Research Thrust R2: Physics-Based Signal Processing & Image Understanding

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NSF Year Two Site Visit
May 21, 2002
A. Overview
B. R2 Fundamental Research
   R2A. Multi-View Tomography
   R2B. Localized Probing and Mosaicing
   R2C. Multispectral Discrimination
   R2D. Image Understanding/Sensor Fusion
C. Summary
A. Overview

Fundamental techniques for subsurface imaging and information extraction
Robust algorithms for image formation in weak signal, high clutter environments
Multisensor, multi-phenomenology fusion algorithms
R2 Objective: Unifying Principles for Subsurface Imaging

- Identify and exploit common structure in underlying Physics
  - Multi-View Tomography (MVT), Localized Probing and Mosaicing (LPM), and Multispectral Discrimination (MSD), ...

- Develop information extraction strategies applicable to broad classes of subsurface imaging problems
  - Integrate Physics-based models into processing
Subsurface Imaging Systems
- Diffuse optical tomography (DOT), electric impedance tomography (EIT)
- Acoustic strain and stiffness imaging
- Ground-penetrating radar imaging
- Laser retinal mapping, acoustic & optical ocean floor mapping
- Hyperspectral coral reef monitoring

Common approaches evaluated across diverse problems
- EIT for soil, medical imaging
- Regularization in DOT, hyperspectral, underground and underwater imaging
- Robust nonlinear inversion for acoustic, GPR imaging
- Mosaicing in ocean floor and laser retinal mapping
- Object-based reconstructions in GPR imaging, EIT, DOT
B. Fundamental Research

- Four project areas, organized by common processing approaches
  - Multiview Tomography (MVT), Localized Probing and Mosaicing (LPM), Multispectral Discrimination (MSD), Image Understanding and Sensor Fusion (IUSF)
  - Organized to foster integration across applications

- Participants: four university partners and affiliates
  - NU: D. Brooks, A. Devaney, M. Maliutov, E. Miller
  - BU: P. Barbone, D. Castañón, L. Felsen, C. Karl, V. Galdi
  - UPRM: S. Hunt, L. Jiménez, F. Gilbes, M. Vélez
  - Partners: S. Lehman (LLNL), H. Singh (WHOI), D. Boas (MGH)
  - Other Universities: M. Kilmer (Tufts), A. Witten (Oklahoma)
  - Students from all four universities
R2A. Multiview Tomography

- Focus of research: Image formation from tomographic measurements
  - Applications in CenSSIS testbeds:
    - EIT, ERT, DOT, GPR, diffraction tomography, CT, elastography

- Diverse applications approached through a common view: statistical physics-based inverse scattering
  - Inverse problem characteristics + physics model + a priori information + robust decision-directed inversion strategy

- Objective: Improved resolution, signal-noise ratio in subsurface imaging
Impedance Tomography

- **Principle:** Apply single frequency electrical currents on electrodes, record resulting voltages
  - Neumann-to-Dirichlet map
  - Estimate conductivity and permittivity

- **Applications**
  - Monitoring Cardiac and Pulmonary Functions
  - Breast Cancer Diagnosis and Screening
  - Cardiac Imaging
  - Environmental Subsurface Monitoring

\[ \nabla \cdot (\sigma \nabla v) = 0 \text{ in } \Omega \]
\[ \sigma \frac{\partial v}{\partial n} = J \text{ on } \partial \Omega \]
Previous Results

- **Previous work**
  - Linear and nonlinear inversion for different array configurations by various groups (including RPI)
  - Optimal configuration design for electrodes
  - Instrument design for different imaging areas
  - Optimal excitation patterns based on eigenfunctions of D-N map
  - Simple commercial instrument (T-Scan) receives FDA approval of Breast Cancer Screening

<table>
<thead>
<tr>
<th></th>
<th>Mamm. alone</th>
<th>T-Scan Adjunctive</th>
<th>McNemar p-value (Mamm vs. adjunctive)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensitivity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Biopsy pos.=50)</td>
<td>60%</td>
<td>82%</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Specificity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Biopsy neg.=223)</td>
<td>41%</td>
<td>57%</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

Sensitivity = # predicted to have cancer / # who have cancer
Specificity = # predicted not to have cancer / # free of cancer
- Experimental verification of advantage of optimal excitation for flat panel arrays
  - Improved detection of inhomogeneities at greater depth than competition

![Graph showing maximum detected distance for different groups.](image)
Impedance Tomography: New Results

- Experimental verification of advantage of optimal excitation for flat panel arrays
  - Improved detection of inhomogeneities at greater depth than competition

- Design and construction of new broadband current/voltage sources for new ACT4 instrument

**ACT 3 (1995)**
- 32 Current sources
- 32 Voltmeters
- 32 Electrodes
- 30 kHz
- 20 Frames / Sec
- Accuracy > .01%
- Reconstructed Voxels = 496
- Resolution = 1 - 3 cm

**ACT 4 (2003)**
- 64 Current sources
- 64 Voltage sources
- 64 Voltmeters
- 64 Electrodes
- 100 Hz - 1 MHz
- 30 Frames / Sec
- Accuracy > .002%
- Reconstructed Voxels = 2016
- Resolution = .3 - 1 cm
Impedance Tomography: New Results

- Experimental verification of advantage of optimal excitation for flat panel arrays
  - Improved detection of inhomogeneities at greater depth than competition
- Design and construction of new broadband current/voltage sources for new ACT4 instrument
- New direct inverse scattering reconstruction algorithm applied to phantom data
  - Direct nonlinear method instead of linear approximation for better quantitative imaging
Current Directions in EIT

- Investigation of broadband (multispectral) excitation for EIT

- Application of planar electrode array to 3-d breast imaging for cancer detection

- Cardiac electric imaging using EIT to provide chest conductivity estimates
  - Joint effort with NU, Utah

- Extensions and application of EIT to Vadose Zone imaging
  - Design and construction of Geophysical Electrode Array
  - Extending prototype testbed concepts for underground
  - Collaboration with Lawrence Livermore
Object-based Inverse Scattering

Problem: Accurate reconstruction of subsurface imagery with limited, noisy data
  - Inverse problem ill-conditioned, but not ill-posed
  - Common approach: regularization by integration of prior information
  - Applications: DOT, GPR, EIT, CT, …

Previous work
  - Reconstructing images as a collection of pixels or voxels
    - e.g. Tikhonov regularization, ART, Filtered back-propagation, …
  - Use of simple shape parameterizations in inverse problems
  - Region boundary parameterizations in image segmentation

Object-based inverse scattering: Use different parameterizations of underlying fields
  - Focused on important features for applications (e.g. regions, boundaries)
  - Characterize in terms of boundaries, regions, textures
  - Osher-Sethian parameterization: level sets for boundaries
Problem: GPR subsurface imaging of loc-contrast buried object with short-pulse time-domain array of transmitter-receivers

- 1 GHz bandwidth
- Born scattering model
- Result: improved shape resolution, contrast estimation
Major Extensions by CenSSIS

- Use of level sets for linear and nonlinear inverse problems
- Nonlinear inversion using adjoint fields
- Textured intensity objects using basis functions
- Object based inversion with multiple objects with different textures
- Integration into contrast source inversion for nonlinear problems
- Integration into dynamic tomography
- Integration of fast forward models from R1 research into object-based inversion methods
  - Fast preconditioned solvers for Helmholtz equations
  - Gaussian beam expansions for transmitted/scattered fields
Sample results

- DOT reflection tomography of absorption region
- Electric Resistance Tomography of buried objects
- Hierarchical segmentation of Brain imagery

Blue = true

Truth

Estimate
Sample Results 2

- Cone-beam X-ray Computed Tomography

Cone-beam X-ray CT

One Object

Two Objects
Field TestBED Experiments

- Acoustic Diffraction Tomography
  - Joint INEEL, NU, Oklahoma
  - Sound velocity profile reconstruction for environmental remediation
Field TestBED Experiments

- **Acoustic Diffraction Tomography**
  - Joint INEEL, NU, Oklahoma
  - Sound velocity profile reconstruction for environmental remediation

- **GPR subsurface imaging**
  - Short pulse array excitation
  - Anomaly shape reconstruction

**Lp-based reconstructions**
- EM-6 @ depth 3.5 cm
- VAL 69 @ depth 8.5 cm

**Backprojection**
TestBED Experiments

- Electrical Resistance Tomography
  - NU, INEEL
  - Object-based reconstruction of anomalies

Test cell to be filled with water at known electrical conductivity for initial testing

Clear Lexan Test Cell
- 0.125 Stainless Steel Rod
- 15 electrodes @ 3” O.C.
- 1/2” PVC
- 32” between electrodes
- 45.25” inside dimension

True object
OB Reconstruction
Standard Reconstruction
Experiments in Progress

- **Diffuse Optical Tomography**
  - Collaboration with MGH
  - Diverse forward models, inversion techniques (e.g. admissible solution ellipsoid algorithm)

- **Acoustic Tomography in MedBED**
  - Forward models under development using calibration experiments
  - Initial inversion approaches formulated
Joint project with Thrust R3
- Developed by students in collaboration with Mathworks
- Object-oriented MATLAB and C++
- Integrates fast forward models, new developments in inverse methods, visualization tools
- Distributed across CenSSIS partners and broader community to use in multiple applications
- Used in DOT, ERT work this year

CenSSIS Applications
- ERT/EIT, Acoustic, DOT, DOT, GPR, Photo-Thermal imaging
 Plans for Next Year

- **Continued refinement of current projects**
  - Further evaluation of similar approaches across diverse TestBED applications
  - Integration of nonlinear models into MVT inversion algorithms
  - Transition of ideas into integrated systems projects
  - Integration of algorithms into MVT toolbox

- **Start new projects motivated by additional testbed applications and systems**
  - Ultrasound tomography for vulnerable plaque
  - Integrated cardiac and electrical impedance tomography imaging
  - Nondestructive evaluation using ERT, DOT excitation
  - Dynamic subsurface imaging for moving objects in radiation therapy
R2B: Summary of Progress in LPM

- Broadly Applicable Core Technology
  - Objects much larger than the field of sensor

- Core Algorithms
  - Generalized Registration
    - Feature Extraction
    - Initialization
    - Robust Hierarchical Estimation of High-Order Models
  - Large-scale Mosaicing by Joint Estimation
  - Signal Corrections
  - Multi-modality Fusion
  - Real-Time Spatial Referencing

- New Driving Applications
  - Two-view confocal microscopy
  - Tumor angiogenesis
  - Proton beam therapy (with MGH)

- Collaborators
  - Charles Stewart (RPI), Ali Can (RPI), Hanumant Singh (WHOI), Qiang Ji (RPI), James Turner (Wadsworth), Howard Tanenbaum, MD.
Progress on Feature Extraction

- Sub-pixel refinement & invariant descriptors
  - Zernike Moments for grayscale interest points (WHOI)
  - Similarity & Affine invariants (RPI)
- Explicit exploitation of feature scale / region in registration
- Maximum exploitation of minimal feature sets
Progress on Automatic Initialization

- Exploiting geometric invariants a broadly applicable approach
- Need to refine and extract maximum information from features
Towards Generalized Registration

- **Formulation rooted in Robust ICP algorithms:**

  \[ E(\theta, C) = \sum_{(p,q) \in C} \rho(d(M(\theta; p), q) / \sigma) \]

- **Main Points:**
  - Joint robust estimation of correspondences and transformations
  - Specializes to major geometry & intensity based methods
  - Accommodates a hierarchy of transformation models
    - Similarity → Affine → Quadratic
    - Can we make model selection automatic?
  - Needs good initialization
    - How far can we exploit invariance concepts?
    - Can we systematically identify and recover from prior steps?
    - Can we exploit uncertainty to drive the estimation?
New Development: Dual-Bootstrap ICP

Iterate until convergence:

- Robust ICP in each focus region

- Bootstrap the model:
  - Low-order for small focus regions;
  - High-order for large
  - Automatic selection

- Bootstrap the focus region:
  - Based on covariance propagation (uncertainty)
Mutual Information Based Change Detection

CT images of the male pelvis

Fundus images of the retina

Idea: Register the images, & extract changes from joint pixel distributions

Joint histograms of image intensities
Application to Confocal Microscopy (BioBED)

Rat Hippocampus

x-z view

Depth Attenuation
New BioBED LPM/MVT Development: Deep 2-view Confocal Imaging

Barriers:
- Cannot increase SNR from single view
- Impractical to rotate specimen (use an inexact flip)

Solution:
- Use MVT and LPM (registration overcomes inexact flip)
- Reconstruct from physics-based signal formation model
- Modify specimen prep protocol to make it practical
Physics-Based Model + MVT + LPM

Pyramidal Dye-Injected Neuron

2002 MSA Presidential Student Award
Parallel advances at WHOI (left) and RPI (right)

Common emerging approach:
- Hierarchical Pair-wise Registration → Joint Refinement → Multi-view illumination correction & signal reconstruction → Multi-scale blending → Map Synthesis
Mosaics: A Rich Basis for Mapping & Referencing

- 233 under-sea mosaic covering ~350 m²
- ~70° Mosaic of Retina

Mosaic-based maps enable spatial referencing (Visual Navigation), which improve upon tracking/dead-reckoning (current SOA)
Progress on Spatial Referencing

WHOI
Visual Navigation Example

RPI
Retinal Spatial Referencing Example
R2B: Looking Ahead

- **Continue to advance state-of-the-art**
  - Core registration & LPM algorithms
  - Novel applications
  - Physics-based imaging models & inversion algorithms
  - Multi-partner papers

- **Year 3 Goals**
  - Achieve a higher level of integration of toolkits
    - Robust & Multi-Modality Registration Toolkits at RPI & WHOI
  - Continue with new applications in radiation treatment planning, BioBED, & SeaBED
  - More emphasis on change understanding systems

- **IPLUS Objective:**
  - Validate & Integrate Emerging Toolkits as SolutionWare
  - Application Server & Message Board for Efficient, Supported Dissemination (an undergraduate-driven endeavor)
Miguel Velez (UPRM), Shawn Hunt (UPRM), Raul Torres (UPRM), Fernando Gilbes (UPRM), Luis Jimenez (UPRM), Charles DiMarzio (NU), Dana Brooks (NU), Knut Stamnes (Stevens Institute of Technology)
Societal Problem
Indoor SeaBED: Detection of Object Under Water with High Absorption and Scattering

\[
S_{US} \approx S_{US}^{wc} \left[ 1 - e^{-2KH} \right] + S_{US}^B e^{-2KH}
\]
State of the Art
Use of Lee’s Semi-analytic Model

\[ S_{\text{Col}}(\lambda_i) = S_{\text{US}}^{\text{wc}}(\lambda_i) \left\{ 1 - e^{-2[a(\lambda_i) + b_b(\lambda_i)]H} \right\} \]

\[ S_{\text{Bottom}}(\lambda_i) = S_{\text{US}}^{\text{B}}(\lambda_i) e^{-2[a(\lambda_i) + b_b(\lambda_i)]H} \]

\[ r_{rs}(\lambda_i) = S_{\text{Col}}(\lambda_i) + S_{\text{US}}^{\text{B}}(\lambda_i) e^{-2[a(\lambda_i) + b_b(\lambda_i)]} \]

\[
\begin{bmatrix}
  b(\lambda_1) \\
  b(\lambda_2) \\
  \vdots \\
  b(\lambda_d)
\end{bmatrix} = \begin{bmatrix}
  r_{rs}(\lambda_1) - S_{\text{Col}}(\lambda_1) \\
  r_{rs}(\lambda_2) - S_{\text{Col}}(\lambda_2) \\
  \vdots \\
  r_{rs}(\lambda_d) - S_{\text{Col}}(\lambda_d)
\end{bmatrix} = \begin{bmatrix}
  a_{11} & 0 & \cdots & 0 \\
  0 & a_{22} & \cdots & 0 \\
  \vdots & \vdots & \ddots & \vdots \\
  0 & 0 & \cdots & a_{dd}
\end{bmatrix} \begin{bmatrix}
  S_{\text{US}}^{\text{B}}(\lambda_1) \\
  S_{\text{US}}^{\text{B}}(\lambda_2) \\
  \vdots \\
  S_{\text{US}}^{\text{B}}(\lambda_d)
\end{bmatrix}
\]

\[ \mathbf{b} = \mathbf{A} \mathbf{S}^{\mathbf{B}} \]

Classification without inversion: Assume \( \mathbf{A} \approx \mathbf{I}, S_{\text{col}}(\lambda_i) = 0 \)

Classification with inversion: \( \mathbf{S}^{\mathbf{B}} = \mathbf{A}^{-1} \mathbf{b} \)

\[ \mathbf{S}^{\mathbf{B}} = \arg \min \left\{ \| \mathbf{A} \mathbf{S}^{\mathbf{B}} - \mathbf{b} \|_2^2 \right\} \]
What Is the State of the Art?

<table>
<thead>
<tr>
<th>Classification Accuracy for no inversion: $A \approx I$, $S_{col}(\lambda_i) = 0$</th>
<th>Classification Accuracy for inversion of Lee Model, $S^B = A^{-1}b$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Object</strong></td>
<td><strong>Object</strong></td>
</tr>
<tr>
<td>19.8818%</td>
<td>99.6246%</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td><strong>Background</strong></td>
</tr>
<tr>
<td>100%</td>
<td>89.7594%</td>
</tr>
</tbody>
</table>
Our Method: Use of Regularization and a-priori spectral measurements of the albedo ($P$)

$$S_{reg}^B = \text{arg min} \left\{ \| AS^B - b \|_2^2 + \lambda^2 \| L(S^B - S^{(0)}) \|_2^2 \right\}$$

$$S_{reg}^B = (A^T A + \lambda^2 I)^{-1} (A^T b + \lambda^2 S^{(0)})$$

What is $S^{<0>}$?

$S^{<0>}$ is a priori spectral measurement of a known object in our indoor SeaBED.
How $\lambda$ is chosen?

$\lambda^*$ that minimize

$\| S_{\text{Regularized Object}} - S_{\text{Object}}^{(0)} \|_2^2$

$\lambda^*$ that minimize

$\| S_{\text{Regularized Background}} - S_{\text{Background}}^{(0)} \|_2^2$
New Results

Classification Accuracy for inversion and regularization

\[
S_{\text{reg}}^B = \arg\min \left\{ \|A S^B - b\|_2^2 + \lambda^2 \left\| L \left( S^B - S^{(0)} \right) \right\|_2 \right\}
\]

<table>
<thead>
<tr>
<th>Classification</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object</td>
<td>97.9311%</td>
</tr>
<tr>
<td>Background</td>
<td>99.9846%</td>
</tr>
</tbody>
</table>
What is next?

A. Integration of Spatial Information in the Regularization Method: Luis Jimenez (UPRM), David Castañon (BU), Dana Brooks (NU):

\[
S_{reg}^B = \arg \min \left\{ \left\| AS^B - b \right\|_2^2 + \lambda^2 \Omega(S^B, S^W) \right\}_2
\]

\(\Omega(S^B, S^W)\) is a measure of the difference between the bottom spectral signature \(S^B\) and signature of its neighbors \((S^W)\).

B. Model \(S_{col}(\lambda_i)\) as clutter. Miguel Velez (UPRM), Shawn Hunt (UPRM), David Castañon (BU)

Incorporation of the 3D statistical model in an inversion scheme using the radiative transfer model.

C. Development of Toolbox for MSD: Charles DiMarzio (NU), David Kaeli (NU), Luis Jimenez (UPRM), Miguel Velez (UPRM), Shawn Hunt (UPRM),
Algorithm Validation and Sensor Fusion using of data gathered at Outdoor SeaBED (Fernando Gilbes (UPRM), Hanu Singh (WHOI), Luis Jimenez (UPRM), Charles DiMarzio (NU):

Sensor

Data

Sensor Fusion MSD+LPM

What is next?
Leverage on SeaBED Experience for BioBED.

SeaBED

BioBED

Luis Jimenez (UPRM), Charles DiMarzio (NU):
**R2D: Image Understanding/Sensor Fusion**

- **Image Understanding:** extracting underlying object structures and properties
  - Extraction of objects from backgrounds, characterization of object class
  - Overlaps object-based techniques

- **Sensor Fusion:** Combination of information from multiple sensors, different times, locations, wavelengths
  - Optical, Infrared, Acoustic
  - X-ray, ultrasound, ...
  - Overlaps LPM, MSD
Projects

- **Change Detection**
  - Use of Mutual Information for change detection in multiple temporal imagery
  - Integration of registration plus anomaly detection

- **X-ray and DOT fusion for breast imaging**
  - X-ray imaging to identify key landmarks such as boundaries

- **Fusion of LPM mosaics, hyperspectral imagery in coral reefs**
  - UPRM/WHOI SeaBED data collection

- **Joint segmentation, motion estimation and fusion in image-guided radiation treatment**

- **Multisensor fusion for plaque characterization**
Multisensor Fusion for Plaque Characterization

- **Idea**: improve tissue classification by using multiple subsurface modalities for common area
  - Simultaneous registration, image formation and classification
- **Approach**: Joint inversion
  - Exploit common object structure even though intensities are weakly correlated
  - Extensions using mutual information concepts

Magnetic Resonance (MR)  Computed Tomography (CT)  Intra-Vascular UltraSound (IVUS)
Initial Results: Fusion of MR and CT

CT Image

Proton density MR Image

Hand-Registered

Jointly-estimated CT

Jointly-estimated MR
**X-Ray Constrained DOT IMAGING**

- **Idea:** Use X-Ray information to assist DOT in object location
  - Adapt regularization to smooth reconstruction outside of area of interest
  - Focus detail of reconstruction

Problem of Interest: 16 sources and 16 detectors

5.5 cm thick phantom with a 2 cm diameter absorbing inclusion.

Born approximation with Tikhonov Regularization.
Optimal regularized reconstructed image without X-Ray information: low contrast

Electronic Noise = 5*1e-12
Shot Noise = 2000, alpha1 = 0.8
Electronic Noise = $5 \times 10^{-12}$ Shot Noise = 2000, alpha1 = 0.8, alpha2 = 0.04

Optimal regularized reconstructed image with X-Ray information: high contrast
C. Summary

- Current investigations focused on important barriers motivated by TestBED applications
  - Functional brain imaging, breast cancer detection, underground anomaly classification, laser retinal imaging, ocean floor mapping, coral reef monitoring
  - Key barriers: Inversion for inhomogeneous, cluttered environments and robust, physics-based processing

- Exploring common approaches across diverse problem to identify unifying principles
  - Regularization in DOT, hyperspectral, underground/underwater imaging
  - Robust nonlinear inversion for acoustic, GPR imaging
  - Mosaicing in ocean floor and laser retinal mapping
  - Object-based reconstructions in GPR imaging, EIT, DOT

- Transitioning ideas to systems with strategic and industrial partners