19th INTERNATIONAL CONGRESS ON ACOUSTICS
MADRID, 2-7 SEPTEMBER 2007

ACOUSTIC RADIANCE TRANSFER METHOD

PACS: 43.55.Cs

Siltanen, Samuel[1]; Lokki, Tapio[2]; Savioja, Lauri[3]
[1]Telecommunications Software and Multimedia Laboratory, Helsinki University of Technology; P.O.Box 5400, FIN-02015 HUT, Finland; Samuel.Siltanen@tml.hut.fi
[2]Telecommunications Software and Multimedia Laboratory, Helsinki University of Technology; P.O.Box 5400, FIN-02015 HUT, Finland; Tapio.Lokki@tkk.fi
[3]Telecommunications Software and Multimedia Laboratory, Helsinki University of Technology; P.O.Box 5400, FIN-02015 HUT, Finland; Lauri.Savioja@tkk.fi

ABSTRACT

Room acoustics can be modeled by simulating the propagation of acoustic energy in the space under consideration. Thus, it is possible to formulate a room acoustic rendering equation which perfectly describes the time-dependent distribution of the energy. The current room acoustics modeling methods can be derived as special cases of this equation. In addition, an acoustic radiance transfer method has been constructed for modeling the sound propagation in environments with arbitrary reflection properties. In other words, specular and diffuse reflections are both modeled simultaneously. In addition, diffraction modeling can be added to the method, although it is not implemented yet. The method produces time-dependent energy responses for a signal emitted from a stationary sound source to each surface element in the modeled space. The output of the presented method can be used for computing acoustic parameters or for listening the responses in desired listening positions. Since the energy distribution on each surface element is known, some visualization techniques, which can be useful for acoustic designers, are presented.

INTRODUCTION

The utilization of room acoustics modeling software has become common in designing spaces where the acoustics is a concern. The quality of the predictions depends on several aspects. The 3-dimensional computer model must be accurate enough, the materials must be modeled properly, and the prediction algorithm must be flawless. Currently, the material representations are quite simplified and the prediction algorithms differ from each other in the way they approach the problem.

There are several geometrical room acoustics modeling techniques. Ray tracing [4] and the image source method [2, 3] are the first ones suggested for computer-aided room acoustics modeling. These techniques and their hybrids are widely used in commercial room acoustics prediction software [4, 5]. The beam tracing algorithms can be seen as optimizations for the visibility computations in the image source method and it has been successfully applied in efficient computation of early specular reflections [6]. Yet another technique is acoustic radiosity [7, 8, 9, 10, 11] which is modeling the diffuse reflections.

These techniques have several things in common, and thus we have been able to formulate an equation which perfectly describes the sound propagation in a closed space, and derive different techniques as special cases of it [12]. In addition, we derived an acoustic radiance transfer method which is able to model arbitrary reflection properties and not only specular or diffuse reflections. This technique allows us to trace the energy distribution per surface element. Novel visualizations are created by using these energy distributions.

RELATED WORK

The room acoustic rendering equation was first introduced by Siltanen et al. [12]. The time-independent form of the equation used with global illumination in computer graphics was given by Kajiya [13] and in the modern form it can be written as [14]:

$$L(x\to\Theta) = L_e(x\to\Theta) + \int f_r(x,\Psi\to\Theta)\, L(y\to-\Psi)\, V(x,y)\, G(x,y)\, dA_y \qquad \text{(Eq. 1)}$$

where $L(x\to\Theta)$ is the outgoing radiance from x in the direction Θ and $L(y\to-\Psi)$ is the outgoing radiance from y in the direction $-\Psi$. $L_e(x\to\Theta)$ is the emitted radiance from point x in the direction Θ, $G(x,y)$ is a geometry term, $V(x,y)$ is a visibility term, and $f_r(x,\Psi\to\Theta)$ is a bidirectional reflectance distribution function. The meaning of the corresponding terms are explained in the context of the time-dependent form presented in the next section.

The flexible representation required for modeling arbitrary reflections can be borrowed from computer graphics where bidirectional reflectance distribution functions (BRDFs) [15] are widely used. This differs from the common practice of giving only diffusion or scattering coefficients to describe the directional distribution of the energy and absorption coefficients to describe the energy losses in reflections [16], although with typical measurement setups the direction-dependent reflection properties are actually retrieved [17].

Extending the radiosity method for arbitrary reflections has been done in computer graphics [18, 19, 20, 21], but adding the time-dependency makes the technique considerably heavier [12].

ROOM ACOUSTIC RENDERING EQUATION

A detailed derivation of the equation can be found in Siltanen et al. [12]. The room acoustics rendering equation is

$$l(x',\Omega) = l_0(x',\Omega) + \int_G R(x,x',\Omega)\, l\left(x, \frac{x'-x}{|x'-x|}\right) dx \qquad \text{(Eq. 2)}$$

where $G \in \mathbb{R}^3$ is the set of all surface points in the enclosure and $l(x',\Omega)$ is the outgoing time-dependent radiance from point x' in direction Ω and $l_0(x',\Omega)$ is the corresponding direct radiance from the source. Here the reflection kernel is defined as

$$R(x,x',\Omega) = V(x,x')\,\rho\left(\frac{x-x'}{|x-x'|}, \Omega; x'\right) g(x,x'). \qquad \text{(Eq. 3)}$$

It consists of a visibility term $V(x,x')$, which is zero if the path between x and x' is occluded and otherwise one, bidirectional reflection distribution function $\rho(\Omega_{\text{in}}, \Omega_{\text{out}}, x')$, which determines the portion of the radiance arriving at point x' from direction Ω_{in} which is reflected to direction Ω_{out}, and the geometry term $g(x,x')$, which is defined as

$$g(x,x') = \left[n(x)\cdot\frac{x'-x}{|x'-x|}\right]\left[n(x')\cdot\frac{x-x'}{|x-x'|}\right]\frac{S_{|x-x'|}}{|x-x'|^2}, \qquad \text{(Eq. 4)}$$

where the propagation operator is defined as

$$S_r I(t) = e^{-\alpha r} S_r I(t) = e^{-\alpha r} I\left(t - \frac{r}{c}\right), \qquad \text{(Eq. 5)}$$

where c is the speed of sound and α is the air absorption coefficient.

In the case of an area source, l_0 represents the radiance emitted by the surface. For point sources, l_0 is considered as the primary reflected radiance instead of defining the source as a part of the surface geometry to make the analysis more convenient. By denoting the position of the source by x_s and the time-dependent intensity of outgoing energy at angle Ω by $P_s(\Omega, t)$, the time-dependent irradiance from the source to point x can be calculated to be

$$E(x) = V(x,x_s)\frac{S_{x-x_s} P_s\left(\frac{x-x'}{|x-x'|}, t\right)}{4\pi|x-x_s|^2}\left[n(x)\cdot\frac{x_s-x}{|x_s-x|}\right], \qquad \text{(Eq. 6)}$$

giving the point the primary reflected radiance

$$l_0(x,\Omega) = \rho\left(\frac{x_s - x}{|x_s - x|}, \Omega, x\right) V(x_s - x)\, g_0(x_s, x)\, P_s\left(\frac{x - x_s}{|x - x_s|}, t\right), \qquad \text{(Eq. 7)}$$

where g_0 is defined as

$$g_0(x_s, x) = \left[n(x) \cdot \frac{x_s - x}{|x_s - x|}\right] \frac{S_{|x_s - x|}}{4\pi |x_s - x|^2}. \qquad \text{(Eq. 8)}$$

For an omnidirectional point source emitting a unit impulse, the outgoing energy is defined as $P_s(\Omega, t) = \delta(t)/4\pi$.

GEOMETRICAL ROOM ACOUSTICS MODELING TECHNIQUES AS SPECIAL CASES

The different geometrical room acoustics modeling techniques can be derived as special cases of the room acoustics rendering equation.

Image source and beam tracing methods

In the basic image source method as well as in the simple beam tracing method, only the specular reflections are modeled. Thus, replacing the reflectance distribution fucntion with the ideal specular reflectance function yields the image source method. This can be written as

$$\rho_{\text{spec}}(\Omega_{\text{in}}, \Omega_{\text{out}}; x) = \frac{\beta(x)}{\Omega_{\text{in}} \cdot n(x)} \delta(\Omega_{\text{in}} - M(\Omega_{\text{out}})), \qquad \text{(Eq. 9)}$$

where δ is the Dirac delta function, M is the mirror reflection transformation $M(\theta, \varphi) = (\theta, \varphi \pm \pi)$, and the reflection coefficient $\beta = 1 - \alpha$ for the absorption coefficient α .

Ray tracing

Some ray tracing methods model only specular reflections [1] in which case the reflection functions are the same as with the image source method. Some other ray tracing algorithms trace also non-specular reflections by determining the reflection direction stochastically [22]. In this case the reflection distribution function ρ corresponds to the reflection probability distribution so that a reflection from a ray incident with angle Ω_{in} is reflected into direction Ω_{out} with probability $\xi(\omega_{\text{in}}, \omega_{out})$, which is the biconical reflectance factor:

$$\xi(\omega_{\text{in}}, \omega_{out}) = \frac{\int \int \rho(\Omega_{\text{in}}, \Omega_{\text{out}}) \cos\theta_{\text{in}} \cos\theta_{\text{out}}\, d\omega_{out}\, d\omega_{in}}{\int \cos\theta_{\text{in}}\, d\omega_{in}}. \qquad \text{(Eq. 10)}$$

Radiosity

The radiosity method can be derived from the room acoustic rendering equation by using a diffuse reflectance function

$$\rho_{\text{diff}}(x) = \frac{\beta(x)}{\pi}, \qquad \text{(Eq. 11)}$$

where β is the reflectivity coefficient of the material at point x . This simplifies the room acoustic rendering equation by omitting the directional dependence:

$$l(x') = l_0(x') + \int R(x, x')\, l(x)\, dx, \qquad \text{(Eq. 12)}$$

where the reflection kernel is simplified to

$$R(x, x') = V(x, x')\, g(x, x') \frac{\beta(x)}{\pi}. \qquad \text{(Eq. 13)}$$

In addition, the geometry G is discretized into elements.

ACOUSTIC RADIANCE TRANSFER METHOD

The acoustic radiance transfer method is described in detail in [12], but a brief explanation is given here.

The initial condition is that the geometry is subdivided into a small number of discrete surface elements or patches. The material properties of each patch are represented as a BRDF.

The algorithm consists of three phases, the initial shooting, iterative energy propagation, and the final gathering. In the initial shooting the energy from the sound source is shot to all patches visible to the source. The energy arriving at each patch can be computed with the equations given above. Once the amount and direction of the energy is known, it can be computed how much of the energy is to be reflected further. This energy is stored in each patch in directional slots. This energy is the undistributed energy of a patch.

In the iterative energy propagation the patch with the highest undistributed energy is chosen. Then the energy is shot from the patch's directional slots to every patch visible in the direction of each slot. This energy is still stored in the patch, but it is marked distributed. The energy arriving at the other patches is stored similarly to the energy received in the initial shooting. The process continues with the next patch with the highest undistributed energy, until the total undistributed energy in the system falls below a predetermined threshold value.

Now each patch contains an energy response which is the sum of the distributed and undistributed energies. All the patches which are visible to the listener are found out in the final gathering phase, and the energy responses are collected from them and accumulated into the listener's perceived energy response.

The acoustic radiance transfer method was evaluated in a realistic test case from which there was measurement data available [12]. In the future, the acoustic radiance transfer method could be extended to handle diffraction and we are currently working on a real-time walkthrough system based on this technique.

ENERGY-BASED VISUALIZATION TECHNIQUES

The acoustic radiance transfer method produces the time-dependent energy distribution for each patch during the iterative propagation phase of the algorithm. These energy distributions can be directly used in visualizations. There are several possible visualization strategies. One approach is to show the total energy per patch received while the sound is propagating in the room. This is helpful in determining whether the sound is evenly distributed.

Since the energy responses are dependent of the direction, the sound energy reflected in the direction of an arbitrarily positioned listener can also be modeled. Thus, it is possible to interactively move the listener position and see the intensity of the patches change in the visualization while the angle between the listener and patches changes. Figure 1 shows the directional responses for different camera, i.e., listener positions in a simple model.

Yet another visualization approach is to model the energy received by each patch during a short time intervals, e.g. one millisecond. By showing consecutive intervals, the sound energy propagation in the room can be examined. The user can adjust the intensity of the colors in relation to the sound energy as well as rewind the time backward and forward. The energy can be shown in a linear scale, but a logarithmic scale is more natural in the case of acoustic energy since the intensity of the color corresponds to the decibel levels of the sound. Figure 2 shows how the acoustic energy propagates in a test model consisting of 1216 patches. Only snapshots of the visualization can be shown here, but the whole time span modeled by the algorithm are available.

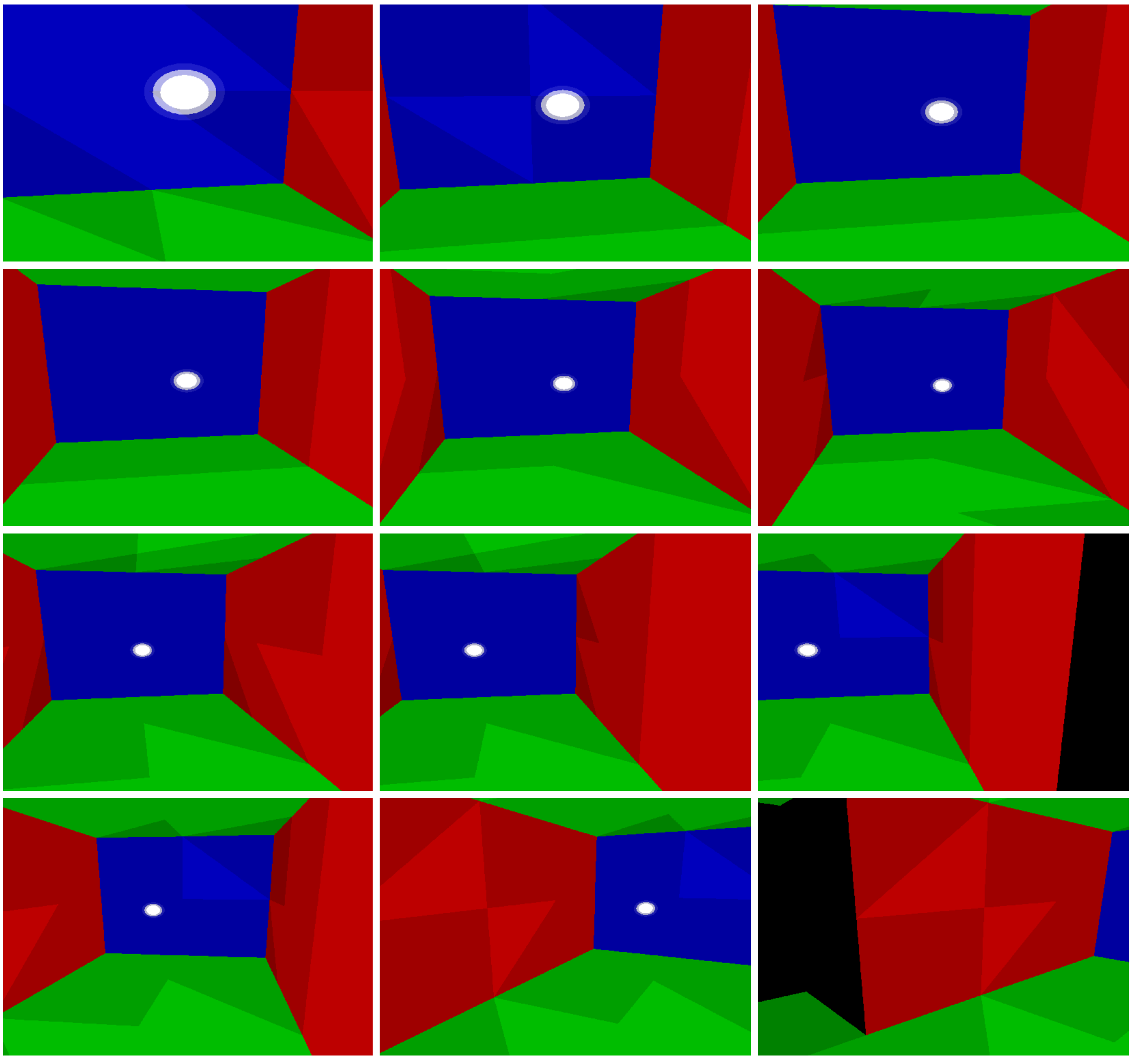

Figure 1. Directionally dependent reflected energy is shown for different camera positions.The brightness of patch corresponds to its reflected energy towards the listener.

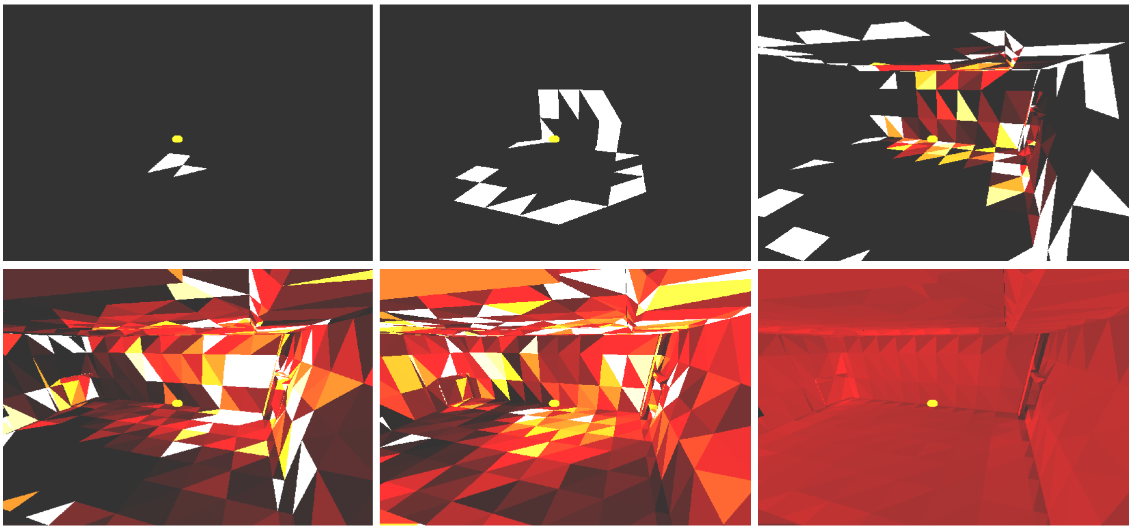

Figure 2. Propagation of the acoustic energy emitted by the source (the dot in the middle) in a model consisting of 1216 patches. A logarithmic scale is used in mapping the energy levels to colors.The top left picture represents the situation 5 ms after the source has emitted a signal. Snapshots of the energy distribution is shown in 5 ms steps so that the bottom middle picture is the situation after 25 ms. The bottom right picture represents the situation when the energy has been evenly distributed to the whole model thereby producing a nearly diffuse sound field.

CONCLUSIONS

A model for acoustic energy propagation is presented in the form of the room acoustic rendering equation. Several widely used geometrical room acoustics modeling methods are shown to be specializations of this model. The acoustic radiance transfer method is derived from the room acoustic rendering equation. The method is an extension of the previous work on the acoustic radiosity method and it can handle arbitrary reflections, represented by acoustic BRDFs. The visualizations based on the energy distributions computed by the method are expected to give added value to the visualizations commonly used in acoustics prediction software. The acoustic radiance transfer method has potential to become an important method to predict room acoustics.

References:

[1] A. Krokstad, S. Strom, S. Sorsdal: Calculating the acoustical room response by the use of a ray tracing texhnique. Journal of Sound and Vibration **8, No.1** (1968) 118–125

[2] J. B. Allen, D. A. Berkley: Image method for efficiently simulating small-room acoustics. The Journal of the Acoustical Society of America **65, No.4** (1979) 943-950

[3] J. Borish: Extension of the image model to arbitrary polyhedra. The Journal of the Acoustical Society of America **75, No.6** (1984) 1827-1836

[4] G. M. Naylor: ODEON – Another hybrid room acoustical model. Applied Acoustics **38** (1993) 131-143

[5] B.-I. Dalenbäck: Room acoustic prediction based on a unified treatment of diffuse and specular reflection. The Journal of the Acoustical Society of America, **100, No.2** (1996) 899-909

[6] T. A. Funkhouser, I. Carlbom, G. Elko, G. Pingali, M. Sondhi, J. West: A beam tracing approach to acoustic modeling for interactive virtual environments. In Proceedings of the 25th annual conference on Computer graphics and interactive techniques (1998) 21-32

[7] M. Hodgson, E.-M. Nosal; Experimental evaluation of radiosity for room sound-field prediction. The Journal of the Acoustical Society of America **120, No.2** (2006) 808-819

[8] E.-M. Nosal, M. Hodgson, I. Ashdown: Investigation of the validity of radiosity for sound-field prediction in cubic rooms. The Journal of the Acoustical Society of America **116, No.6** (2004) 3505-3514

[9] E.-M. Nosal, M. Hodgson, I. Ashdown: Improved algorithms and methods for room sound-field prediction by acoustical radiosity in arbitrary polyhedral rooms. The Journal of the Acoustical Society of America **116, No.2** (2004) 970-980

[10] N. Tsingos, J.-D. Gascuel: Acoustic simulation using hierarchical time-varying radiant exchanges. Unpublished technical report (1997)

[11] T. Lewers: A combined beam tracing and radiant exchange computer model of room acoustics. Applied Acoustics **38** (1993) 161-178

[12] S. Siltanen, T. Lokki, S. Kiminki, L. Savioja: The room acoustic rendering equation. The Journal of the Acoustical Society of America, accepted for publication (2007)

[13] J. T. Kajiya: The rendering equation. Computer Graphics **20, No.4** (1986) 143-150

[14] P. Dutré, P. Bekaert, K. Bala: Advanced Global Illumination. A K Peters, Ltd. (2003)

[15] F. E. Nicodemus, J. C. Richmond, J. J. Hsia, I. W. Gingberg, T. Limperis: Geometric consideration and nomenclature for reflectance. Monograhp 161, National Bureau of Standards (US), Washington, D. C.: National Bureau of Standards (1977)

[16] T. J. Cox, B.-I. L. Dalenbäck, P. D'Antonio, J. J. Embrechts, J. Y. Jeon, E. Mommertz, M. Vorländer: A tutorial on scattering and diffusion coefficients for room acoustic surfaces. Acta Acustics united with Acustica **92** (2006) 1-15

[17] M. Vorländer and E. Mommertz: Definition and measurement of random-incident scattering coefficients **60** (2000) 187-199

[18] D. S. Immel, M. F. Cohen, D. P. Greenberg: A radiosity solution for non-diffuse environments. Computer Graphics **20, No.4** (1986) 133-142

[19] C. Buckalew, D. Fussell: Illumination networks: Fast realistic rendering with general relfectance functions. Computer Graphics **23, No.3** (1989) 89-98

[20] B. Le Saec, S. Christophe: A progressive ray-tracing based radiosity with general reflectance functions. In Proceedings of the Eurographics Workshop on Photosimulation, Realism, and Physics in Computer Graphics (1990)

[21] F. X. Sillion, J. R. Arvo, S. H. Westin, D. P. Greenberg: A global illumination solution for general reflectance distributions. Computer Graphics **25, No.4** (1991) 187-196

[22] H. Lehnert, J. Blauert: Principles of binaural room simulation. Applied Acoustics **36, No.3-4** (1992) 259-291