Quasi Wave Field Synthesis : Efficient Driving Functions for Improved 2.5D Sound Field Reproduction

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ABSTRACT

Optimised driving functions for a rectangular array of loudspeakers are approximated with driving functions with similar form and cost to Wave Field Synthesis (WFS) functions, by using a linear combination of several pre-filters and a delay for each function. The accuracy of the resulting reproductions are compared with WFS reproductions. The aim is provide improved efficient source driving functions in horizontal reproduction.

1. INTRODUCTION

A common loudspeaker array configuration consists of loudspeaker drivers arranged in a horizontal plane on a boundary, and directed towards a listening region in the plane. This allows spatial resolution to be focused horizontally at the expense of losing sound from directions out of the plane. This is called the 2.5D configuration in the context of the Wavefield Synthesis (WFS), [1, 2], and High Order Ambisonics (HOA) [3] synthesis methods, and the term can be applied equally to any synthesis method that is adapted to such a horizontal array. 2.5D has inherent limitations, that are independent of the synthesis method used, due to the dimensional mismatch between the driver and control region. 2D point drivers can control a 2D region perfectly well in the limit of continuous driver spacing by the Simple Source solution [], however 3D point sources cannot perfectly reproduce a plane section of horizontal plane waves. The question then arises what is the best that can be done in 2.5D in two cases: disregarding computational costs, and keeping costs competitive with fast methods that are suitable for interactive applications. A challenging yet common test case arises when plane waves are reproduced over the whole interior of a rectangular array. Plane waves represent distant sources and can be used to build impressions of large spaces using arrays that are comparatively small. Plane wave reproduction requires co-ordination across large sections of the array.

WFS is synthesis method with simple and efficient 2.5D source driving functions. These have the general form:

$$D_j(\omega) = g_j \Delta_j(\omega) F(\omega) S(\omega) \quad (1)$$

where g_i are gains, $\Delta_j(\omega)$ are delays, $F(\omega)$ is a filter and $S(\omega)$ is the source, or in the time domain

$$d_j(t) = g_j \delta_j \cdot f \cdot s(t) \quad (2)$$

Calculation can be divided into two steps:

1. The regular update and interpolation of gain and delay parameters for each driver. The delay and gain are simple functions of source parameters and driver position
2. $f \cdot s(t)$ is calculated first, then each driving function is found by applying delay and gain: $d_j = g_j \delta_i \cdot (f \cdot s(t))$ Hecne the filter is only applied once for each source, and delays are cheap to implement.

Distributed constraints (DC) [4] can be used to find optimal driving functions and reproductions in 2.5D [5]. These functions provide a reference for more efficient methods. In particular in the case of a rectangular boundary the 2.5D WFS errors are significantly greater than the DC reference. The wavefronts are more unstable, there is a narrowing of beams, and power loss over distance is greater. The errors are not surprising considering that 2.5D WFS is derived via a succession of approximations.

2.5D HOA source driving functions are efficient only for plane waves on a circular array. Point sources or other boundary types require much more costly functions compared with WFS, and the whole interior may not be controllable [4]. HOA has many useful features but it is outside the scope of this work, which focuses on improving the accuracy of efficient methods.

2. QUASI WFS

Similarities can be seen between the 2.5D DC and WFS driving functions [5]. Where a WFS function is non-zero it closely matches the DC function. Elsewhere the DC functions can be factored into a delay and a filter that varies gradually along the boundary. This suggests that a small set of pre-filters f_k can be found that can be linearly combined to approximate the DC functions well, in a functional form similar to WFS:

$$d_j(t) = \delta_j . \sum_k g_{jk} \cdot (f_k \cdot s(t)) \quad , \tag{3}$$

where signals $\{f_k \cdot s(t)\}$ are evaluated first.

We refer to this method of synthesis here as Quasi Wavefield Synthesis (QWFS). The cost of evaluating the QWFS pre-filters is low, however in general they depend on source position, unlike the WFS pre-filter. The pre-filters must therefor be pre-calculated and stored along with gain and delay coefficients, to cover the desired locations. Smooth movement can be achieved by interpolation of pre-calculated filters. This approach is used also in WFS implementations in which the gain and delay coefficients for each source location are stored.

The imperfect nature of 2.5D reproduction strongly suggests there are no analytical shortcuts to finding optimal QWFS driving functions for general boundaries. Instead the approach taken is to match QWFS to DC driving functions found numerically. Complex vectors are formed by evaluating the DC driving functions at a set of frequencies. These are used to factor each driving function into a QWFS delay and a residual filter, such that the spectral tilt of each residual phase response is zero. The corresponding WFS driving function delay can be used as an initial guess for the QWFS delay. This avoids high resolution evaluation of the DC functions needed for direct phase unwrapping. Remaining delay adjustment can be made by using the slope of the best-fit line to the phase response of the filter made by factoring out the initial delay guess.

The pre-filters are found by Principal Component Analysis (PCA) applied to the residual complex vectors. Additional weighting is applied proportional to the average absolute value of the vector components. This is because smaller driving functions usually have less influence in the reproduction. The final pre-filters are found by interpolating the evaluated principal component vectors.

The procedure described for finding the QWFS driving functions is complex in comparison to setting up WFS, and must be repeated for each new array. Practical arrays may contain gaps and irregularities that make them unsuitable for WFS, but this does not pose a serious problem for QWFS since it is based on DC. High resolution 2.5D installations are generally permanent, at least in shape if not in location, and also expensive to set up and house. In this context QWFS can be worthwhile.

3. REFERENCES

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