



Integrity ★ Service ★ Excellence

Science of Information, Computation and Fusion

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**Tristan Nguyen
Program Officer
AFOSR/RTC**

Air Force Research Laboratory

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2013 AFOSR SPRING REVIEW



NAME: Tristan Nguyen

BRIEF DESCRIPTION OF PORTFOLIO:

- Research new techniques that enable or facilitate extracting, assembling, and understanding of information collected from multiple sources.
- Challenges:
 1. Dealing with information at different levels of abstraction
 2. Mechanizing patterns of reasoning in terms of computation.

LIST SUB-AREAS IN PORTFOLIO:

Sub-Areas	Objectives
Bottom-up Low-level Data Analytics	• Discover structures in data and shape them into information • Formulate models to describe different data sources • Find efficient and provable computational algorithms
Top-down High-level Information Processing	• Develop expressive, computable representation of information • Synthesize contextual information with observed data through reasoning



Bottom-up Data-driven



Focus On:

- New Data Structures
- Information Extraction Procedures
- Constructive Computational Algorithms
- Provable Performance Guarantees

NEW TRENDS (Dealing with Big Data)

Few data samples in high dimensions

Nonlinear high-dimensional data

Fast approximation algorithms

Integration of multiple models/
techniques

Stay Away From:

- Data Provenance
- Information Management
- Cloud Computing
- Radar, Communications, Signal Processing

} Important but being funded elsewhere
↓



Top-down Concept-driven



Focus On:

- Construction of rich data types
- Models of computation
- New programming language
- Connection with data analytics

NEW TRENDS

Higher-order structures

Constructive techniques

Synthesis of reasoning & computing

Merging qualitative & quantitative models

Stay Away From

- Cognitive modeling
- Decision analysis and modeling
- Current semantic technologies
- Various database models



**Important but being
funded elsewhere**



Similar Programs But with Different Emphases and Approaches



Mathematics of Sensing, Exploitation, and Execution



- Network-based Hard/Soft Information Fusion
- Value-centered Information Theory for Adaptive Learning, Inference, Tracking, and Exploitation
- Revolutionizing High-Dimensional Microbial Data Integration



- Information Integration and Informatics
- EarthCube
- Algorithms for Threat Detection (NSF-DTRA-NGA)



- Information Integration
- Intelligent and Autonomous Systems



Collaborations & Transitions



- **NSF-DTRA-NGA** – *Algorithms for Threat Detection*
- **OSD/AFRL/RH** – *Autonomy*
- **DARPA/AFRL/RV** – *Mathematics of Sensing, Exploitation and Execution (MSEE)*
- **ASD R&E/JCTD** – *Advanced Mathematics for DoD Battlefield Challenges*
- **STTR** – *Space-time Signal Processing for Detecting and Classifying Distributed Attacks in Networks, Numerica Corporation*



Air Force Relevance



**Intelligence, Surveillance,
Reconnaissance**



Autonomy

Technological Applications:

- Information Triage
- Automated Reasoning
- Human-Machine Interface
- Formal Verification



Cyber Domain



**Space Situational
Awareness**





Highlights of Research



Image Articulation Manifolds

R. Baraniuk et al., Rice University



Motivation: Data are “sparsely” collected by a moving platform

Challenges:

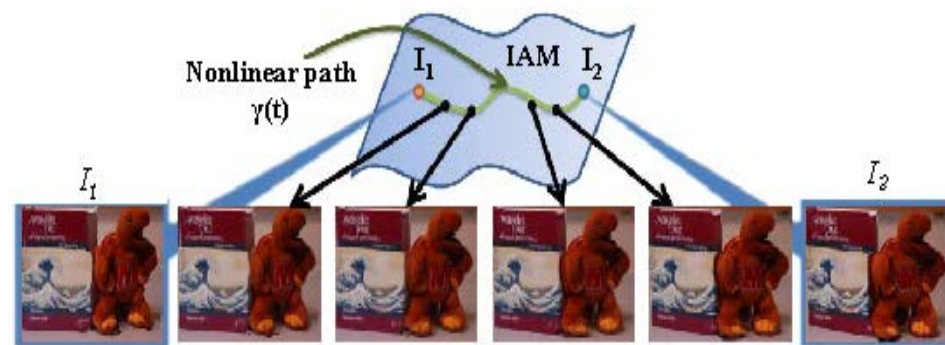
- How to integrate the motion information with data
- Lack of mathematical tools

Objective: To develop a mathematical foundation for Image Articulation Manifolds

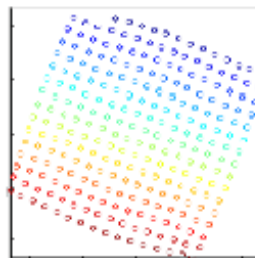
New Techniques:

- Generalization of group action
- Generalization of many ideas in differential geometry

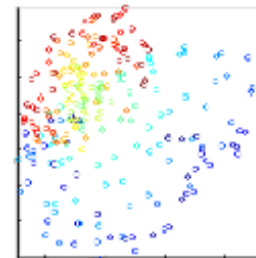
Applications: Beyond videos



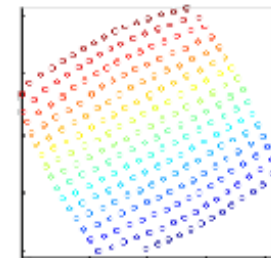
(a) Images



(b) Ground truth



(c) IAM



(d) OFM



Bayesian Nonparametric Modeling of Data

E. Fox et al. – University of Washington, Seattle

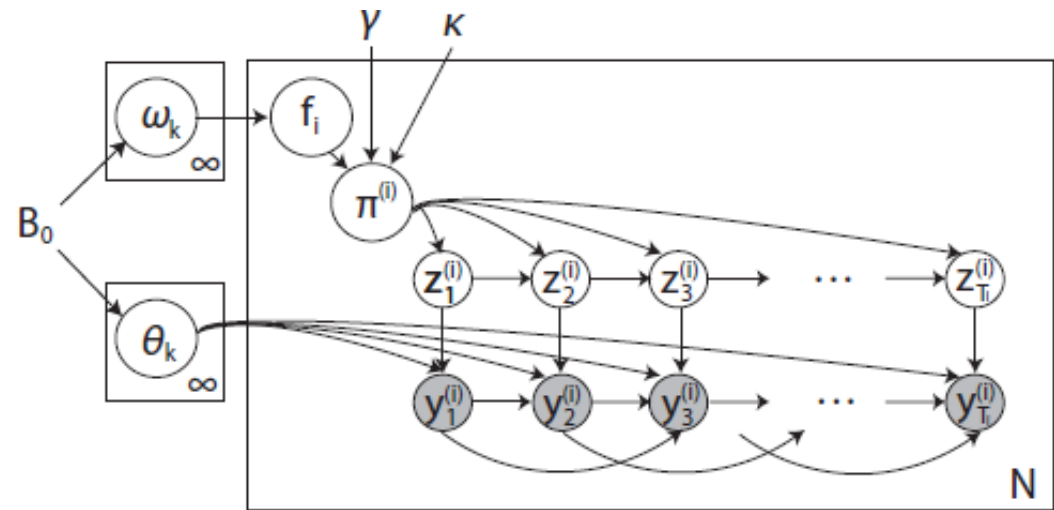


Objective: Relating multiple time series for analysis and fusion

Main Theme: The time-series collection encodes shared dynamic behaviors (features)

New Idea: Using Beta and Bernoulli processes to

- Allow for infinitely many features
- Induce sparsity with shared features.



Notes:

- This generative model provides a probabilistic, top-down model for data sources.
- The PI is collaborating with Ed Zelnio's group in AFRL/RV.



Graph-structured Activation

A. Singh et al., Carnegie Mellon University



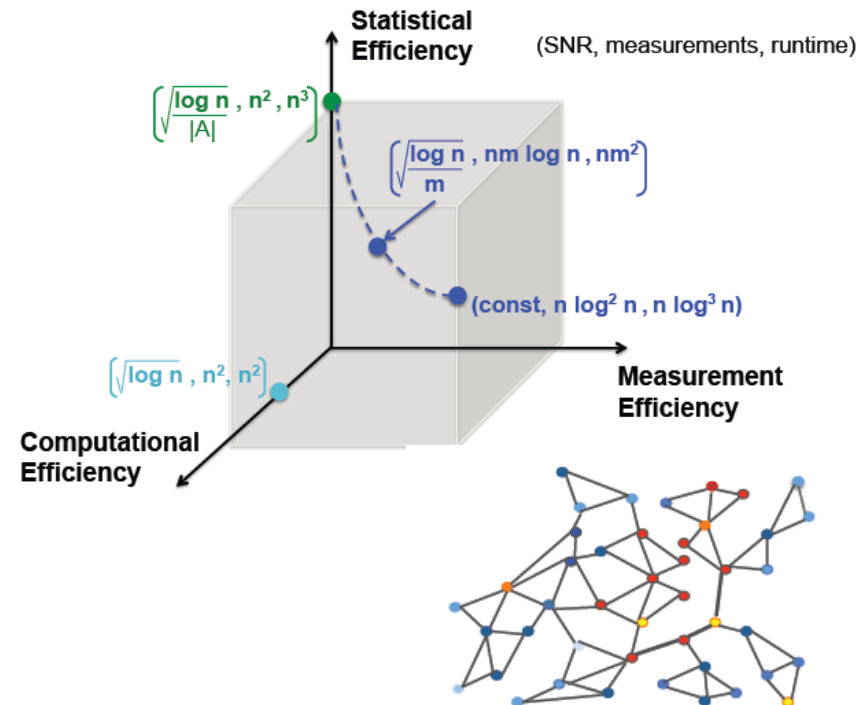
Objectives: Detection and localization of weak structured patterns in large graphs from a small number of compressive measurements.

Achievements:

- Determined the minimum number of measurements and weakest SNR required for detection and localization in lattices.
- Adaptivity of measurements and structure of activation can improve localization but not detection.

Future Research: Consider more general structures of activation on any graphs.

Tradeoffs in Big & Dirty datasets



If the Signal-to-Noise Ratio

$$\frac{\mu}{\sigma} \sim \sqrt{\frac{\log |V|}{|A|}}$$

Can detect patterns at weaker SNR using graph knowledge

where $|A|$ is activation size, then consistent detection is possible.



Homotopy Type Theory for Reasoning & Computing

S. Awodey, R. Harper, J. Avigad, Carnegie Mellon University



Objective: Develop reasoning and computing mechanisms across different domains of information to support information fusion.

Key Ingredients:

- Reasoning - Making inference, generating hypothesis, verifying hypothesis based on observed data
- Computing - Manipulating data or its mathematical structures and connecting with bottom-up data analytics

Motivation: Dependent Type Theory was recently applied (2012) to information fusion and situation awareness. Types allows for expressive data structures and properties (logical, mathematical, etc.)

Technical Approach: Develop Homotopy Type Theory to mechanize reasoning, computing, and constructing data types in the same framework.



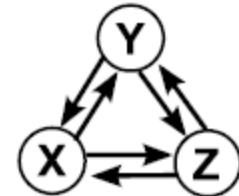
Directed Information & Graphical Models

N. Kiyavash – University of Illinois, Urbana



Objective: To model networks of coupled random processes with causal dependence structures.

$$P(X^n, Y^n, Z^n) \underset{\text{assumption}}{=} \prod_{t=1}^n P(X_t | X^{t-1}, Y^{t-1}, Z^{t-1}) \\ \times P(Y_t | X^{t-1}, Y^{t-1}, Z^{t-1}) \\ \times P(Z_t | X^{t-1}, Y^{t-1}, Z^{t-1})$$



Technical Approaches:

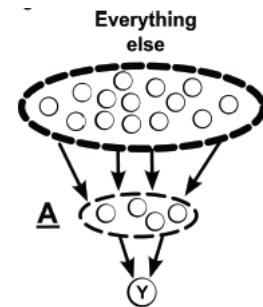
- Discovered two new equivalent graphical models –

Minimum Generative Model Graph



Find the smallest subset of processes $\underline{A}$ satisfying:

$$\mathbb{E} \left[\log \frac{P(\text{future of } \mathbf{Y} | \text{past of } \mathbf{Y}, \underline{A}, \text{everything else})}{P(\text{future of } \mathbf{Y} | \text{past of } \mathbf{Y}, \underline{A})} \right] = 0$$

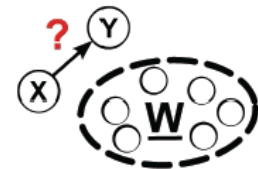


Directed Information Graph



Draw an arrow $\mathbf{X} \rightarrow \mathbf{Y}$ if

$$\mathbb{E} \left[\log \frac{P(\text{future of } \mathbf{Y} | \text{past of } \mathbf{X}, \mathbf{Y}, \underline{W})}{P(\text{future of } \mathbf{Y} | \text{past of } \mathbf{Y}, \underline{W})} \right] > 0$$



- Constructed efficient algorithms to identify these graphs.

Future Research: Can the time-invariance hypothesis on the causal dependence structures be weakened or removed?



Sensor Scheduling for Tracking Resident Space Objects

I. Clarkson, University of Queensland

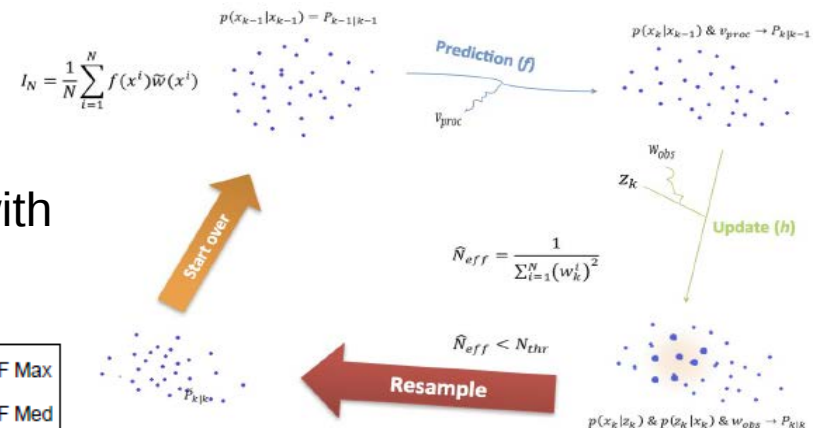


Objective: To improve the current tracking system, Tasking Autonomous Sensors in a Multiple Application Network (TASMAN).

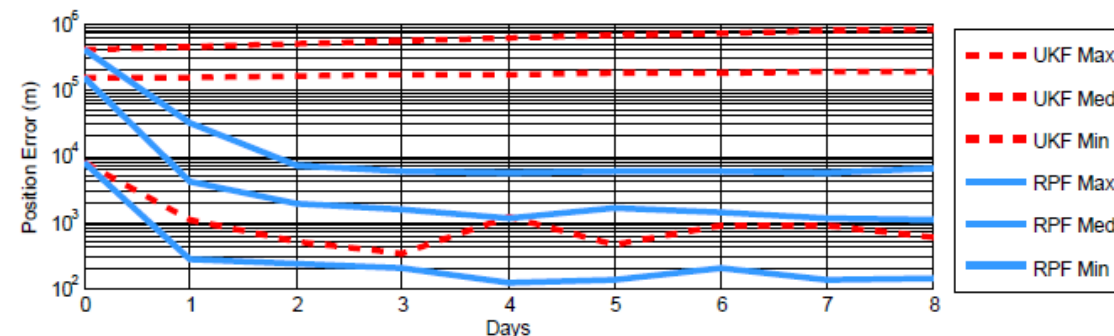
Current Technical Approaches: Unscented Kalman Filter for updating objects' states and setting up scheduling.

Challenge: Objects can be out of field of view in a scheduling period

New Approach: Integrated searching and tracking via particle-filtering (in collaboration with AFRL's AMOS)



Simulated Results





Some Intramural Projects



- **J. Culbertson (RY) & K. Sturtz (Universal Mathematics)**
 - o Categorical Formulation of Probability and Bayesian
 - o Collaborating with D. Koditschek (U Penn) and MURI Team

- **W. Sakla (RY) & T. Klausutis (RW)**
 - o Manifold Learning and Sparse Representation
 - o Will collaborate with a new PI

- **R. Ilin & L. Perlovsky (RY)**
 - o Integration of text with sensor data via parametric models

- **W. Curtis (RW)**
 - o Map-based Particle Filtering for Target Tracking



FY10 MURI - Control of Information Collection and Fusion



- Jadbabaie (control) + 1PhD
- Koditschek (robotics) + 2PhD + 1.5PD
- Kumar (robotics) + 2PhD
- Ribeiro (sig. proc.) + 3PhD



Berkeley

- Ramachandran (info. thry) + 1PhD
- Sastry (control) + 1PhD
- Tomlin (control) + 1PhD + 1PD



Illinois

- Baryshnikov (math) + 1PhD



Minnesota

- Giannakis (sig. proc.) + 4PhD
- Roumeliotis (robotics) + 4PhD



Melbourne

- Howard (comm., radar)
- Moran (appl. math)

Objective: To formulate a new perspective on the joint control of heterogeneous information sources to simultaneously achieve quantified informational and physical objective.

- **RCA.1 Unified Mathematical Representation**
 - for sensor, control, mission objectives
 - incorporating multiple scales of resolution and uncertainty
- **RCA.2 Joint Physical-Information State Descriptors**
 - capturing physical state of the information gathering system and the state of the information
 - include formal expression of constraints limiting state transitions
- **RCA.3 Control-Information Linkage to:**
 - robustly link control actions to information states
 - support feedback to enable simultaneous control of physical and information states

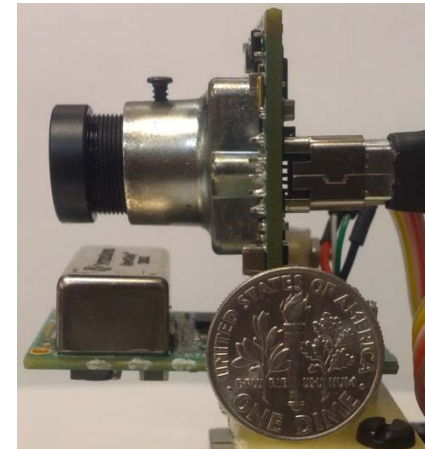


FY10 MURI - Control of Information Collection and Fusion



Consistent Vision-aided Inertial Navigation System (VINS) – S. Roumeliotis et al. (U Minnesota)

- **Challenge:** VINS is a nonlinear estimation problem; Linearized estimators (e.g., Extended Kalman filter (EKF), Unscented (U)-KF) become inconsistent.
- **Solution:**
 - o Determined unobserved directions of the nonlinear system using finitely many Lie derivatives
 - o Linearized states using the observability matrix
 - o Identified cause of inconsistency
 - o Used the computed unobserved directions to improve consistency and accuracy





FY10 MURI - Control of Information Collection and Fusion



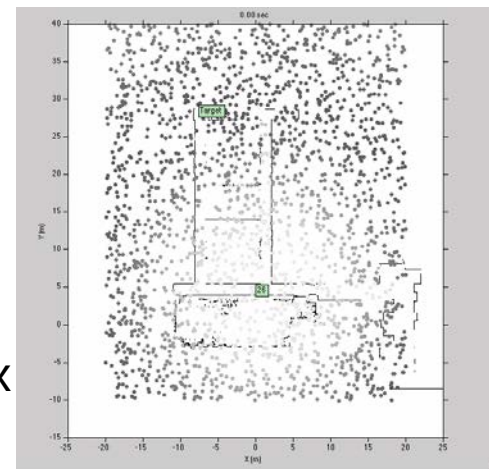
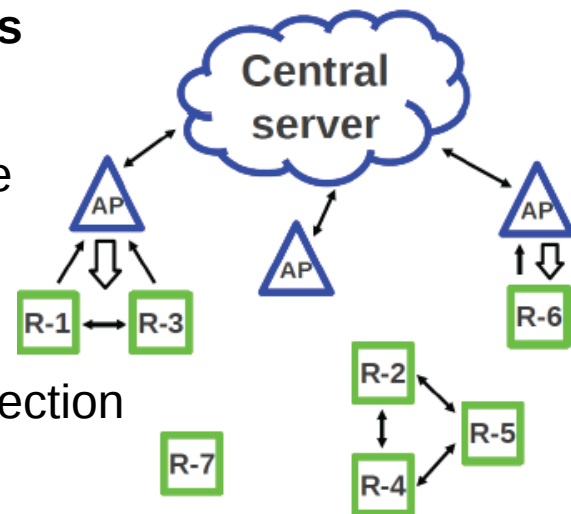
Multi-robot Team To Find Targets and Avoid Hazardous Areas – V. Kumar et al. (U Penn)

Challenge: Sensing, communication, and coordination are coupled.

Solution:

- Distributed algorithms for detection and multi-target detection and localization using
 - o a recursive filter based on Finite Set statistics
 - o approximated gradient of mutual information between sensor readings & target locations.
- Complexity reduction by
 - o clustering robots into groups
 - o adding access points connected to a central server.

Next Step: Empirical validation and merge with VINS in complex environments.

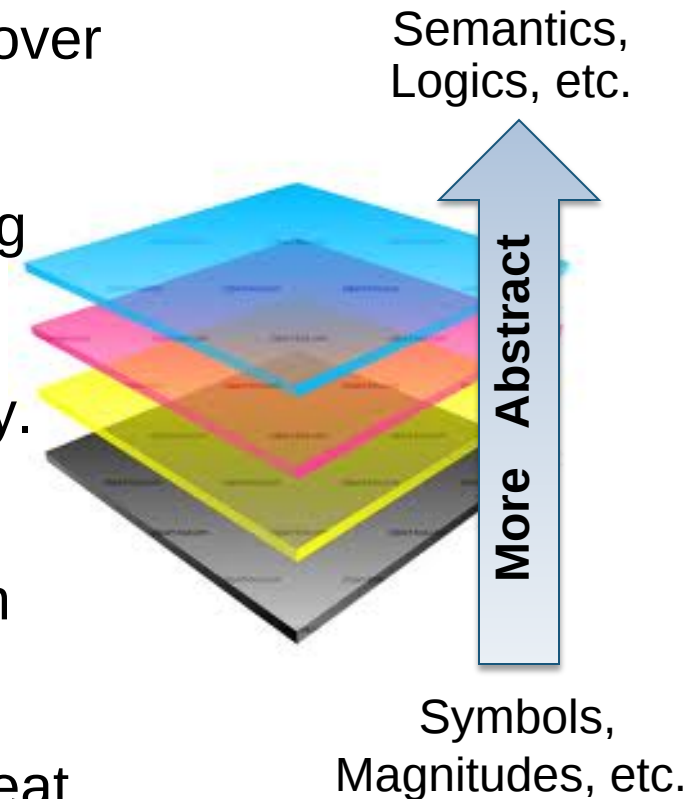




Summary



- Bottom-up data-driven analysis can discover structures in data.
- Top-down conceptually driven processing can integrate these structures.
- These two directions may not align nicely. So recursion may require.
- There are several layers of abstraction in information processing.
- Different technical tools are needed to treat various layers of abstraction.





Thank You!

Comments/Questions?