Toward Realistic Haptic Rendering of Surface Textures

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The emerging science of haptic rendering consists of delivering properties of physical objects through the sense of touch. Owing to the recent development of sophisticated haptic-rendering algorithms, users can now experience virtual objects through touch in many exciting applications, including surgical simulations, virtual prototyping, and data perceptualization. Haptics holds great promise to enrich the sensory attributes of virtual objects that these systems can produce.

New sophisticated haptic-rendering algorithms let users experience virtual objects through touch. The authors systematically investigate the unrealistic behavior of virtual haptic textures.

One area that has received increasing attention in the haptics community is haptic texture rendering, the goal of which is to introduce microgeometry-scale features on object surfaces. Haptic objects rendered without textures usually feel smooth, and sometimes slippery. Appropriate haptic textures superimposed on haptic objects enhance an object's realism. For example, we can make the same cubic structure feel like a brick with rough surface textures or a cardboard carton with finer textures. Clearly, haptic texture rendering is an exciting research field that can take haptic rendering to the next level.

Although much effort has been devoted to haptic texture rendering—mostly in modeling and rendering techniques[1,2]—the research community must overcome many challenges before haptic texture rendering can be widely used in real applications. One common problem in haptically rendered textures is that they are sometimes perceived to behave unrealistically, for example, by buzzing or by the apparent aliveness of a textured surface. Due to the complex nature of the haptic-rendering pipeline and the human somatosensory system, it remains a difficult problem to expose all factors contributing to such perceptual artifacts.

At the Haptic Interface Research Laboratory at Purdue University, we are among the first to have systematically investigated the unrealistic behavior of virtual haptic textures. This article presents a summary of our recent work in this area. We hope this article will stimulate further discussion among haptics researchers and applications developers who are interested in haptic texture rendering. Interested readers may refer to our previous publications for more details.[3-7]

Perceived instability

We use the term *perceived instability* to refer to all unrealistic sensations—such as buzzing—that cannot be attributed to the physical properties of a textured surface being rendered with a force-feedback device. To develop haptic texture-rendering models and methods that can deliver realistic textures to human users, you must understand the conditions under which textured virtual objects are free of perceptual artifacts, and you must also recognize the sources of perceived instabilities. We developed the notion of perceived instability to include the effects of all factors in haptic interaction that can result in unrealistic sensations. As shown in Figure 1, haptic interaction occurs at a haptic interaction tool that mechanically connects two symmetric dynamic systems. In principle, each block in the diagram can contribute to the perception of instability by the human user.

A crucial difference between real and virtual haptic interactions with an object is that a virtual environment imparts no haptic sensation to the user unless the interaction tool penetrates the object surface. The first phase of haptic texture rendering is the computation of the penetration depth and the resulting force command using a haptic texture renderer stored in the computer. For this purpose, most haptic systems repeat several procedures at a high update rate, usually 1 KHz or higher. First, the system measures the position of the haptic interaction tool using position sensors embedded in the haptic interface. The system then compares the measured position of the interaction tool with the location of objects in the virtual environment. If the interaction tool penetrates the surface of any virtual object, a response force is computed and sent to the haptic interface to create the intended haptic effect. Finally, if the state of any virtual object has changed due to the interaction, the system updates the

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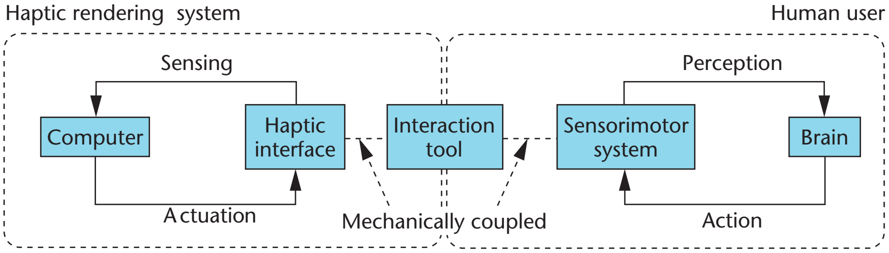
database of virtual objects.



1 Illustration of the key components of the interaction between a haptic rendering system and a human user.

Two of these four steps—collision detection and response force computation—can have a significant effect on perceived instability. These two steps determine the so-called environment dynamics, the reaction dynamics of the haptic renderer to a user input. In most cases, the environment dynamics is an approximation of the corresponding real-world contact dynamics because simulating the actual physics is usually too complex to accomplish in real time. The simplified environment dynamics must preserve the essence of the real contact dynamics to produce sensations consistent with a user's experience and expectation. Otherwise, the user perceives unrealistic behaviors of haptically rendered objects, and perceived instability occurs. This issue has received little attention from the research community because a majority of studies on haptic texture rendering have focused on the development of time-efficient rendering algorithms.

The next phase of haptic texture rendering is the delivery of force to the human user. During this process, the force-feedback device must remain stable to avoid perceived instability. Device instability, such as mechanical resonance, can result in force variations in addition to the force command received from the haptic texture renderer. In our experiences, a user usually judges the haptically rendered textured surface as unstable when an extraneous signal—such as high-frequency buzzing—occurs from the haptic interface. This issue has received much attention in the context of control engineering, although most studies assume a much simpler virtual environment such as a flat wall without any textures.[8] Much work is needed to extend the techniques for solving the hard-wall stability problem.

The last phase of haptic texture rendering is the perception of force by a human user. The human user senses the mechanical stimuli from the haptic interface, extracts information from force variations, forms a percept of the virtual object being rendered, and determines whether the virtual object is realistic. To determine whether the user perceives instability from a textured surface rendered by the haptic interface, we must resort to psychophysical studies. Psychophysics is a branch of psychology with well-developed methodology for studying the relation between geometrical and physical properties of objects and the percept. At this point, little knowledge is available in the literature on the perceived instability of haptically rendered objects, because this is a new research topic that has only become relevant with the recent capability to render haptic virtual environments.

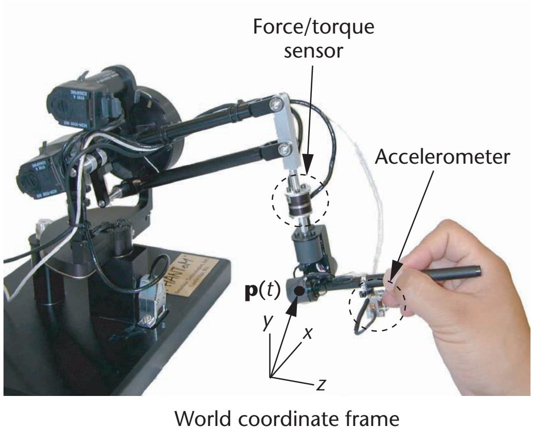
Goals and approaches

Our long-term goal is to develop haptic texture-rendering systems that deliver realistic sensations of virtual haptic textures. To do so requires the appropriate design of a texture renderer, the stable control of a haptic interface, and a better understanding of the somatosensory system. As a first step, our research has focused on understanding the nature of perceived instability. Specifically, we

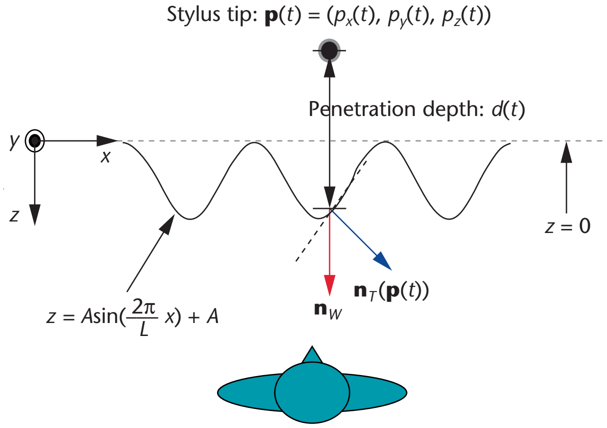
- investigated the conditions under which perceived instability of virtual textures occurs,
- discovered the types of perceived instability frequently reported by human users,
- identified the proximal stimuli that contributed to the perception of instability, and
- unveiled the sources that produced the stimuli.

We conducted psychophysical experiments to quantify the conditions under which users perceived instability from virtual textures and to understand the associated percept. We also measured the physical stimuli delivered by the haptic interaction tool to the user's hand under various conditions where the textures were perceived to be stable and unstable. By analyzing the measured data, we located signal components responsible for the perception of instability. We achieved the last goal by investigating which component in the haptic texture-rendering system generated the signals that led to perceived instability.

Because of the plethora of texture-rendering models and methods, we chose a benchmark consisting of the most essential features common to many texture-rendering systems for studying perceived instability. In addition, we had to consider the effect of user exploration patterns because the user is mechanically coupled to the haptic interface. For the apparatus, we used a Phantom force-reflecting device (from SensAble Technologies) shown in Figure 2. This is the most widely used device for haptics research and applications.



2 Phantom 1.0A used in our studies. This is a modified Phantom instrumented with additional force-torque and acceleration sensors.



3 Illustration of the texture rendering models and methods used in our studies.

For the texture model, we used a 1D sinusoidal grating superimposed on a flat surface (see Figure 3). The grating is represented by

$$z = A\sin\left(\frac{2\pi}{L}x\right) + A$$

in the Phantom world coordinate frame where A and L are the amplitude and wavelength of the grating. Sinusoidal gratings have been widely used as basic building blocks for textured surfaces in studies on haptic texture perception and as a basis function set for modeling real haptic textures.

For collision detection, we used two methods of computing penetration depth $d(t)$:

$$d_1(t) = \begin{cases} 0 & \text{if } p_z(t) > 0 \\ A\sin\left(\frac{2\pi}{L}p_x(t)\right) + A - p_z(t) & \text{if } p_z(t) \le 0 \end{cases}$$

and

$$d_2(t) = \begin{cases} 0 & \text{if } p_z(t) > h(p_x(t)) \\ A\sin\left(\frac{2\pi}{L}p_x(t)\right) + A - p_z(t) & \text{if } p_z(t) \le h(p_x(t)) \end{cases}$$

where $\mathbf{p}(t) = (p_x(t), p_y(t), p_z(t))$ was the position of the Phantom stylus tip and $h(p_x(t)) = A\sin(2\pi/L\, p_x(t)) + A$ was the height of the textured surface at $p_x(t)$. The first method, $d_1(t)$, assumed that collision detection was based on the plane underlying the textured surface ($z = 0$). The advantage of $d_1(t)$ was that we can easily generalize it to textured objects with a large number of underlying polygons because the plane could represent a face on a polygon. The disadvantage was that it introduced discontinuity in computed penetration depth (and subsequently in response force) when the Phantom stylus entered and left the textured surfaces.

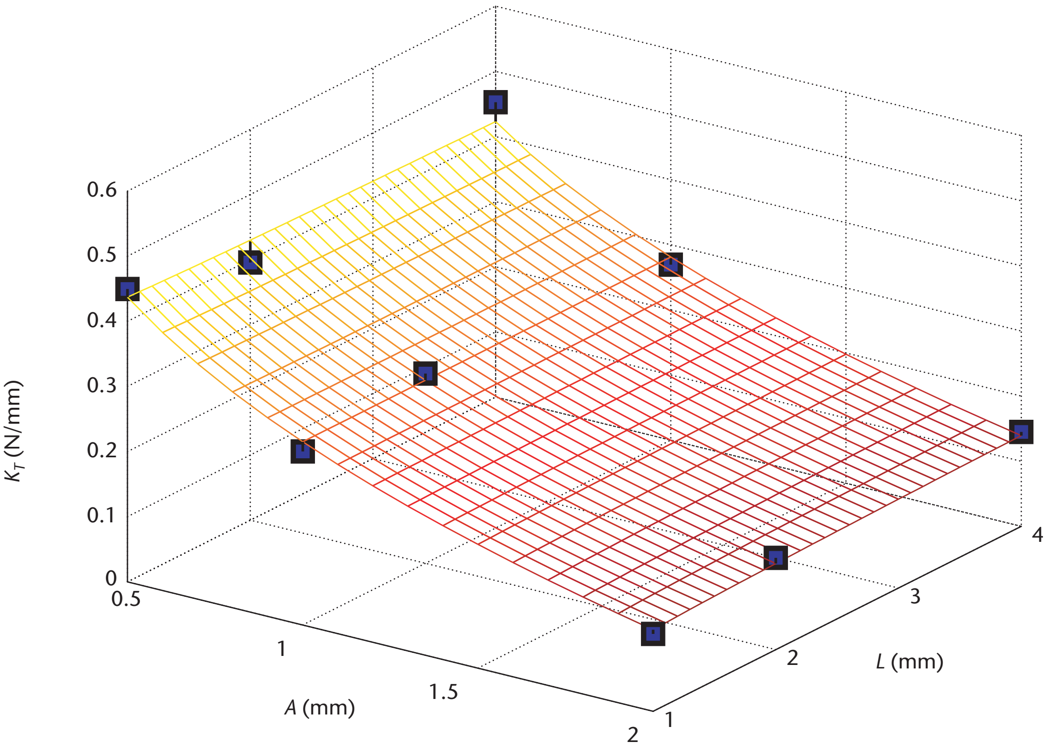
The second method $d_2(t)$ declared a collision as soon as the stylus entered the texture boundary. The advantage of this method was that it ensured a continuous change in computed penetration depth and response force. The disadvantage was that it's much more difficult to apply this algorithm to textured polygonal objects for two reasons. One is the nonlinearity associated with the representation of textured object surfaces that usually requires iterative numerical algorithms for collision detection. The other is the lack of a global representation of the boundaries of the textured virtual objects. In a typical implementation, the polygons and the texture model are stored separately, and the texture model is locally mapped onto a point on the polygon whenever necessary. It's often infeasible to do a global collision detection using only the local information. To the best of our knowledge, the application of the collision detection method based on $d_2(t)$ to a general class of textured objects is still an open research issue.

We employed two basic texture-rendering methods. Both used a spring model to calculate the magnitude of rendered force, but they differed in the way they rendered force directions. Force magnitudes were calculated as $K \cdot d(t)$, where K was the stiffness of the textured surface and $d(t)$ was the penetration depth of the stylus at time t (see Figure 3). In terms of force directions, the first method rendered a force $\mathbf{F}_{mag}(t)$ with a constant direction normal to the flat wall underlying the textured surface. The second method rendered a force $\mathbf{F}_{vec}(t)$ with varying direction such that it remained normal to the local microgeometry of the sinusoidal texture model. Mathematically, $\mathbf{F}_{mag}(t) = Kd(t)\mathbf{n}_w$, and $\mathbf{F}_{vec}(t) = Kd(t)\mathbf{n}_T(\mathbf{p}(t))$, where $\mathbf{n}_w$ was the normal vector of the underlying flat wall, and $\mathbf{n}_T(\mathbf{p}(t))$ was the normal vector of the textured surface at $\mathbf{p}(t)$. Both methods kept the force vectors in horizontal planes, thereby minimizing the effect of gravity on rendered forces.

The two texture-rendering methods are natural extensions of virtual wall rendering techniques. Perceptually, they are very different: Textures rendered by $\mathbf{F}_{vec}(t)$ feel rougher than those rendered by $\mathbf{F}_{mag}(t)$ for the same texture model. Textures rendered by $\mathbf{F}_{vec}(t)$ also feel sticky sometimes.

Our exploration mode refers to a stereotypical pattern of the motions that a user employs to perceive a certain attribute of objects through haptic interaction. We tested two exploration modes—free exploration and stroking. In the free exploration mode, users could determine and use the interaction pattern that was most effective at discovering the instability of the rendered textures. We selected this mode as the most challenging interaction pattern for a haptic texture rendering system in terms of perceived stability. With the stroking mode, users should move the stylus laterally across the textured surfaces. We chose this mode to be representative of the typical and preferred exploration pattern for accurate texture perception.[9]

We conducted psychophysical experiments to quantify the parameter space within which textures were perceived as stable and to categorize the types of perceived instability discovered by users. We employed the method of limits, a well-established classical psychophysical method, in all our experiments.[10] And we employed a diverse range of experimental conditions, with factors including texture model parameter (amplitude and wave-



4 Example of psychophysical results.

length of the 1D sinusoidal gratings), texture rendering method, exploration mode, and collision-detection method. In each experimental condition, a subject's task was to explore a virtual textured plane rendered with Phantom and to decide whether the textured plane exhibited any perceived instability. The dependent variable measured in the experiments was the maximum stiffness K_T under which the rendered textured plane did not contain any perceived instability. A more detailed description of experiment design can be found elsewhere.[3,4,6]

We measured physical stimuli to isolate the signals responsible for the perception of instability and to identify their sources. For this purpose, we added two more sensors—6D force-torque sensor and 3D accelerometer—to the Phantom, as shown in Figure 2, and measured the nine associated physical variables—3D position, 3D force, and 3D acceleration—that were delivered to a user's hand. We collected data for many experimental conditions on the basis of the parameter space obtained from the psychophysical experiments. By comparing the measured data of both perceptually stable and unstable cases in the time and frequency domains, we isolated the physical stimuli that induced the perception of instability. We also investigated the sources for these signals using additional hypothesis-driven experiments.

Parameter spaces

Figure 4 shows an example of a parameter space for perceptually stable haptic texture rendering based on data obtained from the psychophysical experiments. We measured the data when the subject stroked virtual textures rendered with $d_1(t)$ (collision detection based on the plane underlying the textured surface) and $\mathbf{F}_{vec}(t)$ (variable force directions). In the figure, A and L represent the amplitude and wavelength of the sinusoidal texture model, respectively, and K_T denotes the maximum stiffness value under which a virtual texture felt stable. The blue rectangles in the figure represent the stiffness thresholds averaged over three subjects for the corresponding texture model parameters. Also shown is a best-fit surface to the measured data found by regression analysis. The region under the mesh surface represents the parameter space of (A, L, K) for perceptually stable haptic texture rendering, and the region above the mesh surface contains parameters that result in virtual textures that were perceived as unstable.

The most significant result of the psychophysical experiments was that the parameter spaces for perceptually stable texture rendering were limited. See Table 1 for a summary. Under most experimental conditions, the virtual textures that could be rendered without any

Table 1. Average stiffness thresholds for perceptually stable texture rendering.

	$d_1(t)$		$d_2(t)$	
Experiments	**Range (N/mm)**	**Mean (N/mm)**	**Range (N/mm)**	**Mean (N/mm)**
$\mathbf{F}_{mag}(t)$, free exploration	0.0586 – 0.1023	0.0799	0.1813 – 0.5383	0.3486
$\mathbf{F}_{mag}(t)$, stroking	0.4488 – 0.1664	0.3116	0.2490 – 0.6410	0.3603
$\mathbf{F}_{vec}(t)$, free exploration	0.0097 – 0.0367	0.0209	0.0181 – 0.0260	0.0235
$\mathbf{F}_{vec}(t)$, stroking	0.0718 – 0.3292	0.1848	0.3254 – 0.4638	0.3808

perceived instability felt soft—similar to the feel of corduroy. Textures rendered with higher stiffness values usually contained unrealistic sensations, such as buzzing and aliveness. For the haptic texture rendering system used in our experiments to be useful for generating a large range of textures, we need to enlarge the parameter spaces for perceptually stable rendering.

We examined the effects of experiment factors—texture model parameters, collision detection method, texture rendering method, and exploration mode—by applying statistical analysis on the psychophysical results. In general, stiffness thresholds tended to increase when the amplitude of the sinusoidal texture model decreased or when the wavelength increased. Collision detection method $d_2(t)$ resulted in larger stiffness thresholds than $d_1(t)$, except for experiments using $\mathbf{F}_{vec}(t)$ and free exploration where the thresholds were too small to exhibit any trends (see Table 1). In most cases, textures rendered with $\mathbf{F}_{mag}(t)$ (constant force direction) showed larger stiffness thresholds than those with $\mathbf{F}_{vec}(t)$ (variable force direction). On average, textures explored by stroking resulted in larger stiffness thresholds than those by free exploration.

To gain insight into the effects of texture model parameters on perceived instability, we consider the derivative of force magnitude. Let $g(t) = |\mathbf{F}_{mag}(t)| = |\mathbf{F}_{vec}(t)|$ denote force magnitude, and assume that the stylus is in contact with the textured surface. From there we have

$$g(t) = K\left[A\sin\left(\frac{2\pi}{L}p_x(t)\right) + A - p_z(t)\right]$$

Differentiating $g(t)$ with respect to the time variable t results in

$$\dot{g}(t) = 2\pi\frac{KA}{L}\cos\left(\frac{2\pi}{L}p_x(t)\right)\dot{p}_x(t) - K\dot{p}_z(t) \qquad (1)$$

There are two terms in Equation 1 that determine the rate of change of force magnitude. The term on the right, $K\dot{p}_z(t)$, responds to stylus velocity in the normal direction to the underlying plane $\dot{p}_z(t)$ with a gain of K. The term on the left is due to the virtual textures. Here, the lateral velocity of the stylus $\dot{p}_x(t)$ is amplified with three constant gains (K, A, and $1/L$) and one variable gain that depends on the lateral position of the stylus $p_x(t)$. Increasing A or decreasing L results in a faster change in force magnitude which can cause a textured surface to be perceived as less stable, or equivalently, result in a smaller stiffness threshold K_T.

We expected that $d_2(t)$ would generate perceptually more stable textures than $d_1(t)$ because it removed discontinuities in force commands at the texture entry points. This expectation was confirmed, except for the condition where the subjects freely explored the virtual haptic textures rendered with $\mathbf{F}_{vec}(t)$. The stiffness thresholds measured using $\mathbf{F}_{vec}(t)$ and free exploration were practically zero for both $d_1(t)$ and $d_2(t)$, and hence did not exhibit any significant trend. The reason that the textures felt unstable was the presence of strong buzzing noises whenever we positioned the Phantom stylus deep inside the textured surfaces.

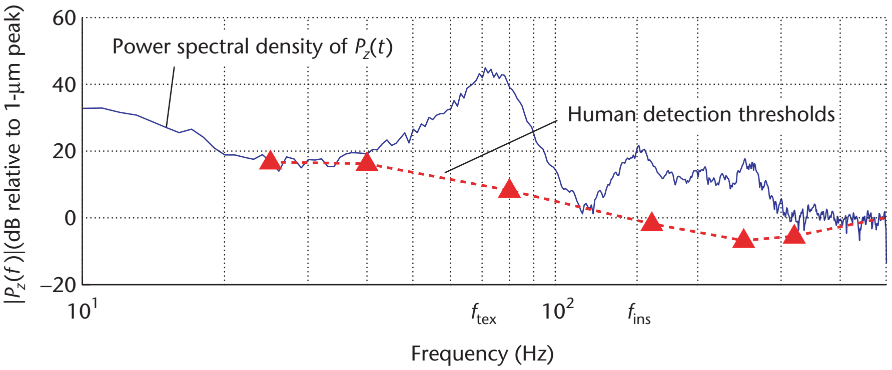
Our finding that textures rendered with $\mathbf{F}_{mag}(t)$ resulted in larger stiffness thresholds than those rendered with $\mathbf{F}_{vec}(t)$ was also consistent with the nature of these two rendering methods. While $\mathbf{F}_{mag}(t)$ imposed perturbations in the force magnitude only, $\mathbf{F}_{vec}(t)$ resulted in perturbations in the force direction as well as force magnitude. The sometimes abrupt changes in force direction could cause virtual textures rendered with $\mathbf{F}_{vec}(t)$ to be perceived as less stable than those rendered with $\mathbf{F}_{mag}(t)$. Perceptually, $\mathbf{F}_{vec}(t)$ is a useful rendering method because it can produce textures that feel much rougher than those rendered with $\mathbf{F}_{mag}(t)$ using the same texture model.

We expected the experimentally confirmed fact that stroking would result in a larger stiffness threshold than free exploration for the same rendering parameters. Our subjects rarely used stroking in the free exploration mode although it was allowed. Instead, they chose to position the stylus at various locations on or inside the virtual textured surface to focus on the detection of perceived instability. Therefore, in the free exploration mode, the subjects concentrated on the detection of unrealistic vibrations in the absence of any other signals. In the stroking mode, the subjects always felt the vibrations due to the stylus stroking the virtual textured surface. They had to detect additional noise to declare the textured surface as unstable. Due to possible masking of the different vibrations coming from the textured surface, it's conceivable that subjects could not detect instability with stroking as easily as they would with static positioning of the stylus. Indeed, our subjects reported that the experiments with stroking were more difficult to perform.

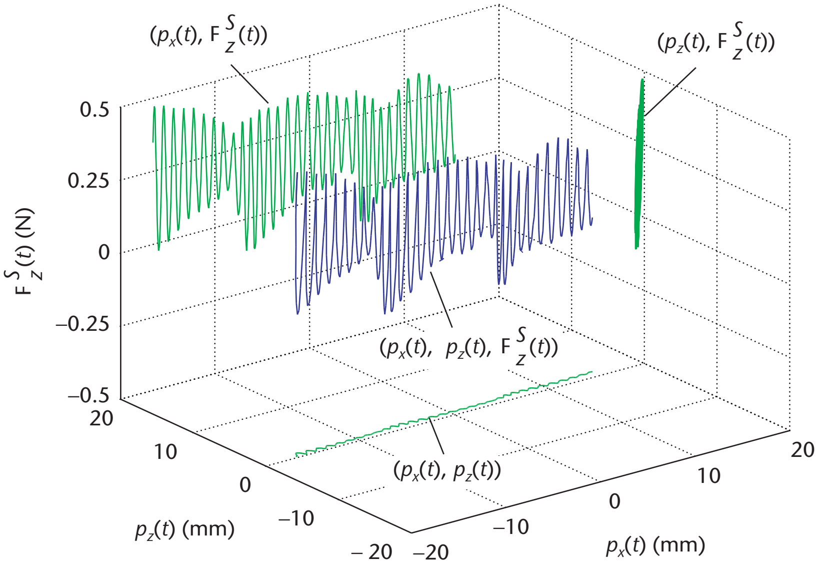
Frequently observed perceived instabilities

We found three types of frequently reported perceived instability in the psychophysical experiments: buzzing, aliveness, and ridge instability. The first two relate to the perception of force magnitude, while the other relates to the perception of force direction. Buzzing refers to high-frequency vibrations that subjects felt at the Phantom stylus when it touched virtual textured surfaces. We observed this type of perceived instability in most experimental conditions, particularly when the stiffness values were much higher than the thresholds measured in the psychophysical experiments. The subjects reported that buzzing appears to be of higher frequencies than the vibrations induced by the stroking of virtual textures.

Measurement data supported the anecdotal report. Whenever the subjects felt buzzing, spectral components in a high-frequency region (roughly 150 to 250 Hz) appeared in the power spectral densities of the vibrations transmitted through the stylus. An example is shown in Figure 5. In this figure, the horizontal axis represents frequency from 10 to 500 Hz, while the vertical axis shows the power spectrum density of $p_z(t)$ (the measured stylus position along the normal direction of the textured plane) in dB relative to 1-micrometer peak sinusoidal motion. We can observe a spectral peak at around 71 Hz. Additional prominent spectral peaks appear in the high frequency region starting at around 150 Hz. The intensities of the high-frequency vibrations are up to 25 dB above the human detection thresholds at the corresponding frequency (the red dotted line). These high-frequency spectral peaks caused the buzzing.



5 Frequency domain analysis of the signals responsible for buzzing.



6 Analysis of aliveness perception in the time domain. $F_z^s(t)$ denotes the force measured along the long axis of the styles.

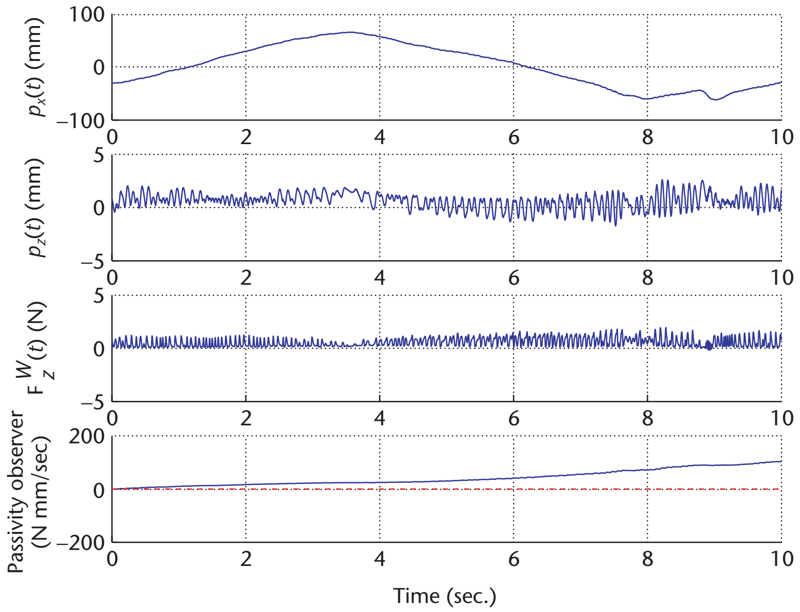
We suspected that the rapidly changing force commands for texture rendering might have excited the high-frequency dynamics of the Phantom, thereby causing high-frequency vibration to be transmitted through the stylus. We therefore measured the frequency response of the Phantom near the origin of its world coordinate frame and found that the Phantom indeed exhibited a mechanical resonance at 218 Hz. This resonance was likely the source of the high-frequency spectral peaks that invoked the perception of buzzing.

The second type of instability that the subjects frequently observed was aliveness. It occurred when the Phantom stylus was apparently held still yet the subject felt pulsating force changes emanating from the textured surface. The sensation appeared to be at a lower frequency than that of buzzing. Aliveness was reported for textures rendered with $\mathbf{F}_{mag}(t)$ (fixed force-direction) using $d_2(t)$ as penetration depth (continuously varying force commands). The measured physical characteristics of perceived aliveness were different from those of buzzing. Analyses in the frequency domain shed little insight on the signals responsible for the percept of aliveness. However, examination of data in the time domain revealed many instances where perceptible changes in force occurred while the stylus was perceived to be stationary in space along the direction of the force changes.

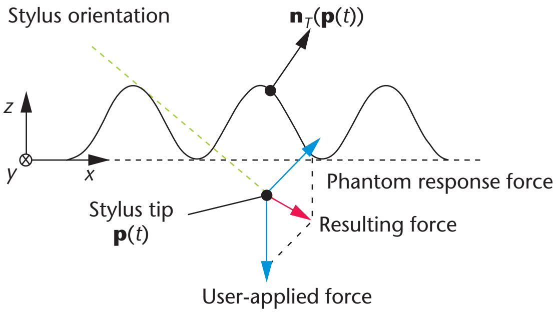
In Figure 6, the two horizontal axes indicate position normal to the textured surface $p_z(t)$ and along the lateral stroking direction $p_x(t)$. The vertical axis shows forces felt by the subject's hand. The duration of the data set is 400 ms. The large change in $p_x(t)$ was the result of the subject stroking the textured surface. In contrast, there was little change in $p_z(t)$. The change in force was on the order of 0.5 Newtons. As a result, the subject felt a noticeable change in normal force although the stylus was perceived to be barely moving into the textured surface. Therefore, the force variation was interpreted as coming from an alive textured surface. Indeed, subjects sometimes referred to the virtual object as a pulsating textured surface. These observations suggest that aliveness was caused by larger-than-expected force variations in spite of position changes that were barely perceivable.

We suspected that, unlike buzzing, which was caused by unstable control of haptic interface, aliveness was probably caused by inaccurate environment dynamics. To investigate this hypothesis, we examined whether it was possible for a user to perceive aliveness while the texture-rendering system including the force-feedback device was stable in the control sense. We applied a passivity-based control theory to data measured from a user interacting with virtual textured surfaces. You can regard a dynamic system as passive if it preserves or dissipates its initial energy despite its interaction with an external system. Because passivity is a sufficient condition for control stability,[8] our hypothesis could be confirmed if we found cases in which a user perceived aliveness from a passive texture rendering system.

Using a passivity observer—an online observer for monitoring the energy flow of a dynamic system—we confirmed that aliveness perception could indeed occur when the haptic texture-rendering system was passive and stable. An example is shown in Figure 7. In this figure, the top panel shows the position data along the lateral stroking direction $p_x(t)$, the second panel shows the



7 **Example of using a passivity observer to analyze data corresponding to aliveness perception. F_z^w denotes the force measured along the direction normal to the textured surface.**



8 **Illustration of the force components involved in ridge instability.**

position variable in the normal direction $p_z(t)$, the third panel shows the force along the normal direction $F_z^W(t)$, and the bottom panel shows the values of the passivity observer. We can see that despite the abrupt force changes that resulted in the perception of aliveness, the passivity observer remained positive. These results provide unequivocal evidence that perceived instability can occur even when a haptic texture-rendering system is passive and stable. We have therefore shown indirectly that environment modeling and human perception can also play important roles in perceived quality of a haptic texture-rendering system.

Consider the difference between touching a real and a virtual surface. When a stylus touches a real surface, it's either on or off the surface, but not inside the surface. When a stylus touches a virtual surface, however, the stylus must penetrate the virtual surface for the user to form a perception of that surface through the resultant force variations. With a real surface, a stylus resting on the surface can remain stationary. With a virtual surface, however, the stylus's position can fluctuate inside the surface and this fluctuation is amplified to result in perceivable force variations by a texture renderer, thereby contributing to the perception of aliveness. It is well known that humans tend to rely more on vision for position-movement information, and that we can easily integrate visual position information with haptic force information. Our relatively poor kinesthetic resolution of unsupported hand movements in free space—combined with our relatively high sensitivity to force changes—is also responsible for the perception of aliveness.

The last type of perceived instability, called ridge instability, is different from the first two types in the sense that it is related to the perception of force directions. We use the term ridge instability to refer to the phenomenon that the Phantom stylus was actively pushed to the valleys of the virtual textures rendered with $\mathbf{F}_{vec}(t)$ when the stylus was placed on the ridges of the textures. When a real stylus rests on the ridge of a real surface with sinusoidal gratings, the reaction force and friction of the surface combine to counterbalance the force exerted by the user's hand holding the stylus, thereby creating an equilibrium. The force rendered by $\mathbf{F}_{vec}(t)$, however, was solely based on the local texture geometry and did not take into account the direction of user-applied force, as illustrated in Figure 8. In this figure, we assume that the force applied by the user was normal to the plane underneath the texture. According to the environment model $\mathbf{F}_{vec}(t)$, the force applied by the Phantom was always in the direction of the surface normal $\mathbf{n}_T(\mathbf{p}(t))$. As a result, the net force exerted on the tip of the stylus—the sum of the forces applied by the user and the Phantom—was directed toward the valley of the sinusoidal grating. Therefore, the subject who tried to rest the stylus on the ridge could feel the stylus being actively pushed into the valley.

Conclusions

In this article, we have shown that current haptic texture-rendering systems might suffer from several types of perceived instability. We also have demonstrated that perceived instability can come from many sources, including the traditional control instability of haptic interfaces as well as inaccurate modeling of environment dynamics and the difference in sensitivity to force and position changes of the human somatosensory system. Our work underscores the importance of developing texture-rendering algorithms that guarantee the perceptual realism of virtual haptic textures. It is our hope that this article will encourage more researchers to contribute to the study of perceived instability of virtual haptic textures. ■

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