Modeling Sound Reflection and Diffraction in Architectural Environments with Beam Tracing

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ABSTRACT

This paper describes and analyzes a beam tracing method for computing sound propagation paths from sound sources to receivers in architectural environments. The algorithm traces polyhedral beams from the location of each sound source through a precomputed data structure encoding spatial adjacencies. The main features of the method are: 1) it enumerates all potential sequences of specular reflection, diffraction, and transmission up to user-specified termination criteria, 2) it enables evaluation of early propagation paths at interactive rates, and 3) it scales to support large, "densely-occluded" architectural environments. It is being used to support real-time auralization in immersive virtual environment applications.

1. INTRODUCTION

Geometric acoustic modeling tools are commonly used for design and simulation of 3D architectural environments. For example, acousticians use CAD tools to evaluate the acoustic properties of proposed auditorium designs, factory planners predict the sound levels at different positions on factory floors, and video game designers provide spatialized sound effects in interactive virtual environment systems.

One major challenge in geometric acoustic modeling is accurate and efficient computation of early sound propagation paths. As sound travels from source to receiver via a multitude of paths containing reflections, transmissions, and diffractions, accurate simulation is extremely compute intensive. Most prior systems for computing early reflections have been based on image source methods [Allen79, Borish84] and/or ray tracing [Krockstadt68], and therefore they do not generally scale well to support large 3D environments, and/or they fail to find many significant propagation paths (e.g., ones due to diffractions).

In this paper, we describe a beam tracing method that computes early propagation paths in 3D models of architectural environments. An important feature of this method is that it finds *all* paths combining transmission, specular reflection, and edge diffraction up to user-specified termination criteria (e.g., all paths arriving within a certain time delay) without sampling or exhaustive enumeration. As a result, it ensures that no propagation paths are missed due to undersampling, and it executes efficiently for large 3D polygonal models. We currently use this method to simulate simple architectural spaces and to spatialize sounds in interactive virtual environment applications.

The remainder of the paper is organized as follows. Section 2 briefly reviews related work in geometric acoustic modeling. Section 3 contains a description of our beam tracing method. Sections 4 and 5 present experimental results. Finally Section 6 contains a brief conclusion, along with a discussion of applications, limitations, and topics for future work.

2. BACKGROUND AND RELATED WORK

The problem of modeling sound propagation can be solved using the Helmoltz-Kirchoff integral equation, which expresses the wave field at every point in space in terms of the wave field at other points (or equivalently on surrounding surfaces). The main challenge in solving this equation is that the wave field has discontinuities due to occlusions, diffractions, and specular highlights, which induce large variations over small portions of the integration domain (i.e. surfaces and/or directions). Due to these discontinuities, no analytic formula can be applied to compute the wave field at a given point in the general case, and solution methods must rely upon sampling or subdivision of the integration domain into separate parts that can be treated efficiently and accurately. Traditionally, four approaches have been used to address this problem: boundary element methods, Monte Carlo path tracing, ray tracing, and beam tracing [Kleiner93, Kuttruff91].

Boundary element methods find an approximate solution to the wave equation by solving the system of equations resulting from discretizing the surfaces into patches [Moore84]. The major problem with this method is that the surface mesh must be fine enough to account for phase differences. Also, it is difficult to adapt the mesh of each surface to capture the irregularities and discontinuities of the wave field, and it is expensive to compute extended form factors, solve three-point transport problems, or store directional basis functions for scenes with non-diffuse surfaces. These problems make boundary element methods impractical for sound simulations at all but the lowest audible frequencies.

Monte Carlo path tracing methods [Kajiya86] solve the integral equation by sampling randomly generated paths from the source to the receiver. In order to avoid large errors (variance) in the computed solutions, the sampling density must fit the shape of the integrand, which is difficult to achieve due to discontinuities in the wave field. Although methods have been proposed to achieve robust and efficient integration, it is still difficult to find the most significant paths, and a large number of samples are needed to render solutions with sufficient fidelity. Since each sample requires a separate set of ray-scene intersection tests, and many of the samples are rejected due to occlusions, these methods generally require long compute times, and thus they are not suitable for interactive applications.

Ray tracing methods [Krockstadt68] find propagation paths between a source and receiver by generating rays emanating from the source (or receiver) position and following them individually as they propagate through the environment. Although this method is very general and simple to implement, it is subject to aliasing artifacts as the space of rays is sampled discretely [Lehnert93]. For instance, receiver position and diffracting edges are often approximated by volumes of space (in order to admit intersections with infinitely thin rays), which can lead to false hits and paths counted multiple times. More often, important propagation paths may be missed by all samples. Moreover, ray tracing is very compute intensive, usually taking minutes to hours to compute a receiver-dependent solution.

Image source methods [Allen79, Borish84] compute specular reflection paths by considering *virtual sources* generated by mirroring the location of the audio source over each polygonal surface of the environment. The key idea is that a direct path from each virtual source has the same directionality and length as a specular reflection path. Thus, specular reflection paths can be modeled up to any order by recursive generation of virtual sources. This method is simple for rectangular rooms [Allen79]. However, in general environments, N^R virtual sources must be generated for R reflections over N polygons. Moreover, for every new receiver location, each of the $O(N^R)$ virtual sources must be checked to see if it is visible to the receiver, since the specular reflection path might be blocked by a polygon or intersect a mirroring plane outside a polygon [Borish84]. As a result, this method is practical only for computing very few specular reflections from stationary sources in simple environments.

Beam tracing methods [Heckbert84, Dadoun85] find propagation paths from a source by tracing beams (i.e., bundles of rays) through a 3D polyhedral environment. In general, a set of beams is constructed that completely covers the space of rays from the source. For each beam, polygons are considered for intersection in order from front to back. As each intersecting polygon P is detected, the original beam is clipped to remove the shadow region. Additionally, new beams may be created representing various types of surface scattering. For instance, a transmission beam may be constructed matching the shadow region, a specular reflection beam may be constructed by mirroring the transmission beam over the plane supporting P, and a diffraction beam may be constructed to represent scattering from a wedge. These new beams are then traced through the environment until some application-specific termination criteria are met (e.g., a maximum propagation delay). The main advantage of this approach is that it finds all propagation paths up to the termination criteria. The disadvantage is that the geometric operations required for beam tracing are more complex than for the individual paths.

3. BEAM TRACING APPROACH

Our approach is a hybrid between beam tracing and path tracing. The general strategy is to trace beams that partition the space of rays into topologically distinct bundles corresponding to different sequences of scattering events at surfaces of the 3D scene (*propagation sequences*), and then use them to guide sampling in a path tracing algorithm. Conceptually, the approach proceeds in two phases. In the first phase, beams are traced to enumerate potential propagation sequences comprising different permutations of diffuse reflections, specular reflections, diffractions, and transmissions. The result of this phase is a set of conservative beams, each containing the bundle of rays potentially traveling along a different propagation sequence. In the second phase, the wave field is evaluated at a point by solution methods that use traced beams to identify subdomains for analytic integration and for structured sampling in a path tracing algorithm. The motivation for this approach is that attributes of a relatively small number of beams traced during the first phase can provide useful information about the wave field that can be used to guide and accelerate evaluation of samples during the second phase. Some advantages of this approach are as follows:

- **Fast Enumeration of propagation sequences:** beam tracing provides an efficient method for finding potential sequences of surface scattering events, without sampling as in ray tracing or path tracing, and without exhaustive search of all surface permutations, as in image source methods. In particular, it provides a deterministic algorithm to enumerate *every* propagation path up to a specified termination criteria without risk of undersampling errors (unlike ray tracing), and it scales to support large architectural environments with many surfaces (unlike image source methods).

- **Spatial coherence in ray intersections:** a priori beam tracing can improve the efficiency of multiple ray intersection tests. Due to coherence in ray space, each beam-surface intersection represents an infinite number of ray-surface intersections. Thus, once a beam has been traced along a certain sequence of surface intersections, generating ray paths following the same sequence becomes a sampling problem rather than a combinatorial problem, and the expensive computation of casting rays through a scene can be avoided for individual samples.

- **Progressive refinement:** characteristics of beams can be used to guide progressive refinement and importance sampling strategies. For instance, bounded estimates of the path lengths or the energy carried by different beams can be used to prioritize beam tracing steps [Funkhouser99, Min00] and/or to determine the number of samples to evaluate for each propagation sequence.

- **Interactive path generation:** the result of a beam tracing computation can be computed off-line and stored in a data structure (e.g., a beam tree) for later evaluation of propagation paths at interactive rates. This feature enables visualization and/or auralization of sound traveling from a stationary source to an arbitrarily moving receiver location (or vice versa) in an interactive application [Funkhouser98].

The challenge of implementing a beam tracing system is to perform polygon sorting, polygon intersections, and beam transformations efficiently and robustly. Although several methods have been proposed to accelerate these geometric operations, including ones based on BSP-trees [Dadoun85], cell adjacency graphs [Fortune99, Funkhouser98, Teller92], and layers of 2D triangulations, there is still work to be done for general scattering phenomena (e.g., diffraction and diffuse reflection) and general 3D scenes (e.g., environments with fine detail).

This paper outlines our recent work on using beam tracing for modeling early propagation paths combining specular reflection and edge diffraction in interior architectural environments. The next section briefly describes our methods, while the following two sections present results of experiments evaluating its efficiency and accuracy. Please see [Funkhouser98, Funkhouser99, Tsingos01] for more details).

4. SIMULATION SYSTEM

Our simulation system takes as input: 1) a model of a 3D environment described as a set of polygons with frequency-dependent impedances or bidirectional scattering filters, 2) a model of a speaker described by a location and angular radiation pattern, and 3) a model of a microphone described by a location and optional angular directivity pattern. The result of the simulation is an estimated impulse response.

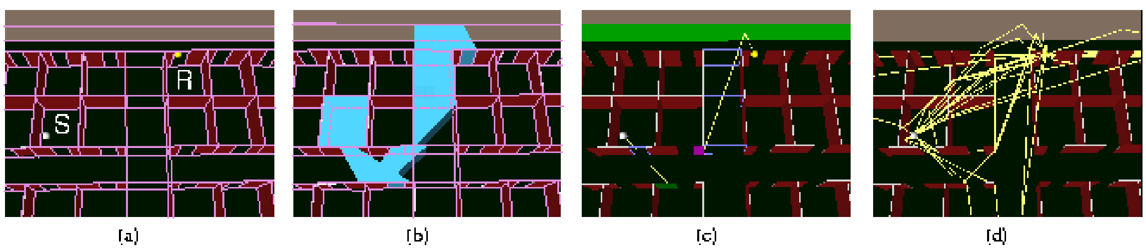


Figure 1: Overview of simulation process: a) Virtual environment (office cubicles) with source S, receiver R, and spatial subdivision marked in pink. (b) Sample reflected and diffracted sound beam (cyan) reaching the receiver. (c) Shortest propagation path generated for the corresponding sequence of reflecting surfaces (green), transmitting portals (purple), and diffracting wedges (magenta). (d) The procedure repeated for multiple beams reaching the receiver.

The system executes in four steps, as shown in Figure 1. In the first step, we build a spatial subdivision data structure representing a binary space partition of 3D space into convex polyhedral cells. The purpose of this step is to decompose space into cells whose boundaries are aligned with polygons of the 3D input model and whose adjacencies are stored explicitly in a graph structure in order to enable efficient traversals of 3D space during beam tracing.

In the second step, we trace the convex polyhedral beams representing different propagation sequences through cells of the spatial subdivision. The traversal starts in the cell containing the speaker location with a beam representing the entire cell. Next, it visits adjacent cells iteratively, considering different permutations of transmissions, specular reflections and diffractions due to the faces and edges on the boundary of the “current” cell. As the algorithm traverses a cell boundary into a new cell, a copy of the current convex pyramidal beam is “clipped” to include the region of space passing through the convex polygonal boundary to model transmissions. At each reflecting cell boundary, a copy of the transmission beam is mirrored across the plane supporting the cell boundary to model specular reflections. At each diffracting wedge, a new beam is spawned whose source is the edge and whose extent includes all rays predicted by the Geometrical Theory of Diffraction [Keller62]. The traversal along any sequence terminates when either the length of the shortest path within the beam or the cumulative attenuation exceed some user-specified thresholds.

The traversal may also be terminated when the total number of beams traced or the elapsed time exceed other thresholds.

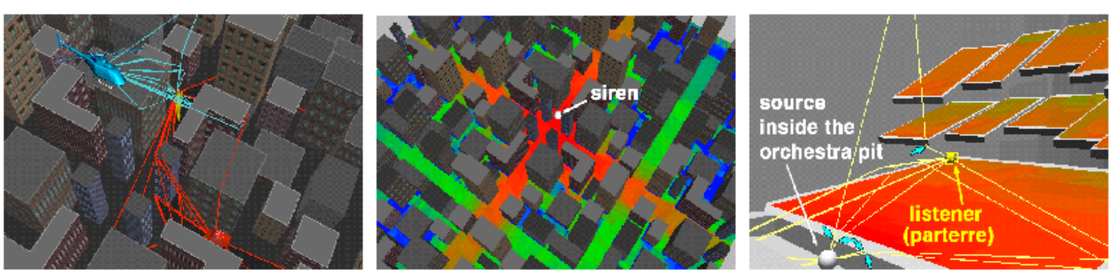
In the third step, for each beam containing the microphone location, we compute the shortest propagation path from the speaker to the microphone along the sequence of transmissions, diffractions, and specular reflections represented by the beam. The intersections with specularly reflecting faces are uniquely determined by the locations of the speaker, microphone, and the intersections with diffracting edges (diffraction points). The diffraction points are found by solving a non-linear system of equations expressing equal angle constraints at diffracting edges. Once the diffraction points are found, we construct a piecewise-linear polyline representing the path along which sound travels from source to receiver along the propagation sequence, from which a length-, angle-, and frequency-dependent filter is computed.

In the final step, for each valid propagation path from the speaker to the microphone, we add its contribution to the simulated impulse response. Our implementation includes source and material filtering effects derived from either measurements or analytical models. We compute diffraction coefficients using the Uniform Theory of Diffraction [Keller62, Kouyoumijan74]. Air absorption due to scattering is also taken into account following the ISO 9013-1 specifications. All calculations are performed in complex Fourier domain at the sampling rate resolution. Our current system uses a sampling rate of 51200 Hz (the sampling rate of our source and material measurements). Thus, for a one second long response we are computing 25600 complex coefficients per path. The simulated transfer function is the sum of the coefficients for all paths, and the final impulse response is the inverse Fourier transform of the sum.

After all beams have been traced up to a user-specified termination criterion and the contribution of all propagation paths have been summed, the resulting impulse response is output for auralization or comparison to measurements.

5. COMPUTATIONAL RESULTS

In order to evaluate whether our beam tracing framework is computationally practical for large architectural environments, we tested it for modeling specular reflection and diffraction in several 3D models (see Figure 2). For each model, we traced beams from a stationary sound source (located at the red/white dots) and stored them in a beam tree data structure. Then, as the sound receiver was moved interactively (located at the yellow dots), we updated propagation paths comprising specular refection and diffraction at interactive rates. All the tests were run on a Silicon Graphics Onyx2 workstation with a 195MHz R10000 processor.

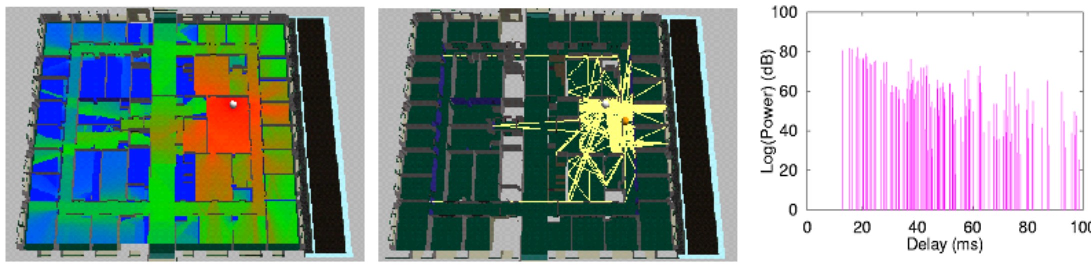


a) City (paths) b) City (power plot) c) Opera de la Bastille

Figure 2: Visualizations of sound simulations in a city (left) and a concert hall (right).

Figure 3 shows a visualization of the simulated results for one 3D model representing a real architectural design (Soda Hall at UC Berkeley). In this case, the model contained 1,762 polygons describing the walls, ceilings, and floors of the building interior. The spatial subdivision constructed

752 cells in 7.1 seconds. Then, the beam tracing algorithm computed 50,000 beams (Figure 3a) comprising specular reflections and diffractions from a source point (white dot) in 13.2 seconds. Next, 75-95 propagation paths (Figure 3b) were updated 20 times per second to a receiver location (pink dot) moving under interactive user control. Finally, echograms (Figure 3c) were computed for specific receiver locations. The system is able to provide interactive updates while visualizing and auralizing sound propagation in this architectural environment.

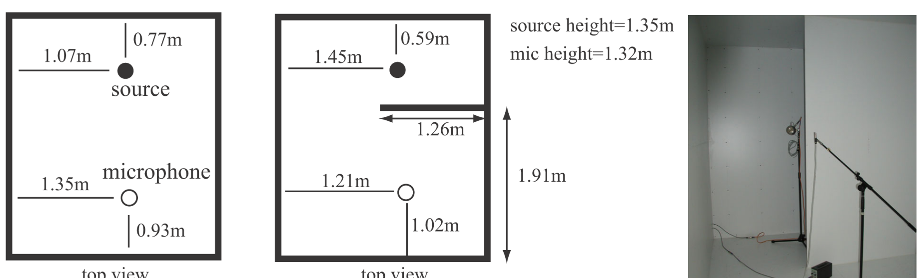


a) Building (power plot) b) Building (paths) c) Building (echogram)

Figure 3: Visualization of a) propagation paths (yellow lines) traced from source (white dot) to receiver (orange dot), b) power plot, and c) echogram simulated with 50,000 beams in model of a building with 1,762 polygons.

6. VALIDATION RESULTS

In order to provide an evaluation of the accuracy of our simulation methods, we compared impulse responses computed with our system versus measurements in two simple environments (see Figure 4). The first is a simple box-shaped enclosure comprising six rectangular panels. The second is the same box-shaped enclosure with a single rectangular panel spanning from floor to ceiling along one half the interior of the box with the speaker and microphone on opposite sides of the panel. The first configuration is *very simple*, yielding only specular reflections -- we use it as a baseline for validation and comparison. The second configuration is a reverberant environment with significant propagation paths combining both edge diffraction and specular reflection. This is a more difficult case, which has not been widely studied. We focus on these simple environments in order to be able to compare the early parts of simulated and measured impulse responses directly, which would be difficult in a complex environment.



(a) empty Bell Labs Box (b) Bell Labs Box with baffle

Figure 4: Two simple environments used for validation experiments. One is a simple six-sided box (left), while the other contains an interior baffle (middle). An interior view of the baffle is shown in the image on the right.

For both configurations, we measured the impulse response of the environment using a Bruel & Kjaer artificial mouth and a 1/2-inch microphone connected to the audio outputs and inputs of a MOTU 828 multi-channel firewire audio interface [MOTU]. The MOTU interface was connected to an off-the-shelf laptop running Windows. The source signal was a repeated chirp stimuli, and the sampling rate was 48KHz. The output signal used to feed the speaker was also fed back into the interface as a reference. We low-pass filtered the resulting response to get an actual bandwidth of 10KHz.

We simulated all possible 1,524 propagation paths with up to 10th order specular reflection in the first configuration (empty box), and 1,358 paths combining up to 4th order specular reflection and 2nd order edge diffraction in the second configuration (with diffracting baffle). These simulation parameters were chosen as a reasonable compromise between simulation accuracy and computational expense (738 and 631 seconds, respectively). Models of both the sound source and panel responses were acquired through measurements in an anechoic chamber.

The simulated and measured impulse responses for each configuration are shown in Figure 5. Note that the fine band simulation with measured source and material characteristics allows us to compare the waveform of the simulated and measured early responses (numbers on peaks of the impulse response on the top-right correspond to identifiers for specific simulated propagation paths). As can be seen, our simulation is able to capture the temporal structure of the impulse response and is also able to capture the effects of the diffraction by the edge of the panel (e.g., first peak of the top curve in Figure 5b).   For comparison, we also plotted a simulated impulse response without diffraction effects (the bottom curve in Figure 5b). We also present in Figure 6 a comparison between spectrograms for the simulated and measured impulse responses. Looking at these plots, we expect that the simulations match the measurements well enough to be useful for prediction or immersive simulation. Please refer to [Tsingos02] for more details.

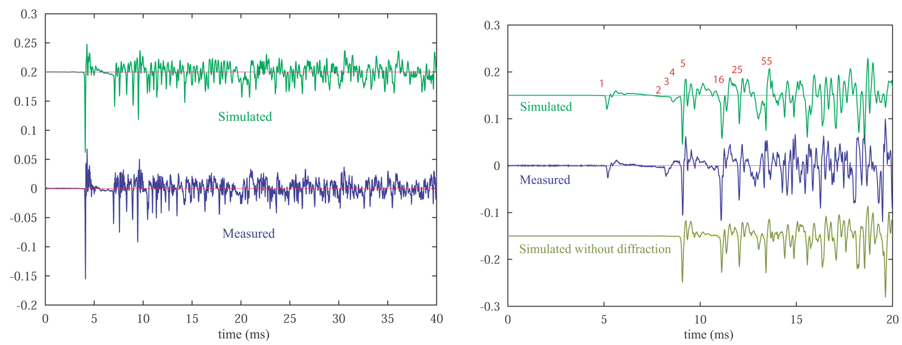
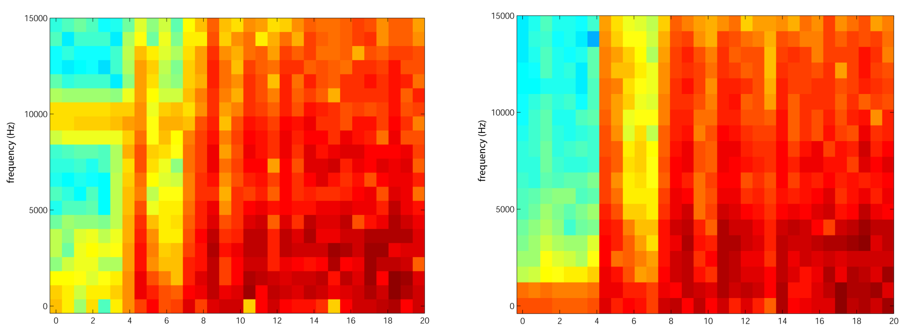


Figure 5: Comparison of simulated (above) and measured (below) impulse responses for the empty box (left) and box with a diffracting baffle (right). The plot on the right includes curves for simulations both with (blue) and without (yellow) diffraction.



a) Measured b) Simluated

Figure 6: Spectrograms of measured (left) and simulated (right) early responses in box with a baffle.

7. DISCUSSION & CONCLUSION

In this paper, we have described a beam tracing approach to simulating sound propagation in architectural environments. Its advantageous features are: 1) it enumerates all potential sequences of specular reflection, diffraction, and transmission up to user-specified termination criteria, 2) it enables evaluation of early propagation paths at interactive rates, and 3) it scales to support large, "densely-occluded" architectural environments (e.g., buildings and cities).

The approach is not without limitations. In particular, the current implementation is practical only for coarsely detailed 3D models, since beams get fragmented in scenes with many free-space cell boundaries [Fortune99, Funkhouser98, Teller92]. Also, it models the building structure at only one scale, which may be appropriate for some sound wavelengths, but not others. Finally, our auralization methods are tuned for interactive applications and thus employ approximations that are quick to compute (e.g., the Geometric Theory of Diffraction) but less accurate than alternative models. In future work, we plan to investigate how our beam tracing methods can be used for enumerating propagation sequences in off-line simulations with more accurate models to improve the efficiency and accuracy of existing acoustics prediction systems.

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