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Authors
Deines, Eduard
Michel, Frank
Bertram, Martin
et al.

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SIMULATION, VISUALIZATION, AND VIRTUAL REALITY BASED MODELING OF ROOM ACOUSTICS

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Deines, Eduard[1,4]; Michel, Frank[1]; Hering-Bertram, Martin[2]; Mohring, Jan[2]; Hagen, Hans[3]

[1]IRTG Kaiserslautern
[2]ITWM Kaiserslautern
[3]University of Kaiserslautern
[4]e_deines@informatik.uni-kl.de

ABSTRACT

We present an audio-visual Virtual Reality display system for simulated sound fields. This system combines the simulation of acoustics inside closed rooms, different approaches for visualizing the sound propagation as well as the auralization of the resulting signals. The room acoustic simulation is performed by use of a particle tracing algorithm, the Phonon Tracing, applied at middle and high frequency range, combined with a wave-based approach (FEM solver) utilized for low frequencies. For a realistic representation of the simulation results we use a stereoscopic back projection system for rendering as well as a professional sound system for audio reproduction. For auralization purposes we developed a soundfield synthesis approach for accurate control of the loudspeaker system.

INTRODUCTION

Acoustics is important for planning of rooms for musical or speech presentations, such as theatres, concert halls, and lecture rooms. Today a computer aided simulation of acoustical behavior inside closed rooms is possible. There exists a variety of simulation algorithms which can be classified into two groups: wave-based and geometric approaches. The former numerically solve the wave equation. They provide accurate results, but the complexity increases drastically with the highest frequency considered. Hence, the wave model is suitable for low frequencies, only. Thus, in room acoustics mostly geometric approaches are applied. Two classical representatives of geometric acoustics are the image source method [1] and the ray-tracing method [16, 17]. An approach making use of advantages of image-source method and ray-tracing is introduced in [25]. Here the visibility check of the image-source algorithm is performed via ray-tracing. Beam-tracing methods [9, 10, 21] overcome the aliasing problem of classical ray-tracing by recursively tracing pyramidal beams, implying the need for highly complex geometric operations. Approaches utilizing the photon mapping algorithm [12] for acoustic simulation also exist [13, 4].

The question comes up for an appropriate visual representation of the simulation results. Stettner et. al. [24] visualize room acoustic quality properties such as clarity or spatial impression by use of specific icons. Furthermore, they color the room boundaries according to the pressure level. Khoury et. al. [14] represent the sound pressure levels inside the room by means of color maps. Additionally, the authors analyze the precedence effect (or law of the first wavefront) by using isosurfaces. Funkhouser et. al. [9] use visualization of source points, receiver points, pyramidal beams, reverberation paths etc. in order to understand and evaluate their acoustic modeling method. The system also provides the presentation of acoustic measures like power and clarity. Existing commercial systems[1,2,3] provide some tools for visualizing the computed acoustic metrics throughout the audience.

Virtual Reality environments provide an immersive representation of computer-generated scenes. Integrating acoustic simulation, visualization, and auralization into the design process

[1] http://www.odeon.dk
[2] http://www.catt.se
[3] http://www.bose.com

aims at interactive design and immediate exploration of virtual models. Several approaches to integrate acoustic simulation into Virtual Reality systems have been proposed in recent years.
The DIVA system [23] provides sophisticated synthesis and spatialization algorithms. Here set of either perception-based or physics-based parameters for auralization is defined. In [22] an audio-rendering system for use in immersive virtual environments, the blue-c, is proposed. It is optimized for efficient rendering of moving sound sources. Since the applications of this system are restricted to fictitional scenes no physical-based acoustic simulation is provided. In [20] the authors describe a four wall VR system for immersive visualization of sound rays propagation inside closed rooms. A real-time audio system applied in a CAVE like environment with four loudspeakers is proposed in [19]. A real-time simulation and rendering of moving sources and listeners is possible.
In the present work we describe an audio-visual Virtual Reality system, which allows computer aided simulation, visualization and auralization of acoustic behavior of a room model. For auralization purposes we combine a FEM approach and phonon tracing [8] in order to obtain a realistic impression of the sound perceived at given listener positions. The wave field synthesis approach then allows a correct auditive output of the convolved signals on professional sound equipment. With our system, a walkthrough of the listener positions is possible, such that a visual and auditive impression of the scene can be provided.
From our visualization, the effect of different materials on the spectral energy distribution can be observed. The first few reflections already show whether certain frequency bands are rapidly absorbed. The absorbing materials can be identified and replaced in the virtual model, improving the overall acoustic quality of the simulated room. A wave front is the pressure wave corresponding to a unit pulse. In order to visualize the wave fronts spread out from the sound source we use both particles (spheres) and surfaces, color coded by use of energy spectra of the corresponding virtual sound particles called phonons. After a sufficient time period, a great number of reflections have occurred, such that individual wave fronts cannot be identified, anymore. The darker the color of spheres or surfaces gets, the more energy has been absorbed by the different materials. Applications of our work include (but are not limited to) the acoustic improvement during architectural design, and equipment phases of class- and congress rooms.

ACOUSTIC VIRTUAL REALITY SYSTEM

In this section we describe our visual and auditive virtual reality display system, see Figure 1. As input our system requires the geometry model of the room, the absorption/reflection properties of the room surfaces, and sources and listener positions. The module “Acoustic simulation” computes the modal state space model (low frequencies) by use of the Finite Element Method (FEM), and the room impulse response (RIR) and the phonon map (middle and high frequencies) by means of phonon tracing algorithm. The simulation approaches are presented in the next section. On the basis of this information the anechoic source signal is modified for sound synthesis in the “Acoustic rendering” module. Thereafter, the sound field synthesis is performed utilizing the acoustic hardware. The “Acoustic Visualization” module provides the visualization of wave propagation from the sound source as well as the visualization of the resulting phonon map, described further on in the text, following by the rendering step (“Visual rendering” module).
For auralization purpose we used our synthesis method (see SYNTHESIS). The loudspeakers of our audio system are driven separately with the corresponding signals. The audio playback is administrated by the master computer and is started in a new process (thread).

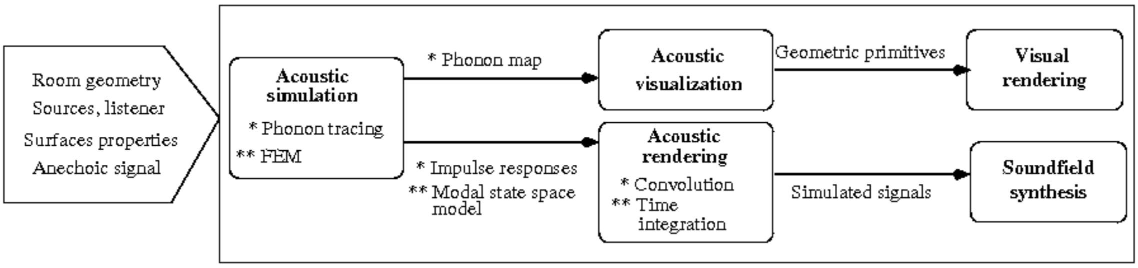

Figure 1 - Modules of the audio-visual Virtual Reality system.

SIMULATION

For the simulation of the acoustics inside closed rooms we apply a combined method. Since in the middle and high frequency range the diffraction is less important we use the phonon tracing algorithm described in [4] for the simulation at these frequency bands. A recent improvement of this algorithm [8] uses Gaussian basis functions with approximate partition of unity to represent wave fronts. This is obtained by constructing the basis functions on the unit sphere around a sound source and dilating them with the traversed distance of the associated phonons. In contrast to the original approach where quadratic attenuation is used because of the spatial particle density, the improved phonon trace facilitates both linear and quadratic attenuation for the simulation of energy and pressure, respectively. Since the sign of energy is always positive, we consider pressure in order to correctly represent annihilation effects. This is obtained by scaling the basis functions according to the wave front propagation. Due to partition of unity, both simulated fields are continuous and smooth.

Phonon tracing or any other methods based on geometric acoustics (ray tracing, mirror image) fail in the low frequency range for two reasons:

1. Wavelengths are of the order of typical dimensions of the room. Hence, diffraction and interference can no longer be neglected.
2. Damping is typically low at low frequencies and reverberation times become too long to be represented by a convolution kernel of reasonable length.

Therefore, we have to fall back on wave acoustics to simulate the low frequency part of the sound field. For closed rooms the wave equation is preferably solved by the finite element method (FEM), which approximates the wave equation by a large system of ordinary differential equations (ODEs) the unknowns of which are the pressures at grid points covering the room. In general, there are by far too many unknowns to solve these systems of ODEs in real time. Hence, we need to reduce the system to a concise statespace model with similar input-output behavior in the frequency range of interest. There are many different approaches to model reduction [2]. The common observation is that system dynamics can often be represented quite well by a superposition of a few (generalized) eigenmodes. The coefficients of these modes are the unknowns of the new reduced system. Finally, assuming samplewise constant input (e.g. acceleration of the loudspeaker membrane) the continuous state-space model is transformed into a discrete one, which can be solved in real time. For a detailed description of this approach we refer to [8].

In practice, a low pass filter is used to split the input signal into a low frequency part and a remainder. The low frequency part (< 300 Hz) is handled in the way described in [8] and the remainder by phonon tracing.

SYNTHESIS

There are two major sound synthesis approaches: wave field synthesis [5] and binaural synthesis [3]. The latter approach uses either headphones or loudspeakers utilizing the cross-talk cancellation [18] to reproduce the sound field simulated at the ears of the virtual listener. The advantages are low cost equipment and low number of channels to be computed. However, the listener needs to wear either headphones or a tracking device. The sound field is only reconstructed for two positions inside the ears, filtered by head-related transfer functions (HRTFs) obtained from psycho-acoustic measurements. For a greater range of accuracy we apply wave field synthesis. The underlying theory is based on Huygens' principle implying that solutions of the Helmholtz equation correspond to distributions of sound sources on the surface of the domain (Kirchhoff-Helmholtz integral, [11]). This continuous distribution is approximated by a finite number of loudspeakers. The higher the number of speakers and the lower the frequency the greater is the sweet spot where the approximation is accurate. Usually, only the sound field of a 2D listening plane is synthesized as this requires already quite large number of speakers. For instance, Fraunhofer IDMT furnished a cinema with 192 speakers to achieve good reproduction at all seats [15]. For our purpose it is enough to have a good reproduction close to the proband's head the position of which is, except for small movements, assumed to be fixed. The present system comprises currently 4 full-band speakers and a bass. In a future system additional speakers will be added. In the following we describe our synthesis approach.

Let $\tilde{p}_i \in \mathbb{R}^{2n_b}$ be a section of the digital signal simulated in point $\tilde{x}_i \in \mathbb{R}^2$ of the horizontal measuring plane cutting the virtual room. n_b is the block length. We choose a power of 2 to speed up later Fourier transforms. The n_p points are distributed equally on a small circle of radius r about the virtual head position. The radius has to be of the same order as the wave length corresponding to the highest frequency to be reproduced: $r \approx \lambda_{\min} = \frac{c_0}{f_{\max}}$.

For $f_{\max} = 20kHz$ and a sound velocity of $c_0 = 343m/s$ the radius is only 12 mm. The exact radius depends on the number of loudspeakers n_l. To get an idea, imagine that an arbitrary sound field of frequency $f_{\max}$ has to be approximated by a polynomial with n_l coefficients which, for small n_l, will be valid only within a small radius. Choosing r this small we avoid artefacts in reproducing the high frequency part of the sound field while, at lower frequencies, the approximation will still be good also for larger radii.

The system for sound field synthesis is made to reproduce sound in n_p fixed positions on a ring of radius r about a point in the projection room. As the proband may change the line of vision in the virtual room these points cannot be directly associated with the n_p points from the fixed grid where sound is simulated. Hence, the simulated samples $\tilde{p}_{i,n}$ of time step n are interpolated and evaluated at the rotated real positions x_i using cubic splines in the angle.

The resulting signals $p_i \in \mathbb{R}^{2n_b}$ are first windowed by a lifted cosine and then subjected to a fast Fourier transform:

$$\hat{p}_i = fft(p_i^w), \quad p_{i,n}^w = 0.5\left[1 - \cos\left(\frac{\pi(n+0.5)}{n_b}\right)\right] p_{i,n} \quad \text{(Eq. 1)}$$

Synthesizing the sound field we assume that the loudspeakers induce plane waves in the central listening position and that time delay and amplification are the same for all loudspeakers. These conditions are met fairly well as we use an anechoic projection room and the speakers are furnished with FIR filters and placed on a circle. However, in a later version the plane-wave assumption will be replaced by using measured impulse responses. So far, the Fourier coefficients $\hat{q}_{j,k}$ of the signal of the *j*-th speaker are computed to satisfy:

$$\hat{p}_{i,k} = \sum_{j=1}^{n_l} \hat{q}_{j,k} \exp\left(-i \frac{\omega_k}{c_0} \langle v_j, x_i \rangle\right) \quad \text{(Eq. 2)}$$

$\omega_k = \pi_{f_s} k / n_b$ is the *k*-th angular frequency, f_s the sampling rate, and v_j the radiation direction of the *j*-th speaker. This leads to a linear system for each frequency:

$$A_k \hat{q}_{.,k} = \hat{p}_{.,k} \quad \text{(Eq. 3)}$$

For stability reasons the number n_p of reproduction points is chosen greater than the number n_l of speakers and (Eq. 3) becomes overdetermined and is solved in a least-squares sense. Moreover, in order to keep speaker signals bounded we introduce a small regularization parameter α:

$$\hat{q}_{.,k} = T_k \hat{p}_{.,k}, \quad T_k = \left[A_k^* A_k + \alpha I\right]^{-1} A_k^* \quad \text{(Eq. 4)}$$

The matrices T_k are computed once for each frequency when initializing the system. As the speaker signals will be real we have $\hat{q}_{.,k} = \hat{q}^*_{.,n_b-k}$ and only half of the systems need to be solved. Next, the $\hat{q}_j$ are retransformed into time domain by the inverse Fourier transform to get q_j^w. The superscript *w* indicates that these speaker signals will reproduce only the windowed measurements. To get the final speaker signals, the first half of q_j^w is added to the last half of the q_j^w computed for the last block:

$$q_j = q_{j,1\ldots n_b}^{w,b} + q_{j,n_b+1\ldots 2n_b}^{w,b-1} \quad \text{(Eq. 5)}$$

Finally, $q_{j,n_b+1\ldots 2n_b}^{w,b}$ is stored for adding in the next step.

VISUALIZATION

In this section we give a brief overview of the visualization approaches of the phonon tracing results. The phonon map characterizes the acoustic behaviour of a scene considering the location of a specific sound source. It consists of the reverberations of a unit pulse, coming from different directions with different time delays and specific pressure and energy distributions.

First we visualize the spatial propagation of sound waves from the source [4]. The corresponding wave front traverses the room and is reflected on surfaces, altering its intensity and energy spectrum. We visualize these sound waves by rendering small spheres representing the phonons. The spheres are colored by means of their spectral energy. Therefore, we use the RGB components, such that blue corresponds to the average of the energy by 40, 80, 160, 320 Hz, green corresponds to the average of energy by 640, 1280, 2560 Hz, and red to the average by 5120, 10240, 20480 Hz. When sliding through time, the spheres follow the simulated phonon paths. To improve the visualization of wave fronts, we use polygonal surfaces with phonons as vertices. Fig. 4 (a+b) shows an example of the described visualization approach.

In another work [7] we present different visualizations of the phonon map. The first three techniques visualize the wave fronts on the scene surfaces independent of listener position. First of all we rendered phonons as color coded spheres at their positions on reflecting surfaces (see Fig. 4 (d)). Furthermore, we visualize the outgoing direction of different particles by use of cones. In the second method we visualized the sound wave fronts reflecting from different materials by use of triangulated surfaces (see Fig. 4 (e)), which are deformed according to the traversed distance of the phonons contributing to this wave front. In the third visualization method we represented the energy distribution on a given scene surface by means of scattered data interpolation (Fig. 4 (c)). All three methods provide the option to render the energy considering the overall frequency spectrum or the energy of only one selected frequency band. Energy is color coded using the RGB color space in the first case and the HSV color space in the second case. Additionally to the methods described above, we visualized the energy received at a given listener position (Fig. 4 (f)). Therefore we render a color coded sphere at the listener position deformed according to the direction and amount of the arrived energy. These visualization approaches allow the visual representation of the phonon map on the scene surfaces as well as the representation of the energy received by a listener.

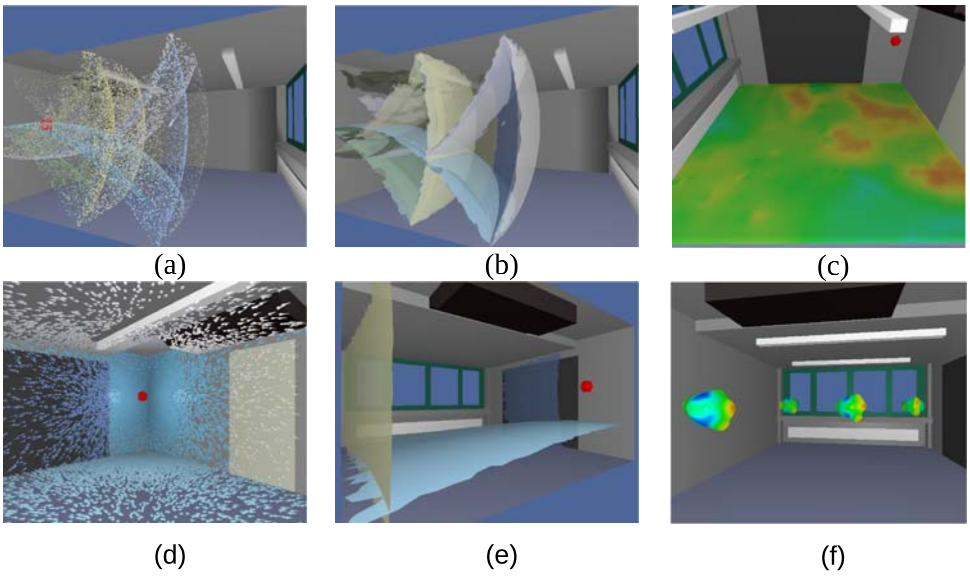

Fig. 4. Visualization of the simulation results calculated using the phonon tracing. (a)Sound particles (phonons) rendered as small colored spheres. (b)Representation of wave fronts by use of triangulated surfaces. (c)Visualization of the energy on the floor at 20 msec for the 160 Hz band using scattered data interpolation. (d)Visualization of particular phonons. (e)Clustered wave fronts. (f)Deformed spheres representation for 1280 Hz band.

CONCLUSIONS

We presented an audio visual Virtual Reality system for room acoustics. For acoustic simulation purposes we combined a geometric approach the Phonon Tracing and *FEM* solver. The auralization is performed over professional sound equipment using our synthesis approach. Furthermore we introduced different visualization techniques of the simulation results (the phonon map) on a stereoscopic display including visualization of individual wave fronts and listener based visualization. The system enables the exploration of acoustical behaviour inside a room visual as well as aural allowing the feasibility to improve the acoustics of the room during the design process. Future work includes the improvement of human interaction feasibilities with the system. Another interesting aspect is an automatic optimization of room geometry and/or surface materials. By means of well defined acoustic metrics a room can be evaluated if it is suitable for speech or music presentations. The challenge is to find an appropriate formal description which concludes how the room shape affects the given metric, to be able to start optimization algorithms for room improvement.

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