STATE-OF-THE-ART IN AURALIZATION OF CONCERT HALL MODELS – WHAT IS STILL MISSING?

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1. INTRODUCTION

Auralization is the process in which a 3-D model of a space is made audible by convolving the impulse response of the space with anechoic stimulus signal [1, 2]. One obvious application area of auralization is the design of concert halls. Many years people have dreamed of the possibility to listen to the designed hall before the actual construction. However, auralization systems do not yet provide authentic auralization which the designer and acoustic consultants could trust. By authentic auralization we mean the creation of a virtual auditory environment that is indistinguishable from the real auditory environment [3, 4]. In this paper, we discuss the auralization of concert hall models by pointing out issues which still need more research as well as issues which have already been solved.

Technically, auralization process is a convolution of anechoic stimulus signal and a spatial impulse response of a space. The spatial impulse response, which contains information about the incoming directions of direct sound and reflections, can be obtained with simulation of sound propagation in a 3-D model. Naturally, spatial impulse responses can also be measured in a real concert hall. In other words, the auralization process requires the simulation or reproduction of the following three issues as accurately as possible:

1. 3-D directivity of sound source(s), e.g., musical instruments
2. sound propagation in a 3-D space, e.g., a concert hall
3. reproduction of spatial sound (also called 3-D sound)

In addition, auralization process needs proper anechoic stimulus signal(s), in a case of a concert hall, such signal is often symphonic music.

2. SOUND SOURCES

The problem of sound source modeling in auralization can be divided into stimulus signal gathering and simulation of directivity of sound sources.

2.1. Stimulus signals

A typical sound source in a concert hall is a symphony orchestra, not a single point source as often applied in concert hall acoustics studies. Therefore, for an authentic auralization an anechoic recording of the whole orchestra is needed, and hopefully so that each player or section is recorded individually. Then, the auralization can be done by treating each single instrument as a point source and an orchestra is constructed as a bunch of point sources.

Only few recordings of anechoic orchestral music are published [5], of which the only one containing the whole orchestra is by Denon [6, 7]. Unfortunately this recording is too noisy for auralization purposes and the whole orchestra has been recorded at the same time with close-up microphones inside a sound absorbing shell constructed on a concert hall stage. With this technique different instruments are not perfectly separated in microphone channels due to the crosstalk in microphone setup. In addition, the floor reflections are present since the floor was not covered with absorbing material. A choral ensemble has also been recorded for research purposes [8]. These recordings are made in an anechoic chamber, but there are only singers. Recently, Vigeant et al. [9] have applied recordings of an orchestra in multi-channel auralization, but the recording process of anechoic stimulus material has not been reported, and recordings are not available.

Lately, we have been recording musical instruments and results of this work are anechoic symphony orchestra recordings [10, 11]. The recording process was a tedious work, but it succeeded quite well and the results can be listened to at http://auralization.tkk.fi. The recordings will be made publicly available for academic purposes in the end of year 2008. We hope that these recordings will help researchers and more auralization studies are will be initiated.

2.2. Directivity of sound sources

Another important issue in auralization is the radiation characteristics of sound sources. In a symphony orchestra each instrument has its own frequency dependent radiation pattern that should be taken into account in the auralization.

Information about directional characteristics of musical instruments has been presented by Meyer [12, 13], and some numerical data on these investigations are available in the Internet [14]. In addition, Fletcher and Rossing [15] discuss directivity of instruments. However, a complete data set of directivities of the instruments of a symphony orchestra has not been presented with detailed documentation of the recording process. The recent anechoic recordings [10] have been made with twenty microphones mounted in a dodecahedron shape around the player. These recordings allow us to analyse the directivities of instruments, but this work is still to be completed in the near future.

In auralization at least two different methods to model the directivity of instruments have been proposed. In first method, directivity filters, designed to match the known directivities, are used for one single recording of an instrument, as presented by Savioja et al. [16]. Another way is to represent a sound source in auralization as a point source, but this point emits different anechoic signals to different directions [17]. This method, called as multi-channel auralization, requires anechoic recordings from multiple directions simultaneously. Both methods have their pros and cons, and more research is needed to find the best possible solution to model sound sources and their directivity characteristics in auralization.

3. ROOM ACOUSTICS MODELING

The room acoustics modeling has been studied for over 40 years, but still no single method has been presented that can handle the whole audible frequency range accurately, and it seems that this will be the case for the near future as well. There are two primary approaces in modeling, for low-frequencies the wave-based techniques provide the most suitable approach whereas the ray-based techniques dominate at higher frequencies.

3.1. Wave-based modeling

Wave-based acoustic modeling aims to numerically solve the wave equation. Traditional techniques are the finite element (FEM) and the boundary element (BEM) methods [18]. However, these techniques are computationally too heavy for dealing the whole audible frequency range.

	Image-source method (beam-tracing)	Ray-tracing	Acoustic radiance transfer
Arbitrary reflections	only specular	yes	yes
Memory consumption	low for early reflections	low	high
Computation time	fast for early reflections	fast	slow
Edge diffraction modeling	can be added	no	can be added
Dynamic listener	yes	no	yes

Table 1: Comparison of ray-based room acoustic modeling methods.

From the auralization point-of-view maybe the most interesting modeling principle is the finite-difference time-domain (FDTD) simulation. Use of regular grid structures enable easy and computationally efficient implementation. Especially one such technique, the digital waveguide mesh method, seems attractive [19]. The method combines techniques from pure FDTD methods and digital signal processing making it possible to use digital filters inside a simulation, for example, as reflection filters at boundaries.

3.2. Ray-based modeling

The ray-based tehcniques are based on the assumption of geometerical room acoustics in which all the wave-phenomena of sound are neglected. This means that sound is assumed to behave similarly to light and can be modeled as rays. The first subgroup of these techniques is formed by the methods finding only the specular reflection paths. The most common such techniques are the image source method and the beam tracing methods. The image source method [20, 21] is based on recursive reflection of sound source(s) against all the surfaces in the room. From computational point of view this is very unefficient, and in practice only low order reflections can be found. Beam-tracing methods, such as [22], are optimized versions for the same purpose being capable to deal with more complicated geometries and higher reflection orders. In some cases, even diffraction can be incorporated into the model [23]. Ray tracing is the most popular offline algorithm for modeling sound propagation [24] since it enables more advanced reflection modeling than the image source method. A common approach is to shoot rays from the sound source in every direction, according to the directivity pattern of the source, and trace each ray until its energy level has decayed below a given threshold and at the same time keep track of instants when the ray hits a receiver. The acoustic radiance transfer is a recently presented acoustic modeling technique based on progressive radiosity and arbitrary reflection models [25].

The comparison of properties of different ray-based methods is presented in Table 1. The acoustic radiance transfer method is the most promising when pursuing towards authentic auralization. In addition, when the computational power of computers grows the digital waveguide mesh method would be a good solution from auralization point of view. Currently, wave-based methods ore only applicable at low frequencies, but together with ray-based methods they are useful.

3.3. Need for measured reflection data

The room acoustics modeling methods can model sound propagation very accurately. In addition, modeling of all kind of reflections with bidirectional reflectance distribution functions (BRDF) [25] can be implemented quite accurately. With BRDFs modeling of sound scattering from surfaces as a function of incoming angle is possible, but the major problem is that measured scattering data is not publicly available. The current definitions of scattering and diffusion coefficients [26] are too coarse and they do not include the data in function of incoming and outgoing directions. The measurement methodology for such measurements is already known [27], but there is a big need to collect a library of acoustic BRDFs. For absorbtion coefficients such library can be found at http://www.ptb.de/en/org/1/17/173/datenbank.htm.

4. 3-D SOUND REPRODUCTION

Human hearing is omnidirectional, we hear sounds from all directions. The room acoustics simulation results, rendered audible with auralization, should also be listened to with a reproduction system that can realiable produce all possible directions. However, in practice it is impossible to use loudspeakers in every directions, thus, multichannel reproduction systems try to cover all the possible directions with a limited number of loudspeakers and signal processing. In headphone reproduction there are only two loudspeakers very close to ears and all directions have to be created with signal processing, usually by applying head-related transfer functions (HRTFs) [3].

From auralization point of view the binaural listening with headphones is the most attracting method, since then the acoustics of the listening room is not a problem. In addition, the filtering of every single reflection with HRTF functions is straightforward, although it requires a lot of processing power. However, it is well know that HRTFs are individual and it is very hard to make authentic auralization binaurally. Headphone equalization is also very tricky at high frequencies [28, 29, 4], above 5-7 kHz the response of headphones at the ear drum is different every time the headphones are put on. It seems that binaural techniques can not be applied in auralization if the aim is authentic auralization over the whole audible frequency range.

Loudspeakers can produce the whole audible frequency range more reliably, but the problems are related to the acoustics of the listening room as well as to the spatial reproduction of every single reflection. The vector base amplitude panning (VBAP) [30] is a simple solution for spatial sound reproduction, since it is computationally inexpensive and it allows the use of arbitrary loudspeaker configurations. In addition, amplitude panning does not create audible artefacts to sound, e.g., phase errors. There are also plenty of other spatial sound reproduction techniques, e.g., Ambisonics [31] and wave field synthesis [32], but they tend to create audible coloration to sound and real 3-D sound reproduction is hard with these methods. To conclude, it can be said that VBAP is suitable for authentic auralization if there are enough loudspeakers and the listening room is as anechoic as possible.

5. AURALIZATION OF MEASURED IMPULSE RESPONSES

Auralization of measured impulse responses is a nice way to study acoustics of existing spaces. However, there are several major problems in obtaining high quality impulse responses for auralization process.

The first one is related to directivity of sound sources. A sound source applied in measurements, should be able to produce directivity patterns similar to musical instruments or a human singer. Some attempts to build a controllable sound source have been reported [33, 34, 35, 36], but still a lot of research is to be done. When a good directivity-controllable source source is available, each single instrument position of an orchestra can be measured with the correct directivity and an orchestra can be represented with a group of individually radiating point sources.

Another major problem is the capture of 3-D sound so that it can later be reproduced transparently. As mentioned earlier, binaural techniques [28, 37, 38] are problematic at high frequencies, although the recordings were done with real heads. For multichannel loudspeaker reproduction a recent technique, spatial impulse response rendering (SIRR) [39, 40, 41] is very promising. With SIRR the spatial impulse response of a hall can be measured and in reproduction it is applied with any loudspeaker configuration. The methodology has also been developed further and directional audio coding (DirAC) [42] enables spatial audio recording and reproduction almost transparently.

6. CONCLUSIONS

The current state-of-the-art in the subfields of auralization is presented. We have tried to cover recent studies on the directivities of sound sources, anechoic stimulus gathering, room acoustics modeling, and 3-D sound reproduction techniques. None of these problems is totally solved, and it seems that auralization can not yet be used as a reliable tool in the design of concert halls. However, very good auralizations are not so far away and we foresee that in few years the quality of auralization of concert hall models is so good that auralization will be very useful tool in all kind of design problems.

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