SENSING SURVEILLANCE & NAVIGATION

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BRIEF DESCRIPTION OF PORTFOLIO:
Integrated/Multi-transmit Radar for Enhanced Imaging Resolution
Innovative Geo-Location with Tracking, Area Denial and Timekeeping

LIST SUB-AREAS IN PORTFOLIO:
Waveform Design/Diversity Exploitation Adaptive to a Varying Channel
“Fully Adaptive Radar” Sensor Processing including MIMO
Sensing for Object Identification: Analysis and Synthesis of Invariants
Integrated Navigation: GPS-based, Inertial, Terrain-following
Who was “Sensing Surveillance”? 

- **1990: Probability and Statistics; Signal Processing**
  - NM- Directorate of Mathematical and Information Sciences
  - Went from emphasis on “Dependability of Mechanical and Human Systems” to Applied Functional Analysis, Wavelet theory, Analytic de-convolution, and more Wavelets
  - Influences: Louis Auslander, E. Barouch, R.R. Coifman, A.V. Oppenheim

- **1996: Signals Communication and Surveillance**
  - NM- Directorate of Mathematical and Computer Sciences
  - Higher wavelet studies, time-scale, time-frequency transformations, Reduced Signature Targets, Low Probability of Intercept transmission, Fusion of diverse sensing modalities (“FLASER”)  
    Gurus: A. Willsky, Ed. Zelnio, S. Mallat

- **2002: Sensing, Surveillance and Navigation**
  - NM- Directorate of Mathematical and Space (and Geo-) Sciences
  - Apply earned mathematical technique and computational/data-handling power:
    - Design of wave-forms for transmit diversity, combine sensing and communication, spectrum maintenance, quantum optics and GPS science
  - Big names: A. Nehorai, M. Zoltowski, R. Narayanan, D.H. Hughes
SS&N Goals

- **Fully Adaptive Radar and Waveform Design**
  - Payoff: Spectral Dominance, enhanced Radar resolution, EW Countermeasures

- **Advances in Automated/Assisted Target Recognition**
  - Payoff: Identify airborne, ground-based, occluded, camouflaged and moving targets.

- **Passive Radar Imaging and “Quantum Entanglement”**
  - Payoff: Perform “surveillance through clouds” by imaging the light source (instead of the object), together with photon counting.

- **Physically Proven Covert Transmission**
  - Payoff: Achieve high-rate, covert communication through free-space channel, based on physical/quantum principles.

- **Non GPS-based Navigation and Geo-location**
  - Payoff: Navigation, location and targeting anywhere, with GPS precision.
Vision
Waveform Diversity

Why?
• Rapidly Dwindling Electromagnetic (EM) Spectrum
• Challenging Environments
• Multi-path Rich Scenarios

Waveform Optimization
• Designed Waveforms for Transmit Adaptivity
• Interference Suppression
• System Constraints

Simultaneous Multi-Function
• Spectrally Efficient Waveform Design
• Enabled Multi-mission Capability
• Joint Adaptivity on Transmit and Receive

Frequency Diverse Array
• Adaptive Range Dependent Beam-patterns
• Electronic Steering with Frequency Offsets
• Inherent Countermeasure Capability

Why?

\[ W_1(t) \quad W_2(t) \quad W_3(t) \quad \ldots \quad W_n(t) \]

J-B Joseph Fourier

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Context and Collaboration

Automatic (Assisted) Target Recognition + 3-D modeling:
ARO/ARL emphasizes underpinnings of landmine detection Adelphi MD
Contacts: Ron Myers, A. Swami, J. Lavery

ONR concentration in statistics of acoustics-based target recognition:
Concentration on mathematical techniques such as “reversed Heat Equation”
Collaborators: B. Kamgar-Parsi, J. Tague, R. Madan, John Tangney

DARPA: Previous MSTARs program known for generation of “real-world data” followed by:
– Mathematics of Sensing, Exploitation, and Execution (MSEE) led by Dr. A. Falcone collaboration with R. Bonneau RSL et al
– 3-D Urbanscape/URGENT and parallel “Visi-building”
– FOPEN project ran in 2000’s, now DARPA ATR is under reassessment

Space-Situation Awareness:
Missile Def Agency Funding for Army Radar at Huntsville, technical tasking to MIT Lincoln Labs; ICBM detection drives Navy Theater Defense (THAD)
International Efforts: DRDC Ottawa (Noise Radar), Singapore Nat Tech Univ (INS and Integrated Geo-location/Timekeeping)
Scientific Challenges and Innovations

Waveform Design:

Mutual Information as metric is underutilized especially in multiple I-O context (Geometric Probability / Entropy), expands upon Kullback-Leibler, Shannon

Inversion of a given Ambiguity Function is critical for interpreting radar returns, can be addressed by Lie’s theory of symmetries of systems of Differential Equations (Conservation Laws)

Selection of the Waveform (Woodward) under time-space channel variation, is Ill-Posed, can be treated by Functional Regularization (Moscow School)

Distributed Synthetic Aperture Radar:

Propagation of singularities (Wave-Front sets) of linear systems (PDE), studied by L. Hörmander, M.Sato and Yves Meyer, is critical to the inversion of Fourier Integral Operators attached to simultaneous Range-Doppler SAR surveillance.

Accurate GPS Interpretation, Distributed Synthetic Aperture Radar:

Hypothesis tests which identify certain central- and non-central \( \chi^2 \) distributions are based on F distributions with degrees of freedom related to the number of channels. This is a Key toward rapid decision: Are there multi-path effects present?
Non GPS-based Navigation: Achieve “Dependable” Precision Navigation and Timing (PNT)

In support of sensing, surveillance, guidance/control in caves, tunnels, under interference

- **(Laser) Scanning for Assured 3-D Navigation of UAV**

- **3D Navigation:**
  - Tight integration of Ladar data with Inertial Measurements,
  - Use IMU for data association; Ladar for IMU calibration

- **Assurance:**
  - Measured solution covariance (position and attitude) enables the implementation of an integrity function,

- **UAV Design:**
  - Hovering sensor platform with a 10-lb payload (platform functions as a sensor gimbal)
**Problem statement:**
Ionosphere scintillation degrades space-based communication, surveillance, and navigation system performance

**Project objective:**
1. Establish an automatic scintillation event monitoring and global navigation satellite signal (GNSS) data collection system at HAARP
2. Develop algorithms to estimate scintillating GNSS signal parameters.
3. Develop robust GNSS receiver algorithms to mitigate scintillation effects

180-element HF heating array creates artificial scintillations at HAARP, AK

Frequent natural scintillations occur at Auroral zone

Phased heating array beam pattern
Current experimental setup at HAARP include 4 antennas, 7 commercial/software defined GPS/GLONASS receivers. Successful scintillation events captured and processed on GLONASS satellites and GPS L1, L2, and L5 bands.

24-hour GLONASS & GPS satellite path over HAARP

GPS PRN25 Scintillation showing more severe response on the new L5 life-of-safety signal
Enablers for Sensing, Surveillance, Navigation

MOTIVATION

• Realize Theme of “Data to Decisions”
  • Operators are overwhelmed by massive volumes of high dimensional multi-sensor data

• Challenges
  - Efficiently process data to extract inherent information
  - Transform “essential” information into actionable decisions

Key Topical Thrust

• Conjugate Gradient method for STAP
  • Overcomes curse of dimensionality by novel model order selection via Krylov subspace
  • Computationally efficient implementation of parametric STAP
  • Attains “matched filter” performance at convergence
  • Unifies information theoretic criteria (K-L and CRB)

CONCEPT / PICTURE

Making Optimal Use of Sensors:
Keeping Your Head above “Torrents of Data”

Key Topical Thrust

• Embedded Exponential Family of PDF
  • Information integration from disparate sensors for detection and classification
  • Breakthrough in Statistical Science: Novel technique for obtaining sufficient statistics
  • Asymptotically optimal in a weak signal scenario: minimizes K-L divergence from reference PDF
Matched Filter and Conjugate Gradient Algorithm

- Optimum matched filter (MF) for multichannel signal detection:

  \[ w_{ MF} = R^{-1}s \]

  - Direct matrix inverse is computationally intensive
  - Need reduced rank solution to reduce training/complexity requirement
  - MF can be obtained by minimizing

  \[ \phi(w) = \frac{1}{2} w^H R w - w^T s \]

  which can be solved by iterative solvers including steepest descent or conjugate gradient (CG) methods

  - CG uses conjugate-orthogonal directions in searching

  \[ k\text{-th CG direction: } d_k \in \text{span}\{Rd_1, \ldots, Rd_{k-1}\}^\perp \]

  and converges in no more than \( M \) iterations

  \( (M \text{ is the dimension of } w) \)
Conjugate-Gradient Matched Filter and Conj - Gradient for Parametric Detection

**KASSPER Data**
output SINR of CG-MF vs. # of CG iterations

**Simulated data**

**MCARM data**

DISTRIBUTION A: Approved for public release; distribution is unlimited.
Detection/Classification

with exponentially embedded family of densities under Kullback-Leibler statistics

- Difficult targets
  - Limited training data
  - Unknown model
  - Dependent measurements
- The EEF combines all the available information efficiently.
  - Sensors are not assumed to be independent.
  - Sensor measurements are succinctly captured via sufficient statistics for the EEF.
  - Asymptotic optimality in K-L divergence
Exponentially Embedded Family Hypothesis Technique

• The exponentially embedded family (EEF) combines all the available information in a multi-sensor setting from a statistical standpoint.

• Create PDF using sufficient statistics from each sensor in a multi-sensor setting

\[ p_\eta(x) = \exp\left( \sum_{i=1}^{p} \eta_i T_i(x) - K(\eta) + \ln p_0(x) \right) \]

where \( T_i(x) \) is the \( i \)-th sensor sufficient statistic

• The Embedded Family of inputs (EEF) asymptotically minimizes the “Kullback-Leibler” (K-L) divergence from the true model

• Implementable via convex optimization.

• Applications: model order selection, detection/classification, intelligent multi-sensor integration.
EEF Effectiveness and Efficiency

Receiver Operating Characteristic under Gen’l Likelihood Ratio

ROC curves for the Generalized Likelihood Ratio Test versus the “clairvoyant” Probability Density Function (PDF)

Correct Classification versus Noise Power

Probability of correct classification for both methods
Indoor Modeling

- DoD Applications of indoor modeling:
  - Operational situational awareness of individual soldiers and common operating picture in complex urban environments
  - Enables virtual walk-through and fly-through
  - Visualization of exterior and interior, seamless transition

- State of the Art for Indoor mapping:
  - Wheeled devices on even, smooth surfaces

- Existing systems cannot deal with uneven surfaces such as staircases, and do not generate textured 3D models

Dr. Avideh Zakhor
Video and Image Processing Lab
University of California, Berkeley
Approach to 3D Indoor Modeling

• Use human operator rather than wheeled devices in order to map/model uneven surfaces, tight environments

  6 “degrees-of-freedom” recovery

• Challenges:
  – Weight/power limitations for human operator with backpack
  – Unlike outdoor modeling:
    • No GPS inside buildings
    • No aerial imagery to help with localization
  – Unlike wheeled systems with only 3 degrees of freedom: x, y, & yaw,
  – Need to recover six degrees of freedom for a human operator: x, y, z, yaw, pitch, roll
L = laser
C = camera
H = horizontal
V = Vertical

Data Acquisition

L-H1
C-
C-R
L-V1
L-V3
L-V2
L-S2
OMS
HG9900
Applanix
HG9900
Laptop
Markov Random Field Formulation of Texture Alignment

- Cast texture selection and alignment as a labeling problem
  [Lempistky and Ivanov, 07]:
- Include image transformations to generate more image candidates

\[
\min(\sum_{i=1}^{N} E_q(l_i) + \lambda \sum_{(i,j) \in \Omega} E_s(l_i, l_j))
\]

**Quality function**

\[
E_d(l_i) = (Tri_i - Cam_i)^2
\]

**Smoothness function**

\[
E_s(l_i - l_j) = \sum_{k=1}^{m} (I_{i_i}(p_k) - I_{i_j}(p_k))^2
\]

- The minimization is a Markov Random Field (MRF) problem which can be solved using Graph Cut. [Boykov et al. 01]

\[
\min(E_q)
\]

\[
\min(E_d + \lambda E_s)
\]

Quality only

(1, 2)

(1, 3)

Quality and smoothness

- \(N\): number of triangles
- \(m\): number of sampling points
- \(Tri_i\): position of the \(i_{th}\) triangle
- \(l_i\): image label for the \(i_{th}\) triangle
- \(Cam_i\): camera position of image \(I_{i_i}\)
- \(I_{i_i}\): image with label \(l_i\)
- \(C_{i_i}\): camera position of image \(I_{i_i}\)
- \(p_k\): the \(k_{th}\) sampling points in an edge

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Interactive rendering of a two-storey model

Point cloud for staircase
Technical Challenges
for interactive 3-D indoor modeling

- Need for accurate localization:
  - More powerful mathematical approaches to sensor fusion
  - Fuse lasers, cameras, IMUs with Kalman & particle filtering
  - More robust loop closure detection with scanners and camera
  - Mathematical techniques to merge multiple local maps to generate a global map.

- Surface reconstruction:
  - Optimization approaches to water tight surface reconstruction

- Simplify models to reduce size:
  - Rendering and interactivity

- Systematic characterization of accuracy
  - Volumetric characterization rather than by localizing
Removing Atmospheric Turbulence

Prof. Peyman Milanfar (milanfar@ucsc.edu)
University of California, Santa Cruz

**Goal:** to restore a single high quality image from the observed sequence
Alternative: Adaptive Optics

Far More Expensive, Large, and Impractical for Tactical Ground Systems
Reconstruction of Distorted Image

Input video

Output frame

Top part of the Water Tower imaged at a (horizontal) distance of 2.4 km

For comparisons see http://users.soe.ucsc.edu/~xzhu/doc/turbulence.htm

Dr. D.H. Hughes, J. Malowicki, P. Cook, AFRL/RITE

“Alpha-Eta” Coherent State Quantum Data Encryption

Phase modulation illustrations of the same symbol at two different times:

Laser Light Electric Field Expectation in Coherent State
\[
\langle \alpha | E_s (r, t) | \alpha \rangle = S(r, t) = |\alpha| \cos \left( \omega_k t - \vec{k} \cdot \vec{r} - \frac{\pi}{2} - \theta \right)
\]

Laser Light in Coherent Quantum States
\[
| \varphi_m^1 \rangle = |\alpha e^{i\theta_m + i\pi} \rangle \quad | \varphi_m^0 \rangle = |\alpha e^{i\theta_m} \rangle
\]

Logic Assignments for Phase Modulation of Laser Light
\[
(0, 1) \rightarrow (| \varphi_m^0 \rangle, | \varphi_m^1 \rangle) \quad \text{m even}
\]
\[
(0, 1) \rightarrow (| \varphi_m^1 \rangle, | \varphi_m^0 \rangle) \quad \text{m odd}
\]
Alpha-Eta Coherent “State Quantum Data Encryption” (QDE) Stationary Experiment

**Objective:** Determine feasibility of NuCrypt LLC’s phase based Alpha-Eta QDE stationary transmission through a turbulent atmosphere

**Approach:** Utilize AOptix “curvature” adaptive optics terminals to compensate for **wave-front phase distortions** over a ten kilometer link

**Result:** Successful demonstration of QDE transmission, and decryption inversion over 10 km free space link.

**Eye Diagrams Illustrating successful decryption of random bit stream**

- **Control (Inside) Simulated Turbulence**
- **Actual (Outside) Real Turbulence**

**Example:**
- **Encrypted Image**
- **Decrypted Image**
• “Designed for Diversity”
  • Detect and Exploit different aspects of target
  • Design and Employ adaptively Multi-Dimensional Wave-forms in Multi-Antenna Sensing & Surveillance Systems
• Develop toolkit for matrix treatment of MIMO radar wave-forms
  • Multiple-Input/Multiple-Output
  • enable performance gains through
    • “transmit” and “receive” diversity
  • Adapt the wave-form at transmit source/receiver

Norbert Wiener
“Cybernetics”

“Mr.” Generalized Fourier Transform
“Mr.” Designed Transmit Waveform

Philip M. Woodward
“Principles of Radar”
Enhanced waveform diversity with unitary scheduling improves target resolution and detection.
Two targets spaced by only $\frac{1}{4}$ chip (rectangular chip pulse shaping): Nine 4-PRI sets (36 PRIs) with each 4-PRI set multiplied by different DT sinewave

\[ \text{SNR} = -10 \text{ dB} \]
Sensing Surveillance Navigation (SS&N) Lab Tasks

S.V. Amphay (RWGI): “Manifold Learning, Information-Theoretic Divergence, and Dimensionality Reduction across Multiple Sensor Modalities” **

Dr. B. Himed (RYAP) “Radar Waveform Optimization” **

Dr. M. Rangaswamy (RYAP), “The Fully Adaptive Radar Paradigm” **

Dr. L. Perlovsky (RYAT), “Theoretical Foundations of Multi-Platform Systems and Layered Sensing” **

Dr. J. Malas (RYAS), “Characterization of System Uncertainties within a Sensor Information Channel” **

Dr. D.H. Hughes (RIGE), “Optical Wireless Communications Research” **

Dr. K. Knox (RDSM), “Improved SSA Imaging by the Application of Compressive Sensing” *

Dr. D. Stevens (RIEG), “Characterization of the Method of Time-Frequency Reassignment” *

Dr. G. Brost (RIGD) “Investigation of Ground-Based Radiometric Characterization of the Slant-Path Propagation Channel for Millimeter Wave Communications” *

*=New for FY12  **=Renewal for FY12