Theoretical Study of Scalable Three-dimensional Radiated Sound Field Reproduction System with Directional Loudspeakers and Wave Field Synthesis

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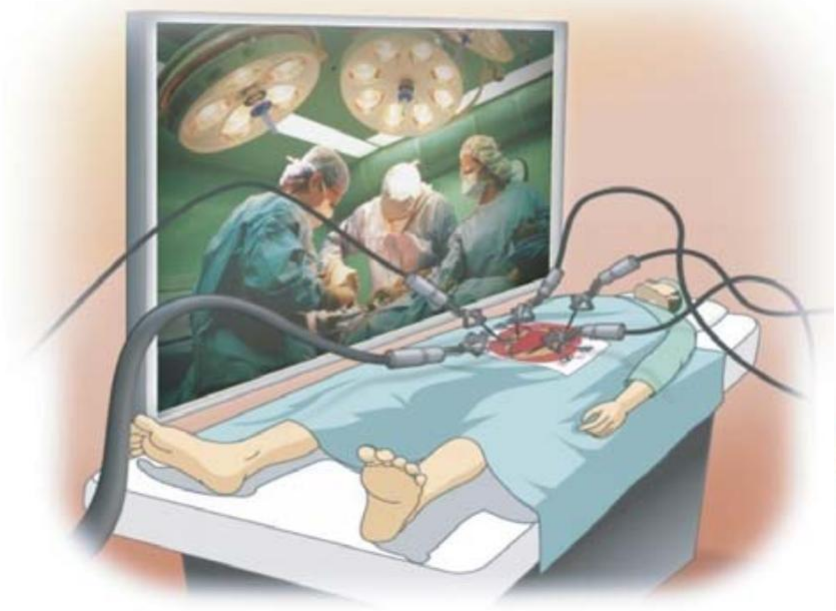
Introduction

- Ultra-realistic communication (URC)
  - Create a "realistic sensation“
  - Use 3D video and 3D audio
- Use Cases
  - Remote operation
  - Teleconference



K. Enami and F. Kishino: "Research on Ultra-realistic Communications", J. IEICE, 93, 5, pp. 363–367 (2010).

Introduction

- Future 3D Television
  - 3D image emitting sound pops up in 3D space
  - People enjoy the sound of the 3D image from any direction without wearing any equipment

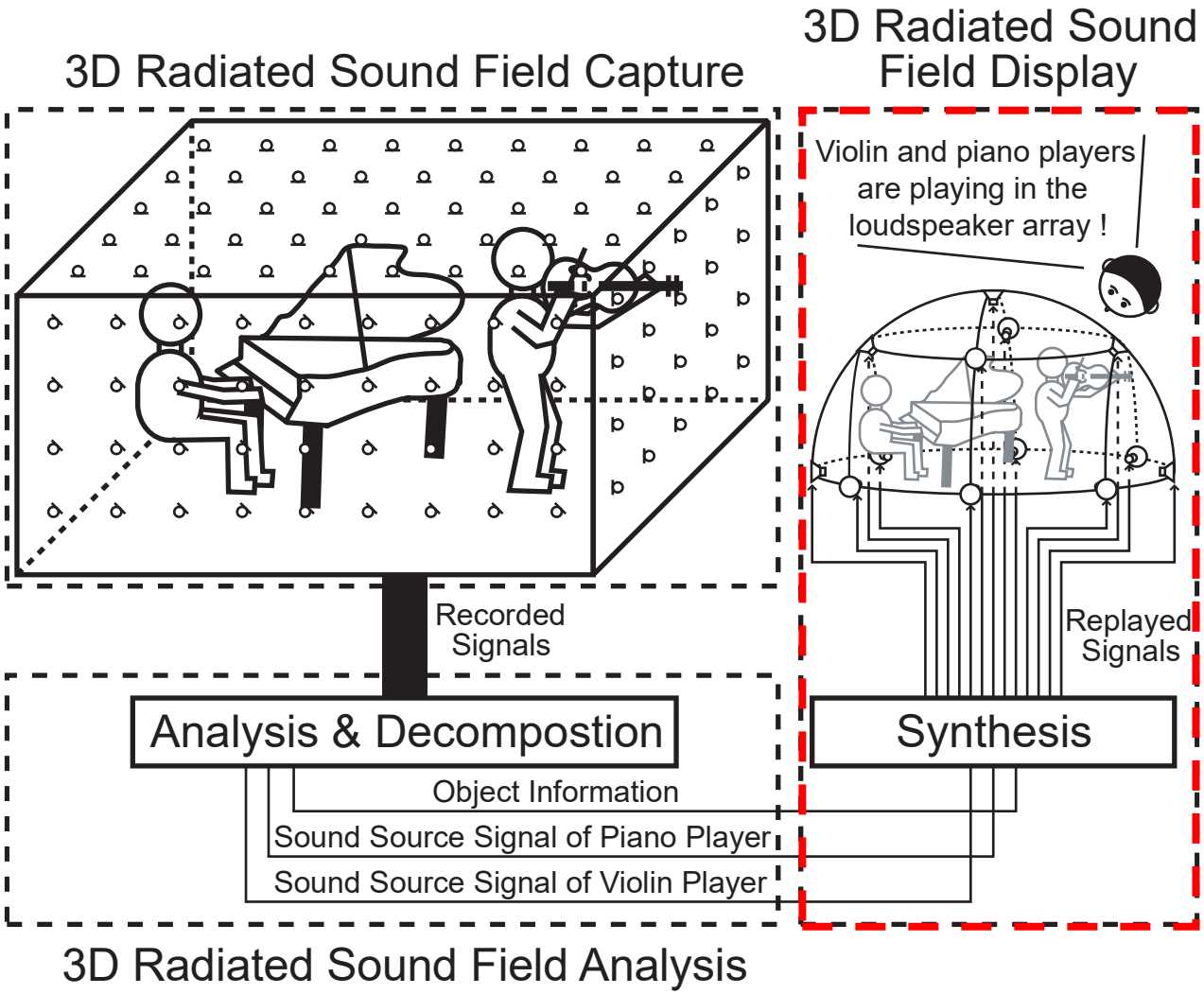
3D sound technology that allows people to hear 3D sound images without wearing headphones

K. Enami: "Research on ultra-realistic communications", ECTI Trans. Elect. Eng., Electro., Comm., 6, 1, pp. 22–25 (2008).

My previous study

- 3D audio for future 3D TV
  - Component
    - Capture
    - Analysis
    - Display

T. Kimura, Y. Yamakata, M. Katsumoto, T. Okamoto, S. Yairi, Y. Iwaya and Y. Suzuki: "Three-dimensional radiated sound field display system using directional loudspeakers and wave field synthesis", Acoust. Sci. & Tech., 33, 1, pp. 11–20 (2012).



My previous study

- 3D radiated sound field reproduction system using wave field synthesis
  - Problem
    - The size of the microphone array is the same as the loudspeaker array
    - It takes a great deal of effort to create an acoustic transfer function database

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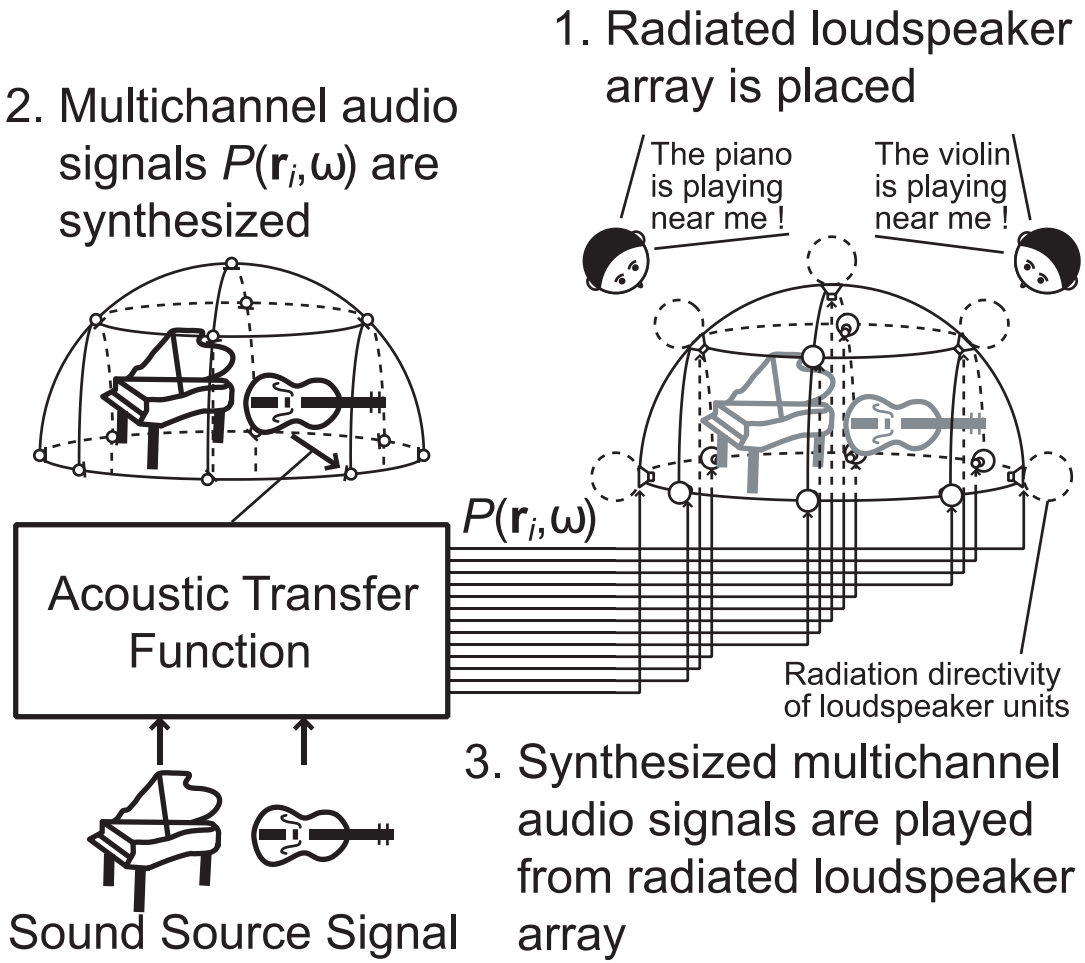
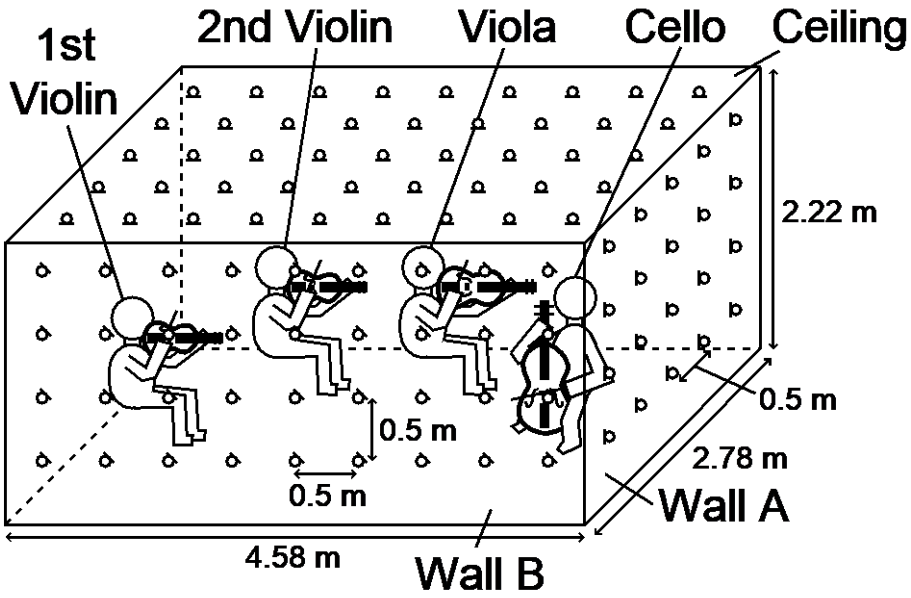


My previous study

- Demonstration of radiated loudspeaker array
  - YouTube
    - https://www.youtube.com/watch?v=hntR0yt-HDw
    - Despite the difference in size between the microphone array and the loudspeaker array, it felt as if a string quartet was being played inside the loudspeaker array



T. Kimura, Y. Yamakata, M. Katsumoto, T. Okamoto, S. Yairi, Y. Iwaya and Y. Suzuki: "Development of real system in near 3d sound field reproduction system using directional loudspeakers and wave field synthesis", Proc. WESPAC, No. 0164, pp. 1–6 (2009).

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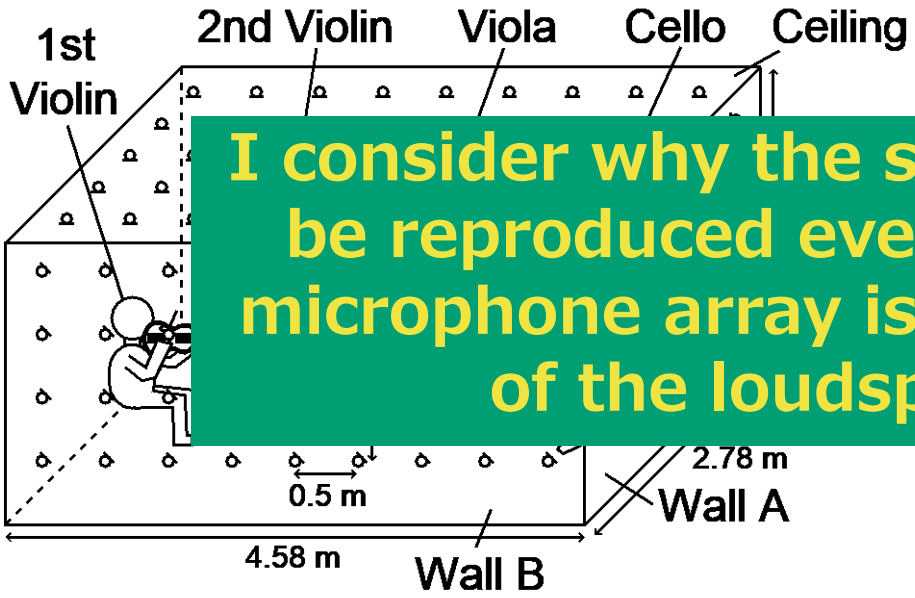
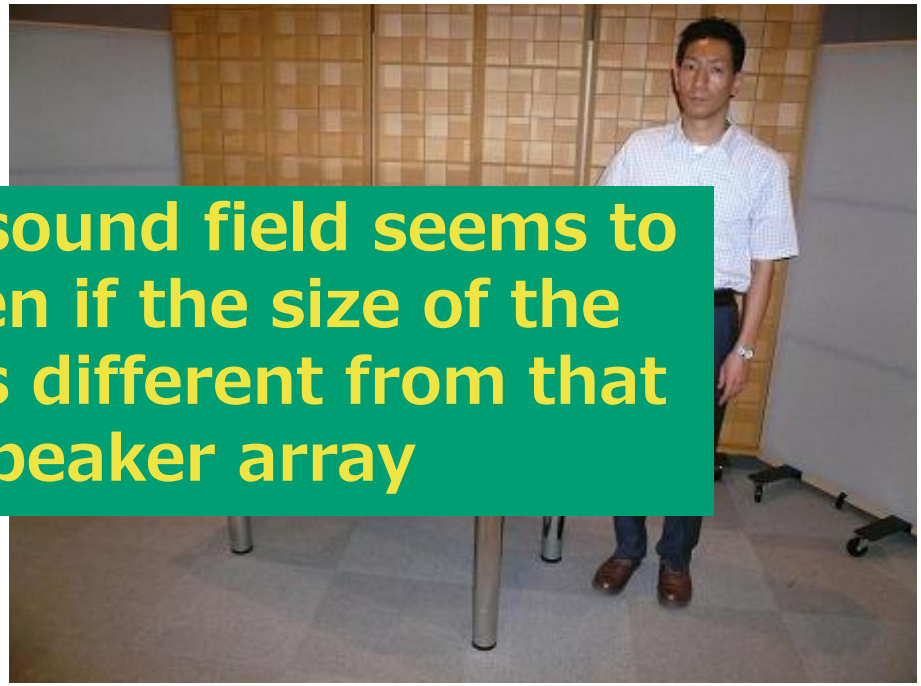


I consider why the sound field seems to be reproduced even if the size of the microphone array is different from that of the loudspeaker array



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Theoretical consideration

- Wave field synthesis formula

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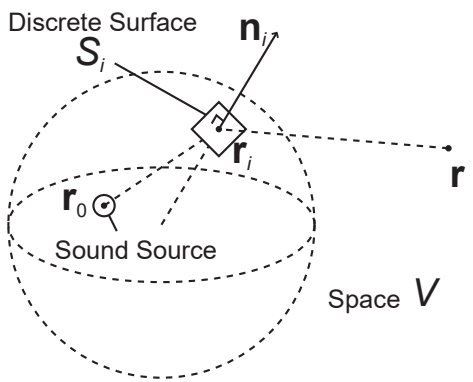
$$P(\mathbf{r},\omega) = \frac{jk}{4\pi}\sum_{i=1}^{M} P(\mathbf{r}_i,\omega)D(\theta_i)\frac{e^{-jk|\mathbf{r}-\mathbf{r}_i|}}{|\mathbf{r}-\mathbf{r}_i|}\Delta S_i$$

$$P(\mathbf{r}_i,\omega) = AD_0(\theta_0,\phi_0)\frac{e^{-jk|\mathbf{r}_i-\mathbf{r}_0|}}{|\mathbf{r}_i-\mathbf{r}_0|} \qquad k = \frac{\omega}{c}$$



- $D(\theta_i)$: Radiation directivity of loudspeaker unit
- A : Amplitude of sound sources
- $D_0(\theta_0,\phi_0)$: Radiation directivity of sound sources
- c : Sound velocity

Theoretical consideration

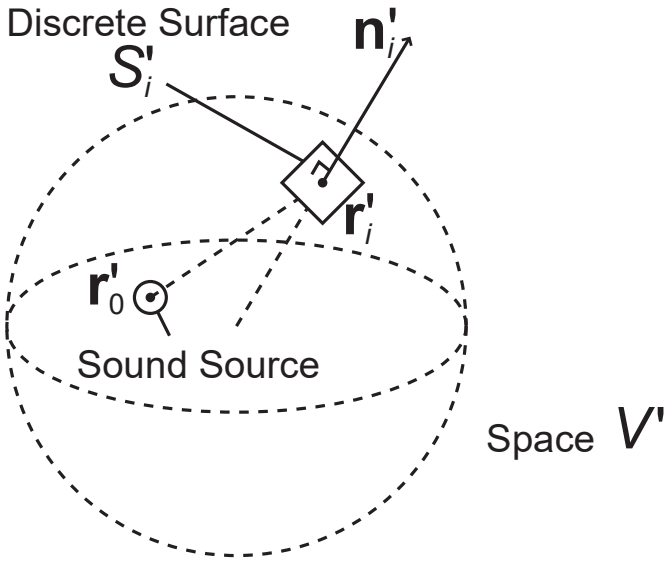
- Microphone array size : α times

T. Kimura, "Theoretical Study of Scalable 3D Radiated Sound Field Reproduction System with Directional Loudspeakers and Wave Field Synthesis," Proc. ASJ Spring Meeting, No. 3-Q-8, pp. 225-228 (2024).

$$P(\mathbf{r}_i', \omega) = AD_0(\theta_0, \phi_0)\frac{e^{-jk|\mathbf{r}_i' - \mathbf{r}_0'|}}{|\mathbf{r}_i' - \mathbf{r}_0'|}$$

$$= AD_0(\theta_0, \phi_0)\frac{e^{-jk\alpha|\mathbf{r}_i - \mathbf{r}_0|}}{\alpha|\mathbf{r}_i - \mathbf{r}_0|}$$

$$= \frac{AD_0(\theta_0, \phi_0)}{\alpha}\frac{e^{-jk'|\mathbf{r}_i - \mathbf{r}_0|}}{|\mathbf{r}_i - \mathbf{r}_0|}$$



- k' : Transformed wavenumber

$$k' = \alpha k = \frac{\alpha\omega}{c} = \frac{\omega}{\frac{c}{\alpha}} = \frac{\omega}{c'}$$

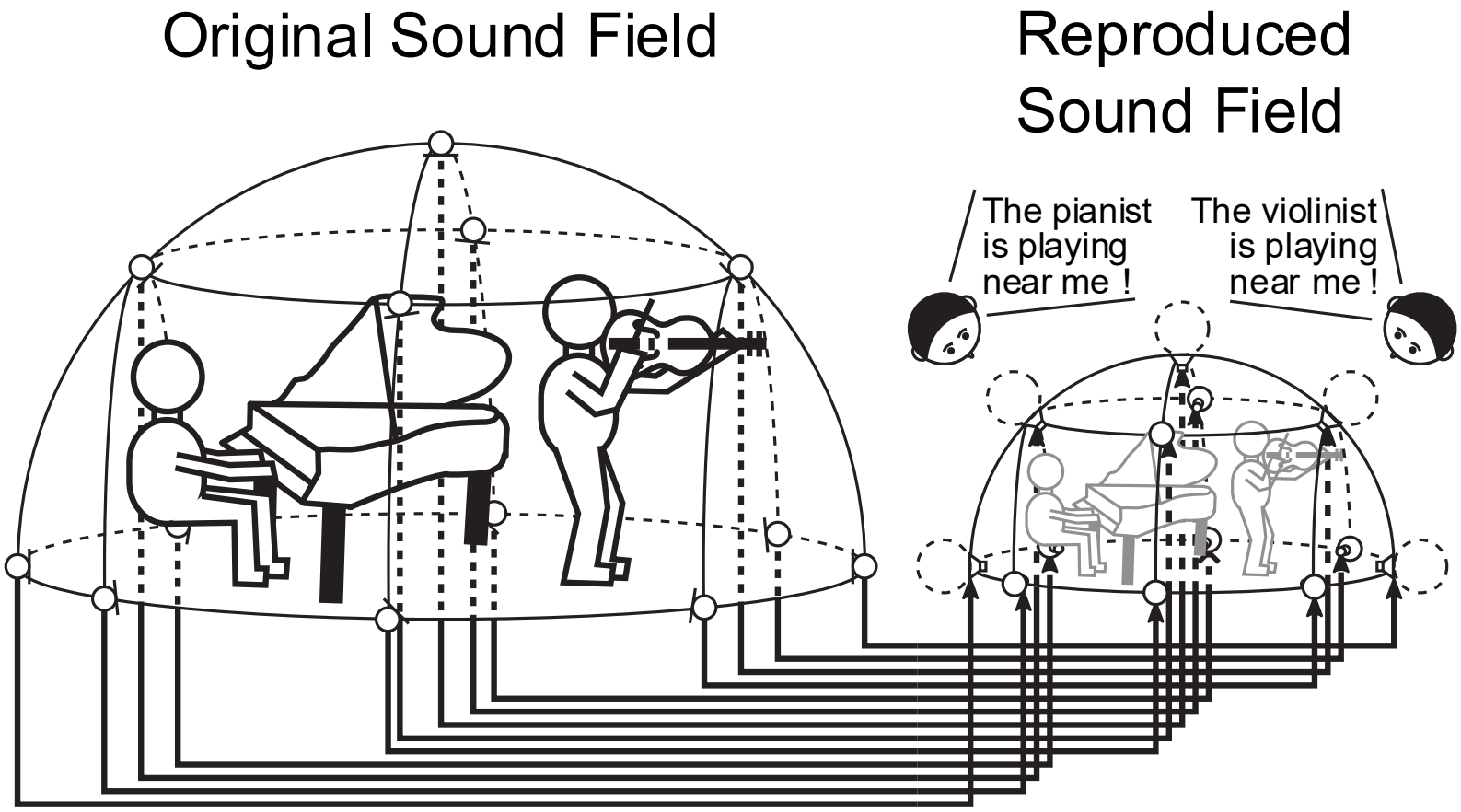
- c' : Transformed speed of sound

$$\mathbf{r}_i' = \alpha\mathbf{r}_i$$
$$\mathbf{r}_0' = \alpha\mathbf{r}_0$$
$$|\mathbf{r}_i' - \mathbf{r}_0'| = \alpha|\mathbf{r}_i - \mathbf{r}_0|$$

The sound field where the speed of sound has changed to 1/α time

Theoretical consideration

- Diagram of proposed system
  - Scaled 3D radiated sound field is reproduced
    - The speed of sound changed



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Conclusion

- 3D radiated sound field reproduction
  - I theoretically investigated the sound field reproduced when the size of the microphone array differs from that of the loudspeaker array

- Scaled 3D radiated sound field is reproduced
  - The condition
    - The arrangement of the microphone and directional loudspeaker is similar
    - The speed of sound changes

Future works

- Validation by computer simulation
- Acoustic measurements and listening tests by radiated loudspeaker array