Detection of Obscured Targets: Signal Processing

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Outline

- Introduction
- Multi-resolution & Multi-modal Signal Processing
  - Physical Basis for Multimodal Processing/Inversion
- Quadtree Imaging
  - GPR processing examples
- Imaging with Acoustic/Seismic Arrays
  - Reverse-Time Processing
  - Near-Field Imaging
- Accomplishments/Plans
Three Sensor Experiment

- A three sensor experiment has been developed to investigate the potential for multimodal processing
  - Electromagnetic Induction (EMI) Sensor
  - Ground Penetrating Radar (GPR) Sensor
  - Seismic Sensor
- Multiple Experimental Scenarios
  - Buried Landmines
  - Buried Clutter Objects
  - Target Distribution
- Properties

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Physical Properties of Target</th>
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<tr>
<td></td>
<td>Permittivity Contrast</td>
<td>Low Conductivity (Dielectric)</td>
<td>High Conductivity (Metal)</td>
<td>Mechanical Contrast</td>
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<tr>
<td>EMI</td>
<td>No</td>
<td>Weak</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>GPR</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes*</td>
<td>No</td>
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<tr>
<td>Seismic</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
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Comparison of EMI, GPR and Seismic Response
VS-50, 1 cm deep
Multi-Sensor Processing

- **GPR** → **Imaging** → **Decision Process**
  - Features
  - ID
- **EMI** → **SigProc** → **Decision Process**
  - Features
  - Exploit Correlation
  - Training
  - Detect
  - Classify
- **Seismic** → **Imaging** → **Decision Process**
  - Features

Multi-Sensor Adaptation

- **GPR** → **Imaging** → **Decision Process**
  - Features
  - Controls
  - Exploit Correlation & Sensitivity
- **EMI** → **SigProc** → **Decision Process**
  - Features
  - Controls
- **Seismic** → **Imaging** → **Decision Process**
  - Features
  - Controls
  - Feedback
- **Feedback**

MURI Review 7-01-04 Scott/McClellan, Georgia Tech
Three Sensor Experiment
Sensor Adjustments and Features

- Adjustable Parameters for all three sensors
  - Frequency range
  - Frequency Resolution
  - Spatial Resolution
  - Integration time/bandwidth
  - Height above ground

- Possible Features for sensors
  - EMI
    - Relaxation frequency
    - Relaxation strength
    - Relaxation shape
    - Spatial response
  - GPR
    - Primary Reflections
    - Multiple Reflections
    - Depth
    - Spatial Response
  - Seismic
    - Resonance
    - Reflections
    - Dispersion
    - Spatial response

Multi-Resolution Processing

Quadtree Imaging @ increasing Resolution (Eliminate Areas)

GPR

Seismic

Multi-band Imaging

Imaging

Features

Decision Process

Exploit

Correlation

Training

ID

Detect

Classify

Target Localization @ specific sites
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Outline

- Quadtree Theory
- Ground Reflection Removal Techniques on Real Data
- 2D Quadtree
  - Synthetic Data Results
  - Real Data Results
- 3D Quadtree
  - Two approaches for 3D Quadtree
  - Synthetic Data Results
  - Real Data Results
Multi-Res Quadtree Algorithm

- Standard Backprojection
  - Space-Time Domain Correlation
  - Significant amount of computations

- Quadtree Algorithm
  - Approximates Standard Backprojection
  - Consists of many sub-aperture and sub-image operations:
    - beamforming over the sensors in sub-apertures with respect to the virtual sensor and sub-images.
    - Significant amount of Time-Domain Interpolation required.

Quadtree BackProjection

- Space-Time Domain Decomposition
  - Image Patch Dividing and Sub-Aperture Formation (Virtual Sensor)
  - Divide and Conquer Strategy

- Computational Complexity $O(N^2 \log N)$
GPR Processing

- Data taken in frequency domain with network analyzer: 500 MHz to 8 GHz
- Imaging
  - **Backprojection** does migration
  - 2-D, extend to 3-D
  - $\omega-k$ algorithms
  - Extend to Quadtree
    - Multi-resolution

Ground Reflection Removal

- Return over VS 1.6 mine

- Interpolate
- Correlate and find the lag
- Subtract Ground Reflection model
Ground Reflection Removal (2D Slices)

Before Ground Reflection Removal

After Ground Reflection Removal

Three Sensor Experiment

- Experimental Scenario #1
  - 6 Mines
  - > 20 Clutter objects
  - Relatively uniform distribution

- Experimental Scenario #2
  - 7 Mines
  - > 25 Clutter objects
  - Non-uniform distribution
Burial Scenario #2

1.8m by 1.8m Scan Region

Seismic Sources

MINES
VS-50
(1.3cm deep)

VS-2.2
(5.4cm deep)

M-14
(1cm deep)

TS-50
(1.3cm deep)

EMF-1
(0.6cm deep)

VS-50
(0.5cm deep)

VS-1.6
(5.1cm deep)

Assorted Metal Clutter
(<3cm deep)

Can
(2.2cm deep)

Rocks
(2, 2.2, 2.5, and 1.3cm deep)

CD
(29cm deep)

“QUADTREE” Burial Scenario-2

Processing with EMI Sensor: 600Hz – 60 kHz

Energy Plot

Break Frequencies
2D Quadtree – Synthetic Data

- Synthetic Data: Point Target at (20, -10)

2D Quadtree – Real Data

Quadtree applied on 2D slice (ground reflection removed)
Quadtree Aperture size is 16. To cover all the data, Quadtree is done 5 times.
3D Quadtree

- **2D Quadtree:**
  - Data(x,t):
    - Sensor #, Fast Time
  - Patches are square
  - Approximate with circles
  - Use P = 2 parent nodes to generate one ‘virtual’ node
  - Divide one patch into 2x2 = 4 sub-patches.
  - Radix-2 algorithm

- **3D Quadtree:**
  - Data(x,y,t):
    - Sensor Position, Fast Time
  - Patches are cubes
  - Approximate with spheres
  - Use P = 4 parent node to generate one ‘virtual’ node
  - Divide one patch into 2x2x2 = 8 sub-patches.

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3D Quadtree – Synthetic Data

Data Properties:

- Target at (26,18,-10)
- 16 x 16 aperture
- 95 % of the surface is eliminated by the Quadtree process.
3D Quadtree – Real Data

One Patch

Ground Reflection Removed
(Real Data)

One 16 x 16 patch over a VS-2.2 mine

68.75 % of the area is eliminated by the first two stages of the Quadtree

Detection Strategy

- **Step 1**: (Scaling) Take first 3 stages of the quadtree and make them comparable by equating the energy sums equal over the whole area.
- **Step 2**: Look for the patches that have a continuously increasing value.
- **Step 3**: Eliminate patches that are 20 dB below the maximum.

Use first 3 Stages (Scaled)
Make Stages comparable

Look for the patches that have a continuously increasing value

Eliminate patches that are 20 dB below the maximum
Real Data Quadtree

Initial Quadtree Patch size is 16 x 16
(32 cm x 32 cm initial area)
step size is 2 cm
Total coverage is 80 x 80
i.e., 25 quadtree patches
Mine areas are found by looking for patches where quadtree focuses.

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Seismic Sensor

Seismic & GPR: Depth and Frequency

GPR Images in depth ranges (20 dB scales)

Energy in reflected seismic waves in frequency bands (20 dB scales)
Outline

- System Setup
- Time Reverse Imaging
  - MUSIC based algorithm
- Time Reversal Matrix based Near field target DOA and Range Estimation
  - 2-D MUSIC algorithm
- Multi-Static Wide-Band RELAX and CLEAN algorithms
- Processing of numerical and experimental data

Active Array System
Time Reverse Imaging*

- Probe the medium containing M targets, with P sources and measure reflections on N receivers

- Each source (P) sends a pulse, and reflections are measured on receivers (N)
  - Form the Response Matrix, \( K(t) \) (P x N x T)

- Process \( K(t) \) in frequency domain
  - One frequency at a time, \( K(\omega) \) (P x N)

* Borcea, Papanicolaou, Tsokga, Berryman, "Imaging and Time Reversal in random media", Inverse Problem 2002
* Prada, JASA, Vol 97, 1996

Time Reversal Matrix based Near Field DOA and Range estimates

- Using Response matrix, form a Time Reversal Matrix, \( K^h(\omega) K(\omega) \)

- **Time Reversal Matrix** can be interpreted as a Covariance Matrix used in standard array processing techniques*
  - Receivers correspond to sensors
  - Sources correspond to snapshots

- Use Time Reversal Matrix for High Resolution near field DOA and Range Estimates

- Improvement in both cross and range resolution

*Prada, JASA, Vol 114(1), July 2003
2-D MUSIC approach*

Use SVD of Time Reversal matrix, $K^H(\omega)K(\omega)$

Form a noise matrix using singular vectors obtained from SVD

$$W(\omega) = [u_{M+1}, \ldots, u_N]$$

where $M$ and $N$ are number of targets and sensors

2-D MUSIC approach

Search for \((R_1, \theta_1)\) estimates by using

\[
P(R_1, \theta_1, \omega) = \frac{1}{a^H(R_1, \theta_1, \omega)WW^Ha(R_1, \theta_1, \omega)}
\]

where

\[
a(R_1, \theta_1, \omega) = \left[1, e^{i\left(\frac{2\pi}{\lambda(\omega)}(R_2-R_1)\right)}, \ldots, e^{i\left(\frac{2\pi}{\lambda(\omega)}(R_N-R_1)\right)}\right]
\]

and \(R_k = \sqrt{R_1^2 + k^2d^2 - 2kdR_1 \sin \theta_1}, \quad k = 2, \ldots, N\)

(w.r.t. first reference sensor)

The \(M\) Peaks of \(P\) are estimates of near field parameters.

Numerical Simulation Setup

Two Targets buried at a depth of 2cm

15 Sources, 6 cm apart

23 Receivers, 4 cm apart
Rayleigh Wave Parameters

Frequency Range Used: 874 Hz – 1000 Hz

Time-Reversal Imaging (Numerical Data)
Near Field Estimates

RX Array at R1

RX Array at R2

Experimental Setup
8 Sources (15cm), 51 Receivers (2cm)
Rayleigh Wave Parameters

**Frequency Range Used:**
300 Hz – 820 Hz

Time Reverse Imaging
Frequency Range used: 300 Hz-820 Hz
Averaging is done

RX Array at R1

RX Array at R2
Near Field DOA & Range Estimates

RELAX and CLEAN algorithms

- Acoustic source localization and signal characterization by using an acoustic array
- RELAX is a parametric approach for point sources
- CLEAN is a non-parametric approach for both point and distributed sources
  - Was developed for Near-Field passive array problem
  - Extended to the problem of active sensing & buried targets
- Both algorithms involve a two-step optimization

Problem Setup

- Passive receiver array
  - Known Green’s function

- M element array, K near-field wideband sources

- Take the DFT of the received signals and then select the L largest frequency components

- Signal waveform vector is modeled as a **deterministic** quantity

**Goal:** Estimate both the source signal \( s \) and the location \( p \) from measured array data

\[
y(\omega_l) = A(p, \omega_l)s(\omega_l) + e(\omega_l), \quad l = 1, \ldots, L
\]

\[
s(\omega_l) = [s_1(\omega_l), \ldots, s_K(\omega_l)] \quad \text{(source signals)}
\]

\[
A(p, \omega_l) = [a(p_1, \omega_l), \ldots, a(p_K, \omega_l)] \quad (M \times K)
\]

\( p = [p_1, \ldots p_K] \) is the vector of 3-D source locations

\[
a(p_k, \omega) = \left[ \frac{1}{r_{1,k}} e^{-j(\omega/c_0)r_{1,k}}, \ldots, \frac{1}{r_{M,k}} e^{-j(\omega/c_0)r_{M,k}} \right]^T
\]

\( r_{m,k} = \text{distance between } m^{th} \text{ sensor and } k^{th} \text{ source.} \)
Least Squares Solution

Estimate \{p, s(\omega_l)\} by minimizing the Wideband LS function:

\[ G_r = \sum_{l=1}^L [y(\omega_l) - A(p, \omega_l)s(\omega_l)]^H[y(\omega_l) - A(p, \omega_l)s(\omega_l)] \]

Fix \( p \) and solve for the optimal \( s(\omega_l) \)

\[ \hat{s}(\omega_l) = (A^H(p, \omega_l)A(p, \omega_l))^{-1}A^H(p, \omega_l)y(\omega_l) \quad l = 1, \ldots L \]

Then substitute this \( \hat{s}(\omega_l) \) into \( G_r \) and perform the minimization w.r.t. to \( p \) (searching required)

\[ \hat{p} = \arg\min_p \sum_{l=1}^L \left\| I - A(p, \omega_l)(A^H(p, \omega_l)A(p, \omega_l))^{-1}A^H(p, \omega_l) \right\| y(\omega_l) \right\|^2 \]

Wideband RELAX algorithm

Suppose there are \( K \) incident signals, and we have estimated the parameters for all signals except the \( k^{th} \) one. Then we can remove the estimates:

\[ y_k(\omega_l) = y(\omega_l) - \sum_{j=1, j \neq k}^K a(\hat{p}_j, \omega_l)\hat{s}_j(\omega_l) \]

Using \( y_k \), form the LS cost function \( G_k \) and solve for \( \hat{p}_k \) and \( \hat{s}_k \)

\[ \hat{p}_k = \arg\min_p \sum_{l=1}^L \left\| \left[I - \frac{a(p_k, \omega_l)a^H(p_k, \omega_l)}{a^H(p_k, \omega_l)a(p_k, \omega_l)} \right] y_k(\omega_l) \right\|^2 \]

\[ \hat{s}_k(\omega_l) = \frac{a^H(p_k, \omega_l)y_k(\omega_l)}{a^H(p_k, \omega_l)a(p_k, \omega_l)}, \quad p_k = \hat{p}_k \]
Wideband RELAX steps

**Step 1:** Assume $\tilde{K} = 1$,
Obtain $(\tilde{p}_1, \tilde{s}_1(\omega))$ with $y_1(\omega) = y(\omega)$

**Step 2:** Assume $\tilde{K} = 2$,
Compute $y_2(\omega)$ by using $(\tilde{p}_1, \tilde{s}_1(\omega))$ from Step 1.
Obtain $(\tilde{p}_2, \tilde{s}_2(\omega))$.
Next compute $y_1(\omega)$ by using $(\tilde{p}_2, \tilde{s}_2(\omega))$ and re-determine $(\tilde{p}_1, \tilde{s}_1(\omega))$.
Iterate these previous sub-steps until practical convergence is achieved

Extend this strategy when $\tilde{K} > 2$

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Wideband CLEAN algorithm

$$G_c = \sum_{l=1}^{L} \|y_n(\omega_l) - a(p_n, \omega_l) s(\omega_l)\|^2$$

$$y_n(\omega_l) = y(\omega_l) - \sum_{\tilde{n}=1}^{n-1} \rho a(\tilde{p}_{\tilde{n}}, \omega_l) \tilde{s}_{\tilde{n}}(\omega_l)$$

where $\rho$ is the loop gain, usually chosen between 0.1 and 0.25.

$$\tilde{p}_n = \arg \max \sum_{l=1}^{L} \frac{|a^H(p_n, \omega_l)y_n(\omega_l)|^2}{\|a(p_n, \omega_l)\|^2}$$

$$\tilde{s}_n(\omega_l) = \frac{a^H(p_n, \omega_l)y_n(\omega_l)}{a^H(p_n, \omega_l)a(p_n, \omega_l)}$$

$p_n = \tilde{p}_n$
Wideband CLEAN steps

Step 1: Choose $\rho$, initialize with $n=1$, and let $y_1(\omega_l) = y(\omega_l)$

Step 2: Estimate $p$ and $s_n(\omega_l)$ for $l = 1, \ldots, L$

Step 3: Subtract out only a fraction $\rho$ of array data from $y_n(\omega_l)$ to get $y_{n+1}(\omega_l)$

Step 4: Save the current estimated signal location and waveform (scaled by $\rho$)

Step 5: Repeat the iterations

Extension to MULTI-STATIC Case

Use Response Matrix

$$K(\omega) = H_1(\omega)D(\omega)H_2(\omega), \quad (N_r \times N_t)$$

$$\hat{p} = \arg \min_{\omega_l} \sum_{l=1}^{L} \left\| I - \frac{a(p, \omega_l)a^H(p, \omega_l)}{a^H(p, \omega_l)a(p, \omega_l)} \right\|^2$$

For a single source, the term in the norm is a vector of size $1 \times N_r$ and the $L_2$ norm for vector is used.

For multiple sources, the norm term is a matrix of size $(N_r \times N_t)$, and we use the matrix $L_2$ norm:

$$\min[L_2(:, 1), \ldots, L_2(:, N_t)]$$

Signal Estimate: $\hat{s}(\omega_l) = \frac{a^H(p, \omega_l)K(\omega_l)}{a^H(p, \omega_l)a(p, \omega_l)}$, \quad ($1 \times N_t$)
Experimental Setup
8 Sources (15cm), 51 Receivers (2cm)

Location Estimates (RELAX)
Experimental

Frequency Range Used:
300 Hz – 820 Hz
Reflected Signal From Targets
8 sources, 8 signals

Iteration #1

Location Estimates (RELAX)

RX Array at R1

Frequency Range Used:
300 Hz – 820 Hz
Location Estimates (CLEAN)

 RX Array at R2

 Frequency Range Used: 300 Hz – 820 Hz

Location Estimates (CLEAN)

 RX Array at R1

 Frequency Range Used: 300 Hz – 820 Hz
Single AP mine in rocks (100)
12 Sources (15 cm), 41 Receivers (2 cm)

Three Receiver array positions

Frequency Range: 500 Hz – 820 Hz
Location Estimates (RELAX)

RX Array at R3

Frequency Range: 500 Hz – 820 Hz

Location Estimates (RELAX)

RX Array at R2

Frequency Range: 500 Hz – 820 Hz
Location Estimates (CLEAN)

RX Array at R3

Frequency Range: 500 Hz – 820 Hz

Location Estimates (CLEAN)

RX Array at R2

Frequency Range: 500 Hz – 820 Hz