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Editorial Special Issue on Enhancement Algorithms, Methodologies and Technology for Spectral Sensing

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Editorial Special Issue on Enhancement Algorithms, Methodologies and Technology for Spectral Sensing

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Abstract:

The paper is an editorial issue on enhancement algorithms, methodologies and technology for spectral sensing and serves as a valuable and useful reference for researchers and technologists interested in the evolving state-of-the-art and/or the emerging science and technology base associated with spectral-based sensing and monitoring problem. This issue is particularly relevant to those seeking new and improved solutions for detecting chemical, biological, radiological and explosive threats on the land, sea, and in the air.

Traditional spectroscopic techniques have been proven successful for the identification of isolated chemical species under highly controlled scenarios within many laboratories for decades through the leveraging of highly mature spectrometer technology. More recently, due to phenomenal developments in imaging camera technologies, there has been very significant progress in the field of imaging spectroscopy. Indeed, multispectral and hyperspectral imaging technologies are already impacting many basic scientific disciplines, e.g., astronomy, agriculture, biology, chemistry, ecology, etc., and as such have already found relevance in many practical applications areas, including but not limited to: chemical and petrochemical processing and safety monitoring, geology and minerals mining, pattern and data mining, security and surveillance, etc. A typical spectral imager collects information from targeted materials and/or objects using specific subportions of the electromagnetic spectrum, most notably from the ultraviolet through the terahertz range. Hyperspectral imagers collect pictures of the same scene at many subbands of the light spectrum to generate a “hyperspectral image cube” that can reveal geometric features and related information based on the relative spectroscopic properties of the target and background that cannot be seen in ordinary broadband intensity camera images. This is true because different materials possess chemical properties that often provide unique spectral signatures from specific subbands of the spectrum. Therefore, it is possible to employ these specific signatures to identify the materials and/or objects present in an imaged scene.

However, each hyperspectral image cube corresponds to a very large volume of data that requires computational intensive data processing. Hence, new algorithms are needed for improving the detection times and the associated probabilities which is of the utmost importance in many applications of interest at this time. While multispectral imagers typically operate at a smaller number of subbands in the spectrum the basic problems are very similar. Spectral imagers have been developed for broadly varying sensing scenarios that range from space exploration to microscopic robotic sensors in the laboratory. These imaging systems are presently being applied and refined for sensing in land (e.g., on surfaces), sea (e.g., in water) and air (e.g., atmospheric) scenarios and are heavily levering new types of technologies and modalities such as time-domain and frequency-domain terahertz-frequency spectroscopy. Since spectroscopic sensing science and technology has important relevance to many disciplines and because its optimum implementation requires enhancements from additional algorithmic (i.e., hardware and software) design and development, any reasonably comprehensive survey of the subject will naturally span many fundamental disciplines such as chemistry, biology, material science, atmospheric science, optics, electronics, etc., as well as the computer and informational sciences.

This multidisciplinary special issue on “enhancement algorithms, methodologies and technology for spectral sensing” has been focused into a common sensors theme by the evolving requirements for multispectral/hyperspectral based detection and identification. Recently, an increased emphasis on reagentless spectroscopy combined with algorithmic enhancement has been motivated primarily by negative performance issues associated with traditional chemical and biological (CB) point and standoff detection techniques. In particular, sensors have been previously developed and fielded that rely heavily on reagents and/or burdensome support structures that are expensive and difficult to maintain and that have serious false alarm issues. Examples of previously implemented technologies include biological assays, mass spectrometry, and ion mobility. Other explored methodologies include novel materials (mips, smart ligands, amino acid sequences, aptamers, sol gel, aerogel, electroconducting polymers, etc.) or bulk property interactions (electrochemistry, surface acoustic wave, surface plasmon resonance, thermal capacity) and combinations of the two.

At this time, extensive expertise has been demonstrated in the multispectral/hyperspectral community for applications such as airborne and space-based sensing and imaging which has proved effective in monitoring weather, resource management (agriculture, forestry), oil/mineral deposits, and CB detection in air releases. Furthermore, there is a rapidly growing interest in the development of post-acquisition (software based) algorithmic or signal-processing based strategies to enhance and aid the functionality of spectral sensors as well as novel acquisition-phase architectures (hardware based) that enable extended functionality and greatly enhanced data processing capabilities. Hence, spectral-based techniques clearly have potential for providing near to mid-term solutions for many of the monitoring problems associated with chemical, biological, radiological and explosive (CBR&E) threats on the land, sea and in the air. However, the ultimate realization of such spectroscopic techniques will probably require the fusion of many types of spectral-sensing techniques and modality along with the leveraging of advanced algorithmic strategies. Therefore, there is an expectation that standoff and point interrogation sensors are evolving that will be able to provide for extremely high confidence in CBR&E detection and monitoring scenarios.

This Special Issue was organized to focus on many of the most important and challenging science and technology issues related to hyperspectral and multispectral sensors with an emphasis on the enhancement algorithms, methodologies, and technologies required for achieving efficient and effective CBR&E detection systems. In particular, this Special Issue on “Enhancement Algorithms, Methodologies and Technology for Spectral Sensing” incorporates a diverse sampling of leading pioneering works on spectroscopic sensing that are being conducted at universities, government laboratories, and commercial laboratories from both within the United States and the from the larger international community. Here, a holistic integrated view on the spectral sensing problem is achieved by constructing a collection of papers that clearly illustrates the role of advanced algorithmic strategies (i.e., software and hardware) in the context of the state-of-the-art sensing methodologies and technologies, and in the context of the continually advancing science and technology base related to sensing/sensors phenomenology, modality, techniques, devices, components, integrated systems, testing, and evaluation.

To achieve these overarching goals, this Special Issue leads off with a focus section on *Algorithms for Spectral Sensing*. Algorithms for spectral sensing are often major research focus areas of academic programs in electrical engineering, mathematics, or computer science, and this Special Issue contains a number of contributions of this type where the work has been adapted and tailored to specific sensor systems. The themes of these papers range from theoretical concepts in sensing, to imaging and data compression, to enhancing and stabilizing imagery, to detection and classification based on spectral signatures, and to methods for calibration of sensor systems. Algorithm developers of modern imaging and spectral-sensor systems face many challenges at this time and the papers in this collection address many of the most important problems. In particular, this section contains one or more contributions on the subjects of: fusion of high-resolution spectral content from spectral imagery with high-spatial-resolution content contained in intensity imagery without altering the spectral information content, as they bear vital signatures of materials; reduction of noise and variability in spectral imagery, both in the spectral and spatial dimensions; strategies for "calibrating" sensors and their data so as to undo the alterations brought about by the environment and other interfering factors in practical sensing scenarios; efficient spectral data compression for reducing the demands related to data storage, communication, real-time processing and analysis; and modeling and classification of spectral data and imagery.

The next major component of this Special Issue contains a set of three sections that independently survey the latest science and technology developments in the context of spectral-based sensing and monitoring for land (and surface), sea (and water) and air (and atmospheric) scenarios. In the first section on *Science and Technology for Land (and Surface) Sensing and Monitoring*, new and novel techniques are discussed such as: new temporal-spectral detection algorithms that enhance the performance of ground-based staring hyperspectral chemical detectors; combined spectral and spatial analysis for remote detection and classification of land-based targets; electrostatic precipitation (ESP) based collection and concentration for achieving very low detection limits in IR spectrometers; and optimization of tradeoffs between spectral resolution and photon collection for realizing effective detection at reduced computational burdens. In the second section on *Science and Technology for Sea (and Water) Sensing and Monitoring*, innovative procedures and recent advances are presented such as: hierarchical lithography for use in the development molecular optoelectronic sensor platforms; decision analytic methods for deriving the appropriate risk targets for use in systems that sense biological agent threats; long-wavelength infrared imaging systems for the detection of submerged scuba divers and port surveillance; nanoshell arrays fabricated using directed assembly of nanospheres that offer the potential for sensitive detection and real-time analysis of bio-molecular interactions near a interfaces; and the use of reactive thin films for IR-based detection of toxic compounds in water. In the third section on *Science and Technology for Air (and Atmospheric) Sensing and Monitoring*, advanced methodologies and evolving technologies are highlighted such as: a microelectromechanical systems (MEMS)-scale photoacoustic chemical sensor that provides for parts-per-billion (ppb) detection limits; a highly effective approach for the detection and identification of gaseous plumes in IR hyperspectral imagery using a divisive hierarchical clustering algorithm; a model for estimating the Receiver Operating Characteristic (ROC) curves for digital fluorescence lidar sensing of aerosol bio-warfare agent (BWA) simulants in the presence of a single aerosol interferent; and, demonstrations of the effectiveness of imaging Fourier transform spectrometry in characterizing combustion events. Collectively, these sections present a clear picture of the current state-of-the-art in spectral-based sensing science and technology.

The last component of this special issue presents an extensive survey of the work on *Frontier (and Emerging) Spectroscopic Science and Technology*. The papers presented in this section cover an array of subject matter areas of direct relevance to those cover in the earlier sections, including but not limited to such topics as: frontier algorithms that leverage phenomenology and novel process; multispectral and multimodality innovations; integrated sensor platforms for enhanced performance; technology enabled innovative spectral sensing; spectral signature phenomenology; novel spectroscopic methodology; THz spectroscopic sensing; nanosensor concepts and devices; and, sensor enhancement techniques. A few specific examples of the novel research and technology developments presented include: the collection of extremely narrow linewidth THz spectral signatures from RNA solution inside nanofluidic channels; a compact wavelength and polarization agile acousto-optic tunable filter (AOTF) based imager effective for imaging both spectral and polarization signatures of laser-induced fluorescence samples; methodologies for developing Surface-Enhanced-Raman Scattering (SERS) substrates useful for the detection of chemical and biological molecules; integrated nanostructure-semiconductor molecular complexes as tools for THz spectral studies of DNA; new sensor signal processing method that improves selectivity, sensitivity and processing speed in systems using Fluctuation Enhanced Sensing methodologies; and graphenated IR screen based spectroscopic platforms that enhance IR and Raman signatures of biomolecules. Therefore, this collection of papers illustrates many of the important pioneering works from the field of spectral-based sensing.

In summary, this Special Issue on “Enhancement Algorithms, Methodologies and Technology for Spectral Sensing” serves as a valuable and useful reference for researchers and technologists interested in the evolving state-of-the-art and/or the emerging science and technology base associated with spectral-based sensing and monitoring problem. This issue is particularly relevance to those seeking new and improved solutions for detecting CBR&E threats on the land, sea, and in the air. The editorial committee would like to express their sincere gratitude to all the authors that contributed to the construction of this Special Issue.