IMMERSIVE VISUALIZATION OF ROOM ACOUSTICS

Tapio Lokki and Ville Nenonen

Helsinki University of Technology
Telecommunications Software and Multimedia Laboratory
P.O.Box 5400, FI-02015 TKK, Finland
Tapio.Lokki@tkk.fi

ABSTRACT

Visualization of sound propagation inside rooms is one of the main purposes of room acoustic simulations. Visualization is often applied in teaching, but also consultants need visualization to understand better the propagation of sound waves in complex cases. Traditionally, propagation paths of sound rays or image sources (representing reflections) have been applied in visualization. In addition, wave field animations on 2-D planes have been applied. In this paper we overview traditional acoustic visualization methods and we present a novel way to look at visualizations in an immersive virtual environment. With virtual reality equipment the user can be immersed inside the 3-D models and look at the visualizations of sound propagation inside the computer model of a room. We present the implemented immersive ray-based animations computed with ray-tracing. In addition, we report particle animations that were implemented to see waveform-like visualizations. Finally, we discuss the benefits of immersive visualization as well as user interface issues.

1. INTRODUCTION

Sound waves propagate in air as longitudinal waves. The waves travel with the aid of air molecules which moves back and forth when carrying the wave. The air pressure oscillates on top of atmospheric pressure so that the air molecules crowded together represent areas of compression and sparse areas represent rarefactions. In text books, the wave motion phenomenon is often visualized with the transverse waves which are more intuitive to understand than longitudinal waves. In addition, reflection, superposition, and interference phenomena can be easily demonstrated with visualization of transverse waves.

The visualization of sound waves in rooms is often done in two dimensions, in a plane. It is easy to understand wave visualizations since everybody is familiar with surface of water and water waves. However, such 2-D visualizations do not tell enough information in all cases since in real life sound propagate in 3D. One big problem in 3-D visualizations is that 3-D information is displayed with 2-D displays. For example, in complex geometries 3-D visualizations becomes messy very fast when more and more reflections occur.

In this article, an overview of traditional visualization methods is given. Basic visualizations of sound propagation as well as visualizations of impulse responses and room acoustical attributes are discussed. Then, we present a project in which sound propagation visualizations were realized with an immersive display, a four-wall immersive virtual reality system. It provides 3-D visual image, which enables to study 3-D visualizations intuitively. The results of the project is overviewed and benefits of immersive visualization are discussed.

2. VISUALIZATION OF ROOM ACOUSTICS

The visualization methods applied to visualize room acoustics can be roughly divided into two groups. They are impulse response (IR) and sound propagation –based techniques, see Table 1. The first group consists of

Based on	Visualization technique	Measurements	Simulations	e.g. ref
impulse response	Energy-time plot	X	X	[1]
	Time-frequency plots	X	X	[1]
	Waterfalls (energy-time-frequency)	X	X	[1]
	3-D IR data ⇒ time-frequency plots	X	X	[2, 3]
	Intensity vector fields	X	X	[4, 5]
	Room acoustical attributes	X	X	[6, 7]
	Coloring of room boundaries	X	X	[6]
sound propagation	Wave fields in a plane		X	[1, 8]
	Ray paths		X	[6]
	Particle clouds		X	[9, 10]
	Image sources	X	X	[11, 12]
	Beam paths		X	[13, 14]
	Diffraction		X	[15]

Table 1: Visualization methods applied to study room acoustics. Notice that all methods based on sound propagation can be visualized as still images or animations.

visualization of measured or modeled IR or room acoustical attributes which are derived from an IR. In some cases, e.g., when trying to identify focus points or flutter echoes, more precise information on sound propagation in an enclosure is needed. Then visualizations based on sound propagation are applied.

2.1. Visualization based on impulse responses

An impulse response is a traditional tool to analyze acoustics of a certain room. It can be measured from a real space or it can be simulated with the computer model of a room. The IRs are usually visualized in energy-time, time-frequency, or energy-time-frequency space. In addition, novel techniques with multiple microphones enable to measure spatial impulse responses from which, e.g., the spatial distribution of reflections can be analyzed [2, 16, 17]. Such directional information is a challenge for visualization. So far vectors on top of energy-time-frequency plots have been applied [3] or reflections are converted to image sources and plotted on top of the photograph of the real space [12]. Vector fields obtained with intensity measurements have been widely applied in studying noise sources, but vector field visualizations in the context of room acoustics are seldom presented.

Room acoustical attributes, e.g., reverberation time or lateral energy fraction, are derived from IRs and the traditional way to visualize results is to plot attribute values in a function of frequency. In current room acoustics prediction software a common way is also to show values on top of surfaces of the 3-D wireframe room model. Visualization is done by coloring surfaces with the values computed on a certain grid. Such coloring is informative, but only one attribute and one frequency band can be visualized at the same time. To visualize many attributes or several frequency bands at the same time graphical icons have been applied [6, 7]. They can be informative, but for some reason no other implementations has been published.

2.2. Visualization based on sound propagation

Almost all commercial room acoustics modeling software apply ray-based modeling which is also called as geometrical acoustics. It is based on sound rays, i.e., it is assumed that sound travel as light. Despite of this crude approximation, it has been shown that acoustics of a room can be reliably predicted with ray-based techniques [18, 19]. With ray-based simulation methods also wave fronts can be visualized if impulse responses are computed in a dense grid. Such a visualization is depicted in Fig. 1 in which sound propagation and reflections are modeled with image source method which is extended to handle also diffraction [20].

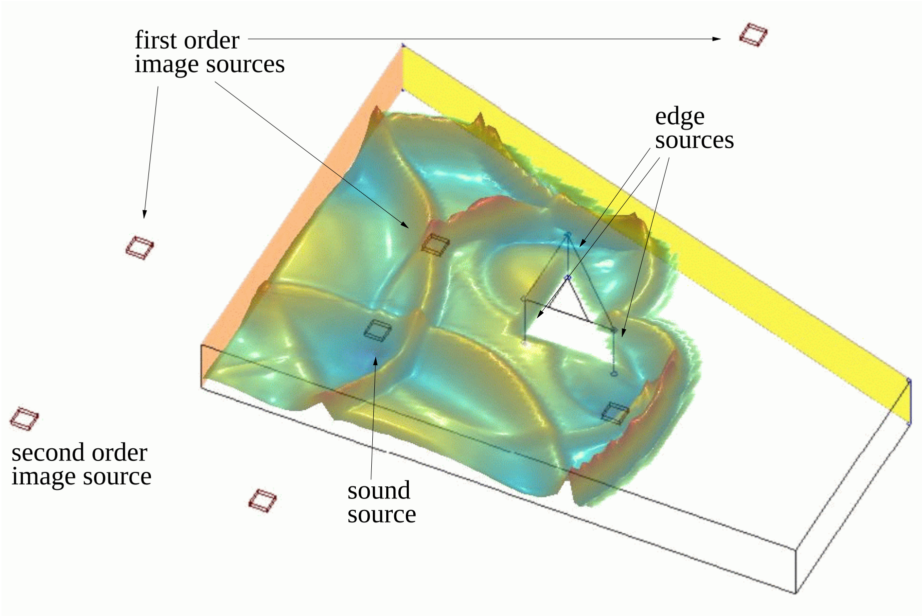

Figure 1: An example visualization created with an extended image-source method. The illustration is created by computing an impulse response in each pixel and by plotting the time moment of the 680^{th} sample which corresponds to 14.2 ms in time [20].

Ray-based room acoustic modeling methods consist of four main methods [21, 22, 14]; ray-tracing, image source method, beam tracing, and radiant exchange method. In addition to four basic principles, many enhanced variants have been presented in the literature.

Maybe the most applied technique in visualization is ray-tracing. A lot of ray paths between source and receiver positions are drawn inside a 3-D model of the room. Such a visualization helps acousticians to study spatial distribution of reflections as well as to identify possible focus points and flutter echoes. Visualizations are often still images and animations are seldom used.

A special case of ray-tracing is recently presented phonon-tracing method [9, 10] which enables visualization of sound waves constructed with thousands of small particles. Particle animations show interestingly the first reflections and how sound is diffused from surfaces. Such visualizations and animations are certainly useful in teaching and also in consultants' design work.

In the image source method sound ray paths are replaced with mirror image sources. They can be visualized as spheres around the 3-D model of a room. Image source visualizations are used in a similar manner than ray-tracing visualizations to study spatial distributions of reflections. In addition, image sources indicate the temporal structure of IR since the distances of image sources from the receiver position are related to propagation times. The image source method can be extended to handle diffraction and visualizations for diffraction image sources has also been proposed [15].

The beam tracing and radiant exchange are good methods for room acoustics prediction, but for visualization purposes no really useful implementations have not been published. However, at least animations of sound energy spreading inside a room should be quite easy to implement with these methods.

The wave-based room acoustical modeling methods numerically approximate solution for the wave equation in a grid of simulation nodes. The results of simulations can be visualized and in theory good wave front visualizations should be possible to produce. However, real 3-D visualizations have not been realized and visualizations are usually done in 2-D planes, similarly as in Fig. 1. Since wave-based methods are often applied in low frequencies, visualizations can be applied, e.g., to study mode distribution in a room.

Figure 2: An immersive visualization of room acoustics. 800 particles, emitted from one source source are animated inside a photorealistic model of an auditorium and a library.

3. IMMERSIVE VISUALIZATION OF ROOM ACOUSTICS

Immersive visualization means that 3-D images are displayed in 3D for the user. To create such a stereoscopic image, a separate image for both eyes have to be rendered. This is achieved with temporal (active stereo) or spatial (passive stereo) multiplexing of images [23]. Immersive visualization can be realized with normal monitor or with head-mounted display (HMD), but often large projection screens are applied to cover the whole field-of-view of the observer.

In the Helsinki University of Technology, we have an immersive visual display system, consisting of four 3 by 3 meters rear-projection screens[1]. The stereoscopic images are reflected into these screens and they are viewed through shutter glasses, i.e., temporal multiplexing of images is used. Since we had this virtual reality equipment available we tried immersive visualization of room acoustics. The idea for immersive visualization came from another project in which methods and techniques were developed for visualizing indoor climate and visual comfort parameters with photorealistic space model in 3-D virtual reality environment [24].

3.1. Implemented immersive visualizations

From all possible visualization techniques, presented in Table 1, we chose ray paths and particles to be tested with immersive visualization. We implemented a ray-tracing algorithm which enabled to add visualizations inside the photorealistic architectural models. Figure 2 shows two example visualizations of sound particles inside an auditorium and a library. The user can freely move (fly) inside the building models and look at how sound propagates inside the virtual model. The implemented visualizations could be rendered as stationary ray paths or animations of rays or particles. In addition, some features of rays and particles were adjustable, such as color and visibility. Different reflection orders could be colored differently or other reflection orders except one could be made invisible.

3.2. Informal evaluation of immersive visualization

The visualization of buildings and architectural models is one of the major application fields of virtual reality technology. The 3-D models of spaces are much more easier to understand and discern when the observer can go inside the 1:1 model and look at photorealistic rendering. The user can interactively move inside the model that often enables a sense of presence in the virtual world. So, it was expected that sound propagation visualizations

[1] http://eve.hut.fi

should also be more intuitive when the observer sees them in real scale inside a realistic environment. In other words immersive visualization should clarify sound propagation intuitively, not only for acousticians, but also for all people. In addition, possible acoustical problems, e.g., flutter echoes could be easy to explain to other designers and customers.

Our implementation showed that immersive visualization benefit visualization of room acoustics. It was fascinating and interesting to be in a realistic virtual room among the sound particles or sound rays. However, due to lack of implementation of all possible visualization techniques and due to computational limitations, we could not study real acoustical problems with immersive visualization. Therefore, the extra benefit of immersion, compared to traditional visualization of sound propagation, remains to be proven in future.

3.3. User interface and interaction considerations

In our implementation the user interaction with the room model and visualizations was limited to free moving inside the model. The control of time in animations would have been a nice feature, so that user could easily wind and rewind rays and particles while looking at them from different viewpoints. Such interaction would enable to study paths of particles much more carefully. However, within the time frame of this project we only implemented such animation control to non-immersive version of the software. Naturally in immersive case some extra device, often called “wand”, for control is needed.

When a lot of particles are used user should be able to choose one wall that reflects particles [10]. Or user should interactively be able to shoot particles towards one wall and then look at how they reflect from this particular surface. With two-handed interaction such features are feasible, and they could help acousticians to study complex cases.

3.4. Discussion and future work

In immersive visualization the images for both eyes have to be rendered in real time. This limits the polygon count of 3-D model and sound rays to a quite small number. In practise, polygon count of visual [24] and acoustical [25] 3-D models has to be reduced automatically. Thus, detailed visual models and big number of sound rays or particles can not be applied in visualization.

In future it would be nice to have more control to implemented animations. A fascinating idea is the possibility to emit particles from your hand (i.e. hand being a sound source) and then look at their propagation and reflections. Sound source directivity could be controled by bending the fingers, for example. Such application would need a data glove and real-time ray-tracing computation. Finally, all visualization techniques, listed in Table 1, should obviously be tested with immersive visualization.

4. CONCLUSION

This paper presents an idea of visualizing sound propagation in an enclosure with 3-D stereoscopic visual display. Although, only the surface of the immersive visualization of room acoustics has been scratched, it was found that in future immersive visualization certainly benefit room acoustic design and presentation of design results to the customers. The combination of auralization and immersive visualization was not studied, but we believe that such an immersive audio-visual experience has a great potential in room acoustics research and design.

5. ACKNOWLEDGEMENT

The authors wish to thank Senate Properties and the Finnish Funding Agency for Technology and Innovation (Tekes) for funding this project.

6. REFERENCES

[1] T. D. Rossing, R. F. Moore, and P. A. Wheeler, *The Science of Sound*, Benjamin Cummings, 3rd edition, 2002.

[2] J. Merimaa, T. Lokki, T. Peltonen, and M. Karjalainen, "Measurement, analysis, and visualization of directional room responses," in *the 111th Audio Engineering Society (AES) Convention*, New York, USA, September 21-24 2001, preprint no. 5449.

[3] J. Merimaa, T. Peltonen, and T. Lokki, "Concert hall impulse responses - Pori, Finland," http://www.acoustics.hut.fi/projects/poririrs/, May 2005.

[4] S. Weyna, "Application of microflown probe to visualization of acoustic power flow," in *Polish-Scandinavian stuructured conference on acoustic*, Poznan-Wagrowiec, Poland, Sept. 11-15 2005.

[5] S. Weyna, "Microflown based identification of vortex shadding in the space of real acoustic flow fields," in *The Twelfth International Congress on Sound and Vibration, ICSV12*, Lisbon, Portugal, July 11-14 2005, Paper 690.

[6] A. Stettner and D. P. Greenberg, "Computer graphics visualization for acoustic simulation," *ACM Computer Graphics*, vol. 23, no. 3, pp. 195–206, July 1989.

[7] M. Monks, B. M. Oh, and J. Dorsey, "Audioptimization: Goal-based acoustic design," *IEEE Computer Graphics and Applications*, vol. 20, no. 3, pp. 76–91, 2000.

[8] T. Yokota, S. Sakamoto, and H. Tachibana, "Visualization of sound propagation and scattering in rooms," *Acoustical Science and Technology*, vol. 23, no. 2, pp. 40–46, 2002.

[9] M. Bertram, E. Deines, J. Mohring, J. Jegorovs, and H. Hagen, "Phonon tracing for auralization and visualization of sound," in *IEEE Visualization*, Minneapolis, MN, USA, Oct. 23-28 2005, pp. 151–158.

[10] E. Deines, F. Michel, M. Bertram, H. Hagen, and G.M. Nielson, "Visualizing the phonon map," in *Eurovis, Eurographics/IEEE-VGTC Symposium on Visualization*, Lisbon, Portugal, May 8-10 2006, pp. 291–298.

[11] J. B. Allen and D. A. Berkley, "Image method for efficiently simulating small-room acoustics," *J. Acoust. Soc. Am.*, vol. 65, no. 4, pp. 943–950, 1979.

[12] Y. Fukushima, H. Suzuki, and A. Omoto, "Visualization of reflected sound in enclosed space by sound intensity measurement," *Acoustical Science and Technology*, vol. 27, no. 3, pp. 187–189, 2006.

[13] T.A. Funkhouser, I. Carlbom, G. Elko, G. Pingali, M. Sondhi, and J. West, "A beam tracing approach to acoustic modeling for interactive virtual environments," *ACM Computer Graphics, SIGGRAPH'98 Proceedings*, pp. 21–32, July 1998.

[14] T.A. Funkhouser, N. Tsingos, I. Carlbom, G. Elko, M. Sondhi, J. West, G. Pingali, P. Min, and A. Ngan, "A beam tracing method for interactive architectural acoustics," *J. Acoust. Soc. Am.*, vol. 115, no. 2, pp. 739–756, February 2004.

[15] V. Pulkki and T. Lokki, "Visualization of edge diffraction," *Acoustics Research Letters Online (ARLO)*, vol. 4, no. 4, pp. 118–123, 2003.

[16] A. Omoto and H. Uchida, "Evaluation method of artificial acoustical environment: Visualization of sound intensity," *Journal of Physiological Anthropology and Applied Human Science*, vol. 23, no. 6, pp. 249–253, 2004.

[17] J. Merimaa and V. Pulkki, “Spatial impulse response rendering I: Analysis and synthesis,” *J. Audio Eng. Soc.*, vol. 53, no. 12, pp. 1115–1127, 2005.

[18] I. Bork, “Report on the 3rd round robin on room acoustical computer simulation - Part I: Measurements,” *Acta Acustica united with Acustica*, vol. 91, no. 4, pp. 740–752, July/August 2005.

[19] I. Bork, “Report on the 3rd round robin on room acoustical computer simulation - Part II: Calculations,” *Acta Acustica united with Acustica*, vol. 91, no. 4, pp. 753–763, July/August 2005.

[20] T. Lokki, *Physically-based Auralization - Design, Implementation, and Evaluation*, Ph.D. thesis, Helsinki University of Technology, Telecommunications Software and Multimedia Laboratory, report TML-A5, 2002, Available at http://lib.hut.fi/Diss/2002/isbn9512261588/.

[21] L. Savioja, J. Huopaniemi, T. Lokki, and R. Väänänen, “Creating interactive virtual acoustic environments,” *J. Audio Eng. Soc.*, vol. 47, no. 9, pp. 675–705, 1999.

[22] U.P. Svensson and U.R. Kristiansen, “Computational modeling and simulation of acoustic spaces,” in *AES 22nd Int. Conf. on Virtual, Synthetic and Entertainment Audio*, Espoo, Finland, June 15-17 2002, pp. 11–30.

[23] W.R. Sherman and A.B. Craig, *Understanding Virtual Reality: Interface, Applications, and Design*, Morgan Kaufmann, 2003.

[24] M. Mantere, “Visualization of flow data in photo-realistic virtual environment,” M.S. thesis, Helsinki University of Technology, Espoo, Finland, 2001.

[25] S. Siltanen, “Geometry reduction in room acoustics modeling,” M.S. thesis, Helsinki University of Technology, Espoo, Finland, 2005.