Theoretical Study of 3D Radiated Sound Field Reproduction System Using Directional Loudspeakers and Boundary Surface Control

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1. INTRODUCTION

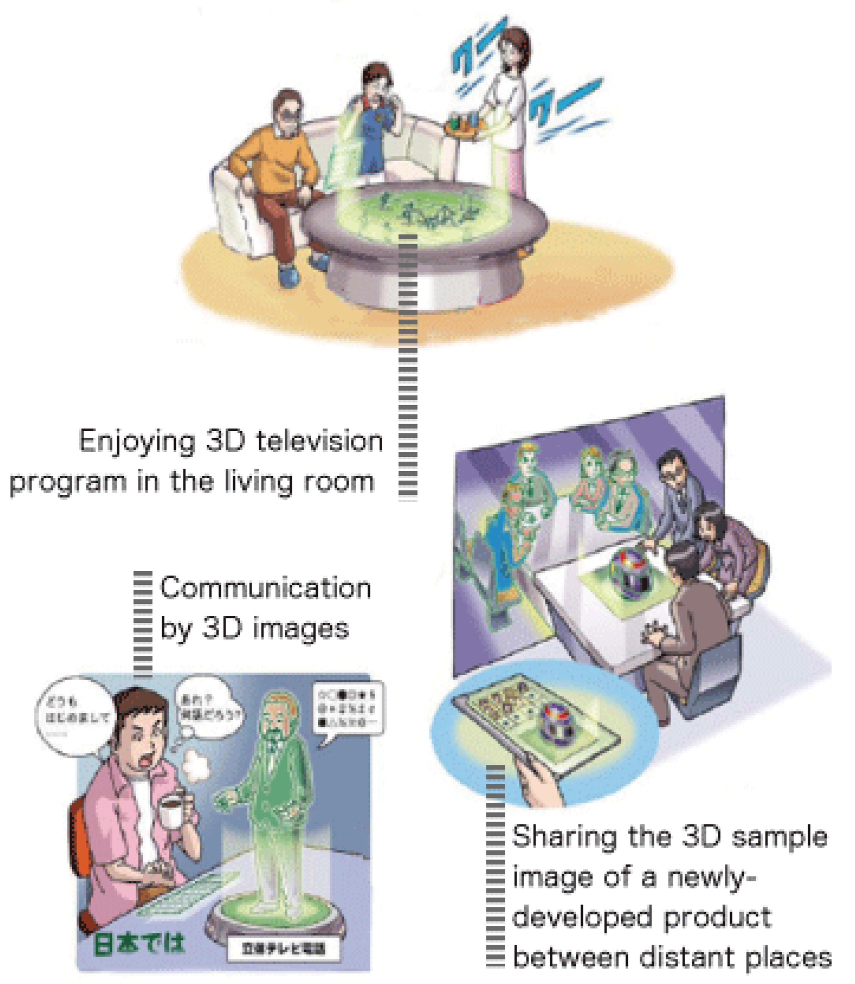
Ultra-Realistic Audio Technique

- Depict **the presence of an object** at a given position
- Listeners around an object can listen to the sound generated by the object

Aim of Study

- We have proposed a conventional system
  - + Near 3D sound field reproduction system using directional loudspeakers and wave field synthesis
- Conventional system
  - + When the size of the loudspeaker array is not the same as that of the microphone array, the 3D radiated sound field captured by the microphone array cannot be accurately reproduced

A novel 3D radiated sound field reproduction system using directional loudspeakers and boundary surface control is proposed



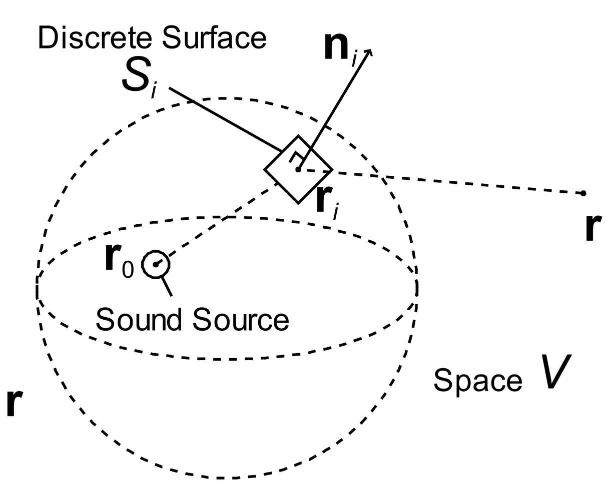
2. THEORETICAL STUDY

Conventional System

- Sound pressure in V can be reproduced if the size of loudspeaker array is the same as that of microphone array
  - + $\mathbf{r}$: Position vector in V
  - + S_i: ith element of S
  - + $\mathbf{r}_i$: Position vector of S_i
  - + M: Total number of elements
  - + ΔS_i: Area of S_i
  - + $D_s(\mathbf{r}_i|\mathbf{r})$: Directivity of loudspeaker at $\mathbf{r}_i$
  - + $G(\mathbf{r}_i|\mathbf{r},\omega)$: Acoustic transfer function from $\mathbf{r}_i$ to $\mathbf{r}$

$$G(\mathbf{r}_i|\mathbf{r},\omega)=\frac{\exp(-jk|\mathbf{r}_i-\mathbf{r}|)}{4\pi|\mathbf{r}_i-\mathbf{r}|}$$

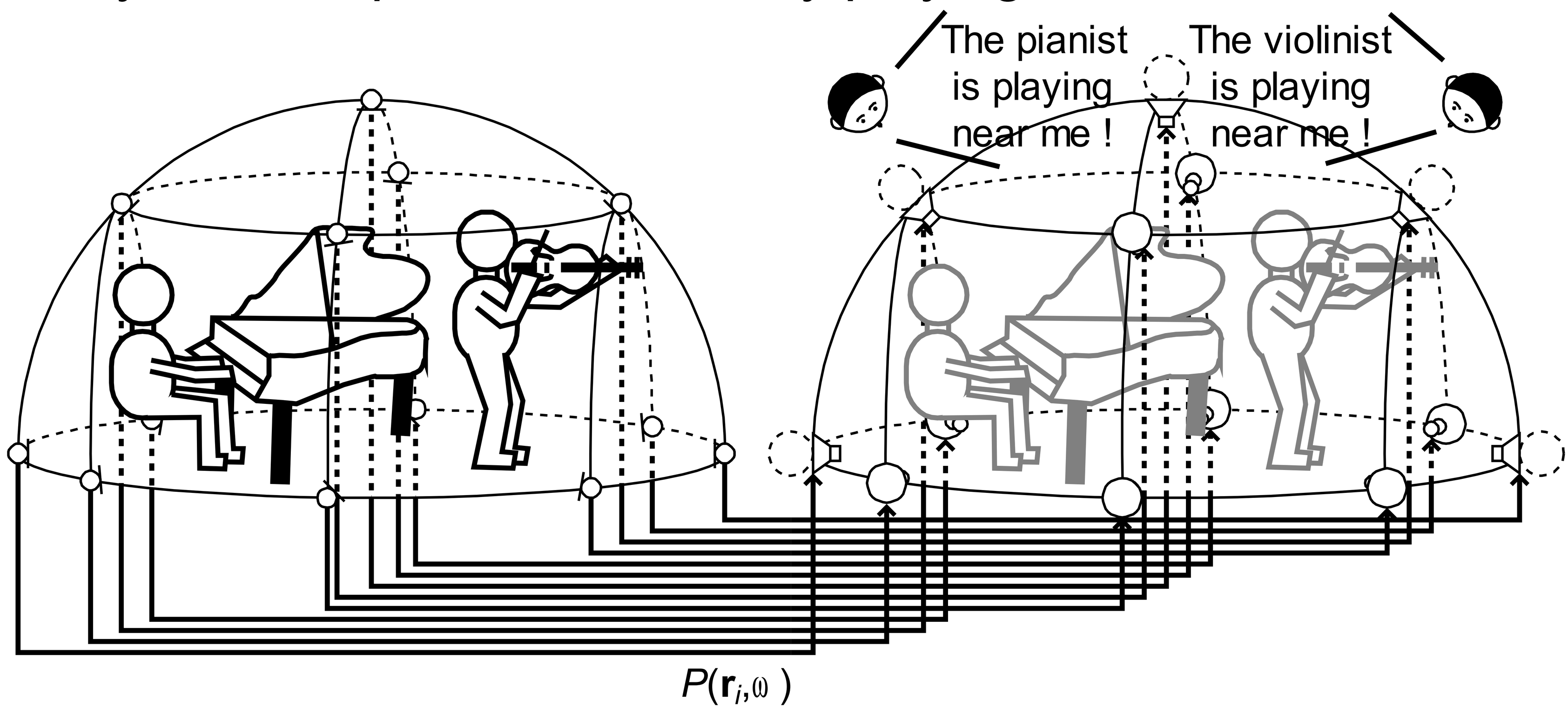
  - + $k(=\omega/c)$: Wave number
  - + c: Sound velocity



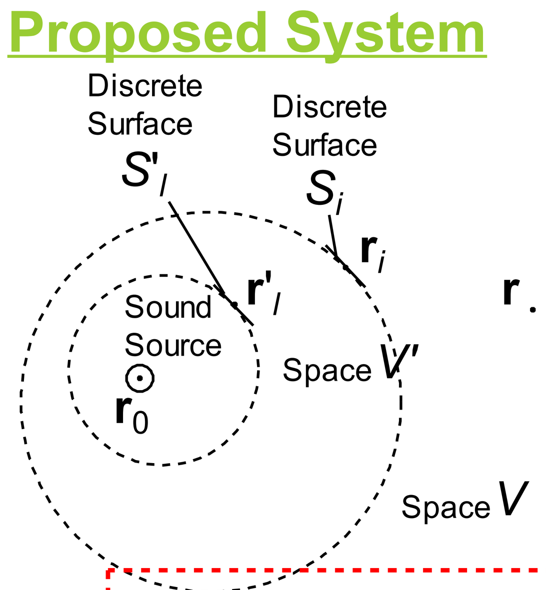
$$P(\mathbf{r},\omega)=jk\sum_{i=1}^{M}P(\mathbf{r}_i,\omega)D_s(\mathbf{r}_i|\mathbf{r})G(\mathbf{r}_i|\mathbf{r},\omega)\Delta S_i \quad (\mathbf{r}\in V)$$

Diagram

1. Sounds are recorded by M microphones
2. Sound fields are reproduced by playing M channels



Proposed System



- Sound field is reproduced in V'

$$P(\mathbf{r},\omega)=jk\sum_{l=1}^{N}P(\mathbf{r}'_l,\omega)D_s(\mathbf{r}'_l|\mathbf{r})G(\mathbf{r}'_l|\mathbf{r},\omega)\Delta S'_l \quad (\mathbf{r}\in V')$$

- $\mathbf{r}_i$ is always in V'

$$P(\mathbf{r}_i,\omega)=jk\sum_{l=1}^{N}P(\mathbf{r}'_l,\omega)D_s(\mathbf{r}'_l|\mathbf{r}_i)G(\mathbf{r}'_l|\mathbf{r}_i,\omega)\Delta S'_l \quad (\mathbf{r}_i\in V')$$

$$P(\mathbf{r},\omega)=jk\sum_{l=1}^{N}P(\mathbf{r}'_l,\omega)\left\{jk\sum_{i=1}^{M}D_s(\mathbf{r}'_l|\mathbf{r}_i)G(\mathbf{r}'_l|\mathbf{r}_i,\omega)D_s(\mathbf{r}'_l|\mathbf{r})G(\mathbf{r}_i|\mathbf{r},\omega)\Delta S_i\right\}\Delta S'_l$$

$$\rightarrow \quad D_s(\mathbf{r}'_l|\mathbf{r})G(\mathbf{r}'_l|\mathbf{r},\omega)=jk\sum_{i=1}^{M}D_s(\mathbf{r}'_l|\mathbf{r}_i)G(\mathbf{r}'_l|\mathbf{r}_i,\omega)D_s(\mathbf{r}'_l|\mathbf{r})G(\mathbf{r}_i|\mathbf{r},\omega)\Delta S_i \quad (\mathbf{r}\in V,\mathbf{r}_i\in V')$$

- System via M-input N-output inverse filters

$$P'(\mathbf{r}'_l,\omega)=\sum_{i=1}^{M}H_{li}(\omega)P(\mathbf{r}_i,\omega) \qquad \sum_{l=1}^{N}H_{li}(\omega)D_s(\mathbf{r}'_l|\mathbf{r}_n)G(\mathbf{r}'_l|\mathbf{r}_n,\omega)\Delta S'_l=\begin{cases}1 & (n=i)\\ 0 & (n\neq i)\end{cases}$$

$$P'(\mathbf{r},\omega)=\sum_{l=1}^{N}P'(\mathbf{r}'_l,\omega)D_s(\mathbf{r}'_l|\mathbf{r})G(\mathbf{r}'_l|\mathbf{r},\omega)\Delta S'_l$$

$$=\sum_{i=1}^{M}P(\mathbf{r}_i,\omega)\left\{\sum_{l=1}^{N}H_{li}(\omega)D_s(\mathbf{r}'_l|\mathbf{r})G(\mathbf{r}'_l|\mathbf{r},\omega)\Delta S'_l\right\}$$

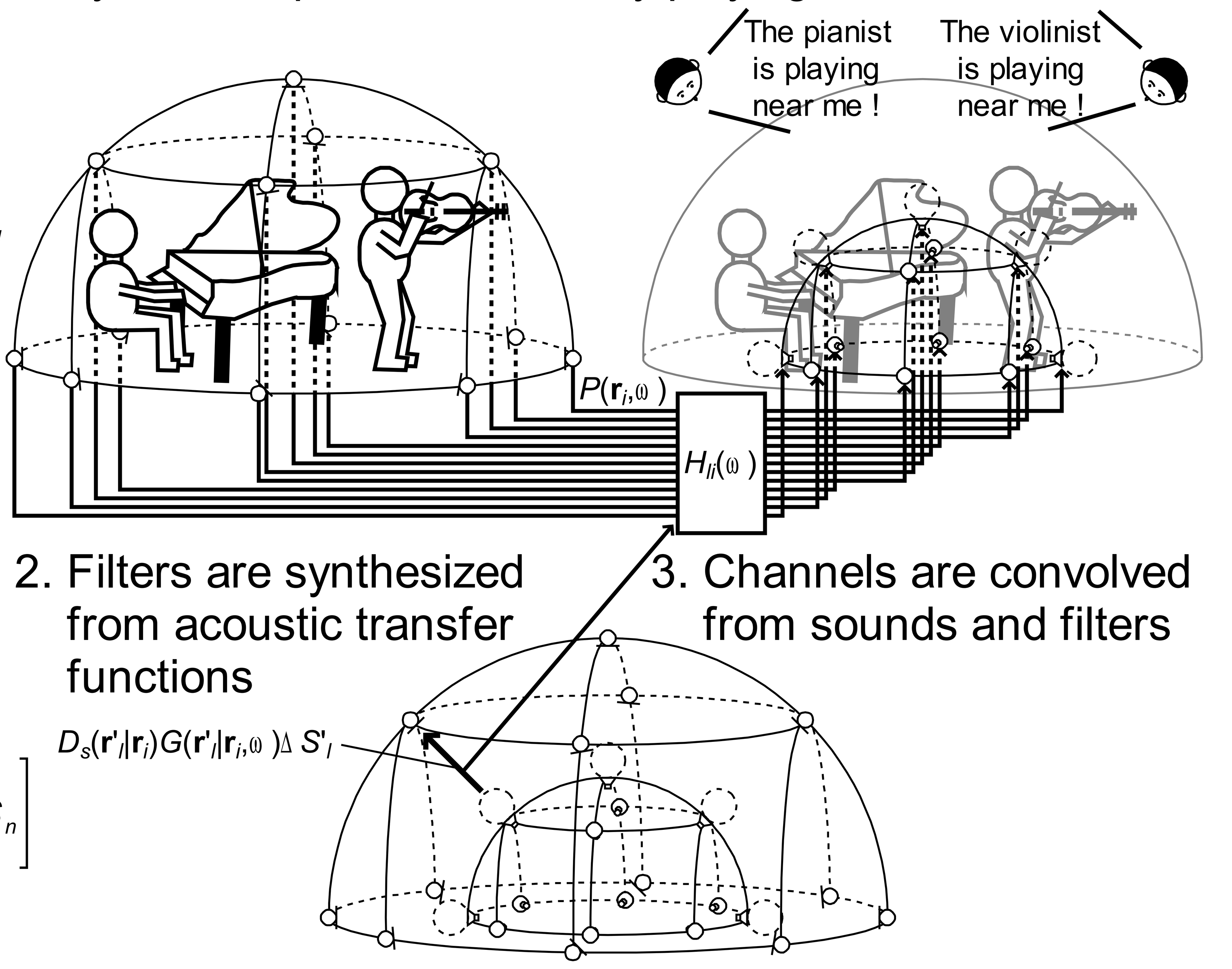
$$=jk\sum_{i=1}^{M}P(\mathbf{r}_i,\omega)\left[\sum_{n=1}^{M}D_s(\mathbf{r}_n|\mathbf{r})G(\mathbf{r}_n|\mathbf{r},\omega)\left\{\sum_{l=1}^{N}H_{li}(\omega)D_s(\mathbf{r}'_l|\mathbf{r}_n)G(\mathbf{r}'_l|\mathbf{r}_n,\omega)\Delta S'_l\right\}\Delta S_n\right]$$

$$=jk\sum_{i=1}^{M}P(\mathbf{r}_i,\omega)D_s(\mathbf{r}_i|\mathbf{r})G(\mathbf{r}_i|\mathbf{r},\omega)\Delta S_i=P(\mathbf{r},\omega) \quad (\mathbf{r}\in V,\mathbf{r}_i\in V')$$

Diagram

- 3D radiated sound field can be accurately reproduced even if the size of arrays is not same

1. Sounds are recorded by M microphones
2. Filters are synthesized from acoustic transfer functions
3. Channels are convolved from sounds and filters
4. Sound fields are reproduced by playing N channels



3. CONCLUSION

- Novel 3D radiated sound field reproduction system is proposed
  - + Directional loudspeakers and boundary surface control technique are used
  - + The inverse filters are used in the conventional 3D radiated sound field reproduction system
- **A 3D radiated sound field can be accurately reproduced in a listening area even if the loudspeaker array is not the same size as the microphone array**
- Future work
  - + Numerical analysis of the reproduced 3D radiated sound field in the proposed system by a computer simulation