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Agenda

Topics and Themes

- Project Goals
- Project Objectives
- Technical Approach
- Expected Results
- Project Elements
  - Information Architecture
  - Virtual Sensors and Sensor Processing
  - Self-organization
  - System Integration
Year 1: Develop an intelligent agent-based information theoretic architecture to enable robust and flexible health and condition monitoring for advanced power plant applications.

Year 2: Develop self-organizing computational algorithms that maximize the collection, transmission, aggregation, and conversion of data into actionable information for monitoring, diagnosis, prognosis, and control of power plants.

Year 3: Demonstrate the viability and efficacy of an agent-based, information-theoretic system for real-time health and condition monitoring of power generation equipment and systems.
### Project Objectives

**Realizing a sensor network for health and condition monitoring**

- Develop the theoretical foundations and the algorithms necessary to **elicit system structure from available measurements**.
- Develop the signal processing, filtering, and inference algorithms and software systems necessary to **detect, diagnose, and prognose** defects, degradation, and faults in power generation systems **at component, subsystem, and system levels**.
- Develop algorithms and software systems that enable a sensor network for condition monitoring of power generation plants to be **adaptive, resilient, and self-healing**.
- Evaluate the effectiveness of these computational algorithms in **maximizing information extracted** from power plant data and **realizing its value** for condition monitoring using a power plant simulation test bed.
Technical Approach

Systems viewed as communication networks

• **System elements are considered as nodes in a communication network;**
  – Elements send “messages” via physical media to other system elements,
  – Elements “process” messages from other elements and alter their states accordingly.

• **Instrumentation provides a means for accessing “messages”;**
  – Messages may be corrupted,
  – Messages may be missing.

• **Proper understanding of the observations requires an understanding of both the processing and the network topology!**
• Information is the amount of surprise contained in data;
  – Data that tells you what you already know is not informative,
  – Not all data is created equal.

• The fundamental measure of information is Shannon entropy:

\[ H(X) = - \sum_{x \in X} p(x) \log_d p(x) \]
Let $X$ and $Y$ be the input and output alphabets, and let $S$ be the set of channel states. An information channel is then a system of probability functions.

Mutual information between the input and output provides a measure of channel transmittance:

$$T(X;Y) = H(X) - H(X \mid Y)$$

The maximum over all distributions is known as the channel capacity.
• Determine the “intrinsic” communications topology provided by available observation processes;
  – Fusing information from multiple sensors,
  – Reconstituting lost or degraded observations,
  – Detect system changes reflected in changing communications topology.

• Identify “correlative” structure of sensor data;
  – Identifying relevant (possibly abstract) subsystems,
  – Mesoscopic models and “summary” variables.
Expected Results

Fundamental building blocks for self-organizing sensor network for condition monitoring

• Accurate, computationally tractable means of computing entropy measures for the processes/components/subsystems/systems of interest.
• Distributed and self-organizing method for using entropy measures to identify intrinsic communications structure of power generation systems.
• Self-organizing method for combining observations with dynamics/behaviors/events of interest.
• Statistical techniques for detecting/classifying/identifying conditions of interest and characterizing severity and prognosis of system performance degradation.
Information Geometry
Accomplishments

• Approach for the Discovery of system structure for health and condition monitoring of power plant equipment
  – Mathematical framework that uses data from sensors to elucidate the underlying structure of a power plant as it evolves in a consistent and theoretically sound manner
  – Appropriate measures for determining connections between system elements in a meaningful way and for determining relevance to monitoring needs
  – Algorithms to compute these measures in an efficient and reliable manner and for eliciting system structure using these measures
Technical Approach

• Components of complex systems “communicate” via internal system dynamics
  – Information theoretic framework
    • Capture important aspects of these “communications”
    • Robust to nonlinearity
    • Inherent information hierarchy aids in system partitioning and decomposition
• Equipment monitoring can be described within a control theoretic context
  – Establish direct connection between information theory and control theory to ensure fundamental soundness of the information theoretic framework
• Focus on the system structure
Consider the nonlinear I/O system:

\[
\text{System } (f(.,.)) \text{ with its states } (x_k)
\]

Inputs \((u_k)\)  
Noise \((v_k)\)  
Outputs from Sensor \((y_k)\)  
Noise \((w_k)\)
We find that

\[ I(y_{1:k}; u_{1:k}) = I(x_{1:k}; u_{1:k}) - I(x_{1:k}; u_{1:k} | y_{1:k}) \]
System Structure Construction

Undirected Weighted Graph

Weighted Adjacency Matrix

<table>
<thead>
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<th>B</th>
<th>C</th>
<th>D</th>
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<td>0.7</td>
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System Structure and Diagnosis

• System Structure is used to detect changes associated with possible failures and faults
  – Pre-processing the information matrix
    • No pre-processing
    • Dimension reduction/projection
      – PCA/ICA
      – Diffusion map
  – Analysis approaches
    • Directly analyze information matrix
    • Analyze eigenvalues/eigenvectors
    • Analyze Laplacian matrix
    • Etc.
Self-Organizing Logic
Objectives

- Develop **adaptive, resilient, and self-healing** sensor network for condition monitoring of complex systems
  - Techniques, algorithms, and software for *dynamically* discovering the intrinsic communication topology of power generation systems.
  - Techniques, algorithms, and software for associating sensor data streams with operational objectives.
  - Techniques, algorithms, and software for reconstituting lost or degraded sensing and communication capabilities.
Challenges and Opportunities

- Scaling problems associated with centralized methods:
  - Complexity,
  - Transmission of large amounts of data to central processes (bandwidth, QoS),
  - Computational footprint (cycles, memory).
- Accommodate existing infrastructure
- Lack of detailed a priori understanding of components, processes, and their interactions
- Wide variation in operating conditions, system permeability
- Ubiquitous computational and (wireless) communication resources
- Power management technologies engendering a new class of instrumentation
  - No umbilical
  - Physically reconfigurable on-the-fly
The aforementioned constraints and opportunities mandate a distributed, agent-based approach and strongly suggest the use of biologically inspired algorithms.

- **Distributed**
  - Monolithic approaches do not scale well and tend to be “brittle,” i.e. do not accommodate new instrumentation or permit reorganizing existing infrastructure without significant rework.

- **Agent-Based**
  - Agent based approaches are flexible and embed inherent system descriptions. They provide a powerful basis for bottom-up application to complex systems and minimize communication requirements while distributing processing tasks in a realistic manner.

- **Biologically Inspired**
  - Biologically inspired approaches provide the machinery necessary to capture emergent phenomena and thus provide a basis for accommodating unanticipated contingencies. This is crucial for large-scale complex systems where all contingencies cannot be enumerated.
Accomplishments

Connecting data to operational needs and objectives

• Discovering the actual topology of the system’s intrinsic communication structure.

• Associating information streams with monitoring processes.

• Extracting information from the relevant data streams for fault detection, diagnosis and prognosis.
Network Discovery

The observation of physical system from a foraging perspective

Agent going from node 3 to node 1:

**Behavior**
- The agent carries some data, described as time series, from its home node to the next one.

**Food Definition**
- The Mutual Information between the time series of node 3 and node 1.

$x_i$: a time series which is the partial observation of the physical system at node $i$

$x_1, x_2$

Forager:
- Logic
- “Food” descriptor ($X_i$)
Foraging Behavior

Foraging Patterns of Three Army Ant Species with Different Diets

- Eciton hamatum
  - Diet: dispersed social insect colonies
  - Food distribution: rare but large

- Eciton rapax
  - Diet: intermediate diet
  - Food distribution: intermediate food source

- Eciton burchelli
  - Diet: scattered arthropods
  - Food distribution: can easily be found but each time in small quantities

These behaviors are used as a basis for optimization approaches due to its tendency to find the shortest path, most notably Ant System and Ant Colony Optimization. These behaviors are adapted to the specifics of the problem at hand.
“Food” for Foragers

\[
\Sigma_{w_1, w_2} = \begin{bmatrix} 7.6766 & -0.9311 \\ -0.9311 & 5.4541 \end{bmatrix}
\]

\[
\Sigma_{w_2, w_3} = \begin{bmatrix} 5.4541 & -0.0772 \\ -0.0772 & 1.8371 \end{bmatrix}
\]

\[
\Sigma_{w_3, w_1} = \begin{bmatrix} 1.8371 & 0.3876 \\ 0.3876 & 9.3388 \end{bmatrix}
\]

\[
\Sigma_{w_1, w_2} = \begin{bmatrix} 9.3388 & -1.4681 \\ -1.4681 & 6.2307 \end{bmatrix}
\]

\[
\Sigma_{w_2, w_3} = \begin{bmatrix} 6.2307 & -0.0935 \\ -0.0935 & 1.5962 \end{bmatrix}
\]

\[
\Sigma_{w_3, w_1} = \begin{bmatrix} 1.5962 & -0.2804 \\ -0.2804 & 9.3388 \end{bmatrix}
\]
Virtual Sensors
Accomplishments

Realizing the value of information

• Signal processing, filtering, and inference algorithms and software systems for the detection, diagnosis, and prognosis of defects, degradation, and faults in power generation systems at component, subsystem, and system levels.
  – Techniques, algorithms, and software for detecting and identifying anomalies and events of interest.
  – Techniques, algorithms, and software for characterizing and classifying observed anomalies at the component, subsystem/process, and system levels and providing diagnoses and prognoses for detected events.
  – Develop techniques, algorithms, and software for reconstituting lost or degraded sensing and communication capabilities.
Challenges and Opportunities

What has to be done and what’s available to do it...

- **Imperfect or incomplete observation processes:**
  - Noise,
  - Sparsity of sensing (both physical and temporal),
  - Inability to directly instrument all components/processes of interest.
- **Accommodate existing infrastructure**
- **Lack of detailed a priori understanding of components, processes, and their interactions**
- **Wide variation in operating conditions, including sensor failures**

- **Ubiquitous computational and (wireless) communication resources**
- **Power management technologies engendering a new class of instrumentation**” => more sensors/higher sampling rates
  - No umbilical
  - Physically reconfigurable on-the-fly
- **Substantial repositories of relevant data available for many components and subsystems.**
Technical Approach

Combining a priori knowledge with information from instrumentation

- Incorporate a priori knowledge of system behaviors and observed phenomena:
  - Focus on meeting operational needs,
  - Specification of known signatures or precursors,

- Augment mapping between sensor output and operational needs with “self-discovery” to improve accuracy, timeliness, and robustness:
  - Verify/augment “known” connections with statistically inferred relationships,
  - Detect/correct erroneous or degraded sensor outputs,
  - Detect and classify/characterize anomalous (unknown) dynamics.

- Provide “best of breed” techniques to characterize anomalies and provide diagnoses/prognoses for detected events:
  - Change detection/classification via filtering approaches,
  - Signature detection/matching via model-based signal processing techniques,
  - Infer causal relationships between observations and condition at all relevant levels of spatio-temporal resolution.
• Faults of Interest
  – Mass Unbalance
  – Misalignment
  – Cracking in Rotor Shafts
  – Other elementary faults such as changes in stiffness, damping and static load, ...

• Operating Conditions
  – Rub Impact
  – Oil whip and Oil whirl
• **Basic idea is to compare observed behavior to models of behavior**
  
  – Can use deviation of measured behavior from expected (modeled) behavior as fault indicator.
  
  – A collection of models can be used to diagnose known faults.
  
  – Higher order error statistics can be used to improve performance.

• **Key design driver is trade-off between fidelity and efficiency.**
• “Modeling” approach is based on classical state estimation methods;
  – Deterministic systems => Luenberger Observer,
  – Non-deterministic systems => Linear or Nonlinear Filters.
• Operate a bank of observers/filters each corresponding to different operating conditions.
System Integration
Self-organizing, information centric sensor network

- **Target System**
  - System Level Fusion
  - Subsystem/Component Level Fusion
  - Nodes can function as hubs, routes or relays
  - Agents can coordinate to discover information structure, verify, observation and reconstitute lost sensing capabilities
  - Elements of the network can reconfigure the network in response to changing operating conditions, sensor failure or equipment faults
  - Heterogeneous Elements comprise a sensor network
  - Advanced nonlinear models and information fusion algorithms imbue system with capability to detect incipient faults
  - Agents are an integral part of sensor network, both producing and consuming information
  - Network provides infrastructure for health and condition monitoring, dynamic configuration of sensor assets, and construction of virtual agents
Simulation Development

System Schematic

- Exhaust Gases
- Coal
- Oil
- Gas
- Combustion Chamber
- Pollution Control
- Steam Boiler
- Pump
- Steam Valve
- Steam Condenser
- Water
- Cooling Water
- Steam Turbine
- Synchronous Generator
- AC Power
- Speed Control
Steam turbine provides rotary power to the generator
Synchronous generator converts the mechanical power into electrical power
3-phase step-up transformer is used to step up the voltage for transmission
Load is connected at the output of the 3-phase transformer
Journal Bearing Test Rig

Physical test rig and 24 state nonlinear model

Legend:

1 – End Bearing
2 – Drive End Balancer
3 – Out Board Balancer
4 – Shaft
5 – Journal Bearing
6 – Load Support
7 – Rods
8 – Beams
9 – Load Measurement Device
10 – Columns
11 – Beam
12 – Knob
13 – Lid
14 – Threaded Rod
15 – Oil Tank
16 – Table Support
17 – Quill Shaft
18 – DC Motor
19 – Key Phasor
20 – Motor Support Base
21 – Aluminum Base

- Refurbished bearing test rig with controllable shaft preload, shaft speed, and disk unbalance.
- Key phasor and Bentley-Nevada proximity probes located at journal bearing.
- 24 state simulation implemented with nonlinear bearing models.
Rolling Element Test Rig

- Housing has 4 DOF - linear springs and dampers
- 8 DOF lumped mass rotor model includes gyroscopic effects. Cylindrical disk is accommodated by redistributing some disk mass to the bearing mass stations
- Each bearing element is a 1 DOF mass with nonlinear Hertzian stiffness and linear damping. 9 elements at drive end, 8 elements at fan end
- Defects are modeled as a change in the radius of the raceway

- 2hp induction motor (left)
- Torque transducer is center
- Dynamometer (right) applies torsional load
- Vibration measured with 5g accelerometer placed on motor housing, 12 o’clock position above drive end bearing
- Data recorded with a DAT (digital tape recorder) at 12k samples/sec.
Bearing Condition Simulator

Matlab-based simulation and diagnostic software
Bearing Fault Simulator

Two modes of operation

(a) Simulation Context Menu

(b) Analysis Context Menu

- Bearing condition monitoring software provides 2 capabilities:
  - Defect simulation of vibratory behavior,
  - Analysis of existing data files, including data from externally generated sources.

- Intended for real time monitoring and can be implemented easily with existing bearing test rigs or other instrumented machinery.
Possible Next Steps

• Demonstration using Alstom’s 1000MWe fossil steam power plant dynamic simulator

- define the scope of fault simulation scenarios for a boiler island and steam plant
- specify a list of dynamic simulation cases with predefined faults:
  - typical sensor faults, actuator faults, process faults;
  - well-developed and incipient fault levels
- specify the noise pattern and levels for the preselected variables
- specify a list of process variables for data recording from simulation – to be distributed for university analysis
- investigate applications to advanced controls and diagnostic monitoring for fossil steam power plants
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