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INTERACTIVE VEHICLE SOUND SIMULATION

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ABSTRACT
Virtual auditory environments are becoming more and more important for the development phase of vehicles, in two main applications: Driving simulators for task-oriented research and interactive sound design tools. In order to achieve an immersive auditory virtual environment, all relevant sound components have to be realized in a realistic way and updated in real-time according to the drivers actions. A concept is presented that covers all classes of relevant sound components: ambient noise, sound events within the cabin, engine, tire and wind sound, sounds of other vehicles, warning signals. Algorithms providing an acceptable balance between optimum simulation quality and required performance have been realized. Driving simulation and sound design applications are discussed, including specific tools for interactive sound engineering. Possible sound and vibration reproduction techniques in car cabins and / or laboratory environments using headphones, and / or loudspeaker arrangements are summarized.

1 - CONCEPT OF A SOUND SIMULATION SYSTEM
The virtual vehicle is doubtless one of the most interesting applications of virtual environment (VE) technologies. The "driver" feels immersed into the virtual world if he receives a plausible feedback to his actions. The most important feedback components are inertial feedback, visual feedback and acoustical feedback including vibrations. Normally a 'mixed reality' scenario is implemented: A real passenger compartment with real control instruments is combined with a simulation of inertial, visual, acoustical and vibrational feedback. For the simulation of the driving situation the following sound components have to be taken into consideration [1]:

- Engine sound, dependent on engine type, speed and load.
- Tire sound, dependent on tire type, speed and road conditions.
- Wind noise, dependent on speed.
- Sounds produced by other dynamically moving objects, especially other vehicles. Those sounds depend on vehicle speed and orientation.
- Background sounds, including interior and exterior sources.
- Commands to the driver.

Dependent on the user requirements more or less simplifications can be made concerning the generation of the different sound components. If the system shall achieve an auditory impression very close to that perceived in a specific real vehicle, a lot of specific recordings of that vehicle have to be stored in a local database. If a 'good impression' is sufficient, more general sounds can be used instead. In both cases synthesized sounds can be included. For sound design applications, additional tools for the interactive manipulation of sound components are required.
Engine sound is the most complex sound dependent on the actual status of the engine described by engine speed (r.p.m.) and load. There are at least two different approaches for the engine sound generation:

1. Waveform synthesis, realised with parallel signal generators generating sine waves or other waveforms. This algorithm is based on the fact that the dominant components of a typical engine sound can be described as a summation of sine waves. Frequencies, volumes and phases of all components depending on engine speed and load are determined by a model derived from an offline analysis of engine recordings. At least 20 - 30 components have to be generated. However, for a fixed throttle position this algorithm would produce a stationary sound, while a real engine always shows a slight instationary speed behaviour. A random-like modulation of some component parameters may be useful in order to simulate this effect. High-frequency noise components cannot be simulated by that algorithm.

2. Playback of an engine sound consisting of subsequent short recordings representing a specific rpm/load situation. For a sufficient database representation sound of about 200 rpm classes and 10 load conditions have to be stored for each engine type to be simulated. During simulation that recording which parameters are closest to the required ones is selected. For constant conditions a randomized playback of different sequences belonging to the same rpm/load class avoids the impression of periodic looping.

1.1 - Principles of binaural technology

In order to generate 3D sound the simulation concept presented in this paper uses binaural technology. For stationary sound sources the interior car sounds are binaurally recorded using a binaural microphone (artificial head or worn by a subject) and stored in a sound database. During simulation sound segments are recalled from the database according to the current driving conditions, defined by engine r.p.m., load and vehicle speed. Each selection of a new segment is optimized with regard to a smooth transition. For constant conditions random principles have to be included in order to avoid periodic sound patterns. Databases of binaural recordings can be used for virtual sound sources remaining in the same position with regard to the driver all the time. Thus, this principle can be applied to engine, wind, tire and background sounds.

All moving virtual sounds have to be generated by binaural synthesis from monophonic sources, i.e. by convolution of the monophonic input sound with head-related impulse responses (HRIR) that include all information about the direct sound path from a sound source at a certain position to both ears. HRIR sets consist of HRIR for several directions, normally all directions required for the simulation. They have to provide a sufficient spatial resolution in order to achieve smooth movements without audible steps. In order to be compatible to the binaural recordings described above the HRIR of an artificial head or of a subject will be used.

To move a sound pattern in the virtual space the signal has to be processed by following steps:

- simulation of the directivity of the sound source.
- simulation of Doppler shift.
- convolution with left and HRIR right according to the direction of the direct sound, and in addition − if required − also for reflections at trees, houses, walls etc.
- if required, reverberation is added to the binaural signal.
- binaural playback.

Since position and speed of the dynamic change permanently, so the system parameters (sound direction, delay, Doppler shift, etc.) have to be adapted in realtime. In a typical driving situation, most dynamic objects represent oncoming or overtaking vehicles, but of course pedestrians or animals can also produce moving sounds.

1.2 - Doppler shifts

For fast moving objects resp. listeners the well-known Doppler-shift has to be considered. For the general situation that both − listener and sound source − are moving, only source velocity components pointing to the listener and vice versa are considered. With v_{S1} denoting the relevant source speed component and v_{L1} denoting the relevant listener's speed component a general expression can be found for the Doppler shift f/f_0:

$$f = f_0 \frac{c + v_{L1}}{c - v_{S1}} \qquad , c > v_{S1}$$

For practical implementation this equation can be used to adjust the sampling frequency of a given pre-recorded sound in order to get the correct Doppler-shift for the output signal. Thus, a time-variant up-/down-sampling algorithm has to be inserted in the signal path. The Doppler-shift has to be calculated before binaural coding, because otherwise the spatial information included in the HRIR would be affected. Since the secondary sound sources may move different with regard to the listener, a different Doppler-shift has to be taken into consideration for each reflection. For practical applications, however, this effect can be neglected due to masking effects.

1.3 - Transfer path analysis

In addition to binaural recordings at the driver's position also sounds generated by binaural transfer path analysis / synthesis [2] can be included into the sound database. For analysis, a set of microphones placed close to the main sound sources are used for recording, in parallel all relevant transfer pathes from those source locations to the driver's position are measured in situ. For synthesis, the binaural sound is re-synthesized summing up the contributions of all transfer pathes. Such a model introduces the possibility to modify the characteristics of a single car component (e.g. an engine mount) and listen immediately to the sound effect perceived by the driver.

2 - SOUND DESIGN TOOLS

For sound design applications, the following tools can be realized online during simulation:

- Changing the complete sound scenario intuitively by just driving virtually.
- A/B comparison between different engines.
- A/B comparison between wind and tire noises.
- Online filtering of those three sound components.
- Recalculation of a binaural transfer path synthesis model as described above. During simulation each transfer path can be modified separately.

The big difference to well-known laboratory sound design tools is that all sound perception effects are perceived within a quite realistic context, namely driving a virtual vehicle.

3 - REPRODUCTION OF SOUND AND VIBRATION IN A CAR CABIN

3.1 - Introduction

As mentioned above, binaural technology is based on the idea of reproduction of the ear signals in order to reproduce the complete hearing sensation as described in [3, 4]. This idea implies the use of headphones since only headphone reproduction ensures that no cross talk between the both channels of the binaural signal occurs by the reproduction system, i.e. the right ear receives only the signal recorded in the right ear and the left ear only that recorded in the left ear.

Sometimes, e.g. in driving simulation, headphone reproduction is not desirable in order to achieve a virtual situation in which all aspects are close to reality. In that case loudspeaker reproduction of all sounds is required.

During the development of the artificial head as described in [5], theoretical research and numerous experiments with loudspeaker reproduction have been performed. Since head-related interaural time differences are included in the HRTF, the spatial definition of auditory events in a loudspeaker playback situation based on artificial head signals often delivers better results than solutions using coincident or semi-coincident microphone techniques. The HRTF is still present in loudspeaker playback, but without coloration of timbre, due to normalizing equalization (e.g. free-field or diffuse field equalization). Head-related time and frequency domain information remains in the loudspeaker reproduction despite the non-binaural presentation mode, giving excellent imaging and transparency.

3.2 - Two-loudspeaker arrangement

Arrangements for loudspeaker reproduction using crosstalk canceling techniques have been described in [6], [7], [8] and [9]. Under ideal conditions (anechoic chamber, exact positioning of the listener, correct equalization) it is possible to achieve the same (or even better) reproduction quality for binaural signals compared to headphones. The disadvantage of this method, however, is that these environmental conditions cannot be easily realized in car cabins.

3.3 - Four-loudspeaker arrangements in rectangular rooms

As an alternative solution a 4 loudspeaker arrangement has been developed, first for rectangular listening studios [10], later it has been adapted to car cabins. The principle of this reproduction technique is very simple: The left hand speakers are fed by the left channel of the binaural signal, the right hand speakers are fed by the right channel of the signal, typically adjusting same levels for front and rear loudspeakers. Each loudspeaker is separately equalized in order to get a correct timbre of the overall sound, delays resulting from different distances to the listener are compensated. The big advantage of such type of reproduction is that small movements of the head of the listener do not disturb the acoustical image, the sound sources stay virtually stable in place, no discoloration of the sound is perceived. Localization tests [10] showed as a general tendency that similar localization accuracy can be achieved by a 4-loudspeaker arrangement in comparison with headphone reproduction. In addition it can be stated that the localization in reverberant rooms gets better compared to the unechoic situation. Additional experiments using the loudspeaker arrangement in a car cabin showed a reasonable spatialization capability [11]. Due to the problematic acoustics in a car cabin the localization accuracy is slightly reduced in comparison with headphone reproduction. Fig. 1 shows a typical application in a car cabin. For sound reproduction the implemented loudspeakers can be used. The four speaker levels have to be balanced carefully. In order to give a more realistic simulation low frequency airborne sound down to 20 Hz is generated by a high quality subwoofer system.

3.4 - The integration of vibration simulation

Realism of virtual environments can be significantly enhanced by the integration of feedback channels not addressing the ears, but the whole body: very low frequency airborne sound as well as structure vibration. For that purpose the binaural technology as described above has to be extended. For recording, multichannel measurement systems have to be used that allow the recording of acoustical and vibrational data simultaneously. As a simplification for some applications (e.g. driving simulation for training purposes) it is sufficient to generate those vibration components directly from the binaural recording by lowpass filtering and equalization. For playback, suitable playback arrangements have to be found.
The vibrational situation in a passenger compartment can be divided into two main categories:

- Vibrational excitation through operational devices, i.e. engine, transmission system, wheels and suspension system. A typical example is the second order of a 4-cylinder engine.
- Vibrational impact by "comfort features", such as power windows, electric sunroof, power seats and electrical mirrors. The electrical devices used here primarily cause low frequent noise shares ("booming") and vibrations.

At present, there is no detailed research yet on the dependencies between vibrational and acoustical perception. Examinations have shown a trade-off phenomena between sound and vibration when the vibration level is in the range of perception threshold: The loudness is judged higher when vibrations are present in this case [12]. The experience when dealing with complaints in vehicles have shown that normally the consideration of vibrations at passenger's seat and of the rotational vibrations at the steering wheel is sufficient for a first approach. The mentioned vibrations represent the major part of relevant influences for the judgement. For particular devices - for example power windows - the excitation of other points at the car body may be considered. Introductory research tests within the European research project OBELICS (BRPR CT96-0242) have shown that the use of combined vibroacoustic playback systems leads to more reliable judgements of sound characteristics and sound quality. Based on this, a suitable vibro-acoustical playback system may consist of airborne sound via head phone(s), low frequent sound (20 - 150 Hz) via subwoofer(s), and vibrations at steering wheel and seat via excitation devices [13]. The set-up of such a system is shown in fig. 1.

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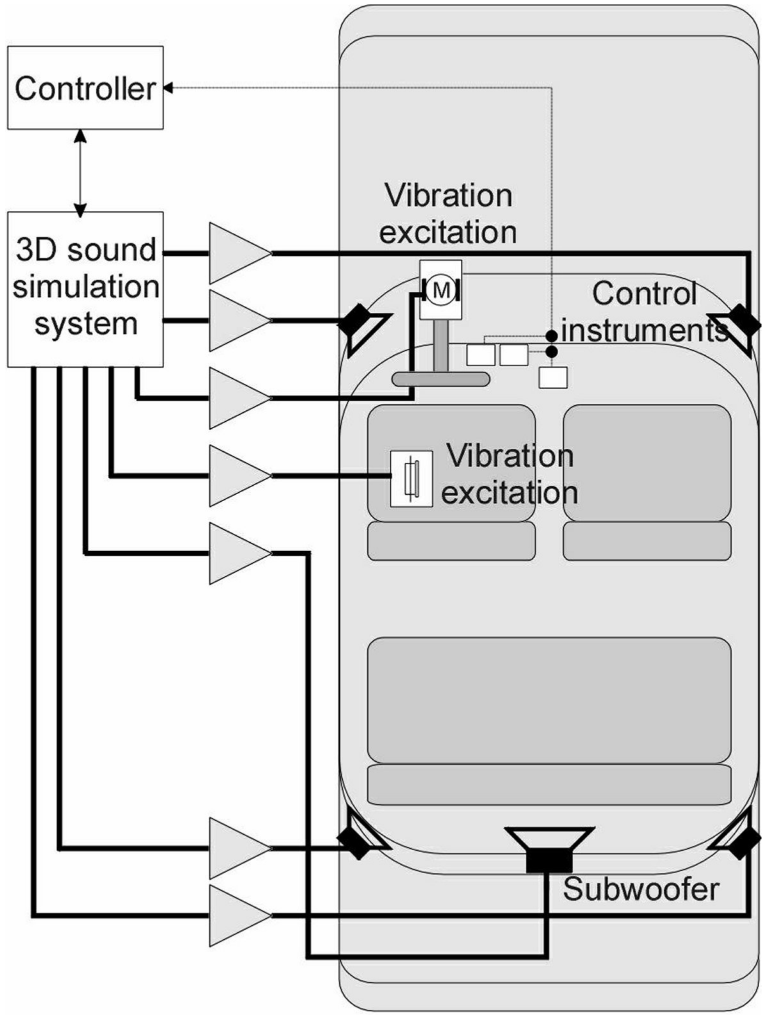

Figure 1: Arrangement for sound and vibration reproduction in a car cabin.

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