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1aSP3. Hybrid immersive three-dimensional sound reproduction system with steerable parametric loudspeakers  

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A loudspeaker must be both dispersive and directive to accurately reproduce spatial audio from digital media. To address this problem, an audio system that has a unique combination of conventional and parametric loudspeakers has previously been proposed and proved to be effective in producing an immersive 3D soundscape. However, this system has two drawbacks: (1) There is only one fixed "sweet spot", and (2) only one listener within the "sweet spot" can enjoy the complete experience. Therefore, a hybrid 3D sound reproduction system combining conventional loudspeakers with a pair of steerable parametric loudspeakers is proposed in this paper. By using this new combination of conventional and steerable parametric loudspeakers, the "sweet spot" can be steered towards the listener's head position. Thus, the listener no longer needs to keep his head stationary while watching movies or playing games, which resulting in a more relaxing and pleasant experience. Furthermore, a dual-beamsteering method is proposed for the parametric loudspeaker, which provides a flexible software-control solution to allow the 3D sound experience to be enjoyed by two listeners simultaneously. This paper provides the system overview and highlights the key processing techniques in rendering a "steerable" immersive 3D soundscape.

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INTRODUCTION

The auditory image of 2D and 3D digital media, such as movies and games, can be decomposed into a series of point-like sources as well as diffused sources. Such a combination of sources is convenient for audio analysis-synthesis, and leads itself to accurate spatial audio reproduction [1]. However, such spatial audio reproduction is difficult to be reproduced using conventional sound systems, mainly because of the dispersiveness of the conventional loudspeakers used in these systems. The auditory images of diffused and point-like sources generated by dispersive and directional loudspeakers, respectively, are shown in Figure 1. The dispersive loudspeakers generally render auditory images that lack of sharpness, due to the room reverberation. Hence, these loudspeakers are well-suited to produce auditory images containing diffused sources. On the other hand, the directional loudspeakers are preferred for rendering point-like sources due to the lack of room reverberation.

Hence, a loudspeaker must be both dispersive and directive to accurately reproduce spatial audio from digital media. To address this problem, we have proposed an audio system that has a unique combination of conventional and parametric loudspeakers in [2]. The parametric loudspeaker for directional sound reproduction was introduced by Yoneyama et al. [3] in 1983. The parametric loudspeaker utilizes an ultrasonic wave beyond human hearing range as a directional carrier. Due to the nonlinear effect in air, the modulated audible sounds are self-demodulated and preserve the sharp directivity of the ultrasonic carrier. Thus, highly directional sound beams can be projected from the parametric loudspeaker even for the low-frequency reproduction.

IMMERSIVE 3D SOUND SYSTEM

The proposed system is referred as the immersive 3D (i3D) sound system, and the block diagram of i3D is shown in Figure 2, where $X_0$, $X_1$, $X_2$, and $X_3$ denote the front left, front right, surround left, and surround right channels, respectively. In order to optimize the listening experience from such a combination of loudspeakers, the primary component analysis (PCA) based cue-ambient decomposition technique proposed by Goodwin and Jot [1] is adapted in the proposed audio system. The extracted cues $C_n$ of the front and surround channels are extracted using

$$C_n^e = \left( \frac{v^H_n X_n}{v^H_n v_n} \right) v_F,$$

$$C_n^s = \left( \frac{v^H_n X_n}{v^H_n v_n} \right) v_S,$$

where the superscript $H$ denotes Hermitian conjugation. The eigenvector for the front and surround channels are denoted as $v_F$ and $v_S$, respectively, and are computed as
\[ \mathbf{v}_b = r_{0,1} \mathbf{X}_0 + \left\{ 0.5 \left[ r_{0,0} + r_{1,1} + \sqrt{\left( r_{0,0} - r_{1,1} \right)^2 + 4 \left| r_{0,1} \right|^2} \right] - r_{0,0} \right\} \mathbf{X}_1, \]

\[ \mathbf{v}_s = r_{2,3} \mathbf{X}_2 + \left\{ 0.5 \left[ r_{2,2} + r_{3,3} + \sqrt{\left( r_{2,2} - r_{3,3} \right)^2 + 4 \left| r_{2,3} \right|^2} \right] - r_{2,2} \right\} \mathbf{X}_1, \]

where \( r_{m,n} \) and \( r_{m',n'} \) represent the auto-correlation of \( \mathbf{X}_m \), and the cross-correlation of \( \mathbf{X}_m \) and \( \mathbf{X}_n \).

**DUAL-BEAMSTEERING METHOD**

Using the same hardware configuration of the single-beamsteering parametric loudspeaker in [4], we propose a symmetric structure (shown in Figure 3) that can generate two steerable audio beams from the parametric loudspeaker in this paper. This proposed structure allows an audio content to be simultaneously delivered to two separate locations. Thereby, the updated i3D system is able to simultaneously reproduce the 3D experience to two listeners by reproducing the cues for two listeners using the dual-beamsteering parametric loudspeakers and the ambience from the conventional loudspeakers. Since the symmetric structure is implemented purely in programming, the hardware configuration of the single-beamsteering parametric loudspeaker is retained and the hybrid 3D sound reproduction system is easily switched on and off through software.
In the proposed symmetric structure, the mainlobes of the primary frequency (PF) waves at \( f_1 \) and \( f_2 \) are steered to two different angles \( \theta_1 \) and \( \theta_2 \) as a result of two groups of delays (\( \tau_{m1} \) and \( \tau_{m2} \) for \( m = 0, 1, \ldots, M - 1 \)) being applied. The mainlobes of the PF waves result in the first lobe of the resultant difference frequency (DF) wave at the desired steering angle \( \theta_a \). At the same time, the grating lobes of the PF waves result in the second beam of the DF wave being steered to the other desired steering angle \( \theta_b \). As the mainlobes (leading to the first beam of the DF wave) and the grating lobes (leading to the second beam of the DF wave) are symmetric to the same angle \( \theta_s \) in the two PF beampatterns, this proposed structure for dual-beam steering is referred as the symmetric structure. The described geometry of the symmetric dual-beam generation is illustrated in Figure 4.

To compute the two steering angles of the PF waves, it is typically assumed that the desired steering angles of the DF wave fulfill the relation of \( \theta_a < \theta_b \), without loss of generality. Referring to Figure 4, the symmetric axis of the dual beams of the DF wave is given by

\[
\sin \theta = \frac{\sin \theta_a + \sin \theta_b}{2}.
\]

Because the mainlobes and the grating lobes are symmetrical to the same axis, the mainlobes of the PF waves are steered to

\[
\sin \theta_{1,2} = \sin \theta_s - \frac{c_0}{2 f_{1,2} d},
\]

respectively.

Based on the product directivity principle [5], the location of the mainlobe of the DF waves is given by

\[
\sin \theta_a = \sin \theta_s - \frac{c_0}{4 f_1 d} - \frac{c_0}{4 f_2 d},
\]

Let \( f_c \) denote the center frequency of the PF waves, i.e. \( f_c = (f_1 + f_2) / 2 \). By substituting (3) into (5), a quadratic equation is obtained as

- \( \theta_a \), \( \theta_b \), \( \theta_s \), \( f_1 \), and \( f_2 \) are the steering angles, the symmetric axis, the center frequency of the primary frequency waves, and the frequencies of the primary frequency waves, respectively.

- \( c_0 \) is the speed of sound in the medium.

- \( d \) is the separation between the two PF waves.

- \( \tau_{m1} \) and \( \tau_{m2} \) are the delays for the two groups of delays.

- \( M \) is the total number of delays.

- \( \theta_1 \) and \( \theta_2 \) are the steering angles of the mainlobes of the PF waves.

- \( \theta_1^* \) and \( \theta_2^* \) are the steering angles of the grating lobes of the PF waves.

\[ 01 \rightarrow 11 \rightarrow 02 \rightarrow 12 \rightarrow 0 \]

FIGURE 3. Proposed symmetric structure of the dual-beam generation of the parametric loudspeaker.

FIGURE 4. Geometry of the dual-beam generation using the symmetric structure.
The solution to the quadratic equation of the center frequency is given by

\[
f_c = \frac{c_0 + \sqrt{c_0^2 + d^2 \left( \sin \theta_b - \sin \theta_a \right)^2}}{2d \left( \sin \theta_b - \sin \theta_a \right)}
\]

Since \( c >> d \left( \sin \theta_b - \sin \theta_a \right) \), is valid when the DF wave is within the speech frequency band, (7) can be simplified as

\[
f_c = \frac{c_0}{d \left( \sin \theta_b - \sin \theta_a \right)} = \frac{c_0}{2d \cos \left( \frac{\theta_a + \theta_b}{2} \right) \sin \left( \frac{\theta_b - \theta_a}{2} \right)}
\]

Equation (8) shows that the center frequency is the only factor that determines the directions of the dual beams when the configuration of the ultrasonic transducer array (UTA) is fixed.

The simulation results in Figure 5 validate the effectiveness of the symmetric structure for generating dual beams using the parametric loudspeaker. The UTA consists of 8 channels and adopts equal weights. The DF waves vary from 0.5 kHz to 10 kHz with a frequency interval of 0.5 kHz. The spacing of the UTA is set to 1.5 cm. The center frequency of the PF waves is calculated using (8) for individual settings of the steering angles. In Figures 5(a) and 5(b), the single beams are steered to \(-15^\circ\) and \(0^\circ\), respectively. In Figure 5(c), the dual beams are steered to \(-15^\circ\) and \(15^\circ\). Lastly, in Figure 5(d), the dual beams are steered to \(-30^\circ\) and \(0^\circ\).

**FIGURE 5.** Comparative results between single-beamsteering and dual-beamsteering methods.
CONCLUSION

A hybrid 3D sound reproduction system combining conventional loudspeakers with a pair of steerable parametric loudspeakers is proposed in this paper. This combination of conventional and parametric loudspeakers is proved to be effective to reproduce an immersive 3D soundscape. By using a pair of steerable parametric loudspeakers, the "sweet spot" of the hybrid 3D sound reproduce system is no longer fixed. The listener can have a more relaxing and pleasant experience for home entertainments, like movies and games. A dual-beamsteering method is also proposed for the parametric loudspeaker. This method is a pure software solution which allows the immersive 3D sound experience to be enjoyed by two listeners simultaneously. Two sound beams are projected from each parametric loudspeaker in the proposed hybrid system and steered to the two listeners at different angular locations by changing the carrier frequency of the parametric loudspeaker.

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