Interactive Acoustic Modeling of Complex Environments

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Abstract

A primary challenge in acoustic modeling is computation of reverberation paths from sound sources fast enough for real-time auralization. This paper describes a beam tracing method based on precomputed spatial subdivision and "beam tree" data structures that enables real-time acoustic modeling and auralization for sound sources at fixed locations in interactive virtual environment applications. The proposed beam tracing method: 1) supports evaluation of reverberation paths at interactive rates, 2) scales to compute high-order reflections and large environments, and 3) extends naturally to compute paths of diffraction and diffuse reflection efficiently.

1 Introduction

Interactive computer-aided acoustic modeling tools are important for design and simulation of three-dimensional environments. For instance, an architect might use an interactive tool to evaluate the acoustic properties of a proposed auditorium. Or, a person might experience the illusion of moving through a 3D virtual environment while immersed in simulated imagery and spatialized sounds.

The main challenge in interactive geometric acoustic modeling is computation of reverberation paths from a sound source to a receiver [7]. As sound may travel from source to receiver via a multitude of reflection, transmission, and diffraction paths, accurate simulation is extremely compute intensive. Prior approaches to geometric acoustic simulation have used the image source method [1, 2], whose computational complexity grows with O(n^r) (for n surfaces and r reflections), or ray tracing methods [6], which are prone to sampling error and require a lot of computation to trace many rays. Due to the computational complexity of these methods, interactive acoustic simulation has generally been considered impractical for complex environments [5].

We have developed a beam tracing method that computes specular reflection and transmission paths from fixed sources in large polygonal models fast enough to be used for auralization in interactive virtual environment systems. The most important contribution of this paper is the idea of precomputing spatial data structures that encode all possible transmission and specular reflection

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paths from each audio source and then using these data structures to compute reverberation paths to an arbitrarily moving observer viewpoint for real-time auralization during an interactive user session. Our algorithms for construction and query of these data structures have the unique features that they scale well with increasing numbers of reflections and global geometric complexity, and they extend naturally to model paths of diffraction and diffuse reflection. We have incorporated these algorithms and data structures into a system that supports real-time auralization and visualization of large virtual environments [3].

2 Beam Tracing Algorithm

We partition our system into four distinct phases (see Figure 1), two of which are preprocessing steps that execute off-line, while the last two execute in real-time as a user interactively controls an observer viewpoint moving through a virtual environment.

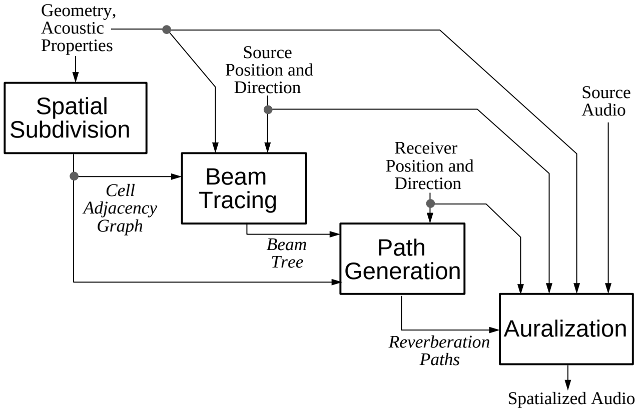

Figure 1: System organization.

First, during the *spatial subdivision phase*, we precompute spatial relationships inherent in the set of polygons describing the environment and represent them in a cell adjacency graph data structure that supports efficient traversals of space.

Second, during the *beam tracing phase*, we use the spatial subdivision to accelerate traversals of space in our beam tracing algorithm. Beams are traced through the cell adjacency graph via a recursive depth-first traversal starting in the cell containing the source point (see Figure 2). Adjacent cells are visited recursively while a beam representing the region of space reachable from the source by a sequence of cell boundary reflection and transmission events is incrementally updated. As the algorithm traverses a cell boundary into a new cell, the current convex pyramidal beam is “clipped” to include only the region of space passing through the convex polygonal boundary polygon. At reflecting cell boundaries, the beam is mirrored across the plane supporting the cell boundary in order to model specular reflections.

While tracing beams through the spatial subdivision, our algorithm constructs a *beam tree* data structure [4] to be used for rapid determination of reverberation paths from the source point later during the path generation phase. The beam tree corresponds directly to the recursion tree generated during the depth-first traversal through the cell adjacency graph. Each node of the beam tree stores: 1) a reference to the cell being traversed, 2) the cell boundary most recently traversed (if

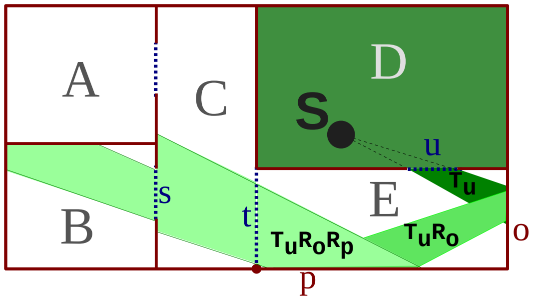

Figure 2: Beam tracing algorithm.

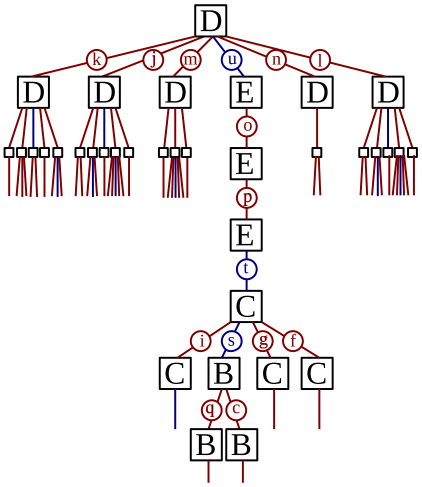

Figure 3: Beam tree data structure.

there is one), and 3) the convex beam representing the region of space reachable by the sequence of reflection and transmission events along the current path of the depth-first traversal. To further accelerate reverberation path generation, each node of the beam tree also stores the cumulative attenuation due to reflective and transmissive absorption, and each cell of the spatial subdivision stores a list of "back-pointers" to its beam tree nodes. Figure 3 shows a partial beam tree corresponding to the traversal shown in Figure 2.

Third, during the *path generation phase*, in which a user (receiver) navigates through the virtual environment interactively, reverberation paths from a particular source point to the moving receiver are generated at interactive rates via lookup in the beam tree data structure. First, the cell containing the receiver point is found by logarithmic-time search of the BSP. Then, each beam tree node, T, associated with that cell is checked to see whether the beam stored with T contains the receiver point. If it does, a viable ray path from the source point to the receiver point has been found, and the ancestors of T in the beam tree explicitly encode the set of reflections and transmissions through the boundaries of the spatial subdivision that a ray must traverse from the source to the receiver along this path (more generally, to any point inside the beam stored with T).

The attenuation, length, and directional vectors for the corresponding reverberation path can be derived quickly from the data stored with the beam tree node, T. Specifically, the attenuation due to reflection and transmission can be retrieved from T directly. The length of the reverberation path and the directional vectors at the source and receiver points can be easily computed as the source's reflected image for this path is stored explicitly in T as the apex of its pyramidal beam. The actual ray path from the source point to the receiver point can be generated by iterative intersection with the reflecting cell boundaries stored with the ancestors of T.

Finally, during the *auralization phase*, each source-receiver impulse response is generated by adding one pulse corresponding to each distinct path from the source to the receiver. The delay associated with each pulse is given by L/C, where L is the length of the corresponding reverberation path, and C is the speed of sound. Since the pulse is attenuated by every reflection and dispersion, the amplitude of each pulse is given by A/L, where A is the product of all the reflectivity and transmission coefficients for each of the reflecting and transmitting surfaces along the corresponding reverberation path. The (anechoic) input audio signal is auralized by convolving it with the binaural impulse responses to produce a stereo spatialized audio signal.

The key idea in this method is that it is possible to use an off-line precomputation to construct a data structure (a beam tree) encoding potential reverberation paths from each static source location and use that precomputed data structure to compute reverberation paths to a moving receiver quickly for auralization.

3 Results

The 3D data structures and algorithms described in the preceding sections have been implemented in C++ and run on Silicon Graphics and PC/Windows computers. During experimentation, we have found that our algorithm supports generation of specular reflection paths between a fixed source and any (arbitrarily moving) receiver at interactive rates in several complex environments. For instance, after 1 minute of precomputation for each source, we are able to compute up to 8th order specular reflection paths to an arbitrarily moving receiver in a large building with more than 10,000 polygons approximately 6 times per second [3].

4 Conclusion

We have developed data structures and algorithms that accelerate computation of reverberation paths from a source position in complex virtual environments. Our beam tracing algorithm scales well to large environment because it traverses a precomputed spatial subdivision represented as an adjacency graph of convex polyhedral cells. Our path generation algorithm executes at interactive rates because it utilizes a precomputed beam tree that encodes regions of space reachable by different sequences of reflections and transmissions. In comparison to previous acoustic modeling approaches, this method supports a unique combination of scale, accuracy, and interactivity. We believe that further work on *interactive* acoustic modeling is warranted as it opens up a plethora of interesting new applications and research possibilities.

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