High-Resolution MIMO DRIR Measurements in an Opera Hall

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Introduction

The use of microphone arrays for room acoustic analysis has been widely studied in recent literature. Directional room impulse responses (DRIRs) are typically measured with spherical microphone arrays (SMA) (see e.g. [1, 2]). In combination with spherical loudspeaker arrays (SLA) also the directivity of the sound source can be controlled (see e.g. [3, 4]). Acoustic energy can be radiated to selected directions in space in order to excite individual reflection paths. This improves the separability of reflections in the analysis of a DRIR, compared to the excitation with an omni-directional loudspeaker (see e.g. [5]).

Acoustic measurement systems that include both array types have only been recently used for room acoustic analysis (see e.g. [6, 7]). Such joint-systems are typically referred to as acoustic multiple-input multiple-output (MIMO) systems, and according to this, the measured DRIRs are typically referred to as MIMO DRIRs. MIMO systems add control over the spatial properties and thus help to improve the spatial resolution of the room acoustic analysis.

A theoretical formulation of joint SMA/SLA MIMO systems was recently presented in [8]. In a more recent work by some of the authors a joint-design approach based on the analysis of spatial-aliasing, spherical-harmonics, and model-mismatch errors was presented [9, 10]. In this paper the latter approach has been used to design a MIMO system for room acoustic analysis [9, 11], which has then been employed to in-situ measurements. MIMO DRIRs were measured for several positions and under different acoustic conditions in the opera hall ("Großes Festspielhaus") of the Salzburg Festival. The following sections describe the design of the high-resolution MIMO measurement system.

Spherical Loudspeaker Array

The SLA has been especially developed to measure directional RIRs. It is employed in a sequential measurement method. The array consists of a rigid sound-hard sphere with a radius of $r = 20$ cm, 28 loudspeakers of three different sizes mounted on the sphere, a turntable for azimuthal rotation, and a mirror-symmetric frame construction [5].

The SLA measurement procedure allows for the synthesis of any arbitrary directivity up to the spherical harmonic order $N = 11$. The measurement involves the rotation of the sphere to 24 angular positions, which results in 672 room impulse response measurements [12]. The total time duration of the measurement for a given SMA/SLA position was about 90 min. To account for the room impulse response variations due to temperature fluctuations the temperature was measured with multiple calibrated sensors distributed over the auditorium and stage. The recorded temperature variation was in the range of 0.25 degrees Celsius during one measurement period.

Using off-line computed directivity control filters [13], the 672 measurements can be superposed for every SMA channel to synthesize any desired source directivity in the post-processing stage. The results for every SMA channel can then be used for further array processing on the receiver side.

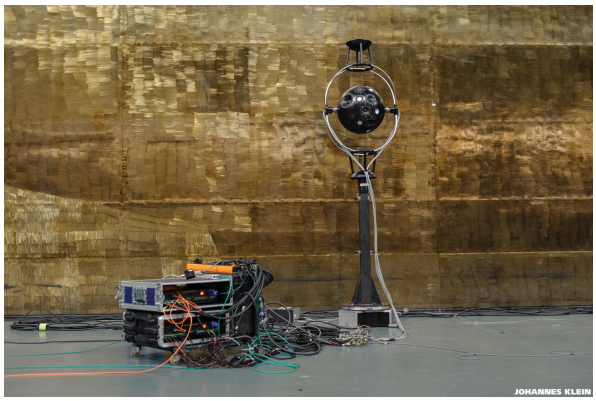

Figure 1: The spherical loudspeaker array (SLA) with the mirror-symmetric frame construction mounted on a turntable and the multi-channel amplifier rack.

Figure 1 illustrates the SLA measurement setup used during the measurements in the opera hall of the Salzburg Festival. This includes the SLA in its frame construction [12] on a stand, the turntable, as well as the amplifiers. The turntable can be remote-controlled using OSC messages, providing a straightforward interface for the different software frameworks used during the measurements ([14, 15], Fig. 5).

Spherical Microphone Array

The SMA has been designed to match the operating frequency range (OFR) of the SLA using the MIMO system model presented in [9, 11]. The array consists of

a rigid sound-hard aluminium sphere with a radius of $r = 12.5$ cm, 64 Sennheiser KE 4-211-2 back-electret microphone capsules, an FPGA-based data acquisition system, and an IP-based multi-channel audio streaming server [16]. The sampling nodes on the sphere correspond to the Sloan-Womersley "hyperinterpolation" (i.e. critical sampling) grid [17]. The SMA captures the 3-D sound field up to the spherical harmonic expansion order $N = 7$.

Figure 2: The spherical microphone array (SMA).

MIMO System

The SLA and SMA performance is limited by several factors that bound the OFR:

- Spatial aliasing errors $\epsilon_{a,S}$ and $\epsilon_{a,R}$: The use of a finite number of transducers in each array results in spatial-aliasing errors, which typically impose limitations at high frequencies.
- Model mismatch errors $\epsilon_{m,S}$ and $\epsilon_{m,R}$: Array inaccuracies such as transducer misplacement, gain and phase errors introduce errors at all frequencies. It can be shown that these errors become dominant at low frequencies when the spatial resolution is enhanced using methods such as the plane wave decomposition, which introduce ill-conditioning at low frequencies (see e.g. [18]).
- Joint SMA/SLA errors: These errors account for all the SMA/SLA cross error terms. It can be shown that these errors are bounded as long as the independent errors mentioned above are bounded (see e.g. [9]).

In [9] we presented a closed-form MIMO system model for the design of a SMA/SLA DRIR measurement system with desired specifications (e.g., minimum SNR, maximum dynamic range, etc.), at a desired OFR, given the array types (e.g., sound-hard rigid sphere) and array geometries.

Figure 3 depicts the independent and total energetic error bounds for the SMA/SLA-system that has been used for the MIMO DRIR measurements at the Salzburg Festival. It can be shown that these errors only depend on the array geometries and that they are independent of the beamforming algorithms applied [10].

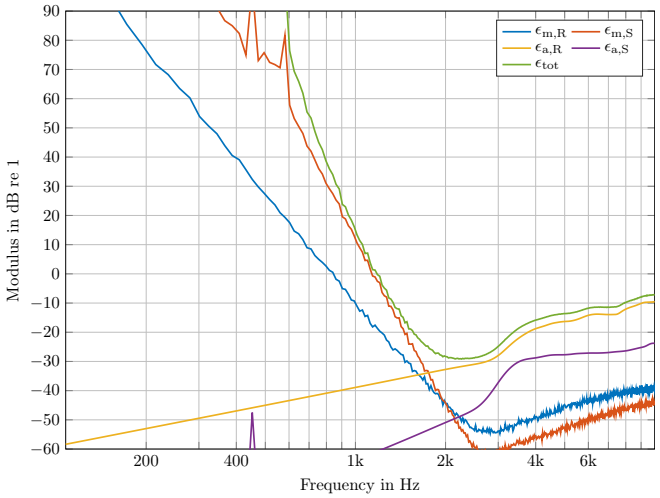

Figure 3: Independent and total energetic error bounds of the applied MIMO system [11] for a spherical harmonic order of $N = 11$.

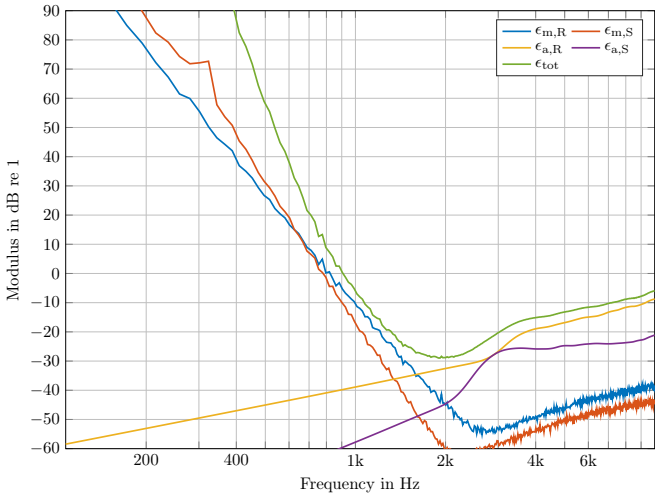

Figure 4: Independent and total energetic error bounds of the applied MIMO system [11] for a spherical harmonic order of $N = 9$.

Restricting the spatial resolution of an array can render an unmatched system feasible. Typically, the spatial resolution is limited by employing a SH order N_e lower than the maximum achievable SH order N. This can be used to "stabilize" the analysis during the post-processing of the data. Figure 4 illustrates this behavior for the discussed MIMO system. In the given example, the spherical harmonic order is reduced to $N = 9$, which results in a much broader OFR compared to order $N = 11$ (see also Figure 3).

Measurement System Setup

Figure 5 shows the graphic representation of the MIMO measurement system and its control structure.

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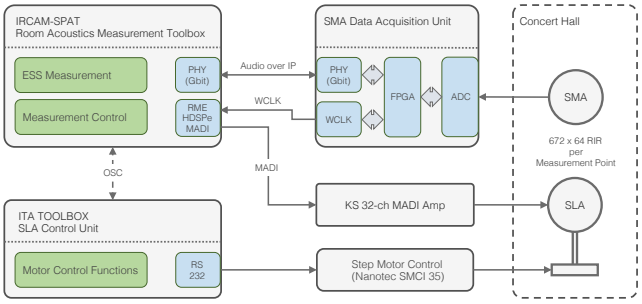

Figure 5: Graphic representation of the MIMO measurement system and its control structure.

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References

[1] Tervo, S., Pätynen, J. and Lokki, T.: Acoustic Reflection Localization from Room Impulse Responses. Acta Acust. United Ac., 98:3 (2012), 418–440

[2] Huleihel N. and Rafaely B.: Spherical array processing for acoustic analysis using room impulse responses and time-domain smoothing. J. Acoust. Soc. Am., 133:6 (2013), 3995–4007

[3] Pasqual, A. M., de Franca, A., Roberto, J., Herzog, P.: Application of acoustic radiation modes in the directivity control by a spherical loudspeaker array. Acta Acust. United Ac., 96:1 (2010), 32–42

[4] Rafaely, B., Khaykin, D.: Optimal model-based beamforming and independent steering for spherical loudspeaker arrays. IEEE Trans. on Audio, Speech, and Lang. Proc., 19:7 (2011), 2234–2238

[5] Pollow, M., Klein, J., Dietrich, P., Vorländer, M.: Including Directivity Patterns in Room Acoustical Measurements. Proc. Int. Congr. on Acoust. (ICA), Montreal, Canada (2013)

[6] Gerzon, M. A.: Recording concert hall acoustics for posterity. J. Audio Eng. Soc., 23:7 (1975), 569–571

[7] Freed, A., Schmeder, A., Zotter, F.: Applications of Environmental Sensing for Spherical Loudspeaker Arrays. IASTED Signal and Image Proc., Hawaii (2008)

[8] Morgenstern, H., Rafaely, B., Zotter, F.: Theory and investigation of acoustic multiple-input multiple-output systems based on spherical arrays in a room. J. Acoust. Soc. Am., 138:5 (2015), 2998–3009

[9] Morgenstern, H., Rafaely, B., Noisternig, M.: Joint Design of Spherical Microphone and Loudspeaker Arrays for Room Acoustic Analysis. Proc. 41st German Congr. on Acoust. (DAGA), Nürnberg, Germany (2015)

[10] Morgenstern, H., Rafaely, B., Noisternig, M.: Design Framework for Spherical Microphone and Loudspeaker Arrays in a Multiple-input Multiple-output System. Submitted to J. Acoust. Soc. Am., (2016)

[11] M. Berzborn, J. Klein, and M. Vorländer. Analysis and Design of a Matched MIMO System Prototype. Proc. 42nd Int. Annual German Congress on Acoustics (DAGA), Aachen, Germany (2016)

[12] Klein, J., Pollow, M., Vorländer, M.: Optimized Spherical Sound Source for Auralization with Arbitrary Source Directivity. Proc. EAA Symposium on Auralization and Ambisonics, Berlin, Germany (2014)

[13] Klein, J., Berzborn, M., Vorländer, M.: Directivity Filter for Sequential Loudspeaker Array Measurements. Proc. 42nd German Congr. on Acoust. (DAGA), Aachen, Germany (2016)

[14] IRCAM Spat Measurement Toolkit, URL: `http://forum.ircam.fr`

[15] ITA-Toolbox, URL: `http://www.ita-toolbox.org`

[16] Reitbauer, C., Rainer, H., Noisternig, M., Rettenbacher, B., Graf, F.: Micarray – A System for Multichannel Audio Streaming over Ethernet. In 5th Congr. of the Alps Adria Acoust. Assoc., Petrcane (Zadar), Croatia (2012)

[17] Sloan, I. H., Womersley, R. S.: The uniform error of hyperinterpolation on the sphere. Advances in Multivariate Approximation, Wiley-VCH Verlag (1998)

[18] Rafaely, B.: Plane-wave decomposition of the sound field on a sphere by spherical convolution. J. Acoust. Soc. Am., 116:4 (2004), 2149–2157.