Utilizing Virtual Reality for Simulating the Auditory Perception In Architectural Designed Spaces

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ABSTRACT:

Rapid development in computer technology has triggered the emergence of new methods and techniques for room acoustics simulations. However, the auditory representation of a simulated space is usually given less attention than the visual representation. This paper demonstrates an approach for simulating the auditory perception in architectural spaces based on auralization, utilizing an immersive virtual computer-generated environment. Detail steps in this approach are provided including the process to transform two-dimensional drawings into room acoustics simulation. Change in the auditory perceptions in an architectural space with variety of design implementations, were recognized. Spatial perception of distance and orientation were explored while architectural elements and acoustical properties of the surfaces were changed with the goal to obtain the anticipated room acoustics quality. While multidimensional virtual environment provides the ability to investigate the visual and auditory perception simultaneously, this approach provides the ability to present computer generated spaces, synthesize auditory events and have users experiencing the architectural design impact. Evaluation of the room acoustics, given the architectural design options can be done at any stage of the design process.

CONFERENCE THEME: On Approaches, Digital Approaches and the "Real World"
KEYWORDS: virtual reality, auditory perception, room acoustics, simulation, auralization.

INTRODUCTION

Architectural space can be described as a three dimensional extension of the world around us, the distances and relationships among people, people and objects, and or between objects (Altman 1980). The three dimensional space is created to serve certain functions and being experience by human senses. Auditory is relevant to the sense of hearing, which involves three elements: 1) the physical nature of the signal, 2) the sensory detection by the nervous system, and 3) the final transformation into a perception. Research in architectural design utilizing virtual environment system has focused on visualization, while relatively little attention to auralization (i.e., rendering spatialized sound based on acoustical modelling). Spatialized sound is important in immersive virtual environment applications since it aids visual ability for localization of objects, separation of simultaneous sound signals, and formation of spatial impressions of an environment (Blauert, 1997). Experiments have shown that more accurate acoustic modelling provides a user with a stronger sense of presence in virtual environments (Durlach, N.I. and Mavor, A.S., 1995). Limitation in visual cueing when objects are outside a user's field of view is overcome with the use of auditory cues. The complexity of virtual environments varies from scenery of enormous objects, buildings, and streets with multiple auditory events to simple spaces with a simple beacon. Visual and auditory stimuli are the primary digital components in providing the human interaction interface. Factors governing the integration of these stimuli into virtual reality (VR) applications particularly to enhance human cognition can be find in references (Suied, Bonneel et al. 2008; Lauter, Mathukutty et al. 2009).

Basic methods and techniques for auditory representation in virtual environment to construct a spatial perception of the VR are provided within this paper. It relies on the simulation of the sound propagation, auralization and auditory reproduction. A brief description of research methods in room acoustics helps to understand the research objectives. The paper focuses on current auralization techniques that use input from computer simulation. Currently, research in this topic is leading to a real-time auralization for dynamic auditory experience within the virtual space (Lentz et al, 2007).

1. RESEARCH METHODS IN ROOM ACOUSTICS

The interrelationship between the room acoustics objective parameters, subjective responses of the listeners and the architectural design strategies have lead to the development of various methods for room acoustics. Research objectives may include diagnostic of the real-space, provide design improvements and evaluation of the design. A brief description about research methods applied in room acoustics is shown in Figure 1. Majority of the techniques are relying on quantifying the acoustical quality using objective parameters calculated from impulse responses. An impulse response is the time response created by the overall sound waves that travels from a source to a receiver along a multitude of propagation paths. Objective parameters measured are then correlated with subjective indices. Given the analysis and interpretation of data from objective and subjective measurements, the room or space is characterize as acoustically desirable or undesirable. Choosing the appropriate method is the key strategy to obtain an optimum design solution.

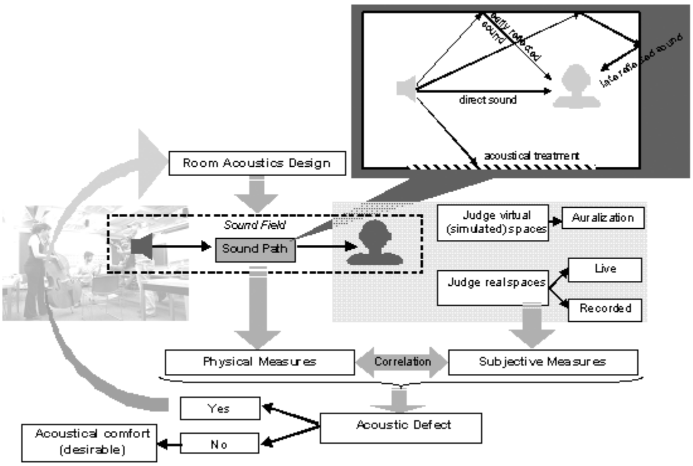

Figure 1. Research in room acoustics design

2. ACOUSTICAL MODELLING

The auditory representation of a virtual space can be synthesized by using three operational parts: sound-field modelling, auralization, and auditory reproduction techniques. The most common computational methods for simulating the propagation of sound through an environment is based on geometrical acoustic modelling (e.g. image source methods, ray tracing, and beam tracing). Many acoustic simulation software are using the combination of ray tracing and image source methods. The source emission patterns, atmospheric scattering, surface reflectance, edge diffraction, and receiver sensitivity for sound waves travelling along each path must be defined as mathematical objects. Acoustic characterization of surfaces are based upon absorption and scattering coefficients.

The acoustical modelling process may vary depends on the complexity of the space geometry and its architectural elements. It is due to the need of a sufficient number of sound rays in order to obtain a reliable computational result. Although, simplification of the modelling reduces the computational time, it also has a downside to the numerical results (Vorlander, 2008; Zeng, X., et al., 2006). A valid approximation for room acoustics simulation is by treating the sound sources as omni-directional point sources since it provides the opportunity to obtain the acoustical impacts from all surfaces. Sound energy profile of a computer simulated impulse response can be quite different with impulse response obtained from measurement in the real-space (Astolfi, 2005; Astolfi et al., 2008). Several attempts however, have been done to eliminate these differences by improvements in the techniques and simulation algorithm (Wang and Vigeant, 2007). Steps required within the acoustical modelling and computer simulation process is described in Figure 2, using a recording studio as an example of the architectural space observed.

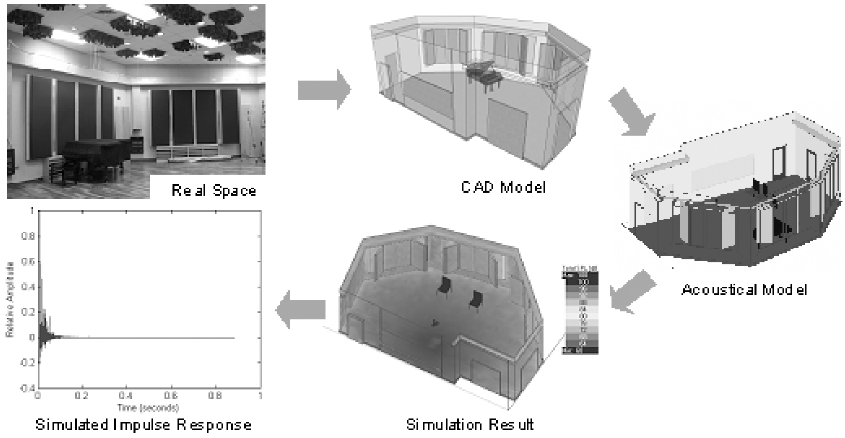

Figure 2. Acoustical modelling and computer simulation process

3. AUDITORY PERCEPTION AND AURALIZATION

Sound waves are being reflected, absorbed, and transmitted as they propagate through an environment. The portion of it being detected by the hearing system is known as the auditory event, which is responsible in creating the auditory perception (Blesser, 2006). Auditory processing by the human brain allows sound to have variety of pitch and loudness (Howard and Angus, 2006). Any objective parameters derived from impulse response measurement in the room of interest can represent average impression of the room acoustics (see Figure 2). However, the auditory event is only covered through a full auditory experience by on site evaluation or by auralization. Detail steps from computer simulation to subjective evaluation of the acoustical condition utilizing VR is described in Figure 3.

Subjective evaluation of real space are having subjects seated in the room and listen to the auditory stimuli while in auralization, subjects listen to audible numerical (simulated, measured, synthesized) data that represent the actual acoustic conditions, without being seated in the real space. General overviews of the auralization can be found in references (Kleiner, M. D., et al., 1993; Lehnert and Blauert 1992).

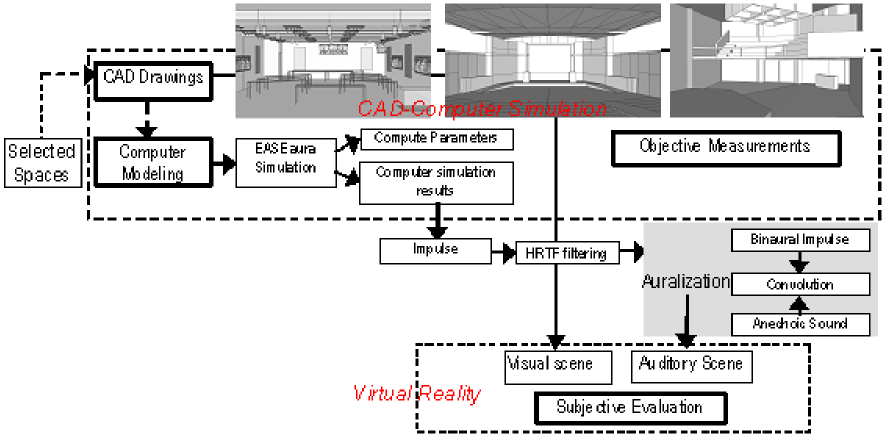

Figure 3. Methods and techniques applied for subjective evaluation of virtual spaces

Using a simulated impulse response and a sound recorded in an anechoic space enables to generate the auditory representation of a virtual space through a signal processing technique known as convolution (Vorlander, 1989). It is the main process in auralization. More advanced techniques which provides ability for real-time auralization have been developed by others (Funkhouser, Carlbom et al. 1999; Lentz et al., 2007). Some have studied the selections of system and technology based on physical design criteria for various applications such as navigation aids, virtual control rooms, integrated multi-modal virtual environment generators, and psychophysical research (Sahrhage 1999; T. Lokki 2000).

The final stage of auralization is reproducing a three-dimensional (3D) sound field for the listener. The sound reproduction utilizes 3D auditory display techniques that can be classified as: 1) binaural and transaural techniques, focuses on recreating the sound field at both ears of the listener using headphones (binaural) or loudspeakers (transaural) and 2) multi-channel auditory displays, construct 3D sound field using an array of loudspeakers. Auditory reproduction through headphones requires a further signal processing for simulating and auralizing impulse response. The delay time of the sound arriving at the left and right ear and sound scattering due to the head, ear pinna, and upper torso should be considered. This process creates a realistic condition as if the room impulse response (RIR) is recorded at the human ears. The transformation of sound-field cues into cues at both the human ear drums can be modelled using binaural technology (Lehnert and Blauert 1992). An algorithm transforms a room impulse response (RIR) into a binaural room impulse response (BRIR) utilizing the head relative transfer function (HRTF). The ability to compare and interpret the time lag between the sounds reaching the right ear versus the left ear provides the localization cues (Zwicker and Fastl, 1999).

4. ACOUSTICAL CONDITION OF THE CAVE

Application of the approach in this paper emphasized on subjective evaluation utilizing digital data with Cave Automatic Virtual Environment (CAVE) system. It is an immersive VR environment system provided in the University of Michigan 3D Lab facility (http://um3d.dc.umich.edu/). Projectors are directed to four projector screens including the floor of a room-sized cube.

4.1. OBJECTIVE MEASUREMENT

An objective measurement of the CAVE facility was conducted utilizing Acoustics camera, a system of multi-microphones arrays based on beam-forming with acoustical imaging algorithms. The background noise level, reverberation time and the loudspeakers performance are the variables measured. Noise image mapping of the CAVE surfaces shown in Figure 4 is used to observe the reflection paths and the directionality of the sound energy coming out from the loudspeakers. The sound recorded by the microphones are shown in the upper bar of the noise image mapping. Colour mappings on the CAVE surfaces are indicating total loudness level (in dB) that arrived at the microphones due to the direct and reflected sounds. The legend interprets the range of loudness level.

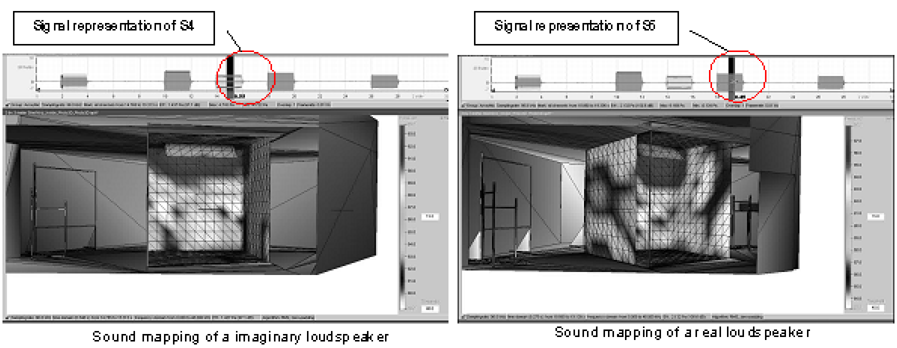

Figure 4. Mapping of the sound propagated inside the CAVE based on Acoustics Camera measurement

Computers, projectors and other electronic devices were producing high ambient noise level and it exceeded 40 dB during the measurement. The average reverberation time (T60) was in the range of 0.5-0.6 seconds. Performances of the loudspeakers were evaluated by displaying a recorded sound of a Mozart's string quartet piece at 8 locations within the virtual space. These positions are shown in **Figure 5** presented in the following section. Source 1, 3, 5, and 7 in the virtual space were matched to the positions of the loudspeakers in the real space.

4.2. LOCALIZATION OF THE CAVE VIRTUAL SOURCES

For VR applications, the auditory display devices should be able to provide 3D localization cues. The signal received at the ears is influenced by all the signals transmitted from the auditory display device together with the transformation that the signal undergoes as it propagates through the sound path. Nine subjects were brought into the CAVE and experience the auditory stimuli that were reproduced in sequence from four loudspeakers (see **Figure 5**). The recorded sounds used as the stimuli were the same with the ones used in the objective measurement.

By using a laser pointer, subjects indicated the locations where the auditory sources were perceived. The process was recorded and results of the laser points are represented on a 3D drawings of the CAVE with the grid scene as shown in Figure 5. Given the high background noise level, subjects within the cubical space were still able to locate the sound sources. The results show that all the sound sources in the virtual space are able to be identified and localized both from the objective measurement and subjective testing.

5. NEW APPROACH AND ITS IMPLEMENTATION AS AN EXAMPLE OF WORK

As mentioned earlier, the application of this approach is for subjective evaluation in room acoustics. The main objective was to understand the impact of diffuser which has become a trend in room acoustics design solution. A recording studio is used as an example of work. Diffusion is considered as an effective acoustic treatment in this type of room to control reverberation by breaking the reflected sound energy into several directions. An object that creates diffusion can be categorized as diffuser. However, acoustical panels labelled as diffusers in practice, might not be the critical element that creates the major diffusion within the sound field. Room size, amount of absorber, diffuser and space layout of variety of architectural spaces are some other variables needed to be study.

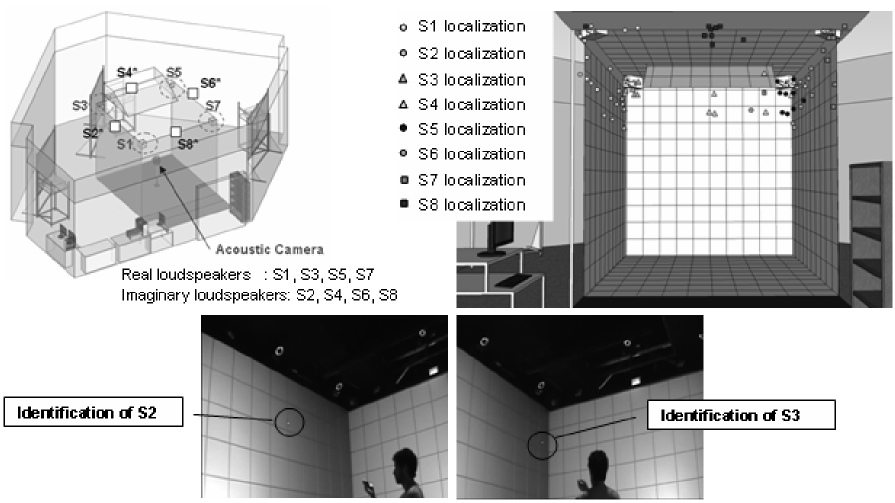

Figure 5. Subjective testing in the CAVE to localize sound sources of the virtual space

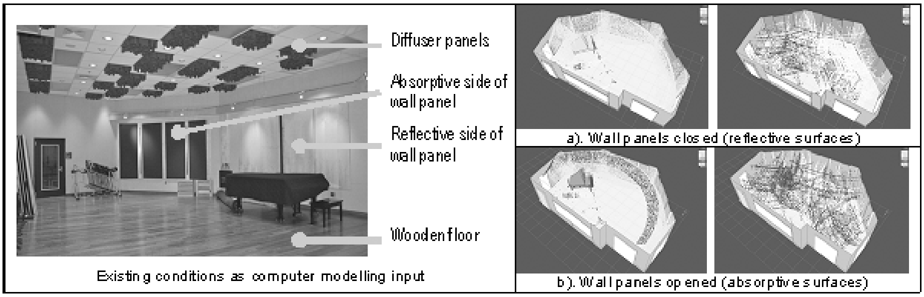

Figure 6. Existing conditions and simulation of the propagated sound waves utilizing ray tracing.

Based on measurements in the actual space and room acoustics computer simulation, several architectural elements were changed. The elements were adjustable two-sided absorptive and reflective panels, diffuser panels on ceiling, and the presence of piano as part of interior layout. The auditory events within these spaces generated from the auralization were expected to be different, particularly in spaces where the objective parameters indicated significant differences.

The architectural elements used as part of the design parameters are shown in Figure 6. Two different space conditions where the adjustable wall panels were positioned as opened and closed are compared using ray tracing techniques. This simulation indicates early and late reflections based on the propagated sound energy due to the amount of absorptions and or reflections from the surfaces of the wall panels.

Before the auditory stimuli was brought into the CAVE, a subjective test was done utilizing computer interface. This included, an investigation of noticeable differences of the recording studio with two conditions, both having the same diffusers and wall panels but with and without piano presence. Subjects listened to two auditory stimuli which correspond to those two space conditions. Subjects were then asked which was the sound that they perceived coming more from their left side. From 28 subjects, 27 of them indicated that the stimulus recorded inside the recording studio without piano is correctly heard from the left side. The results show that piano impacts sound localization. This impact was due to early reflections that interferes with the direct sound. There were differences in the auditory perception within these spaces while no significant difference were shown by the objective parameters. Details of the survey questionnaire and the subject responses is shown in Table 1. Results from auralization as auditory stimuli were utilized for subjective testing to register the auditory perception on the loudness within the degree of just noticeable differences. The clarity and liveliness (echoes) of the room were also investigated.

Auditory stimuli used within the CAVE are wave formatted data files within the sound system capabilities for a given listener's position. In an attempt to evaluate the auditory representation of a designed space, subjects were located at the same position for their selected visual and auditory scene.

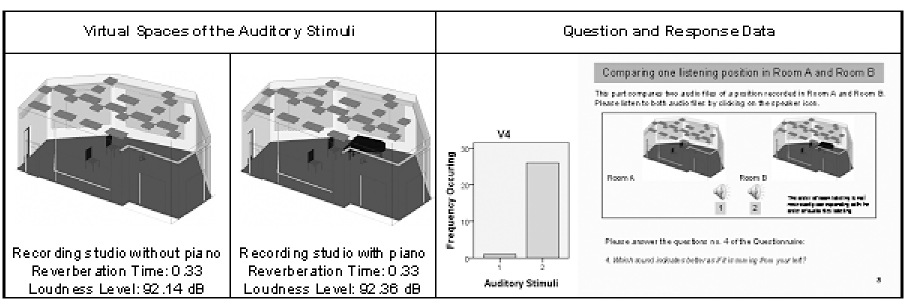

Table 1. Example of a questionnaire for an auditory perception survey utilizing auralization.

This enables one to experience and interpret the room acoustic conditions before and after the design changed. Assessment of the subjective response within the CAVE requires different survey techniques then the one described in Table 1. The use of real time feedback data collection system provides a new alternative to capture the user reaction to a given visual and auditory cue simultaneously. The subject recognition of the sound quality and its room acoustic characteristic may be different with and without the visual stimuli. The advantage of this integrated simulating techniques within virtual environments helps to accelerate decision making during the design process. The following examples are an attempt to show the application of such techniques that combine auralization and CAD computer modelling which include the visual scene information. To experience the 3D-Sound within the recording studio for its architectural features, the sound intensity were measured using

Figure 7. Simulated visual and audio scenes for a recording studio within the CAVE

Acoustic camera system utilizing beam-forming technique and the measured scene were saved in a WRL formatted file. It was then displayed within the CAVE environments. Figure 7 shows the visual representation as overlaid with the acoustical data (acoustical image) obtained from field measurement in the real-space. Table 2 provides an example of the parametric details, architectural configurations and auralization signal representations. This example of work demonstrates the major steps to be considered when utilizing this proposed approach. The true sound representation through its correct auralization combined with head related transfer function as displayed with headphones provides the most realistic feed back from the users. When the research objectives and the questionnaires within a given survey techniques are integrated, then the most reliable results are possible to obtain while using the CAVE or VR system.

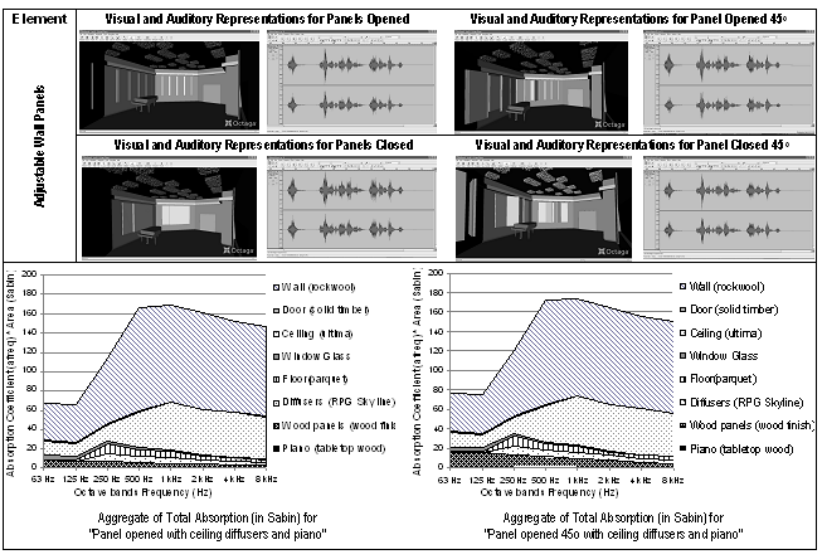

Table 2. Representation of the auditory and visual rendering of the design variations in the recording studio.

CONCLUSION

Given the recommended path within this proposed approach; it is now possible to generate auditory stimuli and eliminate errors during the auditory reproduction in VR applications. Measurements in the CAVE facility, both objectively and subjectively, have shown a relatively high background noise and other acoustical impacts which requires the use of advance headphones system. The subjective testing results for spatial auditory perception are therefore, strongly related to the quality of binaural impulse response as integrated with the quality of acoustical modelling. Choosing the appropriate auditory display devices is also a key factor. In practice, application of this new approach requires basic knowledge of 3D acoustic modelling and experience in room acoustics computation along with signal processing. Depending on the room acoustics properties, results have shown that complex models with some degree of details are necessary or required to address a particular research question. This was shown in the investigation on the piano presence and its impact to the acoustical condition of the recording studio. However, it is important to consider the trade-off between accuracy and computational time since this approach involves many sound signal processing steps and algorithms that are capable to handle architectural complexity as required within the field of audio engineering.

Once an auditory stimuli with an accurate representation of the virtual space is obtained, the challenge is on the experimental setup for the subjective testing. Direct involvement from the researcher in the CAVE and associated technology is often required. Given the visualization of the space and auralization of the auditory stimuli, users can experience the multi-dimensional environment using visual and auditory senses simultaneously. This ability may help architects and designers to accelerate the design decision making process.

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