

PROCEEDINGS OF SPIE

[SPIDigitalLibrary.org/conference-proceedings-of-spie](https://spiedigitallibrary.org/conference-proceedings-of-spie)

Data visualization methods for the blind using force feedback and sonification

Nikolai Grabowski, Kenneth Barner

Nikolai A. Grabowski, Kenneth E. Barner, "Data visualization methods for the blind using force feedback and sonification," Proc. SPIE 3524, Telemanipulator and Telepresence Technologies V, (18 December 1998); doi: 10.1117/12.333677

SPIE.

Event: Photonics East (ISAM, VVDC, IEMB), 1998, Boston, MA, United States

Data visualization methods for the blind using force feedback and sonification

Nikolai A. Grabowski and Kenneth E. Barner

Department of Electrical and Computer Engineering
University of Delaware
Newark, DE 19716

ABSTRACT

Research in the field of scientific visualization has begun to articulate systematic methods for mapping data to a perceivable form. Most work in this area has focused on the visual sense. For blind people in particular, systematic visualization methods which utilize other senses need further development. In this work, we develop methods for adding aural feedback to an existing haptic force feedback interface to create a multimodal visualization system. We examine some fundamental components of a visualization system which include the following: characterization of the data, definition of user directives and interpretation aims, cataloging of sensual representations of information, and finally, matching the data and user interpretation aims with the appropriate sensual representations. We focus on the last two components as they relate to the aural and haptic senses. Cataloging of sensual representations is drawn from current research in sonification and haptics. The matching procedure can be thought of as a type of encoding which should be the inverse of the decoding mechanisms of our aural and haptic systems. Topics in human perception are discussed, and issues related to the interaction between the two senses are addressed. We have implemented a visualization system in the form of a Windows NT application using a sound card and a 3 DOF point interaction haptic interface. The system presents a 2D data set primarily as a polygonal haptic surface although other capabilities of the haptic sense are utilized such as texture discernment. In addition, real time aural feedback is presented as the user explores the surface. Parameters of sound such as pitch and spectral content are used to convey information. Evaluation of the system's effectiveness as an assistive technology for the blind reveals that combining aural and haptic feedback improves visualization over using either of the two senses alone.

Keywords: haptics, sonification, visualization

1. INTRODUCTION

Advances in computer graphics have made possible new and exciting scientific visualization methods. It is common to see a matrix of data represented on the computer screen as a colored surface floating in space, perhaps with axes to provide a frame of reference. Representing numerical data through the symbolism of graphical plotting is basic to scientific work. It provides salient information about the data set without requiring one to sift through all of the numbers.

Computer graphics have also enabled a shift in human-computer interaction from a line by line text format to an increasingly rich graphical format. We no longer think of typing commands at a prompt. Instead, we think of moving things around on a desktop. While a blind person can certainly move the mouse around, he or she has no information about what is happening on the desktop if all feedback is graphical. Importantly, research in haptic and auditory interfaces has brought more than graphical feedback to the computer interface. We can hear auditory cues about events and the status of objects. With a haptic mouse, we can feel the edges of windows and other desktop items. Further, 3 degree of freedom haptic devices allow us to touch computer generated 3D objects.

Haptic and auditory interfaces can provide access to scientific visualization for the visually impaired. Many of the methods for doing this can be borrowed from the methods of graphical scientific visualization. However, it is important to understand the differences among the modalities. Visual and aural information are both global and spatially mapped while haptic information is spatially focused at the point(s) of contact with the body.¹ In addition,

Other author information: (Send correspondence to N.A.G.)
N.A.G.: E-mail: grabowsk@eecis.udel.edu
K.E.B.: E-mail: barner@eecis.udel.edu

Part of the SPIE Conference on Telemanipulator and Telepresence Technologies V
Boston, Massachusetts • November 1998
SPIE Vol. 3524 • 0277-786X/98/\$10.00

131

the information bandwidth of the haptic sense is orders of magnitude lower than that of vision and hearing.²⁻⁵ Thus, a haptic interface alone as a substitute for a graphical interface results in a significant reduction in bandwidth. At the same time, the haptic interface is extremely valuable because it takes advantage of two-way energy flow between the user and the environment. The user gains information through exploration in an intuitive way. To compensate for the bandwidth reduction, sound can be added to the interface. Methods for adding sound can be drawn from the field of sonification. Sound can also be used to enhance the physical aspects of the haptic interaction.

In this paper, we begin by discussing scientific visualization to provide terminology and a framework for representing data. We then discuss ways of using haptics and sound for visualization. Finally, we describe rendering methods and our current implementation.

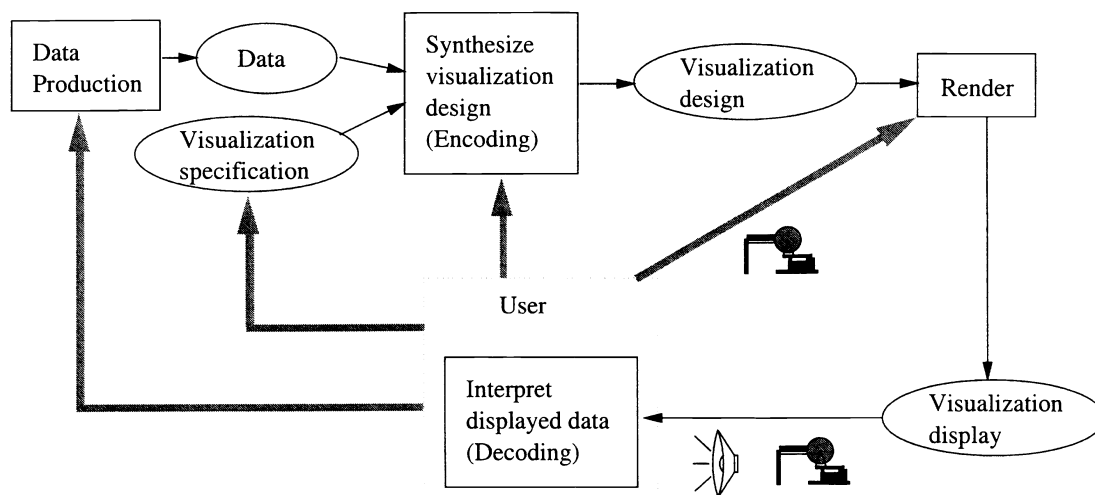


Figure 1. Adaptation of the integrated visualization model from Robertson⁶

2. VISUALIZATION

To visualize is to form a mental image. Research in the field of scientific visualization is concerned with the binding or mapping of data to a form that can be perceived. Figure 1 shows part of Robertson's visualization system model.⁶

Data measured by a sensor or produced by a simulation must enter the visualization system according to a defined data structure. It is important to know things like how many data variables are present, which ones are independent or dependent, whether the data is ordinal or nominal, information about sampling, upper and lower bounds, coordinate systems, scale and continuity of data, etc. We will concentrate on the case of 2D, regularly gridded data which means that we have two independent variables and one dependent variable.

The visualization specification consists of user directives to the system and the user's interpretation aims. Directives might include instructions such as "don't show variable X ," or "show variable X using representation R ." Interpretation aims can be described in terms of the following *data attributes* to be studied:

- values at a point (*point*)
- local distribution of values, such as gradients and features (*local*)
- global distribution of values, such as trends and structure (*global*)

Given the data structure and visualization specification, the visualization design process maps the data to some form of sensory stimulus be it visual, aural, haptic, etc. To perform this mapping, the process uses a catalogue

of sensual representations indexed by the type of data under consideration and by the perceptual task to be accomplished. For example, color is often used to represent *nominal* (classification) data and can show point, local, and global attributes. Spatial information such as height is often used to represent *ordinal* (intrinsic progressive relationship between successive values) data. It conveys local and global data attributes. Sometimes the two are used in conjunction. For example ambiguities in the height of a surface can be made clearer by adding color to redundantly represent height.

Robertson puts forth a systematic approach to choosing visual representations using a *natural scene paradigm*.⁷ This method identifies well-defined properties of a scene that can be appreciated either independently or in relation to each other. It is based on the fact that humans can shift attention from one physical scene property to another or assess properties in relation to each other. Robertson's method considers what kinds of information the scene properties can convey and then associates the properties with corresponding data types and data attributes.

Consider two visual properties of a real-world surface over a 2D spatial field: its height and surface covering. An example would be a terrain covered by various forests. The surface covering would have subparameters such as the type of trees and their density. The covering would be indicated by aspects of color and texture. The type of covering conveys point, local and global attributes of nominal data. The condition of the covering (for example, density of trees) conveys local and global attributes of ordinal data. The surface height also conveys local and global attributes of ordinal data.

3. HAPTIC AND AURAL REPRESENTATIONS

The above discussion of the natural scene paradigm only considered visual representations. Here we describe haptic and aural scene properties. The two modalities can be considered separately and in conjunction.

3.1. Haptics

Haptic interfaces can be used to create the sensation of touching computer generated environments. Much of the research in haptics technology uses mechanical devices to provide a user with kinesthetic force feedback.⁸⁻¹⁴ This feedback conveys perceptual information such as shape, weight, and stiffness. Haptic interfaces, therefore, introduce a unique means of human computer interaction that goes beyond the passivity of a keyboard or mouse. In this paper, we focus on haptic interaction at a single interface point (IP) which can correspond to the scenario of touching with the fingertip or a pencil-like tool.

Considering Robertson's paradigm, the haptic interface can be used to convey surface height and surface covering. These properties are rendered through the interface's response to user exploration. As the user moves the IP through space, a force is exerted on the IP when it reaches a location corresponding to contact with the virtual surface. The result is a kind of "force field" which creates the effect of a surface. The user can tap on it or slide along it. In this way, the user can obtain relative height information. To convey the surface covering, additional forces related to texture and friction can be added to the basic constraint force.

When displaying data as a graphical plot, axes and grid lines often aid comprehension of the data. The haptic correlate of grid lines could be grid planes placed at regular intervals in the haptic workspace. A grid plane can be rendered as a thin, penetrable wall producing a small, but perceivable, force when the IP passes through it. Grid planes can provide discrete reference points or be used as guides along cross sections of the surface.¹⁵

Finally, incorporating the sense of touch into the natural scene introduces possibilities beyond simply finding haptic correlates to graphics. The haptic interface can be used to create *gravity wells*. Gravity wells are attractive forces used to pull the IP to locations of interest. For example, an attractive force could be assigned to the global maximum, and as the user moves along, the IP would be pulled to that location to help the user find it. An attractive force could also be used to hold the IP to the surface itself so that the user would not fly off of sharp corners.

3.2. Sound

Consider again the surface height and covering. Visually, we obtain the shape and surface texture by observing light interacting with the surface. Through haptic interaction, we obtain the shape and surface texture through the opposing forces as we move through space. Aurally, we can also gain information about the surface shape and texture. Sound is closely related to haptic interaction because most collisions and scrapes make sounds. Further, the sounds from these interactions tell us something about the shape and material of the objects involved in the

interaction. Given the surface geometry and defining thickness and material properties, we can use the computer to analyze the structure to find its acoustic response when tapped or scraped. In the case of tapping, consider a bell-shaped surface: when tapping the apex, the sound will have more emphasis on high frequency components than if one is tapping on the bells' body. This enhances the user's sense of surface shape and the IP location. If the surface is textured, the haptic interaction will produce a sonic excitation akin to noise of varying bandwidth depending on surface roughness.

In addition to using a physical model of the surface, many other scene properties can be defined that are drawn from the field of sonification. Sonification is concerned with mapping data to parameters of sound. Although it has become organized as a field of study only within the past decade, researchers have been investigating the mapping of data to sound for many years. Some early uses included tasks such as displaying chemical data to blind students using pitches played in sequence or together as a chord,¹⁶ debugging computer programs,¹⁷ and the well-known Geiger counter.

The visual system is capable of appreciating spatial location, and this visual property can subsequently be used to represent ordinal data. The auditory system can recognize certain properties of sound that can also be used to represent this kind of data. Some properties of sound that can be perceived as taking on progressive values include pitch, loudness, and pulsing speed.

Another property of sound which can represent data is *timbre* (tone color). Although timbre perception is very complex, work has been done to find ways of using it consistently. For example, Barass has outlined a perceptual sound space¹⁸ in which timbre is thought of as the angle on a wheel similar to a color wheel. The radius of the wheel is the brightness which, incidentally, can also display progressive relationships.

3.3. Combining Haptics and Sound

Haptics and sound have their own unique strengths and limitations. The haptic interaction is a direct and intuitive way of obtaining a mental image of the data represented as a surface. However, the fact that haptic interaction is spatially focused presents limitations on how much information the user can take in at one time. Sound can make the information easier to obtain. A basic benefit of sound is the fact that humans can receive multiple streams in parallel. If the user is sliding or tapping along the surface, listening to the resulting sounds, and suddenly encounters a grid plane, the impact with the grid plane can produce an entirely different sound. If the sounds are designed well, such a situation would not be unlike our everyday interactions with the world.

4. RENDERING

4.1. Haptic Rendering

To accomplish haptic rendering, we are using the point force algorithm provided by Sensable TechnologiesTM for their PHANTOMTM haptic interface.¹⁹ The algorithm monitors the location of the IP. When the IP is found to have penetrated the surface of an object in the environment, a normal force is calculated according to a spring-damper model as shown in Fig. 2. The calculation depends on the velocity of the IP and its position relative to the surface contact point (SCP). The SCP is determined by the shortest distance between the IP and the surface. The equation for the force is written as

$$\mathbf{F} = K_{spring}\mathbf{d} + K_{damping}\mathbf{v} \quad (1)$$

where $\mathbf{d}$ is the displacement, $\mathbf{v}$ is the velocity of the IP, K_{spring} is the spring constant, and $K_{damping}$ is the damping ratio.

The software architecture is also provided by Sensable Technologies and is called GHOSTTM. GHOSTTM uses a structure of nodes which can be connected together as trees. The PHANTOMTM itself is a node in the scene graph. GHOSTTM provides some primitive geometry nodes including a polygon tri-mesh. We use this polygon tri-mesh to create the haptic rendering of surface height.

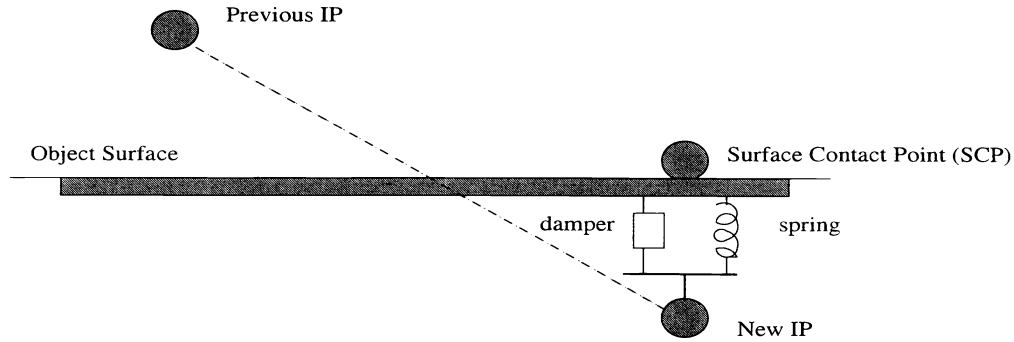


Figure 2. Surface Contact Point (SCP) and Interface Point (IP)

4.2. Impact Sounds

Impact sounds can be rendered through studying the vibration of surface. The development here follows that of Van den Doel and Pai.²⁰ The characteristics of impact sounds are closely related to the geometry and material of the objects involved in the collisions. The development is based on linear vibration analysis and a heuristic for relating the object's vibrations to the sound actually heard.

The displacement, $\mu(\mathbf{x}, t)$, of the surface from equilibrium can be written as

$$\mu(\mathbf{x}, t) = \sum_{n=1}^{\infty} (a_n \sin(\omega_n ct) + b_n \cos(\omega_n ct)) \Psi_n(\mathbf{x}). \quad (2)$$

Notice that each term of the summation is a function of time multiplied by a function of space. The function of space, $\Psi_n(\mathbf{x})$, defines a characteristic shape, or *mode*, of vibration. This shape is scaled by a time varying function, the nature of which is determined by the natural frequency, ω_n . The amplitudes a_n and b_n take a simple form when we consider an impact at some location $\mathbf{p}$ on the surface when it is initially at rest. The initial velocity is taken to be $v_0(\mathbf{x}) = \delta(\mathbf{x} - \mathbf{p})$, with $\delta(\mathbf{x})$ the Dirac delta function. Van den Doel and Pai discuss why the use of the delta function is not strictly correct but is useful for the problem at hand.²⁰ Under these initial conditions, the amplitudes are found as

$$a_n = \frac{\Psi_n(\mathbf{p})}{c\alpha_n\omega_n}, \quad (3)$$

and

$$b_n = 0, \quad (4)$$

where c is a constant related to the speed of sound in the material, and α_n is the norm of mode n . If the modes are normalized, α_n becomes independent of n .

The resulting sound is described as a sum of sinusoids with frequencies $\omega_n c$ and amplitudes a_n^S . The amplitudes a_n^S are related to the vibration amplitudes a_n and are given as

$$a_n^S = \frac{E_{\text{impact}} \Psi_n(\mathbf{p})}{c\omega_n Q(\mathbf{p})d}, \quad (5)$$

where d is the distance from the sound source, E_{impact} is the energy of impact, and

$$Q(\mathbf{p}) = \sqrt{\sum_{n=1}^{n_f} \Psi_n^2(\mathbf{p})}, \quad (6)$$

with n_f the number of modes. The final sound wave also includes two damping factors. One is due to an internal friction parameter, ϕ , and the other serves to control of the overall length of the sound. The sound wave for $t \geq 0$ is

$$p_S(t) = e^{-t/\tau_0} \sum_{i=1} n_f a_i^S e^{-t f_i \pi \tan \phi} \sin(2\pi f_i t), \quad (7)$$

where $f_i = c\omega_n/2\pi$.

For our application, we consider the surface in 3D cartesian space. Thus, the modes in the above discussion will be ordered triples. However, we are concerned with the displacement from equilibrium and the energy of vibration due to an impulse. The impulse will also have three components. The necessary computations will simply involve the dot product between the modes and the impulse vector.

The problem of finding the modes and corresponding natural frequencies can be solved analytically for some special geometries. However, for arbitrary shapes, the finite element method provides a solution. Commercial software is available which performs linear vibration analysis on three dimensional structures.

The above development can be extended to include scraping sounds. Since the impact sound is the response to an impulsive force, the response to an arbitrary force can be obtained through convolution. This principle can be found in basic civil engineering texts.²¹ As the haptic interface slides along the surface, the changing force over time can be used to excite the modes of vibration and determine the resulting sound.

5. IMPLEMENTATION AND RESULTS

The implementation consists of the PHANToM connected to a 300MHz PC, a sound card, and an accelerator for graphic monitoring. All programming is performed in Visual C++. The program can take a matrix of data points or the user can enter a mathematical relationship. From this input, the program generates a polygon tri-mesh surface. This polygonal surface is rendered using the previously described methods with the PHANToMTM. In addition to the surface, we have implemented haptic grid planes which can be turned on and off by the user.

A basic sonification uses the pitch of a sine wave tone to represent the height of the surface. The range and scaling (logarithmic or linear) are left variable so the user can experiment with various settings. The interaction is such that the tone turns on when the user comes in contact with the surface, remains on while the user is sliding along the surface, and turns off when the IP leaves the surface. For the grid planes, we use a distinctive sound to indicate impact with them.

The sound was found to enhance the interface. The grid planes, without sound, were confusing because it was not clear whether the IP was bumping into a feature of the polygon mesh or a grid plane. Sound in this situation, was valuable for distinguishing the surface from the grid planes. The pitch sonification helped with locating local extrema. One could move the IP to the area of an extremum and then listen closely to the varying pitch to "home in" on the peak.

We have also implemented the modal synthesis for impact sounds. We send the surface geometry information to a finite element program to perform the modal analysis. Once the modes and frequencies have been extracted, we can generate the combination of sine waves in real time. The amplitude is scaled by the square of the velocity at the moment of impact.

Figure 3 shows the first six modes of a clamped square plate extracted with the finite element program. The plate is 25 cm square which corresponds approximately to the width of the haptic workspace. It is modeled using 400 quadrilateral thin shell elements. The plate was assumed to be .25 cm thick with the material properties of aluminum. As the plate is struck from the center to the edges, the sound varies from one containing more low frequencies to one containing more high frequencies.

Figure 4 shows the equilibrium position and first five modes of the square plate when one third of it has been raised by 8.75 cm. The modes of vibration are very different for this surface. It produces higher pitched sounds than the square plate. When this surface is struck on the diagonal, the sound is different from when it is struck on the horizontal sections.

The modal analysis of arbitrary surfaces produces a wide variety of tonal combinations. Since the sound level is controlled by velocity of impact, the user can easily choose not to have sound by touching the surface lightly as with a real object.

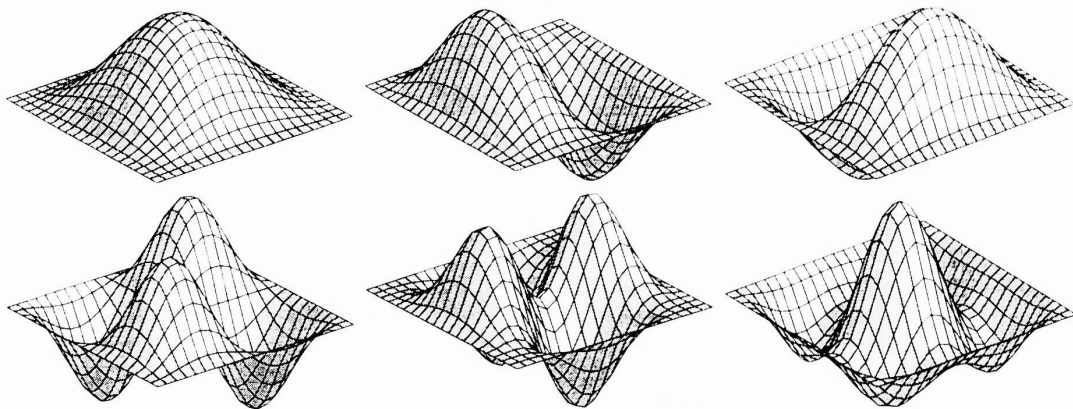


Figure 3. First six modes of a square plate with clamped edges.

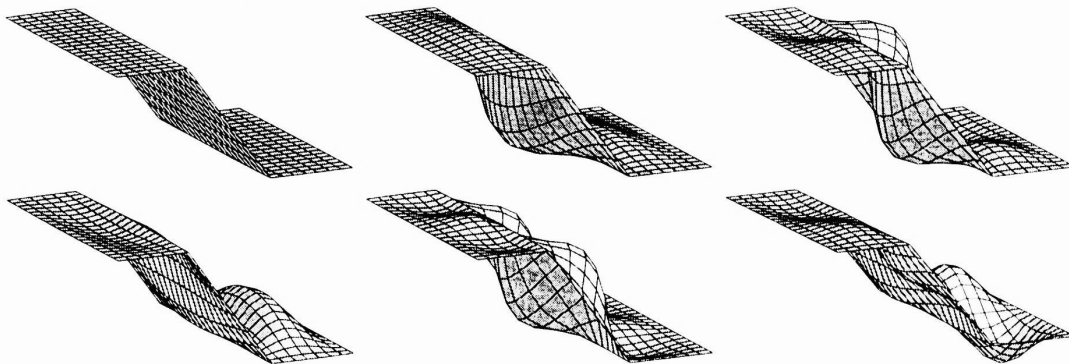


Figure 4. Surface at rest and its first five modes.

6. DISCUSSION

Haptics and sound facilitate visualization when the graphic monitor is not available. Our implementation reveals some benefits of combining the two modalities. Sound helps with differentiating objects in the scene as shown through the implementation of grid planes. Sound also assists with orientation in the environment by highlighting features that may be ambiguous with touch alone. For example, when touching a flat plane, it feels the same whether the IP is in the center or near the edge. Sounds generated by the physical vibration model provide intuitive information about the location of interaction. Furthermore, other capabilities of the auditory system can be exploited through speech output and sonification.

To determine optimal uses of the various haptic and aural visualization methods, psychophysical studies must be conducted. For example, it is not clear what the best force profile would be for grid planes. It is also not clear when various uses of sound cross from being helpful to being distracting. However, a starting point such as the natural scene paradigm is likely to lead to a successful interface because it considers the way humans naturally explore their environment.

Future development of the visualization system implementation will provide the user with more control over haptic and sound variables. The program structure will be more flexible to allow a wide range of experimental possibilities. We will further utilize GHOST's object oriented architecture for haptics. For sound, we plan to investigate the *timbre tree* concept put forth by James Hahn et al.²² It is our hope that continued research in haptic and auditory interfaces will make scientific data more accessible to all.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation, Grant # 9450019.

REFERENCES

1. P. Buttolo, B. Hannaford, and B. McNeely, "Introduction to haptic simulation." Tutorial #2A for the IEEE Virtual Reality International Symposium (VRAIS), Mar. 1996. IEEE.
2. J. Craig, "Vibrotactile pattern perception: Extraordinary observers," *Science* **196**, 1977.
3. K. Kokjer, "The information capacity of the human fingertip," *IEEE Transactions on Systems, Man, and Cybernetics* **SMC-17**(1), 1987.
4. Z. Kuc, "A bidirectional vibrotactile communication system: Tactual display design and attainable data rates," *VLSI and Computer Peripherals*, 1989. COMPEURO '89 - 3rd Annual European Computer Conference.
5. T. L. Brooks, "Telerobotic response requirements," in *Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics*, pp. 113-120, (Los Angeles), 1990. Also Report No. STX/ROB/90-03, STX Corporation, Lanham, MD.
6. P. K. Robertson, "Systematic approaches to visualization: Is a reference model needed?," in *Scientific Visualization: Advances and Challenges*, L. Rosenblum et al., eds., pp. 287-305, Academic Press, 1994.
7. P. K. Robertson, "A methodology for choosing data representations," *IEEE Computer Graphics and Applications* **11**(3), pp. 56-67, 1991.
8. G. Burdea, J. Zhuang, E. Roskos, D. Silver, and N. Langrana, "A portable dextrous master with force feedback," *Presence - Teleoperators and Virtual Environments* **1**(1), pp. 18-27, Mar. 1992. MIT Press, Cambridge, MA.
9. G. Burdea, *Force and Touch Feedback for Virtual Reality*, J. Wiley & Sons, New York, NY, 1996.
10. EXOS, Co., "Sensing and Force Reflecting Exoskeleton (SAFiRE) Specifications." Company brochure. Woburn, MA.
11. H. Iwata, "Artificial reality with force-feedback: Development of desktop virtual space with compact master manipulator," in *ACM Computer Graphics*, vol. 24(4), 1990.
12. B. Jackson and L. Rosenberg, "Force feedback and medical simulation," in *Interactive Technology and the New Paradigm for Healthcare*, K. Morgan, R. Satava, H. Sieburg, R. Mattheus, and J. Christensen, eds., ch. 24, pp. 147-151, IOS Press, Amsterdam, Jan. 1995.
13. T. Massie and K. Salisbury, "The PHANToM haptic interface: a device for probing virtual objects," in *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, ASME Winter Annual Meeting, 1994.

14. M. Minsky, *Computational Haptics: The Sandpaper System for Synthesizing Texture for a Force-Feedback Display*. PhD thesis, Massachusetts Institute of Technology, June 1995.
15. J. P. Fritz, "Haptic techniques for scientific visualization," Master's thesis, Department of Electrical Engineering University of Delaware, Dec. 1996.
16. D. Lunney and R. C. Morrison, "High-technology laboratory aids for visually handicapped chemistry students," *J. Chem. Ed.* **58**(3), pp. 228–231, 1981.
17. D. H. Jameson, "Sonnet: Audio-enhanced monitoring and debugging," in *Auditory Display: Sonification, Audification, and Auditory Interfaces*, G. Kramer, ed., vol. XVIII of *Santa Fe Institute Studies in the Sciences of Complexity*, pp. 253–289, Addison-Wesley, Reading, MA, 1994.
18. S. Barrass, "A perceptual framework for the auditory display of scientific data," in *Proceedings of the Second International Conference on Auditory Display, ICAD '94*, pp. 131–145, November 1994.
19. SensAble Technologies, Inc., Cambridge, MA 02139, *GHOST Software Developer's Toolkit Version 1.2: Programmer's Guide*, September 1997.
20. K. van den Doel and D. K. Pai, "The sounds of physical shapes," *Presence* **7**(4), pp. 382–395, 1998.
21. J. W. Smith, *Vibration of Structures: Applications in Civil Engineering Design*, Chapman and Hall, London, 1988.
22. J. K. Hahn *et al.*, "An integrated approach to motion and sound," *Journal of Visualization and Computer Animation* **6**, pp. 109–123, 1993.