Science of Information, Computation and Fusion

Date: 06 03 2013

Tristan Nguyen
Program Officer
AFOSR/RTC

Air Force Research Laboratory
### Science of Information, Computation and Fusion

**Report Documentation Page**

<table>
<thead>
<tr>
<th>1. REPORT DATE</th>
<th>2. REPORT TYPE</th>
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<td>Presented at the AFOSR Spring Review 2013, 4-8 March, Arlington, VA.</td>
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*Standard Form 298 (Rev. 8-98)*

Prescribed by ANSI Std Z39-18
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:

<table>
<thead>
<tr>
<th>Sub-Areas</th>
<th>Objectives</th>
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| 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

Stay Away From:
- Data Provenance
- Information Management
- Cloud Computing
- Radar, Communications, Signal Processing

NEW TRENDS (Dealing with Big Data)
- Few data samples in high dimensions
- Nonlinear high-dimensional data
- Fast approximation algorithms
- Integration of multiple models/techniques

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

Stay Away From

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

NEW TRENDS

- Higher-order structures
- Constructive techniques
- Synthesis of reasoning & computing
- Merging qualitative & quantitative 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

Technological Applications:

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

Intelligence, Surveillance, Reconnaissance

Cyber Domain

Space Situational Awareness

Autonomy
Highlights of Research
**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
**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.
**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.
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.
Objective: To model networks of coupled random processes with causal dependence structures.

Technical Approaches:

- Discovered two new equivalent graphical models –
  - Minimum Generative Model Graph
  - Directed Information Graph

- 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)**
  - Categorical Formulation of Probability and Bayesian
  - Collaborating with D. Koditschek (U Penn) and MURI Team

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

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

- **W. Curtis (RW)**
  - Map-based Particle Filtering for Target Tracking
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
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:**
- Determined unobserved directions of the nonlinear system using finitely many Lie derivatives
- Linearized states using the observability matrix
- Identified cause of inconsistency
- Used the computed unobserved directions to improve consistency and accuracy
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
  - a recursive filter based on Finite Set statistics
  - approximated gradient of mutual information between sensor readings & target locations.
- Complexity reduction by
  - clustering robots into groups
  - 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.

Symbols, Magnitudes, etc.
Semantics, Logics, etc.

More Abstract
Thank You!

Comments/Questions?