# Virtual Reality for Immersive Auralization of Acoustic Vehicle Alerting Systems

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***Abstract*— Nowadays, there has been a growing interest in virtual reality (VR) technology in the automotive industry, for the virtualization of new vehicle development. This solution allows us to reduce the number of prototypes to be built, increasing the tested cases and at the same time significantly reducing costs and time. In this paper, a methodology is presented to achieve a complete VR auralization of an Active Vehicle Alert System (AVAS) installed on an electric vehicle. A passing maneuver at different speeds was recorded using a dual-lens camera and a spherical microphone array (SMA), while a smartphone inside the car also recorded the position with a specifically developed application. A virtual test environment was developed to auralize the car maneuver in real-time, also considering the directivity and frequency response of the AVAS speaker, the Doppler effect and the reflection on the road. In this way it is possible to immediately replace the type of transducer and sound to be reproduced, allowing the result to be evaluated with immersive tests having a high degree of realism. The future outcome of the research presented will consist of jury tests to objectify the choice of AVAS sounds, based on the different perception of appreciation of people in various countries of the world, also in relation to the type of vehicle. In addition, it will be possible to identify the most perceptible sounds, thus increasing the safety and effectiveness of AVAS itself.**

***Keywords—Acoustic Vehicle Alerting System (AVAS), ambisonics, auralization, automotive, beamforming, immersive spatial audio, Spherical Microphone Array (SMA), Virtual Reality (VR)***

## I. INTRODUCTION

In the last decade, augmented reality (AR) and virtual reality (VR) technologies have found many applications in the automotive industry. A discussion of benefits as well as the barriers of these new tools for automotive applications is presented in [1], [2], while in [3] the authors produced a literary review of the market products, allowing a car marker to choose the best option based on its needs, in consideration of the opportunities and limitations offered by both hardware and software solutions. In [4], [5], it was discussed the potential benefits of using AR/VR for the car customization process, in which the users can visualize and personalize their vehicles in an immersive virtual environment. Similarly, in [6], [7] a solution was presented to evaluate and optimize the user experience with a combination of VR and body information, such as eye tracking, electrocardiogram (ECG), electroencephalogram (EEG), providing deeper insights to car makers of the user interactions with the vehicle. The use of VR is considered no less important in education. In [8], [9] virtual laboratories were employed for automotive engineers' education, while in [10], [11], [12], VR environments were used for enhanced training of vehicle assembly.

The immersive visualization and assessment of vehicle performance is another hot topic for automotive industries. Already in 2012, a VR system based on a 3D engine was used to visualize the effectiveness of an anti-lock braking system (ABS) emulated in real-time under different conditions [13], while in [14], [15] spatial audio recordings obtained with a spherical microphone array (SMA) and a camera array were employed for the sound quality assessment inside car cockpits. In [16], [17], Pinardi et al. presented two microphone arrays specifically developed for evaluating the spatial performance of Active Noise Cancelling (ANC) systems installed on cars.

Nevertheless, the most popular application appears to be the virtualization of new vehicle developing and testing stages. In [18], [19], [20], [21], numerical simulations were employed to obtain head-tracked auralization of the car infotainment systems with three degree-of-freedom (3-dof). In [22], an AR tool was developed to compare manufacturing with the cad design, overlaying the real and the virtual parts. In [23], a VR application was developed to visualize and validate the experiments with autonomous vehicles carried out by car companies. Similarly, in [24] the authors employed immersive simulations to improve autonomous vehicle safety. Finally, in [25] the authors realized an auralization of the Acoustic Vehicle Alerting System (AVAS) installed on electric cars, however not exploiting the potential of VR technology.

In this paper, a 3-dof VR auralization of the AVAS installed on electric cars is presented. The developed solution combines numerical simulations of the AVAS directivity with outdoor measurements of the background, namely the environmental noise and the tire rolling noise, performed with a SMA and a compact dual-lenses camera. A Digital Audio Workstation (DAW) has been used for real-time signal processing: the panoramic video is rendered on a Head Mounted Display (HMD), while the Ambisonics spatial audio is delivered with head-tracked binaural rendering through headphones. The presented work can be employed to optimize the AVAS sounds, allowing sound designers and Noise,

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Vibration and Harshness (NVH) engineers to easily perform immersive tests in a VR environment with a high level of realism. This is a top-of-the-edge topic for car makers, as testified by several publications in the recent period about the optimization of AVAS design [26] and the tuning of the AVAS sounds to improve their recognizability [27] and the interior sound quality [28].

The paper is arranged as follows: Section II.A provides a brief description of the Ambisonics theory, Section II.B presents the method for encoding the 3D directivity of the AVAS source into Ambisonics format, and section II.C illustrates the procedure for background noise recordings. In Section III, the AVAS auralization processing is presented, while Section IV summarizes the conclusions.

## II. Material and Methods

### A. Ambisonics theory

Ambisonics is a method for approximating the spatial information of a sound field in one point of the space with a reduced number of signals. This set of signals is a Spherical Harmonics (SHs) expansion of the sound field at the recording position, where the SHs are basis functions with orthonormal properties for the Fourier transform on a sphere [29]. A microphone array is used to obtain such a set of SHs, by applying a conversion, namely beamforming, of the pressure signals recorded at the capsule positions. Three of the most relevant references, providing a comprehensive discussion of spherical array processing, are [30], [31], [32]. The SHs are calculated as a function of the order $n$ and the degree $m$, as follows:

$$Y_n^m(\vartheta,\varphi) \equiv \sqrt{\frac{2n+1}{4\pi}\frac{(n-m)!}{(n+m)!}}P_n^m(\cos\vartheta)e^{im\varphi} \quad (1)$$

where $\vartheta$ and φ are the azimuth and elevation angles and $P_n^m$ the associated Legendre functions. The SHs up to $n = 3$ and $-3 < m < 3$ can be seen in Fig. 1 (image from [33]). The relation between the number of SHs, *nSH*, and the Ambisonics order $n$ is given by:

$$nSH = (1 + n)^2 \quad (2)$$

Nevertheless, the higher the order, the better the approximation of the spatial information, but also the higher the number of capsules required for the microphone array. The optimal number and positioning of transducers (either microphones or loudspeakers) to build spherical Ambisonics arrays is discussed in [34], [35] and it is beyond the scope of the paper. In this work, the Eigenmike-64 (EM64) was employed, a SMA of 84 mm diameter featuring 64 electret capsules, capable of delivering Ambisonics format up to $6^{th}$ order, that is $nSH = 49$ from (2). The working principles of this microphone array can be found in [36].

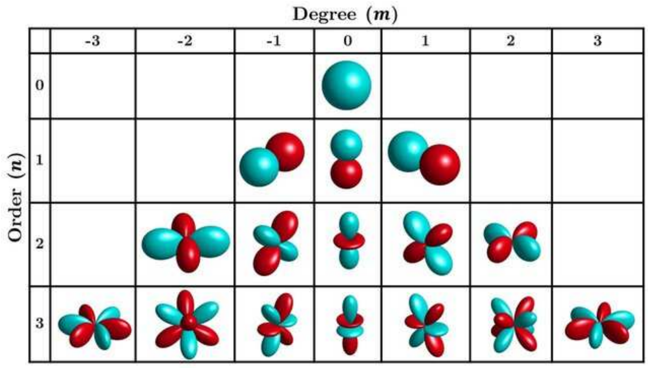


Fig. 1. Real parts of the SHs up to order $n = 3$, with lobes in cyan color indicating positive values and lobes in red color indicating negative values.

### B. AVAS source directivity

In electric cars, as well as the presented work, the AVAS sound is usually reproduced by a loudspeaker installed in the front part of the vehicle [37], [38], despite some car companies replaced the loudspeaker with electrodynamic shakers attached to the car panels [39]. The directivity of the AVAS source is required for a correct auralization. In [40], a process to characterize the AVAS directivity is suggested, making use of pressure measurements performed with a set of microphones in free field. Then, an inverse method is applied to recover a set of vibration patterns of the virtual speaker surface, which can be used to feed a numerical model.

In our work, the opposite approach was employed. A numerical model of the front part of the vehicle was solved with the Finite Elements Method (FEM), with the aim of spatially encoding the 3D AVAS directivity into Ambisonics format. First, two simulations were performed in the frequency range 150 Hz - 2 kHz, which is the same range considered in the current AVAS regulation. In the first simulation, the entire car cabin was considered, while the second was only including the front part of the vehicle. The sound pressure level (SPL) was evaluated and averaged among several points located behind the vehicle, maintaining the same positions in the cases. The comparison between the SPL spectra of the two models (Fig. 2) allowed us to assess that not including the entire cabin does not result in a significant reduction of accuracy. This allowed us to reduce the dimension of the volume to be simulated, thus considerably shortening the computation time.

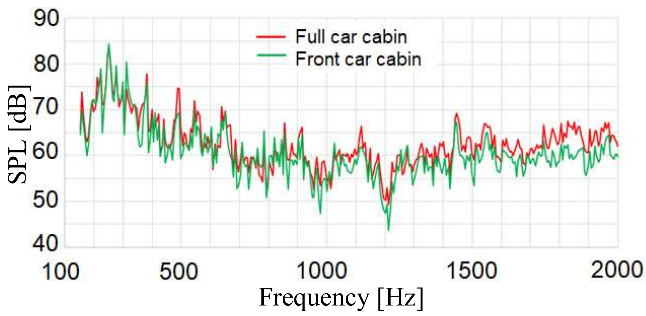


Fig. 2. Comparison of SPL spectra behind the car cabin, when full model (red) and front part only (green) are considered in the numerical model.

To encode the 3D directivity of the AVAS source, a set of virtual pressure microphones was positioned around the front part of the car cabin (red dots in Fig. 3). The number and the positions of these virtual capsules depend on the desired Ambisonics order and the sampling approach. With the aim of balancing the accuracy of the result and the computation effort, Ambisonics 5th order was chosen as target, and the nearly uniform sampling was employed [41], since it reduces the required number of capsules $N$, as:

$$N \cong 1.5 \cdot (1 + n)^2 \tag{3}$$

The positions of the virtual capsules were chosen based on the Spherical Design theory [42], a mathematical method to approximate a unit sphere in $R^n$ with a finite set of $N$ points so that an integral over the sphere of a polynomial of degree $t$ or less is equal to the average value of the polynomial evaluated in the set of $N$ chosen points [34]. Due to the importance of the parameter $t$, they are also called Spherical t-Design. More on Spherical Design is discussed in [43], [44], [45], [46], while in [47] many precalculated spherical designs can be found, for degree $t$ from 1 to 21. When a spherical design is employed for Ambisonics encoding, the relation between the order $o$ and the degree $t$ of the spherical design is as follows:

$$t = 2 \cdot n \tag{4}$$

Being $n = 5$ in the present work, it leads to $t = 10$, which requires $N = 60$. A spherical air domain was defined around the front part of the vehicle (green sphere in Fig. 3), having the minimum radius required to completely include the geometry, thus minimizing the number of elements and therefore the computation time. One can note the floor reflection is not considered in the model. In fact, it will be dynamically calculated in real-time in the DAW processing (see Section III). Eventually, the sound pressure at virtual pressure sensors was obtained by relying on the "exterior field" calculation, a function included in the simulation software.

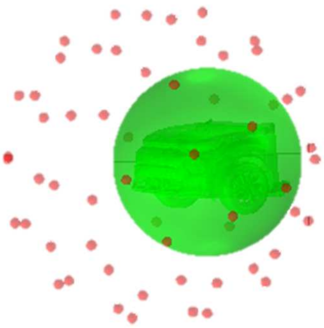

Fig. 3. Virtual pressure microphones (red dots) arranged around the air domain (green volume) surrounding the front part of the vehicle.

The simulation was solved in frequency domain with a constant frequency step, in the range 70 Hz – 5.7 kHz to cover the entire response of the AVAS sound, despite the current AVAS regulation only considers the frequency range 150 Hz – 2 kHz. This was done since the frequency components of the AVAS sound below 150 Hz and above 2 kHz are also required for obtaining a realistic auralization. The result is evaluated at each of the $N = 60$ virtual capsules and converted to time domain by means of the Inverse Fast Fourier Transform (IFFT), thus providing a set of Finite Impulse Response (FIR) filters. The frequency resolution of the numerical simulation was set to have FIR filters with length $L = 8192$ samples, as follows:

$$df = fs \,/\, L \tag{5}$$

where $df$ is the desired frequency resolution and $fs = 48$ kHz is the current standard audio sampling frequency. Hence, it results $df = 5.859375$ Hz. The Ambisonics transform was then applied to the set of FIR filters, producing $nSH = 36$ spherical harmonics. The Ambisonics directivity is therefore represented by a matrix of FIR filters having dimension 1x36x8192 (number of input source, number of SHs, number of samples). The result was evaluated by octave bands averaging, as shown in Fig. 4, where the normalized sound pressures (vertical axis) at each virtual capsule (horizontal axis) are compared, with numerical model results in red and Ambisonics encoding results in blue. One can note that the estimation is very good at low frequency (octave band centered at 125 Hz), while small deviations are found at higher frequencies. An average difference of 3.2 % was found on the entire simulated range.

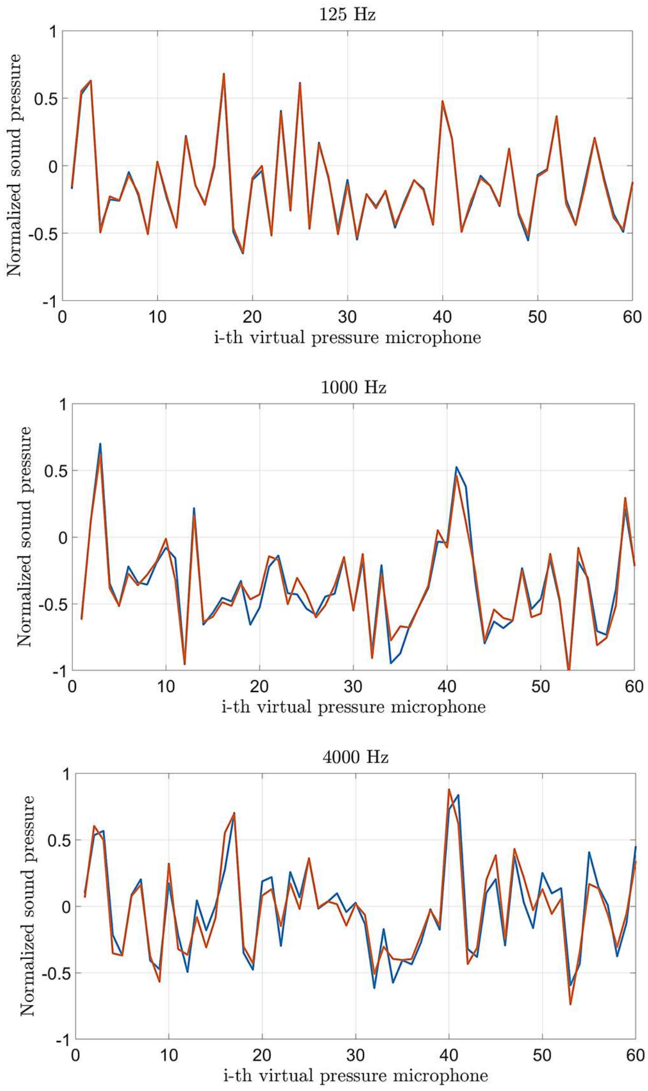


Fig. 4. Comparison of normalized sound pressure values evaluated at the virtual pressure microphones (red) and encoded in Ambisonics format (blue), in the octave bands centered at 125 Hz (top), 1 kHz (middle), 4 kHz (bottom).

### C. Noise recordings

To include the environmental noise, as well as the tire rolling noise and the background video in the VR auralization, a set of measurements were performed in the AVAS test track facility of the Hyundai Kia R&D center, located in Namyang, Hwaseong-si, Gyeonggi-do, Republic of Korea. A full electric segment B car was recorded with the EM-64 and a 360°

panoramic camera. The EM-64 was provided with a wind shield, and the camera was mounted on the top of it, to keep coaxial the acoustic and the visual centers, and avoiding the presence of the array in the video. The recordings consisted of pass-by maneuvers at constant speeds in front of the recording system, at 10-20-30 km/h and reverse, in the range from -40 m to +40 m respect to the center along Y coordinate, at 2 m distance along X coordinate (the reference system can be seen in Fig. 5). The recordings were taken by turning off the AVAS sound, so that only the environmental noise and the tire rolling noise of the car were captured by the microphone array.

The absolute position and time provided by the Global Positioning System (GPS) were also recorded by using an Android smartphone application, namely "Sensorstream IMU+GPS". This app streams the GPS and IMU sensor data over WIFI using the User Datagram Protocol (UDP) and at the same time it can log all the data into a text file. Two smartphones were used, one located at the recording system position and one inside the car. GPS-enabled smartphones typically have an accuracy of 4.9 m [48], which can be considered with an initial calibration of the position. Instead, the differential GPS error is less than 10 cm [49]. The app has been modified and recompiled to stream the GPS data over the Open Sound Control (OSC) protocol and to increase the GPS time resolution up to 20 Hz (standard value for smartphones and navigation systems is 1 Hz). Considering a maximum car speed of 30 km/h, that is 8.33 m/s, the above temporal resolution leads to an additional error of 0.42 m, which is judged acceptable for the purpose of this work. In this way, it has been possible to record the GPS time, and the recording station coordinates (X, Y) synchronously with the multichannel audio from the microphone array. A schematic of the background noise recording system is shown in Fig. 5.

Relying on GPS time, which is the same on the two smartphones, the position of the car was aligned with the audio recording. The audio and video recordings were instead aligned using on the soundtrack recorded by the same camera.

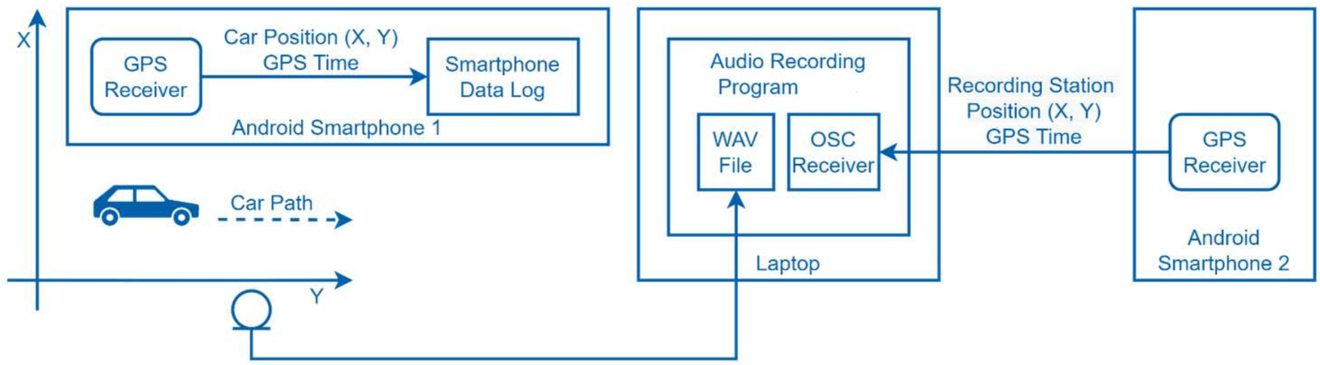


Fig. 5. Schematic of the background noise recording system.

## III. AVAS AURALIZATION

The AVAS auralization, whose processing schematic is shown in Fig. 6, was entirely performed in a real-time DAW, namely Plogue Bidule, making use of three Virtual Studio Technology (VST) plugins, the Room Encoder and Binaural Decoder by IEM [50], and the O7A View by Blue Ripple Sound. The processing is as follows:

1) An AVAS sound player sends the digital mono signal to be auralized to a convolution engine.

2) The FIR matrix of the AVAS source 3D directivity (see Section II.B) is loaded in the convolution engine and convolved with the mono signal to be auralized, producing an AVAS sound with its own directivity, in Ambisonics format.

3) The AVAS sound with its directivity is sent to the Room Encoder plugin. It also receives the car position (X, Y coordinates) that was recorded by the smartphone located inside the vehicle during the background noise recordings (see Section II.C). At this stage, the AVAS sound is effectively auralized, considering the floor reflection, the movement of the sound source and the Doppler's effect.

4) The auralized AVAS sound is sent to the O7A View plugin, which handles the 360° video rendering for VR. It also receives background noise recording, so that the environmental noise and the tire rolling noise are mixed with the auralized AVAS sound. The O7A View plugin also receives head-tracking data from the HMD, performing the counter-rotation of the Ambisonics signals to keep the sound field locked.

5) The Binaural Decoder plugin performs the real-time convolution of the Ambisonics signals with the Head Related Transfer Functions (HRTFs) to deliver the two signals (left ear and right ear) that are reproduced by the headphones. The HRTF is a set of transfer functions, embedded in the binaural decoder, having dimension *nSH* x 2. Therefore, in the present work, 36 x 2. They are measured in an Ambisonics listening room with a dummy head. More on the HRTFs for Ambisonics decoding in VR can be found in [51].

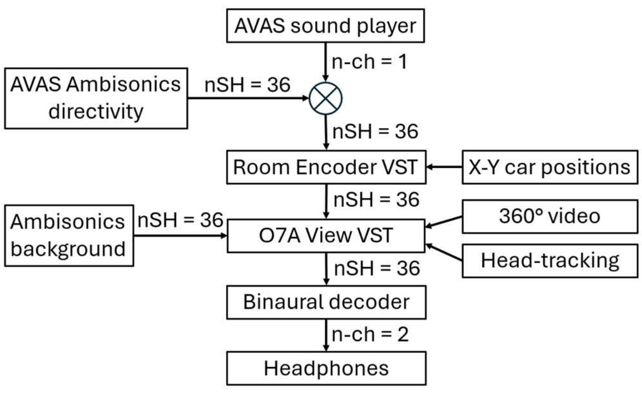


Fig. 6. Processing schematic of AVAS real-time auralization. N-ch is number of channels.

In its original release, the Room Encoder plugin limits the dimension of the volume to 30x30x30 meters, which is too small for the AVAS auralization, considering that the entire maneuver covers 80 meters. Therefore, a customized version was recompiled to increase the maximum dimensions to 300x300x300 m. The plugin allows the user to define an attenuation coefficient for each of the six walls of the room. Since the auralized sound field is free field except for the floor reflection, the attenuation coefficients were set to -50 dB for the walls and the ceiling and to 0 dB for the floor. The source and listener coordinates were defined as in TABLE I. The total number of reflections was set to 1, since only the reflection of the ground must be calculated.

TABLE I. SOURCE AND LISTENER COORDINATES

| **Coord.** | **Position** | |
|---|---|---|
| | ***Source [m]*** | ***Listener [m]*** |
| X | Car position recording | 0 |
| Y | Car position recording | 0 |
| Z | 0.65 above ground[a] | 1 above ground[b] |

a. Height of the AVAS loudspeaker mounted in the vehicle.

b. Height of the EM-64 when recording background noise.

## IV. CONCLUSIONS

An immersive audio-video auralization of the Acoustic Vehicle Alerting System installed on electric cars was presented. The developed solution uses a combination of numerical simulations and field recordings to deliver the panoramic video over a Head Mounted Display and the spatial audio through Ambisonics processing and binaural decoding over headphones.

Numerical simulations were employed to encode the 3D directivity of AVAS source in Ambisonics format, by means of a Finite Impulse Response filter matrix to be applied to the sound to auralize with a convolution. Field recordings were performed with a Spherical Microphone Array to capture the environmental noise and the tire rolling noise generated by the contact between wheels and asphalt. A dual-lenses panoramic camera mounted on the top of the SMA was employed to record 360° videos, while two smartphones were used to acquire the time and the position of both the recording station and the car with an especially modified Android application.

The signal processing is performed in real-time in a Digital Audio Workstation, making use of two VST plugins, the Room Encoder by IEM and the O7A View by Blue Ripple Sound. The room Encoder performs the auralization of the AVAS source, introducing the movement, the ground reflection and the Doppler's effect. The O7A View reproduces panoramic video over the HMD and receives from it the head-tracking data to counter-rotate the Ambisonics signals.

The presented solution allows NVH engineers to easily test as many AVAS sounds, with a significant cost reduction and time saving. Therefore, it will from now on possible to accurately choose the sound for a vehicle in accordance with subjective and objective parameters, such as pleasantness, recognizability, and association of the sound with the type of vehicle. The next step of the research presented will consist of a jury test performed on a set of untrained subjects. Several AVAS sounds will be compared with the aim of objectifying people's preferences.


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