Spatialization Schemata for High-Order Source Directivity

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INTRODUCTION

MOTIVATION

“There is no such thing as nonspatial hearing: all musical hearing has an inherent spatial component, even if it is not noticed by the listener.”

- We consider space as an important aspect / structural element of music composition
- Recent advances in
  - sound source spatialization technologies,
  - (digital) audio signal processing,
  - audio interfaces and audio transmission technologies,
  - loudspeaker design, and
  - CPU processing power
- make large-scale multichannel audio environments for sound source spatialization available for music performance
SOUND SOURCE RADIATION

- Radiated sound of musical instruments is characterized by
  - intensity
  - spectral and temporal attributes
  - directivity in space
- Variation in directivity of (real) instruments affects
  - direct sound and reverberant sound field
  - perception of timbre at the listener position
- Sound source interacts with room acoustic environment
- Accurate / convincing sound synthesis requires modeling the directional radiation patterns
  - sound of live-instruments often coexists with electronic sounds
  - reproduction of radiation characteristics of real instruments
  - spatiotemporal additive synthesis
SPHERICAL WAVE SPECTRUM

- Wave field expansion in spherical coordinates

- Any arbitrary and square-integrable function on the 2-sphere can be expanded into spherical harmonics (inverse Fourier transform)

\[ x(\theta, \phi) = \sum_{n=0}^{\infty} \sum_{m=-n}^{n} \chi_{nm} Y_n^m(\theta, \phi) \]

- with the expansion coefficients (forward Fourier transform)

\[ \chi_{nm} = \int_{S^2} x(\theta, \phi) Y_n^m(\theta, \phi) \, d\Omega \quad \text{with} \quad \int d\Omega = \int_0^{2\pi} d\phi \int_0^\pi \sin \theta d\theta \]

- Provides a general radiation pattern description format
  - independent of the sound field rendering technique later applied
  - compatible and scalable (different playback devices with different reproduction orders)
SPHERICAL WAVE SPECTRUM

- Discrete Spherical Harmonics Transform - notes on sampling the sphere
- **Ideally:** continuous sampling of the sphere
- **Practically:** finite resolution / truncation

\[ p(\theta, \phi) \bigg|_{r_0} = \sum_{n=0}^{N} \sum_{m=-n}^{n} \chi_{nm} \bigg|_{r_0} Y_n^m(\theta, \phi) \]

- Calculating the expansion coefficients from \( K \) sensor signals

\[ p = C_{SH,N_\alpha} \psi_{SH,N_\alpha} \]

- requires to invert the system of linear equations
  - matrices are often **ill/badly conditioned**
  - regularizations
  - etc …
RADIATION PATTERN SYNTHESIS

- Reproduction of directivity patterns using multi-loudspeaker sources (1997 - today)
  - Warusfel, Caussé, Derogis, Misdariis / Ircam
  - Three-dimensional loudspeaker array: *La Timée*
  - Radiation pattern synthesis by combining canonical base functions

- N-body project (1997)
  - P. Cook, D. Trueman / Princeton University
  - First higher order spherical loudspeaker array for musical applications (“Bomb”, “Boulder”, “R12”)

SOUND SOURCE RADIATION

RADIATION PATTERN SYNTHESIS

- RWTH Aachen
  - 2 way system / dodecahedron (2 x 12 speakers)
- IEM, University of Music and Performing Arts, Graz
  - 2 way system / icosahedron (2 x 20 speakers)
- CNMAT, Univ. of California, Berkeley / Meyer Sound
  - 1 way system / icosahedron (120 speakers)
RADIATION PATTERN ANALYSIS

- **Example:** Radiation synthesis using an 8-loudspeaker array
RADIATION PATTERN SYNTHESIS – WFS

- WFS synthesizes the sound field within an extended listening area
- WFS approach: omnidirectional sound sources
- Synthesis of elementary base functions: subset of spherical / circular harmonics
- Manipulation of directivity characteristics
- Only horizontal dependencies in directivity characteristics can be reproduced
- Finite length of loudspeaker array allows synthesis only within a visibility window
- Finite number of loudspeakers yields aliasing and limits the proper reproduction of wave fronts

CONCLUSION

SpatDIF/GDIF:

- Modeling the spatially varying radiation pattern is essential, when
  - e.g. in contemporary music performance – sound of live played instruments coexists with electronic sounds / virtual sounds

- Wave field expansion in spherical coordinates – useful tool for radiation pattern analysis / synthesis

- SH expansion provides general radiation pattern description format
  - independent of the sound field rendering technique later applied
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Spatialization Schemata for High-Order Source Directivity (continued...)

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Layer Model for Spatial Audio
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- Transducer signals: 100khz
Layer Model for Spatial Audio

- Transducer signals: 100khz
- Primitive dimensional attributes: 100-1000hz
Layer Model for Spatial Audio

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Layer Model for Spatial Audio

- Transducer signals: 100khz
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- Perceptual attributes: 10hz
- Cognitive attributes: 1hz
  - “Spatialization schemata”
Perception of Directivity
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- Has significant impact on perceptual attributes:
  - Immersion (random angle directivity)
  - Apparent source width (early reflection structure)
  - Presence / Clarity (late reflection structure)
Mirror reflection model does not hold!
Perception of reflection locations is non-uniform
Perception of constant angular change (correlated change in reflection structure)
Simplified zone model for beam steering
Spatial Schemata

Source Width

Ensemble Width

Room Width

Scene
Spatial Schemata

- SOURCE

Diagram showing spatial relationships: Source Width, Ensemble Width, Room Width, and Scene.
Spatial Schemata

- SOURCE
- ENSEMBLE
Spatial Schemata

- SOURCE
- ENSEMBLE
- ROOM
Spatial Schemata

- SOURCE
- ENSEMBLE
- ROOM
- PATH
Spatial Schemata

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- The Artistic Play of Spatial Organization: Spatial Attributes, Scene Analysis and Auditory Spatial Schemata (Gary S. Kendall and Mauricio Ardila)
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  - Violations of ROOM, SOURCE, etc.
- Anti-physical systems
Schemata for Directivity?
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- DIRECTION
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  - The face of a source (front, back)
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- **FLUX**
  - Change in auditory scene other than PATH transform or birth/death event of an element
Schemata for Directivity?

- **DIRECTION**
  - The face of a source (front, back)
  - Implementation by beam-forming, steering

- **FLUX**
  - Change in auditory scene other than PATH transform or birth/death event of an element
  - Implementation by directivity noise, spherical resonance models, etc
DEMO...