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The Implications of Surface Stiffness for Size Identification and Perceived Surface Hardness in Haptic Interfaces

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Abstract

This paper presents a two-part study of the effects of virtual surface stiffness on haptic perception. First, size identification experiments were performed to determine the effects of system quality, in terms of surface stiffness, on the ability of a human to identify square cross-section ridges by size in a simulated environment. Then, discrimination experiments were performed to determine relationships between virtual surface stiffness and simulation quality in terms of perceived surface hardness. Results of experiments to test human haptic perception for varying virtual surface stiffnesses indicate that haptic interface hardware may be able to convey sufficient perceptual information to the user at relatively low levels of virtual surface stiffness. Subjects, however, can perceive improvements in perceived simulated surface hardness as stiffness levels are increased in the range of achievable parameters for this hardware. The authors draw several conclusions about allowable time delays in a haptic interface system based on the results of the surface stiffness experiments. This paper can be treated as a second part to [1], which presented similar experiments and results for two other machine parameters, maximum force output and system bandwidth.

1 Introduction

The proper design of any machine requires a well-defined set of design specifications. Hardware design specifications for haptic interfaces that relate machine parameters to human perceptual performance are notably absent in the literature, although much work has been accomplished in the field in general [see, for example, the surveys 2, 3]. The absence of these specifications is due primarily because haptic interface design specifications must consider issues of human perception. Human perception, in turn, is complex in nature and difficult to assess quantitatively.

With the recent introduction of several commercially oriented haptic devices and applications, the need for a set of design specifications to guide the cost-optimal design of haptic devices is that much more pronounced. The work presented in this paper is an attempt to characterize the effects of one haptic interface design specification, virtual surface stiffness, on the ability of a human to haptically perceive and distinguish the haptic display of detail. Along with similar characterizations of other design specifications, this work should help form a set of design specifications from which a designer can properly and perhaps more effectively design a stylus-type haptic interface for a given application.

One prior attempt to elucidate the relationship between haptic device design and human perception was the work of MacLean, who investigated the effects of machine sampling frequency and mechanical damping on human perception, and suggested "preliminary" design guidelines for these traits [4]. She further suggested the existence of a disparity between machine quality and function, which is a notion that is corroborated by the findings of this paper. Despite this effort, the vast majority of the research literature related to the topic of hardware design specifications has generally focused on two areas of study including the quantitative measures of human factors and developing measures of machine performance independent of human perception.

Regarding the first area, psychophysical experiments conducted by several research groups have quantified several haptic perception characteristics, such as pressure perception, position resolution, stiffness, force output range, and force output resolution [for example, 5-7]. Since these experiments did not involve haptic interface equipment, however, they were not able to create a direct link between machine performance and human perception during haptic task performance. The experiments performed on length resolution by Durlach et al., for example, quantified the limits (i.e., size identification and discrimination) of human perception of actual objects, but did not draw parallels between human perceptual ability and haptic hardware design [7].

Within the second area of research, optimal machine performance has been characterized in the literature, yet these measures are typically disparate from human perceptual measures. When designing high-performance equipment, designers seek to build a device with characteristics such as high force bandwidth, high force dynamic range, and low apparent mass [8, 9]. These are typically qualitative specifications, however, since the designers have little reference information regarding the quantitative effects of these machine parameters on the performance of humans with regards to perception in a haptically simulated environment. While designers are aware of

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the benefits of "high" bandwidth and "high" force dynamic range, there is a lack of quantitative data to illustrate the relationship between these design parameters for a haptic device and human perception.

Several researchers have incorporated human sensory and motor capability as a prescription for design specifications of a haptic interface [10, 11]. Such measures are logical, though indirectly related to haptic perception and most likely quite conservative for common haptic tasks. Colgate and Brown offer qualitative suggestions for haptic machine design that are conducive to the stable simulation of high impedances [12]. Though simulation of a high impedance is a logical performance objective for a haptic device, the objective is not directly based upon measurements of human perception.

Finally, researchers have studied the effects of software on the haptic perception of virtual environments [for example, 13-15]. Morgenbesser et al., for example, looked at the effects of force shading algorithms on the perception of shapes [15]. Again, these experiments did not address the relationships between haptic interface hardware design and haptic perception.

This paper addresses the relationship between haptic interface hardware and human perception, and in particular measures the effects of varying virtual surface stiffness in a simulated environment on human size identification capabilities and perceived hardness of a haptic environment. Virtual surface stiffness is of interest as a machine parameter because hardware selections, including position sensors and computers, can limit achievable virtual surface stiffnesses. A good discussion of the relationship between hardware and achievable surface stiffness is given in [12].

Human perception of a simulated environment can be considered in terms of either information transfer or perceived quality. Experiments designed to study information transfer from a simulated environment to a human subject seek to quantify the level of system quality necessary to convey sufficient perceptual information to the user for the purpose of completing a defined task. In the study, virtual surface stiffness is varied to understand the effects of this parameter on the ability of subjects to extract haptic information from a simulated environment in a size identification experiment. To understand the effects of surface stiffness on perceived hardness, subjects are then asked to discriminate surfaces by how hard they feel when tapped. Finally, the implications of this data for tolerable system time delays are extrapolated.

2 Methods

Two psychophysical concepts, generally used to quantify perception, are utilized in this study to investigate relationships between hardware design and human perception. Discrimination experiments reveal differential thresholds, or more specifically, the smallest perceivable difference in a parameter between a reference and a test object [16]. In this case, discrimination experiments are used to compare perceived virtual surface hardness of square cross-section ridges placed side by side. Absolute identification paradigms measure a person's ability to categorize parameter values without providing explicit references. For this paper, identification experiments are used to measure haptic performance in a size identification task without regard to perceived simulation quality.

2.1 Apparatus

A three degree-of-freedom manipulator, shown in Figure 1, was designed to exhibit low rotational inertia, minimal friction forces, zero backlash, and high link stiffness [17], which are physical characteristics generally known to facilitate high fidelity haptic simulations [8]. The manipulator is a point-contact force-reflecting device that interfaces with a human through a pencil-type stylus device. Together with computer software designed to simulate virtual environments, the manipulator was used to run several experiments to test the effects of machine design on human perception through a haptic interface. In the experiments described, the manipulator and haptic simulation were utilized as an impedance operator, as illustrated in Figure 2. The haptic interface therefore measured three-dimensional motion and displayed the appropriate three-dimensional force vector, while the human operator was assumed to perform the inverse (admittance) operation. All simulations ran at a sampling frequency of 3000 Hz. This

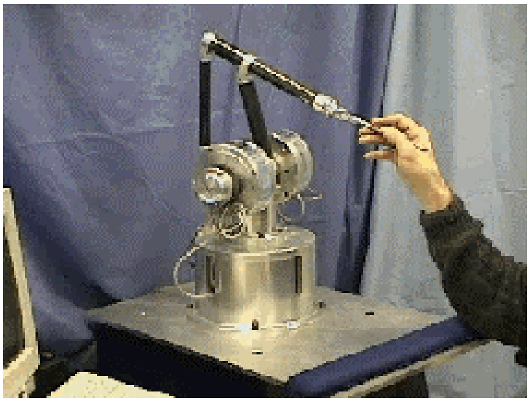
Figure 1. Test subject seated at haptic interface

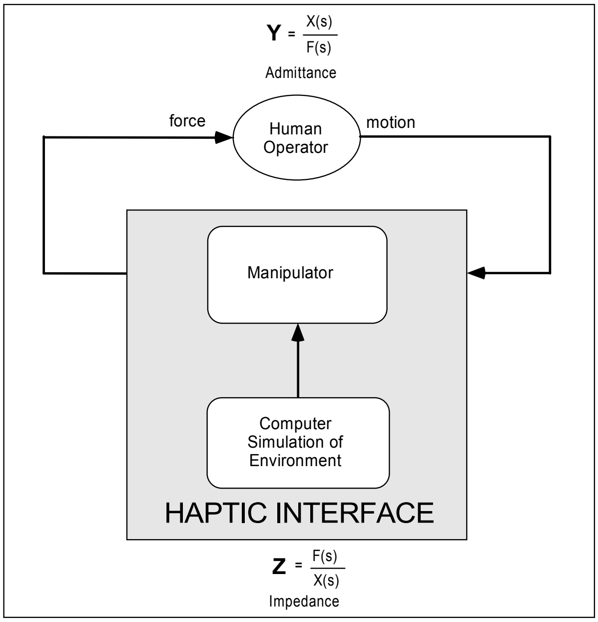

Figure 2. Block diagram of the operator-interface feedback loop

particular apparatus is capable of displaying constant forces of over 10 N in the spatial region of the haptically displayed ridges, and peak forces of roughly 40 N.

2.2 Experimental Paradigms

Perception experiments were conducted for objects of square cross-section, since the shape can be characterized with a single parameter, namely the edge length for square ridges. Unlike a dynamic task, this experiment is purely perceptual with results that are not time dependent. Two experiments are administered, size identification of square ridges (Experiment 1) and surface hardness discrimination of virtual surfaces (Experiment 2).

2.3 Subjects

Six test subjects were used for Experiment 1, and seven subjects were used for Experiment 2. These subjects were chosen from a pool of individuals with varying amounts of experience using a haptic interface. A cross-section of subject types (gender, dominant handedness, and experience with haptic devices) was chosen for each block of testing. During the training sessions and experiments, each subject sat in front of the haptic interface with the dominant hand holding the stylus and the non-dominant hand typing responses on a keyboard. There were no measures taken to obstruct the subject's views of the haptic interface during testing. Since the objective of this work is to explore only the effects of machine parameters on haptic perception, no synthetically generated visual or audio feedback was included in the simulation. Subjects reported that the tasks relied heavily on their sense of touch and little on their sense of sight, despite the ability to see the motion of their hands.

2.4 Procedures

2.4.1 Identification of Size

Size identification tasks determine the ability of a test subject to classify similarly shaped objects, presented one at a time, by size alone. The objects in this case were synthetic ridges displayed on a virtual floor. The center of each ridge was located along the same line in the manipulator’s workspace. Additionally, the floor of the simulated environment was always along the same plane. Each ridge extended across the entire workspace of the manipulator such that if the subject slid the probe along the virtual floor from the front of the workspace to the rear of the workspace in any direction, they would intersect the synthetic ridge. Figure 3 illustrates the three ridge sizes for square cross-section ridges.

A training session occurred before each testing session, allowing the subject to learn the three ridge sizes for that particular session. During the training period, subjects were presented with a virtual ridge displayed with maximum stiffness and were then prompted to enter the number corresponding to that size on a computer keyboard. Instructions indicated that training should cease when the subject felt comfortable with the sizes and confident that s/he could classify ridges by size to the best of their ability. During experimentation, stiffness values were assigned on a trial-by-trial basis, and damping values were calculated to maintain a constant ratio of damping to stiffness of 0.1 (e.g., $k = 1000$ N/m and $b = 100$ Ns/m).

For Experiment 1, each subject was presented with five sessions of testing. A single session consisted of one set of ridge sizes and several randomly presented levels of virtual surface stiffness. The range of stiffnesses used in this experiment was logarithmically distributed across the range of achievable stiffnesses for this hardware. The minimum stiffness tested was 50 N/m. Below this stiffness, the authors could not feel the simulated surface. Test values were then selected in the range of 50 to 1000 N/m. The range of object sizes used in the final sets of experiments was based on previous runs of Experiment 1 with the maximum force output as the machine parameter of interest [18]. Size #1 ridges always had a cross-section of 20 x 20 mm^2. Size #2 and #3 ridges had cross-sections of (20+2d)x(20+2d) mm^2 and (20+4d)x(20+4d) mm^2, respectively. Table 1 shows ridge size differences and stiffness values for the size identification experiments.

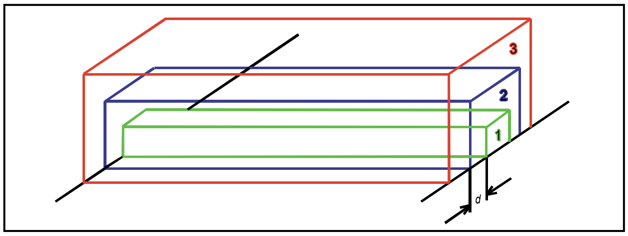

Figure 3. Representation of square cross-section ridges in three rendered sizes showing ridge size difference, d

Table 1. k and *d* values for size identification test sessions

Session Number	Stiffness (k) Values (N/m)	*d* (mm) Size Difference
1	50, 110, 220, 470, 1000	2.50
2	50, 110, 220, 470, 1000	5.00
3	50, 110, 220, 470, 1000	7.50
4	50, 110, 220, 470, 1000	10.00
5	50, 110, 220, 470, 1000	12.50

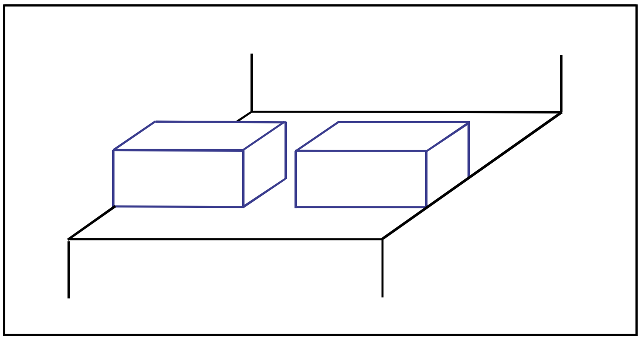

Figure 4. Graphic of quality discrimination test environment

2.4.2 Discrimination of Quality

Size identification tests indicate minimum machine requirements for information transfer purposes. For comparison, additional tests were performed to indicate machine requirements for perceived simulation quality. Surface quality discrimination experiments were designed so that subjects were presented with two square cross-section ridges displayed side by side as shown in Figure 4. In each trial virtual surface stiffness was tested, with one of the two ridges displayed with the maximum capable level of that parameter and the other displayed with a lower level of the same parameter. Valid stiffness levels for testing were defined in the 500 to 1000 N/m range. Lower stiffnesses were obviously discernable when compared to the maximum achievable stiffness and were therefore not used as data points. Table 2 shows stiffness settings for Experiment 2. Forty presentations of each combination were presented, for a total of 200 trials per subject.

Table 2. k presentation pairs for Experiment 2.

k Combinations (N/m)
1000 and 500
1000 and 600
1000 and 700
1000 and 800
1000 and 900

3 Results

3.1 Identification of Size

The percent correct scores for each test subject were plotted versus ridge size difference for each maximum force level. The results were averaged across all test subjects, and a least squares curve fit was performed, utilizing an equation of the form:

$$y = C_1 e^{-\lambda_1 x} + C_2 e^{-\lambda_2 x} \qquad (1)$$

where C_1, λ_1, C_2, and λ_2 were curve-fitting parameters. Note that a two-component exponential curve was utilized because it yielded a noticeably better fit than did a simple exponential.

3.1.1 Experiment 1 – Size Identification

Experiment 1 studied the ability of subjects to classify objects presented one at a time by size. The exponential curves corresponding to average percent correct scores for all subjects were plotted versus each ridge size difference set for all stiffness levels. The results for Experiment 1 are pictured in Figure 5. A 90% correct line was added to the graph to show what was regarded as a good level of correct size identification. The point where each exponential curve fit crossed this 90% correct line was calculated from the curve fit equations, and the resulting data pairs were plotted in Figure 6. The graph shows surface stiffness levels versus difference in ridge radius for Experiment 1. A trend line is overlaid to illustrate this relationship. Exponential curve fits using the two-component equation given previously were performed on the plus/minus standard deviation curves and the 90% correct crossover points were evaluated and added to the graph in Figure 6.

3.2 Experiment 2 – Discrimination of Quality

For interaction with simulated square cross-section ridges via tapping with a probe, subjects responded "right", "left", or "same" when asked which of two ridges felt harder. During experimentation, subjects were not told which ridge had a stiffness of 1000 N/m and which had the lower stiffness value. Figure 7 shows the percent of time each response was given, averaged across all subjects. Error bars are included to illustrate variance in response across test subjects.

3.3 ANOVA Results

To determine the confidence interval for Experiment 1, a three-way analysis of variance (ANOVA) test was performed. Two treatments, the levels of stiffness and the feature size differences, are used, and results are blocked on subjects. The one-way analyses showed 99% confidence intervals for both treatments and the block. High confidence intervals were noted for the two-way interactions involving subjects. These interactions are attributable to non-parallel trends in performance by one subject.

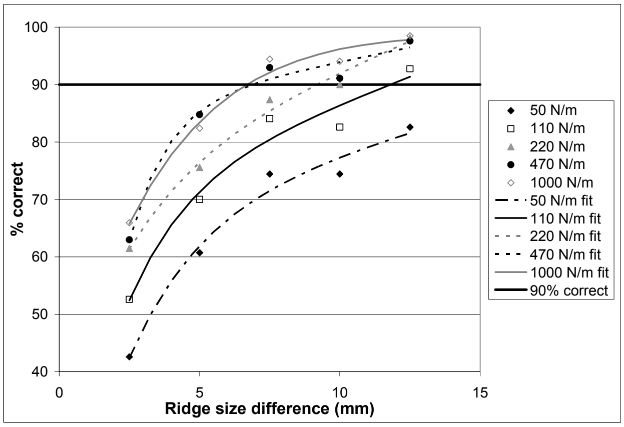

Figure 5. Summary plot of Experiment 1 results (square ridge size identification) for all stiffness levels.

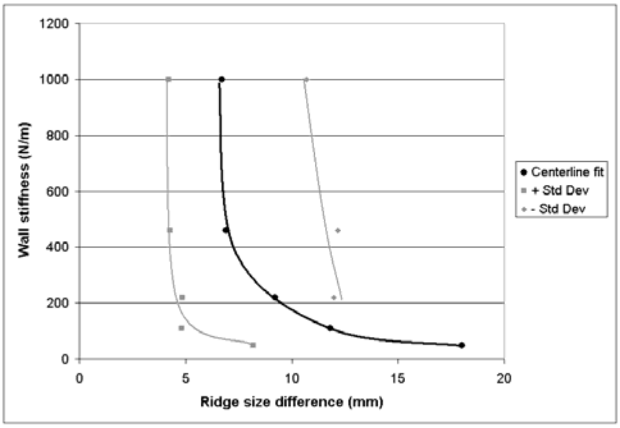

Figure 6. Wall stiffness vs. ridge "radius" size difference (*d*) for Experiment 1 (square ridge size identification).

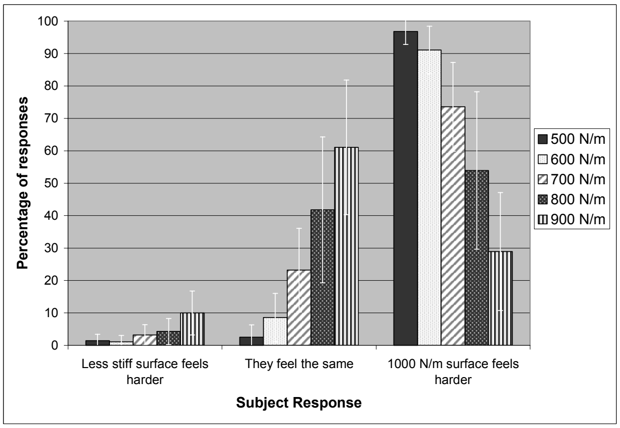

Figure 7. Perceived surface hardness experiment results. Subjects compared a surface with stiffness of 1000 N/m to surfaces with lower levels of stiffness.

4 Discussion

The summary graph of Experiment 1 (Figure 6) shows that as stiffness of virtual walls increases, performance of the size identification task improves. This holds until the stiffness reaches about 300 to 400 N/m, beyond which significant gains in performance are not seen. Once this stiffness level is reached, the average user is able to correctly identify size differences of 7 mm with 90% accuracy. The maximum bound is not calculable for stiffnesses of 50 and 110 N/m because these standard deviation bands did not reach the 90% correct line.

For quality discrimination experiments for varying simulated surface stiffness, subjects reported that stiffnesses of 1000 N/m (the highest level) felt harder than those with stiffness of 500 N/m over 90% of the time. The percent of responses preferring the highest stiffness steadily decreased as the stiffness of the non-ideally simulated ridge surfaces increased. When comparing 900 N/m to 1000 N/m however, the subjects felt the higher stiffness simulated ridge was still harder just under 30% of the time.

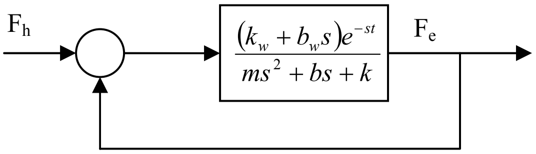

Figure 8. Block diagram of human interaction with virtual wall. F_h is the input force from the human, and F_e is the force due to the virtual environment.

While an understanding of the effects of varying virtual surface stiffness on human haptic perception can aid in the selection of sensors and the determination of minimum update rates for haptic simulations, the results can also be extrapolated to characterize the effects of time delay on human perception in a haptic feedback system. If a haptic system with time delay is represented, for simplicity, as a continuous time system, the block diagram shown in Figure 8 can be used. The time delay can be due to computational or communication delays in either a simulated environment display or teleoperated system. The transfer function for the simplified continuous time system is represented as

$$\frac{(k_w + b_w s)e^{-st}}{ms^2 + bs + k} \tag{2}$$

In the numerator, the wall stiffness and damping are represented by equation 3.

$$k_w + b_w s \tag{3}$$

Typical values for a stiff wall with this hardware are:

$$k_w = 1000 \text{ N/m}$$
$$b_w = 100 \text{ Ns/m}$$

Also in the numerator is the representation of the time delay, e^{-sT}. In the denominator, the human is modeled as a second order system:

$$ms^2 + bs + k \tag{4}$$

with the following parameters:

$$m = 1 \text{ kg}$$
$$b = 5 \text{ Ns/m}$$
$$k = 25 \text{ N/m}$$

These values were derived experimentally from frequency response data for this haptic device. The wall model, given in equation 3, can also be written as:

$$k_w(1 + \alpha s) \tag{5}$$

where k_w is a gain equal to the wall stiffness and α is a constant ratio of wall damping to wall stiffness.

In the case of a 10 msec time delay, positive gain and phase margins exist. These conditions indicate that for this amount of delay, the system remains stable. When the time delay is increased to 50 msec, negative gain and phase margins are seen and the system is now unstable. In order to maintain stability with the increased time delay, the gain of the system can be decreased. According to the transfer function for this system, the gain is equivalent to the simulated wall stiffness. Therefore, a decrease in wall stiffness (k_w) will assure stability in the presence of time delays.

For this system model of the human interacting with a virtual surface via a haptic interface, there is a gain margin of approximately 24 dB with a 1 msec time delay. In order to maintain this stability margin with increasing time delay, the gain of the system, which is the virtual surface stiffness, should be decreased. Table 3 shows system gains (surface stiffnesses) and the corresponding time delays for the virtual wall and human arm model.

For the size identification task, performance gains were not significant for stiffnesses above about 400 N/m. This corresponds to a time delay of approximately 2.5 msec with a gain margin of 24 dB for this hardware. Note that the same stiffness could be simulated with greater equivalent time delays for lower levels of stability robustness (i.e., smaller gain margins). In fact, an analysis based on the frequency response of the described system suggests that this system could simulate a stiffness of 400 N/m with a time delay of 35 msec in the limiting case of zero gain margin. This implies that a haptic system could sustain 35 msec of time delay and still convey sufficient information to the user for task performance, though the system would barely be stable.

Table 3. Virtual surface stiffness values for 24 dB gain margin in the presence of varying time delays.

Surface Stiffness (N/m)	Time delay (msec)
1000	1
400	2.5
200	5

5 Conclusions

Identification tests were performed to characterize the effect of virtual surface stiffness on haptic size identification. For haptic simulation in a stylus-type interface, the following relationships were observed:

- Stiffnesses above 400 N/m do not provide any significant improvements in performance (defined at 90% accuracy) for size identification tasks with ridges of square cross-section.

To ascertain perceived surface hardness rather than just information transfer, surface hardness discrimination tasks were performed for paired levels of virtual surface stiffness. For the experiments performed, the following conclusion was drawn:

- Perceived simulation quality (determined by comparing perceived surface hardness of a simulated ridge) increases without bound for the range of system parameters used in these experiments (surface stiffness of 500 to 1000 N/m)

These observations indicate that haptic interface hardware may be capable of conveying significant perceptual information to the user at fairly low levels of virtual surface stiffness. This being the case, higher levels of virtual surface stiffness in a haptic simulation notably improve the quality of simulation in terms of perceived simulated surface hardness.

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7 References

[1] M. Kilchenman and M. Goldfarb, "Force saturation, system bandwidth, information transfer, and surface quality in haptic interfaces." Proceedings of the IEEE International Conference on Robotics and Automation, pp.1382-1387, 2001.

[2] G. C. Burdea, *Force and Touch Feedback for Virtual Reality*. John Wiley and Sons, Inc.: 1996.

[3] M. A. Srinivasan, "Haptic Interfaces," in N. I. Durlach and A. S. Mavor (Eds.), *Virtual Reality: Scientific and Technological Challenges*, Chap. 4, National Research Council, National Academy Press, Washington, D. C.: 1994.

[4] K. E. MacLean, "Emulation of Haptic Feedback for Manual Interfaces," Ph.D. Thesis, MIT, 1996.

[5] G. L. Beauregard, M. A. Srinivasan, and N. I. Durlach, "The Manual Resolution of Viscosity and Mass." In Proceedings ASME Dynamic Systems and Control Division, DSC-Vol. 57-2, pp. 657-662, 1995.

[6] H. Z. Tan, M. A. Srinivasan, B. Eberman, and B. Cheng, "Human factors for the design of force-reflecting haptic interfaces." In Proceedings ASME Dynamic Systems and Control Division, DSC-Vol.55, pp. 353-359, 1994.

[7] N. I. Durlach, L. A. Delhorne, A. Wong, W. Y. Ko, W. M. Rabinowitz, and J. Hollerbach, "Manual discrimination and identification of length by the finger-span method." Perception and Psychophysics, Vol. 46, pp. 29-38, 1989.

[8] R. Ellis, O. Ismaeil, and M. Lipsett, "Design and evaluation of a high-performance prototype planar haptic interface." Advances in Robotics, Mechatronics, and Haptic Interfaces, DSC-Vol. 49, pp. 55-64, 1993.

[9] T. L. Brooks, "Telerobotic Response Requirements." In Proceedings of the IEEE Conference on Systems, Man, and Cybernetics, pp. 113-120, 1990.

[10] C. D. Lee, D. A. Lawrence, and L. Y. Pao, "A high-bandwidth force-controlled haptic interface," In Proceedings ASME Dynamic Systems and Control Division, DSC-Vol.69-2, pp. 1299-1308, 2000.

[11] B. D. Adelstein and M. J. Rosen, "Design and implementation of a force reflecting manipulandum for manual control research," In Advances in Robotics, H., Kazerooni, Ed. New York: ASME, 1992, pp. 1-12.

[12] J. E. Colgate and J. M. Brown, "Factors affecting the Z-width of a haptic display." In Proceedings IEEE International Conference on Robotics and Automation, pp. 3205-3210, 1994.

[13] P. A. Millman and J. E. Colgate, "Effects of non-uniform environment damping on haptic perception and performance of aimed movements." In Proceedings ASME Dynamic Systems and Control Division, DSC-Vol. 57-2, pp. 703-711, 1995.

[14] L. B. Rosenberg and B. D. Adelstein, "Perceptual decomposition of virtual haptic surfaces." In Proceedings of the IEEE Symposium on Research Frontiers in Virtual Reality, San Jose, CA, pp. 46-53, Oct. 1993.

[15] H. B. Morgenbesser and M. A. Srinivasan, "Force shading for haptic shape perception." In Proceedings ASME Dynamic Systems and Control Division, DSC-Vol. 58, pp. 407-412, 1996.

[16] G. A. Gescheider, *Psychophysics: Method, Theory, and Application* (2nd ed.). Hillsdale, New Jersey: Lawrence Erlbaum Associates, 1985.

[17] C. M. Perry, "Design of a High Performance Robot for Use in Haptic Interface and Force Feedback Research." Master's Thesis, Dept. of Mechanical Engineering, Vanderbilt University, 1997.

[18] M. Kilchenman and M. Goldfarb, "Implications of haptic interface force saturation on the haptic display of detail." Proceedings of the ASME International Mechanical Engineering Congress and Exposition, DSC-Vol. 69-2, pp. 1125-1131, 2000.