Crosstalk Cancellation for Spherical Loudspeaker Arrays

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Introduction

Spherical loudspeaker arrays for directivity pattern synthesis of natural sound sources have been recently reconsidered in electro-acoustic research [3, 4, 5]. Quite some time after the pioneering works in that field [1, 2], multichannel hardware and computational resources are easy to obtain, and the design and control issues receive increased interest. The loudspeaker arrays considered here consist of transducers mounted into the rigid surface of a spherical or polyhedral shell. The enclosure volume in this shell acoustically couples the motion of the transducer cones. Directivity pattern synthesis, however, requires individual control over these motions. On one hand, encapsulated enclosures behind each transducer minimize acoustic coupling. On the other hand, a shared enclosure is easy to construct and supports playback at low frequencies. To control the acoustically coupled loudspeakers in that case, a computationally expensive multiple-input-multiple-output cross-talk canceller (MIMO-XTC) has to be employed. This work discusses a spherical harmonics subspace approach for MIMO-XTC in rigid spherical/platonic loudspeaker arrays. It can be shown that matrices involved in the MIMO-XTC task become sparse within the spherical harmonics subspace, and largely reduce the computational demands.
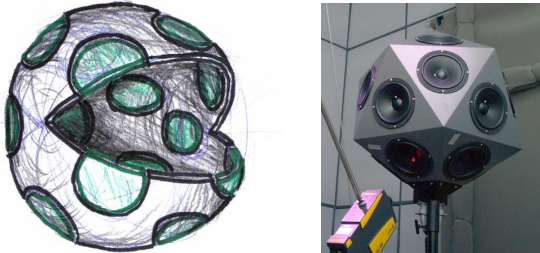

Figure 1: Section through spherical loudspeaker array model. Icosahedral loudspeaker array.

MIMO-Crosstalk and Cancellation

Acoustic crosstalk in the arrays introduced above (Fig. 1) has been modeled in [5]. Basically, an electro-acoustic transfer matrix $\mathbf{C}(\omega)$ can be computed, relating input voltages $\vec{u}$ to output loudspeaker velocities $\vec{v}$. We achieve direct control over the velocities $\vec{v}$ using a discrete-time MIMO-XTC system $\mathbf{W}(\omega)$, with the input feeds $\vec{v}_{ctl}$

$$\vec{v} = \mathbf{C}(\omega) \cdot \vec{u}, \tag{1}$$

$$\vec{v} = \underbrace{\mathbf{C}(\omega) \cdot \mathbf{W}(\omega)}_{=\mathbf{I}} \cdot \vec{v}_{ctl} \implies \mathbf{W}(\omega) = \mathbf{C}^{-1}(\omega). \tag{2}$$

An N_{pt} block convolution MIMO-XTC filter for L loudspeakers requires N_{pt} matrix multiplications of $L \times L$ non-zero coefficients.

MIMO-XTC in Spherical Harmonics

The spherical harmonics expansion of the surface velocity on the spherical loudspeaker array was described in [5] as $\vec{\Upsilon} = \mathbf{A} \cdot \vec{v}_{ctl} = \mathbf{A} \cdot \mathbf{C}(\omega) \cdot \vec{u}$. It linearly combines the set of *loudspeaker apertures* on the array. In greater detail, the expansion $\mathbf{A} = \mathrm{diag}_{\mathrm{SH}}\{\hat{A}_n\}\,\mathbf{D}$ consists of sampled spherical harmoncis $\mathbf{D}$ and the rotationally symmetric membrane aperture shape $\hat{A}_n$ common to all speakers [5].

We introduce a higher-order Ambisonics (HOA) decoder $\mathbf{B_N}$ to directly control the velocity components $\vec{\Upsilon}_N$ of an N-truncated subspace of the spherical harmonics

$$\vec{\Upsilon}_N = \underbrace{\mathbf{A_N}\,\mathbf{C}(\omega)\,\mathbf{W}(\omega)\,\mathbf{B_N}}_{=\mathbf{I}} \cdot \vec{\Upsilon}_{N,ctl}, \tag{3}$$

$$\mathbf{B_N} = \mathbf{A_N^H}\left(\mathbf{A_N}\mathbf{A_N^H}\right)^{-1}, \tag{4}$$

where the superscript $()^{\mathbf{H}}$ denotes the conjugate transpose. It is important to choose a suitable spatial sampling and $N \leq \sqrt{L} - 1$ to obtain a non-singular matrix inverse.

Interchanging the decoder with the MIMO-XTC $\mathbf{W}(\omega)$, we define a new subspace MIMO-XTC-SH $\tilde{\mathbf{W}}(\omega)$ with reduced dimensions. Equating $\mathbf{B_N}\,\tilde{\mathbf{W}}(\omega) = \mathbf{W}(\omega)\,\mathbf{B_N}$ and left multiplying with $\mathbf{A_N}$ yields (see Eq. 4):

$$\tilde{\mathbf{W}}(\omega) = \mathbf{A_N} \cdot \mathbf{W}(\omega) \cdot \mathbf{A_N^H}\left(\mathbf{A_N}\mathbf{A_N^H}\right)^{-1}. \tag{5}$$
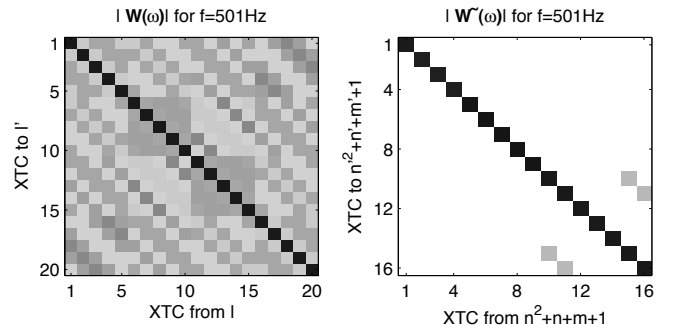

Figure 2: The icosahedral loudspeaker MIMO-XTC matrix $\mathbf{W}(\omega)$ (left) becomes sparse in its subspace representation $\tilde{\mathbf{W}}(\omega)$ (right); the 500Hz slice is depicted here.

Diagonalization: If the sampled spherical harmonics form an orthonormal subspace $\mathbf{D_N}\mathbf{D_N^H} = \mathbf{I}$, i.e. $\mathbf{A_N}\mathbf{A_N^H} =$

$\mathrm{diag_{SH}}\{\hat{A}_n^2\}$, $\mathbf{D_N}$ readily displays eigenvectors of the array geometry. Consequently, the subspace XTC-system $\tilde{\mathbf{W}}(\omega)$ will become diagonal. However, even in a more general case, a diagonalizing/sparsifying effect is noticeable, when performing the XTC in the spherical harmonics subspace (Fig. 2, Fig. 3).
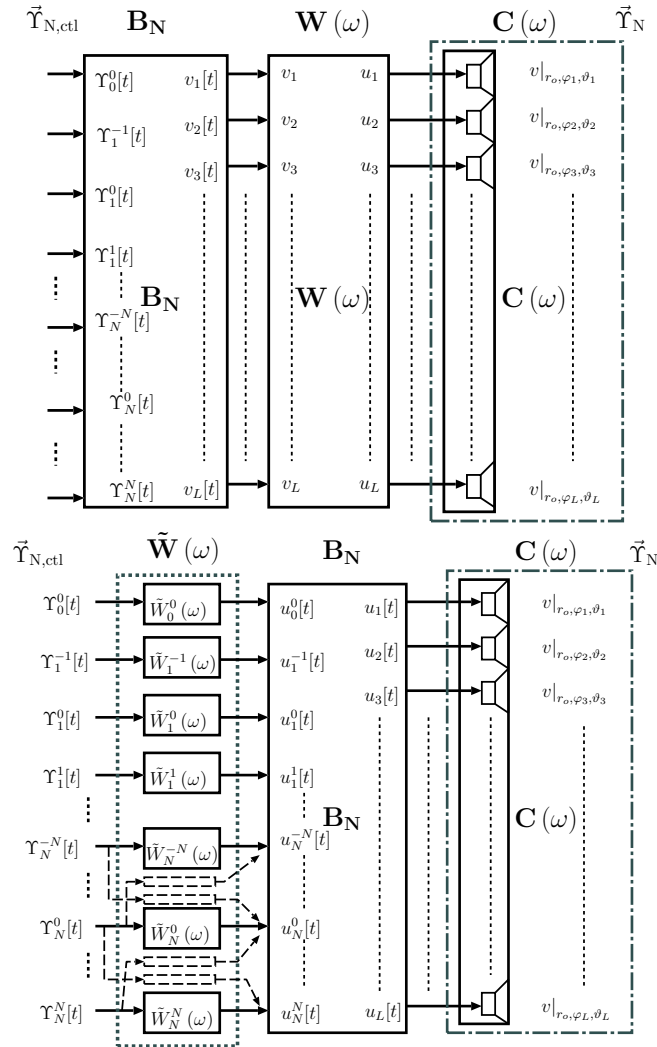

Figure 3: On top: crosstalk cancelled spherical loudspeaker array control (Eq. 3); bottom: its sparse, if not diagonal, representation in the spherical harmonics subspace (Eq. 5).

Example: Icosahedral Array

Applying the analytic model presented in [5] to model an icosahedral loudspeaker array with radius r_o =30cm, we determine a MIMO-XTC system $\mathbf{W}(\omega)$. The corresponding matrix at 500Hz, just below the angular aliasing bound 800Hz, is shown in Fig. 2. It clearly indicates the sparse structure of the transformed system $\tilde{\mathbf{W}}(\omega)$. Fig. 4 provides an overview over all frequencies and illustrates different classes of magnitude responses in $\mathbf{W}(\omega)$ and $\tilde{\mathbf{W}}(\omega)$.

Conclusions

We have shown considerable benefit in using the spherical harmonics subspace for crosstalk cancellation in spheri-
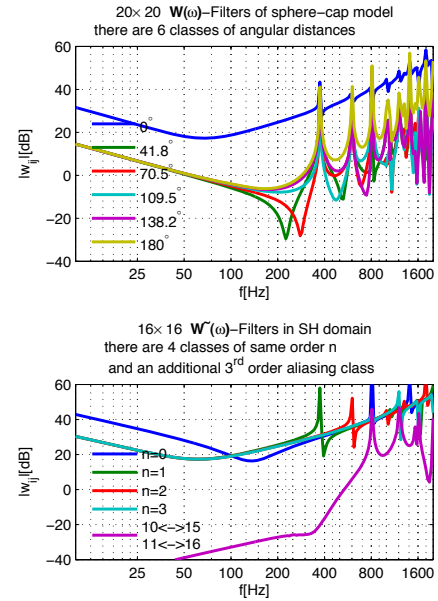

Figure 4: As expected from the 6 distance classes on the icosahedral array, there are 6 different transfer functions (magnitude depicted) for crosstalk cancellation. In the figure with the spherical harmonics subspace method below, 5 different responses emerge, corresponding to the orders n, as well as two identical crosstalk paths between the modes 10↔15, and 11↔16.

cal loudspeaker arrays. With $(N+1)^2 \approx L$, the interchanged order for the HOA decoder and XTC reduces the high computational cost of the $O\left(L^2\right)$ MIMO-XTC to a sparse/diagonal $O\left(L\right)$ MIMO-XTC-SH.

Acknowledgements

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