Science of Information, Computation and Fusion

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Integrity ★ Service ★ Excellence

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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/RY** – *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

Cyber Domain

Technological Applications:

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

Autonomy

Space Situational Awareness

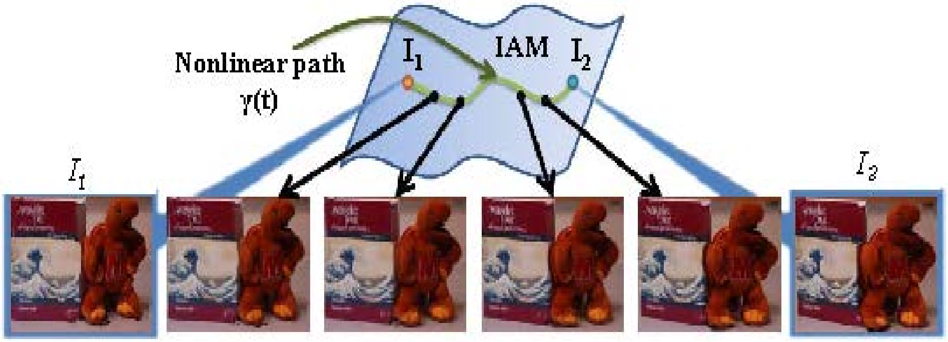
Highlights of Research

Image Articulation Manifolds

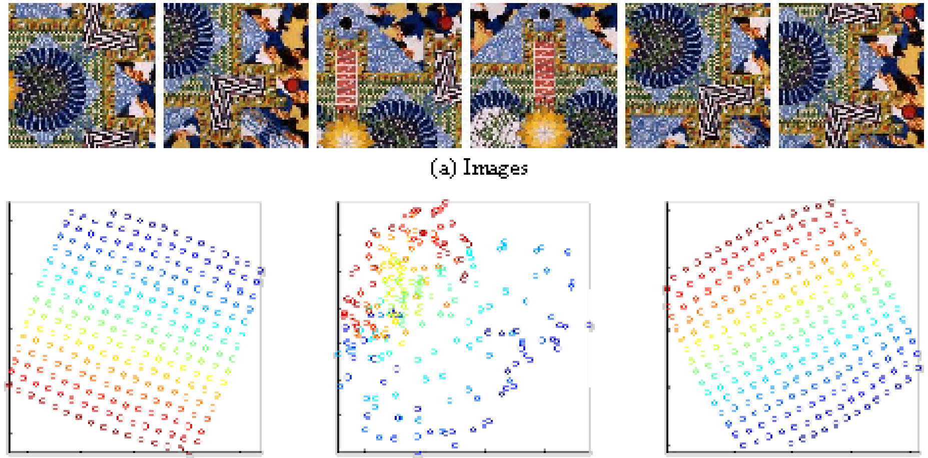
R. Baraniuk et al., Rice University

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



(a) Images

(b) Ground truth (c) IAM (d) OFM

New Techniques:
- Generalization of group action
- Generalization of many ideas in differential geometry

Applications: Beyond videos

Bayesian Nonparametric Modeling of Data

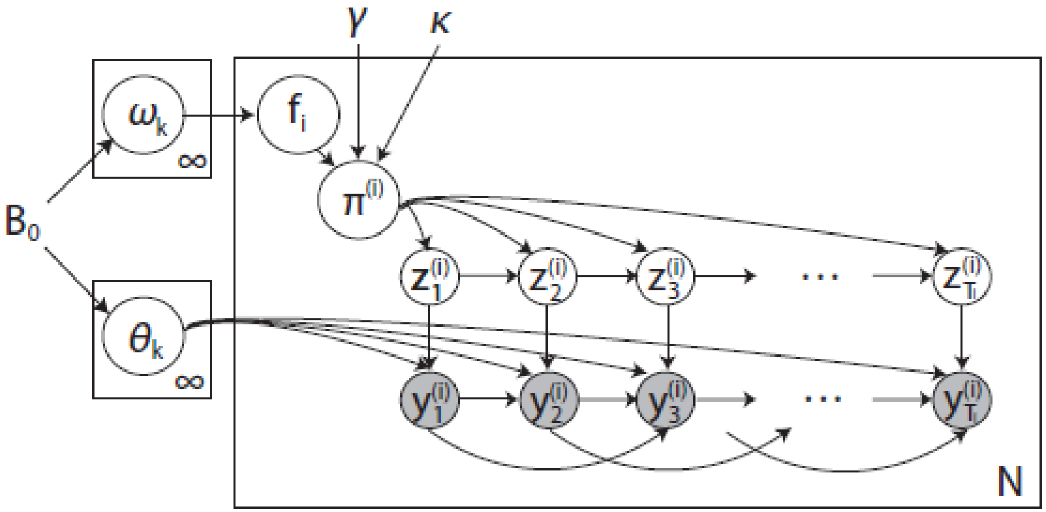
E. Fox et al. – University of Washington, Seattle

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/RY.

Graph-structured Activation

A. Singh et al., Carnegie Mellon University

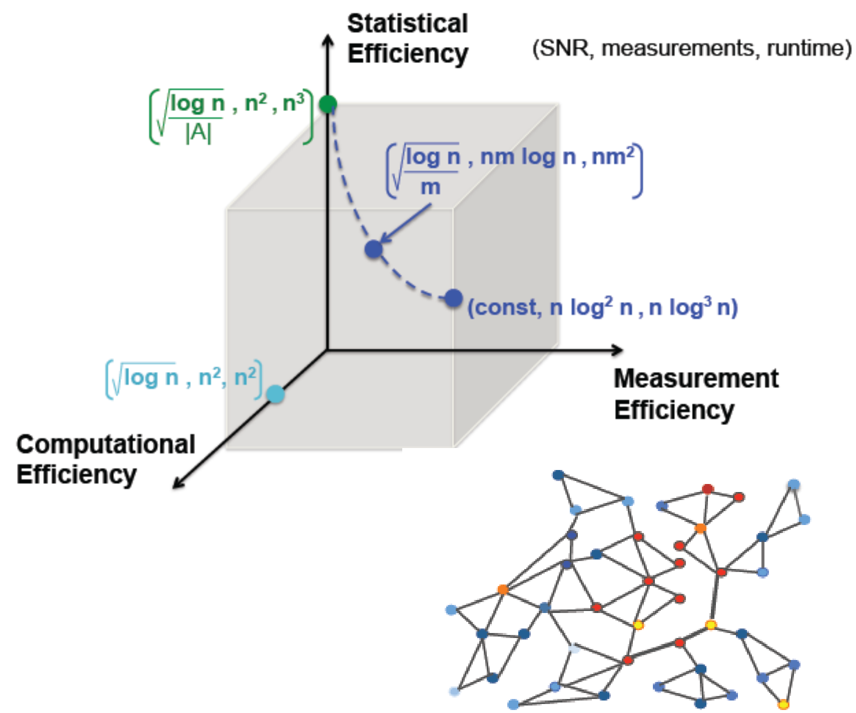
Objectives: Detection and localization of weak structured patterns in large graphs from a small number of compressive measurements.

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

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

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

Can detect patterns at weaker SNR using graph knowledge

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

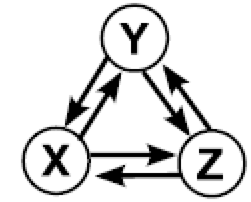
Motivation: Dependent Type Theory was recently applied (2012) to information fusion and situation awareness. Types allows for expressive data structures and properties (logical, mathematical, etc.)

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

N. Kiyavash – University of Illinois, Urbana

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

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



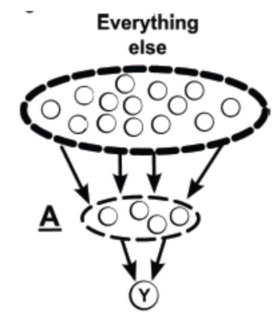
Technical Approaches:

- Discovered two new equivalent graphical models –

Minimum Generative Model Graph →

Find the smallest subset of processes **A** satisfying:

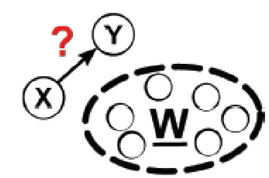
$$\mathrm{E}\left[\log \frac{P(\text{future of } \mathbf{Y} | \text{ past of } \mathbf{Y}, \underline{\mathbf{A}}, \text{ everything else})}{P(\text{future of } \mathbf{Y} | \text{ past of } \mathbf{Y}, \underline{\mathbf{A}})}\right] = 0$$



Directed Information Graph →

Draw an arrow **X→Y** if

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



- Constructed efficient algorithms to identify these graphs.

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

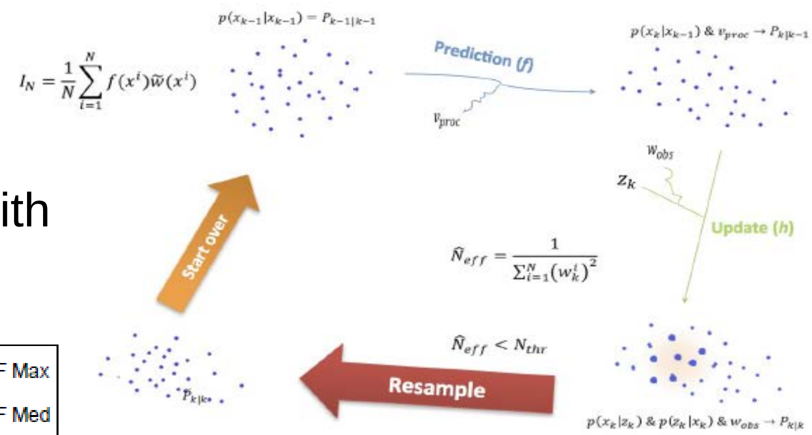
Sensor Scheduling for Tracking Resident Space Objects

I. Clarkson, University of Queensland

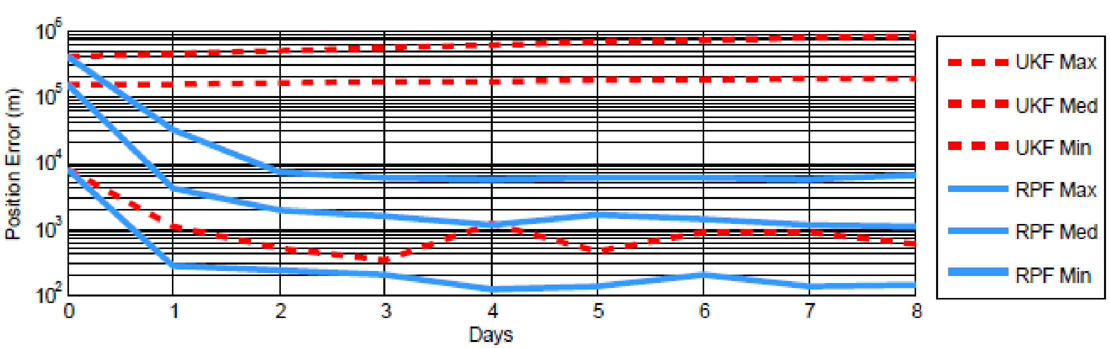
Objective: To improve the current tracking system, Tasking Autonomous Sensors in a Multiple Application Network (TASMAN).

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

Penn
University of Pennsylvania

- 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

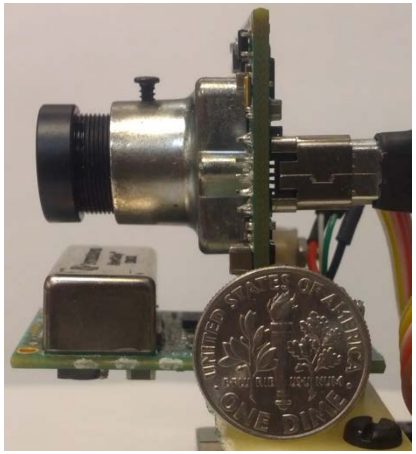
- Howard (comm., radar)
- Moran (appl. math)

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)

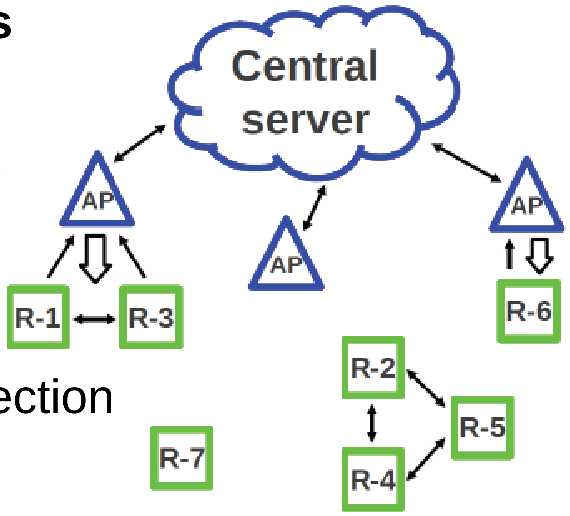


- **<u>Challenge</u>:** VINS is a nonlinear estimation problem; Linearized estimators (e.g., Extended Kalman filter (EKF), Unscented (U)-KF) become inconsistent.

- **<u>Solution</u>:**
    - 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

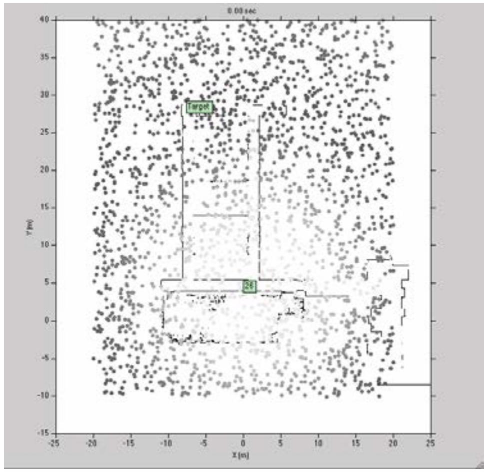
Multi-robot Team To Find Targets and Avoid Hazardous Areas – V. Kumar et al. (U Penn)



<u>Challenge</u>: Sensing, communication, and coordination are coupled.

<u>Solution</u>:

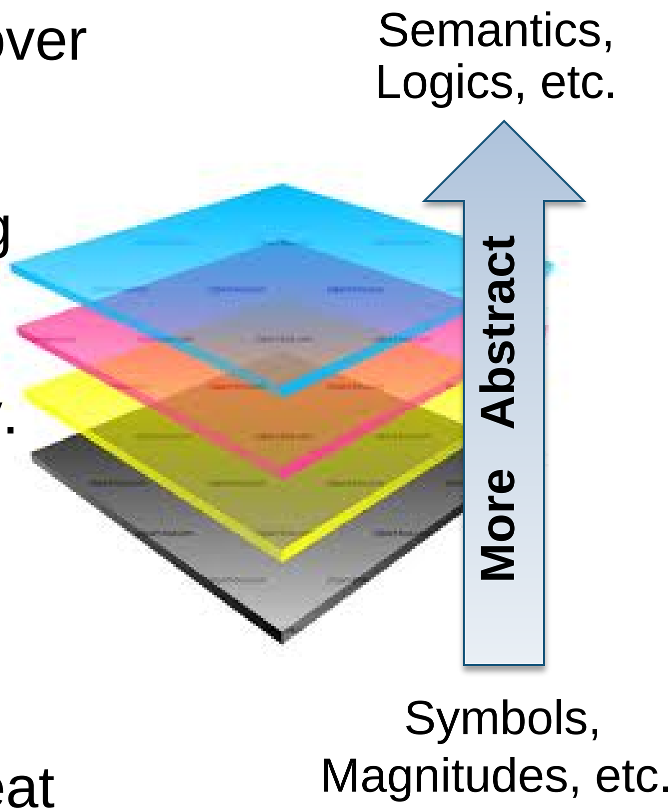
- Distributed algorithms for detection and multi-target detection and localization using
  - o a recursive filter based on Finite Set statistics
  - o approximated gradient of mutual information between sensor readings & target locations.
- Complexity reduction by
  - o clustering robots into groups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



<u>Next Step</u>: 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?