High-resolution beamforming in ultrasound imaging

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Journal Publications

Conference Presentations


Sonar:

Beamforming

**Delay-and-Sum, DAS:** Pre-determined aperture shading, delay, and sum:

\[ A(t) = \sum_{j=1}^{M} w_j x_j (t - T_j) \]

- \( w_j \): typ. rectangular or Hamming (real, symmetric)
Rectangular or Hamming?

Examples of beampatterns (two wiretargets, 80 mm)

Unity gain in desired direction

Strong targets
Origins

Terminology

- High resolution beamforming
- Minimum variance beamforming
- Capon beamforming
- Adaptive beamforming
  - But not phase aberration correction

Beamforming: Matrix formulation

- Single-frequency output of beamformer: \( y = w'x \), where \( w \) has phase
- Power: \( P_{yy} = yy' = w'x(w'x)' = w'xx'w = w'R_{xx}w \)
- Signal, \( x \propto e \), steering vector
- Broadband: sum over all frequencies
  \( \Leftrightarrow \) delay-and-sum beamformer:
  \[
y(t) = \sum_{m=0}^{M-1} w_m y_m(t - \Delta_m)
\]
Steering vector

- Signal, $x \propto e$, steering vector
  
  $$
  e = \begin{bmatrix}
  \exp(-j \cdot \vec{k}_0 \cdot \vec{x}_0) \\
  \vdots \\
  \exp(-j \cdot \vec{k}_{M-1} \cdot \vec{x}_{M-1})
  \end{bmatrix}
  $$

- Plane wave:
  $$\vec{k}_m = \vec{k}_0 = \frac{2\pi \zeta}{\lambda}$$

- Uniform Linear Array:
  $$\vec{x}_m = m \cdot d \cdot i_x$$

- Plane wave on ULA:
  $$\exp(-j \cdot \vec{k}_m \cdot \vec{x}_m) = \exp(-j \frac{2\pi}{\lambda} m \cdot d \cdot \zeta i_x) = \exp(-j \frac{2\pi}{\lambda} m \cdot d \cdot \sin \phi)$$

Minimum variance beamforming

- Minimize output power:
  $$\min_{w} \begin{bmatrix} w^H R w \end{bmatrix}_{a \cdot \tilde{I}}$$

- subject to unity gain in desired direction:
  $$w^H a = 1$$

- Because of pre-steering and pre-focusing (straight ahead):
  $$a = \tilde{1}$$
Minimum variance

- Weight:
  \[ w = \frac{R^{-1}e}{e^H R^{-1}e} \]

- Complex weights vary with covariance matrix, i.e. the data and direction (in e)
- Results in adaptive suppression in the direction of the largest interferers
- Result: \( P_{MV} = w^H R_{xx} w = 1/(e^H R^{-1} e) \)

Minimum variance beamforming

- In practice, \( R \) is replaced by the sample covariance matrix
  - Only a few time-samples are available
- Averaging in space and time
  - Subaperture averaging
    - Diagonal loading: \( R \) is replaced by \( R + \delta \cdot \text{tr}(R) \cdot I \)
Adaptation to Medical Ultrasound

• Focused System
  – Pre-beamforming of receiver: steering and focusing
  – Adaptive beamformer only applies complex weights to model deviations

• Transmitter beam
  – Unfocused or focused beam like in medical scanners
  – Single beam, ~omnidirectional:
    – Plane wave as in acoustic streaming imaging

• From Passive to Active System
  – Coherence
  – Target cancellation
  – Illustrated in next plots

Smoothing and conditioning

1. Subaperture averaging
2. Diagonal loading
   – add uncorrelated noise
   \[ R + \delta \cdot \text{tr}(R) \cdot I \]
3. Radial averaging
4. Sub-band processing,
   split in many narrowband estimates
5. Lateral averaging
6. Frame to frame averaging
No subarray averaging, Heavy diagonal loading, else single points also suffer

6.5 subarrays averaged, Light diagonal loading

Spacing: 1.5 mm

Two targets, unresolvable by DAS

Partial cancellation without subarray averaging; ~15 dB loss
Single target

Subarray averaging makes little difference

Distribution of pixel amplitudes
Preferred approach

- Subarray averaging:
  - Ensures a good covariance matrix estimate
  - Is essential to avoid cancellation due to coherence.
- Diagonal loading:
  - For robustness
- Radial averaging
  - Improved speckle
  - Only for covariance estimate, not for beamforming
Related work

- Mann and Walker, Ultrasonics 2002
  - Beamwidth reduction and sidelobe suppression
  - No subaperture averaging, only single wire target, less coherency problems
  - Improved contrast on cyst phantom
  - Frost beamformer – Capon with FR
- Sasso and Cohen-Bacrie (Philips), ICASSP 2005
  - Improved contrast on simulated data
  - Subaperture averaging and time averaging over neighbor beams
  - Robustness with diagonal loading, tested on array with random element position errors
  - Only tested on single wire target and cyst, not tested handing of coherent targets
- Synnevåg et al, IEEE TUFFC, 2007
  - Two very close targets, closer than the limit which can be resolved by DAS. Using this scenario, we have demonstrated that better resolution than DAS was possible even with coherent targets
  - Improved resolution and contrast on wire pairs and heart phantom
- Holfort et al. (IEEE Ultrason. Sym 2007)
  - Implicit time averaging since they split the transducers bandwidth into independent bands by FFT, performed independent high-resolution beamforming per band, and combined them.
  - Single transmission: very high frame rate
- Vignon and Burcher (Philips), T. UFFC March 2008
  - Time averaging over small range gate: better speckle statistics

Comments

- Fall-back to delay-and-sum:
  - Subaperture averaging as the subaperture size -> 1:
    » = delay-and-sum beamforming
  - Diagonal loading as the diagonal term becomes dominant:
    » = delay-and-sum beamforming
- Variation of a single parameter allows one to adjust the method so that it falls back to conventional delay-and-sum beamforming.
- Challenge:
  - How to do subaperture averaging on a curved transducer? (curved array or sonar array)
Results: simulated data

- Field II
- 96 element, 4 MHz transducer
- All transmitter / receiver combinations
- Applied full dynamic focus
- White gaussian noise added

Simulated data-set

Transducer

Spacing 2 mm
Depth 30, 40, 50, 60, 70, 80 mm
Parameters

- Aperture: M=96
- Subapertures that overlap with L-1 elements
  - L=48, 96-48+1 = 49 averages
  - L=32, 96-32+1 = 65 averages
  - L=18, 96-18+1 = 79 averages
- Small amount of diagonal loading
  - R is replaced by R + δ · tr(R) · I
  - Ensures good conditioning of R
  - Default: δ=1/(100·L) where diagonal term is e = δ · tr(R)
  - [Have also used up to δ=1/L ⊗ i.e. same variance for R and the added white noise]
Examples of beampatterns (two wire targets, 80 mm)

Unity gain in desired direction

Strong targets
Robust adaptive beamforming

- Processed the data with 5% error in acoustic velocity
- Applied regularization:
  - Replaced $R$ with $R + \varepsilon I$
  - Large $\varepsilon \Rightarrow$ delay-and-sum

5% error in c: Sensitivity to subarray size
Phase aberrations

- Point target at 70 mm, 2.5 MHz 64 element phased array
- 1D aberrations: time-delays as if the aberrator was on the transducer surface.
- Unweighted delay-and-sum (DAS) beamformer and a MV beamformer.
Aberrator

– Correlation length: 2.46 mm
– Delay
  » Weak (imaging through thorax): 21 ns rms/90 ns peak
  » Intermediate (abdominal imaging): 35 ns rms/150 ns peak
  » Strong (abdominal imaging): 49 ns rms/210 ns peak
  » Very strong (breast imaging): 68 ns rms/290 ns peak

Results, phase aberration

• Main lobe of the MV beamformer was narrower or approximately equal to that of DAS
  – -6 dB lateral beamwidth being 40%, 67%, 83%, and 106% of DAS for the four cases.
• The aberrations affected the sidelobe structure producing non-symmetric patterns, but with comparable values for the maximum sidelobe levels.
  – For the weak aberrator, the MV beamformer performed better (1-5 dB) than the DAS beamformer.
• A slight reduction in sensitivity.
  – Very strong aberration: the main lobe value was decreased by 1.4 dB compared to the DAS beamformer.
  – For the other scenarios: the decrease was 0.9, 0.6, and 0.4 dB.
Phase aberrations and MV

- MV – balancing of performance and robustness.
  - Spatial smoothing, diagonal loading, time averaging over about a pulse length
- MV: substantial decrease in main lobe width without increase in sidelobe level in aberrating environments.
  - It does not degrade the beam even with very strong aberrators.
  - MV can handle realistic aberrations with a performance which is better than or equal to that of DAS.

Experimental data

- Specially programmed GE Vingmed ultrasound scanner
  - 96 element, 3.5 MHz transducer @ 4 MHz
  - Specially made wire target, spacing 2 mm

- Biomedical Ultrasound Laboratory, University of Michigan
  - 64 element, 3.5 MHz transducer
  - heart-phantom
Point targets: GEVU scanner

4 MHz, 96 el., 56 mm depth. TX focus 56 mm, dynamic rx focus
L=32 subaperture, no time averaging, $\delta = 1/(10 \cdot L)$

L=32 subaperture, 2K+1=17 time averages, $\delta = 1/(10 \cdot L)$
Beampatterns (cyst)

- MV
- Rectangular
Other benefits than resolution

- Reduced transducer size
  - 18.5 mm transducer (DAS) vs 9.25 mm transducer (MV)

- Parallel receive beamforming
  - 32 Tx/rx lines (DAS) vs. 8 Tx lines (MV with 4 parallel beams)

- Increased penetration depth
  - 3.5 MHz transmission (DAS) vs. 2 MHz transmission (MV)


Half the transducer size
Half the transducer size (2)

Half the transducer size (3)
4 times wider transmit beam & parallel receive beams = 4 times the frame rate

Parallel receive beams (2)
Parallel receive beams (3)

2 MHz vs. 3 MHz transmission
Computational cost

- M elements, L-size subarrays
- Delay is the same as for delay-and-sum
- Matrix inversion $2L^3/3$ or $O(L^3)$ + estimation of weights
  - Saves computations by using smaller subarrays, L, instead of more diagonal loading
- Application of weights (= DAS): $O(M)$

Simplified Capon

- Select the window with smallest output among $P=4-12$ pre-defined windows rather than estimate window from data
  - No matrix inversion $2L^3/3$, only $P \times$ DAS: $2P \cdot M$
    - Ex: $M=96$, $L=32 \Rightarrow 2L^3/3 \approx 22000$ vs $P=10$: $2P \cdot M \approx 2000$
  - More robust than Capon: no possibility for signal cancellation if windows have been chosen properly
Conclusion

• Applied MV beamformer to medical ultrasound imaging
• Balancing of performance and robustness.
  – Spatial smoothing which is important for dealing with multiple reflectors
  – Diagonal loading which helps make the method robust
  – Time averaging over about a pulse length in estimating the covariance matrix. The latter ensures that the speckle resembles that of DAS.
• Shown improvement in image quality of realistic images
• Demonstrated 3 examples where MV may be beneficial
  – Smaller aperture, higher framerate, lower frequency
• Several methods for reducing computational cost
• Needs more testing on relevant image data