Center for Subsurface Sensing & Imaging Systems

Research Overview

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Center for Subsurface Sensing & Imaging Systems

Research Overview

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R1-A  Nonlinear and Dual Wave Sensors

Bahaa Saleh, Deputy Director

Advanced Imaging Modalities

- Nonlinear & Quantum Optical Imaging
- Acousto-optic imaging (AOI)
- Interferometric Fluorescence Microscopy
- Elasticity Imaging
- THz Imaging
Theme of R1A Research

Multimodal & Multispectral Subsurface Imaging

Multimodal Imaging

- **R1A p2** “Pulsed Acousto-Optic Imaging (AOI) and its Fusion with Commercial B-mode Ultrasound Imaging,” P. Lai

- **R1A p3** “Double Holographic Interferometry Using Optical and Electrical Techniques,” P. Land
Quantum-OCT

= imaging using two broadband beams, spectrally correlated at the photon level

- **R1A p1** “Quantum Optical Coherence Tomography,”
  D. Goode
**R1-A Research Projects**

- **R1A p5** “Spectral Self-interference Fluorescence Microscopy in 4Pi Mode,” M. Dogan


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**Multispectral Imaging**

SSIF

- **Excitation**
  - Broadband Fluorescence

- **Fluorophore**

- **Mirror**
R1-A Research Projects

- **R1A p4** “Quantitative Three Dimensional Elasticity Imaging,” M. Richards
- **R1A p7** “TeraHertz Wave Emitters and Detectors,” J. Liu
<table>
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R1-B Effective Forward Models

Carey Rappaport, Associate Director

Summary

• Models to capture realistic geometry
• Models that consider complex media properties
• Forward-Inverse models
R1-B Research Topic 1: Models to Capture Realistic Geometry

- **R1B p3** “A Fast Matlab-based 3D Finite Difference Frequency Domain (FDFD) Method and Its Application to Subsurface Scatterers,” Q. Dong
- **R1B p7** “2D FDTD Simulation of a Confocal Microscope Configured for Theta Line Scanning,” B. Simon
- **R1B p8** “Photo-Thermal Coherent Confocal Microscope,” S. Sullivan, M. Andrews, M. Bouchard
- **Soil p2** “Analysis of Simulated Variation in Dielectric Properties of Reinforced Concrete Systems,” K. Belli
- **Soil p3** “Use of Cross Well Radar for Tunnel Detection,” C. Kurison
- **Soil p5** “Minimally Invasive Microwave Measurement and Modeling of Dielectric and Physical Properties of Sandy Soil,” C. Kurison
- **Soil p7** “Cross-well Radar as a Non-Invasive Technique for Detection of Compounds,” M. Serrano
R1-B Research Topic: 2 Models that consider complex media properties

- **R1B p2** “Modeling FDTD Wave Propagation in Dispersive Media Using Four-Zero Conductivity Function,” M. Jalalinia

- **R3A p1** “Acceleration of the 3D FDTD Algorithm in Fixed-Point Arithmetic Using Reconfigurable Hardware,” W. Chen

- **Soil p4** “Detecting Soil Disturbance Using Cross Well Radar,” C. Kurison

- **Educ p5** ”User and Developer Interface Improvements to an FDTD Simulation,” S. Baum
R1-B Research Topic 3: Forward-Inverse Models

- **R1B p1** “The Semi-Analytic Mode Matching (SAMM) Algorithm for Efficient Computation of Near Field Scattering from Borehole Antennas in Lossy Ground,” A. Morgenthaler


- **R1B p5** “A Product-of-Convolutions Model for Three-Dimensional Microscopy; Comparison to Born and Rytov Models,” H. Sierra-Gil

- **R1B p6** “A Novel Modeling and Inversion Method to Image Weakly Scattering Sub-Cellular Structure,” E. Karbeyez

- **R2A p2** “Characterization of Anomaly in Dispersive Background with Random Rough Surface,” R. Firoozabadi

- **Soil p6** “Sensor Fusion to Enable Rapid Field Characterization of Subsurface Soil to Assess Trafficability,” R. Gamache
### Association with Systems Areas

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<td>• Accurate laser/skin model</td>
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<td>• Crosswell radar for DNAPL and borehole detection</td>
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<td>Models that consider media dependence</td>
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<td>• Automatic dispersion model generation</td>
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<td>• Acceleration of code by more than 30X</td>
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<td>• Implementation as part of secondary school ed. Initiative</td>
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<td>Forward-Inverse models</td>
<td>S1, S3, S5</td>
<td>• Mitochondrial distribution imaging</td>
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<td>• Rough soil surface/anomaly reconstruction</td>
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</tbody>
</table>

*Impact*:
- **R1B Project**
  - Models to capture realistic geometry
  - Models that consider media dependence
  - Forward-Inverse models
- **S Project**
  - S1, S3, S5
Center for Subsurface Sensing & Imaging Systems

Physics-Based Signal Processing and Image Understanding

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David Kaeli
**R2 in CenSSIS**

**Fundamental Science**

**L1**
- General information extraction approaches
- Application instantiations

**L2**
- Algorithm requirements
- Common mathematical structures

**L3**
- Biological-Medical Applications
  - Breast Imaging
  - Radiation therapy
  - Retinal surgery

- Environmental-Civil Applications
  - Vulnerable plaque
  - Cellular Imaging
  - Coral Reef Monitoring
  - Pollution monitoring
  - Mine Detection

**Validating TestBEDs**
R2A. Multiview Tomography

- **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**

\[ Y = T(\alpha, S, \gamma) + w \]
R2A Highlights This Past Year

- Continued refinement of techniques for transition to System Applications
  - EIT, DOT for breast imaging instruments in S3
  - Elastography based on 3D CT from tomosynthesis

- Expansion of algorithm approaches
  - Nonlinear inversion approaches
  - Boundary element techniques for EIT
  - 4-D inverse problems (DOT, PET, others)
  - Multispectral DOT with spectral priors
  - Multisensor, multi-modal inversion
  - Time reversal imaging

- Inversion techniques for new modalities
  - Quantum OCT, Nano-imaging
Motivating Application: Breast Cancer

- Special Session this AM
  - Talks on Tomosynthesis, EIT, DOT, Elastography in context

Student Posters

- R1A p4  M. Richards et al, “Quantitative Three Dimensional Elasticity Imaging”
- R2A p3  Boverman et al, “Model-Based Methods for Image Reconstruction in Optical Tomography”
- R2A p4  Nuba et al, “Reconstructing Hemodynamic Parameters in Diffuse Optical Tomographic Breast Imaging”
R2A Overview - 2

- **R2A Focus Session Wednesday**
  - 3 talks on MVT methods: Miller, Karl, Isaacson

- **Other Multi-View Tomography Posters 1**
  - **R2A p1** Gruber et al, “Non-Iterative Inverse Scattering of Multiple Scattering Inhomogeneities”
  - **R2A p2** Firoozabadi et al, “Characterization of Anomaly in Dispersive Background with Random Rough Surface”
  - **R2A p5** Laxminarayan et al, “Reduced Dimensional Kalman Filtering for Diffuse Optical Tomography in Functional Brain Imaging”
R2A Overview - 3

- **R2A p12** Yarman et al, “Exponential Radon Transform Inversion Based on the Harmonic Analysis of the Euclidean Motion Group”
- **R1A p6** Davis et al, “Multi-Element Detectors to Utilize Out-of-Focus Light and Synthesize Optimal Apertures in Confocal Microscopy”
- **R2D p5** Pavlovich et al, “Parameters Estimation in QOCT”
- **R2D p7** Liang et al, "Image Enhancement in Detection of Coronary Stenosis by MDCT"
R2D Highlights This Past Year

- **Low Contrast Segmentation**
  - Statistical characterization of prior shapes using feature distributions
  - Low order parametric models for prostate segmentation

- **Hyperspectral Cancer classification**
  - Optical biopsy techniques using novel fiber instruments
  - Similar techniques as in R2C

- **Intensity-modulated radiation therapy**
  - Collaboration with MGH, MSKCC
  - Machine learning + optimization techniques

- **Change Detection and Registration**
  - Remote sensing applications
  - Data fusion
Brief Overview of R2D

- **R2B-D Focus session**
  - Talk on Intensity-Modulated Radiation Therapy - Radke

- **Student Posters**
  - **R2D p1** Yang et al, “The GDB - ICP: From Initialization, Estimation, to Decision”
  - **R2D p3** Vidolova et al, “Change Detection and Visualization”
  - **R2D p5** Pavlovich et al, “Parameters Estimation in QOCT”
  - **R2D p6** Litvin et al, “Image Segmentation Using Feature Distribution Based Shape Priors”
R2D Overview - 2

- **R2D p7** Liang et al, “Image Enhancement in Detection of Coronary Stenosis by MDCT”
- **R2D p8** Lu et al, “Reduced-Order Parameter Optimization for Prostate Intensity-Modulated Radiotherapy”
- **R2D p9** Jeong et al, “Modeling Inter- and Intra-Patient Anatomical Variation Using a Bilinear Model”
- **R2D p10** Martin et al, “Optimizing Intensity Modulated Radiation Therapy with Motion Uncertainty”
- **R2C p2** Duarte-Carvajalino et al, “Segmentation of Hyperspectral Imagery Using the Stabilized Inverse Diffusion Equation”
Association with Systems Areas

S1  Cell Counting, Quadrature Tomography

S2  IMRT, Optical Biopsy, 4-D Inverse Problems

S3  Multi-view Tomography for EIT, DOT, Elastography

S4  Change Detection, Multispectral Classification

S5  Crosswell tomography, Rough Surface Imaging, Time Reversal Imaging
General Trends:

1. Maturing of core registration & mosaicing tools
2. Shift towards toolkits & applications
3. Much interaction with other thrusts
Generalized Registration

- R2D p1 “The GDB – ICP: From Initialization, Estimation, to Decision,” G. Yang
Large-Scale Mosaicing

Mosaic created by Hanumant Singh, Woods Hole Oceanographic Institution/Copyright 2004
Institute for Exploration. The images for this mosaic were taken by the
Hercules ROV during an expedition led by Dr. Robert Ballard from the University of
Rhode Island's Institute for Archaeological Oceanography.

- R2B p8 “Visually Augmented Navigation on the RMS Titanic,” R. Eustice
- **R2B p2** "MDL-based Dendrite and Spines Extraction in 3D Fluorescence Images“ X. Yuan
- **R2B p5** "Interest Operator for Hyperspectral Images“ A. Mukherjee
- **R2B p7** "Robust 3-D Modeling of Tumor Microvasculature Using Superellipsoids“ A. Tyrrell
Change Analysis

- R2B p1 "Automated Extraction of Cell Lineages and Spatial Migration Paths in Live C. elegans Embryos from 4D Fluorescence Microscopy Image Sequences" G. Lin & Y. Chen
- R2B p4 "A Functional Model for C. Elegans Locomotory Behavior Analysis and Its Application to Tracking" N. Roussell
- R2B p6 "Summarizing Change Using Normalized Compression Distance and Gap Statistic Clustering" A. Cohen
- R2D p3 “Change Detection and Visualization,” E. Vidolova
Main Driving Applications

1. Biological Microscopy
2. Diagnostic Change Detection
3. Image-Guided Therapy
4. Coral Reef Monitoring
   Deep-water archaeology
Center for Subsurface Sensing & Imaging Systems

Multispectral Discrimination

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David Castañón
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David Kaeli
Spectral Sensing and Imaging @ CenSSIS

Remote Sensing

Broadband Probe, \( P \)

Detectors at different wavelengths, \( Y_i \)

Clutter

Medium

object

Elastic-Scattering Spectroscopy

Probes at different wavelengths, \( P_i \)  

1 2 .. \( J \)

Multispectral DOT

Detectors at different wavelengths, \( Y_i \)

\( Y(\mathbf{r}, \lambda_i) = T(\mathbf{r}, \alpha(\beta(\lambda_i)), S_i, \gamma_i) + w(\mathbf{r}, \lambda_i) \)
Types of Spectral Sensing

Irregular sampling
Low to high spectral resolution

Continuous sampling
High spectral resolution

\[ Y(r, \lambda_i) = T(r, \alpha(\beta(\lambda_i)), S_i, \gamma_i) + w(r, \lambda_i) \]
Goals of Spectral Sensing & Imaging (R2C)
Estimation, Detection, Classification, or Understanding

**Estimate:** probed spectral signature \( \{\alpha(x,y,\lambda)\} \)
physical parameter to be estimated \( \{\beta(x,y,\lambda)\} \)

**Detect:** presence of a target characterized by its spectral features \( \alpha \) or \( \beta \)

**Classify:** objects based on features exhibited in \( \alpha \) or \( \beta \)

**Or Understand:** object information, e.g., shape or other features based on \( \alpha \) or \( \beta \). Integrating spatial and spectral domains.

Examples of \( \beta \)
- Crop health
- Chemical composition, pH, CO₂
- Metabolic information
- Ion concentration
- Physiological changes (e.g., oxygenation)
- Extrinsic markers (dyes, chemical tags)
MSD Research Across Thrusts

L3
Bio-Med
S1
Enviro -Civil
S4
Benthic Habitat Mapping

L2
Validating TestBEDs
SeaBED

L1
Fundamental Science
R1: Radiative Transfer Modeling
R2: Multispectral Discrimination
R3: Algorithm Implementation
R2C Research Work

- **Image Representation**
  - Scale space representation of hyperspectral imagery, R2C p2

- **Image enhancement**
  - SNR improvement talking advantage of spectral oversampling
  - Hyperspectral image reconstruction, R2C p2

- **Unmixing of Hyperspectral**
  - Fully constrained abundance estimation
  - Unsupervised unmixing, R2C p4
  - Combined unmixing and parameter estimation, Sea p2

- **Pattern Recognition**
  - Dimensionality reduction
  - Regularized parameter estimation for distributions
  - Subsurface detection and classification algorithms
  - Integration of spectral and spatial domains

- **Change detection**
  - Temporal PCA
  - Interest Operators R2B p5
  - Multiband Adaptive Semiparametric Change Detection, R2D p2
Algorithm Implementation (R3)

MATLAB Toolbox, R3B p1

Supervised Classification Module

Unsupervised Classification Module

Parallel and Distributed Computing, R3A p6

Hardware Implementation in FPGA/DSP, R3A p4
Related Posters

- **R2C**
  - **R2C p1**: Tianchen Shi / NU, MultiSpectral Imaging for Skin Chromophores and Blood Vessels
  - **R2C p2**: Julio Martin Duarte-Carvajalino, Segmentation of Hyperspectral Imagery Using the Stabilized Inverse Diffusion Equation
  - **R2C p3**: Alejandra Umana-Diaz, Restoration of Hyperspectral Imagery
  - **R2C p4**: Yahya Masalmah, Unsupervised Spectral Unmixing of Hyperspectral Imagery

- **R2B**
  - **R2B p5**: Amit Mukherjee, Abhishek Gattani, Andrew Bagdanov, Summarizing Change Using Normalized Compression Distance and Gap Statistic Clustering

- **R2D**
  - **R2D p2**: Karin Griffis, Joint Multiband Adaptive Semiparametric Change Detection in Remote-Sensing Imagery
  - **R2D p4**: Eladio Rodriguez-Diaz, Optical Diagnosis of Cancer Using Elastic-Scattering Spectroscopy
Related Posters

**R3A**
- **R3A p4:** Javier Morales, FPGA Implementation of the ISRA Algorithm
- **R3A p6:** Carolina Gerardino, Yamil Rivera Rivera, Utilizing High-Performance Computing to Investigate Performance and Sensitivity of an Inversion Model for Hyperspectral Remote Sensing of Shallow Coras

**R3B**
- **R3B p1:** Samuel Rosario-Torres, An Update on Hyperspectral Image Analysis Toolbox

**SeaBED**
- **Sea p1:** James Goodman, SeaBED: A Controlled Laboratory and Field Test Environment for the Validation of Coastal Hyperspectral Image Analysis Algorithms
- **Sea p2:** James Goodman, Hyperspectral Remote Sensing: Preliminary Results From the 2004 AVIRIS Mission to Puerto Rico
Provide researchers with a set of testing facilities and data for assessing the analysis capabilities of spectral subsurface aquatic remote sensing.

1) Indoor tank
2) Outdoor tank
3) Field site
Benthic Habitat Monitoring and Mapping
Driving Application in Spectral Sensing (Wed)

**Estimate:**
\[ \{ \alpha, \beta \} \]
- Atmospheric constituents
- Aquatic optical properties
- Aquatic constituents
- Benthic composition
- Bathymetry (water depth)

**Detect:**
- Healthy/unhealthy coral
- Unexploded ordinance
- Human induced changes

**Classify:**
- Coral distribution
- Seagrass density
- Benthic habitat maps

**Understand:**
- Environmental stressors
- Seasonal/annual changes
- System productivity

**Detectors at different wavelengths, \( Y_i \)**
Airborne or Satellite Multi/Hyperspectral

Upwelling Photons measured as At-Sensor Radiance
R3 Research Thrust Overview

- Utilize latest developments in hardware and software enabling technologies to address CenSSIS barriers
- Make direct impact on a number of S-level projects
- Develop a common set of tools and techniques to address SSI problems:
  - Hardware parallelization and acceleration
  - Software toolboxes
  - Image database management and tools
- Support CenSSIS computing needs
R3A Research Projects


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**Multispectral/Hyperspectral Data**

**Image Space Reconstruction**

**3D FDTD**

**Classification Map**

**HIAT Processing Methods**

- Image Enhancement
- Feature Selection/Extraction
- Post Processing
- Classification

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**INVASIVE CARCINOMA #1**

**INVASIVE CARCINOMA #2**
R3B Research Projects

3 R3B Software demonstrations:

- “Hyperspectral Image Analysis Toolbox,” S. Rosario
- “4-D Visualization,” N. Dedual
- “The CenSSIS Citation Indexing System,” E. Arzuaga, et. al.
- **R3B p2** “Online Image Tagging,” M. Alshawabkeh


- **R3B p6** “The CenSSIS Image Database ,” F. Yang
R3B Research Projects

R3B p2 - NSF REU projects

- **R3B p7** “A Byte of Python,” S. Hunter - impacting the S1 project

- **R3B p8** “Developing a 4D Slicer Camera System Tool,” B. Johnson - impacting the S2 project
### Impact on System Level Projects

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<td>S3</td>
<td>Acceleration of tomosynthesis &lt; 5 minutes</td>
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<td>S4</td>
<td>Acceleration of code by more than 25X</td>
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<td>Image database</td>
<td>S1, S4</td>
<td>Developing customized database interfaces to facilitate rapid data entry</td>
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<tr>
<td>Image database</td>
<td>S2</td>
<td>Developing more accurate tumor tracking algorithms</td>
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<tr>
<td>Solutionware toolboxes</td>
<td>S2, S3</td>
<td>Providing 4-D visualization</td>
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| Educ p1 | B. Roysam (RPI)  
B. Yazici (RPI) | CenSSIS Educational Component at RPI |
|---------|------------------|-------------------------------------|
| Educ p2 | B. Campbell (BU) | Summer 2005, Boston University; CenSSIS  
Education and Educational Outreach  
Summary |
| Educ p3 | K. Matarese (BU) | Ultrasonic Phased Array Imaging System |
| Educ p4 | J. Matloff (BU)  | Image Guided Navigation System |
| Educ p5 | S. Baum (NU)     | Developing FDTD Code While Teaching High  
School Science |
| Educ p6 | S. Baum (NU)     | Subsurface Imaging-Themed Computer  
Games and Machine Activities |
| Educ p7 | C. Duggan (NU)   
J. Noss  
P. Damiani  
S. Melachrinoudis  
E. Jerison | CenSSIS - K-12 Outreach Programs - RET and  
Young Scholars |
| Educ p8 | H. Esiely Barrera  
(UPRM) | CenSSIS Educational Component at UPRM |
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<td>Soil p9</td>
<td>M. Urie (NU)</td>
<td>Image Acquisition of Underground Contaminant Transport</td>
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