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DETECTION OF REAL AND VIRTUAL FINE SURFACE FEATURES WITH A HAPTIC INTERFACE AND STYLUS

Aaron M. West and Mark R. Cutkosky
Center for Design Research
Stanford University
Stanford, California 94305-2232
amwest@cdr.stanford.edu

ABSTRACT

In this paper we discuss the results of displaying fine surface features using a haptic interface. A stylus was connected to a haptic interface and configured so that users could explore real and virtual surfaces using the same apparatus. The surfaces consisted of sinusoidal profiles with amplitudes of 0.01–10 mm and with frequencies of 1–20 cycles over a length of 85 mm. Subjects were asked to explore the surfaces at will and count the number of waves detected. When exploring physical profiles, tests were conducted using a stylus with friction and a "frictionless" stylus with a roller. For comparison, tests were also conducted using the subjects' fingertips instead of a stylus for physical surface exploration. Our results show that subjects' perceptions of sinusoidal features on virtual and physical walls are qualitatively similar. At spatial frequencies of 0.24 cycles/mm and greater, the ability of humans to accurately count virtual and physical waves was also similar, despite the limited stiffness and bandwidth of the haptic interface. The results provide insight for the display of fine features such as ridges or grooves on a virtual wall.

Key Words: haptic, perception, simulate, texture.

1. INTRODUCTION

A common way to explore surface features on objects is to drag a finger across them. As the features become smaller and more closely spaced they become indistinguishable as individual elements, and are perceived as texture on the object surface. The transition from "features" to "texture" can often be shifted to finer scales by using a stylus or a fingernail. For example, field geologists and paleontologists may use a fingernail or a stylus probe for exploring fine features on specimens (Vermeij, 1996). As the reader can probably verify, dentists also commonly use sharp tools to probe the insides of cavities and other features on teeth.

The sensitivity of a stylus for probing fine surface features is greatest when the stylus is light and stiff. For example, Professor G.J. Vermeij, a blind paleontologist, has pioneered the use of hypodermic needles for exploring fine striations and crennelations in fossil shells and counting dentate features. Vermeij uses the needles to obtain geometric information about surface profiles at sub-millimeter scales and to explore areas inaccessible by larger instruments. The technique has been so successful that it has been adopted by some of his sighted colleagues (Vermeij, 1996).

The results obtained by scientists like Vermeij lead us to consider whether a stylus might be useful for exploration of remote or virtual surfaces using a haptic interface to recreate the forces and vibrations that a user would experience. This scenario immediately raises a number of questions about the nature of those forces and vibrations, how to model them, and how to display them with a haptic interface.

Unlike a pulpy fingertip, a sharp stylus responds individually to each small feature on an object surface. Siira, et al (1996) propose that dynamic interactions associated with sliding across a textured surface can be approximated with roughness characteristics. However, to recreate the forces and vibrations experienced by a person probing surfaces with a stylus, the stylus/object contact dynamics must be modelled.

In this paper we restrict our attention to surface features consisting of sinusoidal waves of various wavelengths and amplitudes. For such profiles it is not difficult to show that the normal and tangential forces experienced by a subject dragging a stylus over the surface will be approximately sinusoidal as well (West, 1997). We investigate the scales at which individual peak or valley features give way to general sensations of roughness or smoothness when dragging a stylus over manufactured surfaces and virtual surfaces created with a haptic interface. Our preliminary findings also shed light on the effects of contact friction and

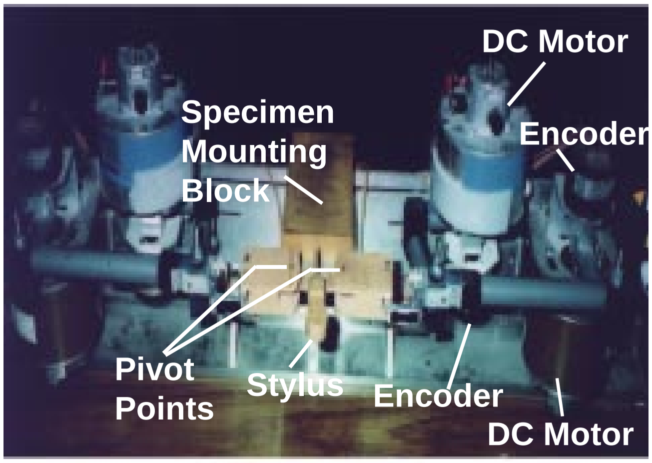

Fig. 1. Planar manipulator.

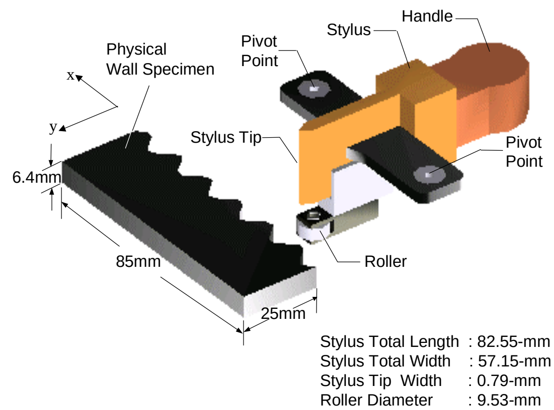

Fig. 2. Stylus and sinusoidal profile.

grasp choice on the ability of subjects to accurately detect fine features.

2. RELATED WORK

Many researchers have performed useful studies to define and improve the process by which a haptic interface transmits physical interactions with a remote or virtual world to a human user (Adachi et al 1995; Bergamasco and Prisco 1995; Colgate et al 1993; Fasse and Hogan 1994; Lederman and Klatzky 1987; Love and Book 1995).

Other relevant work concerns the development of haptic interfaces and tactile displays (Kaczmarek et al 1994; Kontarinis and Howe 1994; Shimoga et al 1995; Siira and Pai 1996; Wantanabe and Fukui 1996). Many researchers have used these devices to address the issue of tactile feedback and surface texture display. A controlled localized current has been used to excite afferent touch fibers to produce sensations of vibration, tingle, and pressure (Kaczmarek et al 1994). Ultrasonic vibration has been used to alter the surface configurations for the purpose of creating smooth, rough, and sticky surfaces (Wantanabe and Fukui 1995). However, to our knowledge, none of these works has demonstrated the use of tactile displays to produce geometric surface features at the sub-millimeter levels.

Feedback of vibratory information (such as might be encountered with a stylus or other tool) has also been investigated (Kontarinis and Howe 1994) and shown to improve human performance for certain tasks. In work by Minsky et al (1990), control algorithms were used on a haptic interface device for the study of surface texture. A joystick was converted into a haptic device that uses in its control algorithm, spring forces based on a local gradient to simulate fine grained surfaces. However, this work is concerned with describing the degrees of roughness, softness, and stickiness of a surface rather than its profile.

3. EXPERIMENTS

3.1 Apparatus

A pair of two degree-of-freedom manipulators were connected to a stylus to create a linkage supporting the stylus (see Figs. 1 and 2). For each manipulator, there are two direct-drive DC motors and two optical encoders. The resulting apparatus has three degrees of freedom in the plane and a positioning resolution of approximately 0.05 mm in the X (side to side) and 0.04 mm in the Y (into and out of the wall) directions.

The stylus was constructed of rigid high-density foam[1] to minimize its inertia and provide damping to reduce high frequency vibrations. When used with a physical wall specimen, the stylus contacted the specimen with either the stylus tip or a roller which provided a “frictionless” contact.

The physical wall specimens (Fig. 2) were created using wire E.D.M. machined aluminum. All specimens were 85 mm long with a 6.4 mm face width. The specimens had varying wave amplitudes between 0.01 mm and 10.0 mm and frequencies between 1 and 20 cycles per 85 mm of specimen length.

When dragging a light, compliantly-supported stylus over a sinusoidal profile, the normal and tangential contact forces are also approximately sinusoidal. Therefore, the manipulandum used simple proportional control laws to create virtual walls with a sine-wave profile. The magnitude of the force at the stylus tip is proportional to the distance penetrated into the virtual surface:

$$F_{mag} = k \cdot (y_{wall} - y_{tip})$$

where y_{wall} is the vertical position of the virtual wall, y_{tip} is the vertical position of the needle tip, and k is the gain constant. The horizontal and vertical forces at stylus tip are calculated by scaling F_{mag} with the normalized horizontal and vertical components of the vector tangent to the penetration point. The sampling rate for all experiments was 300Hz. The stiffness in the normal direction for virtual walls was set to 20 N/cm to avoid any problems with jitter or instability.

3.2 General procedures

Human subjects were asked to explore the walls and identify the number of sinusoidal cycles present. A sine-wave profile was

1. Renshape 450

chosen because of its distinguishable contours as well as its continuous and well-defined analytical description. Experiment 1 involved exploration of virtual walls, whereas experiments 2abc involved three different methods for exploring physical walls. Experiment 1 lasted approximately 3 hours for each subject. Experiment 2 lasted approximately 1.5 hours for each subject. A fifteen-minute break was given to each subject mid-way through the completion of experiment 1 and in between parts b and c of experiment 2.

Two groups of subjects were chosen to perform the experiments. For the first group, one female and one male Stanford University graduate student each performed tests with virtual walls with amplitudes varying between 0.03 mm and 10.0 mm in height and with 1–20 waves per virtual specimen. After preliminary review of the results obtained with these two subjects, additional tests were conducted with seven (5-male, and 2-female) new subjects. The second group of subjects also participated in Experiments 2abc.

For each test, the subjects performed several trials of exploring the virtual or physical specimen. Each trial represented a randomly chosen, unique value for the amplitude and frequency of the profile. Subjects were given ninety seconds to complete their explorations, after which they were asked to stop and report the number of waves detected and to comment on what they felt. The subjects were not required to use the entire ninety seconds. No type of audible or visual feedback was allowed for either set of experiments. The duration of each trial and the number of sinusoidal cycles reported by each subject were recorded at the end of each trial. Subjects' comments and behavior were also noted throughout the experiments.

3.3 Experiment 1: Exploration of virtual walls.

For experiment 1, subjects performed self-directed exploration procedures on virtual walls with sinusoidal profiles. No information about the wall's profile or location prior to the start of the first trial was given to the subjects. During this trial, the subjects were asked to find the wall and identify any of its distinctive features. Subjects were given five minutes to perform trial 1 so that they could establish and practice their exploration procedures. After completing the first trial, the subjects were asked to draw the wall's profile on a sheet of paper.

Next, the subjects were told that the remaining trials would involve more virtual walls with sine-wave profiles that may or may not change in amplitude and frequency. They were asked to only report what they felt in terms of the number of sinusoidal cycles, with up to one quarter of a cycle resolution.

The first group of two subjects performed each test shown in Table 1 in the Appendix. The ranges of amplitudes and frequencies were established through preliminary experimentation by the first author. Based on the results obtained with the first group, a second group of seven subjects performed the tests listed in Table 2 in the Appendix. The parameter values for these additional tests were selected to provide more data in regions for which the first two subjects had shown error rates of greater than 50% when counting waves.

3.4 Experiments 2: Exploration of tangible walls

A second set of experiments was conducted with physical wall specimens with sinusoidal profiles. In the first two parts of this set, experiments 2a and 2b, subjects used the same stylus apparatus (Fig. 2) as in experiment 1 to explore physical specimens. For tests 2a, the stylus tip with a hard, frictional contact was used. For tests 2b, a small roller was mounted to the tip of a stylus to create a nearly frictionless contact. For comparison, tests 2c were conducted in which the subjects explored the profiles with their index fingers. Table 3 in the Appendix lists the specimens tested for experiments 2abc.

4. PSYCHOPHYSICAL RESULTS

In this section we analyze the average results of the two groups of subjects tested. For experiment 1, we first present the data as it was collected, i.e, the average number of sinusoidal cycles detected versus the number of cycles present for each test. We then consider the same results in terms of an average error rate (DER) defined as follows,

$$DER = \frac{(actualwaves - wavesdetected).}{actualwaves}$$

We considered a DER of 50% or more to be an indication that subjects were unable to count features accurately. This admittedly somewhat arbitrary cutoff ratio was found to correlate well with the comments from subjects concerning their perceived ability to count features.

4.1 Experiment 1

The averaged results for both groups of subjects exploring the virtual walls are shown in Fig 3. Each data point corresponds to the average number of cycles detected for a particular virtual specimen. The symbols in the legend denote the actual number of sinusoidal cycles present for the corresponding test. Each curve tracks the results for a particular wave frequency (number of cycles present over the specimen length) with different points along the curve corresponding to different wave amplitudes. For example, in Fig. 3, the upper curve corresponds to the average results for tests in which the virtual samples had 20 cycles. The data point just outside the "unstable region" in the upper right corner corresponds to 20-cycle specimens with an amplitude of 1.0 mm. The fact that this point lies nearly on the 20 cycle ordinate means that nearly all subjects correctly identified the number of cycles for these specimens. In contrast, we see that for 20-cycle specimens with a wave amplitude of 0.05 mm, the average number of cycles detected, approximately 16, is noticeably different from the number present.

Looking more broadly at the results in Fig. 3, we observe three distinct regions in feature amplitude/frequency space. The central "discernible" region represents feature size and frequency scales for which subjects' average DER remained below fifty percent.

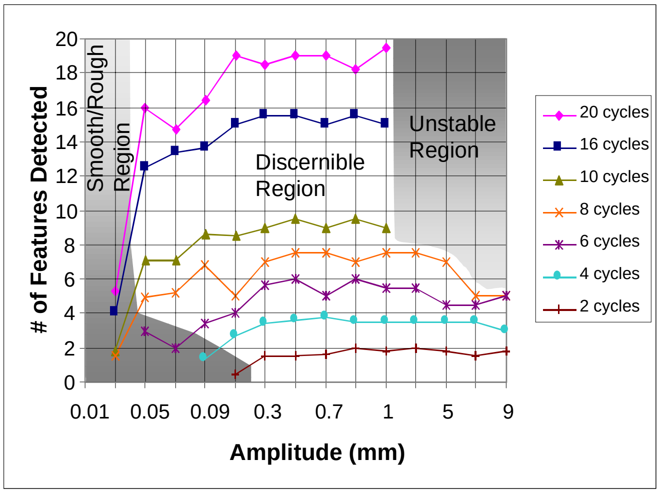

Fig. 3. Experiment 1 - average number of cycles detected versus feature amplitude for virtual walls. (Legend shows actual number of waves for each test.)

The left shaded area denotes regions in which subjects were unable to count features and in which they also reported that surfaces appeared to have a “smooth” or “rough” texture, depending on the number of cycles present. A “smooth” experience took place for frequency and amplitude values in which the subjects were unable to discern any troughs or bumps. A “rough” experience occurred for frequency and amplitude values that created a perceptible texture as the subjects moved rapidly back and forth across the surface. However, the subjects were unable to detect any features at the slower exploratory speeds. There was no sharp distinction between the smooth and rough areas in this region. Subjects comments varied as to which sinusoids felt rough and which felt smooth.

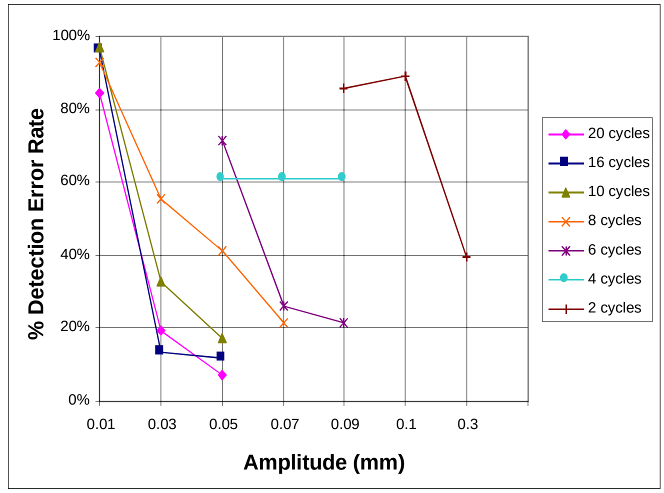

Fig. 5. Experiment 2a - average error rate versus feature amplitude for physical walls and frictional contact.

In the unstable region on the right of Fig. 3, a combination of high frequencies and amplitudes caused the system to vibrate. The precise values at which these instabilities occurred depended on the subject’s grasp of the stylus. In some cases the subjects were able to detect the presence of waveforms; however, the large vibrations made it impossible for them to maintain contact with the wall and perform their exploration procedures.

The average DER for the second group of subjects is plotted in Fig. 4. This graph will be compared with results obtained for the same group of subjects in experiment 2. The graph shows similar error rate trends among the low frequency tests (2-6 cycles) and among the high frequency (10-20 cycles) tests. The low frequency curves appear to generate a DER below 50% until the amplitude decreases to approximately 0.1 mm. The high frequency sinusoids generate a DER below 50% for amplitudes above 0.04 mm.

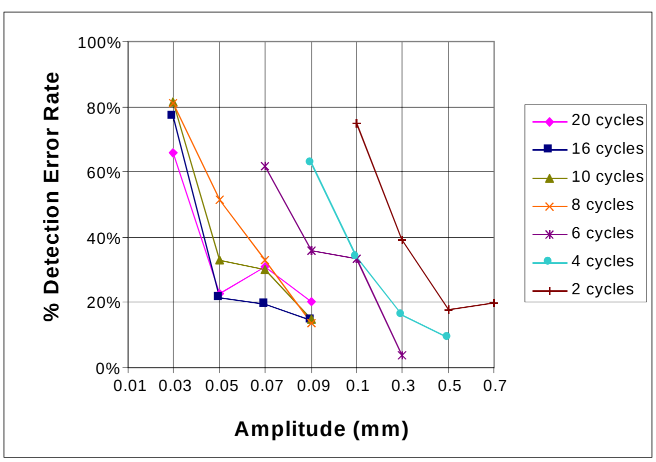

Fig. 4. Experiment 1- average error rate versus feature amplitude for virtual walls.

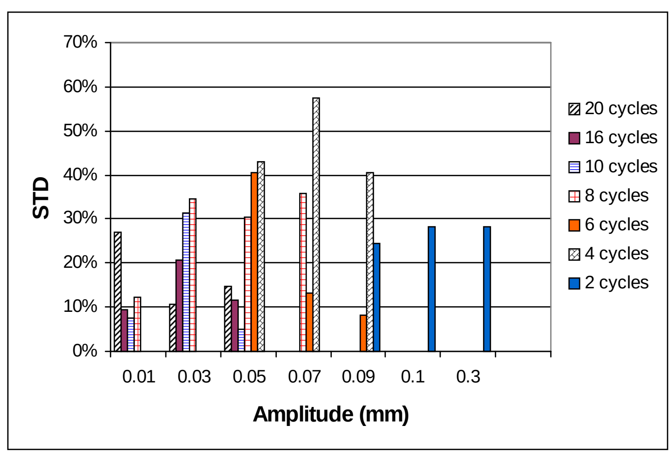

Fig. 6. Standard deviation of error rate for results in Fig. 5.

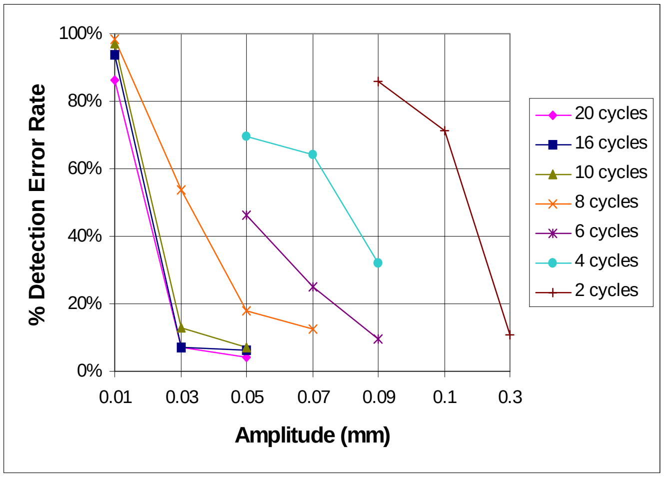

Fig. 7. Experiment 2b - average error rate versus feature amplitude for physical specimens and frictionless contact.

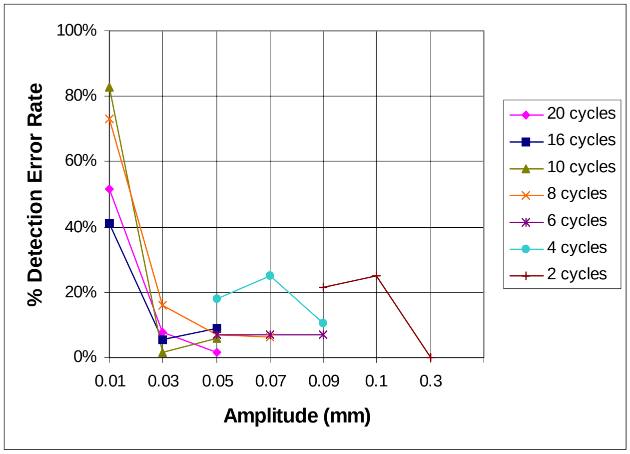

Fig. 9. Experiment 2c - average error rate versus feature amplitude for physical specimens and fingertip.

4.2 Experiment 2

Part 2a: The results for the second group of subjects exploring physical specimens with the frictional contact stylus are shown in Figs. 5 and 6. The average percentage DER is plotted in Fig. 5. The tests with 6-20 cycles show a common trend in which the DER decreases rapidly for amplitudes of greater than 0.01 mm. For samples with very few cycles the results are less consistent.

Additional insight can be gained by examining the standard deviations in Fig. 6. In general, the standard deviations were lower for the tests with higher wave frequencies. In some cases, the lowest amplitudes also showed an increase in variability.

Part 2b: The tests in experiments 2a were repeated for a stylus with a roller attached to the tip. The results of the average error rate, DER, and standard deviation in the error rate, STD, are shown in Figs. 7 and 8. The results are generally similar to those obtained with a frictional stylus. For trials with 10 or more cycles the average percentage DERs below fifty percent are lower for the frictionless case than for the friction case.

Part 2c: Experiments 2a and 2b established that the ability of subjects to accurately detect small surface waves was not greatly affected by the presence or lack of friction when using a stylus. For comparison, the same subjects were also asked to explore the physical specimens using their fingertips. The results of these trials are shown in Figs. 9 and 10. Inspection of Fig. 10 shows that the average DER is significantly less than the values

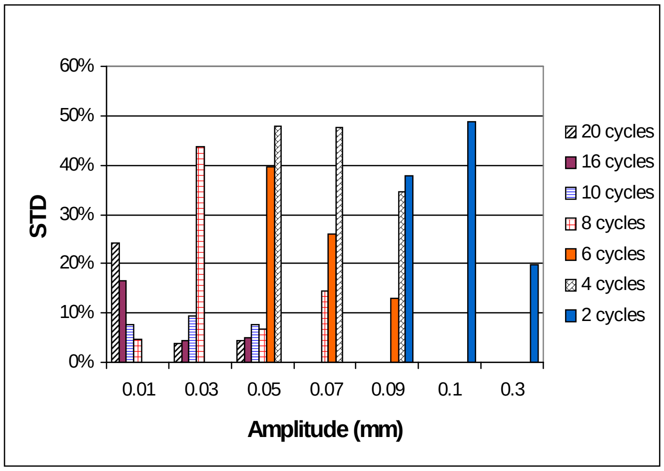

Fig. 8. Standard deviation of the average error rate versus feature amplitude for results in Fig. 7.

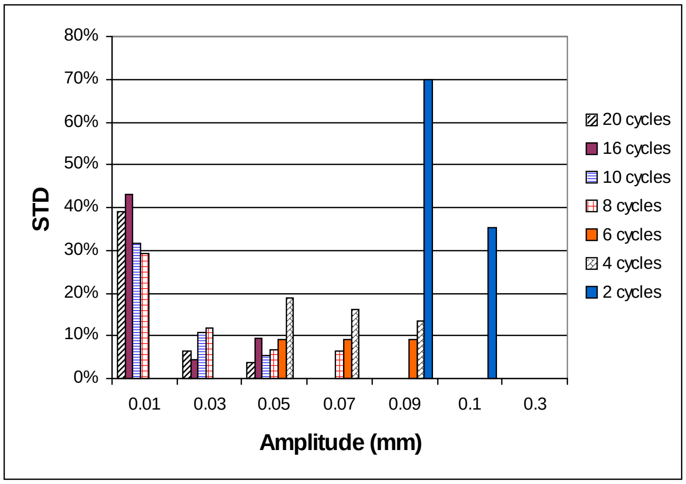

Fig. 10. Standard deviation of the average error rate versus feature amplitude for results in Fig. 9.

Fig. 11. Different grasps used for holding the stylus during experiment 2.

obtained with a stylus for most tests. Only at the smallest amplitudes were the results similar.

5. DISCUSSION

5.1 General experimental results

With the apparatus employed for these experiments, the subjects performed better when using their fingertips than when using a stylus for all but the highest frequencies tested. Both the average error rates and the variability between subjects were lower with fingertip experiments. This is probably a reflection of the size of the stylus and of the awkwardness imposed by having it connected to a planar manipulator. The fact that the stylus performed best (i.e., almost as well as fingertips) at higher frequencies is also to be expected. At these frequencies the sharp stylus point has the advantage of being able to fall into troughs that are too small for a fingertip.

Although stylus exploration did not perform well at the trials with the lowest amplitudes it would be interesting to see how the comparative performance of exploration with the stylus and the fingertips would change at these amplitudes if the spatial frequency was increased.

The general trend for the variations between subjects is to decrease with increasing wave amplitude. However, this trend is not observed at the lowest amplitudes. This is because the lowest amplitudes tested for each spatial frequency represented the limits of almost all subjects' ability to detect undulations in the profiles. However, at the next largest amplitudes some subjects were clearly able to detect features while others were not - hence a large variability in the data.

5.2 Comparison of virtual and physical walls

The trends in the average error rates for the virtual and physical sets of experiments were similar, despite the limited stiffness and positioning resolution of the apparatus. As one might expect, the average error rates for counting features are higher for the virtual walls, especially at low amplitudes. To obtain better performance with features of low amplitude and high spatial frequency it will clearly be necessary to improve the bandwidth of the manipulator.

Another measure of the ease with which subjects could detect features is the time duration for each trial. The amount of time that subjects required for exploring with their fingertips was significantly less than for exploring with a a stylus. However, the amount of time required for stylus exploration of physical or virtual walls was essentially the same.

A concern in the case of the virtual walls is the subjects' motion profiles as they traced the surface. Because of the manipulator's inability to create a stiff virtual wall, the subjects' trajectories were not always representative of a straight wall with a superimposed sinusoid of the amplitude ostensibly being generated by the device.

5.3 Exploratory grasps

Exploratory grasp choices varied across subjects, but subjects generally maintained the same grasp throughout the two experiments. Typical grasps are shown in Fig. 11. Subjects reported using either a "light" or compliant grasp or a "stiff" grasp. We have designated the former as low impedance and the latter as high impedance. An interesting observation is that subjects using the low impedance grasps tended to perform better than subjects using high impedance grasps in the trials where relatively controllable vibrations were present. Some subjects also reported that they were able to control system vibrations by using a low impedance grasp.

5.4 Exploratory procedures

Two types of exploratory procedures (Lederman and Klatzky, 1987) were observed. Some subjects started by moving laterally across the wall at relatively high speeds to get a general idea of the frequency and amplitude of the sinusoid. Afterwards, subjects would try to position the stylus on either the right of left edge of the wall and proceed to trace the wall counting either bumps or troughs. For most subjects the orientation of the stylus remained perpendicular to the wall. However, a few subjects tended to slant the stylus in the direction of travel and reported they could feel the stylus twisting about an axis perpendicular to the X and Y axes shown in Fig. 2 as they travelled across bumps.

Some subjects reported the task of finding the edge of the wall to be difficult. This phenomenon occurred because of the discontinuity in force at the wall edge. Some subjects reported their counts might be off slightly because of this effect. Virtual damping was used when there was no wall contact, to minimize this problem.

5.5 Individual difficulties

During trial 1, most subjects were able to identify the one-cycle sine-wave. However, a few subjects had problems initially with discerning the trough. Often, subjects would detect the right edge and start to move horizontally towards the left edge, initially detecting the bump. As they moved across the bump and into the trough region the penetration distance into the wall would decrease, generating lighter forces than those at the bump. Subjects that did not increase the penetration distance would not identify the bump.

Not shown in any of the plots are negative average error rates (i.e., detecting more cycles than actually present). However, for the frictional contact case, a few subjects reported 2-4 cycles greater than the actual number present. This may reflect that they were confused as to whether they were detecting a bump or a change in the friction force. One subject also "over detected" for the fingertip exploration case. This occurred for a high frequency sample. Several subjects reported that the bumps for this sample were so close together that they were confused about whether or not they detected one bump or multiple bumps. This indicates a limit being reached for detecting sinusoids with small spatial frequencies.

6. CONCLUSIONS

Our initial results show that there exists a boundary in amplitude and spatial frequency, below which the error rate for detecting individual features exceeds 50%. This boundary is relatively consistent across subjects and exists for virtual as well as physical walls. However, the absolute size range associated with the boundary will depend on the type of stylus being used and the stiffness and bandwidth of the haptic interface. There is some indication that as the spatial frequency of features increases, the performance of stylus improves as compared to a fingertip. We also found that for exploring physical walls, the subject to subject variability was greatest for features of low amplitude, or height.

7. FUTURE WORK

Immediate plans are to measure the forces generated during the physical wall experiments and compare their values to those generated in the virtual wall experiment. We hope to determine what values of forces need to be implemented in the virtual experiment to produce results similar to those in the frictionless case for the physical wall. We would also like to more closely compare the motion trajectories of the subjects during the virtual wall experiments with the profile of the virtual sinusoid being implemented to better understand the distortions. Finally, we wish to perform the virtual wall experiment on a different haptic device to determine how the results will vary across haptic platforms.

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APPENDIX
Details of surfaces tested in the experiments

Table:1. Trials for experiment 1 - first group

Trial	Amplitude (mm)	Wave Cycles	Trial	Amplitude (mm)	Wave Cycles	Trial	Amplitude (mm)	Wave Cycles	Trial	Amplitude (mm)	Wave Cycles
1	10	1	21	0.09	10	41	0.05	20	61	0.09	8
2	3	4	22	0.5	2	42	0.07	8	62	0.7	20
3	0.9	20	23	0.3	20	43	0.7	6	63	0.3	4
4	0.7	10	24	0.9	8	44	1	2	64	0.9	10
5	0.3	8	25	1	10	45	0.1	8	65	1	4
6	5	8	26	0.07	10	46	0.09	4	66	7	8
7	0.9	6	27	0.9	2	47	0.1	16	67	0.9	16
8	0.7	4	28	0.09	6	48	0.5	10	68	1	20
9	0.5	6	29	7	4	49	1	8	69	0.05	10
10	0.3	10	30	9	8	50	0.1	2	70	5	4
11	0.5	8	31	0.07	20	51	0.09	20	71	9	4
12	0.3	16	32	5	2	52	0.5	16	72	0.5	20
13	0.03	20	33	7	6	53	0.5	4	73	9	6
14	0.07	6	34	0.03	8	54	3	6	74	7	2
15	1	16	35	0.1	4	55	0.3	2	75	0.1	20
16	0.7	16	36	0.1	10	56	0.07	16	76	0.7	2
17	0.1	6	37	1	6	57	0.7	8	77	0.03	10
18	0.05	8	38	0.3	6	58	3	2	78	0.05	6
19	0.09	16	39	9	2	59	0.9	4	79	0.03	16
20	0.05	16	40	5	6	60	3	8			

Table:2. Trials for experiment 1 - second group

Trial	Amplitude (mm)	Wave Cycles	Trial	Amplitude (mm)	Wave Cycles
1	10	1	16	0.03	8
2	0.1	2	17	0.09	20
3	0.09	6	18	0.09	8
4	0.3	4	19	0.7	2
5	0.09	4	20	0.07	6
6	0.07	8	21	0.05	20
7	0.07	10	22	0.05	8
8	0.03	16	23	0.09	16
9	0.07	20	24	0.3	2
10	0.1	6	25	0.05	10
11	0.03	10	26	0.1	4
12	0.5	4	27	0.05	16
13	0.5	2	28	0.3	6
14	0.03	20	29	0.09	10
15	0.07	16			

Table:3. Trials for experiments 2abc

Trial	Amplitude (mm)	Wave Cycles	Trial	Amplitude (mm)	Wave Cycles
1	0.1	2	12	0.03	8
2	0.07	8	13	0.09	2
3	0.05	10	14	0.05	4
4	0.05	16	15	0.01	8
5	0.07	4	16	0.03	16
6	0.07	6	17	0.05	20
7	0.03	20	18	0.05	8
8	0.01	16	19	0.05	6
9	0.09	6	20	0.09	4
10	0.01	20	21	0.3	2
11	0.01	10	22	0.03	10