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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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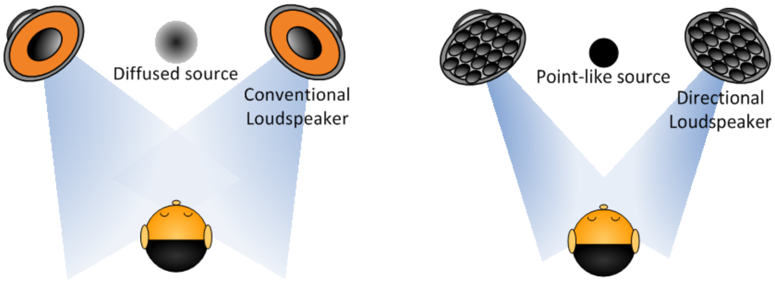
INTRODUCTION

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.



(a) (b)

FIGURE 1. Auditory images from (a) conventional and (b) directional loudspeakers.

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 $\mathbf{X}_0$, $\mathbf{X}_1$, $\mathbf{X}_2$, and $\mathbf{X}_3$ 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 $\mathbf{C}_n$ of the front and surround channels are extracted using

$$\begin{aligned} \mathbf{C}_n^{\mathrm{F}} &= \left(\frac{\mathbf{v}_{\mathrm{F}}^H \mathbf{X}_n}{\mathbf{v}_{\mathrm{F}}^H \mathbf{v}_{\mathrm{F}}} \right) \mathbf{v}_{\mathrm{F}}, \\ \mathbf{C}_n^{\mathrm{S}} &= \left(\frac{\mathbf{v}_{\mathrm{S}}^H \mathbf{X}_n}{\mathbf{v}_{\mathrm{S}}^H \mathbf{v}_{\mathrm{S}}} \right) \mathbf{v}_{\mathrm{S}}, \end{aligned} \tag{1}$$

where the superscript H denotes Hermitian conjugation. The eigenvector for the front and surround channels are denoted as $\mathbf{v}_{\mathbf{F}}$ and $\mathbf{v}_{\mathrm{S}}$, respectively, and are computed as

$$\begin{aligned} \mathbf{v}_{\mathrm{F}} &= r_{0,1}\mathbf{X}_0 + \left\{ 0.5\left[r_{0,0} + r_{1,1} + \sqrt{\left(r_{0,0} - r_{1,1}\right)^2 + 4\left|r_{0,1}\right|^2} \right] - r_{0,0} \right\} \mathbf{X}_1, \\ \mathbf{v}_{\mathrm{S}} &= r_{2,3}\mathbf{X}_2 + \left\{ 0.5\left[r_{2,2} + r_{3,3} + \sqrt{\left(r_{2,2} - r_{3,3}\right)^2 + 4\left|r_{2,3}\right|^2} \right] - r_{2,2} \right\} \mathbf{X}_3, \end{aligned} \tag{2}$$

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

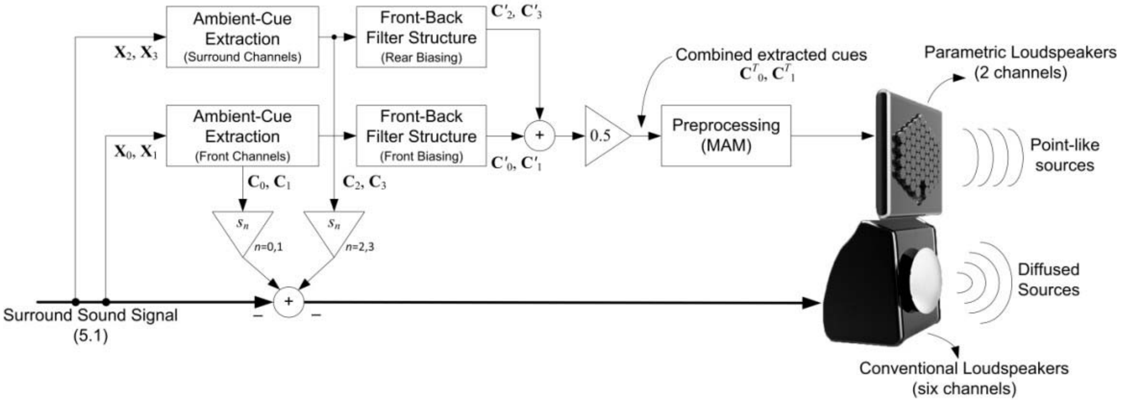


FIGURE 2. Block diagram of proposed audio system (i3D system) which uses the conventional and parametric loudspeakers.

However, there is only one fixed "sweet spot" of the current i3D system due to the narrow beamwidth of the parametric loudspeaker, which is used for rendering point-like sources. As such, the effectiveness of the i3D system is reduced when the listener stretches his body or moves around in a middle of a movie. By adopting phased array techniques, beamsteering of the audible sound was implemented for the parametric loudspeaker and a unique grating lobe elimination phenomenon was addressed in [4].

Therefore, in this paper, we propose a hybrid 3D sound reproduction system, which combines conventional loudspeakers with a pair of steerable parametric loudspeakers. This proposed system is able to render the cues to one or two listeners simultaneously. The steerable parametric loudspeakers also permit one or two listeners to enjoy the immersive 3D sound experience at their preferred locations instead of at a fixed "sweet spot".

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 though software.

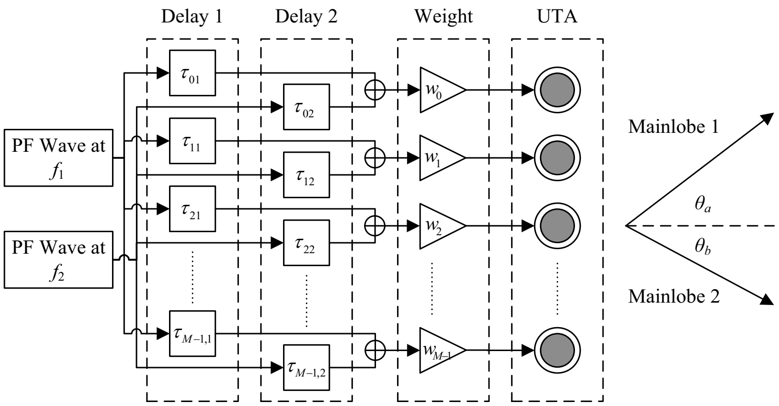


FIGURE 3. Proposed symmetric structure of the dual-beam generation of the parametric loudspeaker.

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 θ_1 and θ_2 as a result of two groups of delays (τ_{m1} and τ_{m2} for $m = 0, 1, ..., M-1$) 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 θ_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 θ_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 θ_s in the two PF beampatterns, this proposed structure for dual-beamsteering is referred as the symmetric structure. The described geometry of the symmetric dual-beam generation is illustrated in Figure 4.

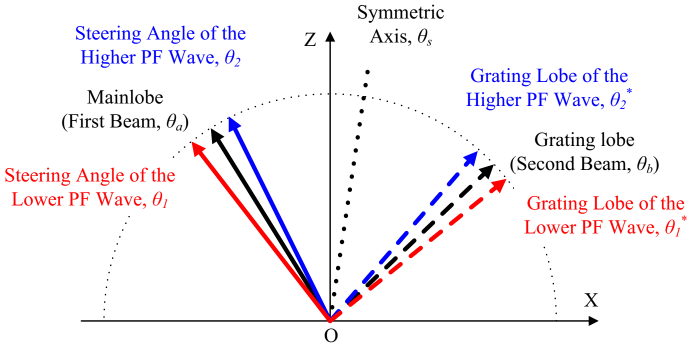


FIGURE 4. Geometry of the dual-beam generation using the symmetric structure.

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

$$\sin\theta_s = \frac{\sin\theta_a + \sin\theta_b}{2}. \tag{3}$$

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

$$\sin\theta_{1,2} = \sin\theta_s - \frac{c_0}{2 f_{1,2} d}, \tag{4}$$

respectively.

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

$$\sin\theta_a = \frac{\sin\theta_1 + \sin\theta_2}{2} = \sin\theta_s - \frac{c_0}{4 f_1 d} - \frac{c_0}{4 f_2 d}. \tag{5}$$

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

$$\left(\sin\theta_b-\sin\theta_a\right)f_c^2-\frac{c_0}{d}f_c-\left(\sin\theta_b-\sin\theta_a\right)\frac{f_d^2}{4}=0. \tag{6}$$

The solution to the quadratic equation of the center frequency is given by

$$f_c=\frac{c_0+\sqrt{c_0^2+d^2\left(\sin\theta_b-\sin\theta_a\right)^2 f_d^2}}{2d\left(\sin\theta_b-\sin\theta_a\right)}. \tag{7}$$

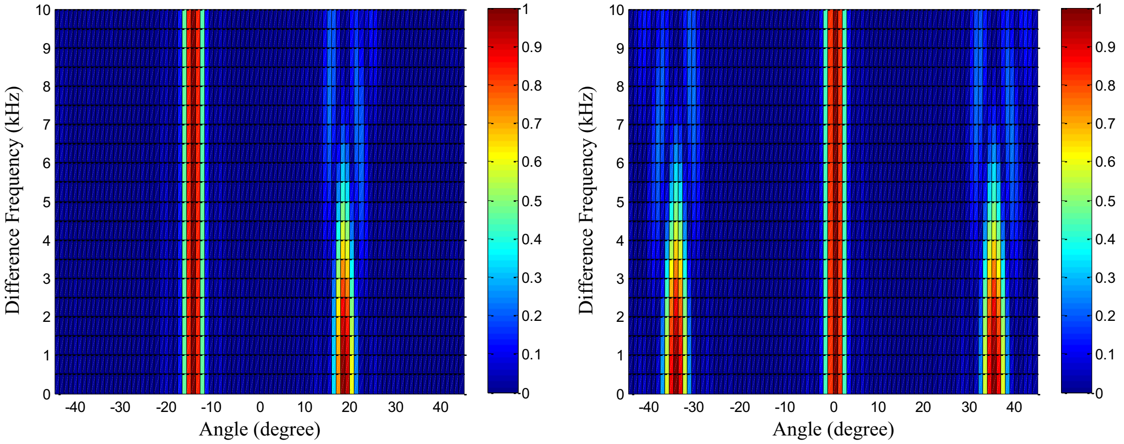
Since $c >> d\,(\,\sin\theta_b - \sin\theta_a\,)\,f_d$ is valid when the DF wave is within the speech frequency band, (7) can be simplified as

$$f_c=\frac{c_0}{d\left(\sin\theta_b-\sin\theta_a\right)}=\frac{c_0}{2d\cos\left(\frac{\theta_a+\theta_b}{2}\right)\sin\left(\frac{\theta_b-\theta_a}{2}\right)}. \tag{8}$$

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° and 0°, respectively. In Figure 5(c), the dual beams are steered to -15° and 15°. Lastly, in Figure 5(d), the dual beams are steered to -30° and 0°.

(a) Single beam steered at -15°   (b) Single beam steered at 0°



(c) Dual beam steered at -15° and 15°   (d) Dual beam steered at -30° and 0°

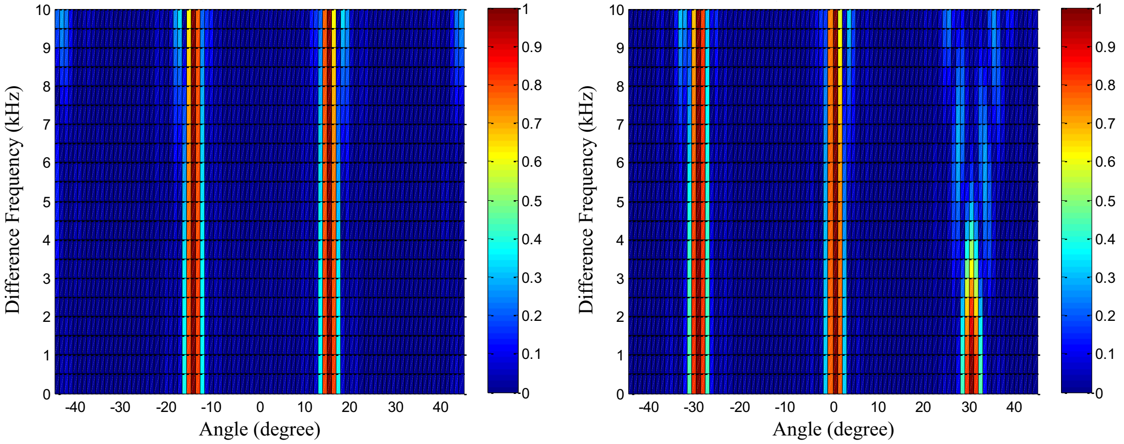


FIGURE 5. Comparative results between single-beamsteering and dual-beamsteering methods.

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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