THE DEVELOPMENT AND IMPLEMENTATION OF ADAPTIVE BEAM TRACING

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Abstract

The appearance of ever faster and cheaper computer technology has facilitated the use of computer modelling to predict the room acoustics of architectural enclosures. The goals of such models being to either provide accurate analytical data or approximate real-time prediction in conjunction with binaural rendering. Classic techniques such as ray tracing and the image method have been complimented with triangular and conical beam tracing methods. The adaptive beam tracing method seeks to eliminate missing or duplicated images associated with ray and beam techniques whilst providing performance gains over the image method. This paper aims to discuss the implementation, advantages and problems associated with adaptive beam tracing and possible future applications.

1 INTRODUTION

The 'Adaptive Beam Tracing Algorithm' was developed at the School of Acoustics and Electronic Engineering, The University of Salford for the prediction of the acoustics of architectural enclosures. The method aims to eliminate holes and overlaps in the predicted sound field by modelling it as a set of beams who's reflected components are based on the shapes of room surfaces. The method also facilitates the calculation of diffuse sound propagation by managing the energy transfer from a specular model to a diffuse model. This 'Adaptive Beam Tracing' method compares well with other methods in terms of speed and accuracy although is relatively difficult to implement successfully for complicated enclosures.

2 PREVIOUS METHODS

Although one can make a rough estimate for reverberation time for a given room based on volume, surface area and absorption (Sabine, Eyring, etc), more sophisticated computer models seek to predict the propagating sound field and hence reverberant profile of the room. Examples model the sound field as rays, beams or images.

Ray tracing (Kulowski[1]) creates a dense spread of rays, which are subsequently reflected around a room and tested for intersection with a spherical detector. The energy attenuation of the intersecting rays and distances travelled are used to construct an echogram. Although relatively simple to implement the algorithm has inherent systematic errors (Lehnert[2]) where by spurious reflections can be created due to using a non point detector whilst other valid reflections missed as the rays diverge.

The image method as demonstrated by Borish[3] and (Lee and Lee[4]) overcomes these problems by instead calculating images of the sound sources in reflecting walls. Higher order images are in turn calculated and so on until an echogram is produced. Although initially much faster than ray tracing the image method slows exponentially with increasing orders of reflection as the number of possible though not necessarily valid images increases. Invalid images must be eliminated with validity and visibility tests. Some applications such as Volander [5] use a hybrid of the two methods to improve speed and accuracy.

There are also conical (Maercke & Martin [6]) and triangular (Lewers[7]) beam tracing methods available. Beams are reflected around a room and tested for illumination of the detector. These algorithms provide the speed of ray tracing with the accuracy advantages of being able to use a point detector. However since cones and triangles represent approximations of the propagating sound field, overlaps and missing reflections can happen and so have to be compensated for statistically.

3 THE IMPLEMENTING THE BEAM TRACING METHOD

3.1 Overview

Essentially the adaptive beam-tracing algorithm models a propagating sound field in a virtual room space as a set of diverging beams. When a beam encounters walls of the room, new reflected child beams will be spawned with dimensions based on sections of illumination. Hence the beams can be used to...

- search for a detector and so predict a specular impulse response
- impart diffuse energy to walls with respect to time for use in a radiant exchange model.

Hence the combined specular and diffuse predictions can be used to determine the room's reverberant decay profile and import parameters such as T60, EDT, ELEF, etc.

3.2 Implementation

The development of the adaptive beam-tracing algorithm as a user-friendly windows application has been greatly facilitated by the object orientated structure of C++. A number of elemental classes were defined including...

Vectors ... $v = (x, y, z)$ as given by coordinates in 3D world space

Polygons...as given by bounding vectors $P = (v_1, v_2, v_3, \ldots)$

Planes...as given by a bounding polygon and equation of plane $n \cdot v_1 = D$

Rays...as given by start position, direction and time travelled i.e. $r = s + ct$

From such elements more sophisticated classes were hence defined providing templates for dynamic object creation. These include...

Beam ... as given by an array of rays $bm = (r_1, r_2, r_3, \ldots)$ that define it's boundaries together with energy data that takes account of the beams reflection history

Wall ... includes a plane object, absorption and diffusion coefficients and record of energy imparted with respect to time to be used later for emulating diffusion.

Using a twenty-sided icosahedron (Fig. 1) to describe the initial sound field from an omni-directional source a set of twenty beams were created. Each beam consisting of a diverging set of rays.

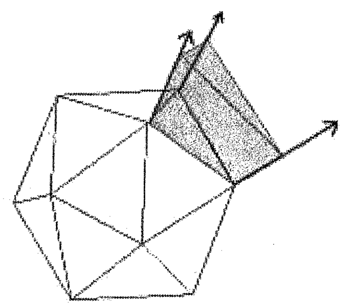

Figure 1: Twenty-sided icosahedrons determines initial beams

For each respective beam the program loops through the walls of the room space to test for intersection. The nearest intersection of a beam's ray with a wall's plane that satisfies a simple 'in boundary' test is hence used as a starting point to determine sections of illumination.

Defining sections of illumination is crucial to adaptive beam tracing, as these sections of illumination will hence be used to define and hence spawn new child beams that describe the reflected sound field. This can be done by temporarily describing the both the parent beam boundaries and any nearby plane boundaries as a set of 'edge planes' (Fig. 2) that will in effect corral the progress of a 'descriptor ray' which moves coplanar with the illuminated wall in question.

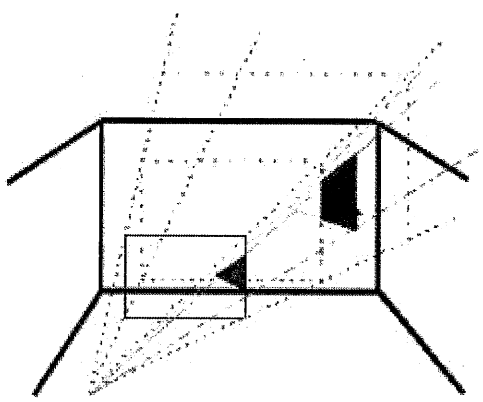

Figure 2: Edge planes defined by beam and wall boundaries

Each 'edge plane' is the extrapolation of a beam edge or plane edge to very large distance relative to the beam source. An 'edge plane' can be represented by the polygon

$$P_e = (s_{bm}, v_1, v_2)$$

where v_1 and v_2 the vertices of the edge extrapolated to a very large distance relative to the beam source s_{bm}. The 'edge plane' can also be represented by its normal n_e and plane coefficient D where

$$D = n_e.s_{bm}$$

The direction of the 'descriptor ray' is given by the intersection of an 'edge plane' with the wall being illuminated. Given it starts at an intersection s_d a descriptor ray can be represented by

$$r_d = s_d + c_d t$$

Where c_d is as the cross product of an 'edge plane' normal n_e with the illuminated wall's normal n_w

$$c_d = n_e \times n_w \text{ or } c_d = n_w \times n_e$$

When a descriptor ray reaches a wall edge a new descriptor ray is spawned along adjacent edges of illumination where needed (Fig. 3).

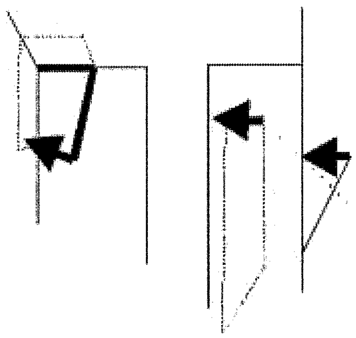

Figure 3: Descriptor rays defining sections of illumination based on beam and plane edges.

Hence numerous adjacent sections of illumination (Fig. 4) can be determined for one beam from which reflected child beams will be spawned.

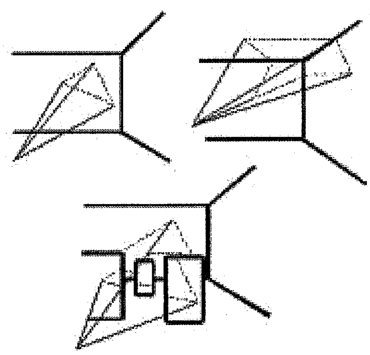

Figure 4: Sections of illumination.

For each section of illumination a new child beam is created with it's own new virtual beam source (Fig. 5). Such child beams can hence be pushed and popped off a stack of such objects awaiting further processing.

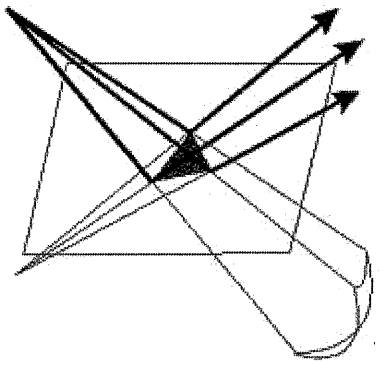

Fig 5: A new child beam from a section of illumination

Upon reflection specular beam energy is lost to wall absorption and the diffuse system. Hence given the parent beam energy E_b, the wall absorption coefficient α and diffusion coefficient δ the reflected beam energy E_r is

$$E_r = E_b(1-\alpha)(1-\delta)$$

Note that the beam energy in the specular model is essentially the original source energy minus energy lost to wall absorption and diffusion after reflections. The beam serves as a detector finder its specular energy value being independent of the beam's cross-sectional area. On finding the detector the energy incident on the detector takes account of $1/r^2$ and air attenuation, where r is the distance the beam has travelled.

3.3 The Diffuse System

During the specular beam tracing process, time and plane dependant energy information passes to the diffuse system. The diffuse model requires the proportion of diffuse sound energy that the beam has imparted to the wall with respect to time and so is dependant on the beam's cross-sectional area. This energy is proportional to $\frac{\Delta\Omega}{\Omega}$, where $\Delta\Omega$ is the solid angle subtended by an area of illumination and Ω is the solid angle subtended by a sphere. The solid angle subtended by the beam is calculated by extrapolating all constituent beam rays to an equal arbitrary distance L, hence the resulting extrapolated polygon of area A is used to determine the proportion of energy incident E_d where

$$E_d \propto \frac{\Delta\Omega}{\Omega} E_b\,\delta(1-\alpha) \propto \frac{E_b A \delta(1-\alpha)}{4\pi L^2}$$

Every wall is assigned a plane impulse response that serves as a record of diffuse energy imparted by beams with respect to time. The plane impulse response consists of energy bins at discrete time intervals Δt. When a beam is incident on a wall the imparted beam energy E_d is added to the time bin corresponding to the average time the beam has travelled.

Upon completion of the specular beam tracing a separate diffuse sound profile is calculated using a radiant exchange process. For every time interval of every plane impulse response, the corresponding diffuse energy is re-radiated to all other planes (Fig. 6).

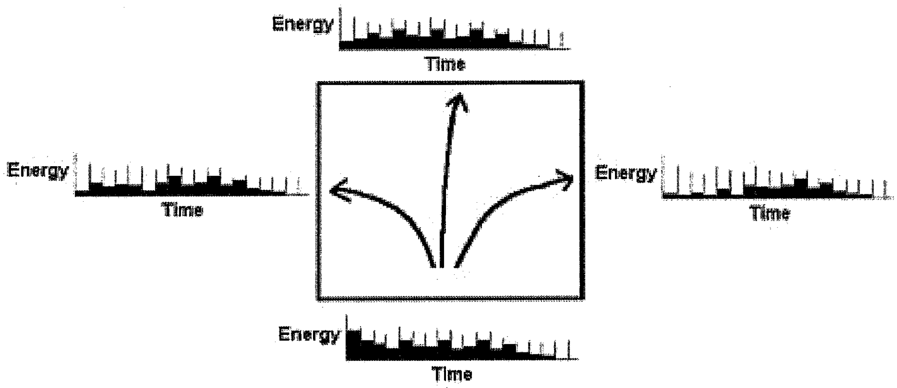

Fig 6: Shows energy/time data from a given plane reradiated to other planes

Each receiving plane hence has a proportion of this energy added to its plane impulse response at a time interval corresponding to an average distance between the radiating and receiving planes. These energy portions received will in turn be re-radiated to other planes later on during the exchange process and so on. The exchange process cycles through successive time intervals redistributing energy until an arbitrary time that is much greater that the maximum selected order of beam reflection. How much diffuse energy each plane receives is dependant on a form factor between the radiating and receiving planes. The plane form factor F_{ij} (Lewers[7]) between two planes is the fraction of energy diffusely emitted from surface *i* that reaches surface *j* as given by

$$F_{ij} = \frac{1}{A_j} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi r^2} dA_i A_j$$

where A_i is the surface area of the emitting surface, r is the length of the line joining the two elemental areas and θ_i and θ_j are the angles formed between this line and the respective plane normals. The form factor be calculated as the average solid angle subtended by the receiving plane relative to grid of points on the radiating plane.

When the radiant exchange process is completed diffuse energy at the detector can be calculated. For each time interval of each plane impulse response diffuse energy is re-radiated to the detector. Hence a diffuse impulse response at the detector is built up allowing for the forms factors and distances between the detector and radiating planes.

3.4 Recombining Specular and Diffuse Components

The adaptive beam tracing algorithm like all other methods can only calculate specular reflections to a finite order, hence remaining energy is assumed to pass to a totally diffuse system to be later used in radiant exchange. This can be implemented by assuming plane diffusion coefficients have the value 1 for high orders of reflection. However, an abrupt crossover can leave artefacts in the predicted sound decay curve. Thus, a more gradual crossover to totally diffuse over a range of high order reflections was implemented.

Given specular and diffuse impulse responses the two must be combined to produce an accurate profile of the room's acoustics. Clarity and Deulikiet can be calculated simply by integrating specular and diffuse energies with respect to time. In order to calculate Reverberation Time and Early Decay Time a profile of sound energy decay is needed. This is done combining specular and diffuse impulse responses. Then using a backwards integration method Schroeder[9] a decay profile is built up (Fig.7). A linear regression on the resultant curve can be used to determine RT and EDT.

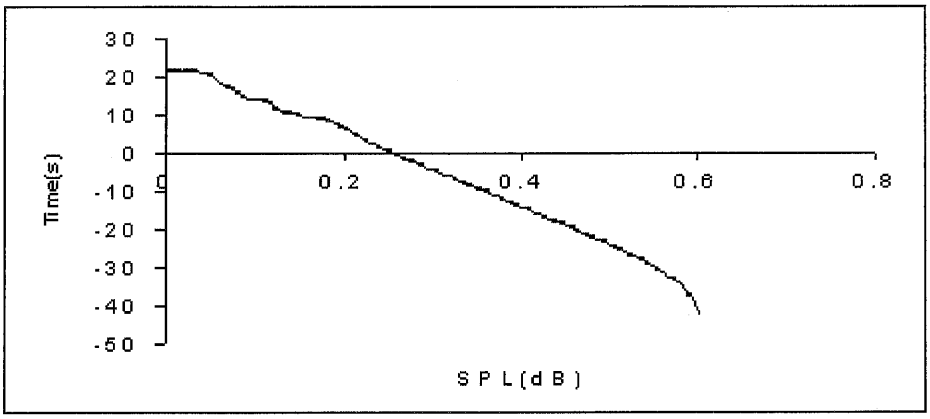

Fig 7: The Schroeder backwards integration based on specular and diffuse impulse responses

4 Comparisons with Other Methods and Real Measurements

4.1 Comparison with the Image Method and Ray Tracing

Comparisons of the adaptive beam tracing algorithm for accuracy and speed were made with an implementation of ray tracing and of the image method. All methods were tested with the same hall data to produce a specular echogram of sound energy incident at a detector location with respect to time. The ray tracing algorithm was implemented to use a spherical detector hence a record of rays intersecting was built up. Rays with same plane to plane path would sometimes be recorded while other valid ray paths missed. These systematic errors for ray tracing were demonstrated by Lehnert[2] who subsequently suggested a criterion for ray density based on detector size and the mean free path of the hall. The image method used was based on an efficient algorithm (Lee and Lee[4]) which takes account of obstructions and invalid images. The adaptive beam tracing as expected produced near identical impulse responses to the image method for a variety of simple room models.

Comparisons of calculation time were made for the three methods using a relatively slow personal computer. Fig. 8 shows that Ray Tracing can be fast with an arbitrary number of rays used across a range of orders of reflection, however systematic errors increase. By applying an error criterion to specify the number of rays used for a given detector size (Lehnert[2]), ray tracing was demonstrated to be much slower than beam tracing. The image method is the fastest for low orders of reflection, however calculation times increase exponentially with orders of reflection or number of planes used. Hence, beam tracing is the fastest algorithm for all but the lowest orders of reflection or simplest of halls.

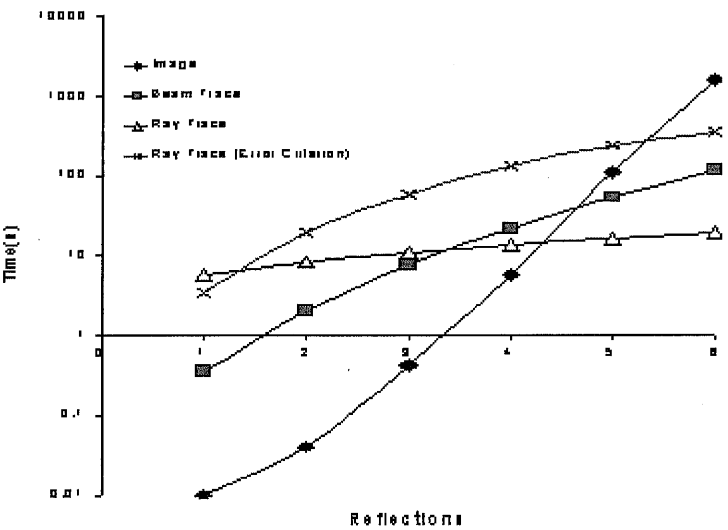

Fig 8: Comparison of computation times for several methods on slow personal computer

4.2 Comparison with Measured Results

The adaptive beam-tracing algorithm was applied to a number of real halls for comparisons with measured results. For example measured acoustic parameters from a previous study (Howarth[10]) of a lecture hall often used from music (Fig. 9) were compared with predicted RT, EDT and C80 values. The results for R.T. (Fig. 10) show a good correlation (~8%) with measured although usually less than predicted demonstrating a possible loss of predicted energy for higher orders of reflection, overestimation of absorption coefficients and failure to take into account ambient noise. The results for E.D.T. and C80 typically show a similar correlation.

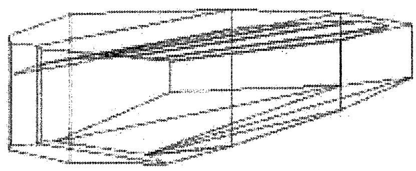

Fig 9: Lecture hall commonly used for music performance

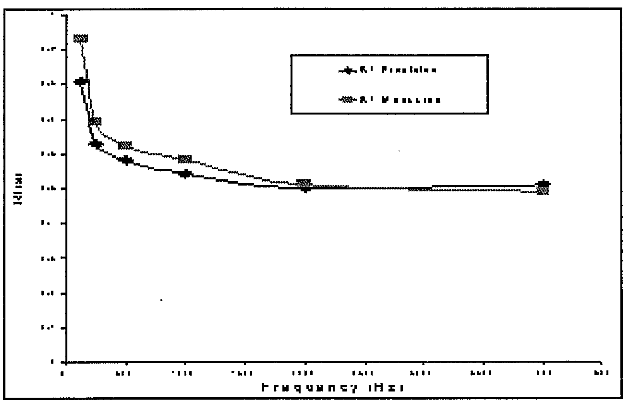

Fig 10: Comparison of predicted and measured reverberation times

5 Problems and Limitations of Method

That algorithm works well with very simple rooms, however has serious stability problems with increasingly complex rooms and higher orders of reflection. A number of key problems arise from

- Increasing beam size with respect to planes
- Decision making errors during the determination of sections of illumination
- Dealing with low errors margins in original plane data
- Managing transition from specular to diffuse

Quite quickly the solid angle subtended by a beam becomes greater than that of the planes illuminated, the result being plane boundaries lying total within beam illuminations. This can be tested for and the beam sub-dived so that beam ray intersections lie within all planes. This works well though the result is an exponential increase in child beams with respect to orders of reflection. Also with increasing beam size important energy/time data for the diffuse model becomes less accurate.

When using descriptor rays to describe sections of illumination a high degree of decision making is required to determine which edges to follow next. This is especially important with corners where under certain circumstances (usually arising from errors in the plane data) wrong turns to be made. Although a strict set of clockwise/anticlockwise sense rules and validity tests have been developed to guide the description process the algorithm will under some circumstances can get confused thus have to abandon the occasionally beam to avoid being stuck in a loop. Sub diving the start beams can reduce the effect though this will slow performance and just postpone similar problems to be experienced later by more beams.

For predicting room acoustics parameters such as RT, EDT and C80 the specular algorithm appears to give best results when used as a means of determining first order input into the diffuse (radiant exchange) model.

The algorithm may also be better suited to determining fast lower order specular impulse responses for real time applications rather than detailed acoustic prediction of very complicated hall scenarios. Though more stable implementations are constantly being developed.

6 Conclusions

The adaptive beam tracing algorithm has some advantages with respect to speed and accuracy over previous methods. The algorithm seeks to eliminate systematic errors resulting from overlaps and omissions in predicted sound propagation whilst facilitating an integrated calculation of specular and diffuse systems so removing the need for some empirical adjustments. The algorithm copes well with many hall scenarios by inherently dealing with occluding planes however it is difficult to implement successfully for complex scenarios owing to a relatively low error tolerance and stability problems.

7 References

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