Theoretical Study and Numerical Analysis of 3D Sound Field Reproduction System Based on Directional Microphones and Boundary Surface Control

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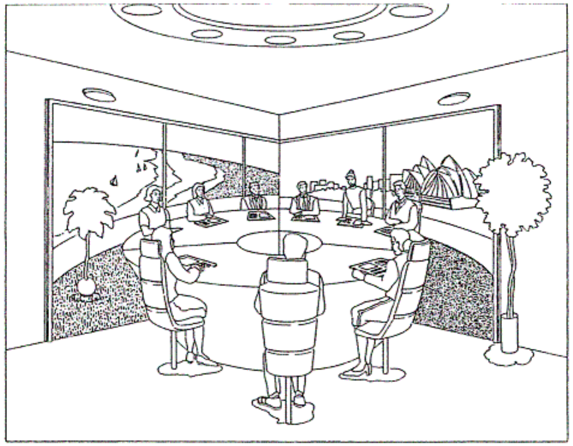
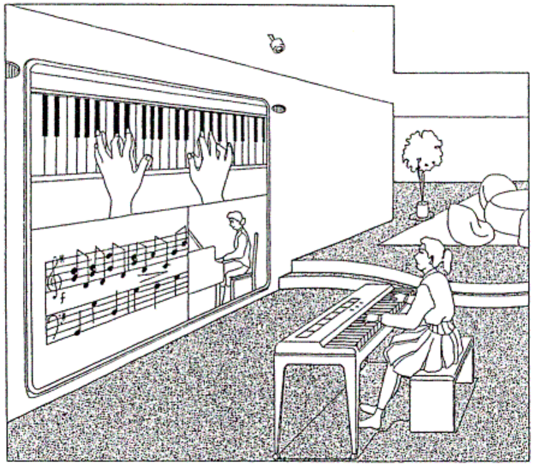
3D Sound Field Reproduction System

- Facilitate more realistic experience
- Tele-conference
  - People in different places feel **as if they have a meeting in the same room**

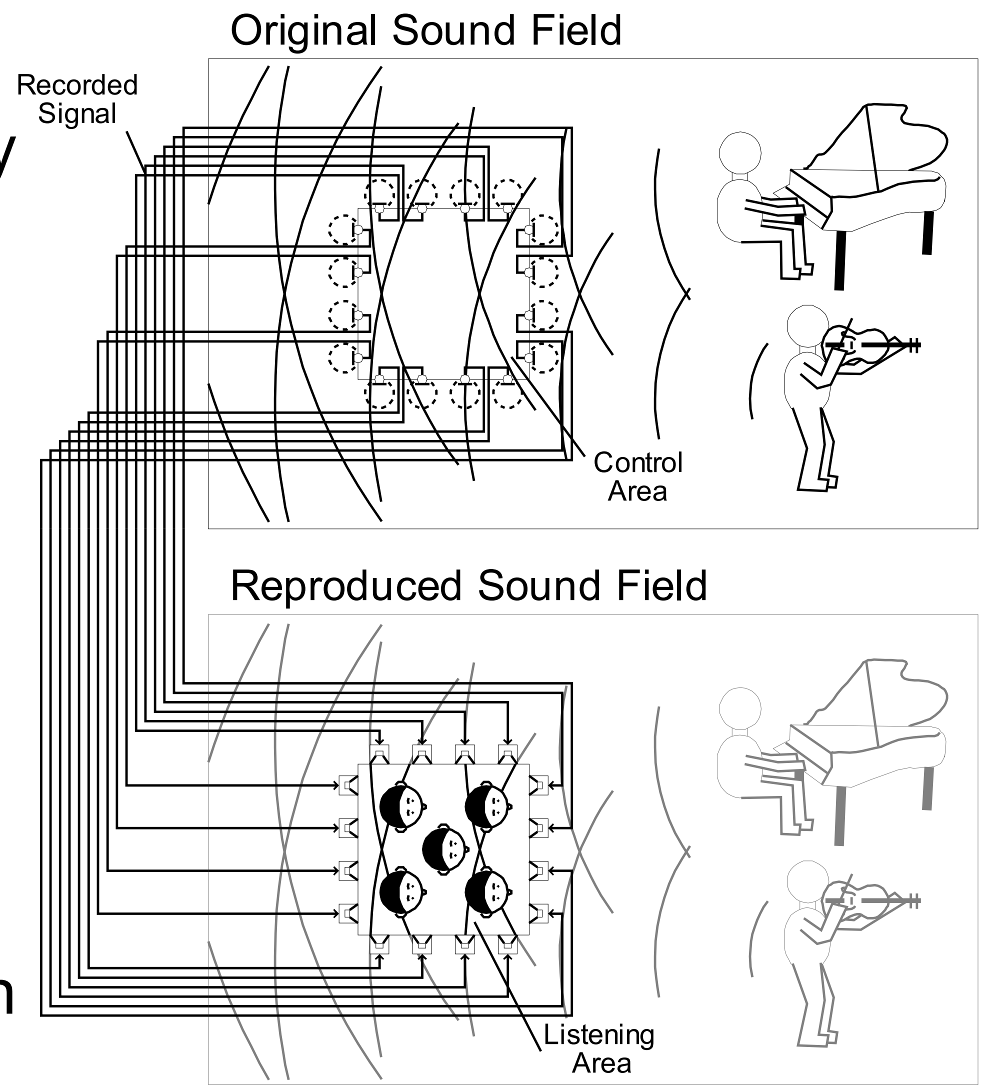


- Tele-ensemble
  - People in different places feel **as if they play a music in the same concert hall**



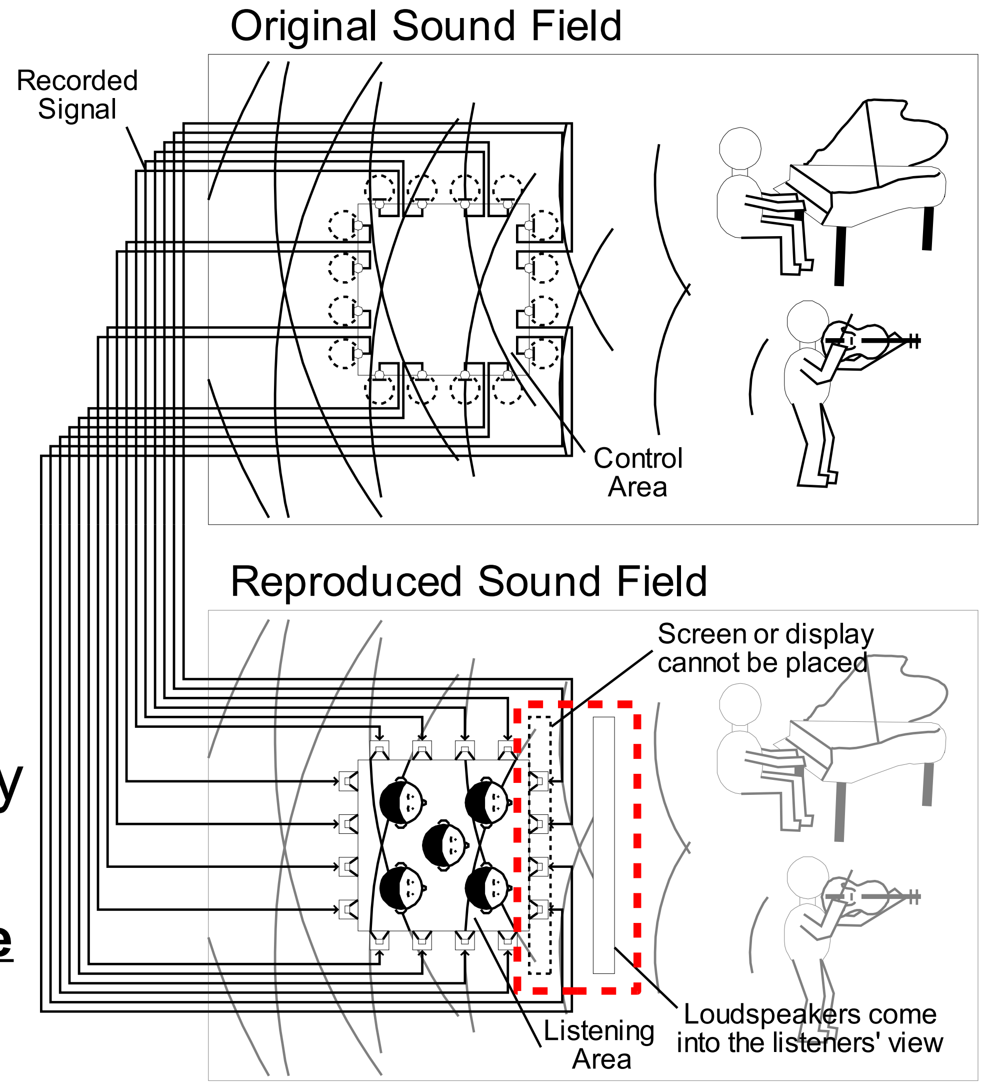
Wave Field Synthesis System

- Original sound field
  - Sound is recorded by directional microphones
- Reproduced sound field
  - Recorded sound is replayed by loudspeakers
  - Wave fronts are accurately reproduced based on Huygens' principle



Problem of Conventional System

- Audio-visual system
  - Screen or display should be placed on or outside the boundary surface
  - On the boundary surface
    - **Screen or display cannot be placed**
  - Outside the boundary surface
    - **Loudspeakers come into the listeners' field of view**



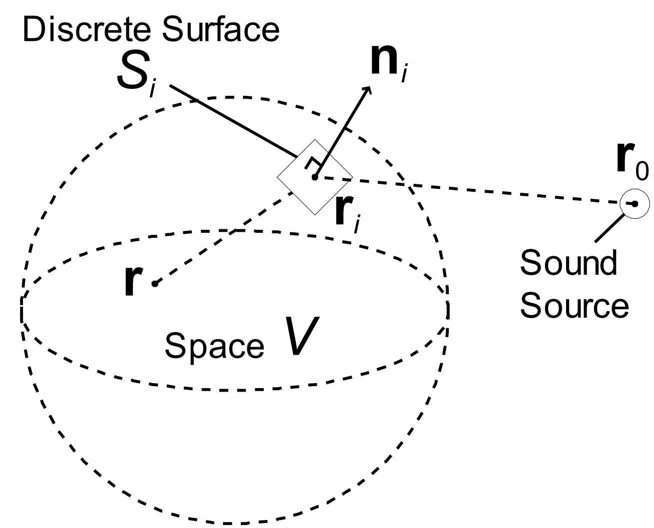
Aim of Study

- A novel 3D sound field reproduction system is proposed
  - Based on directional microphones and boundary surface control
  - Reproduce the 3D sound field without requiring loudspeakers to be placed at the boundary surface
- Theoretical Study
  - The 3D sound field can be accurately reproduced by carrying out inverse filtering based on acoustic transfer functions
- Numerical Analysis
  - A computer simulation is performed

Theory of Conventional System

- 3D sound field can be reproduced in V

$$P(\mathbf{r},\omega)=jk\sum_{i=1}^{M} D_m(\mathbf{r}_0|\mathbf{r}_i)P(\mathbf{r}_i,\omega)$$
$$G(\mathbf{r}_i|\mathbf{r},\omega)\Delta S_i \quad (\mathbf{r}\in V)$$



  - $k(=\omega/c)$: Wave number
  - c: Sound velocity
  - ΔS_i: Area of S_i
  - M: Number of S_i
  - $\mathbf{r}_0$, $\mathbf{r}_i$, $\mathbf{r}$: Position vector of sound source, S_i and V
  - $P(\mathbf{r}_i,\omega)$, $P(\mathbf{r},\omega)$: Sound pressure of $\mathbf{r}_i$ and $\mathbf{r}$
  - $D_m(\mathbf{r}_o|\mathbf{r}_i)$: Directivity of microphones
  - $G(\mathbf{r}_i|\mathbf{r},\omega)$: Acoustic transfer function from $\mathbf{r}_i$ to $\mathbf{r}$

Theory of Proposed System (1)

- 3D sound field is reproduced in V'
  - $\Delta S'_l$, N: Area and number of S'_l

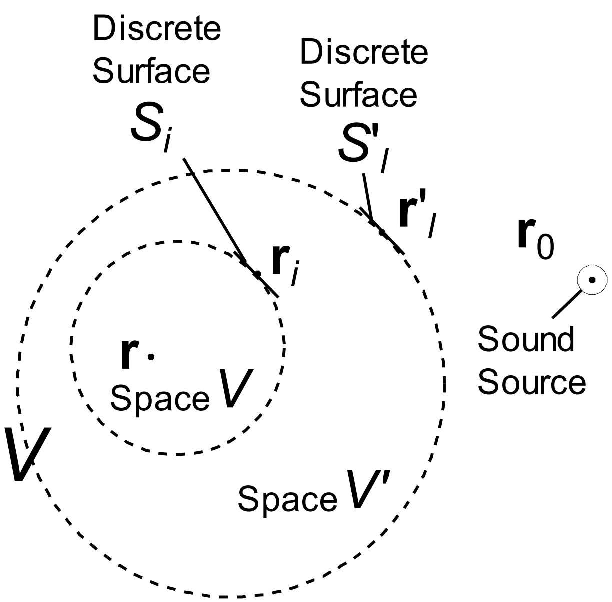
$$P(\mathbf{r},\omega)=jk\sum_{l=1}^{N} D_m(\mathbf{r}_0|\mathbf{r}'_l)\,P(\mathbf{r}'_l,\omega)\,G(\mathbf{r}'_l|\mathbf{r},\omega)\,\Delta S'_l \quad (\mathbf{r}\in V')$$

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

$$P(\mathbf{r}_i,\omega)=jk\sum_{l=1}^{N} D_m(\mathbf{r}_0|\mathbf{r}'_l)\,P(\mathbf{r}'_l,\omega)\,G(\mathbf{r}'_l|\mathbf{r}_i,\omega)\,\Delta S'_l \quad (\mathbf{r}_i\in V')$$

- 3D sound field is reproduced in V
  - There are sound sources in $\mathbf{r}'_l$

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



Theory of Proposed System (2)

- 3D sound field is reproduced in V'
  - $\Delta S'_l$, N: Area and number of S'_l

$$P(\mathbf{r},\omega)=jk\sum_{l=1}^{N} D_m(\mathbf{r}_0|\mathbf{r}'_l)P(\mathbf{r}'_l,\omega)\underline{G(\mathbf{r}'_l|\mathbf{r},\omega)}\Delta S'_l \quad (\mathbf{r}\in V')$$

$$P(\mathbf{r},\omega)=jk\sum_{l=1}^{N} D_m(\mathbf{r}_0|\mathbf{r}'_l)P(\mathbf{r}'_l,\omega)\left\{\underline{jk\sum_{i=1}^{M} D_m(\mathbf{r}'_l|\mathbf{r}_i)G(\mathbf{r}'_l|\mathbf{r}_i,\omega)G(\mathbf{r}_i|\mathbf{r},\omega)\Delta S_i}\right\}\Delta S'_l \quad (\mathbf{r}\in V,\mathbf{r}_i\in V')$$

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

Theory of Proposed System (3)

- System via *M*-input *N*-output filters $H_{li}(\omega)$

$$\underbrace{P'(\mathbf{r}'_l,\omega)}_{\text{Filtered signal}}=\sum_{i=1}^{M} H_{li}(\omega)\underbrace{D_m(\mathbf{r}_0|\mathbf{r}_i)P(\mathbf{r}_i,\omega)}_{\text{Recorded signal}}$$

- Reproduced 3D sound field $P'(\mathbf{r},\omega)$

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

$$=\sum_{i=1}^{M} D_m(\mathbf{r}_0|\mathbf{r}_i)P(\mathbf{r}_i,\omega)\left\{\sum_{l=1}^{N} H_{li}(\omega)\boxed{G(\mathbf{r}'_l|\mathbf{r},\omega)}\Delta S'_l\right\}$$

$$\boxed{G(\mathbf{r}'_l|\mathbf{r},\omega)}=jk\sum_{i=1}^{M} D_m(\mathbf{r}'_l|\mathbf{r}_i)G(\mathbf{r}'_l|\mathbf{r}_i,\omega)G(\mathbf{r}_i|\mathbf{r},\omega)\Delta S_i$$

$$(\mathbf{r}\in V,\mathbf{r}_i\in V')$$

Theory of Proposed System (4)

- $H_{li}(\omega)$ is defined as inverse filters

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

- Reproduced 3D sound field $P'(\mathbf{r},\omega)$

$$P'(\mathbf{r},\omega) = jk \sum_{i=1}^{M} D_m(\mathbf{r}_0|\mathbf{r}_i) P(\mathbf{r}_i,\omega) \left[\sum_{n=1}^{M} G(\mathbf{r}_n|\mathbf{r},\omega) \left\{ \sum_{l=1}^{N} H_{li}(\omega) D_m(\mathbf{r}'_l|\mathbf{r}_n) G(\mathbf{r}'_l|\mathbf{r}_n,\omega) \Delta S'_l \right\} \Delta S_n \right]$$

$$= jk \sum_{i=1}^{M} D_m(\mathbf{r}_0|\mathbf{r}_i) P(\mathbf{r}_i,\omega) G(\mathbf{r}_i|\mathbf{r},\omega) \Delta S_i = P(\mathbf{r},\omega)$$

3D sound field can be reproduced in space *V*

$$(\mathbf{r} \in V, \mathbf{r}_i \in V')$$

Diagram of Proposed System (1)

- Directional microphones are placed and sound is recorded
  - Directional microphones are directed toward the outside of the control area

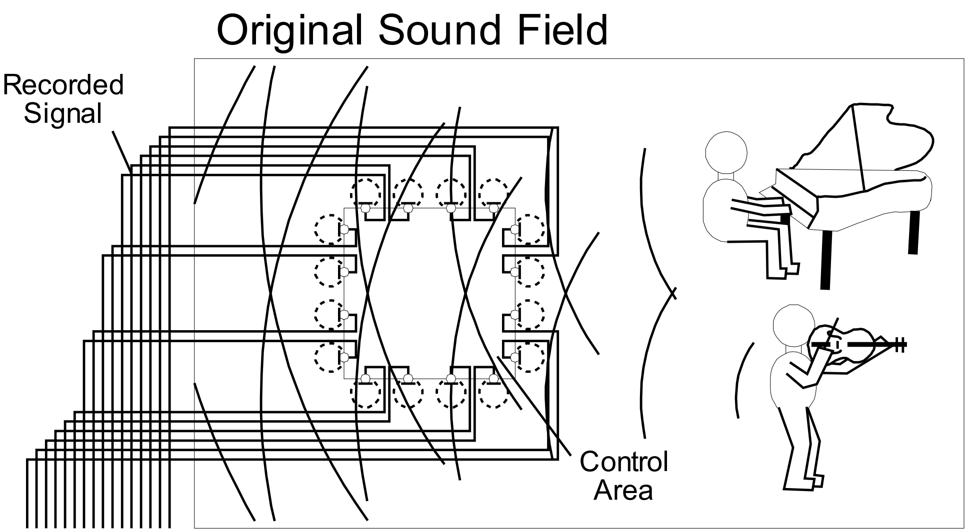


Diagram of Proposed System (2)

- Directional microphones and loudspeakers are placed
  - The position and direction of directional microphones are the same as in the recording
  - Loudspeaker array envelops microphone array

Reproduced Sound Field

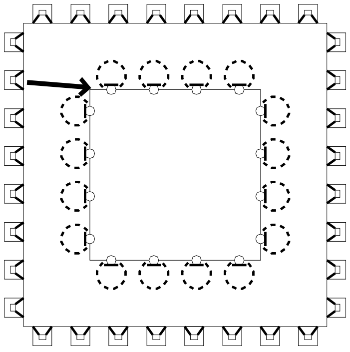


Diagram of Proposed System (3)

- Acoustic transfer functions are measured and the inverse filters are calculated

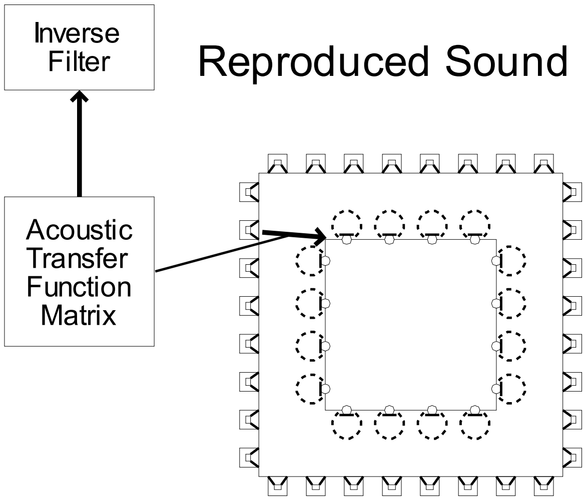


Diagram of Proposed System (4)

- Recorded signals are filtered by the inverse filters, and the filtered signals are played by loudspeakers
  - Listeners feel as if they are listening to the sound in the original sound field

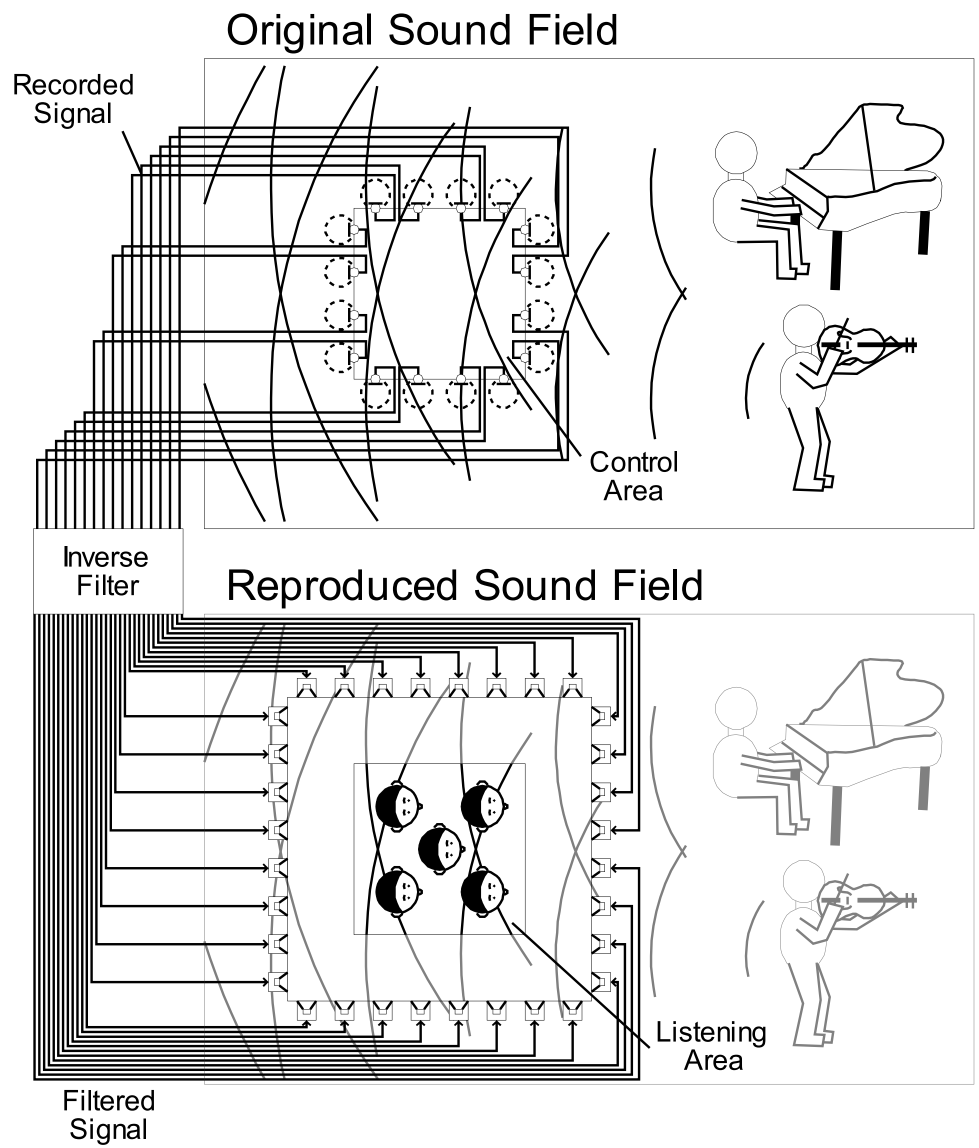
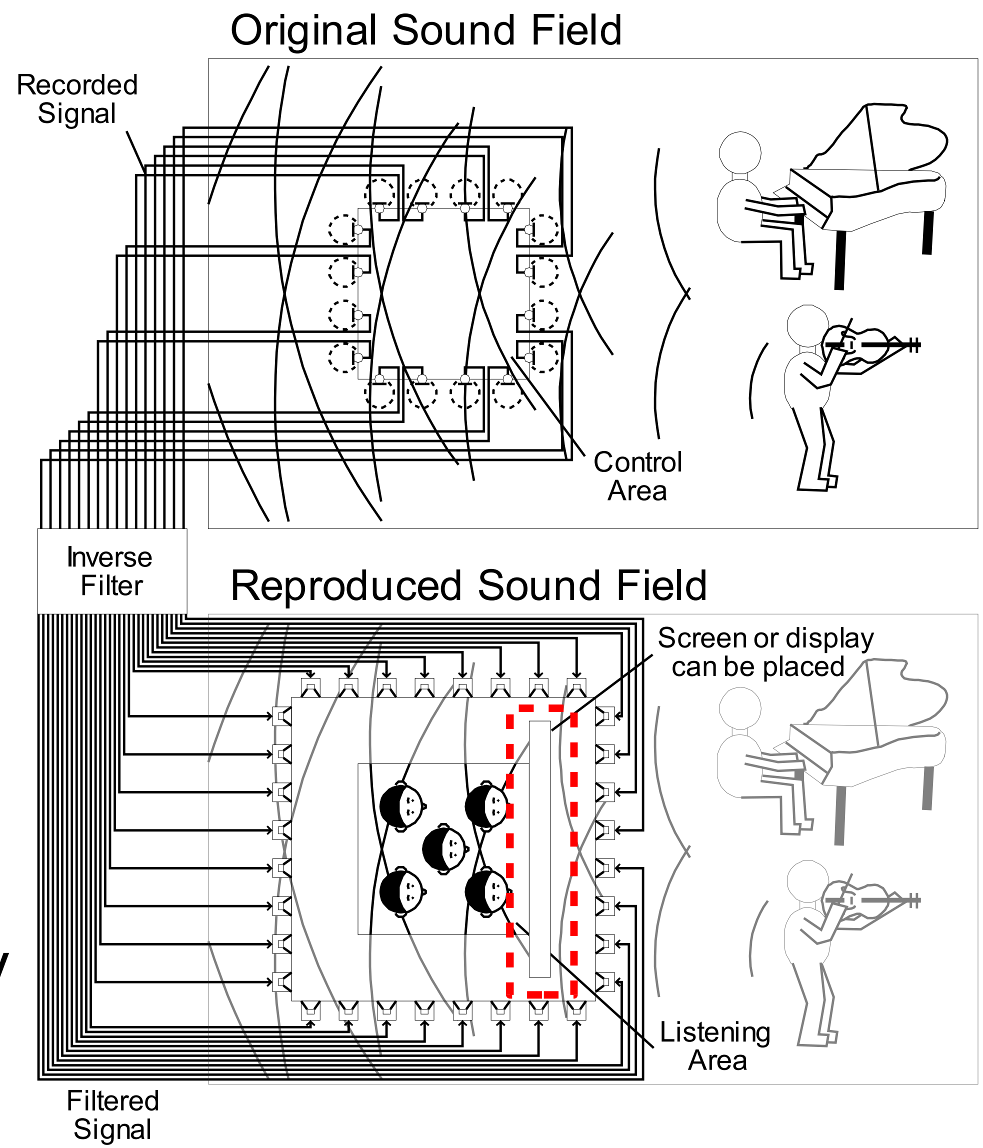


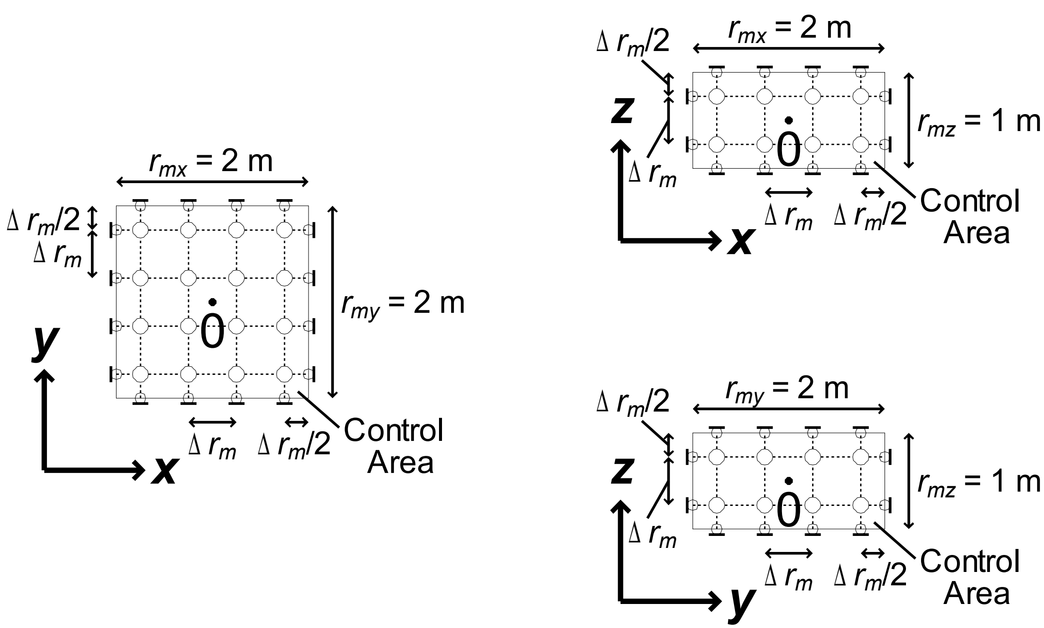
Diagram of Proposed System (5)

- Directional microphones do not need to be placed during playing
- It is possible to construct an audio-visual system
  - Screen or display of the visual system can be placed on or outside the boundary surface



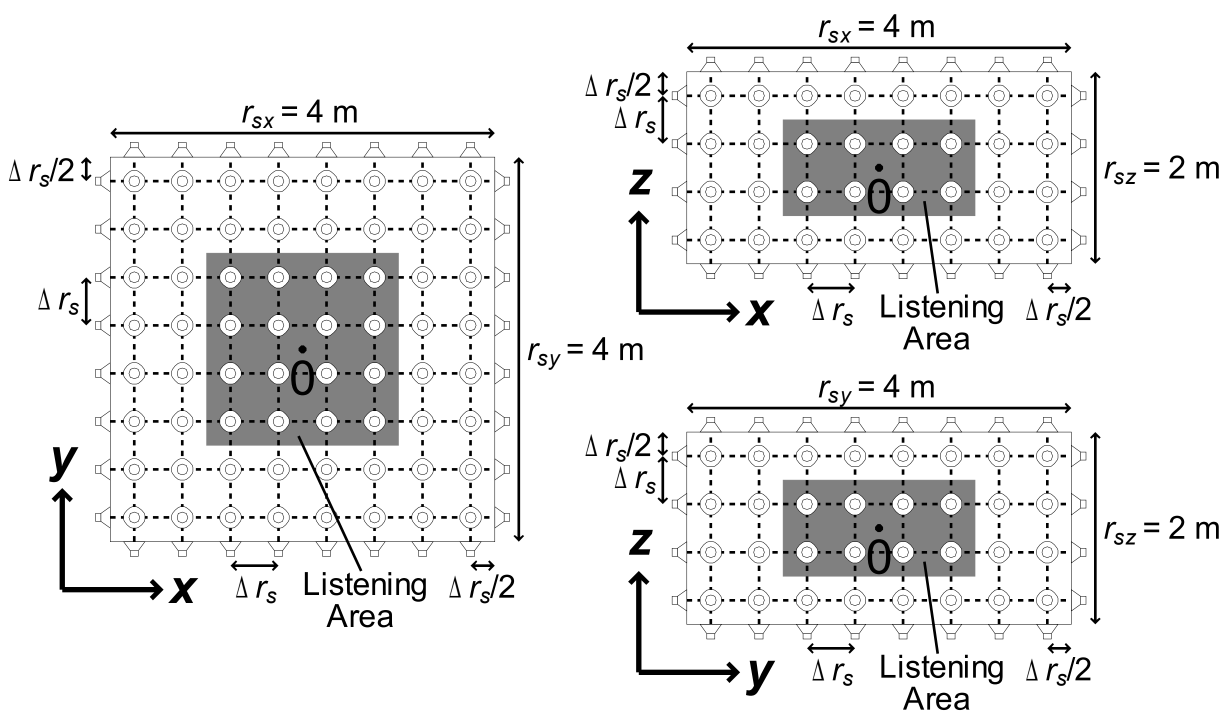
Original Sound Field

- Control area
  - Size...2 m width, 2 m depth, 1 m height
- Microphone array (placed on 6 planes)
  - Size...2 m width, 2 m depth, 1 m height



Reproduced Sound Field

- Listening area (same size as control area)
  - Size…2 m width, 2 m depth, 1 m height
- Loudspeaker array (placed on 6 planes)
  - Size…4 m width, 4 m depth, 2 m height



Original Sound Field Synthesis

- Sound source signal $s(t)$
  - Sinusoidal signal (frequency f, amplitude A)

$$s(t) = A \sin 2\pi f t$$

- Sound pressure in the original sound field
  - $\mathbf{r}_0$: Position vector of sound source
  - $\mathbf{r}$: Position vector of point in control area
  - c: Sound velocity

$$p_o(\mathbf{r}, t) = \frac{1}{|\mathbf{r} - \mathbf{r}_0|} s\left(t - \frac{|\mathbf{r} - \mathbf{r}_0|}{c}\right)$$

$$= \frac{A}{|\mathbf{r} - \mathbf{r}_0|} \sin\left\{2\pi f \left(t - \frac{|\mathbf{r} - \mathbf{r}_0|}{c}\right)\right\}$$

Reproduced Sound Field Synthesis (1)

- Recorded signal $x_i(t)$ (i=1...M)
  - $\mathbf{r}_i$: Position vector of ith directional microphone
  - $D_m(\mathbf{r}_o|\mathbf{r}_i)$: Directivity of ith directional microphone
  - M: Number of directional microphones

$$x_i(t) = \frac{D_m(\mathbf{r}_0|\mathbf{r}_i)}{|\mathbf{r}_i - \mathbf{r}_0|} s\left(t - \frac{|\mathbf{r}_i - \mathbf{r}_0|}{c}\right)$$

$$= \frac{D_m(\mathbf{r}_0|\mathbf{r}_i) A}{|\mathbf{r}_i - \mathbf{r}_0|} \sin\left\{2\pi f\left(t - \frac{|\mathbf{r}_i - \mathbf{r}_0|}{c}\right)\right\}$$

Reproduced Sound Field Synthesis (2)

- Filtered signal $y_l(t)$ (l=1...N)
  - Ξ_{li}(=$|H_{li}(\omega)|$): Absolute value of inverse filters
  - Θ_{li}(=arg$H_{li}(\omega)$): Angle of inverse filters
  - M: Number of directional microphones
  - N: Number of loudspeakers

$$y_l(t) = \sum_{i=1}^{M} \Xi_{li} x_i \left(t - \frac{\Theta_{li}}{2\pi f} \right)$$

$$= \sum_{i=1}^{M} \frac{\Xi_{li} D_m(\mathbf{r}_0 | \mathbf{r}_i) A}{|\mathbf{r}_i - \mathbf{r}_0|} \sin\left\{ 2\pi f \left(t - \frac{|\mathbf{r}_i - \mathbf{r}_0|}{c} \right) - \Theta_{li} \right\}$$

Reproduced Sound Field Synthesis (3)

- Sound pressure in reproduced sound field
  - $\mathbf{r}'_l$: Position vector of lth loudspeaker
  - N: Number of loudspeakers

$$p_p(\mathbf{r},t)=\sum_{l=1}^{N}\frac{1}{|\mathbf{r}-\mathbf{r}'_l|}y_l\left(t-\frac{|\mathbf{r}-\mathbf{r}'_l|}{c}\right)$$

$$=\sum_{l=1}^{N}\sum_{i=1}^{M}\frac{\Xi_{li}D_m(\mathbf{r}_0|\mathbf{r}_i)A}{|\mathbf{r}-\mathbf{r}'_l||\mathbf{r}_i-\mathbf{r}_0|}\sin\left\{2\pi f\left(t-\frac{|\mathbf{r}-\mathbf{r}'_l|+|\mathbf{r}_i-\mathbf{r}_0|}{c}\right)-\Theta_{li}\right\}$$

Parametric Condition

Amplitude (A)	1
Frequency (f)	63, 125, 250, 500, 1000 Hz
Distance (d)	2, 10, 50 m
Direction vector ($\mathbf{u}$)	$(1,0,0)^T(1/\sqrt{2},1/\sqrt{2},0)^T(2/3,2/3,1/3)^T$
Sound velocity (c)	340 m/s
Microphone number (M)	576
Microphone interval (Δr_m)	0.1667 m
Loudspeaker number (N)	2304
Loudspeaker interval (Δr_s)	0.1667 m

$$D_m(\mathbf{r}_0|\mathbf{r}_i)=\begin{cases}\cos\theta_{im} & (\theta_{im}\le 90^\circ)\\ 0 & (\theta_{im}>90^\circ)\end{cases}\qquad \cos\theta_{im}=\frac{\mathbf{n}_{im}\cdot(\mathbf{r}_0-\mathbf{r}_i)}{|\mathbf{n}_{im}||\mathbf{r}_0-\mathbf{r}_i|}$$

– $\mathbf{n}_{im}$: Directional vector of ith directional microphone

Synthesis of Conventional System

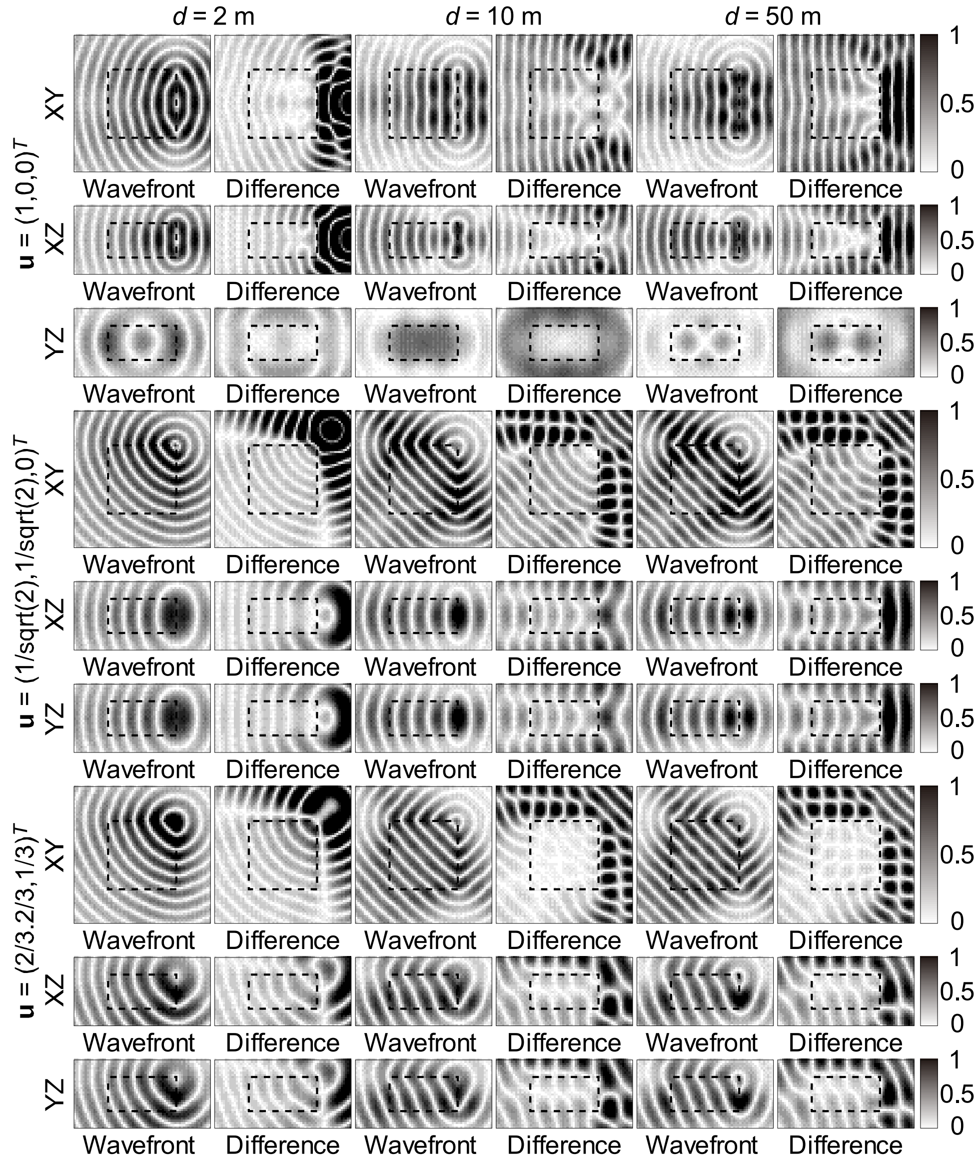
- Listening area (same size as control area)
  - Size...2 m width, 2 m depth, 1 m height
    - Same size as proposed system
- Loudspeaker array (placed on 6 planes)
  - Size...2 m width, 2 m depth, 1 m height
    - Half scale size as proposed system

$$p_c(\mathbf{r},t)=\sum_{i=1}^{M}\frac{1}{|\mathbf{r}-\mathbf{r}_i|}x_i\left(t-\frac{|\mathbf{r}-\mathbf{r}_i|}{c}\right)$$

$$=\sum_{i=1}^{M}\frac{D_m(\mathbf{r}_0|\mathbf{r}_i)A}{|\mathbf{r}-\mathbf{r}_i||\mathbf{r}_i-\mathbf{r}_0|}\sin\left\{2\pi f\left(t-\frac{|\mathbf{r}-\mathbf{r}_i|+|\mathbf{r}_i-\mathbf{r}_0|}{c}\right)\right\}$$

Results of Conventional System

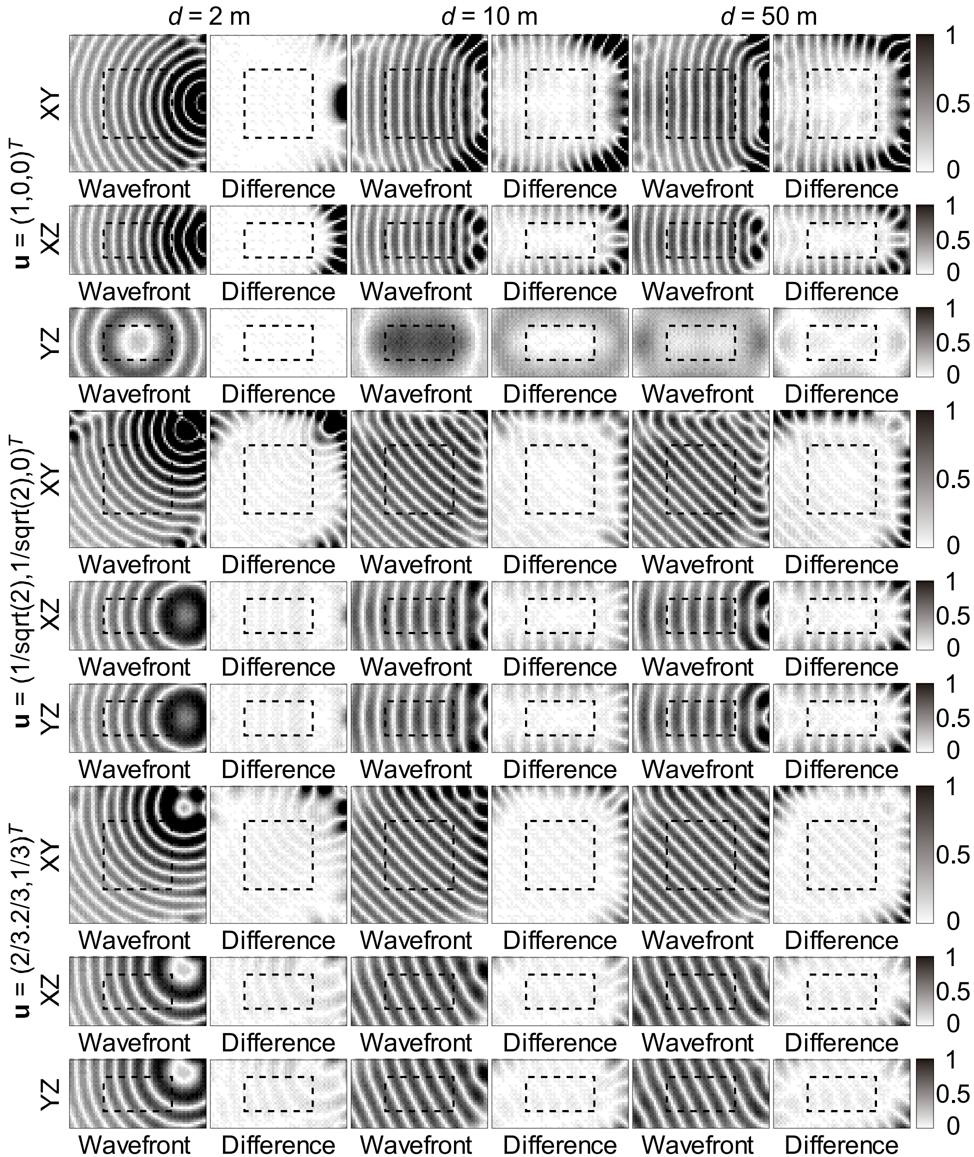
- Wave fronts are not accurately reproduced
  - Differences are not white



Results of Proposed System

- Wave fronts are accurately reproduced
  - Differences are white

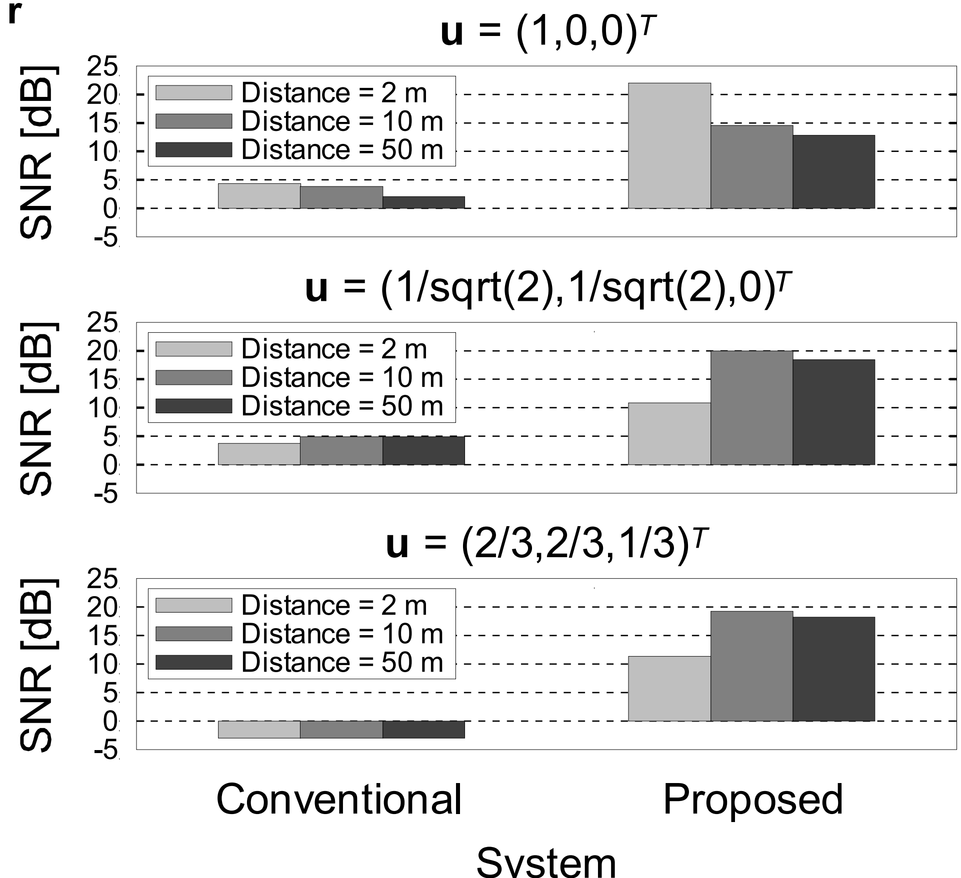
Proposed system can reproduce wave fronts more accurately than conventional system



Results of Signal-to-Noise Ratios

$$\mathrm{SNR} = 10\log_{10}\frac{\sum_{f}\sum_{\mathbf{r}}\left\{p_o(\mathbf{r},0)\right\}^2}{\sum_{f}\sum_{\mathbf{r}}\left\{p_{c(p)}(\mathbf{r},0)-p_o(\mathbf{r},0)\right\}^2}$$

- Conventional system
  - Lesser than 5 dB
- Proposed system
  - Greater than 10 dB
- Wave fronts can be accurately reproduced in the proposed system



Conclusion

- 3D sound field reproduction system based on directional microphones and boundary surface control is proposed
  - Constructed by using the inverse filters in the conventional system
  - Reproduce a 3D sound field in a listening area even if loudspeakers are not placed on the boundary surface
- Computer simulation
  - The proposed system can reproduce wave fronts more accurately than the conventional system

Future Works

- Further study for an actual room
  - The effect of reflected and reverberant sounds in a room
  - The variation of the acoustic transfer functions by the placement of the screen or display
- The reduction of the number of microphones and loudspeakers
  - The evaluation of the performance of the constructed real system by listening tests