Gordon Center for Subsurface Sensing & Imaging Systems

Research Thrust R2

Physics-Based Signal Processing and Image Understanding

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R2’s Role in CenSSIS

- **Biological-Medical Applications**
- **Environmental-Civil Applications**

**Algorithm requirements**
- **Common mathematical structures**

**Application instantiations**
- **General information extraction approaches**
R2 Thrust Organization

- **R2A: Multiview Tomography**
  - David Castañón

- **R2B: Localized Probing and Mosaicing**
  - Badri Roysam

- **R2C: Multispectral Discrimination**
  - Miguel Vélez-Reyes

- **R2D: Image Understanding**
  - Richard Radke
Focus of research: Image formation from tomographic measurements
- Modalities of interest in CenSSIS:
  - EIT, ERT, DOT, GPR, diffraction tomography, CT, ultrasound, elastography

Diverse applications approached through a common view: statistical physics-based inverse scattering
- Inverse problem goals + physics model + solution representation + robust decision-directed algorithm

Objective: Improved resolution, signal-noise in subsurface imaging

\[
Y = \mathcal{T}(\alpha, S, \gamma) + w
\]
Major Results: High-Resolution Inversion

- **Example: Object-based inverse scattering**
  - Extension to MVT of computer vision concepts
  - Characterize objects in terms of boundaries, regions, textures
- **CenSSIS-developed theory, many applications**
  - DOT, GPR, PET, EIT, ultrasound, Hyperspectral, ...
**High Intensity Focused Ultrasound (HIFU)**
- Used to necrose cancerous tissue
- HIFU perturbs both sound speed and acoustic attenuation
- Usual beamforming methods insufficient

**HIFU Lesions**
- Shape: cigar (without cavitation) or tadpole (with cavitation)
Physics-Based Inversion Approach

- Multi-parameter acoustic inversion (contrast in sound-speed & attenuation)
  - Models from collaborations with R1 colleagues
  - Born approximation
- Low contrast object embedded in highly cluttered background
  - Limited angle so exploit regularization techniques (total variation)
  - Assume lesion profile is spatially constant
- Sound speed and attenuation are constant multiples of one another
Initial Results

- Formulated as convex optimization problem
  - Determine single contrast function and proportionality constant
  - Minimize total variation of contrast subject to data residual constraint

- Experiment Set-up:
  - 17 uniformly spaced frequencies [2,5] MHz
  - 11 curved rectangular elements (BK8665) focused 7 cm away from the center element

- Future work:
  - Use of advanced regularization (cartoon-texture decomposition)
  - Extensive testing with “exact” synthetic data, clutter

Example reconstruction (30 dB SNR), error in c~3%
High-Resolution Plaque Imaging

- Goal: diagnose atherosclerosis plaque buildup non-invasively using multiple modalities
  - Problem: calcium blooming distorts severity of stenosis
  - Collaboration with MGH
Ex Vivo Results

- Cadaveric heart in thorax phantom
- Siemens Sensation-64 MDCT
  - 120-kVp, pitch=0.2, 330-ms rotation, 12-cm FOV
- Algorithm: MBAI (model-based algebraic iteration) from 2007-8
Region of Interest Tomography

- Calcium artifact is small in size
  - May be acceptable to process sub-volume of data
  - Use filtered backprojection volume \( f \) to initialize process

- Want to work with \( f_{ROI} \) and projection \( g_{ROI} \)
- But \( g_{ROI} \) is corrupted by data from \( f_{ROI}^+ \)

Solution
- Delineate \( f_{ROI} \) from FBP image
- Estimate \( f_{ROI}^+ \)
- Compute \( g_{ROI}^+ \) from \( H \cdot f_{ROI}^+ \)
- Remove projections from areas outside of \( f_{ROI} \) to work only with \( g_{ROI} \)

Result: ability to work with smaller volume, performing fewer projections

From S. Do, Z. Liang, W. C. Karl, T. Brady, H. Pien, “A projection-driven pre-correction technique for reconstruction of helical cone-beam cardiac CT,” SPIE Med Imaging 2008
In Vivo MBAI Processing – Stent 1

B35f  MBAI  B46f
In Vivo MBAI Processing – Stent 2

B35f  MBAI  B46f
GP-GPU – nVidia

- Working with R3 researchers to develop nVidia solution
- Approx 15x speedup on single GeForce 8800
  - 128 processors
- Implementing code on Tesla S870 1-U compute server
  - 512 processors
  - 6GB dedicated RAM
New Focus: Multi-modal Plaque Imaging

- **Multimodal integration of PET and rapid CT**
  - PET/FDG imaging of plaque inflammation
  - Non-invasive, early detection of vascular disease would be a game changer

- **Challenges:**
  - Low resolution of PET
  - Long integration times
  - Motion: breathing, cardiac motion

- **Approach:**
  - New superresolution methods for joint PET/CT
  - Integrate cardiac and respiratory motion
  - Incorporate instrument response model

PET overlay (colored) on CT (gray) showing blurring of stented vessel in PET.
Outline of Approach

- **Video CT delineates major motion of heart and vessels**
  - Can integrate video techniques (e.g. optical flow) to estimate motion

- **Temporal inversion of PET data using motion compensation and boundary data from CT**
  - Compensate both for cardiac and respiratory motions
  - Motion: breathing, cardiac motion

- **Incorporate limitations of instrument model for robust inversion**
  - Errors in temporal segmentation, instrument resolution
  - Frame alignment, motion estimation errors
Preliminary results

Reference Activity Image
Conventional PET Image
New Superresolution Approach
Goal: Dose Reduction while Retaining Diagnostic Quality

Approach:
- Develop and apply new iterative methods for CT reconstruction
- Inclusion of source and detector response function

Conventional Full Dose  
Conventional 25% Dose  
New IRT 25% Dose  
Note preservation of detail
**Impedance Tomography**

- **Principle:** Apply electrical currents on electrodes, record resulting voltages
  - Estimate conductivity and permittivity
  - Multiple frequencies: spectral content

- **Applications**
  - Breast imaging, chest imaging

- **R2 Requirements:**
  - High sensitivity and specificity
  - Mammography and Ultrasound Geometry

**Relevant physics:**
- Electromagnetic Theory

ACT 4 instrument & processing for MGH breast imaging experiments
Multimodality Breast Imaging: X-Ray and EIT

Admittivity loci for 6 frequencies (5 Khz – 1 MHz)

ROI 1

ROI 2

Linearity is strong
Indicator of carcinoma: LCM Statistic
Very Preliminary results from Patient study at Mass. General.

<table>
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<th>Breasts containing malignancies</th>
<th>Breasts not containing malignancies</th>
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<td>40</td>
<td>49</td>
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</tbody>
</table>

Linear Correlation Measure (LCM) for 49 breasts studied.
Sensitivity = 100%, Specificity = 89%.
New Instrument: Handheld Ultrasound and EIT

Handheld probe to combine EIS with US in one exam.
Collaboration with R1, R2

New Challenge: Ultrasound-augmented inversion of EIT in open domains
Enhanced Approach: Direct Nonlinear Inversion Methods

- **Nonlinear direct inversion algorithm (d-bar)**
  - Noniterative, suitable for real-time implementation
  - Complex geometric optics

- **Tested in L2 testbed for dynamic breast imaging with 2-D circular geometry**
  - Extension of direct approach for other geometries, inverse problems under development

- **New ideas for extension to 3D geometries**

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Given $\Lambda_\sigma$ find $\mu$?

1. Find $\Psi$ on $\partial B$:

   $[I + S(\Lambda_\sigma - \Lambda_1)] \Psi = \exp(i\zeta \cdot p)$ on $\partial B$

   $(Sw)(p) = \int_{\partial B} G(p - t)w(t)ds(t)$

   $-\Delta G = \delta$, $G \approx \exp(i\zeta \cdot p)$ as $|p| \to \infty$

2. Compute scattering transform

   $t(k) = \int_{\partial B} \exp(i\zeta \cdot p) (\Lambda_\sigma - \Lambda_1) \Psi(p)ds(p)$

3. Solve $\bar{\partial}$ equation for $\mu(p, \zeta)$;

   $\frac{\partial \mu}{\partial \bar{k}} = \frac{1}{4\pi k} t(k) \exp(i(\zeta + \bar{\zeta}) \cdot p) \bar{\mu}(p, k)$

4. Take $\lim_{k \to 0} \mu(p, \zeta) = \sigma^{1/2}(p)$
Future Directions

- Additional adaptation of algorithms to applications
  - HIFU, multi-modal breast imaging, luggage and body scans, ...

- Exploration of new directions
  - Compressive sensing
  - Sparse aperture reconstruction
  - Controlled active sensing
  - Reconstruction under significant motion

- New applications
  - Security, energy, health care, ...
R2-Related Posters

- **R1A p1** “Advanced Image Processing in Cardiac PET/CT to Enhance Early Detection of Coronary Artery Diseases,” S Ambwani, WC Karl, H. Pien
- **R2A p2** "Advanced Tomosynthesis Workstation" HE Guven, EL Miller, RO Cleveland
- **MedP1** “Combined EIT Regional Admittivity Spectra and X-Ray Tomosynthesis for Breast Cancer Detection,” D. Ardrey, G. Saulnier, D. Isaacson
- **R2B p1** "Quantifying Biomarkers in Histopathology Samples with Cellular Scale and Specificity using Multiplex Immunostaining and Quantitative Image Analysis" K Grama, B Roysam
- **R2B p2** "A Functional Model for Automated Segmentation and Tracking of C. Elegans Locomotive Behavior During Chemotaxis“ TT Turnquest, K Kutten, B. Roysam
- **R2B p4** "Segmentation and Tracking Algorithms on Parallel Hardware,“ A Narayanaswamy, B Roysam
- **R2B p5** "New Method for Segmenting Dendritic Spines from 3D Confocal Microscopy Images,“ H Sharafeddin, B. Roysam
- **R2B p6** "Automated Methods for Profiling the Axonal Transport of Secretory BDNF Granules in Live Cultured Neurons from Time-lapse Microscopy Data,“A Mukherjee , B Roysam , S Kaech Petrie,G Banker
**R2-Related Posters**


- **R2C p3** "Detection of Interest Point for Multispectral and Hyperspectral Images Using Lowe’s Approach and Anisotropic Diffusion," L Paola Dorado-Munoz, A Mukherjee, M Velez-Reyes, B Roysam

- **R2C p4** "A Comparison of Unmixing Algorithms for Hyperspectral Imagery,“ A Santos-Garcia, M Velez-Reyes, S Rosario, JD Chinea

- **R2C p5** "Comparison of Basis-Vector Selection Methods for Target Detection,“ C Pena Ortega, M Velez Reyes

- **R2C p6** “Hyperspectral Texture Synthesis by Multiresolution Pyramid Decomposition,

- **R2C/Dp7** "A Tunable, Multi-scale, Multi-band Segmentation Procedure for Remotely-Sensed Imagery,“ K Griffis, M Bystrom

- **R2C/D p8** “Pattern Recognition Methods for Spectral Classification in ESS Diagnosis of Cancer,“ E Rodriguez-Diaz, DA Castanon, IJ. Bigio

- **R2D p1** "Shape Simulations and Image Segmentation for Image-guided Radiotherapy,“ S Chen, R Radke"
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- **R2C p3** "Detection of Interest Point for Multispectral and Hyperspectral Images Using Lowe’s Approach and Anisotropic Diffusion," L Paola Dorado-Munoz, A Mukherjee, M Velez-Reyes, B Roysam
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R2-Related Posters

- **R2D p2** "Robust Estimation of a Random Parameter in a Gaussian Linear Model with Joint Eigenvalue and Elementwise Covariance Uncertainties,“ R Mittelman, EL Miller
- **R2D p3** "Enhancing Embryo Viability Identification Using 3d Dic Microscopy Images,“ H Sierra, C DiMarzio, D Brooks
- **R2D p4** "Modeling Habituation in Evoked Response in Rat EEG Via a Dynamical Modeling Habituation in Evoked Response in Rat EEG Systems Based Neural Mass Model." S Laxminarayan, D Brooks, G Tadmor, MA Franceschini, E Miller
- **R2D p5** "Theoretical Models for Imaging Distributed Fish Groups in an Ocean Eaveguide Eith Eide-area Sonar Including Multiple Scattering,” M Andrews, P Ratilal
- **R2D p6** "Temporal and Spatial Coherence of Fish Scattered Returns,“ Z Gong, P Ratilal
- **Sea p1** "Benthic Habitats Mosaics from the PR Hyperspectral Survey," L Alvarado Ortiz, M Velez Reyes, S Rosario Torres, J Goodman
- **Sea p2** "Hyperspectral Image Registration and Fusion for Underwater Applications,“ CJ Solis Ramirez, RE Torres
- **Sea p3** "Modification of the SeaBed Autonomous Underwater Vehicle for Hyperspectral Image Acquisition,“ CJ Solis Ramirez, RE Torres
- **Sea p4** "Analysis of Fish Low Frequency Target Strength,“ D. Tran, Z Gong, M Andrews, P Ratilal
- **Soil p1** "Detection of DNAPLs in Underground Systems using Cross Well Radar Technology,“ J Toro Vázquez, R Rodríguez Solis, I Padilla