ULTRASONIC ARRAY IMAGING USING CDMA TECHNIQUES

Yannis S. Avrithis, Anastasios N. Delopoulos
and Grigorios C. Papageorgiou

Department of Electrical and Computer Engineering
National Technical University of Athens
157 73 Zographou, Athens, GREECE

Objectives

- Ultrasonic imaging through phased-array transducers operating in continuous wave mode
- Array element excitation with wideband signals generated by pseudorandom codes, similarly to code division multiple access (CDMA) systems
- Transmit and receive beamforming for steering different codes at each direction
- Unified theoretical model incorporating time and frequency division techniques

Limitations of Conventional Systems

- Phased array transducers of 64 to 256 elements currently used, operating in pulse-echo mode at 2 to 20 MHz & providing gray-scale images at a rate of more than 20 frames/second

- 3-D image capabilities through 2-D transducer arrays impose new requirements on ultrasonic imaging systems: simultaneous image line acquisition necessary

- Typical 2-D arrays require more than 15000 elements, resulting in electrical interconnection and impedance mismatching problems

- Grating lobes limit dynamic range and consequently contrast resolution

Advantages of Proposed Technique

- Parallel acquisition of large number of measurements corresponding to different directions
- Significantly higher lateral and contrast resolution
- Axial resolution close to that of conventional phased arrays
- Real-time implementation of 3-D image generation possible

1-D Signal Reconstruction (conventional)

Conventional system consisting of a single transducer element operating in pulse-echo mode and scanning one image line:

$$\widehat{R}_p(t) = \int_0^{T_m} R(\tau)p(t-\tau)d\tau$$

where

$R(t)$: actual reflection coefficient at depth $z = ct/2$
$p(t)$: pulse used to excite the transmitter
$T_m = 2z_{max}/c$
z_{max}: maximum depth of reflecting body
c: velocity of sound propagation in medium

1-D Signal Reconstruction (proposed)

- Transmitter excited by long duration, wideband acoustic signal

$$a(t) = \sum_{j=-\infty}^{\infty} a_j p(t - jT_c)$$

  where $\{a_j\}$: discrete pseudorandom sequence (signature) of period L, generated by finite-length shift register, T_c: pulse duration

- Reconstruction of $R(t)$ based on

$$\widehat{R}_c(t) = \int_0^T h(u) r(t-u) du$$

  where

  $r(t) = \int_0^{T_m} R(\tau) a(t-\tau) d\tau$: received signal
  $h(t) = a(T-t)$, $t \in [0, T]$: matched filter
  $T = LT_c$: period of $a(t)$

1-D Signal Reconstruction (proposed)

- Reconstruction similar to pulse-echo mode:

$$\hat{R}_c(t) = \int_0^{T_m} R(\tau) C_a(t-\tau) d\tau$$

where $C_a(t)$: autocorrelation function of $a(t)$, since both $p(t)$ and $C_a(t)$ act as delta functions in respective integrals

- It can be shown that

$$\hat{R}_c(t) = \sum_{n=-1}^{M} \tilde{R}(t + (n-l)T_c) c(n-l)$$

where

$c(n)$: discrete periodic autocorrelation function of $\{a_j\}$
$T_m = MT_c$, $l = \lfloor t/T_c \rfloor$
$\tilde{R}(t) = \int_0^{T_m} R(\tau) C_p(t-\tau) d\tau$
$C_p(t)$: autocorrelation function of $p(t)$

2-D Signal Reconstruction (no beamforming)

- With N_c code sequences, $a_i(t)$, $i = 1, 2, \ldots, N_c$, and no beamforming (omnidirectional transmitters and receivers),

  $$\widehat{R}_k(t, \theta) = \sum_{i=1}^{N_c} \int_0^{T_m} R(\tau, \theta) C_{k,i}(t - \tau) d\tau$$

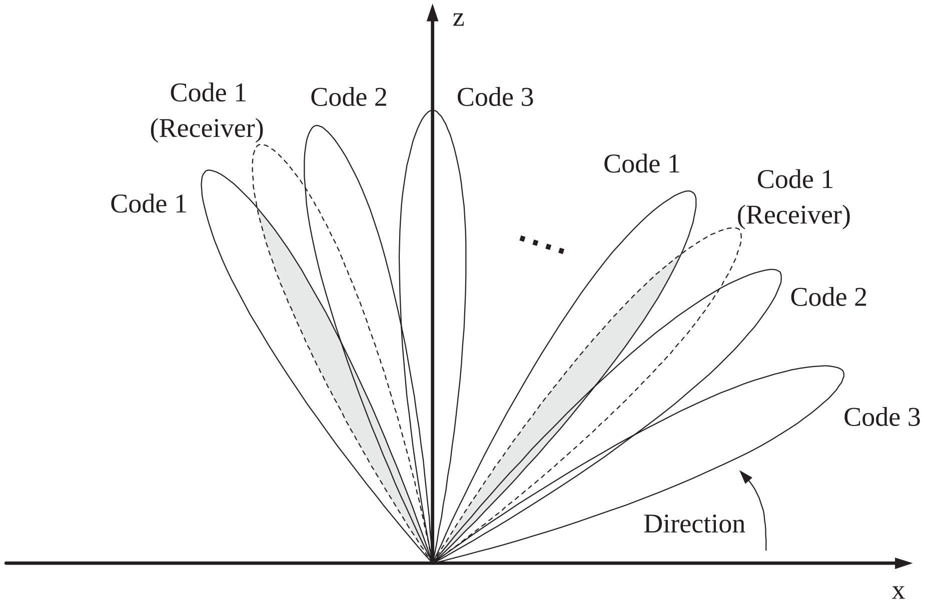
  where $C_{k,i}(t)$: cross-correlation function between code sequences $a_k(t)$ and $a_i(t)$

- Code sequences designed so that $C_{k,i}(t)$ is negligible if $i \neq k$. Possible candidates: *Gold* sequences or a small, suitably selected set of M-sequences

Transmitter and Receiver Beamforming

- N_θ transmitter patterns steered at directions θ_i, $i = 1, 2, \ldots, N_\theta$ and assigned unique code sequences. Sequences repeated periodically if $N_\theta = KN_c$

- Main lobe of each receiver overlaps two neighboring transmitter lobes:



2-D Signal Reconstruction (with beamforming)

- Similarly to 1-D case,

$$\widehat{R}_k(t,\theta) = \sum_{i=1}^{N_c} \sum_{n=-1}^{M} \tilde{R}_i(t+(n-l)T_c,\theta)c_{k,i}(n-l)$$

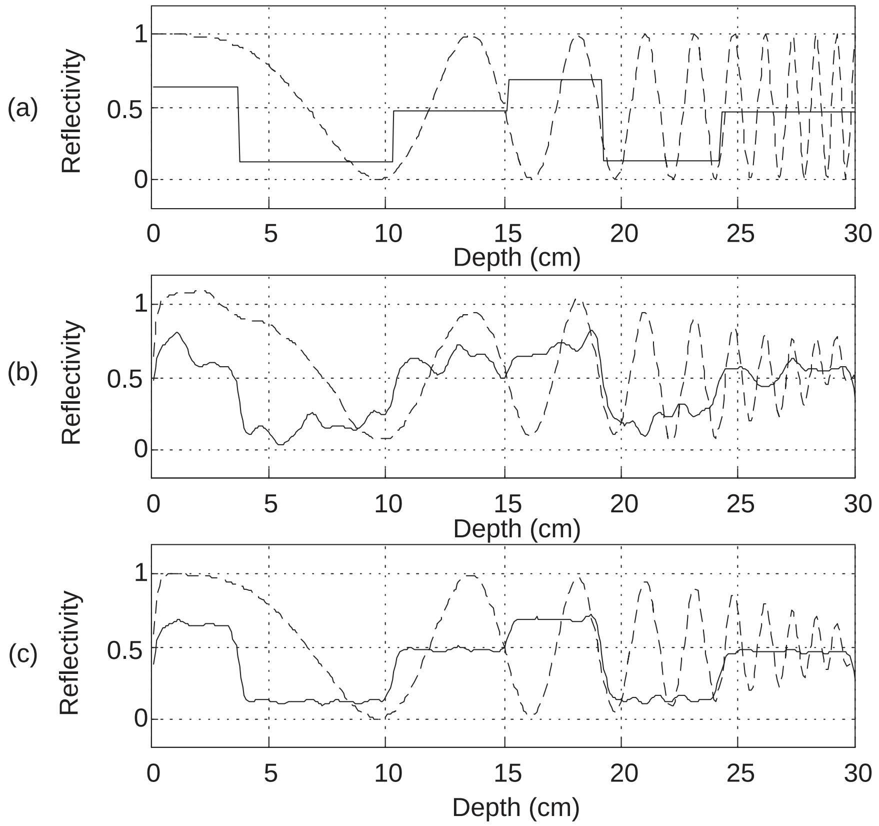
  where

  $c_{k,i}(n)$: discrete cross-correlation function of $\{a_j^{(k)}\}$ & $\{a_j^{(i)}\}$
  $\tilde{R}_i(t,\theta) = \int_{\theta_1}^{\theta_2} G_i^T(\phi)G_\theta^R(\phi)\tilde{R}(t,\phi)d\phi$
  $G_i^T(\phi)$: i-th transmitter gain pattern
  $G_\theta^R(\phi)$: receiver gain pattern steered at direction θ
  $\tilde{R}(t,\phi)$: defined similarly to $\tilde{R}(t)$

- i-terms ($i \neq k$) removed with interference suppression technique

Simulation Results (1-D reconstruction)

Two 1-D signals reconstructed with 2 M-sequences, $L = 2^9 - 1 = 511$, $T_m = 63T_c$ ($M = 63$), so that $T \simeq 8T_m$:



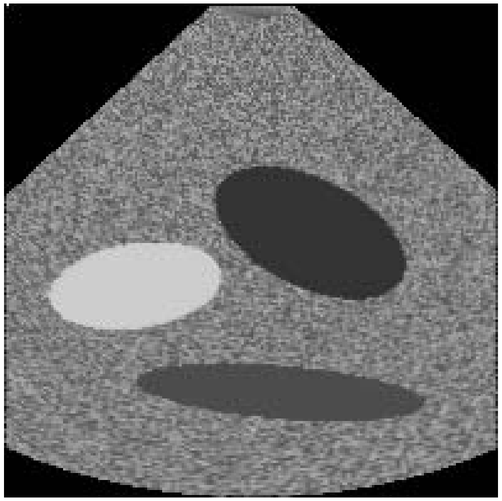
Simulation Results (2-D reconstruction)

- Reconstruction of 2-D cyst phantom with 3 primary M-sequences of $L = 2^{11} - 1 = 2047$, $N_\theta = 24$ transmitter & receiver array gain patterns, and $T_m = 255T_c$ ($M = 2^8 - 1$). 24 code sequences obtained by 8 phase shifts of primary sequences, since $T \simeq 8T_m$

- Acquisition of $N_t = L/M = T/T_m = 8$ image lines at each sequence period, at different time 'slots' for each direction: *time division*

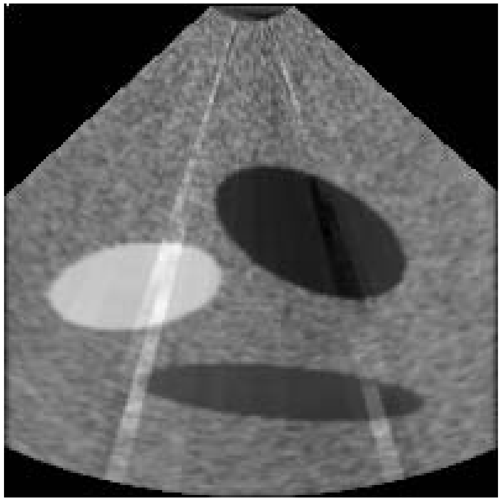
- Possible division of bandwidth in N_f frequency bands: *frequency division*

Simulation Results (2-D reconstruction)

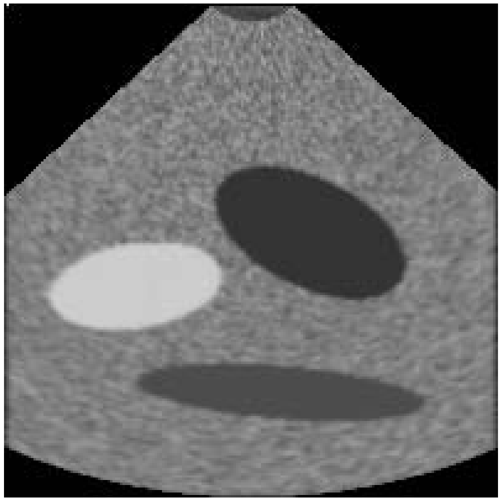


Original 2-D cyst phantom

Conventional Reconstruction



Proposed (without correction)



Proposed (with correction)

Conclusions

- Parallel acquisition of large number of measurements corresponding to different directions: real-time implementation of 3-D image generation possible

- Significantly higher lateral and contrast resolution

- Possible optimization of system performance through selection of design parameters (N_c, N_θ, N_t, N_f, K, L, no. of elements etc.), depending on system characteristics (desired spatial and contrast resolution, acquisition speed, total available transducer bandwidth, operating frequency etc.)