Two New Approaches to the Simulation of Acoustic Spaces

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ABSTRACT

The "traditional" models for room-simulation algorithms rely upon idealized assumptions which greatly simplify acoustic reality. The justification for these assumptions is to decrease to a manageable level the complexity involved in simulating natural spaces. This paper explores two algorithms where concerns for efficiency and computational complexity were not major factors. The first algorithm uses fractal techniques to generate delays intended to model the reflections of sound from a complex surface (such as a canyon wall). The second algorithm simulates the acoustic response characteristics of arbitrarily-shaped rooms by modelling the action of "packets of air" contained within the rooms.

A truly wonderful capability of digital synthesis and signal processing is the ability to simulate an acoustic space. The creation of an auditory ambience can be one of the most evocative tools a computer musician has at his or her disposal. Much research has gone into designing better and more efficient methods for producing the impression of acoustic space, with the bulk of the research effort concentrated on simulating large, indoor rooms. The "standard" paradigm for this simulation is to synthesize the initial response of the room by modelling the primary (and often secondary) wall reflections using a ray-tracing approach, and then recreate the subsequent diffuse reflections with a recirculating reverberator scheme. This method is quite good, both in the fact that it captures most of the important acoustic cues used to decode the aural experience of space, and also because the implementation is relatively straightforward and fast (see [Moore, 1990] for a good discussion of this technique). There are some limitations to the model, however. It is difficult to simulate rooms of arbitrary shape and size, or rooms with objects placed at locations which would interfere with a spreading sound wavefront. It is also nearly impossible to create the sensation of an outdoor space using the ray-tracing/diffusion method.

The Fractal Reverberator -- Outdoor Spaces

While it seems extremely difficult in principle to simulate the sound of "the outdoors" -- so much is dependent upon information about the environment gained through other sense modalities -- it should be possible to recreate the sound of certain specific outdoor features. In particular, the sound of acoustic reflections from canyon or mountain walls, or the diffuse sound of reverberation in a forest could be modelled using discrete delay lines with delay times corresponding to a reconstruction of the reflective surfaces present in the actual outdoor environment (see figure 1). If the delay line lengths were based upon some physical system, it would represent an extreme case of the ray-tracing approach, where every delay corresponded to a sound waveform vector from a single reflective surface. By borrowing some techniques from the graphical simulation of landscapes using fractal algorithms [Mandelbrot, 1977], it is possible to greatly simplify the calculation of the delay line lengths.

The basic algorithm for generating the delay lengths is straightforward: simply take a pattern of delays

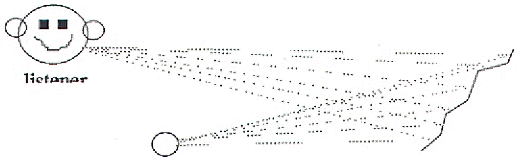

Figure 1: Reflections from a natural surface

(with corresponding attenuations) and repeat it recursively within the delay intervals of the original pattern (see figure 2). Used with no modification of the original pattern in the recursing process, this technique will yield a variety of interesting comb filter-like effects. The pitch of the comb will be related to a common delay time generated by the recursion. Rarely does "the outdoors" sound like comb filters, however. If the pattern is modified during the recursion, a variety of delay effects, including the effect of an outdoor space, can be achieved.. The beauty of fractal algorithms is that they seem to capture the undulations and indentations of natural surfaces with a high degree of accuracy. Thus, realistic delays from a simulated mountain wall or forest can be generated quite easily using this technique.

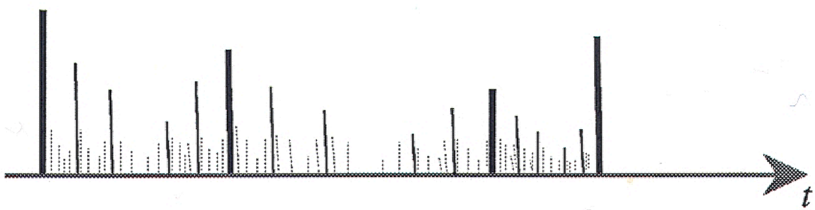

Figure 2: Fractal delay pattern

Direct Simulation of Room Acoustics

As good as the ray-tracing/diffusion model is for creating a room-like ambience, it has some limitations. The ray-tracing technique used to generate the initial room response characteristics is based upon idealized assumptions about room geometry. Rooms which are constructed as simple polygons (usually rectangles) make the computation of the waveform vectors relatively simple. Any additional "features" in the room greatly increase the complexity of the ray-tracing approach. Also, because the initial reflections from the walls of the simulated room are thought of as single vectors, it is practically impossible to create a wall with varying acoustic properties (draperies, wall-hangings, etc.).

The direct simulation approach allows for the design of rooms with arbitrary shapes and varying acoustical characteristics. It is also quite simple to insert objects with acoustic properties anywhere in the room. The technique works by modelling the entire acoustic waveform as it expands and reflects through the room. A room is thought of as an array of nodes. Each node represents a "packet" of air. Sound propagates through the room by passing samples through each node to neighboring nodes in the direction of the wavefront travel (see figure 3). Every node delays the sound according to the width of the "packet" represented by the node. Other attributes can by stored on the individual node-objects, thus making it easy to create different acoustical features. Sound sources and receivers can also be inserted as attributes of particular node-objects.

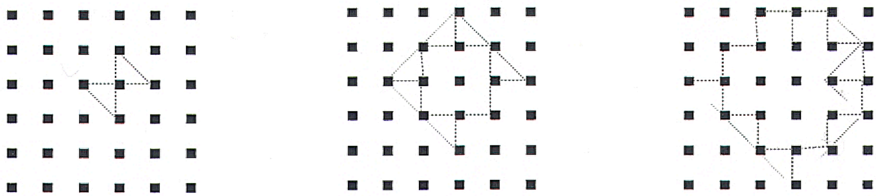

Figure 3: Waveform travelling through nodes in direct simulation

Difficulties

If the grid for the nodes in the direct simulation model is regular (as in figure 3), then the resulting sound will have a sharp resonance corresponding to the comb filter created by the sound path delay of each node. In this case, sound would always be delayed by a multiple of the "unit" node delay. This effect can be eliminated by deforming the node matrix or by randomizing the node pattern throughout the room. Another solution is to make the nodes represent a packet of air exactly one sample wide.

The problem with this second solution is the general problem with both the fractal reverberator and the direct simulation room model. Both are not 'efficient' in any sense of the word. The fractal reverberator typically generates hundreds of taps on a delay line which must be accessed for each sample computed. The direct room simulator requires an enormous amount of computation, since every single node must be updated for every sample. On a Sun 3/280 running with a Sky floating point accelerator, a moderate-sized room required 50,000 cpu seconds to generate one second of sound. It is doubtful that either of these algorithms will see widespread use in the immediate future.

References

Moore, F. R., *Elements of Computer Music*, Prentis Hall, Englewood, NJ, 1990.

Mandelbrot, B., *The Fractal Geometrry of Nature*, W. H. Freeman and Company, New York, 1977.