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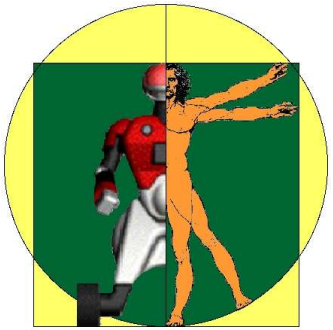

Localization of Simultaneous Moving Sound Sources for Mobile Robot Using a Frequency-Domain Steered Beamformer Approach

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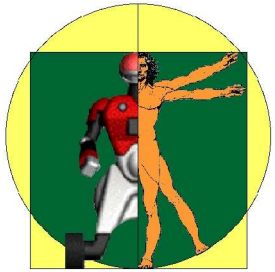
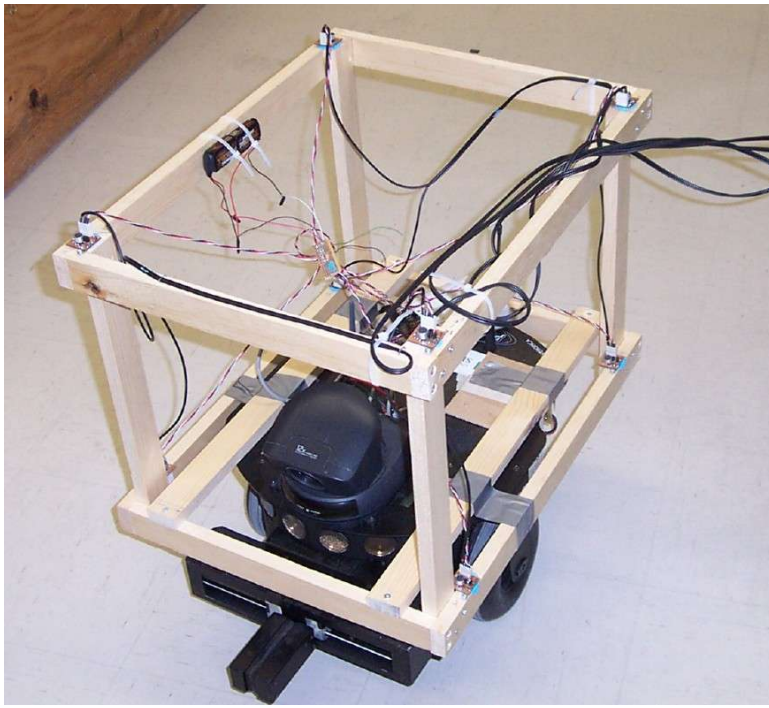
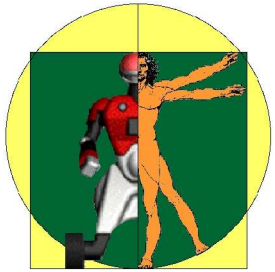


Approaches to Sound Source Localization

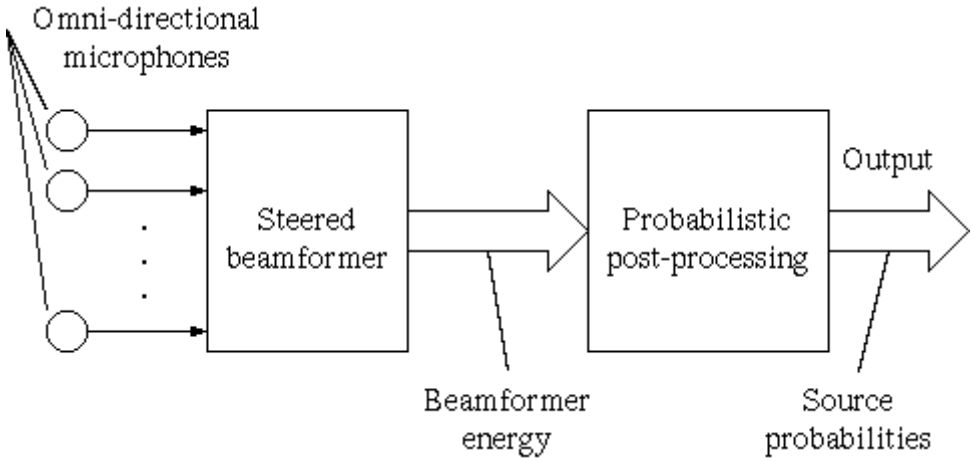
- Binaural audition
  - Two microphones
  - Interaural phase difference
  - Interaural intensity difference
  - Imitate human auditory system
- Microphone array audition
  - Larger number of microphones
  - Phase difference only
  - Increased redundancy compensating for high complexity of human audition

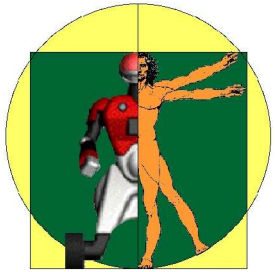




Approach Overview

- Sounds arrive at microphones with different delays (depending on distance)
  - Hypothesis: point sound sources
- Steered beamformer: scans all directions for energy peaks
- Probabilistic post-processing: applies Bayesian inference





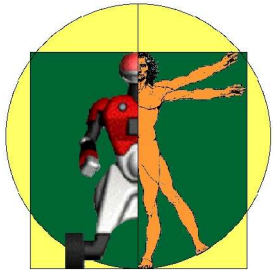
Steered Beamformer

- Delay-and-sum beamformer

$$y(n) = \sum_{m=0}^{M-1} x_m \left(n - \tau_m\right)$$

- Beamformer energy

$$\begin{aligned} E &= \sum_{n=0}^{L-1} \left[y(n)\right]^2 \\ &= \sum_{n=0}^{L-1} \left[x_0\left(n-\tau_0\right) + \ldots + x_{M-1}\left(n-\tau_{M-1}\right)\right]^2 \end{aligned}$$



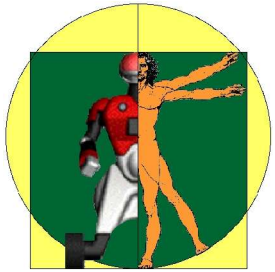
Frequency Domain Computation

$$E = \sum_{m=0}^{M-1} \sum_{n=0}^{L-1} x_m^2 (n - \tau_m)$$

$$+ \quad 2 \sum_{m_1=0}^{M-1} \sum_{m_2=0}^{m_1-1} \sum_{n=0}^{L-1} x_{m_1} (n - \tau_{m_1}) x_{m_2} (n - \tau_{m_2})$$

$$E = K + 2 \sum_{m_1=0}^{M-1} \sum_{m_2=0}^{m_1-1} R_{x_{m_1}, x_{m_2}} (\tau_{m_1} - \tau_{m_2})$$

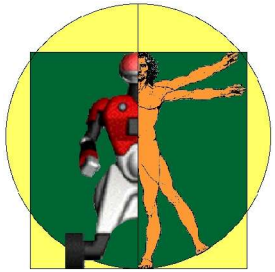
$$R_{ij}(\tau) \approx \sum_{k=0}^{L-1} X_i(k) X_j(k)^* e^{\jmath 2\pi k \tau / L}$$



Spectral Weighting

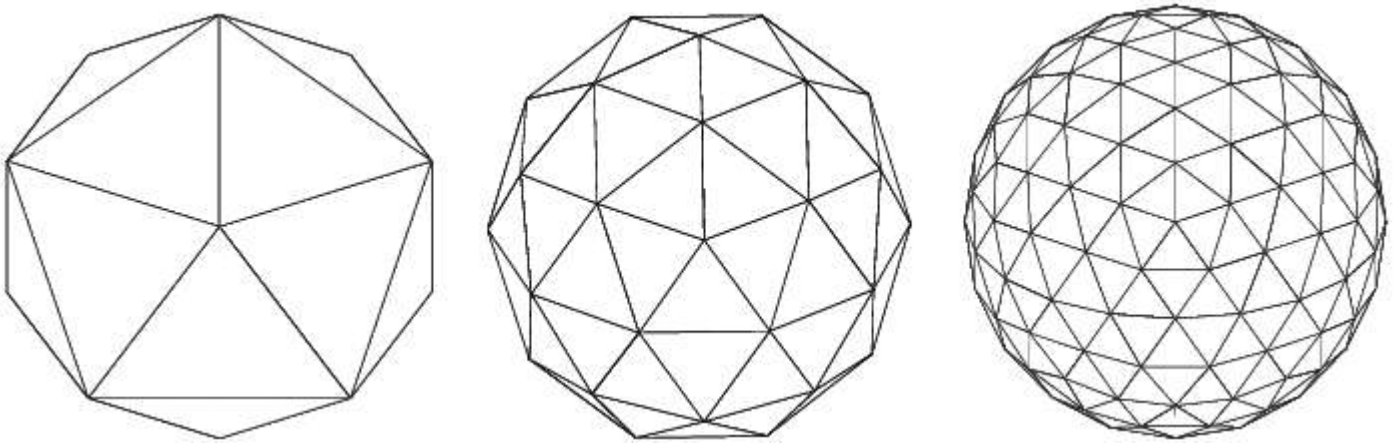
- Cross-correlation peaks are very wide
  - Poor angular accuracy
  - Overlap between close sources
- Solution: spectral weighting
  - Whiten spectrum
  - Give less weight to noisy regions of spectrum

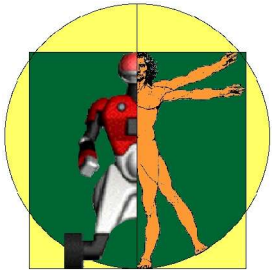
$$R_{ij}^{(e)}(\tau) = \sum_{k=0}^{L-1} \frac{w^2(k) X_i(k) X_j(k)^*}{|X_i(k)|\,|X_j(k)|} e^{\jmath 2\pi k\tau/L}$$



Search

- Set of possible directions of arrival represented as sphere
- Defining a homogeneous grid
  - Recursive subdivision of icosahedron
  - Resulting grid with 2562 points

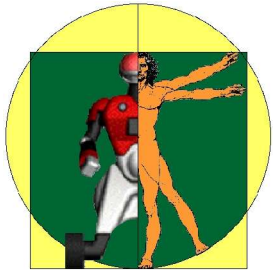




Search

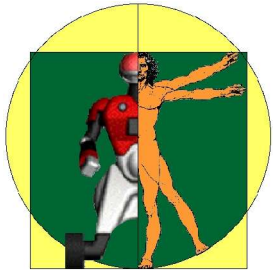
- Find directions with highest energy

for $k = 1$ to desired number of sources **do**
  for all grid index d **do**
    $E_d \leftarrow 0$
    for all microphone pair ij **do**
      $\tau \leftarrow lookup(d, ij)$
      $E_d \leftarrow E_d + R_{ij}^{(e)}(\tau)$
  $D_k \leftarrow \text{argmax}_d\ (E_d)$
  for all microphone pair ij **do**
    $\tau \leftarrow lookup(D_k, ij)$
    $R_{ij}^{(e)}(\tau) \leftarrow 0$

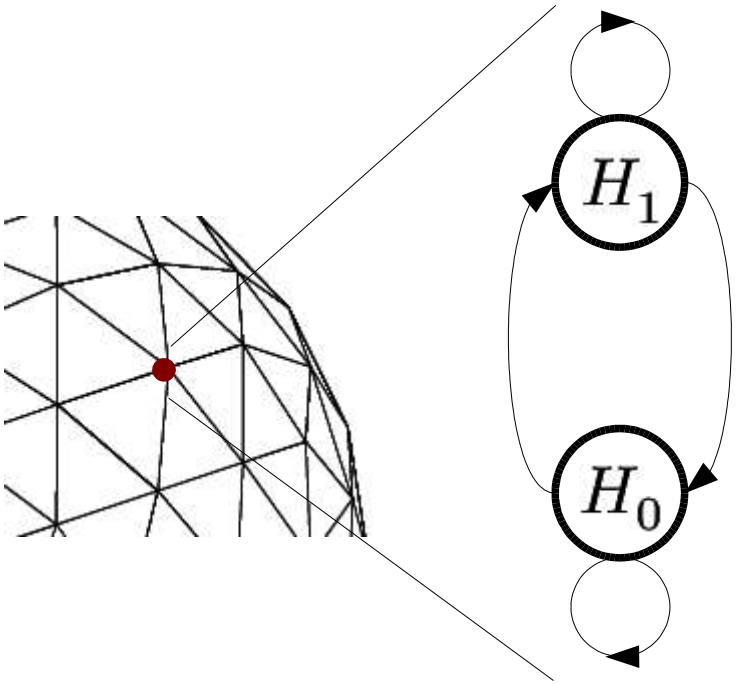


Bayesian Post-filter

- Data from beamformer is noisy
- Express localization in terms of source probability of presence
- Probability computed for each grid point
- Use Bayes' rule to compute probability using past and present observations



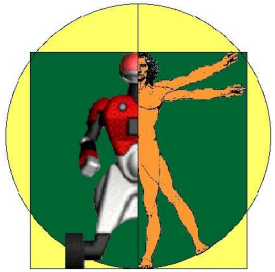
Bayesian Post-filter



$P\left(H_1^n \,|o_n\right)$ beamformer probability

$P\left(H_1^n \,|\mathbf{O}_{n-1}\right)$ *a priori* probability

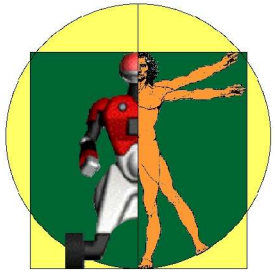
$P\left(H_1^n \,|\mathbf{O}_n\right)$ combined probability



Estimator Combination

- All previous steps computed twice
  - Short frames (~40 ms)
  - Medium frames (~200 ms)
- Need to combine both estimators
  - Estimators are not independent
- Weighted geometric average of the dependent case and the independent case:

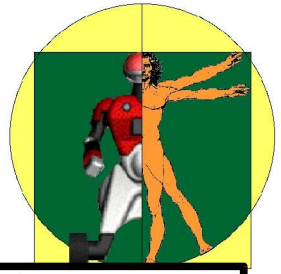
$$P(H_1|\mathbf{O}^s,\mathbf{O}^m) \approx [P_d(H_1|\mathbf{O}^s,\mathbf{O}^m)]^{\beta} \cdot [P_i(H_1|\mathbf{O}^s,\mathbf{O}^m)]^{1-\beta}$$



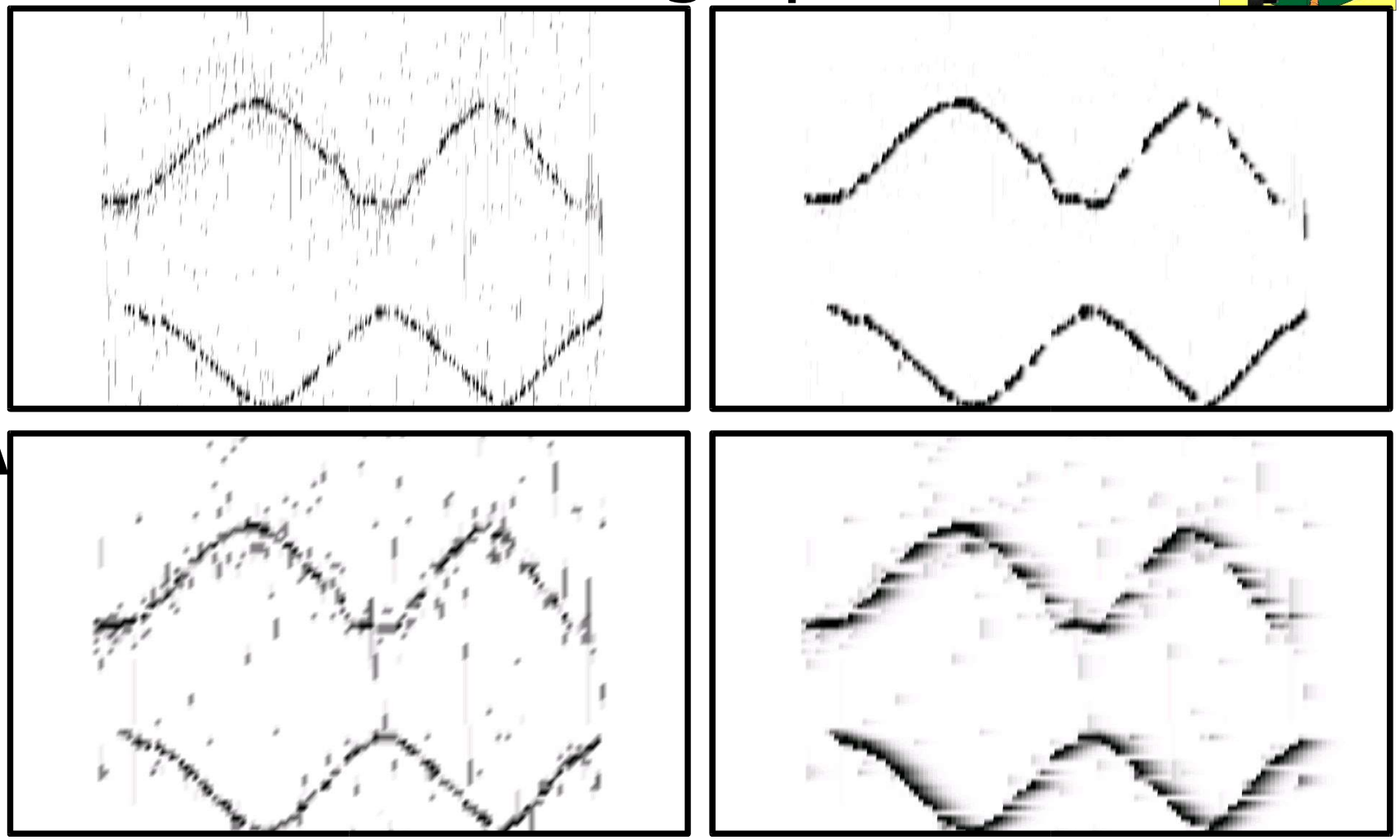
Results

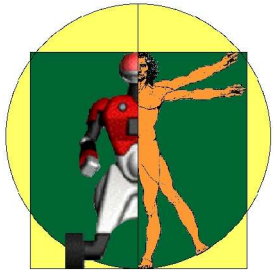
- Detection accuracy over distance
  - Different sounds
  - Rate of detection(#detections / #occurences)

Sound source	3 m	5 m	7 m
Hands clapping	92%	94%	84%
Speech (“test”)	100%	90%	42%
Noise burst (250 ms)	100%	100%	100%



Results (2 moving speakers)





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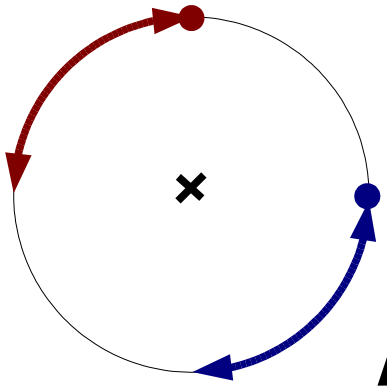
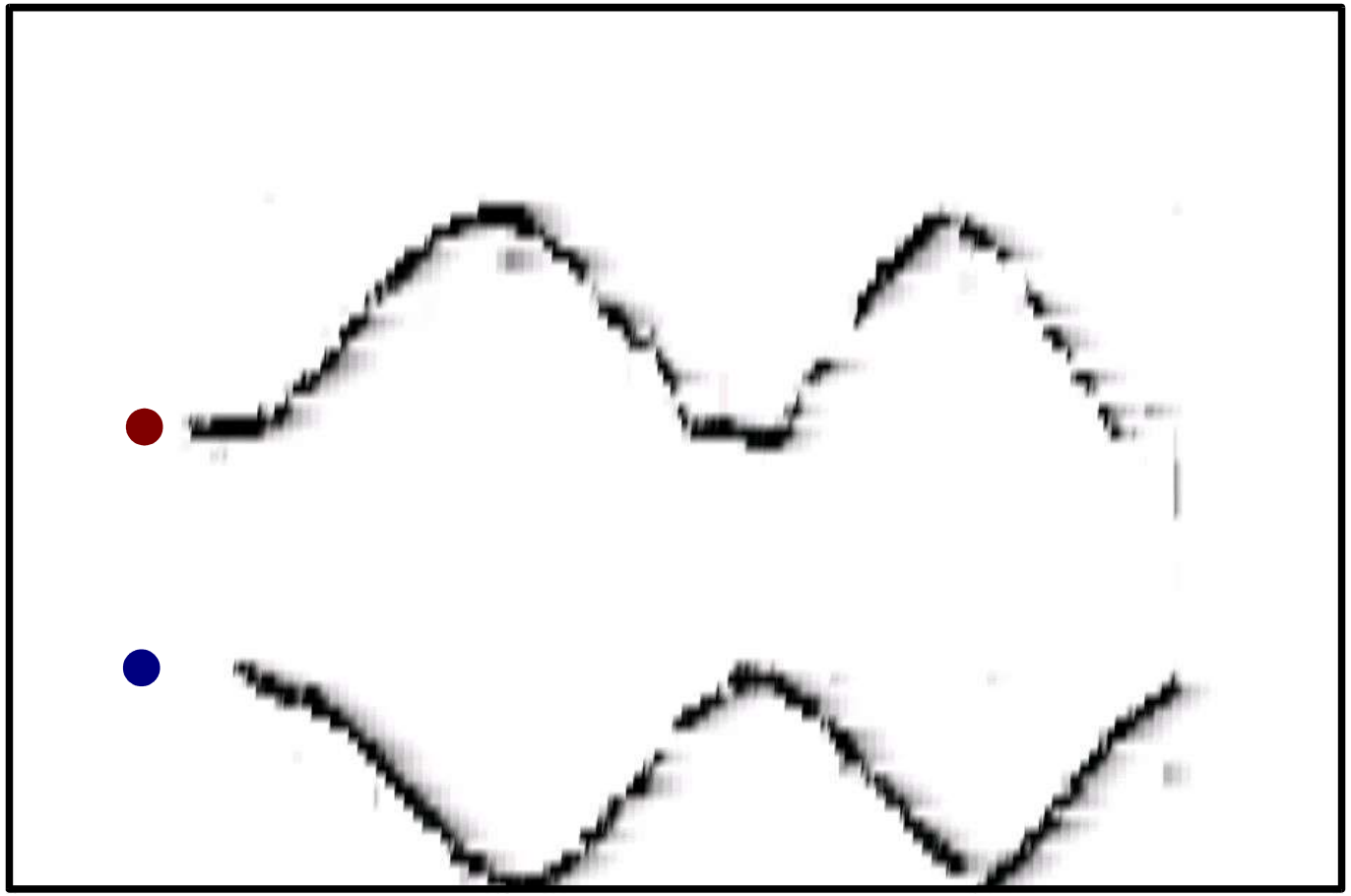
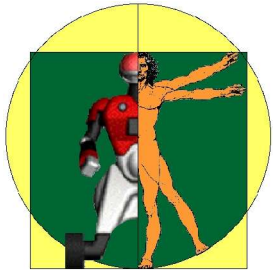
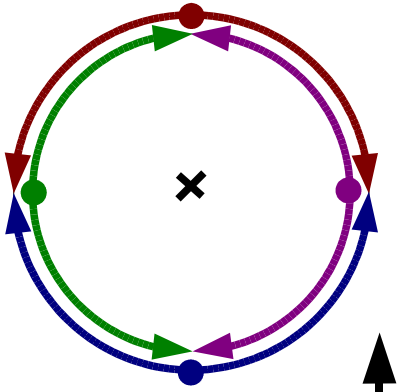
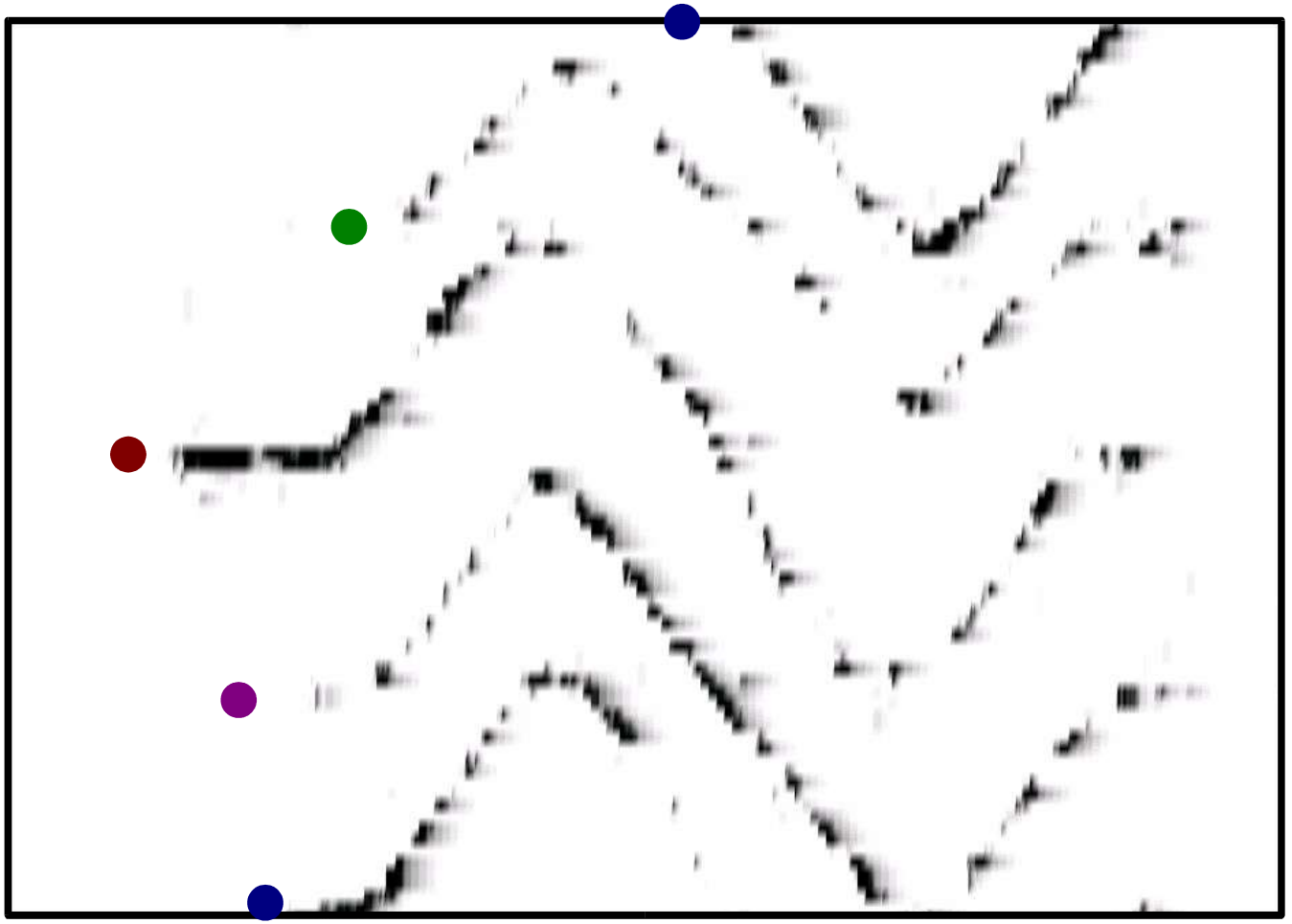


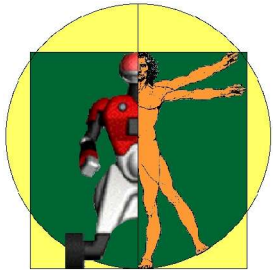




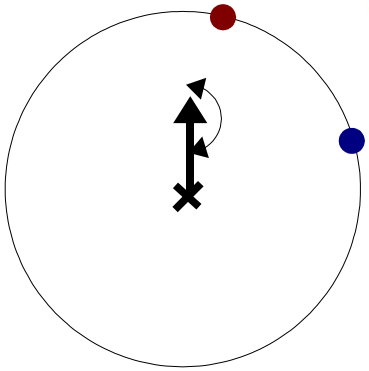
Results (4 moving speakers)



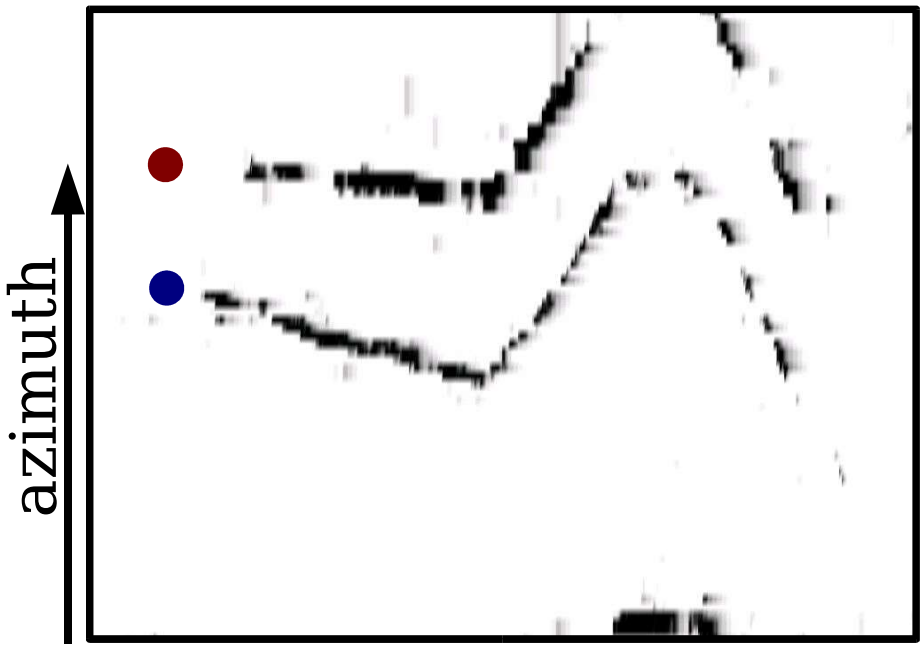


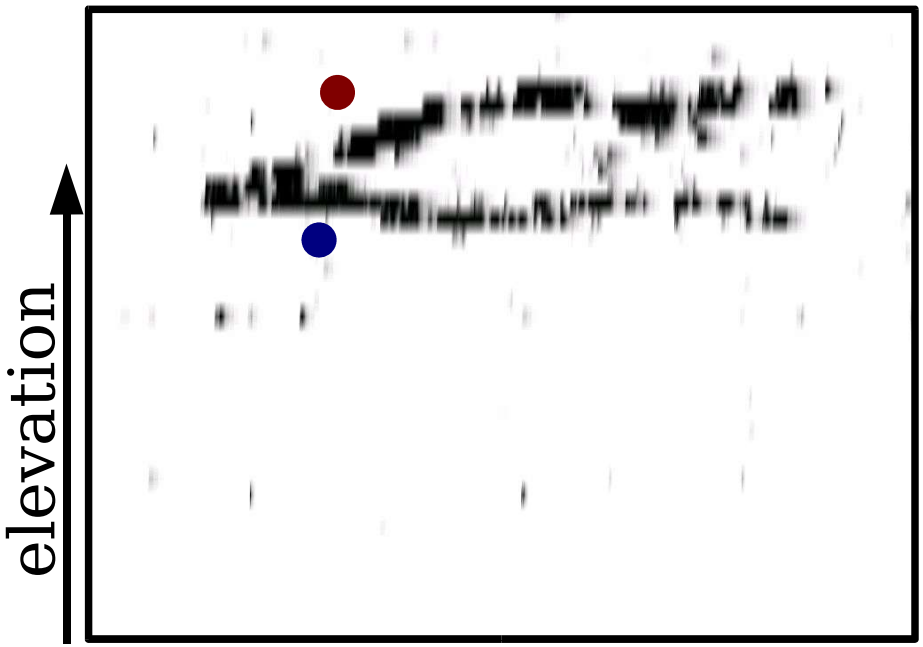


Results (moving robot)

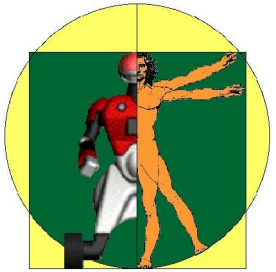


- Localization in 3D



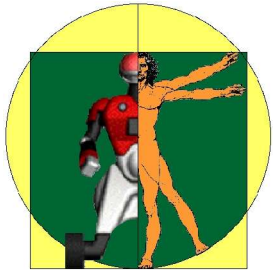


time



Conclusion

- Robust localization of sound sources
  - Moving sources or robot
  - Up to 4 simultaneous sources reliably
  - Reliable detection up to 5 meters
- Two-step method
  - Steered beamformer
  - Bayesian post-filter
- Related work
  - Tracking sources over time
  - Separating sound one mic separated



Questions?