REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
15/05/2006

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
15 May 2004 - 14 May 2006

4. TITLE AND SUBTITLE
Integrated Radar Imaging, Target Tracking and Sensor Scheduling

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-04-1-0371

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Edwin Chong
Louis L. Scharf

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Colorado State University
Office of Sponsored Programs
Fort Collins, Co 80523-2002

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research /NM
4015 Wilson Blvd
Mail Room 713
Arlington, VA 22203

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

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

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution A; approved for public release; distribution unlimited

AFRL-SR-AR-TR-06-0146

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This project had a start date of 15 May 2004 and an end date of 15 May 2006. During this time, we made good progress toward our goals in radar imaging, distributed detection, and sensor scheduling for target tracking. In the area of radar imaging, we have established a duality between radar imaging and time-varying spectrum analysis that is bringing insight into waveform design. For distributed detection we have proved an information-theoretic theorem that establishes the rate at which the ROC curve of a dense sensor network of one-bit sensors converges to the point where the probability of false alarm Pf is 0 and the portability of detection Pd is 1.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU		

Final Report:
Integrated Radar Imaging, Target Tracking, and Sensor Scheduling
Agreement # FA9550-04-1-0371

Edwin Chong* (PI) and Louis L. Scharf** (Co-PI)
Department of Electrical and Computer Engineering
*Department of Mathematics
**Department of Statistics
Colorado State University
Ft. Collins, CO 80523
Phone: 970-491-2979
Fax: 970-491-2249
Email: {echong,scharf}@engr.colostate.edu

May 2006

1 Objectives

Traditional, single-site radars and tracking systems factor into uncoupled, individually-optimized subsystems. We continue to claim that even in multiple-site systems, this basic factorization of subsystems holds up. However, as sensors become cheaper and more capable they will be distributed in random networks that communicate multi-site, multi-dimensional, multi-modal measurements to a global processor. When the data from such sensors are transmitted, unprocessed, they overwhelm the bandwidth of the network and the processing bandwidth of the global processor. Thus, some processing must be local, and the results of this processing must be efficiently coded for transmission to a global processor for fusing and decision making. Accordingly, we have developed a mathematical framework for integrated sensing and processing (ISP) for sensing networks.

The general goal of our research program was to integrate radar imaging, target tracking, and sensor scheduling. The specific issues we addressed are these:

- Radar imaging from multisensor arrays, to estimate range-Doppler and angle-angle rate scattering functions at controllable resolutions, depending on tracking requirements and sensor scheduling constraints.
- Distributed detection in sensor networks.
- Signal and window designs for imaging at variable resolutions, information rates, and confidences.
- Subspace beamforming for active and passive sensing.
- Automatic trade-off of beamforming and diversity in multisensor arrays, using recently discovered properties of conjugate gradient beamformers.
- Investigation of multiple coherence and canonical coordinates for registering or merging information from distributed sensor suites.
- Target tracking using particle filtering, a sequential Monte Carlo method for on-line learning in a Bayesian framework.
- Sensor scheduling for target tracking in sensor networks, including extensions to target classification and identification.

2 Overview of Effort

This project had a start date of May 15, 2004, and an end date of May 15, 2006. During this time, we made good progress toward our goals in radar imaging, distributed detection, and sensor scheduling for target tracking. In the area of radar imaging, we have established a duality between radar imaging and time-varying spectrum analysis that is bringing insight into waveform design. For distributed detection we have proved an information-theoretic theorem that establishes the rate at which the ROC curve of a dense sensor network of one-bit sensors converges to the point where the probability of false alarm P_F is 0 and the probability of detection P_D is 1. We have developed a theory of subspace beamforming that may be used to image distributed targets. And we have further refined our understanding of warp converging conjugate-gradient algorithms. On the topic of sensor scheduling, we have developed a modular framework for using Monte Carlo sampling for sensor management in target tracking. Our approach is flexible in that it can accommodate a variety of sensor models and tracking environments, as long as they can be specified as a module in our Monte Carlo simulation. We have also tackled the problem of tracking multiple targets with multi-sensor activation. Finally, we have incorporated network bandwidth control into sensor management by developing a duality-based distributed algorithm for flow-control in tracking and surveillance networks.

Our accomplishments are reported in the publications listed in 5. In the next section, we provide a summary of the significant work accomplished.

3 Accomplishments/New Findings

3.1 Radar Imaging

In the area of radar imaging, we have developed a four-corners description of the imaging problem. This description establishes connections between ambiguity functions, correlation functions, time-frequency distributions, and frequency-frequency spectra. These connections show that radar imaging is dual to the problem of time-frequency spectrum analysis in the sense that the aim of a time-frequency spectrum analyzer is to produce a thumb-tack distribution in time and frequency, whereas the aim of radar imaging is to produce a thumb-tack in range-Doppler. This duality brings window design for time-frequency spectrum analysis into play for radar imaging. As an unexpected result of this work we have established that Sussman's identity, Moyal's formula, and Janssen's equality are all simple Fourier transform identities of a more fundamental identity for two-variable convolutions [2]. We have extended this work to multi-sensor, vector-valued (as in polarization), ambiguities in space and time, using subspace filters.

3.2 Subspace and Distributed Detection

In [4], the problem of detection in a dense network of one-bit sensors has been framed. Moreover, a theorem has been proved that for unbiased sensors (a technical term defined in the paper), the (P_F, P_D) pair of the network converges to $(0, 1)$, making the network "asymptotically perfect." The theorem and result are information-theoretic in the sense that the rate of convergence depends on power through local SNR and bandwidth through number of sensors. Moreover, the rate is linear in bandwidth and logarithmic in power, as is usual. In our continuing work, we aim to extend this result to b-bit sensors and to m-ary classification. We have extended this result to binary trees of one-bit sensors and proved a convergence result.

We have the beginnings of a theory of information-theoretic imaging, wherein analog waveforms are designed to image a discrete distribution of complex scattering coefficients. The point of view is that the scattering coefficients, drawn from a source distribution, are to be communicated to a receiver array. The problem of waveform design is then a source coding or *precoder* problem of maximizing the rate at which the scattered field brings information to a receiver or *equalizer*. This problem was briefly outlined in our original DARPA proposal.

Our recent results on subspace beamforming have been adapted to active sensing of distributed targets, where the key idea is to image at two time scales using one time scale to learn the scattering environment and the other to detect.

3.3 Sensor Scheduling for Target Tracking

One of the key problems in the design and operation of modern tracking systems is sensor scheduling, which aims to improve tracking system performance, utilize limited system resources more effectively and efficiently, and offer much faster adaptation to changing environments. The basic problem is to select which sensors to activate for target tracking over time to trade off tracking performance with sensor usage costs. We approach this problem by formulating it as a partially observable Markov decision process (POMDP), by developing a Monte Carlo solution method using a combination of particle filtering for belief-state estimation and sampling-based Q-value approximation for lookahead. To evaluate the effectiveness of our approach, we considered a simple sensor-scheduling problem involving multiple sensors for tracking a single target (see [5] and [1]).

In this work, we explored the sensor-scheduling problem within a POMDP framework but without relying on analytic expressions for belief states. Instead, we develop a Monte Carlo solution approach that combines particle filtering for non-Gaussian, nonlinear belief-state estimation, and a Q-value approximation method for solving the POMDP via "lookahead." Our goal was to design a policy for sensor scheduling to manage (simultaneously) tracking performance and sensor usage. The Q-value approximation method aims to deal with the

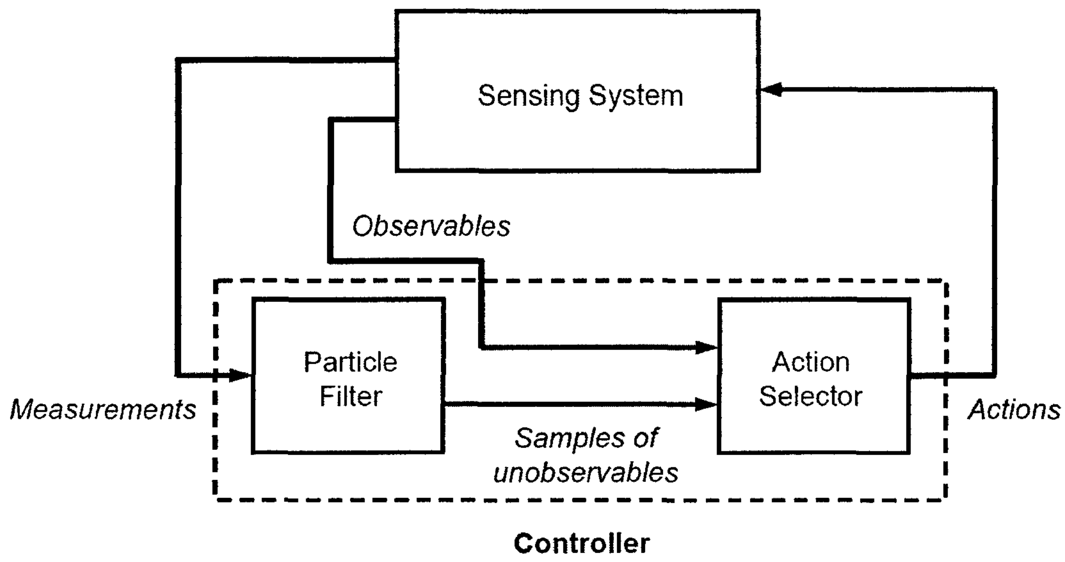

Figure 1: Basic control architecture with particle filtering and rollout.

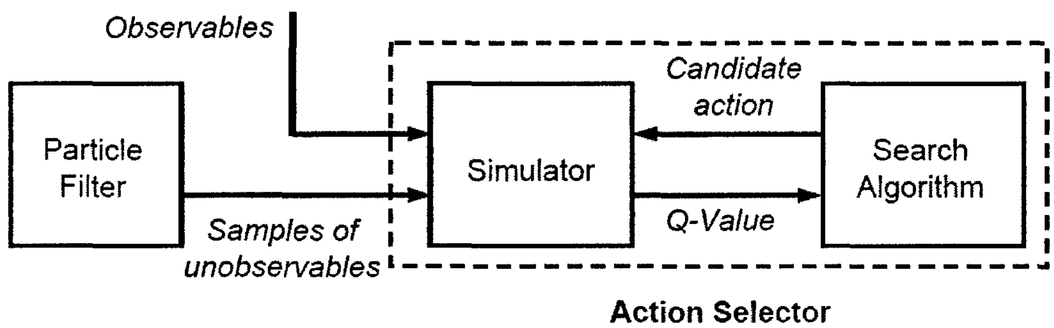

Figure 2: Components of the action selector.

issue that the state space for the POMDP model can be very large, practically ruling out the use of methods that rely on direct reasoning with the state space for computing an optimal policy.

Particle filtering is a promising Monte Carlo method for posterior-distribution estimation, working with random samples drawn from the process distribution. The Q-value approximation method involves computing, for each candidate action to be taken, a value of the "cost" of that action (the Q-value) and selecting the action with minimum cost. Our approach blends the two separate techniques in a natural way. The particle filter provides the Q-value approximation method a set of states (particles) to initiate the evaluation processes, and in return the Q-value approximation method delivers updated actions for the particle filtering belief-state estimation. Figure 1 shows the control architecture, while Figure 2 shows the action selector in this setting.

Our Monte Carlo approach for approximating POMDP solutions has some beneficial features. First, it is flexible in that a variety of sensor management scenarios can be tackled using the same framework. This is important because of the wide variety of sensors that may be encountered in practice. Second, the method does not require analytical tractability; in principle, it is sufficient to simulate a system component, whether or not its characteristics are amenable to analysis. Third, the framework is modular in the sense that models of individual system components (e.g., sensor types, target motion) may be treated as "plug-in" modules. Fourth, the approach integrates naturally with existing simulators (e.g., Umbra). Finally, the approach is inherently non-myopic, allowing the trade-off of short-term gains for long-term rewards.

We have developed a method to deal with multi-target tracking with multi-sensor activation. While much of our work began by focusing on Q-value approximation methods, our more recent work impacts the design of the particle filter tracker. Two factors need to be considered in this design. First, because we are measuring multiple targets, we have to incorporate data-association methods. Second, the activation of multiple sensors entails the fusion of multiple measurements of each target. Our approach here involved the development of a sequential JPDA method in the particle filter for belief-state updates in our sensor management framework. This turned out to be a challenging task. Our preliminary empirical results suggest that significant performance gains are possible with our approach [8].

3.4 Decentralized Rate Control for Tracking and Surveillance Networks

A conventional approach to network resource management entails formulating the task as a nonlinear optimization problem with some appropriate objective function. Typically, this objective function represents a network-oriented performance measure, such as throughput, average delay, or packet loss rate. The introduction of general utility functions as decision-making criteria in network-control mechanisms, such as congestion control, admission control, packet scheduling, and power control in wireless networks, has brightened the prospects of allowing user-oriented goals to drive network resource management. This is an important turn, because purely network-oriented goals do not always reflect positively on end-user criteria, which usually varies with application domain.

In this work, we consider the particular application domain of sensor networks—for tracking and surveillance—and explore the use of utility functions for driving flow-rate control. In such a system, multiple sensors collect measurements of physical quantities within some region containing targets of interest. The sensors participate in a network, communicating their measurement data to one or more destinations, typically commanders or command centers. Tracking and surveillance networks frequently suffer from significant communication-resource constraints, necessitating management of flows over these resources.

We adopt a duality formulation of the flow-control problem, giving rise to a primal-dual iteration mechanism for rate updates. This approach is familiar in the networking literature. However, it turns out that the specific characteristics of sensor networks in this application domain require the use of *joint* utility functions (which cannot be written as the sum of utilities associated with individual flow rates). This nonseparability of the objective function prohibits the direct application of standard primal-dual iterations, if we wish to maintain the decentralized nature of the scheme.

The requirement for joint utility functions in tracking and surveillance sensor networks stems from the geometric synergies associated with multiple sensors measuring common physical quantities (e.g., the location of a target). Information from multiple sensors can usually be combined (fused) to exploit the diversity in the measurements, which implies that the value of the joint measurements exceeds the sum of the values of the individual measurements. For example, in video applications, the range to a target generally cannot be determined using a single observer (absent ground constraints or other information). A similar situation often exists with radar systems, in which case very accurate range information is available, but angular errors can be quite large. Networked tracking systems with sensors that lack quality information in some dimension benefit greatly from multiple observers, gaining the geometric diversity needed to form good quality tracks.

Moreover, when a sensor is measuring multiple quantities (e.g., the locations of two targets), the tradeoff in the information rate being transmitted from the sensor through scarce networking resources (bandwidth) often depends on what information on these quantities is available from other sensors. For example, if a sensor has sight of two targets, one of which is already well covered by another sensor, it may be more valuable for the (first) sensor to be transmitting sensing data for the other target.

The problem then becomes one of determining the group of sensors and their relative contributions that provides the best information on a target. To this end, one can define a joint utility function that provides a measure of effectiveness as a function of the rate at which information of different *types* is received. For example, an "information type" might be defined to be observations corresponding to a particular sensor-target pair, or perhaps a search for new targets by a particular sensor. This joint utility function and its derivatives are evaluated at certain points in the network at which the flows are collected, such as command centers.

The resulting problem has a simple form: maximize the (generally nonlinear) joint utility subject to bandwidth and flow constraints. Global planning methods for solving this problem can suffer when used in rapidly-changing environments—objective functions or constraints may change too quickly for a centralized solver to adapt and communicate a new strategy. A decentralized solution makes sense: as local conditions or commander needs change, communications can be adapted so as to best utilize the available bandwidth.

This work is reported in [7]

4 Personnel Supported

Principle Investigator: Edwin K. P. Chong (Colorado State University).

Co-Principle Investigator: Louis L. Scharf (Colorado State University).

Consultants: David C. Farden (North Dakota State University) and John Gubner (University of Wisconsin, Madison).

Post-Doctoral Fellows: Ying He, Yun Li, and Ali Pezeshki.

5 Publications

[1] Y. He and E. K. P. Chong, "Sensor scheduling for target tracking: A Monte Carlo sampling approach," *Digital Signal Processing*, to appear.

[2] D. C. Farden and L. L. Scharf, "The Sussman, Moyal, and Janssen Formulas Follow as Fourier Transform Identities of a More Fundamental Convolution Identity," *IEEE Signal Processing Magazine*, submitted September 2005, to appear 2006.

[3] D. C. Farden and L. L. Scharf, "Estimating Time-Frequency Distributions and Channel Scattering Functions using the Rihaczek Distribution," *IEEE Sensor Array and Multichannel Signal Processing Workshop*, Sitges, Spain, July 18, 2004.

[4] J. Gubner, "Cost Minimization of Distributed Detection Systems that use Decision Averaging," unpublished notes, September 2, 2004.

[5] Y. He and E. K. P. Chong, "Sensor scheduling for target tracking in sensor networks," in *Proceedings of the 43rd IEEE Conference on Decision and Control (CDC'04)*, Atlantis Resort, Paradise Island, Bahamas, December 14–17, 2004, pp. 743–748.

[6] Y. He and E. K. P. Chong, "Sensor scheduling for target tracking: A Monte Carlo sampling approach," in *Proceedings of the 2005 Workshop on Defense Applications of Signal Processing (DASP'05)*, The Homestead Resort, Midway, Utah, March 27–April 1, 2005 (Invited paper).

[7] E. K. P. Chong and B. E. Brewington, "Distributed communications resource management for tracking and surveillance networks," in *Proceedings of the Conference on Signal and Data Processing of Small Targets 2005* (SPIE Vol. 5913), part of the *SPIE*

Symposium on Optics & Photonics, San Diego, California, July 31–August 4, 2005, pp. 280–291.

[8] Y. Li, L. W. Krakow, E. K. P. Chong, and K. N. Groom, "Dynamic sensor management for multisensor multitarget tracking," *Proceedings of the 40th Annual Conference on Information Sciences and Systems*, Princeton, New Jersey, March 22–24, 2006 (Invited paper), pp. 1397–1402.

[9] A. Pezeshki, L. L. Scharf, and H. Cox, "On linearly- and quadratically-constrained quadratic minimization problems for beamforming and diversity combining," *Linear Algebra and Its Applications,* submitted Aug. 2005.

[10] L. L. Scharf, E. K. P. Chong, and Z. Zhang, "Algebraic equivalence of matrix conjugate direction and matrix multistage filters for estimating random vectors," *Forty-third IEEE Conference on Decision and Control,* Atlantis Resort, Paradise Island, Bahamas, December 14-17, 2004.

[11] L. L. Scharf, A. Pezeshki, and M. Lundberg, "Multi-rank adaptive beamforming," *IEEE Workshop Stat. Signal Processing,* Bordeaux, France, July 17-20, 2005.

[12] L. L. Scharf, H. Ge, and M. Lundberg, "Detection, estimation, and beamforming in expanding subspaces," *Joint US-Australian Workshop on Defense Applications of Signal Processing,* Oct. 31-Nov. 4, 2004 (Conference Postponed to March 2005)

[13] L. L. Scharf, A. Pezeshki, M. Lundberg, and H. Cox, "A generalized sidelobe canceller formulation for a multi-rank Capon beamformer," Thirteenth Annual Workshop Adaptive Sensor Array Process., Lexington, MA: Lincoln Lab, Mass. Inst. Tech., June 7–8, 2005.

[14] A. Pezeshki, L. L. Scharf, M. Lundberg, and E. K. P. Chong, "Constrained quadratic minimizations for signal processing and communications," in *Proceedings of the Joint 44th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC'05)*, Seville, Spain, December 12–15, 2005, pp. 7949–7953.

[15] H. Cox, A. Pezeshki, L. L. Scharf, M. Lundberg, and H. Lai, "Multi-rank adaptive beamforming with linear and quadratic constraints," *Thirty-ninth Asilomar Conf. Signals, Syst., Comput.*, Pacific Grove, CA, Oct. 30–Nov. 2, 2005.

[16] A. Pezeshki, L. L. Scharf, J. K. Thomas, B. D. Van Veen, "Canonical coordinates are the right coordinates for low-rank Gauss-Gauss detection and estimation," *IEEE Trans. Signal Processing*, submitted May 2005, to appear 2006.

6 Interactions/Transitions

6.1 Participation in meetings, conferences, and seminars

Professors Louis Scharf and Edwin Chong presented their work at numerous workshops, conference, and invited lectures, one at the invitation of Dr. Sjogren at the AFOSR review at North Carolina State University.

6.2 Consulting and advisory functions

Professor Edwin Chong engaged in a collaborative effort with Sandia National Labs (Albuquerque, NM) on sensor management for target tracking. He also collaborated with Numerica Corporation (Fort Collins, CO), on sensor and communication resource management.

6.3 Transitions

Professors Louis Scharf and Edwin Chong held a meeting in January 2005 with Drs. Cochran, Moran, and Howard to explore transitions of their work on imaging, tracking, and scheduling to waveform design and scheduling.

Professor Edwin Chong continues to work with Sandia National Labs (Albuquerque, NM) to implement the sensor management framework developed here on their simulation platform, Umbra. He also continues to work with Numerica Corporation to integrate the sensor management framework with their particle filtering software.

Professor Edwin Chong held meetings with Dr. Bob Bonneau (AFRL) to discuss transitions of the sensor management work here to AFRL's radar testbed.

7 Inventions and Patent Disclosures

None to date.

8 Honors and Awards

[1] Edwin K. P. Chong: Fellow of the IEEE, 2004, "for contributions to communication networks and discrete event systems."

[2] American Society for Engineering Education (ASEE) Frederick Emmons Terman Award, 1998. The Terman Award is bestowed annually upon an outstanding electrical engineering educator under 45 years of age in the United States or Canada, in recognition of the educator's contributions to the profession.

[3] Louis L. Scharf: Fellow of the IEEE, 1986, "for contributions to the theory and practice of statistical signal processing."

[4] Louis L. Scharf: Technical Achievement Award from the IEEE Signal Processing Society for contributions to the theory and practice of statistical signal processing, 1995.

[5] Louis L. Scharf: Society Award from the IEEE Signal Processing Society for contributions to the theory and practice of statistical signal processing, 2005.