ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Architectural Acoustics
Session 2aAAa: Adapting, Enhancing, and Fictionalizing Room Acoustics I

2aAAa5. Adapting spaciousness of artificial, enveloping reverberation in multichannel rendering based on coded sequences

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For virtual room environments, adapting realistic reverberation and enhancing reverberation are critical for producing a convincing immersive experience. Also, in perceptual studies of room-acoustics using virtual room environments, using the appropriate enveloping reverberance to correlate perceived room size and apparent source-width to the virtual space, is a challenging task. This research applies to both binaural rendering and a multi-channel loudspeaker reproduction that can be employed in simulating such an environment. Approaches to adapting and enhancing spaciousness within the context of artificially generated reverberation are investigated via psychoacoustics tests. The pseudo-random properties of coded signals based on reciprocal maximum-length sequences allow for a deterministic, controllable decorrelation between all reverberation channels. For this challenging task, shapes of both sound energy decays and spatial profiles have been found to be decisive for creating successful immersive environments. This paper discusses potential values for fundamental research in room-acoustics and for educational purposes in seeking a broadened understanding of perceived spaciousness and reverberance in varying contexts.

Published by the Acoustical Society of America through the American Institute of Physics
I. INTRODUCTION

For virtual room environments, adapting realistic reverberation and enhancing reverberation are critical for producing a convincing immersive experience. Also, in perceptual studies of room-acoustics using virtual room environments, using the appropriate enveloping reverberation to correlate perceived room size to the virtual space, is a challenging task. This paper discusses an approach to creating artificial natural sounding reverberation tails for both binaural rendering and a multi-channel loudspeaker reproduction that can be employed in simulating such an environment. Approaches to adapting and enhancing spaciousness within the context of artificially generated reverberation are investigated via psycho-acoustics tests. The pseudo-random properties of coded signals based on reciprocal maximum-length sequences allow for a deterministic, controllable decorrelation between all reverberation channels. For this challenging task, shapes of both sound energy decays and spatial profiles have been found to be decisive for creating successful immersive environments.

II. ARTIFICIAL REVERBERATIONS USING CODED SEQUENCES

Most recent overview on all-pass-filter artificial reverberators, originated from Schroeder\(^1\) can be found in Refs. [2,3]. Another line of development is the reverberators using finite-impulse-response (FIR) filters, probably due to Moorer,\(^4\) who proposed to construct an exponential decaying random-noise at late part of a room impulse response, when convolved with anechoic sound materials, artificial reverberations with desirable degree of reverberance can be created. There have been need to render the FIR-filter-based artificial reverberations binaurally, such as binaural room-acoustic simulations,\(^5\) where the tails of binaural room impulse responses can be replaced by exponentially decaying random noise. The decay rates (reverberation times) are to be determined via the statistical room-acoustic principle, or other room-acoustic information will be first extracted from the early part of detailed room-acoustic simulations. Such schemes have recently been used also for some psycho-acoustics studies including perceptual aspects of acoustically coupled-volume systems.\(^6\)

In principle, an artificial, spatial enveloping reverberation for a binaural rendering can be archived when two pieces of random noise in late reverberation tail can be arranged incoherent, without using geometrical-acoustics room-acoustic simulation (e.g. ray-tracing) to simulate the late reverberation tails which would be extremely time-consuming at the current technology of numerical simulations. For this purpose, reciprocal Maximum-Length Sequence (MLS) pairs have been used,\(^7\) since the cross-correlation between each pair given the MLS degree is of low-value. The intriguing points of using MLS-pairs, in comparison with those used in previous work are that MLS-pairs (and the related coded sequences) possess deterministically predictable values of cross-correlation, they are in low values, hardly any other random noise signals can be found as low as these.\(^7\) Lower values correspond to high degree of spaciousness in the perceived enveloping reverberance. In addition to the highest achievable degrees of spaciousness, one can use a mix-network\(^8\) to control the cross-correlation values of the mixed MLS-pair for binaural channels, so that the degree of spaciousness can also be adjusted. This is of practical value, since different enclosure-conditions will provide different spaciousness, in addition to the reverberance. As recent psychoacoustical investigations\(^8\) have demonstrated, simply shaping the decaying slopes of random noise in the late reverberation tails for achieving artificial reverberations using FIR-filtering technique will not be sufficient in terms of naturalness and envelopment of the artificial reverberation. The recent work\(^8\) adjusts decaying-slopes (for controlled reverberance) in individual octave bands. In each single band, the target-reverberation time will shape the exponential decaying envelop of the reciprocal MLS-pair. In addition, spatial indices (\(SI = 1 - IACC\)) which are complimentary to interaural cross-correlation coefficients (\(IACC\)) of the binaural reverberation tails in the individual bands have also to be adjusted accordingly in order to achieve targeted degree of spaciousness. Figure 1 illustrates the procedure of the binaural artificial reverberation with controllable spaciousness and reverberance. A reciprocal MLS pair is first octave-band filtered. Two channels of band-pass filtered pseudo-random noise are mixed with a mixing factor \(k\), with \(0 \leq k \leq 1\) and \(k\) being octave-band index running from 63 Hz to 8 kHz at each octave-band step including one more band to go up to the Nyquist-frequency. The band-pass filtered pseudo-random noise of sufficient length is then shaped by an exponential decaying envelop \(E = \exp(-6.9 \cdot t/T_k)\) with the desired reverberation time \(T_k\) within octave band \(k\). In Fig.1 between ‘A’ and ‘B’ the two channels of band-pass filtered,
reciprocal MLS-pair are mixed to obtain desired ‘spatial index’ (SI). All band-pass filtered, mixed decaying noise will be summed up to form the broadband resulting ‘binaural’ reverberation tails (late portion of room impulse responses).

This artificial enveloping reverberation scheme using reciprocal MLS-pairs provides the following advantages. Firstly, maximum-length sequences of length between $2^{216} - 1$ and $2^{219} - 1$ are typical lengths used for the artificial reverberation application of wide variety of room types. The reciprocal MLS pairs are easily generated, they provide sufficient reverberation density when sampled using standard audio sampling frequencies. Secondly, perfect spectrum-flatness of each individual maximum-length sequence ensures the colorless reverberance. Furthermore, low-values of cross-correlation of reciprocal MLS pairs and related coded sequences ensure high degree of spaciousness. Any reduced degrees of spaciousness can be straightforwardly achieved by a mixing network, as shown in Fig.1.

III. SPATIAL PROFILES

In order to create naturally sounding, enveloping reverberation, in addition to a desired reverberation time profile, the spatial index profile has also to be adjusted. Figure 2 illustrates three different profiles of special indices obtained from analysis of experimentally measured binaural room impulse responses in existing real concert halls and churches.
Figure 3 illustrates the special indices when adjusting the mixing factor $\alpha_k$. The dotted lines show the results when the mixing factors are identical for all the bands. The solid line shows a targeted profile of the spatial indices.

Figure 4 shows the psychoacoustic test results based on 18 subjects. Two convolved sound samples are presented to subjects binaurally via a headphone. The subjects were asked to select which of two sounds naturally when paying attention to the spatially sounding reverberation. Three choices are given, A, N or I (indistinguishable). The results labeled by N (‘natural’) are associated with the sound sample convolved with experimentally measured binaural room impulse responses in a concert hall (Troy Music Hall), whereas the ones labeled by A (‘artificial’) are associated with the sound sample convolved with the artificial reverberation tail, the decay time and spatial indices profiles are precisely created as measured ones. The direct sound and early reflection portion (up to 90 ms from the direct sound) are still taken from the measured binaural room impulse responses, but appended with the artificial reverberation tails created using the procedure described above (see Fig.1). The spatial-index profile is adjusted as shown in Fig. 3 (solid line). When using ‘flat’ spatial profiles labeled by $\alpha_k$ -value = 0.2, the hearing test results of taking the natural sound samples dominate significantly (91.4%). This is clear evidence that the natural sounding, enveloping reverberance can only be achieved when the spatial indices of artificial binaural reverberation tails have to be finely matched with those from experimentally measured ones or at least taking the trend from the experimental observations.
IV. ADAPTING SPACIOUSNESS

Once the overall spatial profile with the highest spatial indices (as shown, e.g. by solid-line curve in Fig. 3) is selected/given, any lower spatial indices can be adjusted again, while keeping the overall-trend of the spatial profiles as given. This is accomplished using Martin’s algorithm. The hearing tests using the sound samples having the spatial profiles as shown in Fig.5 (a) have demonstrated that the perceived spaciousness is changing accordingly from ‘perceived spatially’ to ‘perceived less spatially’ as illustrated in Fig.5 (b). To be precise: when ‘Pair 2’ are presented to 18 subjects binaurally, 73.1% subjects judge the sound sample with the spatial Profile 3 as perceived more spatially than the one with the spatial Profile 2 as labeled in Fig.5 (a).

V. MULTI-CHANNEL SETTINGS

In addition to the binaural implementation, the technique has also been extended to multiple (M) reverberation channels. The reciprocal maximum-length sequence pairs can straightforwardly be combined to provide a large number of Gold-sequences with mutually low cross-correlation among all sequences. The network between ‘A’ and ‘B’ in Fig. 1 now can be expressed as

$$
\begin{bmatrix}
1 & \alpha & \cdots & \alpha \\
\alpha & \ddots & \ddots & \vdots \\
\vdots & \ddots & \ddots & \alpha \\
\alpha & \cdots & \alpha & 1
\end{bmatrix}
$$

(1)

For an adaptation of different spaciousness, an algorithm, inspired by Martin has been found to be practically effective

$$
\begin{bmatrix}
\cos \theta & k \cdot \sin \theta & \cdots & k \cdot \sin \theta \\
k \cdot \sin \theta & \ddots & \ddots & \vdots \\
\vdots & \ddots & \ddots & k \cdot \sin \theta \\
k \cdot \sin \theta & \cdots & k \cdot \sin \theta & \cos \theta
\end{bmatrix}
$$

(2)

where \(\cos^2 \theta + (k \sin \theta)^2 + \cdots + (k \sin \theta)^2 = 1\) and \(k = 1/\sqrt{S-1}\) with \(S\) being the number of channels and \(\theta = \arcsin(1 - SI_{\text{mix}})/2\). This scheme with controllable spatial indices has also been validated via psychoacoustics experiments for four reverberation channels.
VI. SUMMARY

With rapid advances of high-speed digital processing, a framework based on finite-impulse-response filtering can now be efficiently implemented in real-time with a large number of parallel channels when simulating virtual room environment. In this framework the direct sound and the early reflection portion predominantly determine the apparent source width and the room-size, but a natural sounding enveloping reverberation needs to match the perceived room size. This work employs reciprocal maximum-length sequences (MLS) for creating binaural reverberation tails appended to the early portion of binaural room impulse responses. For multiple channel settings, Gold sequences derived from the MLS pairs are used. The spatial shaping algorithms have been tested for both binaural and multi-channel settings. This technique is of practical value in virtual auditory environment for adopting enclosures when instantaneously changing the room-sizes. It can also be employed for enhancing and even fictionalizing virtual room-acoustic environment. The technique can also benefit the educational and fundamental research effort in the near future.

REFERENCES