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<b>6. AUTHOR(S)</b> R. Moses, D. Castanon, M. Cetin, E. Ertin, J. Fisher, A. Hero, C. Karl, L. Potter, A. Srivastava, A. Willsky	<b>5d. PROJECT NUMBER</b>
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**14. ABSTRACT**  
This report summarizes the research activities of this MURI project during the first 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

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## 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 2006 to 30 April 2007

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

The research program has already resulted in significant advances in the three core research challenge areas, and also in cross-area collaborations and joint research efforts.

In the area of **front-end signal processing**, new sparse imaging and information extraction approaches for circular SAR measurements have been developed, and both models and processing methods for non-conventional data geometries suitable for sensor management and decision-directed fusion have been derived. The developed feature models have both parameters estimates and feature uncertainties that can be used as inputs in hierarchical information fusion algorithms. In the area of **sensor management**, information-theoretic bounds as well as sequential and adaptive algorithms for waveform scheduling and aperture selection have been developed, and we have begun to investigating non-myopic approaches to management that integrate elements of off-line learning with on-line resource allocation in order to develop real-time algorithms capable of scaling to large multimodal sensing scenarios. In the area of **information fusion**, we have developed a framework for efficient fusion algorithms, new methods for tracking and behavior characterization, and have begun to address issues in robustness to calibration errors or unreliable communication

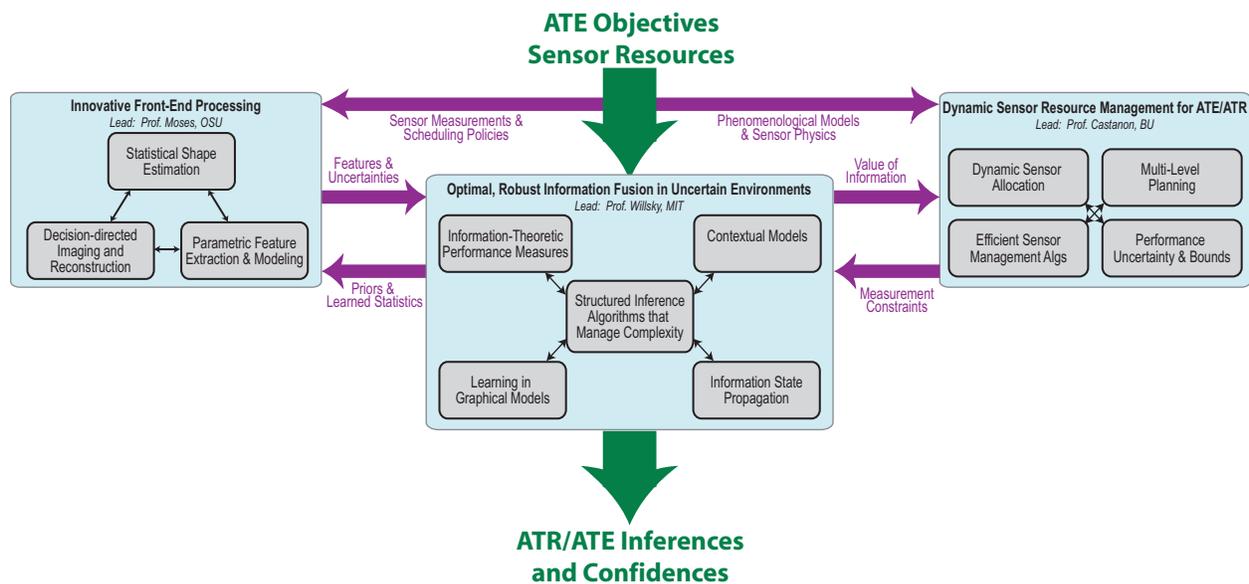


Figure 1: System-theoretic approach to inference-driven ATE. Front-end processing and sensor management are directed to support ATE inference, and provide information and uncertainties that are aggregated to quantify ATE inference performance.

among distributed sensors. These accomplishments and continued research directions are detailed in Section 4

The team has been engaged in several collaborative research activities. In December 2006, the MURI team held a two-day workshop in Boston to facilitate detailed research presentations and discussions. More than 25 research posters were presented, and several joint research interactions across topic areas and universities resulted. Additionally, Professor Al Hero of University of Michigan was on sabbatical leave during Autumn 2006 with Professor Willisky's group at MIT. Several joint research topics have resulted from these 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.

Several students working on this MURI have spent summer 2006 at AFRL in Dayton or at companies working on target recognition and exploitation problems. Additional internships are planned for Summer 2007.

### 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 first 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:* [19], [27]

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.

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.

The models have also been applied to extract extended target information from SAR data using non-conventional processing approaches. Typical SAR image formation methods assume the observed scene is characterized by a collection of independent point scatters. Imaging methods that handle both non-isotropic 3D scattering behavior have been developed. These methods are amenable to more complex observation geometries, can be extended to multi-channel data and are robust to data loss.

### **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)

*Topic:* Signal Processing, Information Fusion

*Publications:* [52], [1] [41], [40], [42], [20]

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.

Advances in of joint image formation and anisotropy characterization in wide-angle SAR have been made. The main idea is to perform joint anisotropy characterization and imaging (reflectivity estimation), by posing both problems as sparse signal representation problems. One general principle in previous work on the anisotropy problem has been to divide the full wide-angle aperture into smaller subapertures and form a sequence of subaperture images with inherently reduced cross-range resolution for use in further processing. Another general principle has been to develop parametric models for angle-dependent scattering behavior. The proposed methodology does not suffer a reduction in resolution because the entire available aperture is used and is more flexible than parametric models. The proposed framework solves for multiple spatial locations jointly, ameliorating the ill-effects of close proximity neighboring scatterers. In wide-angle imaging, besides anisotropy becoming prominent, certain scattering mechanisms appear to migrate in their spatial location as a function of aspect angle. This type of scattering, which has not been given much heed in past work, is well-incorporated into the overcomplete basis formulation. A graph-structured interpretation is developed leading towards novel approximate algorithms to solve the inverse problem. These algorithms, having reduced memory requirements, may well find application in a wide variety of sparse signal representation settings beyond the specific problem of anisotropy in SAR. The inter-relationship 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.

The estimation approach has also been developed and demonstrated for tomographic imaging with a spatially varying blur. The blur is parametrized, and image values are jointly estimated with the spatial map of blur parameters. Application is demonstrated in electron paramagnetic resonance (EPR), where the blur is due to local oxygen pressure. The proposed approach provides lower mean square reconstruction error and a 30:1 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.

Techniques for joint enhancement and regularized tomographic inversion of multichannel SAR data have also been developed. For multichannel data, independent enhancement of each channel degrades the relative phase information. Two methods have been developed for solving the joint reconstruction problem with constraints on pixel magnitude: a gradient-based technique and a Lagrange-Newton-based technique. The algorithms have been shown to provide effective 3D feature sets from sparse aperture SAR data.

**Information Fusion for Multistatic MIMO with calibration errors***Researchers:* Alfred Hero (UM), Mike Davis (UM)*Topic:* Information Fusion, Signal Processing*Publications:* [55]

This project aims to develop optimal radar imaging and fusion methods for multistatic MIMO imaging platforms. A hybrid Cramér Rao lower bound has been formulated to explore the effect of small miscalibration errors on achievable image resolution and MSE. Numerical evaluations of the CRB are presently being conducted to explore fundamental limitations and feasibility of deploying a network of cooperating earth, air and space based multistatic MIMO radars. The Directed Study Report by Masters student Mike Davis [55] provides details on the derivation of the hybrid CRB.

**Efficient Fusion Algorithms***Researchers:* Alan Willsky (MIT), Venkat Chandrasekaran (MIT), Jason Johnson (MIT)*Topic:* Information Fusion*Publications:* [36], [37]

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. It is in this area that significant recent advances have been made in developing powerful and nearly optimal algorithms. New results include: (i) so-called “embedded subgraph” algorithms with easily verified conditions for optimality; (ii) a very powerful approach to near-optimal estimation based on thinning complex models in the context of recursive fusion; and, (iii) a new approach to building and “thinning” graphical models based on the principle of maximum entropy.

**Novel methods for the tracking and behavior characterization of multiple targets***Researchers:* Alan Willsky (MIT), Emily Fox (MIT), Michael Chen (MIT), Ahmed Fasih (OSU)*Topic:* Information Fusion, Signal Processing*Publications:* [31], [35]

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. In particular, the scalability is of considerable importance in military contexts such as tracking in urban environments. In Summer 2007 Ahmed Fasih at OSU will apply these techniques to tracking from SAR video, as part of his summer internship at SET Corporation.

**Asynchronous Hierarchical Estimation with Unreliable Communications**

*Researchers:* David Castañón (BU), Venkatesh Saligrama (BU)

*Topic:* Information Fusion, Sensor Management

*Publications:* [51]

This research addresses the problem of protocols for information distribution from networks of sensors that perform local processing to estimate the states of individual objects. Prior work in distributed estimation focused on a synchronous paradigm where multiple sensors used reliable communications networks to distribute local estimates and compressed information. This work focuses on a paradigm with lossy communications, whereby sensor communications may be lost. The goal is to explore local coding strategies to ensure that little information is lost even though messages are lost in the network. The research is investigating alternative protocols to guarantee that optimal or near-optimal estimates can be constructed in the presence of lossy communications.

**Dynamic Model Identification for Unknown Shapes**

*Researchers:* David Castañón (BU), Randy Moses (OSU), Christian Austin (OSU), Michael Rodehorst (BU)

*Topic:* Information Fusion, Signal Processing

*Publications:* [58], [21]

This research addresses the problem of estimating extended objects in the absence of detailed models of object structure. The goal is to develop algorithms capable of learning the detailed models from multiple measurements through information fusion, and using the models to refine the position, velocity and orientation information of the object. Objects are represented as distributed collections of features. In one approach, the algorithm tracks individual features and learns their coherent motions to build a rigid body model of features rotating and translating around a nominal centroid. Features that are initially obscured can be discovered using additional measurements, and thus grow the model details to better explain the position. Currently, these algorithms are tailored to exploit LADAR sensing. The goal is to be able to adaptively build dynamic 3-D templates of unknown objects for automated target exploitation. In a second direction, distributed features from interferometric SAR (IFSAR) are combined to develop a composite 3D shape estimate of the object from a collection of ISFAR image pairs collected at different orientations. The approach is to first detect which regions of high energy in the scene correspond to a dominating scattering center whose 3D location can be accurately estimated from two SAR images at closely-spaced elevation angles. Scattering regions that pass the detection test are used to estimate 3D object scattering; multiple images can be noncoherently combined to reconstruct a more complete object representations. As part of this research, detection errors and scattering location estimation errors are quantified.

**3D Target Reconstruction for Circular SAR**

*Researchers:* Emre Ertin (OSU), Randy Moses (OSU), Lee C. Potter (OSU)

*Topic:* Signal Processing

*Publications:* [26], [27], [29]

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 datadome released by AFRL and measured CSAR data from the AFRL GOTCHA program.

**Advances in Shape Analysis of Curves and Surfaces**

*Researchers:* Anuj Srivastava (FSU), Shantanu Joshi (FSU)

*Topic:* Signal Processing

*Publications:* [14], [4], [15], [13], [16]

This research improves on the past ideas and implementations 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:* [32]

This research addresses the two 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. Recent advances significantly improve the ability to automatically select reconstruction hyperparameters that currently must be manually selected.

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. This research is developing imaging algorithms that exhibit robustness to such errors. The modality of particular interest is SAR. For SAR, existing autofocus-based techniques for dealing with model errors are not satisfactory in a sparse aperture imaging context. These techniques rely heavily on conventional image formation, and view the best model parameter estimate as the one that improves the conventional image in a particular fashion. Yet, in sparse aperture imaging contexts, conventional images are often not of acceptable quality, even if there are no model errors. This research is formulating problems and solutions to joint sparse aperture imaging and model error correction.

### **Sequential Adaptive Waveform Scheduling and Aperture Selection**

*Researchers:* Alfred Hero (UM), Lee Potter (OSU), Raghuram Rangarajan (UM), Raviv Raich (UM), Rizwan Ahmad (OSU)

*Topic:* Sensor Management

*Publications:* [7], [53]

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. In the paper [7] (in press) it is demonstrated that for fixed average energy surprisingly large gains in MSE can be achieved by a simple energy packetization procedure. The radar initially probes the medium with a small amount of energy and, depending on the measured return, a decision is made to send (or not) a “confirmation probe” based on initial return using an optimal thresholding function. If a confirmation probe is sent then the process is repeated. Performance gains have been demonstrated in detection, classification and estimation tasks and can be surprisingly large, e.g., greater than 5dB gain for estimating a reflectivity parameter in additive white Gaussian noise [7].

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  $N$ ; however, practical applications may call for arbitrary  $N$  and may deny some angles as unobservable. This is the case, for example, for radar apertures flown in urban environments. A modification of Fekete points on  $S^3$  is presented. The approach is demonstrated for spectral-spatial imaging using electron spin resonance. The technique currently gives a fixed sampling pattern, and therefore may be considered open-loop sensing; data-adaptive strategies are under consideration.

### **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], [44], [45], [56]

This research addresses the development performance bounds for information-theoretic sensor management. Both off-line and on-line open-loop bounds which relate greedy sensor selection criterion to optimal (yet intractable) sensor selection have been developed. The bounds are suitable for performance prediction and estimation. Additionally, these bounds have led to the development of

tractable sensor management methods in the presence of resource constraints.

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. The approach under investigation is to combine off-line learning models that work on using multimodal information for classification of potential targets, with on-line resource allocation models that distribute the available sensing resources among large numbers of targets using pricing strategies. The hypothesis is that off-line learning can identify the relative value of the different types of information provided by different sensor types towards object identification, whereas on-line resource allocation can equilibrate the loads imposed on the different sensors across the suite of objects of interest.

### **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:* [50], [8]

This research was motivated by a sensor management problem posed by Williams, Fisher and Willsky concerning the management of reporting sensors and fusion center locations for estimating the states of objects using a network of sensors in the presence of costly communications. The goal of the research was to develop insights into simple management strategies by analyzing a limit model where the cost of information and estimation error was greatly simplified, thus reducing the combinatorial complexity associated with sensor selection. Analysis of the limit model established a threshold strategy for determining how to switch fusion center locations adaptively based on estimated object position. The results of the limit problem provide simple, interesting strategies for controlling the fusion center location and reporting sensors in networks of symmetric sensors.

This research also considers the problem of managing a set of sensors to observe objects incurring infrequent maneuvers. The goal is to classify objects by observing the types of maneuvers that the objects incur. This requires high data rate observations near the time of maneuvers, which in turn requires careful management of sensor attention to provide such observations. The goal of the research is to develop agile sensor management algorithms that can focus attention on important objects that may be undergoing revealing maneuvers in order to provide accurate classification on those objects.

## **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 Castan, 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

**MIT:** Venkat Chandrasekaran; Michael Chen; Emily Fox; Jason Johnson; Mike Siracusa; Kush Varshney; Jason Williams

**Boston U.:** Birant Borten; Brian Corwin; Paul DeBitetto; Darin Hitchins; Karen Jenkins; Ivana Stojanovic

**Michigan:** Mark Davis, Raghuram Rangarajan

**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) Participation/presentations at meetings, conferences, seminars, etc.

- Fortieth Asilomar Conference on Signals, Systems and Computers, Nov 2006.
  - E. Ertin attended and presented a paper [26].
  - John Fisher, Michael Siracusa and Emily Fox attended, presenting two papers.
- SPIE Defense and Security Symposium. Algorithms for Synthetic Aperture Radar Imagery Conference, Orlando, FL, April 2007.
  - M. Çetin and R. Moses served as invited panelists.
  - E. Ertin, J. Jackson, R. Moses and N. Ramakrishnan attended and presented three papers [27], [19], [20].
- SPIE Defense and Security Symposium. Intelligent Computing Conference, Orlando, FL, April 2007.
  - E. Ertin attended and presented a paper [28].
  - E. Ertin served as the Conference co-chair.
- IEEE Conference on Signal Processing and Communications Applications, June 2007.
  - M. Çetin has been asked to give an invited paper [42] at a special session on Radar and Sensor Signal Processing.

- AFOSR FITE workshop, Lincoln Lab, Aug. 2006.
  - Alfred Hero attended.
- Army Workshop on Image Understanding, College Park, MD, Jan. 2007.
  - John Fisher, Alfred Hero, Randy Moses, and Anuj Srivastava gave invited presentations. Anuj Srivastava organized and chaired the workshop.
- CIA, Langley, VA, December 2006.
  - Alfred Hero gave an invited presentation.
- ASME 2nd Annual Dayton Engineering Sciences Symposium, Wright State University, October 30, 2006.
  - Julie Jackson attended and gave an invited presentation.
- 2007 Ohio Space Grant Consortium Research Symposium, Ohio Aerospace Institute, Cleveland, OH, April 20, 2007.
  - C. Austin attended and gave an invited presentation.
- Eleventh International Conference on Artificial Intelligence and Statistics Workshop.
  - John Fisher, Michael Siracusa, Jason Johnson, and Venkat Chandrasekaran attended and presented three papers.
- 14th Annual Adaptive Sensor Array Processing Workshop
  - John Fisher, Emily Fox and Kush Varshney attended, presenting two papers.
- Ninth International Conference on Information Fusion
  - Emily Fox attended and presented one paper.
- 2007 International Conference on Acoustics, Speech, and Signal Processing
  - John Fisher, Michael Siracusa and Jason Williams attended, presenting 2 papers.
- 2006 Conference on Decision and Control, in San Diego, CA.
  - David Castañón attended, presenting 2 papers.
- Joint Conference of 12th In Vivo EPR Spectroscopy and Imaging 9th International EPR Spin Trapping/Spin Labeling, 29 April-3 May 2007, Chicago, IL.
  - Subhojit Som attended and presented one paper [52].

## (b) Consultative and Advisory Functions

- 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 integrating 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 Luetzgen).
- D. Castañón served on the Air Force Scientific Advisory Board and participated in the SN review in the fall of 2006.
- D. Castañón served on a study panel on the utility of small satellites for tactical ISR (Spring-Summer 2007).
- R. Moses, L. Potter, and E. Ertin provided technical consultancy and guidance on polarimetric features for EO systems to Dr. Greg Arnold at AFRL (various dates 7/20/06–2/1/07)
- E. Ertin has been invited to provide technical consultancy at the ATR Modeling Workshop organized by AFRL, SNAR, 6/16/07.
- A. Hero served as member of National Research Council.
- A. Hero served on the Technical Assessment Board for Army Research Laboratory (ARLTAB), and as member of ARLTAP SED Division Panel review, 2006.

## (c) Technology Assists, Transitions, and Transfers

- A. Srivastava's research at FSU on Statistical Shape Analysis has been selected by the Northrup-Grumman Company for an Innovation Alliance Award. This funding is being used to develop collaborations with Dr. Steven Schwartz and his team at the Northrup-Grumman company. Northrup-Grumman is expected to provide a dataset for ATR under clutter in Summer 2007.
- A. Hero directed the research of Mark Davis of General Dynamics - Advanced Information Systems while he was a M.S. student at UM in 2006. Results of this research will be used in developing information fusion techniques for uncalibrated multistatic MIMO radar networks.
- R. Moses' Ph.D. student, Julie Jackson, was a summer intern at AFRL in Dayton, OH during Summer 2006.
- R. Moses' Ph.D. student, Ahmed Fashi, was a summer intern at SET Corporation, Dayton, OH during Summer 2006.

- The results of this MURI's research on LADAR model identification and on radar scheduling for maneuver estimation have been provided to Lincoln Laboratory for application in related studies.
- Members of the MURI team are working with Draper Laboratory on developing methods for the fusion of visual landmarks with other sources of geolocation information.

## 7 Inventions and Patent Disclosures

None

## 8 Honors and Awards

### (a) Honors and Awards Received During the Grant Period

- D. Castañón was voted President Elect of the IEEE Control Systems Society.
- A. Srivisatva's Ph.D. student, Shantanu Joshi, was awarded the Graduate Student Research and Creativity Award for 2007. Only two students were selected in STEM areas for the whole of FSU.
- A. Hero's Ph.D. student, Raghuram Rangarajan, received UM Rackham Graduate School Distinguished Achievement Award (only awarded to one student in a UM graduate program) for research related to this project.
- R. Moses' Ph.D. student, Julie Jackson, was awarded Best Paper Prize at the ASME 2nd Annual Dayton Engineering Sciences Symposium.

### (b) Lifetime Achievement Honors

- Alfred Hero was named Fellow of IEEE and awarded the IEEE Third Millenium Medal.

## 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] 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.

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- [2] 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.
- [3] 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. (scheduled for publication).
- [4] C. Samir, A. Srivastava, and M. Daoudi, “Three-dimensional face recognition using shapes of facial curves,” *IEEE Transactions on Pattern Analysis and Pattern Recognition*, vol. 28, no. 11, pp. 1858–1863, 2006.
- [5] 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.
- [6] L. Taycher, J. W. Fisher III, and T. Darrell, “Combining object and feature dynamics in probabilistic tracking,” *Computer Vision and Image Understanding (special issue)*, 2007. (to appear).
- [7] 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).
- [8] 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).
- [9] E. Klassen and A. Srivastava, “A path-straightening approach for finding geodesics on shape spaces of closed curves in  $R^3$ ,” *SIAM Journal on Computing*, 2006. (submitted).
- [10] S. Joshi and A. Srivastava, “Intrinsic bayesian active contours for extraction of object contours in images,” *International Journal of Computer Vision*, Aug. 2006. (submitted).
- [11] C. Samir, A. Srivastava, M. Daoudi, and E. Klassen, “An intrinsic framework for analysis of facial surfaces,” *International Journal of Computer Vision*, Mar. 2007. (submitted).
- [12] H. Cao, E. Ertin, and A. Arora, “Min-max equilibrium of networked differential games,” *ACM Transactions on Autonomous and Adaptive Systems*, 2007. (submitted).
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- [15] 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.

- [16] 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), Aug. 2007.
- [17] L. Moore and L. Potter, “Three-dimensional resolution for circular synthetic aperture radar,” in *Algorithms for Synthetic Aperture Radar Imagery XIV* (E. G. Zelnio and F. D. Garber, eds.), vol. 6568 of *Proceedings of SPIE*, (Orlando, FL.), 9-13 April 2007.
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