An Overview of the Center for Subsurface Sensing and Imaging Systems (CenSSIS)

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This paper will present an overview of the research program of the Center for Subsurface Sensing and Imaging Systems (CenSSIS). The CenSSIS mission is to revolutionize the existing technology for detecting and imaging biomedical and environmental-civil objects or conditions that are underground, underwater, or embedded in the human body. Multi-disciplinary resources to accomplish this mission are drawn from a team of four core academic partners (Northeastern University - lead, Boston University, University of Puerto Rico at Mayagüez and Rensselaer Polytechnic Institute) and five strategic affiliates (Massachusetts General Hospital, Memorial Sloan-Kettering Cancer Center, Idaho National Engineering and Environmental Laboratory, Lawrence Livermore National Laboratory and Woods Hole Oceanographic Institution). A key element of the CenSSIS mission is to immerse students in efforts to solve important real-world problems such as noninvasive breast cancer detection or underground pollution assessment.

Four CenSSIS testbeds are used to validate research results by generating data on well-characterized “ground-truth” targets and backgrounds. Testbeds have been established for medical ultrasonic imaging (MedBED), underground cross-well radar imaging (SoilBED), and an autonomous underwater vehicle to image coral reefs (SeaBED).

Our Center has focused upon articulating and attacking the barriers to developing effective and quantitative subsurface target detection and inversion methods. Subsurface sensing problems exist in many domains, including underground, underwater, biological, and medical imaging. The intent is that progress in one domain will further progress in other domains. Some of the barriers that we identified are:

1) Lack of fundamental knowledge about forward scattering in complex media. Non-linear interactions, dual-wave scattering mechanisms, and coherent imaging in highly scattering media are examples of fundamental limitations to electromagnetic, optical, or acoustic sensing.
2) Inadequate techniques for inversion. Current inverse-scattering techniques to quantitatively image objects in random inhomogeneous and highly cluttered environments are limited.
3) Subsurface recognition strategies are not well developed. The problem of recognition and identification of subsurface conditions with limited views under highly obscuring media is unsolved. Of particular concern is the lack of a theoretical basis for combining different sensor inputs to optimize the information obtained. Sensor or information fusion is often applied on an ad hoc basis so that success in one problem is not easily applied to other domains.
iv) **Forward modeling of large complex scattering geometries is too slow for real-time applications.** Progress is required in both efficient approximate forward solvers and in hardware/software implementation of processing.

v) **Test facilities are needed with sufficient flexibility and sensor reconfigurability to permit the optimization of sensor modality/configuration for processing strategies based on recognition and decision objectives.**

vi) **Techniques for rapid processing, cataloging, storage, and retrieval of large image databases are not sufficiently developed.**

This list is not exhaustive, but it suggests that subsurface sensing is impeded by barriers in a) the development and accurate modeling of novel physical sensing mechanisms, b) the design of efficient inverse algorithms to extract appropriate and definitive information about subsurface objects and conditions from the physical probes, and c) subsurface data and information management. The fusion of more than one physical probe and the analysis of complementary information from multiple probes is an important avenue to progress in difficult subsurface sensing problems. The URSI talk will address research efforts within the first two of these three broad categories.

In the first three years of CenSSIS, its computational modeling effort has evolved into a focus on Effective Forward Models. This has two parts: (1) efficient modeling to test the feasibility of a particular sensing concept and to determine sensor configuration design; and (2) forward modeling to provide a mathematical description of the sensing problem for inverse scattering computation. The former is a computational tool used to characterize and optimize a physical sensor, such as ground penetrating radar. The latter, "inverse-forward models" serve as the bridge between the sensor design and reconstruction algorithms to generate simulated data for a fixed sensor configuration and serve as an integral part of the inversion technique.

Not all codes serve both purposes. For example, there are very accurate modeling codes which, due to their computational complexity are unlikely be used in inverse scattering (3D Finite Difference Frequency Domain, FDFD, for wave problems). Then, there are the modeling codes which are relatively slow today, but which are being accelerated for eventual use as inverse-forward models: the FDTD on a chip. We employ many fast codes that approximate the true physics (hence the speed) but whose accuracy is insufficient to usefully capture all the clutter and multiple scattering effects (Born approximation methods, as used in underground halfspace scattering). Finally, there are codes which do both: 2D FDFD, developed for humanitarian mine detection applications, Semi-Analytic Mode Matching SAMM, developed for an efficient calculation of rough surface scattering.

The Center’s research on information extraction focuses on the development of mathematical techniques for obtaining relevant information from the signals collected by subsurface sensing mechanisms. The goal is to identify common mathematical structures and develop general approaches that are applicable across diverse application domains. The reconstruction research is divided into four areas, representing distinct problem
classes and information extraction strategies. Each of the areas is developing algorithms that are broadly applicable across different applications in these problem classes. The four areas are summarized as follows:

**Multi-View Tomography (MVT)** is concerned with problems where individual sensors capture integrated properties of overlapping areas of the observed subsurface region. These problems arise in many applications instantiated in our testbeds, ranging from ground penetrating radar subsurface imaging in SoilBED and quadrature tomographic microscopy in BioBED to Diffuse Optical Tomography and Electric Impedance Tomography in MedBED.

**Localized Probing and Mosaicing (LPM)** is concerned with problems where individual sensor information reflects properties of a highly localized sub-region of the subsurface problem of interest. In these problems, determination of the global properties of the material requires registration and fusion of the multiple sources of localized information. Current applications which require LPM strategies involve retinal subsurface imaging in MedBED, underwater imaging with sidescan sonar in SeaBED, and confocal microscopy in BioBED.

**Multi-Spectral Discrimination (MSD)** is concerned with problems where sensors collect information on the observed problem of interest across multiple cross-registered spectral bands. Properties of the subsurface volume of interest must be inferred from fusion of the spectral information. Testbed applications that require MSD strategies are skin and brain imaging in BioBED and MedBED, and underwater quantitative imaging from airborne or satellite based hyperspectral sensors in SeaBED.

**Image Understanding and Sensor Fusion (IUSF)** aims to extract useful information from the images generated by subsurface inverse problems, such as the underlying object structure contained in a subsurface environment. In many cases, combination of diverse sources of information, obtained at different times and with different modalities, is needed to characterize the structure of the subsurface phenomena under observation.

Current applications that require IUSF include shape estimation for buried object classification in SoilBED, multisensor fusion for coral reef monitoring in SeaBED and for tumor detection and localization in MedBED. Further information on CenSSIS can be found on its website, [http://www.censsis.neu.edu](http://www.censsis.neu.edu)