quantitative way in which the virtual dimension is subjectively experienced. A reasonable strategy in most cases is, we believe, to arrange the mapping in such a way that a series of physically equal intervals along the real dimension is represented by a series of subjectively equal intervals along the virtual dimension. In addition, it is probably advisable that there be a rough equivalence across virtual dimensions in the range of subjective magnitudes (of stickiness, bumpiness, etc.) available for use in the haptic representation.

Psychophysical Magnitude Functions. To achieve these conditions it is necessary to measure the psychophysical magnitude function for each of the virtual dimensions, e.g., the mathematical relationship between stickiness (a subjective property) and friction (a physical property). It is known that for many perceptual dimensions, such as the brightness of lights and the loudness of sounds, this function is a "power law" in which subjective intensity is proportional to physical magnitude raised to a power that varies from one dimension to another (Stevens, 1961). We have determined the psychophysical magnitude function for four possible virtual dimensions: friction (and its subjective correlate, stickiness), vibration amplitude (vibration intensity), resistance to downward force - or linear spring constant (stiffness), and bump size (bumpiness). While bumpiness is closely related to roughness, a subjective dimension that has been the subject of considerable earlier study (Johnson, 1992; Klatzky, 1999), the other dimensions have been much less studied, in large part because of the difficulty of manipulating the corresponding physical property. The PHANTOM, however, enables us to treat these properties as truly continuous variables, greatly increasing the analytical power of our psychophysical techniques.

Method. In our experiments, subjects hold the stylus in their right hand, as they would a writing instrument, and move its virtual tip in a circular path, 40 mm in diameter, on the virtual surface. They view a monitor on which an actual-size diagram of the track appears, and the tip of the stylus is represented by the cursor, a yellow spot. In order to keep the speed of movement relatively constant, a target (a red line oriented radially) moves along the track at the rate of 2 cm/sec. Subjects attempt to keep the cursor superimposed on the target by moving the stylus tip at the same rate. The cursor grows larger as the stylus tip is depressed farther into the surface; subjects are instructed to depress the stylus until the cursor just fills the width of the track, indicating that the stylus tip is pressed 2 mm into the surface. Subjects receive extended practice until they are reasonably skilled at carrying out these tasks.

Psychophysical measurements are made using free magnitude estimation. On a trial, the subject makes one circuit of the path while attending to a particular dimension designated in advance by the experimenter, and then responds by keying in a number reflecting the subjective magnitude of that property in the particular surface presented on that trial. Dimensions are studied one at a time, within successive blocks of trials; only the designated property varies in magnitude from trial to trial within a block, the other properties being held constant at "default" values. For each dimension, eight values of the stimulus property spanning a twenty-fold range are presented, five times each, to each participant.

Results. Mean estimates of the 32 different stimuli are obtained for each subject, converted to logarithms, and averaged across subjects. The resulting overall means for a group of five subjects are shown in Figure 8, with the data for each dimension plotted separately. The results show clearly that, with the exception in some cases of the lowest stimulus, the power law applies to these haptically perceived dimensions of virtual surfaces, in that the points lie close to a line in these log-log coordinates. Power functions, calculated on the basis of the seven highest stimulus values, have exponents that range from 0.76 (for bumpiness) to 1.26 (for stickiness). Thus if we decide, in subsequent experiments, to use stimulus ranges that are subjectively equivalent across dimensions, the range of bump sizes will need to be 5/3 as great (in logarithmic units) as the range of frictional coefficients.

Future Work. When this initial scaling study is completed, we plan to turn our attention to the issue of how different dimensions interact, by measuring the perceived degree of difference between stimuli. By studying different dimensional combinations, we hope to find ways to manipulate the degree of independence with which multiple properties of a nano-surface are perceived. This would enable users to focus their attention on a single dimension when it is paramount, but to search for particular combinations of dimensional values when these are important.

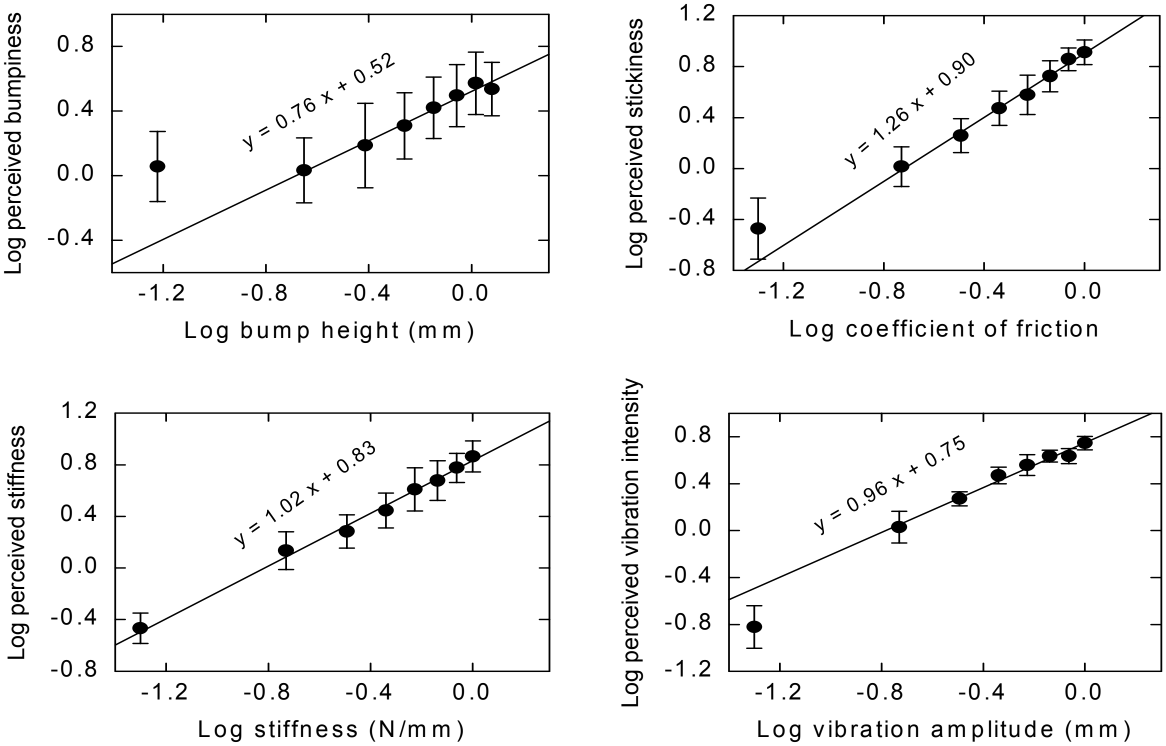

Figure 8: Psychophysical magnitude functions for four dimensions of virtual haptic surfaces. Each point is the mean magnitude estimate of five subjects; error bars show ± 1 S.E.M. Note that the lowest stimulus value does not conform to the power law in the cases of bumpiness, stickiness, and vibration intensity.

Conclusions

This research demonstrates the feasibility of implementing a perceptually linear mapping of data to haptic stimuli within a virtual environment. The psychophysical results reported here demonstrate that the subjective intensity of haptic virtual properties are well described by the power law, a function already known to apply to real properties in several sensory modalities (Stevens, 1961; Gescheider, 1997). This finding simplifies the task of appropriately scaling the properties of a multidimensional haptic display so that equal physical steps in an underlying data set are presented as equal perceptual steps along the haptic dimension assigned to it. This technique can be applied to any application involving data display on surfaces, and it appears to be most useful when the user is interacting with the surface and modifying the underlying data sets – precisely when conventional graphical visualization techniques are inappropriate (Hollins, 2000). As such, these techniques complement the visual display of multiple data sets.

Acknowledgements

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