SOUND MAPPINGS FOR SURFACE VISUALISATION

Rosane Minghim* and A.R. Forrest
University of East Anglia
School of Information Systems
Norwich NR4 7TJ
U.K.
e-mail: rm@sys.uea.ac.uk, forrest@sys.uea.ac.uk

Abstract

This paper is concerned with the development of a system to support Scientific Visualisation by utilising the sound channel. The mappings presented here are intended to support understanding and interaction with surface data. This is done by using sound signals associated with methods of analysis of surfaces to help the interpretation of surface shape, data, and classification. Several examples of sound mappings are presented and the implications for data interaction are discussed.

Introduction

The complexity and volume of data in Scientific and Engineering Applications have generated a great variety of data display techniques and systems to help the user analyse important aspects of data. Visual presentations, however, pose a number of different problems: the representation is not always adequate, interaction is difficult, and the 2D nature of display devices forces a reduction of dimension in data, with consequent loss of information. Different representations for the same information are necessary to help the user gain new insight and identify different aspects of data [Kel 93].

Until now, the great majority of interfaces to help visualise and interpret data have been exclusively visual. Recent work on sound display of data has shown the special capabilities of sound signals to help interact with data and image in order to produce a better and faster understanding of patterns. This can be used to complement graphical displays in order support identification of aspects of data not immediately available solely from use of visual channel [Kra 94a].

Here we are concerned with the development of sound tools to be used simultaneously with visual tools to represent surface data. It is argued that sound can be specially useful for the scientist and engineer in a way that is supportive and additional to graphical information. The individual sound mappings have specific functions inside the framework of analysis of spatial structures. The intermediate goal is to study the effectiveness of sound to convey information on such data. The future goal is to provide a powerful set of sound mapping techniques to be used in a framework of presentation of multi-dimensional and multi-variate data in all areas of Scientific Visualisation.

Visualisation and Surfaces

In the area of 3D visualisation, methods of presentation can generally be classified as Surface Techniques or Volume Techniques[Wol 93]. The former uses surface representations to gain insight into 3D or higher order information whilst Volume Techniques draw pictures by directly handling information in 3D space. These techniques can be combined or alternated to produce a more intuitive representation of the original data for volumetric data sets.

Although recent efforts in Volume Rendering have become a central point of discussion and development in Scientific Visualisation and it is expected that more modelling and rendering will be based on Volume techniques [Kau 93], surfaces will always play an important role as a basis for data mapping and interpretation. Therefore, improvement of the detection, interpretation and interaction with surface data has continuously been a field where many efforts have been made in Scientific and Engineering applications [Hea 91] [Yun 92] [Yag 92] [Fol 93] [Bec 86]. One single display of a large amount of data can generate a different number of different surfaces. In many cases the correct interpretation of their properties is fundamental.

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* Universidade de São Paulo, ICMSC, CP 668, São Carlos - SP, Brazil, e-mail: rminghim@icmsc.sc.usp.br

There are several aspects of surface data presentation and interaction in which sound display can give good support to graphical techniques. In this research, the approach was to look for ways of improving detection and analysis of complex data by means of the sound channel.

Sound at the Interface

Pioneering work on using sound at the interface [Yeu 80] [Bly 82a, 82b] [Mez 84] and in multi-parameter sound presentation [Pol 54] as well as on the potentiality of presentations of data on two channels simultaneously [Lov 70] have indicated a strong case for the use of sound at the computer interface. Since then, much work has started and some interesting results have been achieved in the field of sound as a tool in computer applications [Bux 90] [Kra 94a]. In work to support the display of *events*, particularly interesting results were obtained by Gaver [Gav 86,89,90,91a, 91b, 93b] and by Blattner et al. [Bla 89] [Bre 93] [Jon 89].

Progress is also starting to be made in the particular field of *data* presentation, especially in multivariate data presentation [Sca 91,94] [Kra 94b] more particularly in systems where graphical display is used in parallel with audio signals [Sca 91] [Smi 91] [Rab 90] [Eva 90] and in systems connected to the area of Scientific Visualisation [Ash 92] [Bla 92]. 3D sound is also expected to play an important rôle in the presentation of multi-dimensional objects [Wen 92]. These results have provided important conclusions and guidelines for the mapping of data onto properties of sound. Some of the advantages and disadvantages of sound presentation are:

Advantages: It is an alternative representation for certain types of information which are difficult to represent graphically; it provides relief for the usually overloaded visual channel; it promotes a sense of engagement; it can be used in monitoring situations outwith the visual field; it is a very advanced human sense for detection; it allows a limited possibility of passive perception; it improves memory support, and it improves access for visually impaired users.

Disadvantages: Insufficient research in the field of auditory interpretation of complex sounds makes it difficult to design proper sonifications; ambiguity may occur when a mapping is generalised; masking is a serious problem; there are difficulties in testing techniques by properly controlled experiments; and training is usually necessary.

Some of the difficulties in working with sound are also shared by graphical representations, but sound perception has particular components very different from visual perception. In particular, sounds usually represent temporal structures while spatial structures are properly represented visually. The mapping of data to sound, however, can encompass both aspects (temporal and spatial). Masking in hearing is also more likely to occur for simple structures than in vision. As in vision, or perhaps more so, resolution of sound signals is relatively poor compared to the continuous nature of some objects in everyday life.

The word *Sonification* has been generally used to indicate the mapping to sound of some sort of numerical data with the intention of conveying information [Sca 94].

MIDI and Sound

The widespread availability of multimedia brings sound synthesis and playback closer to the programmer. From all the possibilities for sound creation, we chose to use MIDI controlled equipment. MIDI is generally used by all digital musical instrument manufacturers and most sound boards and sound software allow for manipulation and creation of MIDI files. Sound *quality* is an important issue in order to explore human capabilities of sound perception and understanding in full. Therefore the choice of sound equipment was based on both flexibility and sound production capabilities.

Perceptual Aspects of Hearing

The stimulus for using sound comes from the amazing capabilities of human hearing to understand information. In everyday life one interacts with sound constantly and there is no reason why the same capabilities should not be applied to complex computer-user interfaces. The sonification method being developed is based on properties of timbre perception [Gre 77,78][Sla 68,85][Wes 79] as well as on relatively new results in perception of complex sounds such as Auditory Scene Analysis and Sound Grouping [McA 93] [Bre 93b] [Wil 94]. Furthermore considerable aid in memorising events and objects is obtained from audio redundancy [Cro 93]. Besides musical listening, the sonifications encompass aspects of everyday hearing, that is, the capabilities of human hearing that allow us to recognise properties of sound sources [Gav 93a].

The Sonification Approach

Based on perceptual aspects of Sound Perception that have previously proved useful, on new results in Perception of complex sound signals, and on Music and Composition, the basic idea is to present the user with multiple simultaneous streams of sound, helping him learn about surface properties by recognising differences and similarities between the different streams. Aspects of curvature and properties of the surface being analysed are responsible for controlling the parameters of the sound synthesis in the mappings we have implemented.

Sound is an extremely rich form of communication as well as very powerful representative tool. Sound as a signal has in itself a great number of structures and nuances that can be manipulated and sensibly detected and interpreted by our perceptual systems.

Most of us have the experience of associating meaning to sound sources and sequences of sounds and have realised that this is a skill that can be easily learned. The decision of what sound to use in each situation depends on some basic issues:

1. The particular sound structures and combinations which can be detected and interpreted by the human hearing apparatus.
2. What meaning is 'naturally' attributed to a particular sound.
3. What new meaning can be attributed to a particular sound or sound structure (or the other way round, for that matter) which can be learned and which does not conflict with preconditioned standards.
4. What sound and meaning association may be used to represent the particular event, action or object under analysis.

Sonification of Surface Data

Graphics Basics

The basic graphics software used in this work to produce surface representations was NCSA Image, available as public domain software from NCSA (National Centre for Supercomputing Applications - USA). All graphic, interactive and sound functions described here were developed as extensions to the Image environment.

NCSA Image offers a number of viewing possibilities for Scientific Data. For volumetric data it implements the Marching Cubes algorithm [Lor 87] for isosurface generation. Volumetric data is organised in a 3D regular grid, with specific real values at each position of the grid.

Direct Sonification of Data

The first sound mapping of data is direct transformation of the original data into sound notes. Sometimes a large amount of information can be obtained by observing the original data straight from the volumetric grid, independent of any particular rendering option. This is cannnot be done using numbers. By sonifying data values, the user is capable of *verifying trends* and *identifying values*_that 'stand out' in the set in a particular region. In addition, the sound helps identification of patterns. In direct sonification the data was quadractically mapped to frequency and volume. High values are mapped to high frequency and low values to low frequency. Two options of sonification are available:

1. all values: all values of the grid are translated into sound notes.
2. isovalues: only the values that correspond to the isosurface values are translated into sound.

If the current data set is partial, two choices exist for each of above options:

1. The program sonifies only the region being shown. This helps analyse relationships between values of the selected region.
2. The program sonifies all data, and the region being shown is highlighted on screen, so that the user can compare the data in the region to the whole of the data set.

In this sonification, sound is partially compensating for the loss of information that happens when isosurfaces are calculated.

The 3D grid is mapped onto a two-dimensional grid so that the user has a 'frame' for interpretation of data position in space. Sounds are displayed as the cursor is moved around the grid. Figure 1a presents the 3D grid and Figure 1b presents an illustration of the 2D grid mapping on the screen. Figure 1c summarises the grid sonification choices.

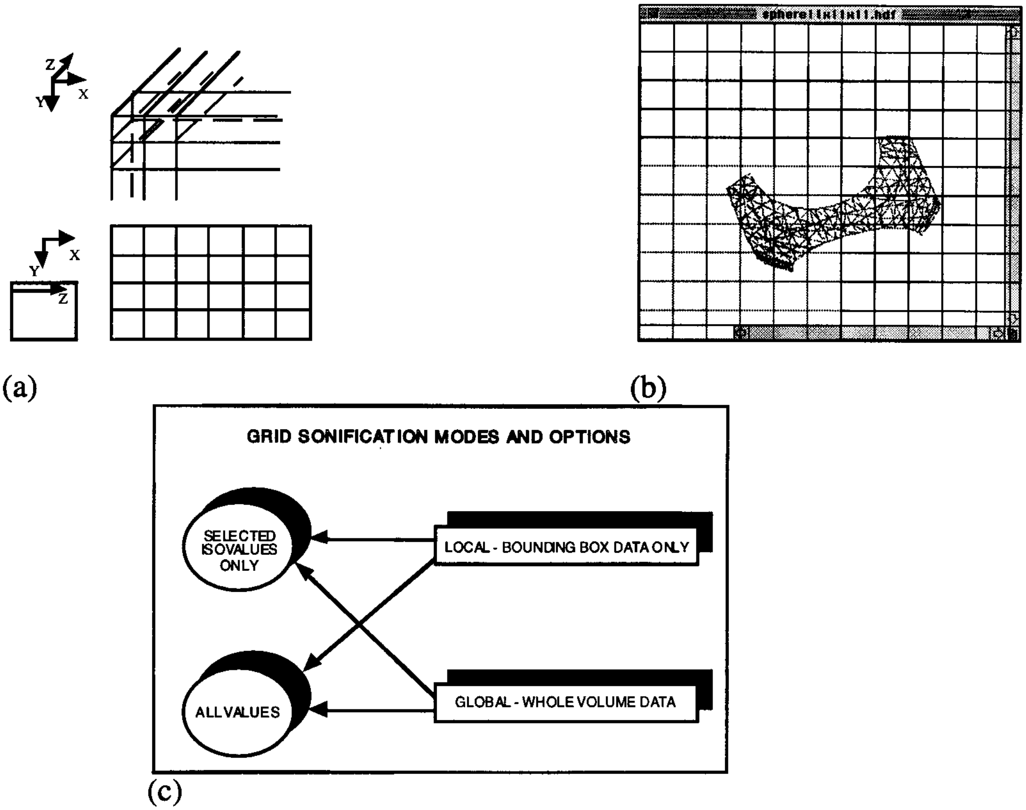
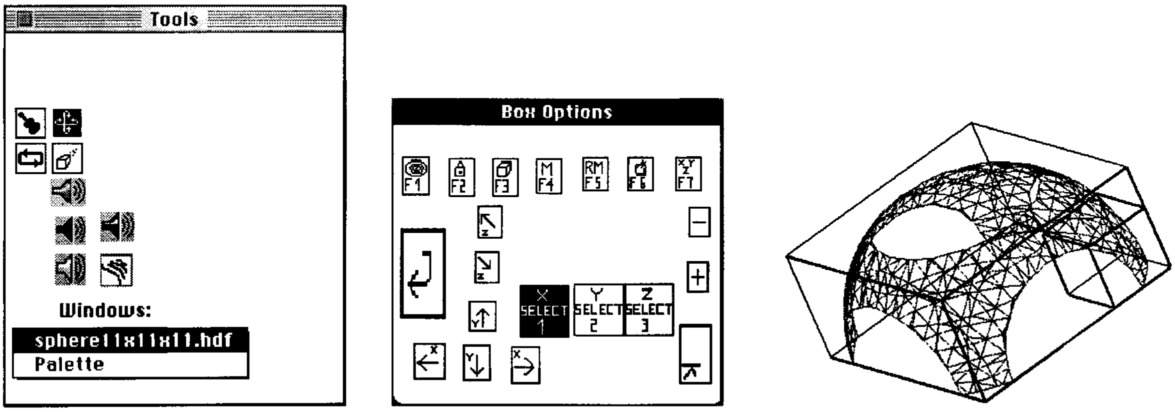


Figure 1: Grid Sonification
(a) Grid mapping from 3D volume to 2D grid on Screen
(b) Screen during the process of grid sonification for a partially presented surface with highlighted sub-grid.
(c) Options for Grid Sonification in SSound.

Volume Scan

Because of the volumetric organisation of many Scientific and Engineering data sets, volumetric 'search' is a useful tool to explore and interact with data. A 'Volume Scan' scheme was developed. After the initial generation of the isosurface(s) associated with the current data, the user can choose to scan the data by 'moving' a volume probe around the volume of the section being analysed. Figure 2b shows the dialogue associated with the volume scan and Figure 2c shows an example view during the volume scan process. Figure 2a shows the options in the Tools dialogue of NCSA Image with the extensions for sound manipulation and isosurface selection.

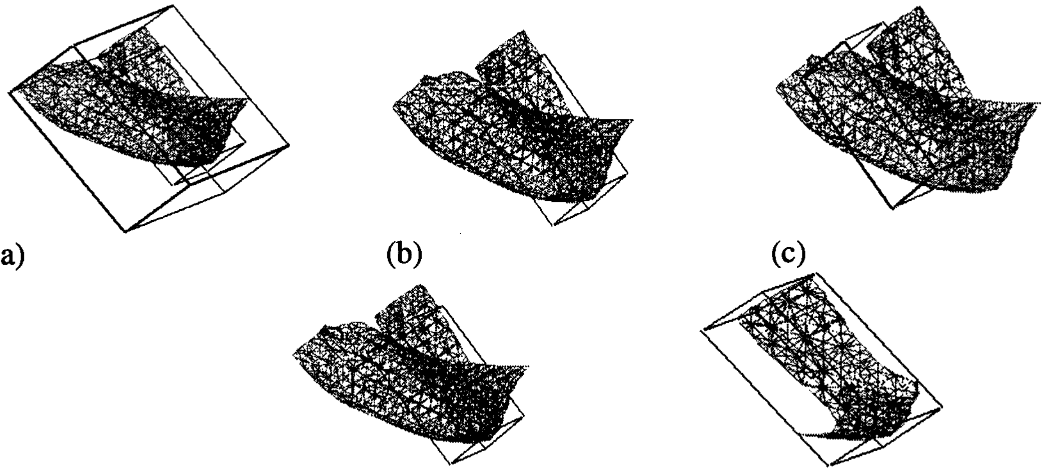
Figure 3 presents a sequence of steps in a typical volume scan operation. User access to functions can be made either by clicking the mouse over the dialogue or by pressing the corresponding functions on the keyboard. The user can move the volume probe around, memorise intermediate positions and 'listen' to sounds that give information about the contents of the volume probe and about the relation of those contents to the global content of the bounding box. Alternatively, the current volume probe can be selected as the next bounding box of the next rendering process. The size of the volume probe can change at any time.



(a) (b) (c)

Figure 2: Volume Scan Image Extensions

(a) NCSA Tools dialogue with SSound Extensions to Image
(b) Dialogue for volume Scan. Corresponding keys on the keyboard have the same functions.
(c) Surface slice with bounding box and volume probe.



(a) (b) (c) (d) (e)

Figure 3: Volume Scan example

(a) Surface rendering after a set of volume scan operations, rendering and view change.
(b) Picture in (a) after erasing bounding box (F3)
Volume probe position and size memorised at this point (F4 - M)
(c) Change of position of box probe
(d) Situation in (b) is restored (F6 - RM)
(e) Volume probe is selected and used as new bounding box in rendering process.

Any of the other shape representation sonifications can be used to analyse the contents of volume probe.

The Score Scheme

The Marching Cubes algorithm defines which voxels in the grid are intercepted by the isosurface by checking the data value in each crossing of the 3D grid against the isosurface value. If in one voxel there are values greater and smaller than the value being checked, the isosurface intercepts that voxel. The number of triangles formed in each voxel is indirectly determined by the number of values that are greater or smaller than the isosurface value.

The Score Scheme uses this latter fact to determine a number of points for each unit voxel as a function of the number of triangles of the surface it contains. This is responsible for determining the 'population' inside a particular voxel, a particular volume probe, or the whole of the bounding box itself.

Volume Scan Sonification

The sonifications that accompany the Volume Scan (functions F1, F6 and F7) are meant to help the user select a portion of the surface he wants to analyse, investigate, render or print. Using vision alone it is confusing to identify the correct position of the probe. Three sonifications are available.

The first sonification presents two musical tones. The first tone indicates 'how much' of the volume probe is occupied, by comparing the number of triangles generated with the maximum number of triangles possible. The second tone indicates 'how much' of the total surface is contained in the current volume probe.

The second sonification also presents two tones. It splits the current volume into two halves, in the currently selected direction (x, y or z). The first tone is presented to the left ear and indicates 'how much' of the content of the current volume probe is in the low range of the selected axis. The second tone is presented to the right ear and presents the same information for the high range part of the selected axis. This is useful to recognise in which 'direction' the majority of the surface is localised, thus 'orienting' the movement of the volume probe. Additionally this function helps to provide 'orientation' of axes for the user to be able to define future changes in view point.

The third sonification is simply a sequential presentation of the second sonification in the three directions (x then y then z) to be employed once the user is practised in recognising the correct meaning of the tones.

All the Volume Scan sonifications map high populations to low frequencies and low populations to high frequencies. This is so because our auditory impression of something 'full' or 'crowded' is represented by low frequencies. Sound intensity is controlled inversely. Additionally, timbre changes with 'population', that is 'richer' timbres for high values and 'thinner' timbres for low values, to provide a perceptually meaningful display. The orientation left->right for stereo field distribution is compatible with western writing convention.

Shape recognition

One of the most important interaction functions with surfaces is the recognition of shape and parameters of form associated with that surface. Several possible descriptions of surfaces are possible, each one giving some particular information about the object. Several of these surface properties were sonified. Figure 4 shows the components of two of those properties.

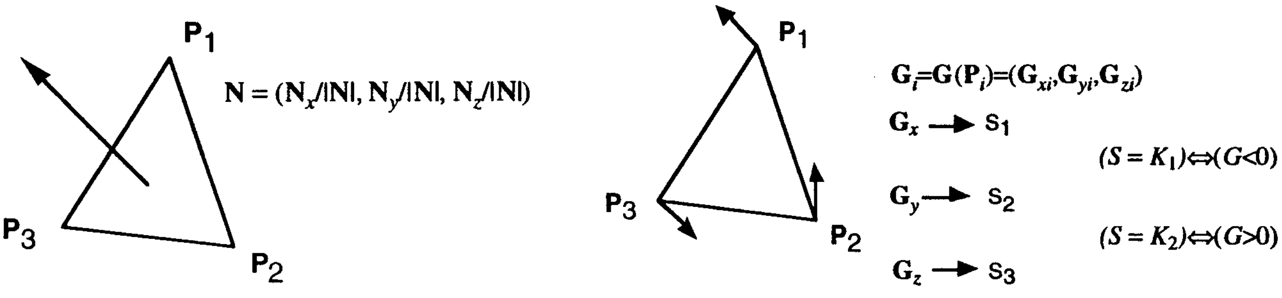


Figure 4: Normal and Gradient Sonification

Gradient Sonification

Changes the surface function can be mapped to sound to convey information about 'unexpected' or invisible changes. By mapping the surface gradient into sound during surface rendering, the user can observe changes in shape which might not be clear visually. Two types of gradient sonification were employed.

In the first, the partial derivatives in the x, y, and z directions were mapped into three sound streams S1, S2 and S3. The streams are created and played back for each vertex of the linear approximation of the surface in question, as they are graphically presented. Each particular stream changes pitch as gradient signal changes. By noticing changes in pitch, the user is able to decide whether there was change in gradient signal and if so, if in one or more directions, by comparing consecutive sounds.

In the second sonification, the streams are created in the same form. However, there is memory between different streams, so that each stream is presented continuously, unless a change in gradient signal occurs, in which case only the correspondent streams change. This generates the very interesting effect of causing changes in rhythm as well as frequency depending on how much change occurs.

Normal Sonification

In a polygonal definition of objects, normally the process of rendering the final image is simplified and can be done in real time. However, close examination of portions of surfaces can cause visual ambiguity in direction of parts of the surface.

In this sonification, sound is used to convey information of change of position from one polygon to the next. The differences in coordinates in the x, y and z directions are presented in a chord, where changes in z controls pitch and changes in x and y control stereo balance. By hearing the sound the user can detect the nature of the position change from one polygon to the other, depending on balance (if the sound moves from right to left, left to right, or not at all).

This sonification is independent of the orientation of the surface with respect to the observer. The same mapping can be changed to reflect viewpoint by decomposing the normal coordinates in orthogonal directions with respect to the perspective plane.

Curvature Sonification

Curvature information for surfaces can be used to generate sound parameters to help the user identify and 'visualise by ear' aspects of shape. The shape of the surface at a point generates the basic sonification unit that is applied to the presentation and interaction with the whole of the surface according to the rendering process.

Assuming the surface is given some adequate parametric representation:

$$\mathbf{x}(u,v) = f_1(u,v)\mathbf{e}_1 + f_2(u,v)\mathbf{e}_2 + f_3(u,v)\mathbf{e}_3,$$

it is possible to calculate, for each point P:

First Fundamental Form

$$I = d\mathbf{x} \bullet d\mathbf{x} = Edu^2 + Fdudv + Gdv^2$$

$$E = \mathbf{x}_u \bullet \mathbf{x}_u$$

$$F = \mathbf{x}_u \bullet \mathbf{x}_v$$

$$G = \mathbf{x}_v \bullet \mathbf{x}_v$$

Second Fundamental Form

$$II = -d\mathbf{x} \bullet d\mathbf{N} = Ldu^2 + 2Mdudv + Ndv^2$$

$$L = -\mathbf{x}_u \bullet \mathbf{N}_u$$

$$M = -\frac{1}{2}(\mathbf{x}_u \bullet \mathbf{N}_v + \mathbf{x}_v \bullet \mathbf{N}_u)$$

$$N = -\mathbf{x}_v \bullet \mathbf{N}_v$$

Using these relationships it is possible to calculate a number of curvature values, some of which are more useful than others in conveying shape information [Sei 92][Ric 88]. The sonifications were based on the following curvature calculations:

Mean Curvature:

$$H = \frac{1}{2}(\kappa_1 + \kappa_2) = \frac{EN + GL - 2FM}{2(EG - F^2)}$$

Gaussian Curvature:

$$K = \kappa_1 \kappa_2 = \frac{LN - M^2}{EG - F^2}$$

Normal Curvature:

$$\kappa_n = \frac{L(du/dt)^2 + 2M(du/dt)(dv/dt) + N(dv/dt)^2}{E(dv/dt)^2 + 2F(du/dt)(dv/dt) + G(dv/dt)^2}$$

where (dv/dt) represents a particular direction at point P.

In addition, a sonification based on geodesic curvatures was implemented.

Christoffel symbols of the second kind:

$$\Gamma^1_{11} = \frac{GE_u - 2FF_u + FE_v}{2(EG - F^2)} \quad \Gamma^1_{12} = \frac{GE_v - FG_u}{2(EG - F^2)} \quad \Gamma^1_{22} = \frac{2GF_v - GG_u - FG_v}{2(EG - F^2)}$$

$$\Gamma^2_{11} = \frac{2EF_u - EE_v + FE_u}{2(EG - F^2)} \quad \Gamma^2_{12} = \frac{EG_u - FE_v}{2(EG - F^2)} \quad \Gamma^2_{22} = \frac{EG_v - 2FF_v + FG_u}{2(EG - F^2)}$$

$$\Gamma^k_{ij} = \Gamma^k_{ji}$$

Γ^k_{ij} is dependent only on the first fundamental coefficients and their derivatives

Geodesic curvature vector of a curve C on a Surface S at a point P:

$\mathbf{x} = \mathbf{x}(s) = \mathbf{x}(u(s), v(s))$ is a natural representation of C.

$\mathbf{k}_g = (\mathbf{k} \bullet \mathbf{U})\mathbf{U}$

where **U** is the vector in the tangent plane at P that forms a right-handed orthonormal triad $(\mathbf{T}, \mathbf{U}, \mathbf{N})$.

T is the unit tangent of C at P. **k** is the curvature vector of C at P.

Geodesic Curvature

$k_g = \mathbf{k} \bullet \mathbf{U} = [\mathbf{tkN}]$

$$k_g = [\Gamma^2_{11}(\frac{du}{ds})^3 + (2\Gamma^2_{12} - \Gamma^1_{11})(\frac{du}{ds})^2(\frac{dv}{ds}) + (\Gamma^2_{22} - 2\Gamma^1_{12})\frac{du}{ds}(\frac{dv}{ds})^2$$
$$-\Gamma^1_{22}(\frac{dv}{ds})^3 + \frac{du}{ds}\frac{d^2v}{ds^2} - \frac{d^2u}{ds^2}\frac{dv}{ds}]\sqrt{EG - F^2}.$$

Various mappings from curvature values to sound were implemented and a combination of these sounds are presented when lines on the surface are drawn on screen. Several options for drawings and combinations of drawings are available in association with the sonifications.

The primary parameters of sound used in curvature mapping were varied. In general, pitch represented change in curvature value, stereo balance represented change in curvature vector position, and those properties were combined with variation in volume, timbre and tempo or rhythm to indicate surface shape change. Special cases in shape variation are indicated by special standard timbres.

Geodesics

A curve C along which $\mathbf{k}_g = \mathbf{0}$ is called a *geodesic line* or simply *geodesic*.

Setting $(\frac{du}{ds})_0 = \frac{du_0}{\lambda}$ and $(\frac{dv}{ds})_0 = \frac{dv_0}{\lambda}$, where $\lambda = E_0 du_0^2 + 2F_0 du_0 dv_0 + G_0 dv_0^2$,

The solution of the equations:

$$\frac{d^2u}{ds^2} + \Gamma^1_{11}(\frac{du}{ds^2})^2 + 2\Gamma^1_{12}\frac{du}{ds}\frac{dv}{ds} + \Gamma^1_{22}(\frac{dv}{ds})^2 = 0$$

$$\frac{d^2v}{ds^2} + \Gamma^2_{11}(\frac{du}{ds})^2 + 2\Gamma^2_{12}\frac{du}{ds}\frac{dv}{ds} + \Gamma^2_{22}(\frac{dv}{ds})^2 = 0$$

with initial conditions:

$$u(0) = u_0,\ v(0) = v_0,\ \frac{du}{ds}(0) = (\frac{du}{ds})_0,\ \frac{dv}{ds}(0) = (\frac{dv}{ds})_0$$

is the geodesic line $\mathbf{x}(u(s), v(s))$ through an arbritrary point $\mathbf{x}(u_0, v_0)$

in the direction $(\frac{du}{ds})_0 : (\frac{dv}{ds})_0$

Drawing of geodesics on a surface gives a good indication of shape since they are lines of minimum length on a surface and we tend to interpret lines as surface curvature lines or geodesics [Ste 88]. Therefore the sonification based on geodesics should prove useful in sound mappings to identify shape.

In the neighbourhood of a point P on a surface, there exists one and only one geodesic through P in any given direction. So, given a point and a specific direction, it is possible to calculate (or approximate) a geodesic in that direction.

Geodesic Sonification

Once the geodesic is defined, mapping to frequency is executed to create the serialisation of the surface 'audible image' using function progression over the geodesic. This mapping is combined by *timing* and *intensity* control so that increasing values give the impression of 'slow' progression while decreasing values reflect 'speeding up'.

Memory of Shape

A further mapping is created to associate a particular sound (duration of approximately 6 seconds) to each particular surface. The user has the options of creating a 'sound signature' or an 'earcon' of the surface so that by listening to the signature he can remember shape information. This identity can be used to help catalogue compressed images of surfaces with accompanying sound.

Timbre Control and Perception Reinforcements

All the sound parameters mentioned above for the sonifications were the basic sounds. Their choice relied on the perceptual properties of human hearing, that is, what aspects and combinations of aspects give the user better perception of the sound signal. In many cases, however, sound stimuli can be misunderstood due to masking, unexpected recombination of sounds, or the fact that the perception of a combined sound is not obtained by the perception of parts. Thus, several tricks can be used to ensure a good rate of recognition of the sounds. In every sonification, sound properties were reinforced by proper control of volume, effects, and timbre.

The control of timbre is an essential part of a sonification, since it is the timbre property of sound which allows us to identify properly the source in everyday life and is therefore the most meaningful of all properties, apart from being itself a multi-dimensional property. Thus a number of 'timbre scales' were prepared so that it is possible to change timbre during the sonifications. Movements 'up the scale' select a richer timbre while 'down the scale' movements perform changes to a softer (or thinner) timbre. This association is used throughout the sound functions so as to use the nature of the timbre to suggest the nature of the event or data.

The platform

This work was implemented on an Apple Macintosh Quadra 950, in MPW C, with the sound being produced by a KORG Wavestation SR Synthesiser Module via a MIDI interface.

Conclusions

Once the effectiveness of sound representation for 3D form, shape and interaction is established, it is expected that it might be developed as an integral part in most visualisation systems. The help that may come from sound to the whole process of data understanding and manipulation is invaluable. It contributes towards relieving the visual channel, usually overloaded by graphical information, to detect and interpret 'hidden' or missing data, and to engage the user to the task at hand. Research in the use of sound as an interaction tool, as opposed to simple accompaniment of animations, is just beginning. However, the development and use of sound tools has in most cases proved that effort worthwhile. The mappings involving shape description of surfaces can be used not only as a direct tool for surface interaction but also to produce sound in situations that can be modelled by the same type of equations and structures. The next step in the research involves use of this approach for higher dimensional of data.

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