# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. REPORT DATE** *(DD-MM-YYYY)*
30-05-2008

**2. REPORT TYPE**
Annual Performance

**3. DATES COVERED** *(From - To)*
01-05-2007 - 30-04-2008

**4. TITLE AND SUBTITLE**
MURI 06: Integrated Fusion, Performance Prediction, and Sensor Management for Automatic Target Exploitation

**5a. CONTRACT NUMBER**
FA9550-06-1-0324

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
R. Moses, D. Castanon, M. Cetin, E. Ertin, J. Fisher, A. Hero, C. Karl, L. Potter, A. Srivastava, A. Willsky

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Ohio State University Research Foundation
1960 Kenny Rd.
Columbus, OH 43210

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
USAF, AFRL
Air Force Office of Scientific Research
875 N. Randolph St.
Arlington, VA 22203

**10. SPONSOR/MONITOR'S ACRONYM(S)**
AFOSR/ND

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release; distribution is unlimited.

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
This report summarizes the research activities of this MURI project during the second year. Significant research advances have been made in the areas of innovative sensor signal processing, information fusion, and sensor management, and several cross-disciplinary problems in these three areas have been addressed. The MURI team has been active in research dissemination via publication and attendance at conferences and workshops, and has engaged in technology transformation via student internships and participation in government workshops and research direction discussions.

**15. SUBJECT TERMS**
sensor fusion, sensor signal processing, information fusion, sensor management

| 16. SECURITY CLASSIFICATION OF: a. REPORT | b. ABSTRACT | c. THIS PAGE | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| U | U | U | UU | | Randolph L. Moses |

**19b. TELEPHONE NUMBER** *(Include area code)*
614 292 1325

Reset

# ANNUAL PERFORMANCE REPORT

Contract/Grant Title:
(MURI '06) Integrated Fusion, Performance Prediction, and Sensor management for Automatic Target Exploitation

Contract/Grant #: FA9550-06-1-0324

Reporting Period: 1 May 2007 to 30 April 2008

Randolph L. Moses (Ohio State U)
David Castañón (Boston U)
Mujdat Çetin (MIT and Sabanci U)
Emre Ertin (Ohio State U)
John W. Fisher III (MIT)
Alfred O. Hero III (U Michigan)
Clem Karl (Boston U)
Lee C. Potter (Ohio State U)
Anuj Srivastava (Florida State U)
Alan Willsky (MIT)

Principal Investigator:
Randolph L. Moses, Professor
Department of Electrical and Computer Engineering
The Ohio State University
2015 Neil Avenue
Columbus, OH 43210
Tel: 614 292 1325
Email: moses.2@osu.edu

Submitted to: Dr. David Luginbuhl
Program Manager
Software Engineering and Information Management
Air Force Office of Scientific Research
875 N. Randolph Street
Arlington, VA 22203

# 1 Objectives

The objective of the research program is to develop an integrated systems theory for automated target exploitation (ATE) that jointly treats information fusion, control, and adaptation using multiple, dynamic multi-modal sensor platforms in resource constrained environments. The research program addresses three inter-related research challenge areas, with an emphasis on the cross-coupling issues between these areas. The program is developing techniques for optimal, **robust information fusion in uncertain environments**. Graphical models are used to aggregate information at multiple levels and scales in architectures that incorporate both top-down (context and behavior) and bottom-up (feature and shape parameter) information flows. Graphical models also exploit statistical structure to manage computational complexity and facilitate on-line learning. Information-theoretic performance metrics are used to evaluate overall ATE performance and to inform both sensor management and front-end processing. These metrics provide for consistent fusion of disparate sources, enabling multi-sensor, multi-modal solutions. Optimal fusion is achieved by coupling with both inference-directed **innovative front-end processing** and **dynamic sensor resource management** that supports ATE inference. Front-end signal processing algorithms aim to extract optimal feature sets from sparse aperture data. The program develops robust, decision-directed imaging and reconstruction methods that can adapt to context and to changing inference objectives. Non-myopic sensor management and control strategies for sensor platform trajectories are developed that optimally achieve sensing and exploitation objectives. Figure 1 illustrates the research structure and the critical cross-disciplinary topics that enable a multidisciplinary solution to the automatic target exploitation problem. Collectively, the research program provides an end-to-end solution from processing of raw sensor data to fusion from multiple sensors and modalities to sensor management and control, focused on a common ATE inference objective.

There has been no change in the objectives.

# 2 Status

During the two years of this MURI, we have made significant advances in all three of the core research challenge areas, and have also made significant strides in cross-coupling research between the core areas.

In the area of **front-end signal processing**, we have continued to develop and refine new sparse imaging and information extraction approaches for sparse aperture SAR measurements and both models and processing methods. During the last year, we have demonstrated on measured data a model-based feature extraction method for 3D features from 2D apertures. We have begun developing methods for more general wide-aperture and ultra-narrow band multi-static sensing configurations. Additionally, from the physics-based modeling approach, we have abstracted a simple, image-based processing that provides approximately the same features with over three orders of magnitude reduction in the computation time. We have also made advances in what we refer to as front-end complexity reduction, i.e., structuring and/or compressing complex and high-dimensional raw data in order to zero in on information content critical to specific tasks such as discrimination. Methods developed and under development include: (a) new approaches to

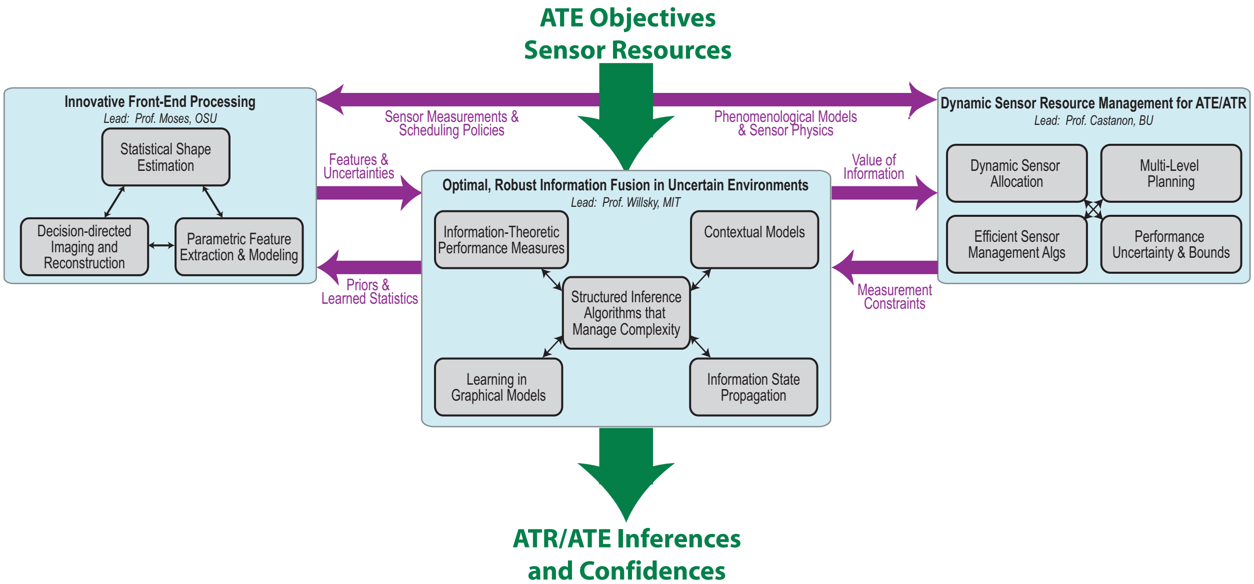


Figure 1: System-theoretic approach to inference-driven ATE. Front-end processing and sensor management are directed to support ATE inference, and provide information and uncertainties that are aggregated to quantify ATE inference performance.

sequential compressed sensing; (b) methods for learning discriminative graphical models, i.e., ones that emphasize what is salient in the data for the purposes of discrimination or recognition; and (c) methods blending manifold learning and level-set methods for the learning of low-dimensional manifolds and decision regions within those manifolds.

In the area of **sensor management**, we continue to develop information-theoretic performance bounds, and continue on adaptive algorithms for waveform scheduling and aperture selection. Previous work on information theoretic bounds using analytic information measures has been extended to the case where information measure are estimated with bounded error. Additionally, these bounds have been incorporated into a new sensor management algorithm with computable performance guarantees. Worst case complexity analysis of information driven sensor management has been extended to incorporate target dynamics, sensor noise models and sensor density. Optimal two stage beam scheduling strategies have been developed for wide area search under a sparse target occupancy assumption. Significant performance gains are demonstrated for a simulated W-band imaging radar. In addition, a non-myopic embedded simulation method was developed for multi-target radar tracking through dynamic random media such as turbulence, precipitation, or cloud cover. We have also continued the development of pricing algorithms for distributed multi-platform sensor management. Finally, we have started the development of algorithms for sensor management algorithms in support of 3-D target recognition using feature-based representations of underlying objects.

In the area of **information fusion**, we continue to develop and refine our framework for efficient fusion algorithms, and have addressed issues in robustness to calibration errors or unreliable communication among distributed sensors. In particular, during this past year we have had major successes in developing (a) new and scalable fusion algorithms; (b) new methods for learning sparse (and hence tractable) graphical models for information fusion; and (c) new methods for learning dynamic behavior models and using these models to detect changes in behavior. We have also continued the development of lossless distributed information fusion protocols for target state estimation in the presence of lossy communications.

In the area of **cross-coupling research**, the team has engaged in several collaborative research activities. Several joint research topics are currently being pursued as a result of these and previous interactions, including topics on model-based imaging and feature extraction, tracking, and sensor management, as well as cross topics on information-based scheduling and feature extraction for fusion.

The work on front-end complexity reduction—in particular the work on learning discriminative graphical models and the work on blending manifold learning and level-set methods to learn decision rules for discrimination—cut across both front-end signal processing and information fusion and treat these in a unified manner. In addition, the methods for learning discriminative graphical models also has strong ties to sensor and processing management, as the methods we are developing provide guidance on sequential information queries which provides a framework not only to determine the next data to collect to enhance decision performance but also the next processing step to be taken.

A number of team members have been active in research interactions and technology transitions in the form of research interactions, graduate committees, and technical presentations, as well as internships with government and industry. Several students working on this MURI have spent summer 2007 at AFRL in Dayton or at companies working on target recognition and exploitation problems. Prof. Çetin is co-advising BU student Ivana Stojanovic and has co-authored joint papers resulting from this work. He will spend part of summer 2008 at Boston University as a Visiting Research Scientist. In addition, Prof. Hero served on the PhD committee for Dr. Joshua Ash (Ohio State); Dr. Ash is now a postdoctoral researcher under this MURI.

# 3 Website

The website for this MURI program is: `http://projects.csail.mit.edu/atemuri/wiki`

The website contains information on the principal researchers involved in the program (including links to web pages for each), on research efforts associated with this MURI, on publications, on recent events and highlights, and on code and data sets developed under the program.

# 4 Accomplishments and New Findings

Below is a summary of the research accomplishments for the second year of the program. These accomplishments fall within and across the three primary research challenge areas addressed under this program: Information Fusion, Signal Processing, and Sensor Management. Many of these activities are cross-disciplinary and address more than one theme.

**Feature Extraction and Model-Based 3D Imaging from Sparse Apertures**

| | |
|---|---|
| *Researchers:* | Randy Moses (OSU), Lee Potter (OSU), Mujdat Çetin (MIT and Sabanci U), Clem Karl (BU) Julie Jackson (OSU), Samir Sharma (OSU), Ivana Stojanovic (BU) |
| *Topic:* | Signal Processing |
| *Publications:* | [32, 41, 58, 59] |

This research addresses the development of parametric models and of model estimation procedures that provide 3D features of scenes or targets interrogated by a radar sensor. Parsimonious and representative electromagnetic models of radar scattering, suitable for feature-based information fusion and sensor management, are being developed. In addition, the research considers algorithms for estimating the number, type, and characterizing parameters of features from sparse radar apertures. In particular, 3D features that describe the scene are sought using radar measurements on sparse 2D apertures. Scattering model selection, parameter identifiability, and model estimation accuracy expressions have been derived. A flexible feature set for use in multi-modal information fusion from sparse sensor apertures has been developed.

Also during the last year, model-based imaging was proposed as a means of exploiting object structure to achieve resolution in three dimensions from two dimensional radar apertures. During the last year, we have demonstrated the processing on measured data from the Gotcha X-band collection. Additionally, from the physics-based modeling approach, we have abstracted a simple, image-based processing that provides approximately the same features with over three orders of magnitude reduction in the computation time.

The parametric scattering models have also been employed for three-dimensional radar imaging from sparse, multi-pass synthetic apertures. Conventional image formation from such sparse aperture results in high and irregular side lobes. While maximum likelihood estimation is hampered by an intractable cost surface with many local minima at wavelength spacings, a non-coherent detection strategy results in a cost surface with large region of attraction about the true minimum. The physical optics models provide features for high confidence identification of stationary targets and feature-aided tracking of moving targets. Results have been computed for X-band phase histories collected by an airborne sensor.

We have also developed new parametric scattering models for bistatic and multistatic radar measurements. These models provide feature sets that can be used for feature-based target exploitation, such as target classification or feature-based tracking. We have generalized geometric theory of diffraction solutions for scattering mechanisms in a plane to develop three-dimensional models for canonical scattering shapes. The generalization from 2D to 3D and from monostatic to multistatic is significant because management of multiple radar sensors involve non-planar apertures and bistatic or multistatic measurements.

**Complexity Reduction and Learning Models for Discrimination**

| | |
|---|---|
| *Researchers:* | Alan Willsky (MIT), John Fisher (MIT), Sujay Sanghavi (MIT), Kush Varshney (MIT), Lav Varshney (MIT), Vincent Tan (MIT) |
| *Topic:* | Signal Processing, Information Fusion, Sensor Management |
| *Publications:* | [17], [46], [66], [53], [70], [65] |

This new research topic, which has three components, primarily deals with research that cuts across signal processing and information fusion, but one part of this work also has implications for sensor and computational resource management. The first component of our research has produced a new set of methods and results for compressed sensing, i.e., the front-end reduction of data volume while preserving all critical, but typically far sparser or lower-dimensional, information. In particular, we have developed theoretical results that show that if compressed sensing is performed sequentially rather than in batch, then one can much more easily and directly determine the intrinsic sparsity or dimensionality of the key information variables. The second component of our research combines methods of dimensionality reduction/manifold learning with level set methods. The basic idea is to use expert-classified, high-dimensional training data in order to identify the actionable information embedded in those data sets (i.e., the lower-dimensional manifold containing the key decision variables) as well as the decision boundaries within these lower-dimensional manifolds (using level set methods). Part of the motivation for this research is to learn from experts—e.g., image analysts. That is, rather than to have experts try to explain the rules that they use—a notoriously suspect and fragile approach, we let their actions, i.e., results of their analyzing data sets provide the basis for our discovering not only what is important in their decision-making but also (through the recovered decision regions) what criterion they are implicitly using in reaching their decisions. The third portion of this new research area aims to perform complexity reduction rather than dimensionality reduction—i.e., to keep the original high-dimensional data but to build tractable graphical models connecting the components of these high-dimensional data and then to use these tractable models for discrimination. A crucial aspect of our work is that we build our models using as an objective the fact that they are to be used for discrimination—i.e., emphasizing the fact that it is probability of error in future decisions that is most crucial. This leads to models that emphasize what is salient about each decision class i.e., what most distinguishes it from others rather than capturing details that are common to all classes. Moreover, by building models that attempt to capture saliency in an ordered fashion i.e., first the most salient aspect, then the next, etc., as captured by which nodes and edges are kept in a sequence of nested graphs we provide a guide to querying for discrimination, i.e., which feature should be looked at first, which relationships among features should be looked at before others, etc. This provides guidance not only to resource management for signal processing but also to sensor resource management if some of those features represent measurements that have yet to be made.

**Advances in Regularized Tomographic Inversion for Imaging and Feature Extraction**

| | |
|---|---|
| *Researchers:* | Mujdat Çetin (MIT and Sabanci U), John Fisher (MIT), Alan Willsky (MIT), Lee Potter (OSU), Randy Moses (OSU), Emre Ertin (OSU), Kush Varshney (MIT), Naveen Ramakrishnan (OSU), Subhojit Som (OSU), Clem Karl (BU), Zhuangli Liang (BU), Ivana Stojanovic (BU) |
| *Topic:* | Signal Processing, Information Fusion |
| *Publications:* | [24], [36], [60], [69], [54] [10],[61] |

This research addresses several interrelated topics for regularized tomographic inversion and the associated problem of feature estimation for target exploitation and information fusion. Issues associated with anisotropic scattering characterization, 3D image formation from sparse apertures, and multichannel data have been addressed.

We have conducted two lines of research and made significant progress on the problem of joint image formation and anisotropy characterization in wide-angle SAR. In our first piece of work (which has been described in last year's report as well), the main idea is to perform joint anisotropy characterization and imaging (reflectivity estimation), by posing both problems as sparse signal representation problems. We have developed a framework which solves the problem for multiple spatial locations jointly, using graph-structured approximate algorithms to solve the inverse problem. In addition, the interrelationship between points, as parts of larger objects, is also considered. Through extensions to the sparsifying regularization cost function, certain object-level preferences are encoded within the image formation process. This is a principled attempt towards the objective of decision-directed imaging, exploiting high-level information in front-end signal processing. We have completed our experimental analysis and submitted our work for journal publication.

Motivated by the approach described above, we have initiated a second line of research with a complementary perspective on the problem. In particular, while still posing the problem as one of joint imaging and anisotropy characterization, the structure we incorporate regarding anisotropy here involves piecewise smoothness of the scattering response as a function of the viewing angle. These approaches estimate a dense orientation dependent scattering field, providing new information on target behavior. We have started extending these results to circular SAR, non-conventional multi-static sensing configurations as well as ultra-narrow-band SAR.

A parametric approach has been developed and demonstrated [10] for tomographic imaging in three dimensions with a spatially varying blur. The blur is parametrized, and image values are jointly estimated with the spatial map of blur parameters. The processing is an example of using non-linear manifolds to exploit sparsity in inverse problems. Application was demonstrated in electron paramagnetic resonance (EPR), where the blur is due to local oxygen pressure. The proposed approach provides lower mean square reconstruction error two orders of magnitude reduction in data collection time compared to existing techniques. The EPR mapping of oxygen pressure holds clinical potential for radiation therapy dosing and for noninvasive monitoring of stints.

We have introduced a low-complexity recursive procedure for Bayesian estimation in linear regression models [52, 61]. Recent literature in compressive sensing has given performance guarantees for simple algorithms when sparse signals and nearly orthogonal measurement operators combine to yield a single, unique interpretation of data. More generally, however, inverse problems yield ambiguous interpretation, and compressive sensing fails to detect and report the ambiguity-thus failing in inference tasks. Importantly, radar imaging is not itself a system goal, but is rather a means to support inference tasks. For data processing with linearized signal models, we have developed a fast method to compute all high-probability interpretations of the data and to report confidence labels in the form of posterior probabilities. A Gaussian mixture is chosen as the prior on the unknown parameter vector. The algorithm returns both a set of high posterior probability mixing parameters and an approximate minimum mean squared error (MMSE) estimate of the parameter vector. Emphasis is given to the case of a sparse parameter vector. Numerical simulations demonstrate estimation performance and illustrate the distinctions between MMSE estimation and maximum *a posteriori* probability (MAP) model selection. The proposed tree-search algorithm provides exact ratios of posterior probabilities for a set of high probability solutions to the sparse reconstruction problem. These relative probabilities serve to reveal potential ambiguity among multiple candidate solutions that are ambiguous due to low signal-to-noise ratio and/or significant correlation among columns in the super-resolving regressor matrix.

In addition, new methods for simultaneously controlling multiple diverse features in tomographic reconstructions are being developed. In our previous work on feature enhanced SAR image creation, the feature enhancement effect was mutually exclusive (e.g. either point *or* region based features were emphasized, but not both simultaneously). Many other tomographic problems have features of conflicting natures co-existing in a signal image. To address such challenges, new multi-component tomographic image formation methods are being developed allowing independent control of multiple feature behaviors. The work was applied for artifact mitigation in cardiac computed tomography.

These advanced tomographic methods come at the cost of increased computation over conventional image formation approaches (such as the polar format algorithm). To be useful in practice this increased computational burden must be overcome. In the last year parallel implementations of canonical components of our tomographic methods have been investigated. Multiple levels of parallelism are being investigated. One approach has been straightforward implementation using the message passing interface (MPI) API, allowing execution on conventional Beowulf-type clusters. Another level has focused on porting these routines to general-purpose graphical processing units (GP-GPUs). A third approach is investigating use of IBM's cell architecture. These implementations will allow many advanced tomographic methods to be treated as "commodity" processing components, much as the FFT is today.

This research addresses several interrelated topics for regularized tomographic inversion and its associated feature estimation for target exploitation and information fusion. Issues associated with anisotropic scattering characterization, 3D image formation from sparse apertures, and multichannel data have been addressed.

**Efficient Fusion Algorithms**

| | |
|---|---|
| *Researchers:* | Alan Willsky (MIT), Venkat Chandrasekaran (MIT), Jason Johnson (MIT) Dmitry Malioutov (MIT), Myung Jin Choi (MIT), Alfred Hero (UM) |
| *Topic:* | Information Fusion |
| *Publications:* | [51], [16], [45], [18] |

This research addresses the development of efficient algorithms for fusing disparate sources of information through the use of graphical model representations. For problems of interest in this MURI—in which the available information sources may include raw sensor data (e.g., SAR imagery), dynamic tracks of objects, and context (such as behavior models, e.g., coordinated activities of multiple objects)—graphical models provide a unifying framework in which to fuse information for automatic target exploitation. While such models are natural for such problems, thanks to their great expressivity, they also present significant challenges in terms of developing scalable fusion algorithms.

During the past year we have developed a very powerful and flexible approach to near optimal fusion based on Lagrangian relaxation, involving the breaking up of a large complex graph into a set of tractable ones and requiring consistency among the fused inferences produced resulting from all of these tractable subproblems This method grew directly out of earlier work, in collaboration with BAE Systems Advanced Information Technologies (formerly ALPHATECH) on developing new methods for multi-target data association algorithms but has now been generalized to be far more powerful and generally applicable. In addition, we have developed a new framework for multiresolution graphical modeling that leads to powerful new multipole estimation algorithms involving sweeps both within and across resolutions.

**Novel methods for the tracking and behavior characterization of multiple targets**
*Researchers:* Alan Willsky (MIT), Emily Fox (MIT), Michael Chen (MIT)
*Topic:* Information Fusion, Signal Processing
*Publications:* [4], [39], [67], [80]

This research addresses the development of a new generation of algorithms not only for tracking multiple objects but also for learning and characterizing maneuver and behavior patterns of these objects. One part of our work in this area has aimed at exploiting a new graphical modeling framework—based on so-called Hierarchical Dirichlet Processes—to learn maneuver and behavior patterns of targets of interest. Such information is of potentially great value in providing kinematic cues to complement direct sensor measurements of targets of interest. In addition, we have also introduced a new graphical model for multi-target tracking which, together with emerging methods of inference on such models, offer the potential for new algorithms with drastically different architectures than those currently used in practice and with superior scalability. The scalability is of considerable importance in military contexts such as tracking in urban environments.

During this past year we have continued our work on learning and detecting changes in behavior patterns, including a very recent demonstration of the power of this methodology for identifying and detecting switches among dynamic models in a manner that is very robust. In particular, the same algorithm, with no tuning of parameters or models at all, successfully performed on-the-fly learning and simultaneous segmentation not only of motion maneuver models real data of bee dances, but of drastically different data sets (stock market data, audio signals involving determining the number of speakers in a room, what each sounds like, and when each is talking with no prior information on any of these). In addition, we have now demonstrated the power of our new graphical model-based approach to multi-target tracking in drastically reducing computational complexity with no loss in performance. This is significant in part because our method thus allows far longer data windows to be considered without drastic hypothesis pruning, making the incorporation of latent data or so-called track-stitching (association of track fragments separated by a considerable gap in time) seamless.

**Asynchronous Hierarchical Estimation with Unreliable Communications**
*Researchers:* David Castañón (BU), Venkatesh Saligrama (BU)
*Topic:* Information Fusion, Sensor Management
*Publications:* [1], [31]

We have continued our work on protocols for information distribution from networks of sensors that perform local processing to estimate the states of individual objects using communications where packets can be lost and not retransmitted. This paradigm is better suited for surveillance applications than TCP/IP models, because retransmission of old information is often irrelevant. Our prior work developed local strategies for coding information that guaranteed recovery of centralized performance in the presence of limited message losses. However, the amount of coding required scaled exponentially with the number of sensors involved in the network. We have developed alternative protocols where the coding overhead scales linearly with the number of sensors, and the resulting algorithms provide near-optimal fusion performance. The resulting protocols use versions of multiple-access communications that impose an event-driven order among the communicating sensors.

**3D Target Reconstruction for Circular SAR**
*Researchers:* Emre Ertin (OSU), Randy Moses (OSU), Lee C. Potter (OSU)
*Topic:* Signal Processing
*Publications:* [58], [41], [59], [14]

This research considers processing of SAR data collected on multiple complete circular apertures at different elevation angles. We focus on the problem of three dimensional target reconstruction for multi-pass circular SAR. Circular SAR (CSAR) has two unique features due to its wide-angle non-planar collection geometry. First, it provides wide-angle information about the anisotropic reflectivity of the scattering centers in the scene. Second, unlike the linear collection geometry, circular SAR reveals three dimensional information about the location of the scattering centers in the spotlighted area even from a single elevation angle. We considered three techniques for 3D object reconstruction for Circular SAR. The first method uses single-pass CSAR measurements and infers three dimensional shape from multi-view layover using prior information about target scattering mechanisms. The second method is a parametric method that extends the IFSAR technique of height estimation to multiple passes using high-resolution spectral estimation algorithms. The third method is a nonparametric enhanced imaging algorithm with regularization terms providing a sparse description of the target scene that is consistent with the collected SAR data with reduced sidelobes and noise artifacts. We have illustrated the performance of the proposed techniques using simulated backscatter data on backhoe data dome released by AFRL and measured CSAR data from the AFRL GOTCHA program.

Radar resolution in three dimensions is considered for circular synthetic apertures at constant altitude. Traditional measures of resolution evaluate zero crossings of the ambiguity function along the $x$, $y$ and $z$ spatial axes. However, the limited angular persistence of reflectors encountered in practice renders the traditional measures inadequate for circular synthetic aperture radar imaging. Statistical measures of uncertainty in reflector location are used to quantify resolution in three dimensions as a function of scattering persistence and radar system parameters. The analysis shows that three-dimensional localization of a reflector requires a combination of large radar cross section and large angular persistence. Results were reported in a journal manuscript [14].

**Advances in Shape Analysis of Curves and Surfaces**
*Researchers:* Anuj Srivastava (FSU), Shantanu Joshi (FSU), Ian Jermyn (INRIA, France), Wei Liu (FSU)
*Topic:* Signal Processing
*Publications:* [72], [19], [73], [34], [40]

We have continued our research activity in statistical analysis of shapes of curves and surfaces. One of the accomplishments is a new representation of curves in $\mathbb{R}^n$ that greatly simplifies the computation of geodesic paths under the well-respected elastic metric. Each curve is represented a square-root velocity function and the elastic metric reduces to the convenient $\mathbb{L}^2$ metric in this representation. This idea is closely related to representation of probability density functions by their positive square-roots, so that the Fisher-Rao Riemannian structure on the space of probability densities becomes a unit sphere in an $\mathbb{L}^2$ space. This approach is being applied to the following problems: (i) statistical analysis of shapes fiber tracts in DT-MRI data of human brain, (ii) shape analysis of facial surfaces where each surface is considered an indexed collection of facial curves, and (iii) shape analysis of trees detected in aerial images, for help in classification. These tools are also useful in learning probabilistic models for planar shapes, and in the use of such models for extracting object contours from noisy, cluttered image data.

**Advances in Decision-Directed Reconstruction Techniques**

| | |
|---|---|
| *Researchers:* | Mujdat Çetin (MIT and Sabanci U), Ozge Batu (Sabanci U), Ozben Onhon (Sabanci U) |
| *Topic:* | Signal Processing |
| *Publications:* | [37] |

This research addresses a number of related issues that enable decision-directed methods for sparse reconstruction and feature extraction.

Sparse reconstruction techniques combine mathematical models of the data collection process with contextual information about the scene to be imaged. When such pieces of information are combined in the right manner, these techniques provide robust and feature-enhanced reconstructions, providing significant improvements over conventional imaging approaches. However, how to select the hyperparameters that ensure a reasonable balance of different pieces of information has been an open issue. Within the last year, we made progress in developing automatic hyperparameter choice techniques particularly for sparse-aperture radar imaging problems. In particular, we have developed and analyzed algorithms based on Generalized Cross Validation (GCV) and Stein's Unbiased Risk Estimator (SURE) for parameter choice. We have demonstrated the effectiveness of our techniques [57, 63] on the Backhoe dataset distributed by AFRL.

The research has also addressed the problem of sensing model errors in sparse aperture imaging problems. Front-end signal processing in sparse aperture imaging requires the use of a mathematical model of the data collection process for effective scene reconstruction. Yet, in many scenarios, there are uncertainties in the observation model, e.g., due to imperfect knowledge of the position of the sensing platform. Such model errors lead to various artifacts in the reconstructed images, which could have adverse effects on the performance of the ATE system that utilizes these images. Within the last year, we developed an initial framework for addressing this problem within the context of SAR image reconstruction. In particular we have posed the problem of imaging and model error correction as a joint optimization problem. Our preliminary results indicate the effectiveness of this approach in reconstructing images with significantly reduced artifacts, which appear in conventional images due to imperfect knowledge of the sensing model parameters.

The research also considers the problem of decision-directed feature enhancement. Our previous work on feature-enhanced SAR imaging has focused in enhancing one particular type of feature in image reconstruction. This research, initiated within the last year, develops algorithms that enhance multiple types of features, hence providing the capability to effectively handle more complicated scenes.

**Sequential Adaptive Waveform Scheduling and Aperture Selection**

*Researchers:* Alfred Hero (UM), Lee Potter (OSU), Raghuram Rangarajan (UM),
*Topic:* Sensor Management
*Publications:* [29], [5], [15]

This research project addresses waveform scheduling for detection, estimation and classification. For active sensing modalities, e.g. radar or EO, sequential decision theory can significantly improve performance.

We have developed an energy packetization approach for adaptive waveform scheduling that has shown significant reduction in mean-squared error. The radar initially probes the medium with a small amount of energy and, depending on the measured return, a decision is made whether or not to to send a "confirmation probe" based using an optimal thresholding function.

A sphere sampling approach has also been developed for four-dimensional tomographic imaging. Spherical t-designs provide exact integration of low order spherical polynomials at certain sampling sizes $N$. A multi-resolution quadrature method was presented [15] for integration over the sphere. The set of sampling points contains a sequence of nested subsets, each providing an approximately uniform covering of the sphere. The proposed $M$atryoshka covering of the sphere allows multi-resolution imaging whereby a user can progressively monitor inversion of the sampled Radon transform. Simulation and measured results illustrate application to tomographic imaging in three dimensions.

**Performance Bounds and Real-Time Algorithms for Sensor Management**

*Researchers:* John Fisher (MIT, Alan Willsky (MIT), Jason Williams (MIT), David Castañón (BU), Karen Jenkins (BU), Darin Hitchins (BU)
*Topic:* Sensor Management, Information Fusion
*Publications:* [43], [3]

This research is also aimed at developing approaches to non-myopic sensor management that are suitable for real-time execution in large scenarios involving multiple sensors. A major hurdle in this step is predicting the improvement in ATE performance from sensor actions in the absence of analytic performance bounds. To address this, we have been investigating simulation based techniques for evaluation of improvement in ATE performance metrics under alternative sensor management policies. We have recently applied these approaches to the development of distributed sensor management strategies for multiple sensor platforms observing multiple objects. We propose to extend these models to incorporate the multistatic parametric scattering models developed in our sensing research.

We have also continued our work on using combinatorial optimization techniques for coordination of sensing activities from multiple platforms. This year, we focused on investigating the use of assignment techniques based on pricing of sensing time, and evaluating the relative advantages of such techniques versus greedy algorithms.

**Sequential Adaptive Beam Scheduling**
*Researchers:* Alfred Hero (UM), Eran Bashan (UM), Raviv Raich (UM)
*Topic:* Sensor Management
*Publications:* [29], [12], [75], [76]

Building on the work reported last year, [29], we have continued to develop optimal two stage scheduling methods for wide area search. As reported last year the paper demonstrated that for fixed average energy surprisingly large gains in MSE can be achieved by a simple energy packetization procedure when searching a given cell for presence of a target. The optimal strategy of [29] optimized energy (or dwell time) over the temporal domain but did not optimize over the spatial search part of the problem, i.e. optimal beam scheduling. This past year we have turned our attention to optimal two stage beamscheduling. In our recently accepted journal paper [12], also published as technical report [75], we established a Bayes optimal two stage policy for fixed resolution wide area search. This policy rank orders a set of Bayesian probabilities of target presence at each pixel updated after a first stage low SNR search. The second stage searches only those cells whose probabilities are above a certain threshold determined by the assumed sparisty, the SNR, and the extent of the search area. Under the assumption that the number of targets is small (sparsity assumption) gains in MSE and detection can be as high as 20dB in some scenarios for a given total search time constraint. The work is applied to a simulated W-band radar imaging example. A second paper is in preparation that extends the framework [23] to multiresolution beam scheduling where both beam direction and beam width are designed adaptively to optimize target detection performance in wide area search problems.

**Multi-modality non-myopic adaptive waveform scheduling**
*Researchers:* Alfred Hero (UM), Edwin Chong (CSU), Chris Kreucher (General Dynamics)
*Topic:* Sensor Management
*Publications:* [68]

We have continued to develop embedded simulation methods for non-myopic sensor management under the partially observed markov decision process (POMDP) stochastic scheduling model. With collaborators Edwin Chong (Colorado State University) and Chris Kreucher (General Dynamics) we have extended our previous information gain multiple target tracking framework to tracking through random media, e.g. due to turbulence or cloudcover. The non-myopic gains shown in our previous work are maintained as long as the dynamic model for the random medium is known along with the model for the target dynamics. This work will soon appear as an invited paper at the Workshop on Discrete Event Systems (WODES) [68].

**Adaptive Data Fusion in Sensor Networks**
*Researchers:* David Castañón (BU), Venkatesh Saligrama (BU), Shuchin Aeron (BU), Brian Corwin (BU)
*Topic:* Sensor Management, Information Fusion
*Publications:* [7]

This research was focused on developing algorithms for adaptive data fusion in networks of sensors where there is a communication cost associated with sending information among sensors. A similar version of the problem, considered earlier by our colleagues Williams, Fisher and Willsky, resulted in very complex algorithms. We explored a limit version of the problem that reduced the combinatorial complexity associated with sensor selection, by assuming homogeneity in the nature of information collected from each sensor and dense coverage. We analyzed the limit model, and developed characterization of the optimal strategy for determining when to communicate and where communications should be directed. The results provided a simple set of strategies for controlling the dynamics of information fusion in sensor networks.

## 5 Personnel

The principal faculty and senior researchers supported under this research program are:

**Ohio State:** Dr. Emre Ertin, Prof. Randy Moses, Prof. Lee Potter

**MIT:** Prof. Mujdat Çetin (visiting), Dr. John Fisher, Prof. Alan Willsky

**Boston U.:** Prof. David Castañón, Prof. Clem Karl

**Michigan:** Prof. Al Hero

**Florida State:** Prof. Anuj Srivastava

In addition, Professor Venkatesh Saligrama at BU, and Dr. Mark Kliger and Dr. Raviv Raich at UMich, have been involved with the program; they have provided both synergy and leverage for the activities under this MURI.

Graduate students involved in this research program are:

**Ohio State:** Christian Austin; Kerry Dungan; Ahmed Fasih; Julie Jackson; Naveen Ramakrishnan; Subhojit Som; Justin Ziniel.

**MIT:** Venkat Chandrasekaran; Michael Chen; Emily Fox; Jason Johnson; Mike Siracusa; Kush Varshney; Jason Williams; Dmitry Malioutov; Myung Jin Choi; Vincent Tan.

**Boston U.:** Birant Borten; Brian Corwin; Paul DeBitetto; Darin Hitchins; Karen Jenkins; Ivana Stojanovic, Zhuangli Liang, Sonal Ambwani.

**Michigan:** Raghuram Rangarajan (Graduated with PhD in Aug 2007), Eran Bashan (Graduated with PhD in May 2008), Christine Kim.

**Florida State:** Shantanu Joshi; Wei Liu

In addition, graduate students Ozge Batu and Ozben Onhon at Sabanci University in Turkey are collaborating in this effort under the direction of Prof. Mujdat Çetin.

# 6 Interactions and Transitions

(a) Workshop and Session Leadership

- David Castañón was the General Chair of the 2007 Conference on Decision and Control, held in New Orleans, LA.
- Alfred Hero organized and chaired the Army Workshop on Signal and Information Processing, Ann Arbor, MI, July 2007. This workshop identified high-priority basic research needs in signal processing and inference for automatic target exploitation.
- Anuj Srivastava is one of the guest editors of a special issue of the journal IEEE Transactions on Pattern Analysis and Machine Intelligence on "Shape Modeling in Image."
- E. Ertin attended and gave a tutorial talk on learning spatial models for indoor tracking of wireless nodes.
- Emre Ertin served as Conference co-chair for the SPIE Defense and Security Symposium Intelligent Computing Conference, Orlando, FL, March 2008.
- Randy Moses organized and chaired a special session on Sparse Reconstruction for Radar at the SPIE Algorithms for Synthetic Aperture Radar Imagery Conference, Orlando, FL, March 2008.
- Lee Potter gave a keynote presentation at the SPIE Algorithms for Synthetic Aperture Radar Imagery Conference, Orlando, FL, March 2008.
- Mujdat Çetin chaired a session on Wireless Sensor Networks at the IEEE Conference on Signal Processing, Communications, and their Applications, Aydin, Turkey, April 2008.
- Anuj Srivastava gave an invited talk at the SAMSI Workshop on Geometry and Statistics of Shape Space, SAMSI Institute, Research Triangle Park, NC, July 2007.
- John Fisher organized and chaired a special session on statistical signal processing in sensor networks at IEEE Statistical Signal Processing Workshop, Madison, WI, September 2007.
- John Fisher presented a tutorial on distributed detection and estimation in sensor networks at IEEE Statistical Signal Processing Workshop, Madison, WI, September 2007.
- John Fisher participated in the National Academy of Science workshop on Disrupting IED Terror Campaigns: Predicting IED Activities, Washington, DC, March, 2008.

(b) Participation/presentations at meetings, conferences, seminars, etc.

- IEEE Computer Vision and Pattern Recognition (CVPR) Conference, Minneapolis, MN, June 2007.
  - Shantanu Joshi attended the conference and presented two papers.

- 15th Annual Adaptive Sensor Array Processing Workshop, Lexington, MA, June 2007.
  - Randy Moses and Emre Ertin attended, presenting two papers.
- 2007 Fusion Workshop. Al Hero made an invited presentation at a special session on Sensor Management organized by Emmanuel Duflos.
- Army Workshop on Signal and Information Processing, Ann Arbor, MI, July 2007.
  - Alfred Hero organized and chaired this workshop
  - John Fisher, and Randy Moses attended and gave invited presentations.
- International Conference on Information Fusion, Quebec, Canada, July 2007.
  - E. Fox attended and presented one paper.
- Energy Minimization Methods in Computer Vision and Pattern Recognition (EMMCVPR) Conference, Hubei, China, August 2007
  - Anuj Srivastava presented two papers and chaired a session.
- IEEE 2007 Statistical Signal Processing Workshop, Madison, WI, August 2007.
  - J. Fisher, V. Chandrasekaran, E. Ertin, A. Willsky, V. Tan, M.J. Choi attended and presented 5 papers.
- The 45th Allerton Conference on Communications, Control, and Computing, Urbana-Champagne, IL, Sept. 2007 .
  - A. Willsky, and J. Johnson attended and presented 2 papers.
- 46th Annual Conference on Decision and Control, New Orleans, LA, December 2007
  - David Castañón organized the meeting and presented one talk.
- Conference on Neural Information Processing Systems (NIPS), Vancouver, Canada, Dec. 2007
  - V. Chandrasekaran, D. Malioutov, and A. Willsky attended and presented 3 papers.
- 2008 Information Theory and Applications Workshop, La Jolla, CA, Jan.-Feb. 2008.
  - J. Fisher attended and presented 1 paper.
- SPIE Defense and Security Symposium. Algorithms for Synthetic Aperture Radar Imagery Conference, Orlando, FL, March 2008.
  - C. Karl, M. Çetin and L. Potter served as invited panelists.
  - K. Dungan, E. Ertin, J. Jackson, R. Moses, C. Karl, I. Stojanovic, M. Çetin, and O. Batu attended and presented 8 papers.
- SPIE Defense and Security Symposium. Intelligent Computing Conference, Orlando, FL, March 2008.

  - E. E. Ertin attended and gave a tutorial talk on Learning spatial models for indoor tracking of wireless nodes.

- IEEE Conference on Signal Processing and Communications Applications, June 2007.
  - M. Çetin presented an invited paper at a special session on Radar and Sensor Signal Processing.

- 2008 Ohio Space Grant Consortium Research Symposium, Ohio Aerospace Institute, Cleveland, OH, April 2008.
  - C. Austin attended and gave an invited presentation.

- 2008 International Conference on Acoustics, Speech, and Signal Processing
  - Emre Ertin, John Fisher, Al Hero, Randy Moses, Joshua Ash attended, presenting 8 papers.

- International Conference on Machine Learning, Helsinki, Finland, July 2008.
  - E. Fox will attend and present 1 paper.

(c) Consultative and Advisory Functions

- A. Hero was a participant and one of 6 invited speakers at the National Research Council meeting on detection of IEDs (March 2008).
- A. Hero organized the Workshop on Signal and Information Processing for the Army Research Office in Aug. 2007.
- Prof. Willsky is the sole academic on the Senior Review Panel for DARPA's POSSE (Persistent Operational Surface Surveillance and Engagement) program. This program aims at intergrating multiple sources of information to discover patterns of behavior and identify threats in urban environments, with a specific focus on detecting IED emplacements, pinpointing materiel caches, and ultimately identifying bombmaking facilities. The sensors to be used include GMTI, SAR, E/O, and Hyperspectral.
- Prof. Willsky continues as Chief Scientific Consultant to BAE Systems Advanced Information Technologies (formerly ALPHATECH, Inc.) where a considerable portion of his activity falls within BAE-AIT's Fusion System and Technology Division (led by one of Prof. Willsky's former Ph.D. students, Dr. Mark Luettgen).
- D. Castañón served on the Air Force Scientific Advisory Board. In this role, he served on the review panels for AFRL RM and AFRL RW in the fall of 2007. He was part of the study on *Operational Utility of Small Satellites* which was finished in Summer, 2007. He will be one of the two leaders of the review team that will evaluate AFRL-RY in the fall of 2008, including the work on ATE/ATR.
- A. Hero served as member of National Research Council.

- A. Hero served on the Technical Assessment Board for Army Research Laboratory (ARLTAB).

(d) Technology Assists, Transitions, and Transfers

- A. Srivastava has collaborated with research groups in different application domains to apply tools from statistical analysis of shapes. Firstly, there has been several experiments and results that show that shape can be an important factor for diagnosis using medical images. In particular, Srivastava participated in a study that quantifies changes in shapes of corpus callosum in human brain due to Williams Syndrome (paper is being written about these results). He also participated in study of shapes of fiber structure in human brain using HARDI data [55]. Secondly, he is continuing to work with a research group at the University of Lille 1, France, on analyzing shapes of facial surfaces using laser scan data [20, 21]. Thirdly, he has collaborated with Prof. Rama Chellappa and Ashok Veeraraghavan on development of statistical models of shapes and execution rates of activities to help recognize human activity in video [22].
- Al Hero served on the Ph.D. committee for Joshua Ash (Ohio State) in December 2007; Dr. Ash is a postdoctoral researcher for this MURI.
- Al Hero has transitioned sensor management techniques partially developed under this MURI to TechFinity, Inc, under a Missile Defense Agency program. Dr. John Armenian is the point of contact at TechFinity and Tracy Wnentworth is the contact at MDA.
- A. Willsky and J. Fisher are involved in collaborations and interchanges with MIT Lincoln Laboratory, transitioning their research on information fusion using graphical models, sensor resource management, and multi-target tracking and discrimination.

# 7 Inventions and Patent Disclosures

None

# 8 Honors and Awards

(a) Honors and Awards Received During the Grant Period

- D. Castañón is serving as President of the IEEE Control Systems Society in 2007.
- A. Hero serves as President of the IEEE Signal Processing Society.
- A. Willsky has been appointed Acting Director of MITs Laboratory for Information and Decision Systems.
- Müjdat Çetin has received The Turkish Academy of Sciences Young Scientist Award.

- One part of our work on shape analysis [6] has received the 2007 Elsevier Signal Processing Journal Best Paper Award.
- Anuj Srivastava has received the Graduate Mentor Faculty Award from FSU in 2008. This award is given to faculty "whose dedication to graduate students and commitment to excellence in graduate education and mentoring have made a significant contribution to the quality of life and professional development of graduate students".

## 9 Publications

The following is a list of papers, theses, and other publications of research supported in whole or in part by this project.

[1] D. A. Castañón and V. Saligrama, "Reliable Distributed Estimation with Intermittent Communications," in *Network Sensing, Information and Control* (V. Saligrama, ed.), Springer-Verlag, 2007.

[2] R. Rangarajan, A. Hero, and R. Raich, "Optimal sequential design of experiments for estimation in linear models," *IEEE Journ. on Selected Topics in Signal Processing*, vol. 1, pp. 67–78, June 2007.

[3] J. L. Williams, J. W. Fisher III, and A. S. Willsky, "Approximate dynamic programming for communication-constrained sensor network management," *IEEE Transactions on Signal Processing*, vol. 55, pp. 3995–4003, August 2007.

[4] E. B. Fox, J. W. Fisher III, and A. S. Willsky, "Detection and localization of material releases with sparse sensor configurations," *IEEE Transactions on Signal Processing*, 2007 (to appear).

[5] R. Ahmad, D. S. Vikram, B. Clymer, L. C. Potter, Y. Deng, P. Srinivasan, J. L. Zweier, and P. Kuppasamy, "Uniform distribution of projection data for improved reconstruction quality of 4D EPR imaging," *Journal of Magnetic Resonance*, vol. 187, pp. 277–287, Aug. 2007.

[6] J. Kim, M. Cetin, and A. S. Willsky, "Nonparametric shape priors for active contour-based image segmentation," *Signal Processing*, vol. 87, no. 12, pp. 3021–44, 2007.

[7] S. Aeron, V. Saligrama, and D. A. Castañón, " Energy Efficient Policies for Target Tracking in Multihop Sensor Networks," *IEEE Transactions on Signal Processing*, May 2008.

[8] A. W. V. Chandrasekaran, J.K. Johnson, "Estimation in gaussian graphical models using tractable subgraphs: A walk-sum analysis," *IEEE Transactions on Signal Processing*, vol. 56, pp. 1916–1930, May 2008.

[9] R. Ahmad, D. S. Vikram, L. C. Potter, and P. Kuppusamy, "Estimation of mean and median p02 values for a composite EPR spectrum," *Journal of Magnetic Resonance*, vol. 102, pp. 269–274, June 2008.

[10] S. Som, L. C. P. R. Ahmad, D. S. Vikram, and P. Kuppusamy, "EPR oximetry in three spatial dimensions using sparse spin distribution," *Journal of Magnetic Resonance*, 2008. (to appear).

[11] D. M. Malioutov, J. Johnson, M. J. Choi, and A. S. Willsky, "Low-rank variance approximation in gmrf models: Single and multi-scale approaches," *IEEE Transactions on Signal Processing*, 2008 (accepted).

[12] E. Bashan, R. Raich, and A. O. H. III, "Optimal two-stage search for sparse targets using convex criteria," *IEEE Trans. on Signal Processing*, vol. Accepted for publication, 2008.

[13] K. Varshney, M. Cetin, J. W. F. III, and A. S. Willsky, "Sparse signal representation in structured overcomplete dictionaries with application to synthetic aperture radar," *IEEE Trans. Signal Processing*. To appear.

[14] L. J. Moore and L. C. Potter, "Three-dimensional resolution in circular synthetic aperture radar," *IEEE Transactions on Image Processing*. in review; submitted August 2007.

[15] R. Ahmad, L. C. Potter, and P. Kuppusamy, "Multi-resolution uniform sampling for 3D tomography," *IEEE Transactions on Medical Imaging*. in review; submitted September 2007.

[16] M. Choi, V. Chandrasekaran, D. M. Malioutov, J. K. Johnson, and A. S. Willsky, "Multiscale stochastic modeling for tractable inference and data assimilation," *Computer Methods in Applied Mechanics and Engineering*, 2008 (to appear).

[17] K. R. Varshney and L. R. Varshney, "Quantization of prior probabilities for hypothesis testing," *IEEE Transactions on Signal Processing*, 2008 (under review).

[18] J. Johnson and A. Willsky, "A recursive model-reduction method for estimation in Gaussian Markov random fields," *Submitted to IEEE Trans. Image Processing*, vol. 17, pp. 70–83, January 2008.

[19] A. Srivastava and I. H. Jermyn, "Looking for shapes in two-dimensional cluttered point clouds," 2008.

[20] A. Srivastava, C. Samir, S. H. Joshi, and M. Daoudi, "Elastic shape models for face analysis using curvilinear coordinates," 2008.

[21] C. Samir, A. Srivastava, M. Daoudi, and E. Klassen, "An intrinsic framework for analysis of facial surfaces," 2008.

[22] A. Veeraraghavan, A. Srivastava, and R. Chellappa, "Rate-invariant recognition of humans and their activities," 2008.

[23] E. Bashan and A. O. H. III, "Two-stage multi-scale search for sparse targets," *IEEE Trans. on Signal Processing*, vol. In preparation, 2008.

[24] S. Som, L. C. Potter, R. Ahmad, and P. Kuppusamy, "A parametric approach to spectral-spatial EPR imaging," *Journal of Magnetic Resonance*, vol. 186, pp. 1–10, May 2007.

[25] U. Grenander, A. Srivastava, and S. Saini, "A pattern-theoretic characterization of biological growth," *IEEE Transactions on Medical Imaging*, vol. 26, no. 5, pp. 648–659, 2007.

[26] D. Kaziska and A. Srivastava, "Classification of cyclostationary processes on nonlinear shape manifolds for gait-based human recognition," *Journal of American Statistical Association*, Dec. 2007.

[27] W. Mio, A. Srivastava, and S. Joshi, "On shape of plane elastic curves," *International Journal of Computer Vision*, vol. 73, pp. 307–324, July 2007.

[28] L. Taycher, J. W. Fisher III, and T. Darrell, "Combining object and feature dynamics in probabilistic tracking," *Computer Vision and Image Understanding (special issue)*, vol. 108, pp. 243–260, 2007.

[29] R. Rangarajan, A. Hero, and R. Raich, "Optimal sequential design of experiments for estimation in linear models," *IEEE Journ. on Selected Topics in Signal Processing*, 2007. (to appear).

[30] K. R. Varshney, M. Cetin, J. W. Fisher III, and A. S. Willsky, "Sparse representation in structured dictionaries with application to synthetic aperture radar," *IEEE Transactions on Signal Processing*, accepted for publication 2008.

[31] V. S. S. Aeron and D. A. Castanon, "Energy efficient policies for distributed target tracking in multihop sensor networks," *IEEE Trans. Signal Processing*, 2007. (submitted).

[32] J. A. Jackson, B. D. Rigling, and R. L. Moses, "Canonical scattering feature models for 3D and bistatic SAR," *IEEE Transactions on Aerospace and Electronic Systems*, 2008. (submitted).

[33] H. Cao, E. Ertin, and A. Arora, "Min-max equilibrium of networked differential games," *ACM Transactions on Autonomous and Adaptive Systems*, 2007. (submitted).

[34] S. H. Joshi and A. Srivastava, "Intrinsic bayesian active contours for extraction of object contours in images," *International Journal of Computer Vision*, 2006. (in review).

[35] S. H. Joshi, E. Klassen, A. Srivastava, and I. H. Jermyn, "An efficient representation for computing geodesics between n-dimensional elastic shapes," in *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, June 2007.

[36] K. Varshney, M. Cetin, J. W. F. III, and A. S. Willsky, "A sparse signal representation-based approach to image formation and anisotropy determination in wide-angle radar," in *IEEE Conference on Signal Processing and Communications Applications*, (Eskisehir, Turkey), June 2007.

[37] O. Batu and M. Cetin, "Non-quadratic regularization-based image deblurring: Automatic parameter selection and feature-based evaluation," in *IEEE Conference on Signal Processing and Communications Applications*, (Eskisehir, Turkey), June 2007.

[38] A. Fan, J. Fisher III, W. Wells III, J. Levitt, and A. Willsky, "Mcmc curve sampling for image segmentation," in *Medical Image Computing and Computer-Assisted Intervention - MICCAI 2007* (N. Ayache, A. Ourselin, and A. Maeder, eds.), pp. 477–485, Springer-Verlag, 2007.

[39] E. Fox, E. Sudderth, and A. Willsky, "Hierarchical dirichlet processes for tracking maneuvering targets," in *Proceedings of the International Conference on Information Fusion, Quebec, Canada*, July.

[40] N. Balov, A. Srivastava, C. Li, and Z. Ding, "Clustering and classification of open curves in $r^3$ with applications to shape analysis of fiber bundles," in *Proceedings of Sixth International Workshop on Energy Minimization Methods in Computer Vision and Pattern Recognition (EMMCVPR), Hubei, China*, August 2007.

[41] E. Ertin and R. L. Moses, "Three dimensional target reconstruction from multi-pass circular SAR," in *Proceedings of fifteenth annual adaptive sensor array processing workshop. ASAP 2007*, (Lexington, MA), June 2007.

[42] M. J. Choi and A. S. Willsky, "Multiscale gaussian graphical models and algorithms for large-scale inference," in *Proceedings of IEEE 2007 Statistical Signal Processing Workshop*, August.

[43] J. L. Williams, J. W. Fisher III, and A. S. Willsky, "A constraint generation integer programming approach to information theoretic sensor resource management," in *Proc. IEEE Workshop on Statistical Signal Processing*, August 2007.

[44] S. H. Joshi, A. Srivastava, E. Klassen, and I. H. Jermyn, "Removing shape-preserving transformations in square-root elastic (sre) framework for shape analysis of curves," in *Proceedings of Sixth International Workshop on Energy Minimization Methods in Computer Vision and Pattern Recognition (EMMCVPR), Hubei, China*, August 2007.

[45] V. Chandrasekaran, J. Johnson, and A. Willsky, "Maximum entropy relaxation for graphical model selection given inconsistent statistics," in *Proceedings of IEEE 2007 Statistical Signal Processing Workshop*, August.

[46] S. Sanghavi, V. Y. F. Tan, and A. S. Willsky, "Learning graphical models for hypothesis testing," in *Proceedings of IEEE 2007 Statistical Signal Processing Workshop*, August.

[47] E. Ertin, "Gaussian process models for censored sensor readings," in *Proceedings of IEEE/SP 14th Workshop on Statistical Signal Processing. SSP '07.*, (Madison, WI), pp. 665–669, Jul 2007.

[48] J. Johnson, D. Malioutov, and A. Willsky, "Lagrangian relaxation for map estimation in graphical models," in *Proceedings of 45th Annual Allerton Conf. on Communication, Control and Computing*, September.

[49] J. Chandrasekaran, J. Johnson, O. Kreidl, D. Malioutov, S. Sanghavi, and A. Willsky, "Message passing and distributed statistical inference," in *Proceedings of 45th Annual Allerton Conf. on Communication, Control and Computing*, September.

[50] A. Srivastava, I. H. Jermyn, and S. Joshi, "Riemannian analysis of probability density functions with applications in vision," 2007.

[51] V. Chandrasekaran, J. Johnson, and A. Willksy, "Adaptive embedded subgraph algorithms using walk-sum analysis," in *Proceedings of the Advances in Neural Information Processing Systems*, December.

[52] P. Schniter, L. C. Potter, and J. Ziniel, "Fast bayes matched pursuits," in *Proc. Workshop on Information Theory and Applications (ITA)*, Jan. 2008.

[53] J. W. Fisher III, V. Y. F. Tan, and A. S. Willsky, "Learning max-weight discriminative forests," in *Proceedings of Information Theory and Applications Workshop*, January.

[54] Z. Liang, S. Do, W. C. Karl, T. J. Brady, and H. H. Pien, "Cardiac ct artifact mitigation through decomposition-based image reconstruction," in *Proceedings of SPIE: Physics of Medical Imaging*, vol. 6913, February, 18-21 2008.

[55] M.-C. Chiang et al (including Srivastava), "Mapping genetic influences on brain fiber architecture with high angular resolution diffusion imaging (hardi)," in *Proceedings of International Symposium on Biomedical Image: From Nano to Macro*, 2008.

[56] M. Uney and M. Cetin, "Target localization in acoustic sensor networks using factor graphs," in *IEEE Conference on Signal Processing, Communications, and their Applications*, (Aydin, Turkey), April 2008.

[57] O. Batu and M. Cetin, "Hyper-parameter selection in non-quadratic regularization-based radar image formation," in *Algorithms for Synthetic Aperture Radar Imagery XV* (E. G. Zelnio and F. D. Garber, eds.), Proc. SPIE, (Orlando, FL), March 2008.

[58] E. Ertin, R. L. Moses, and L. C. Potter, "Multibaseline IFSAR for three dimensional target reconstruction," in *Proceedings of SPIE* (E. G. Zelnio and F. D. Garber, eds.), vol. 6970, March 2008.

[59] R. L. Moses and J. Ash, "Resursive SAR imaging," in *Proceedings of SPIE* (E. G. Zelnio and F. D. Garber, eds.), vol. 6970, March 2008.

[60] I. Stojanovic, W. C. Karl, and M. Cetin, "Joint space-aspect reconstruction of wide-angle sar exploiting sparsity," in *Proceedings of SPIE: Algorithms for Synthetic Aperture Radar Imagery XV*, vol. 6970, Mar. 2008.

[61] L. C. Potter, P. Schniter, and J. Ziniel, "Sparse Reconstruction for RADAR," in *Proceedings of SPIE: Algorithms for Synthetic Aperture Radar Imagery XV*, vol. 6970, Mar. 2008.

[62] K. E. Dungan, L. C. Potter, J. Blackaby, and J. Nehrbass, "Discrimination of Civilian Vehicles using Wide-angle SAR," in *Proceedings of SPIE: Algorithms for Synthetic Aperture Radar Imagery XV*, vol. 6970, Mar. 2008.

[63] O. Batu and M. Cetin, "Hyper-parameter selection in advanced synthetic aperture radar imaging algorithms," in *IEEE Conference on Signal Processing, Communications, and their Applications*, (Aydin, Turkey), April 2008.

[64] V. C. Myung Jin Choi and A. S. Willsky, "Maximum entropy relaxation for mutiscale graphical model selection," in *Proceedings of ICASSP*, April.

[65] K. R. Varshney and L. R. Varshney, "Minimum mean bayes risk error quantization of prior probabilities," in *Proceedings of ICASSP*, April.

[66] V. Y. F. Tan, J. W. Fisher III, and A. S. Willsky, "Learning max-weight discriminative forests," in *Proceedings of ICASSP*, April.

[67] E. Fox, E. Sudderth, M. Jordan, and A. Willsky, "Message passing and distributed statistical inference," in *Proceedings of the International Conf. on Machine Learning*, July.

[68] E. Chong, A. Hero, and C. Kreucher, "Monte-carlo-based partially observable markov decision process approximations for adaptive sensing," in *Proc. of Workshop on discrete event systems (WODES)*, Aug. 2008.

[69] I. Stojanovic, W. C. Karl, and M. Cetin, "Sparsity-based reconstruction of wide-angle sar," in *2008 IEEE Intl. Conf. Image Processing*, (San Diego), Sept. Submitted.

[70] K. R. Varshney and A. S. Willsky, "Supervised learning of classifiers via level set segmentation," in *Proceedings of IEEE International Workshop on Machine Learning for Signal Processing, (under review)*, October 2008.

[71] M. Siracusa and J. W. Fisher III, "Tractable bayesian learning of switching autoregressive trees," in *Proceedings of the Conference on Neural Information Processing Systems*, 2008.

[72] S. H. Joshi, E. Klassen, A. Srivastava, and I. H. Jermyn, "An efficient representation for computing geodesics between n-dimensional elastic shapes," in *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, June 2007.

[73] M. Kulikova, M. Mani, A. Srivastava, X. Descombes, , and J. Zerubia, "Tree species classification using radiometry, texture and shape based features," in *European Conference on Signal Processing (EUSIPCO), Poland*, p. to appear, 2007.

[74] A. Srivastava, I. H. Jermyn, and S. H. Joshi, "Riemannian analysis of probability density functions with applications in vision," in *IEEE Conference on Ccomputer Vision and Pattern Recognition (CVPR)*, (Minneapolis, MN), June 2007.

[75] E. Bashan, R. Raich, and A. O. H. III, "Adaptive sampling: Efficient search schemes under resource constraints," tech. rep., University of Michigan, Communications and Signal Processing Lab., Tech. Rep. 385, Aug. 2007.

[76] E. Bashan, *Efficient Resource Allocation Schemes for Search.* PhD thesis, 2008.

[77] D. Malioutov, *Approximate inference in Gaussian graphical models.* PhD thesis, MIT, Cambridge, MA, May 2008.

[78] J. Johnson, *Convex Relaxation Methods for Graphical Models: Lagrangian and Maximum-Entropy Approaches.* PhD thesis, MIT, Cambridge, MA, 2008.

[79] V. Chandrasekaran, "Modeling and estimation in gaussian graphical models: Maximum-entropy relaxation and walk-sum analysis," Master's thesis, MIT, Cambridge, MA, 2007.

[80] Z. Chen, "Efficient multi-target tracking using graphical models," Master's thesis, MIT, Cambridge, MA, May 2008.

[81] M. Choi, "Multiscale gaussian graphical models and algorithms for large-scale inference," Master's thesis, MIT, Cambridge, MA, 2007.

[82] N. Ramakrishnan, "Joint enhancement of multichannel synthetic aperture radar data," Master's thesis, The Ohio State University, Mar. 2008.