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A real-time virtual reality building acoustic auralization framework for psychoacoustic experiments with contextual and interactive features

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ABSTRACT

The auralization of sound insulation between adjoining rooms in virtual reality (VR) environments describes the sound transmission between enclosures, where sound insulation prediction methods are applied for a high-quality auditory stimulus. In this context, a real-time building acoustic auralization framework in 3D audio-visual technology is developed to introduce more realism and contextual features into psychoacoustic experiments. This paper describes the design and implementation of this framework that is a vital part of 3D-immersive sound rendering VR-Systems. This framework relies on up-to-date knowledge of building acoustic prediction models and enables a perceptually accurate airborne sound insulation auralization in simulated environments, including important effects such as sound transmission, source directivities, and source / receiver room acoustics. Despite this realistic sound insulation, rendering between adjoining rooms, not only the indoor sources are supported at runtime, but also outdoor moving sources such as vehicles. All features are evaluated by investigating both, the overall accuracy of the building acoustics filters and the performance of implemented algorithms. This framework was used in psychoacoustic experiments by presenting a virtual building scenario, for an office to office situation, to the user with Head-Mounted-Display.

Keywords: Building Acoustic, Auralization, Psychoacoustic, Perception

1. INTRODUCTION

Sound is crucial for creating a convincing virtual reality (VR) experience, because auditory cues are relevant for the sensation of being present in an actual, physical space. It contributes to the user's sense of immersion. Building acoustics deals with sound transmission between the adjacent rooms connected through structural elements of the buildings (1). This paper deals with the creation of an acoustic virtual reality (AVR) experience of building acoustic auralization from a technical point of view. Creating this virtual world and all the objects in it (i.e. audio and visual) is implemented in a real-time VR framework, which can be used for audio-visual demonstrations and, furthermore, for psychoacoustic experiments with contextual and interactive features (2). We introduce and discuss the basics of 3D graphics rendering tools which are vital for our building acoustics implementation to create an environment and the techniques such as audio rendering, real time convolution, filter design and building acoustic plugin that make our objects appear realistic. Above all, the focus is to pay more attention to the requirements of virtual reality, including performance issues, making sure that the audio filters run fast enough in VR. We make use of the professional game and VR engine, Unity 3D. Unity is one of the most demanding game engines and is a relatively easy to use, however, fully featured.

The recent up-to-date work in acoustic virtual reality is available for room acoustical simulations and auralization, implemented in VR environments. Up to our knowledge, building acoustic auralization has not been implemented in VR environments. To achieve this, three levels of implementation are associated with a universal platform for such kind of advanced VR environments (3). First, the sound insulation prediction models and building acoustic filter design strategies. Second the filters rendering techniques: such as sound insulation, convolution, binaural 3D real-time interactive audio-visual VR technology. The general flow diagram of our technical framework is shown in Figure 1. The focus in this paper is on the third part; the implementation of building acoustics in VR and creating interactive scenes, the performance of rendering engine, and the interactive psychoacoustic experimental environment by creating an example of work performance in a short-

term memory experiment.

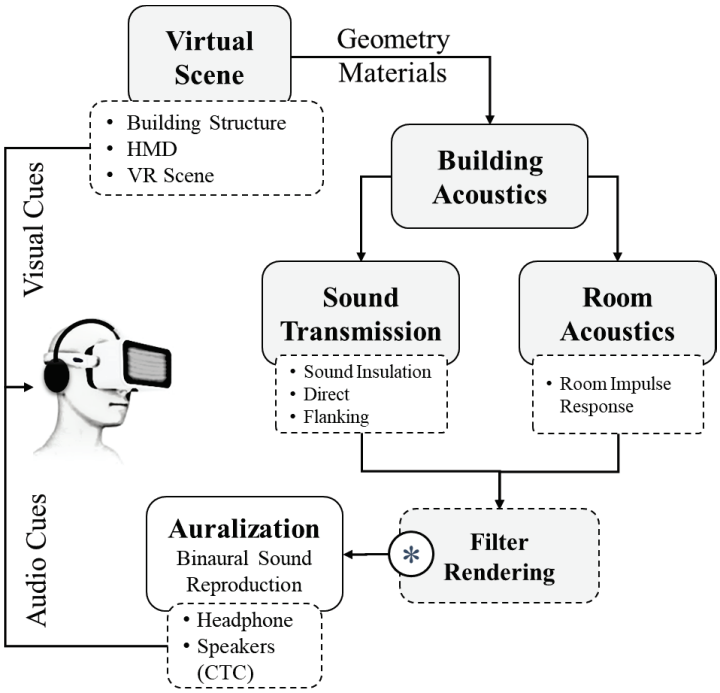

Figure 1 - Building acoustic auralization process and VR implementation design

2. VIRTUAL REALITY FRAMEWORK

In building acoustics, the sound insulation prediction was first introduced by Gerretsen (4), based on classical sound insulation theory (e.g. Vigran (5)). Subsequently, the first application of auralization of airborne sound insulation was introduced by Vorländer (6) and Thaden (7). They proposed sound insulation model based on ISO 12354-1 and designed an auralization framework by developing sound insulation filters. These filters were used to calculate airborne sound transmission paths from source to receiver placed in simple adjacent rooms of a building and made use of binaural technology for reproduction. Later on, certain improvements were made by (8-9) in these approaches, such as; source position, its directivity and incident sound intensity on the source room elements (i.e. source room walls), which was calculated based on room acoustics of the source room (reverberation of the source room from ISO standards), on contrast to common practice of assuming a purely diffuse sound field in the source room walls for all transmission paths from source to receiver. Further, improvements were proposed by (3), such as including the synthesized room impulse response based on one-third octave band values of the reverberation time and representing each radiating element (i.e. receiver room walls) by a set of evenly distributed point sources (i.e. secondary sources) on its surfaces.

The latest available auralization framework is now integrated into virtual reality. This auralization framework might be used in listening experiments and would be able to allow the test subjects to perform any task of daily life's work or learning under conditions of usual behaviour and movement. Therefore, it is intended to create more ecologically valid noise perception tests in real-time virtual reality environment. To achieve this, we make use of the professional game and VR engine software Unity (11) as our virtual environment renderer. Unity is one of the most demanding game engine and visual rendering software, which is relatively easy to use, compared to other available game engines. However, it contains all necessary tools that are needed for our purpose. It also supports the architectural constructions importing feature, directly from other third-party commercial software such as SketchUp-2017 (12), AutoCAD etc. The building of Institute of Technical Acoustics (ITA) of RWTH Aachen University is selected as a working site, as shown in Figure 2.

The choice of a suitable 3D architectural modelling software is necessary for creating a virtual building scene. SketchUp-2017 it is used to design the ITA building in a CAD model, which is imported into Unity, where the rest of the graphical features were integrated into the scene, such as

the audio source (i.e. noise source), the listener, a camera view (i.e. to visualize the scene) and the interactive scene (i.e. a scene for listening tests and psychoacoustic evaluation). Once the building model is designed, the rendering process can start. For graphical rendering there exist many third-party plugins such as Oculus Rift Unity integration plugin, Steam VR plugin etc. with basic audio rendering features such as reverberation and simple room acoustic mixers etc. These auralization features, however, are supporting only free field conditions or generic reverberation, which are not appropriate for specific auralization purposes. Therefore, the sound insulation auralization model described above is implemented for audio rendering and auralization into Unity by using its scripting features (e.g. Unity supports java and C# languages for scripting and customizing the scenes).

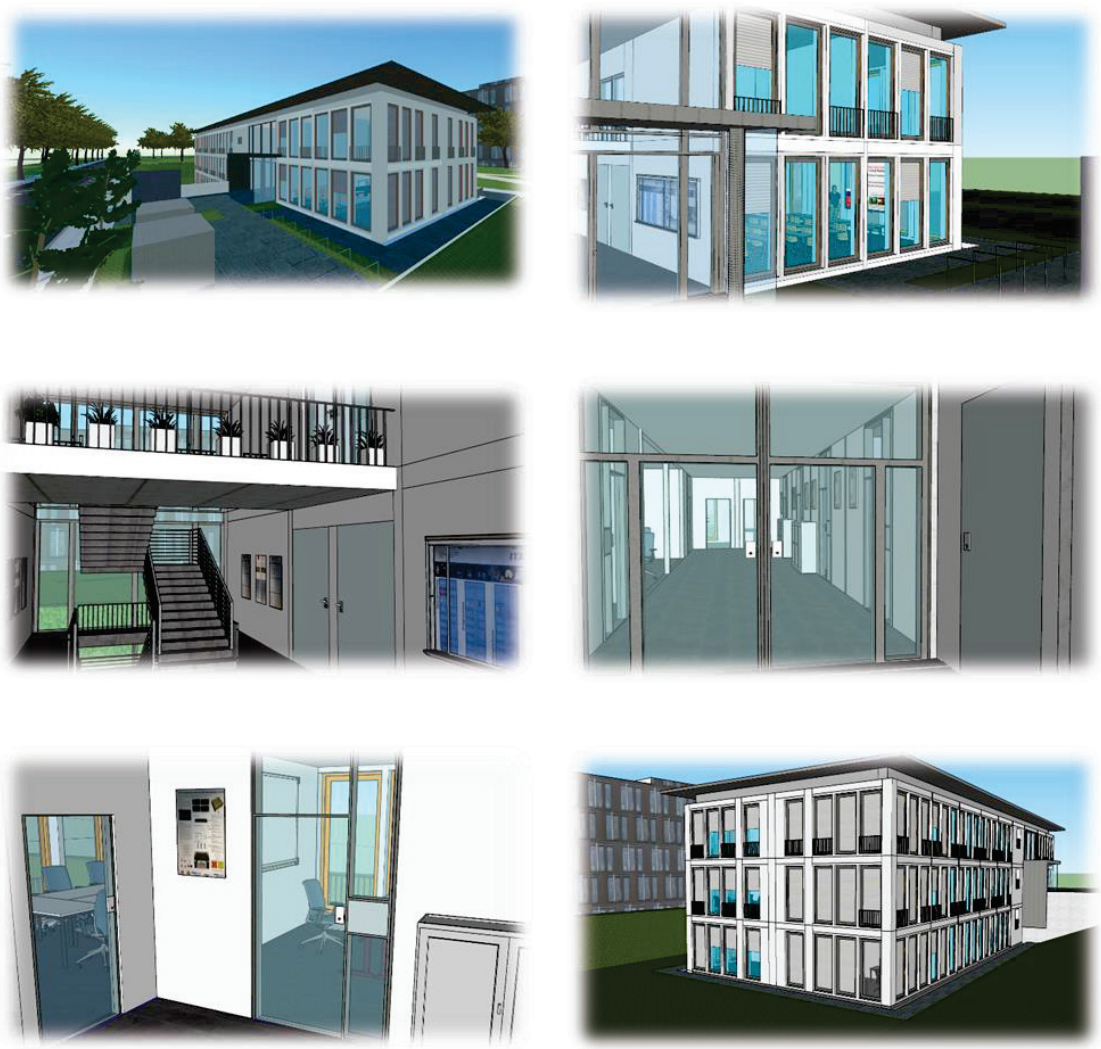

Figure 2 – ITA building: indoor/outdoor scenes in Unity

2.1 Implementation of Building Acoustic Filters

A software framework is described which includes the selection of materials to room surfaces, detection of source and receivers' positions, selection of structural properties of the building elements, the input audio files and sound card channels for auralization. The complete processing chain is shown in Figure 3. Some of the important plugin and features for the framework are listed below.

- Building acoustic model (sound insulation prediction model)
- Building acoustic filters (sound transmission)
- Architecture geometry manipulation
- Ray casting

- Real-time source receiver detections
- HRTF database (ITA dummy head recordings)
- FFT and iFFT libraries (open source from MIT USA)
- Interpolation
- Convolution
- Audio filter rendering
- Visual rendering

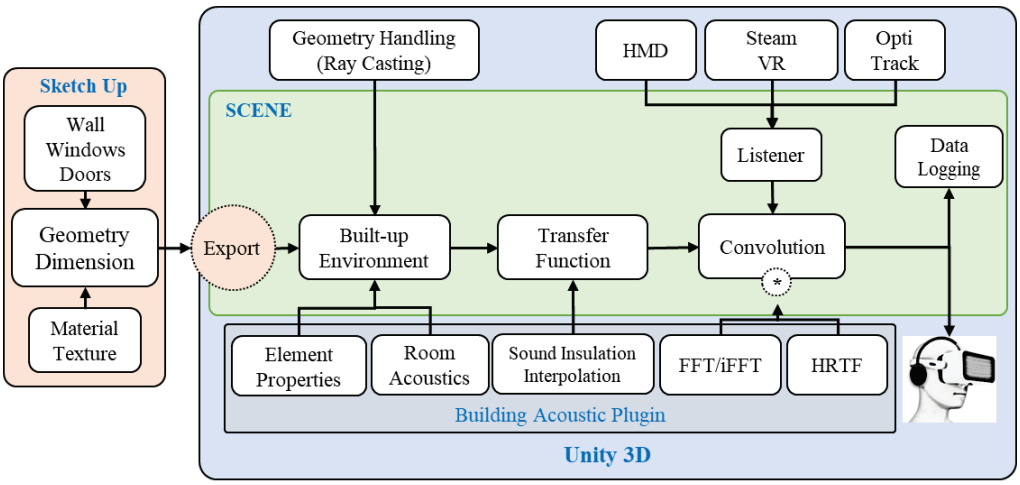

Figure 3 - Auralization Framework processing chain in Unity

2.2 Virtual Geometry Manipulation

A plugin was developed that lists building elements with the geometric dimension and material properties, by using ray casting approach. The material properties can be pre-defined or interactively assigned to elements through graphical user interface in Unity as show in Figure 4. This process provides the geometric data for calculation of sound insulation metrics. This process is performed before the auralization process starts and, hence, is required only for initialization of the main framework.

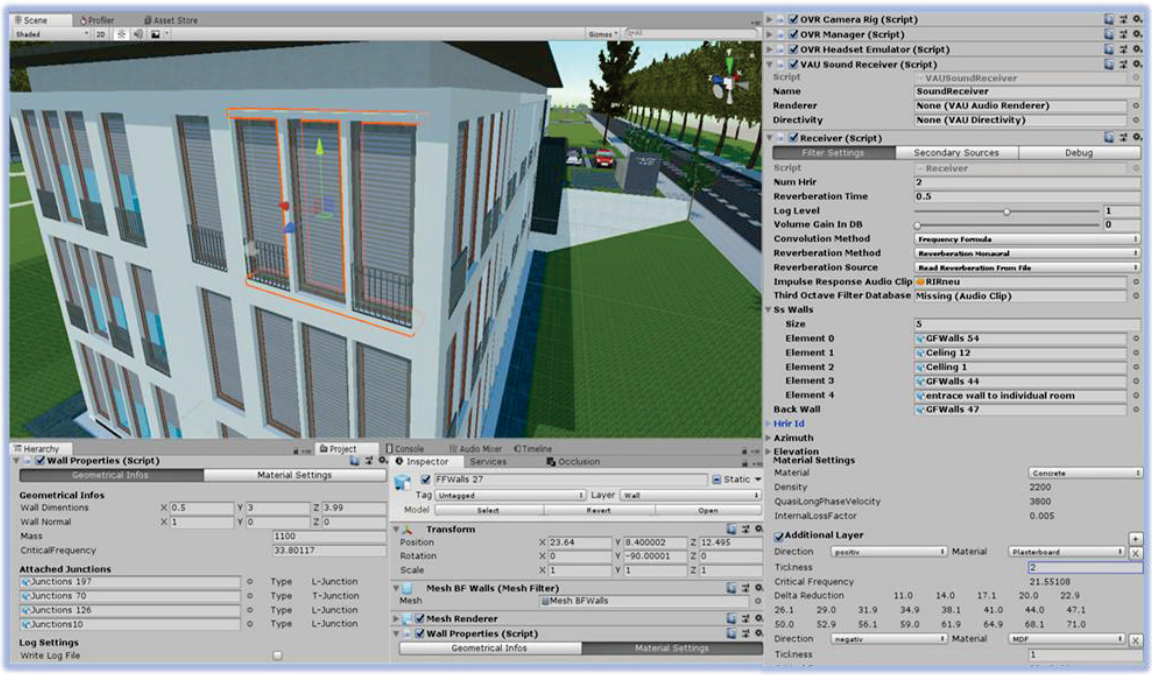

Figure 4 - Implementation: Assigning material parameters to building elements and calculations for geometric input data

2.3 Sound Insulation Metrics and Transfer Functions

The second process detects sound source and receiver positions, orientations in the dwelling (i.e. source and receiving rooms). The sound insulation metrics (i.e. the input data for filters) for each element of source and receiving rooms are calculated, and subsequently both the rooms and building acoustic transfer functions for each path (direct as well as flanking) are computed in terms of transmission coefficients or the normalized level differences (D_{nT}) spectra in one-third octave bands in the frequency range of 50 Hz to 5000 Hz. These spectra are interpolated by using a 4097 points cubic spline interpolation to get suitable audio filter with an appropriate frequency resolution for the selected adjacent rooms. Afterwards, these spectra are used to calculate the final transfer functions from the sound source to the secondary sources (patches, for reference (3)) by adding the different flanking transmission paths.

2.4 Real-Time Rendering and Auralization

Once the sound insulation filters and HRTFs data are available, the real-time convolution process for these filters is performed. Inside the receiving room, each secondary source (SS) of each element (i.e. wall) are considered as independent radiating elements.

Figure 5 - Real-time auralization and listening test scene

The directional cues for binaural signals from these radiating elements relative to the listener are considered by applying the HRTF regarding the incident angles to the listener's head. An inverse Fourier transform (iFFT) and summation is processed to get final binaural signal in time domain for auralization. The secondary sources are located at different distances relative to the listener. Therefore, they are amplitude-weighted and delayed according to the dimensions of the receiving room and the position of the listener. The final step is to convolve the binaural signal with sound or speech signal for auralization. Normally, the sound file has 24 bit and 44.1 kHz sampling rate. This operation is performed by FFT/iFFT (including overlap add method) by dividing the source signal into frames of 256 samples, transforming to frequency domain, multiplying with binaural filters and converting back to time domain. In this way, the whole rendering chain works in real time and with this, the interactive scenarios can be created in which the listener can freely move (turn the head or walk around) in the receiving room.

3. PERFORMANCE

The performance of the framework is verified for initialization and the real-time processes. Initialization include geometry manipulation, filter construction and insulation metric calculation along with room impulse response synthesis for source and receiving rooms. Real-time processing involves convolution by FFT and iFFT, source and receiver position updates (including head movements) and binaural filters. Figure 6 shows the time consumed by each major process. All computations are performed on desktop personal computer featuring an Intel Core i7-7700 CPU @ 3.60 GHz multi-core with 16 GB RAM, Windows 10 (64-bit) operating system.

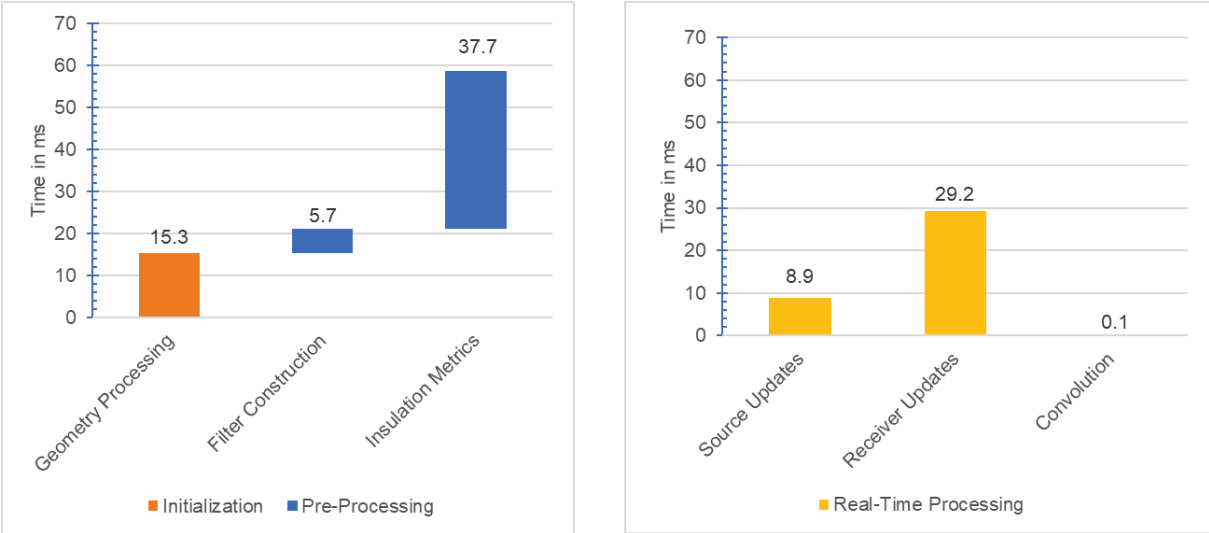

Figure 6 - Performance of the building acoustics VR plugin

4. AUDITORY-VISUAL ENVIRONMENTS

In this section, it is discussed the possibility to use this framework as a platform for psychological and psychoacoustic test environments such as cognitive performance tests under different building acoustic conditions. With this, novel experiments on noise effects, on evaluation of noise and speech effects on humans in built-up environments can be performed which go beyond the traditional listening experiments. As an example, the design of a test paradigm is explained for real-time interactive insulation auralization and for perceptual evaluation of noise stimuli with more realism and more contextual features.

4.1 Example VR Scene

To conduct a listening experiment, a test paradigm is required which explains the tasks for the participants. The scene was designed using the VR framework with a research objective of studying the cognitive performance at presence of background noise in a building. The specific question was if frequency-specific sound insulation and speech signals transmitted through the wall creates impact on the cognitive performance, in particular in comparison of intelligible and non-intelligible speech. In the scene, the participants were presented a virtual reality environment, where they are sitting in an office-like receiving room, performing a cognitive task of verbal serial recall on the screen and hence evaluating the verbal short-term memory capacity. Their answers were recorded under different background stimuli of “irrelevant speech”, originating from the neighbouring office (source room) (10). The test is designed to study the impact of meaning of background sound (intelligible speech vs. non-intelligible speech) on the cognitive performance, the sound insulating components of the building are selected in the way that the final binaural signal at the listener’s ear presents bad and good sound insulation. To present the scene to the participants for this in VR, the head-mounted display HTC Vive is used in Virtual Reality Lab. The headset uses "room scale" tracking technology, allowing the user to move in 3D space and use motion-tracked handheld controllers to interact with the environment. The results are going to be published soon.

4.2 Software Features

In order to present different background building acoustical conditions to the participants, several features can be switched on or off in a particulate test design. Activation and deactivation of room acoustics (i.e. reverberation etc.), source/receiver characteristics (i.e. position and/or orientation and directivity etc.) and most importantly the choice of the methods for sound insulation filter construction. These options can be selected during the configuration and initialization of the VR environment.

5. SUMMARY

A real-time VR auralization framework is introduced that relies on present up-to-date knowledge of building acoustic simulation techniques. It is implemented in Unity graphics rendering and game

engine software. This framework enables several important features along with sound insulation auralization for adjacent rooms. It is intended to use this platform for listening experiments where it allows the test subjects to perform any task of daily life's work or learning under conditions of usual behaviour and movement, creating more realistic noise perception tests in real-time virtual reality environments. Furthermore, in the next version of this framework, sound insulation auralization against outdoor sound source will be incorporated.

ACKNOWLEDGEMENTS

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