Opportunities for ultrasonic imaging with software beamformation

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Topics

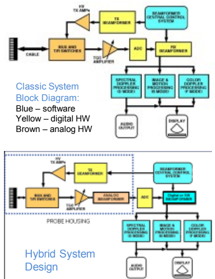
- Ultrasound scanner as a probe and a processor
- Software beamformation (SWBF)
- What can SWBF do for you?
- Some examples

Scanner Size Migration over last 20 years

Size & cost reductions largely due Moore's Law.

How do we get to SWBF?

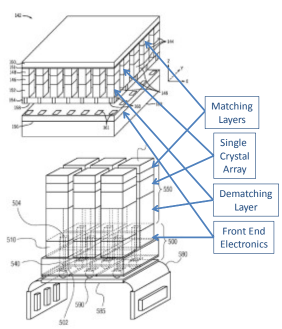
- Need for Miniaturization
    - Today, numerous vendors have tablet and handheld systems
  - Major enablers
    - Migration of functionality to software
    - Migration of electronics to handle
    - Size reduction for remaining ASICs



These developments have enabled today's handheld & tablet systems

Implementation of beamformation in probes

- Example from 2D arrays:
  - Multi-layer device
    - Matching layers
    - Single crystal array
    - Dematching layer
    - Front end electronics for preamplification, pulsing and beamformation
  - In a cardiac 2D array, there are some 2.5 – 3K elements
  - Abdominal designs, 9K
  - The element pitch is around 300 – 400 microns.



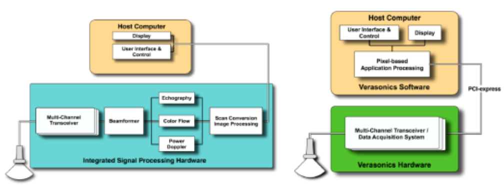
Software Beamformation

Software Beamformation

- Software Beamformation:
  - Processor-based signal processing of channel data. For example:
    - Apodization and beamformation delays
    - Filtering of individual element echoes
    - More flexible array processing techniques
  - New reconstruction techniques
    - Beamformation other than delay-sum
    - Plane wave beamformation

SWBF has the potential to launch a new era for ultrasound scanners

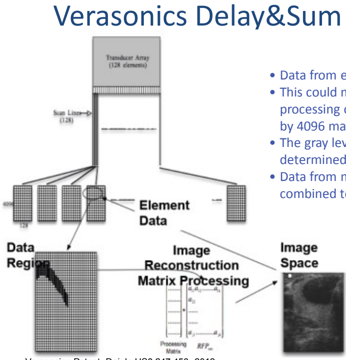
Software Beamformation, Verasonics



- Verasonics is a pioneer in SWBF.
- Only HW needed is a front end – pulsers, pre and TGC amps, and A/D converters and a PCI Express interface to a PC.
- Most of that hardware can be moved into the probe …
- The inventors refer to this as "pixel-based" processing.

Scanners composed of a probe & a processor

Software Beamformation (SWBF), Verasonics Delay&Sum Example



Verasonics Patent, Daigle US8,247,456, 2012

- Data from each acoustic line stored.
- This could mean real-time storage and processing of more than a hundred 128 by 4096 matrices.
- The gray level for any given pixel can be determined by a matrix multiplication.
- Data from multiple transmits can be combined to enhance data quality.

Why is this happening now?

- Today, we have compact processing power that, in real-time, is able to:
  - Receive, store, and transfer RF data sets from the array elements.
  - Process the channel data as the user wishes before beamformation or other image formation.
  - Implement a variety of different beamformation methods.
- Further improvements depend on our innovation and the evolution of processing power.

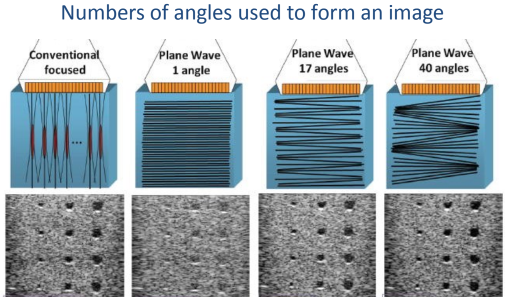
If only Moore's Law could hang around a bit longer …

Examples

- Imaging of other parameters than amplitude
  - Spatial coherence – Jeremy Dahl at Stanford, Gregg Trahey at Duke
- Adaptive imaging
  - Adjust delay parameters to correct for speed of sound variations
  - Minimum variance beamformation – U. of Oslo, others
- Ultrasound tomography
  - Reconstruction of sound speed images from ring array data – Karmanos Cancer Institute, Delphinus, Inc., Carson/Hooi at U. of Michigan
- Beamformation as a more general inverse problem
  - Define new inversion matrices
- Compressed sensing & ultrasound
  - Minimize temporal and spatial sampling rates
  - Eldar & others at Technion

Plane Wave Imaging

Numbers of angles used to form an image



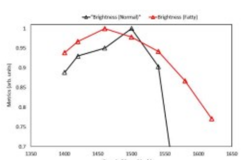
From Tanter & Fink: UFFC 61(1), Jan 2014

PICMUS Challenge at IUS2016

Additional Examples

Clinical Application: Estimation of the speed of sound in tissue

- SWBF opens up several methods for SOS estimation:
  - BF w. different speeds or channel delays
  - Superposition of data acquired from different angles (Jaeger, Frenz)
  - Creation of a virtual point source (Montaldo) w. spatial coherence.
- In all of these, SWBF supplies the easiest implementation.



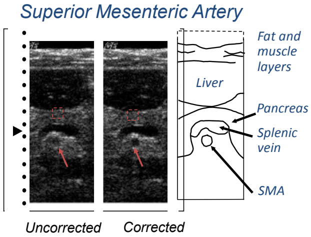
Goals of SOS estimation may be image quality improvement or SOS-based diagnosis.

Example: In-Vivo Time Delay Correction

Pancreas and Superior Mesenteric Artery

One approach:

- Use the beamsum as a template to adjust channel delays.
- In the image shown, contrast improves significantly.
- Example where individual channel processing is necessary



Rigby, K. W. (1995). *U.S. Patent No. 5,388,461*

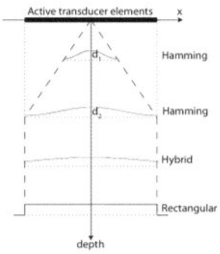
SMA 4.4 dB darker, pancreas 1.4 dB brighter

6 dB acoustic contrast improvement in SMA realized.

SWBF Example: Minimum Variance Beamformation

- The expression gives the beamsum signal, *z[n]*, for a D&S beamformer.
- With D&S, apodization weights, w_m ,may vary with depth with the aperture size.
  - One could also alter the shape of the apodization function w. depth
  - However, their values are **predefined** and not altered during reception.

$$z[n] = \sum_{m=0}^{L-1} w_m[n]x_m[n - \Delta_m[n]]$$



SWBF Example: Minimum Variance Beamformation

- With MVBF, we introduce a new step to modify the w_m values from their predetermined set.
- MV beamformer calculates a new set of w_m values based on the minimization of the variance of *z[n]*.
- The overall goal is to minimize energy while maintaining desired focus & steering.

$$z[n] = \sum_{m=0}^{L-1} w_m[n]x_m[n - \Delta_m[n]]$$

$$z[n] = \boldsymbol{w}[n]^H \boldsymbol{X}[n]$$

Variance of z[n] is given by:

$\mathrm{E}[|z[n]|^2] = w[n]^H \boldsymbol{R}[\boldsymbol{n}]w[n]$
where
$\boldsymbol{R}[n]$=$\mathrm{E}[\boldsymbol{X}[n]\boldsymbol{X}[n]^H]$

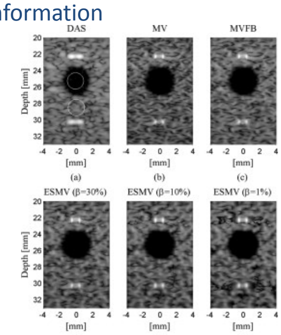
The required minimization:

$$\min_{w[n]}[w[n]^H \boldsymbol{R}[n]w[n]]$$

Synnevåg, J. F., Austeng, A., & Holm, S. (2009). Benefits of minimum-variance beamforming in medical ultrasound imaging. *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on, 56*(9), 1868-1879.

SWBF Example: Minimum Variance Beamformation

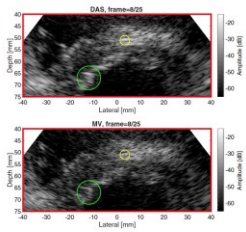
- Some imaging results from an advanced form of MVBF.
- Images shown use:
  - Delay & Sum
  - Minimum Variance
  - Minimum Variance with forward/back filtering of R[n]
  - Eigenspace-based MV with three parameter settings
- There is clear improvement with MV over basic D&S.



Mehdizadeh, Saeed, et al. "Eigenspace based minimum variance beamforming applied to ultrasound imaging of acoustically hard tissues." *Medical Imaging, IEEE Transactions on* 31.10 (2012): 1912-1921.

SWBF Example: Minimum Variance Beamformation

- Clinical assessment of MVB was performed by the S. Holm group at U. of Oslo.
  - Upper image: conventional D&S
  - Lower image: MVB
- It does appear that there is an improvement, albeit a subtle one.



Rindal, Ole Marius Hoel, et al. "Hypothesis of Improved Visualization of Microstructures in the Interventricular Septum with Ultrasound and Adaptive Beamforming." *Ultrasound in Medicine & Biology* (2017).

Summary of the talk

- Introduction of new SWBF platforms driving research.
- We briefly discussed several new beamformation methods, many others under development.
- Ultrasound scanners will become more reconstruction oriented, not just plain D&S.
- There are several ultrasound manufacturers already selling SWBF systems.

Thank You!

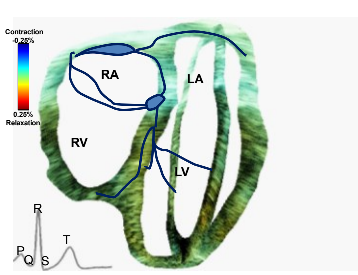
Some Implications

- Smaller, lighter systems coming
  - Going beyond Sonosite, GEHC Vscan, or Philips Visiq
- More specialized scanners
  - Today, most laptops, handhelds are multi-purpose
    - This probably will not be the case in the future
  - New clinical applications under development
  - Possibly physiological (e.g. blood pressure) monitoring
- Scanners will begin to overcome limitations of ultrasound
  - Correction for speed of sound variations
  - Minimum variance processing

Note: the Flexible Ultrasound Scanner should be a great tool for testing SWBF methods.

Back-up Slides

Transthoracic Electromechanical Wave Imaging (EWI) in a normal human heart



Provost et al., PNAS, 2011

Additional examples

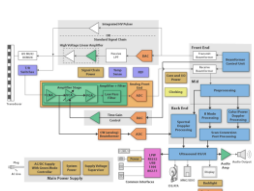
- Imaging from multiple look directions
  - Retention of and beamformation with complex data between transmits
- Retrospective transmit focusing
  - Dynamic focusing on both transmit & receive
- Aperture adjustments based on coherence
  - Analysis of quality of received data
  - Greater emphasis on coherent echoes
  - Ability to reject unwanted acoustic noise
- Greater degree of automated operation
  - Reduce user dependence
  - Real-time assessment of image quality metrics

Compressed sensing in ultrasound

- CS has had significant impact in CT & MRI.
- With SWBF, CS may have an impact in US.
  - Y. Eldar's group has championed methods in the area.
- Key feature is to consider ultrasound echoes to be composed of sums of identical pulses.
  - Each pulse can be defined by a delay and amplitude.

Another interesting development …

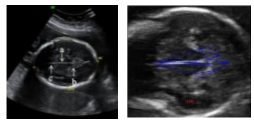
- Semiconductor Companies
  - Traditional Role:
    - Suppliers of integrated circuits for US
  - Emerging Role:
    - Front end subsystem suppliers
    - Computing engines for beam, image formation and processing
    - MEMS transduction (e.g. cMUTs)???
  - Possible Impact:
    - Significantly reduced hardware role for traditional scanner suppliers?
    - Will the differentiation among the suppliers be based on software?

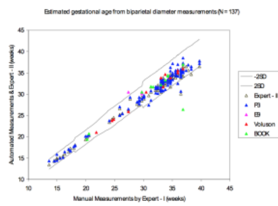


Today, Texas Instruments offers products for each colored block in the diagram.

Example: Gestational Age Estimation

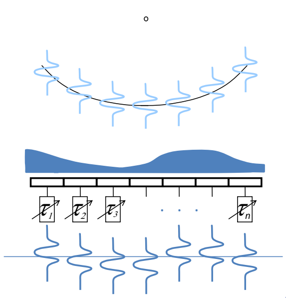
- Two projects:
  - Computer assessment of accuracy of the selected BPD imaging plane.
  - Automate the BPD measurement itself.
- Results are comparable to human experts.
  - Most fall within +/- 2 SD





Annangi. P et al, SPIE Medical Imaging 2011, Vol. 7968
Liu, X. et al, SPIE Medical Imaging 2012, Vol. 8320

SWBF Example: Dealing with Aberration



Point-like scatterer

Spherical wavefronts

Aberrating Layer, Transducer c □ c_0

Geometric beamforming delays

Channel data poorly aligned

Rigby, K. W. (1995). *U.S. Patent No. 5,388,461*

Compare each channel to beamsum, adjust delay to match.

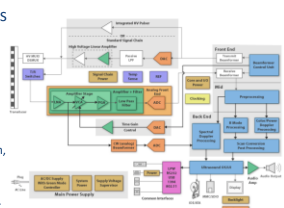
Another interesting development …

Role of Semiconductor Companies

Traditional Role
- Suppliers of specialized ICs
  - TGC amplifiers
  - A/D converters
  - Multiplexing

Emerging Role
- Front end subsystem suppliers
  - Chip sets from pulsers to A/Ds
- Computing engines for beamformation, image formation and processing
- MEMS transduction (e.g. cMUTs)???

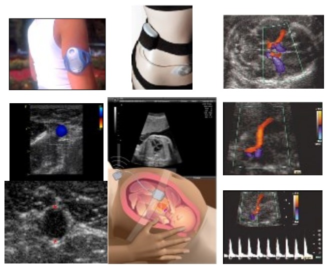
Potential Impact
- Significantly reduced hardware role for traditional scanner suppliers (e.g. GE)
- Will the differentiation among the suppliers be based on software?
- Very nice benefit for academic researchers



TI offers products for each colored block in the diagram

Ultrasound in Patient Monitoring?

- We have looked at the possibility of ultrasound-based patient monitoring.
- Some needs:
  - Automatic searches for clinical targets
  - Continously & automatically measure desired parameters
  - Report results on a continuing basis



Probe beamformer delay circuitry

- The upper figure suggests an implementation for a multi-stage beamformer.
- Several different methods have been developed for realizing the delays:
  - Quantized phase delays with all-pass filters
  - Heterodyned delays
  - Sampled-capacitor delays or charge-coupled devices.
- The last option would appear to be superior.