APPLICATION OF VIRTUAL ACOUSTIC ENVIRONMENTS IN THE SCOPE OF AUDITORY RESEARCH

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RESUMO
Avaliações significativas no campo da Acústica Virtual facilitam a simulação de cenários acústicos controlados que serão subseqüentemente usados para a reprodução de campos sonoros plausíveis ou mesmo autênticos. Tais cenários controlados introduzem possibilidades interessantes para o projeto e a condução de experimentos auditivos, pois visam à representação das condições da vida real, aumentando potencialmente a validade dos resultados experimentais. As vantagens dessa abordagem são óbvias quando se trata da simulação de cenários com diferentes condições acústicas de sala, contendo várias fontes de som estáticas ou em movimento, o que seria desafiador e impraticável para ser criado por meio de fontes sonoras reais em ambientes laboratoriais. Nesta contribuição, é apresentado um conceito para a condução de experimentos auditivos baseados em ferramentas de realidade virtual de ponta, além de fornecer exemplos de interfaces para software de simulação acústica de salas, um ambiente de auralização em tempo real e pesquisas sobre aparelhos auditivos.

Palavras-chave: Acústica virtual, simulação acústica, processamento de sinais, áudio espacial.

ABSTRACT
Significant advances in the field of Virtual Acoustics facilitate the simulation of controlled acoustic scenarios to be subsequently used for the reproduction of plausible or even authentic sound fields. Such controlled scenarios introduce interesting possibilities for the design and conduction of auditory experiments as they aim at representing real-life conditions, therefore, potentially increasing the validity of experimental results. The advantages of this approach are obvious when it comes to the simulation of scenes with varying room acoustic conditions containing multiple static or moving sound sources, which would be challenging and impractical to be recreated by means of real sound sources in laboratory environments. In this contribution, we present a concept for the conduction of auditory experiments based on state-of-the-art virtual reality tools and provide examples for interfaces to room acoustic simulation software, a real-time auralization environment, and research hearing aids.

Keywords: Virtual Acoustics, acoustical simulation, signal processing, spatial audio.

1. INTRODUCTION

Over the last years, advances in the research areas of psychoacoustics, room acoustics and signal processing, as well as hardware and software systems made it possible to develop robust virtual acoustics tools which can be applied for auditory research. In the last three decades, various scientific validations and evaluations including round-robin comparisons have been conducted in the fields of room acoustics simulation [1–5] and auralization [6–8],...
on the input data of geometrical acoustics-based simulations [9], [10], especially on head-related transfer functions (HRTFs) [11–13], and on binaural synthesis [14–18]. Also the domain of spatial audio reproduction, based on either simulated or measured data, and for both, binaural headphone reproduction [19–22] or for various types of loudspeaker reproduction methods, have been extensively studied [23–28]. Reference data for future evaluations [29], [30] as well as toolboxes for technical evaluations [31] and terminological inventories for a perceptual evaluation [32–34] of virtual acoustic environments (VAEs) are also available to the research community. Despite the availability of various approaches, software and data, conducting listening experiments using VAEs is still a challenging process which requires extensive background knowledge of fundamental concepts as well as a thorough configuration and calibration of the selected soft- and hardware. In this paper, we present a conceptual approach for the application of tools and interfaces for the conduction of auditory experiments, e.g., for speech perception in different room acoustic conditions [35].

2. APPLICATION OF VIRTUAL ACOUSTIC ENVIRONMENTS IN AUDITORY EXPERIMENTS

The design of experiments typically involves the generation of an acoustic scene, which the test subject will perceive during the experiment. Figure 1 shows a conceptual overview how such a scene can be created and reproduced.

![Figure 1: General concept for the application of virtual acoustic environments for auditory experiments. A virtual scene is described by source definitions and room acoustic parameters. Output signals are simulated in real-time and reproduced via headphones or loudspeaker-based reproduction systems. In case of a binaural headphone or loudspeaker reproduction, the user’s movement is captured by a tracking system, affecting the simulated output signals. Depending on the type of the experiment, the test subject then has to describe its perception, for example, by answering a questionnaire, or has to perform a specific task, like localizing one or more sound sources. Such an acoustic scene includes at least one sound source, which](image)

DOI: 10.17648/sobrac-87162
is characterized by its level, its directivity information, its source signal and its position and orientation in three-dimensional space. The latter can also be varied over time through the definition of trajectories. As general environment, the virtual scene can either be an outdoor scenario or an indoor scenario, in which case the appropriate modeling of room acoustics is additionally required. To increase the level of immersion and realism, interaction of the user within this acoustic scenario should be allowed. Translatory movements in auditory experiments, however, are typically not present to a high degree [27], referring to a seated subject, reducing the complexity of simulation updates to rotatory movement only.

According to the position and orientation of the subject, and the current state of the virtual scene, a simulation engine calculates updated audio signals of this scene. As headphone reproduction is an established reproduction tool in auditory research, these signals are typically rendered based on binaural technology [36–38], using either generic HRTF data sets measured from an artificial head [39] or individual HRTF datasets [40]. A head tracking system is necessary to adjust the direction of the incident sound waves in the current scene if the test person rotates the head. In case of headphone reproduction, the signal processing block should include an appropriate headphone equalization filter [22], [41] compensating for the headphone’s transfer function. Additional signal processing is also required depending on the selected loudspeaker reproduction method, such as Higher-Order Ambisonics (HOA) [42], Vector Base Amplitude Panning (VBAP) [28], or binaural loudspeaker reproduction using crosstalk cancellation (CTC) [17], [44], which also depends on head tracking information.

3. TOOLS AND INTERFACES FOR VIRTUAL ACOUSTIC ENVIRONMENTS

In this section, different tools and interfaces, intended for an application in listening experiments, are presented. To encourage reproducible research, most of the tools are either open-source projects or are well documented in several publications and available for the research community. Figure 2 presents the software modules and interfaces which were applied in the design, preparation and conduction of auditory experiments.

![Figure 2: Schematic workflow of the applied software modules to generate virtual acoustic environments for auditory experiments.](image)

The virtual scene can be designed inside the popular 3D modeling software SketchUp (Trimble Navigation Ltd.). A plug-in extension interfacing the simulation environment Room Acoustics for Virtual Environments (RAVEN, see Section 3.2) is used to
place sound source and receiver objects, and to apply acoustic properties, such as absorption and scattering coefficients, to the surfaces of the scene. Room impulse responses (RIRs) and/or binaural room impulse responses (BRIRs) can either be simulated directly from SketchUp or, after the relevant information has been exported to model and project files, can be generated via RAVEN’s MATLAB (The MathWorks, Inc.) interface class itaRavenProject, which is part of the ITA-Toolbox (see Section 3.1). The simulated BRIRs can be loaded and exchanged in the real-time auralization environment Virtual Acoustics (VA, see Section 3.3.1), which can also be controlled via the MATLAB interface class itaVA as part of the ITA-Toolbox.

3.1 ITA-Toolbox

The ITA-Toolbox is an open-source toolbox for MATLAB developed at the Institute of Technical Acoustics at the RWTH Aachen University [45], [46] and available in a GIT repository on www.ita-toolbox.org. It applies object-oriented programming concepts facilitating the handling of audio and simulation data, including corresponding audio metadata. The toolbox further provides a framework for the playback and recording of arbitrary audio data as well as the measurement of transfer functions including individually calibrateable input and output measurement chains. Commonly used signal processing methods for the processing of audio signals and measurement data are implemented. Arbitrary signals are generated in a user-friendly manner using signal generator implementations included in the toolbox. It can also be used to assure calibrated playback levels for auditory experiments, as well as for the measurement and calculation of equalization filters compensating for the influence of hardware-related transfer functions. Various plot routines are included for the graphical output of all kinds of relevant acoustic data. New users will benefit from several available tutorials and demonstrations enabling a quick start. Communication with other auralization software modules is realized through interfaces to control the room acoustic simulation software RAVEN and the real-time auralization environment VA, which both will be presented in the following sections.

3.2 Room Acoustics for Virtual Environments (RAVEN)

As simulation tools based on geometrical acoustics [47] provide an efficient way to generate plausible simulation results in form of RIRs, they can be applied for an auralization in auditory experiments. In addition to commercially available software packages, such as ODEON, CATT-Acoustic or EASE, also publicly available research tools, like EVERTims [48] or RAZR [49], have emerged. For more than a decade, the software library RAVEN has been developed at the Institute of Technical Acoustics at RWTH Aachen University [50], [51]. The core simulation engine is written in C++ and is based on a hybrid simulation model [52] applying an image source model to calculate direct sound and early reflections, and a ray tracing algorithm for the calculation of the energy decay curves. The simulation core was validated in different projects [55], [56] and has been extended with additional functionality to simulate diffraction [57], multi-room scenarios [58] and level-of-detail modelling for frequency-dependent room geometries [59]. It includes filter synthesis methods for the calculation of RIRs and BRIRs, for RIRs in the Spherical Harmonics-domain for HOA reproduction, as well as for RIR-based sound reproduction using VBAP. The software can either be used as a real-time simulation module or as command line-based software, using the itaRavenProject interface class of the ITA-Toolbox to generate RIR files in WAV format. The recently developed RAVEN SketchUp plug-in allows for an...
integrated scene definition in an established 3D modelling program and supports real-time visualization [60] and real-time auralization [61] of a SketchUp room model. In general, RAVEN can be also applied as a real-time simulation tool for listening experiments, for example, by connecting it to VA (see Section 3.3.1) [62]. However, limited real-time processing capacities of standard desktop computers might lead to audible processing delays in scenes with a high number of sound sources and complex geometries [23]. Thus, for listening experiments, it is favorable to use RIRs which have been pre-calculated. In such a configuration, VA is capable of rendering only the direct sound in real-time, while additionally convolving the reflections, stored in static (B)RIRs not including the direct sound, with the sound source signal. Although RAVEN is not available as an open-source project, most parts of the software are freely available for academic purposes. Please contact the authors for further information.

3.3 Real-Time Auralization Environment

The creation of VAEs for auditory experiments which can be explored interactively requires a real-time auralization system. Such systems usually comprise a software framework for real-time rendering purposes, a physical reproduction system, and a motion tracking device capturing the user movements.

3.3.1 Virtual Acoustics

Virtual Acoustics (VA) is a real-time auralization framework for scientific purposes providing modules and interfaces for auditory experiments as well as audio support for audio-visual demonstrations or multimodal experiments. It is open-source, fully controllable and follows the principles of reproducible research. Libraries, Windows applications and documentation can be downloaded from virtualacoustics.org. The core of VA is written in C++ but can be controlled via a network interface which is available in different scripting and programming languages such as C#, Python and Matlab, as well as the VR environment Unity. Due to the modular implementation concept, arbitrary renderer and reproduction instances can be combined and run in parallel. The only limitation is determined by the available processing power of the host computer running the VA application. The framework offers many options for dedicated purposes when, for example, designing and conducting auditory experiments. Re-usability of established modules as well as simple extensibility is achieved by special implementations in the context of prototyping, as done for the realization of a hearing aid rendering and reproduction system [23].

3.3.2 Tracking System

Binaural synthesis relies on the relative position and orientation of the test subject to the sound sources in the VAE. Therefore, a motion tracking system is needed to compensate for movements of the test subject. Additionally, some reproduction techniques such as a CTC reproduction also rely on the test subject’s position and orientation relative to the loudspeakers. Tracking of body parts, like the hands, or devices, such as a flight stick, allows for further interaction with and control over the virtual scene. Currently, an OptiTrack (NaturalPoint, Inc.) motion tracking system (with Flex 13 cameras) is supported and can be initialized via VA’s MATLAB interface. However, all tracking devices supported by Unity can be integrated to update positions and orientations of sound sources and listeners in the designed virtual scene.

DOI: 10.17648/sobrac-87162
4. APPLICATIONS

There are numerous potential application areas for VAEs. This section presents two examples for application of VAEs in experimental environments.

4.1 Multimodal experiments

To increase the level of immersion and create an audiovisual experience for the test subject, high quality visual feedback has to be provided in addition to the audio reproduction. The integration of VA into Unity, based on an extension, makes it possible to easily render visual feedback for head-mounted displays such as the Oculus Rift or HTC Vive, cf. Figure 3. If visual feedback is of less relevance, experiments can also be conducted in an acoustically optimized laboratory environment including a loudspeaker array and a one-sided stereoscopic projection showing the virtual scene in front of the user, as depicted in Figure 4.

![Figure 3: Subject with a head-mounted display and an interaction device. A spatial audio reproduction is either accomplished via loudspeaker or headphones.](image1)

![Figure 4: Subject inside a virtual reality laboratory including a loudspeaker array and a stereoscopic projection system. Presented is an auralization and a visualization of a historic church scenario [63].](image2)

4.2 Experiments on subjects with hearing loss

An expansion of the investigation group to subjects with hearing loss fitted with bilateral hearing aids introduces new requirements for the system design. The concept of an extended binaural real-time reproduction system with an interface to research hearing aids (RHAs) is depicted in Figure 5.

Designed for subjects with mild to moderate hearing loss, the system follows a combined reproduction strategy where binaural signals are not solely reproduced over a pair of RHAs but also over loudspeakers in combination with CTC filters, accounting for the subject’s residual hearing capabilities. This approach made it necessary to extend the acoustical simulation by a multi-channel filter synthesis module facilitating the simulation of binaural hearing aid (HA) signals at the RHAs’ microphone positions, in addition to the binaural signals at the entrance of ear canals. The HA signals are based on measurements of so-called hearing aid-related transfer functions (HARTFs), cf. [64], [65], measured from the RHAs, the latter ones rely on conventional HRTF data sets (for an overview on available directional open-source data sets, visit opendaff.org).

DOI: 10.17648/sobrac-87162
Before played back over RHAs, the simulated HA signals are additionally processed on a master hearing aid real-time software platform [66] emulating conventional HA algorithms with full access to all involved algorithm parameters. The binaural signals for the external sound fields are carefully delay-compensated in relation to the HA signals accounting for real-life HA delays [67]. The system relies on the processing power of VA for real-time filter synthesis and employs RAVEN for additional room acoustic simulations, thus potentially increasing the validity of experimental results obtained from experiments on subjects with hearing loss fitted with HAs. Detailed information about the accomplished system including an objective evaluation thereof can be found in [23].

5. SUMMARY

This article provided a brief conceptual overview on how virtual scenes can be created and auralized for an application in auditory experiments. Based on a set of software and hardware tools, virtual scenes with varying room acoustic conditions including multiple static or moving sound sources can be auralized by means of different spatial audio reproduction technologies. Complex virtual scenes and increasing demands with regards to plausibility and immersion also increase the effort for the researcher when preparing experiments and require a certain expertise. Robust soft- and hardware solutions have to be carefully selected, configured and combined to achieve the desired acoustical conditions in the experiment. The presented tools can be used as powerful instruments to improve the design and conduction of auditory experiments. Most of them are available open-source and well documented, keeping even a technically complex experiment comprehensible, and in this way promoting the principles of reproducible research.

REFERENCES


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