An Information Theoretic Framework and Self-organizing Agent-based Sensor Network Architecture for Power Plant Condition Monitoring: DE-FE0007270

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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

Project Goals

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

- 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 Theory

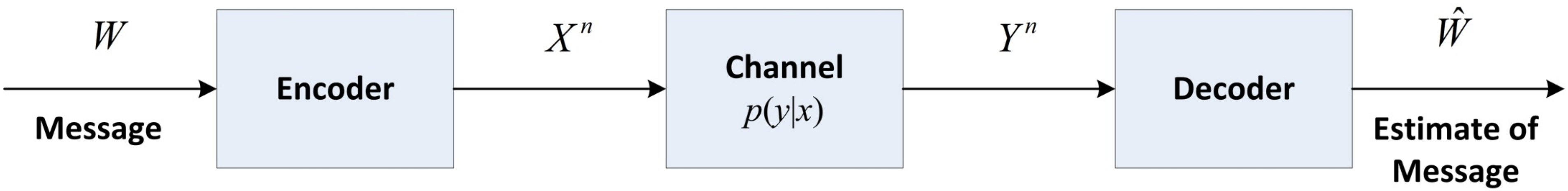
Data and Information are not the same!

- **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:***

$$H(X) = -\sum_{x \in X} p(x) \log_d p(x)$$

Information Channels

Modeling Information Flow



- **Let X and Y be the *input* and *output alphabets*, and let S be the set of channel states. An information channel is thena system of probability functions**
- **Mutual information between the input and ouput 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*.**

Information Structure

- **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

- **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

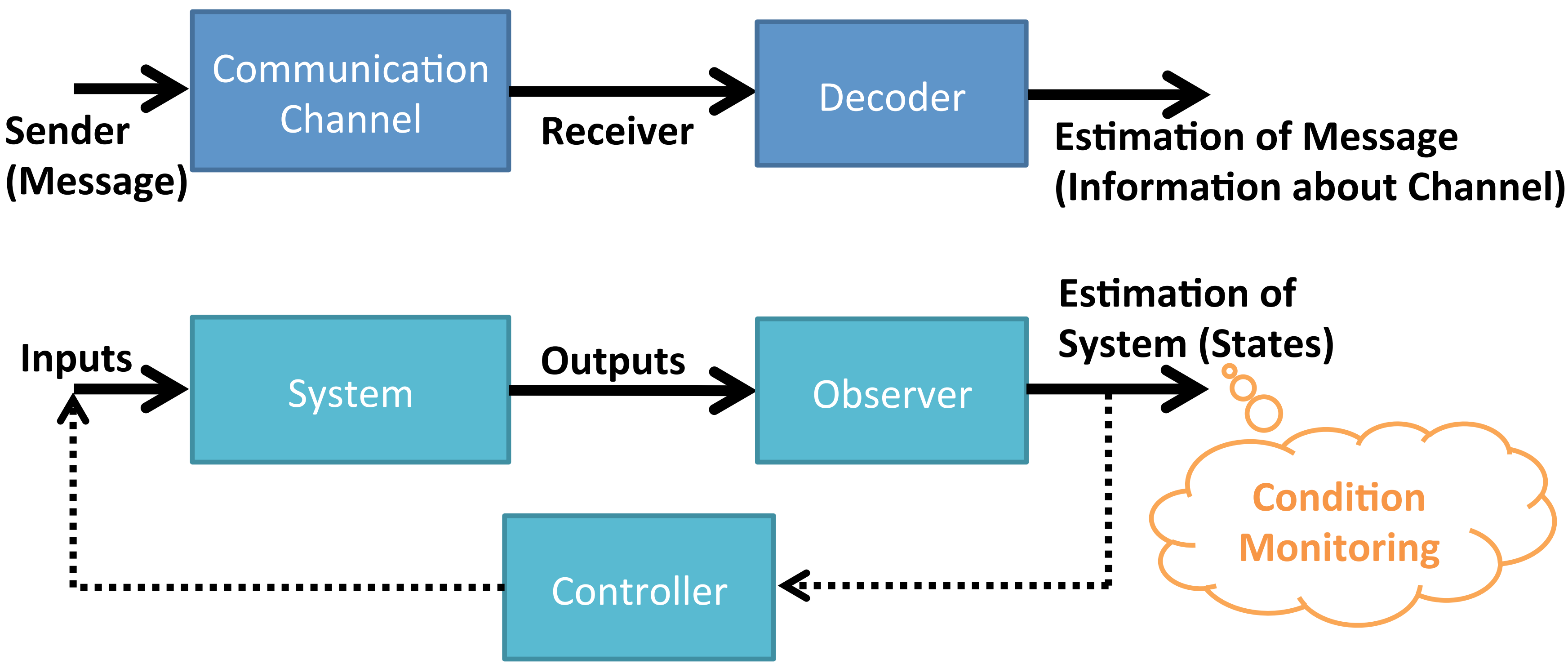
- Approach for the Discovery of system structure for health and condition monitoring of power plant equipment
  - Mathematical framework that uses data from sensors to elucidate the underlying structure of a power plant as it evolves in a consistent and theoretically sound manner
  - Appropriate measures 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**

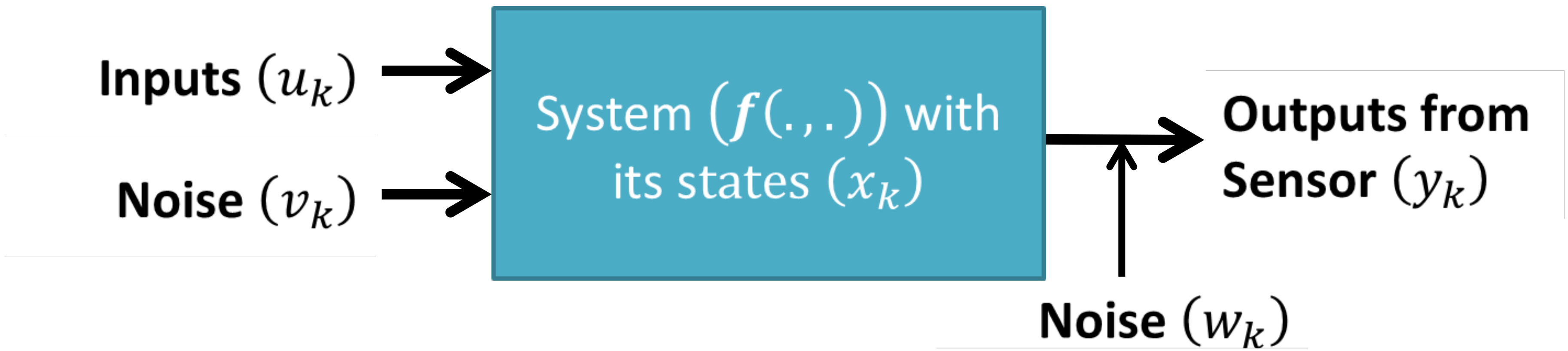
Communication Channels and Feedback Systems

- Focus on the system structure



Information Measures in Nonlinear Systems

Consider the nonlinear I/O system:



Information Measures in Nonlinear Systems

- We find that

$$I(y_{1:k}; u_{1:k}) = I(x_{1:k}; u_{1:k}) - I(x_{1:k}; u_{1:k} | y_{1:k})$$

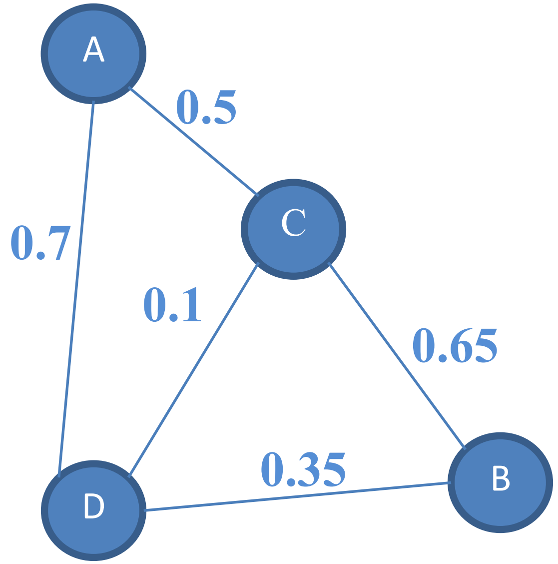
Connection between Inputs and Outputs

Connection between Inputs and System

Connection between System and Outputs (Inverse relationship)

System Structure Construction

Undirected Weighted Graph



Weighted Adjacency Matrix

	A	B	C	D
A	0	0	0.5	0.7
B	0	0	0.65	0.35
C	0.5	0.65	0	0.1
D	0.7	0.35	0.1	0

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

Self-organizing sensor networks support condition monitoring

- 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

Challenges

- **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**

Opportunities

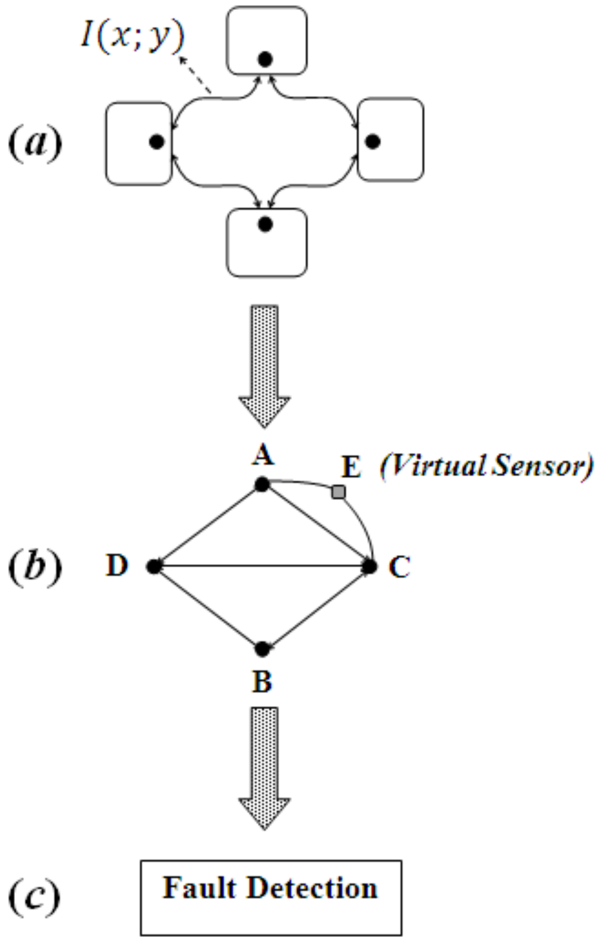
- **Ubiquitous computational and (wireless) communication resources**
- **Power management technologies engendering a new class of instrumentation**
  - No umbilical
  - Physically reconfigurable on-the-fly

Technical Approach

- **The aforementioned constraints and opportunities mandate a distributed, agent-based approach and strongly suggest the use of biologically inspired algorithms.**
- **<u>Distributed</u>**
  – 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.
- **<u>Agent-Based</u>**
  – 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.
- **<u>Biologically Inspired</u>**
  – 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



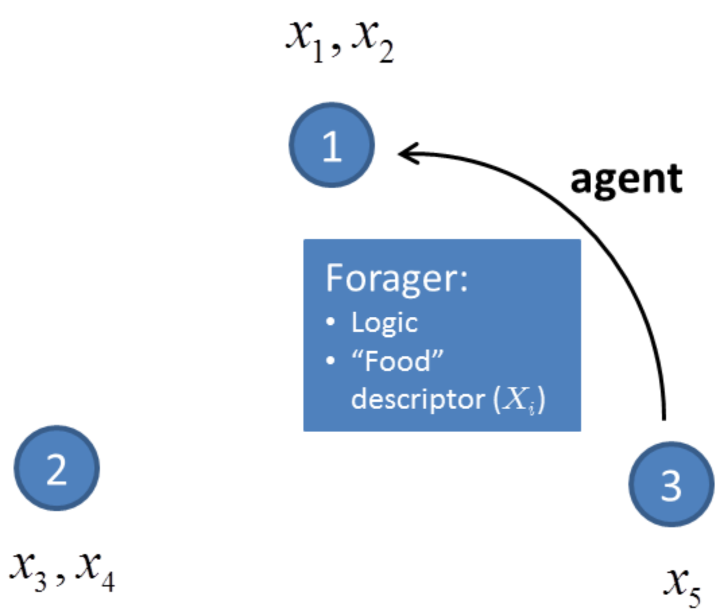
- Discovering the actual topology of the system's intrinsic communication structure.

- 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



$\boldsymbol{x_i}$: a time series which is the partial observation of the physical system at node ***i***

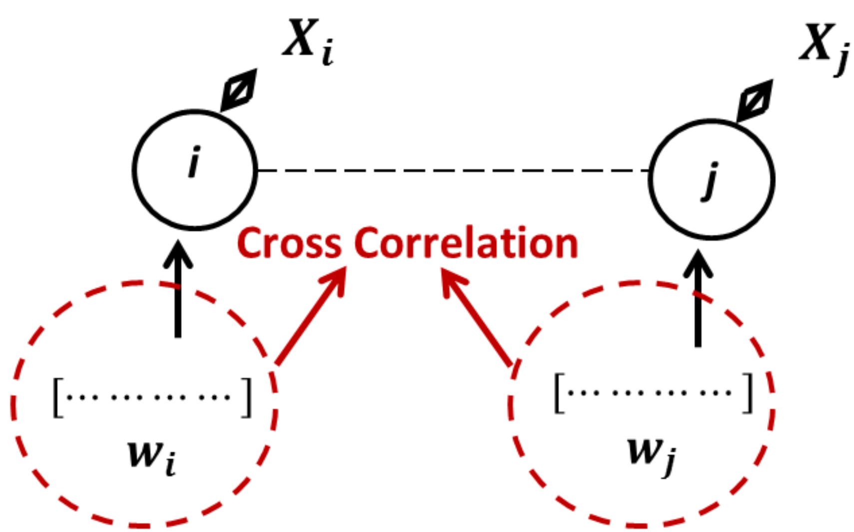
<u>Agent going from node 3 to node 1:</u>

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.



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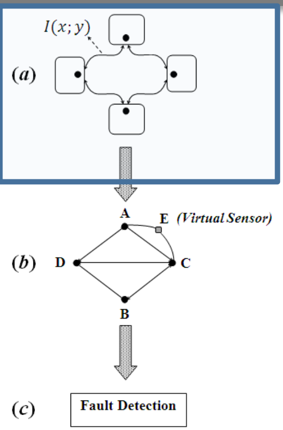
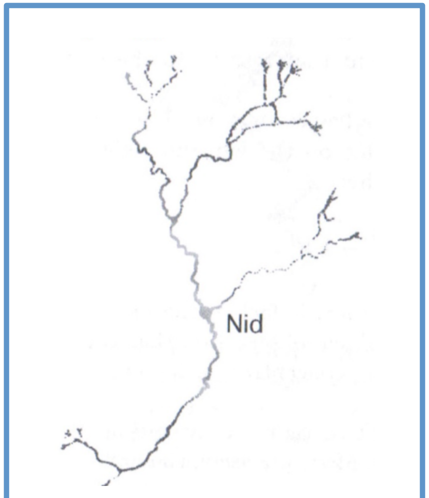
Foraging Behavior

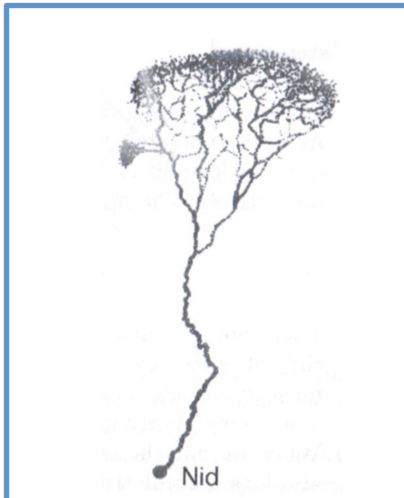
Foraging Patterns of Three Army Ant Species with Different Diets





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

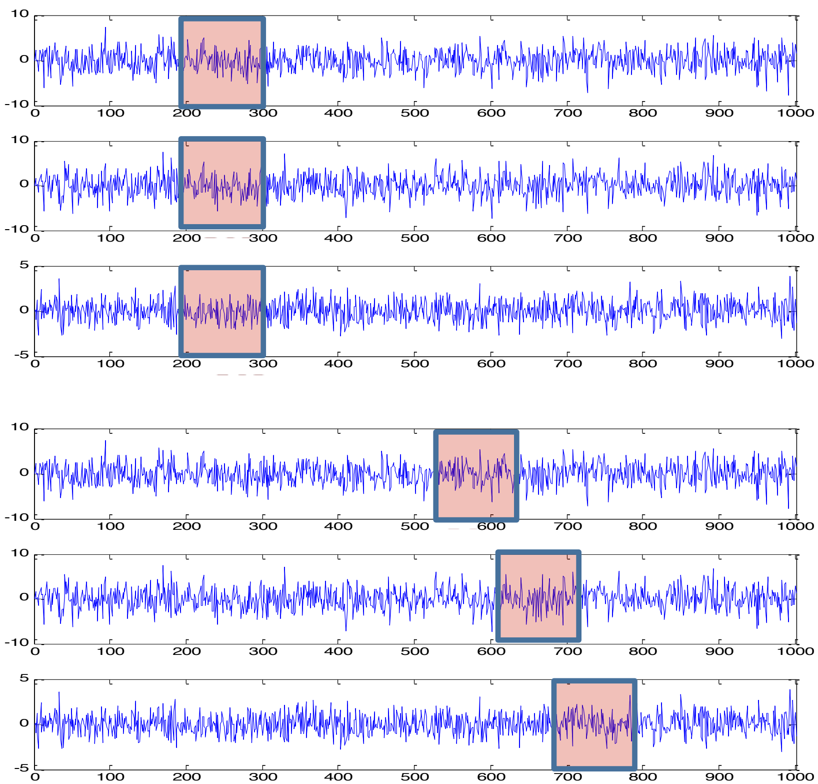
- **Eciton rapax**
- **Diet:** intermediate diet
- **Food distribution:** intermediate food source



- **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



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

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

$$\Sigma_{w_3,w_1} = \begin{bmatrix} 1.8371 & 0.3876 \\ 0.3876 & 7.6766 \end{bmatrix}$$

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

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

$$\Sigma_{w_3,w_1} = \begin{bmatrix} 1.5962 & -0.2804 \\ -0.2804 & 9.3388 \end{bmatrix}$$




Virtual Sensors

Accomplishments

- **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.

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Challenges and Opportunities

What has to be done and what's available to do it…

Challenges

- **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**

Opportunities

- **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.

Scenario Elements

- 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

Observer/Filter-Based Fault Detection and Diagnosis

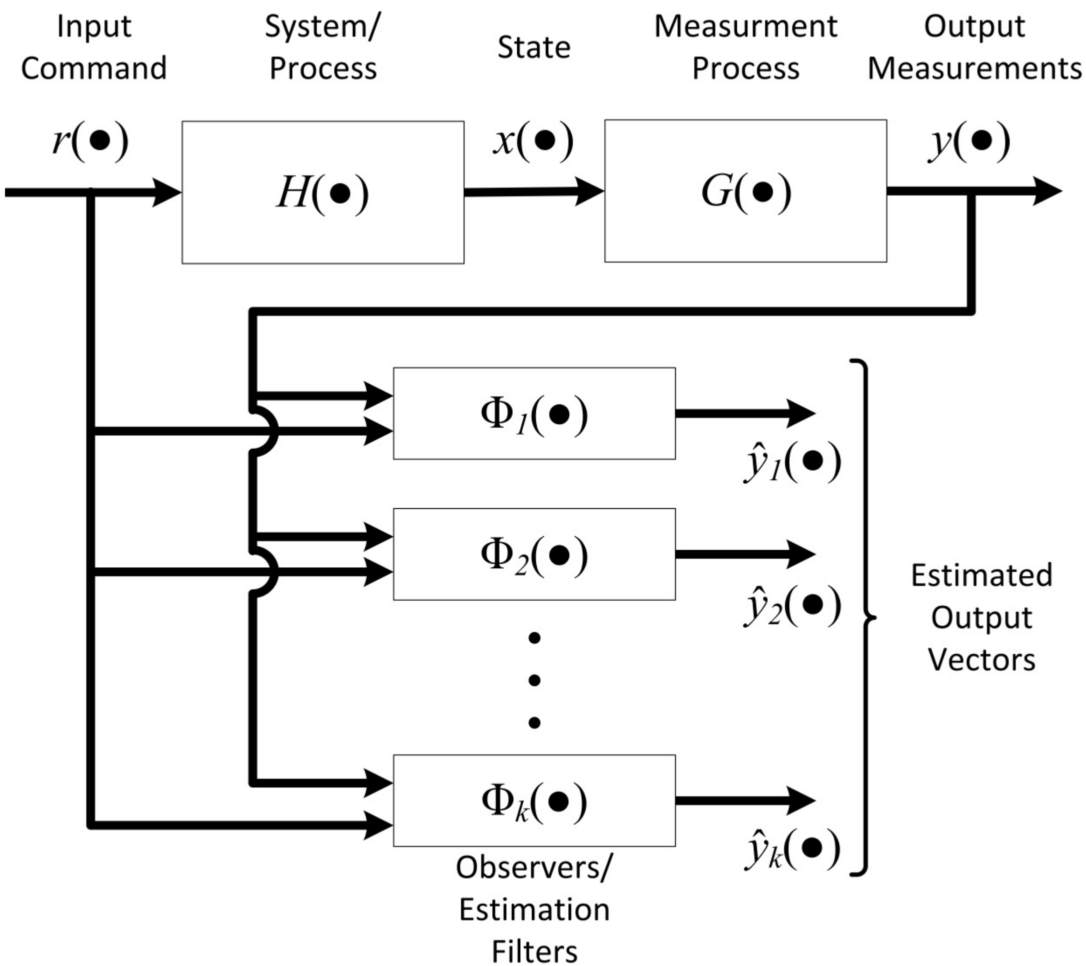
Key Concept

- **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.**

Technical Approach

Use of Observer/Filter Banks

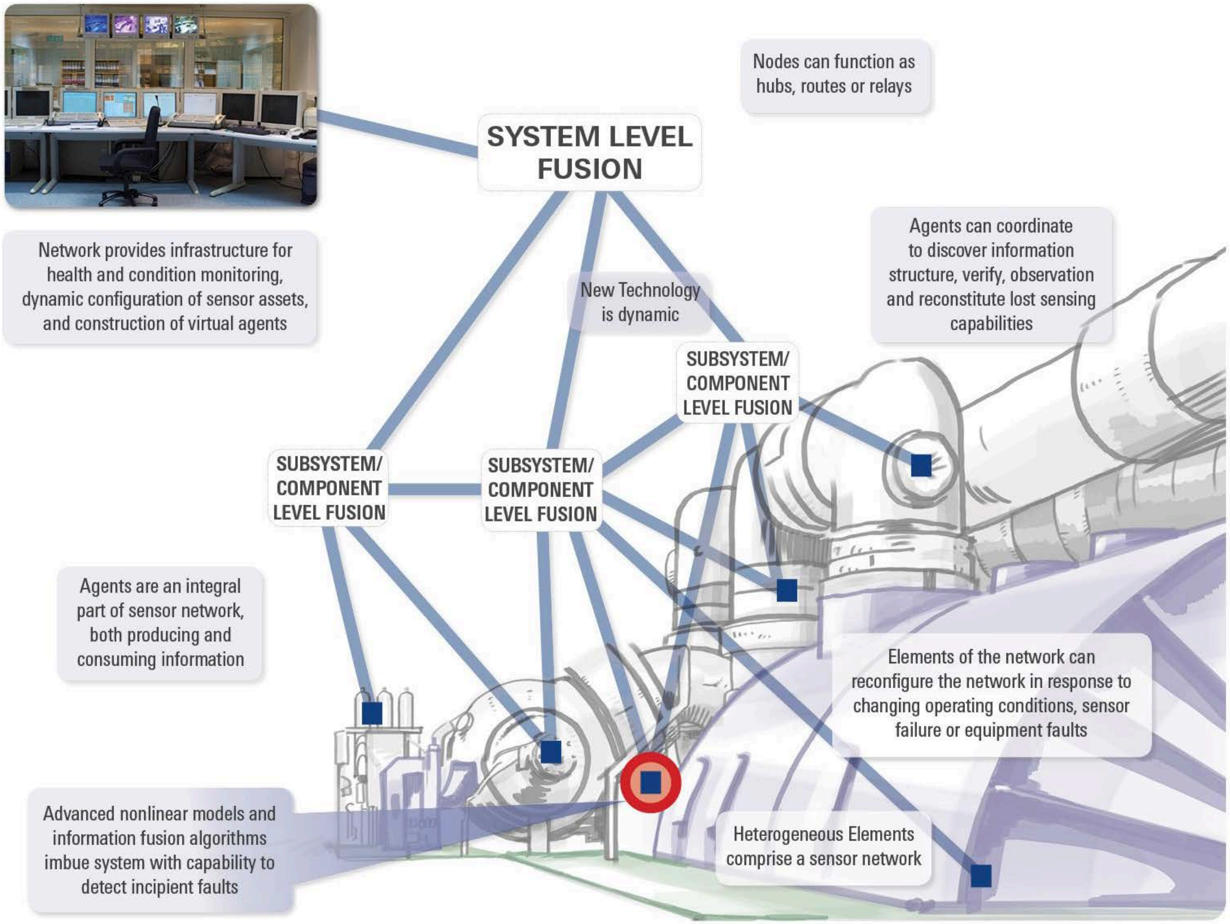
- **"Modeling" approach is based on classical state estimation methods;**
  - Deterministic systems => Luenberger Observer,
  - Non-deterministic systems => Linear or Nonlinear Filters.
- **Operate a bank of observers/filters each corresponding to different operating conditions.**



System Integration

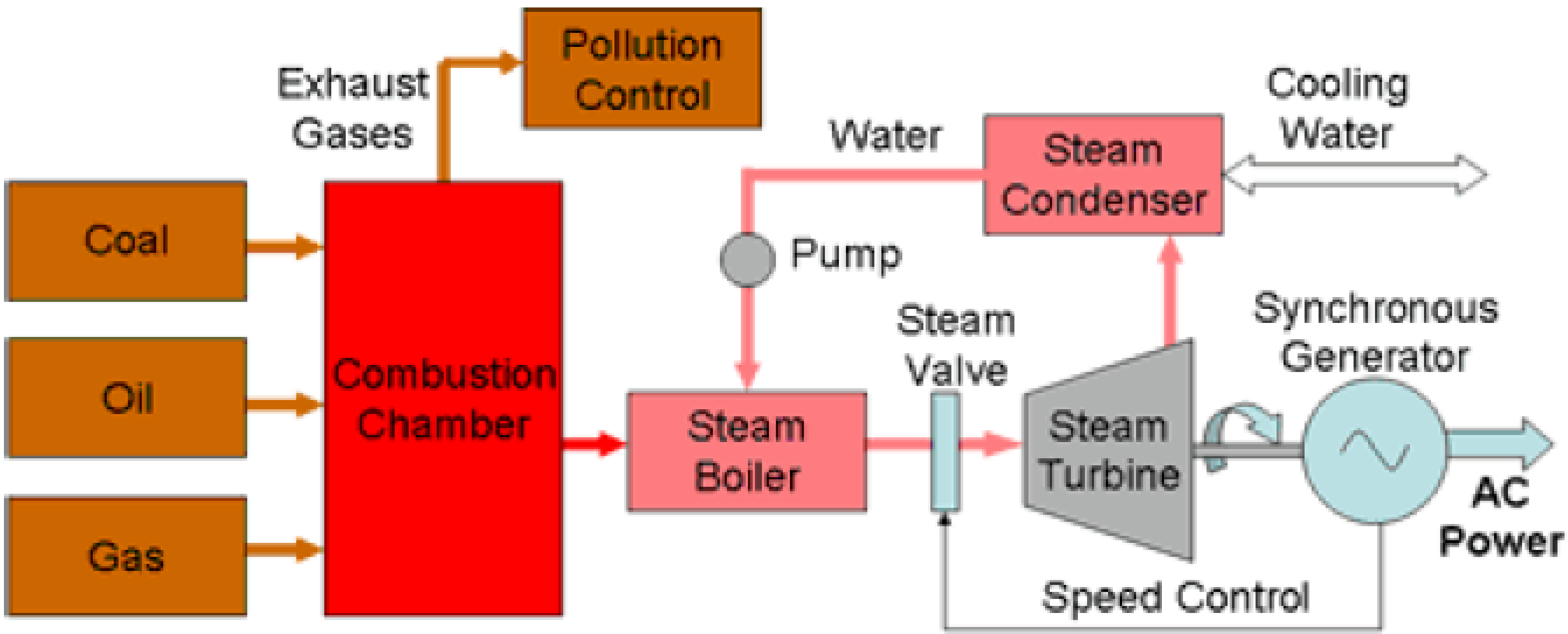
Target System

Self-organizing, information centric sensor network



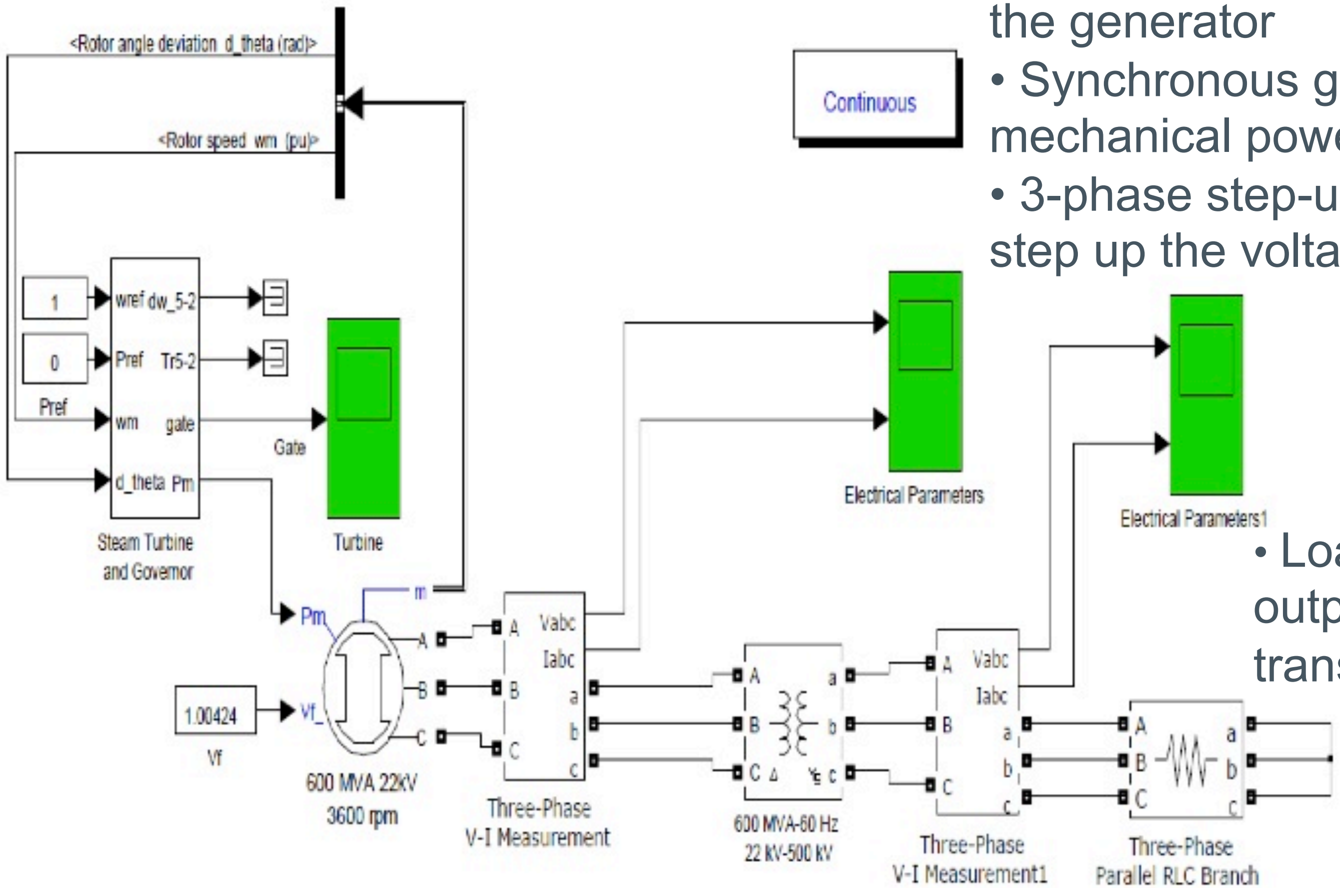
Simulation Development

System Schematic



Simulation Development

Preliminary Model



- 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

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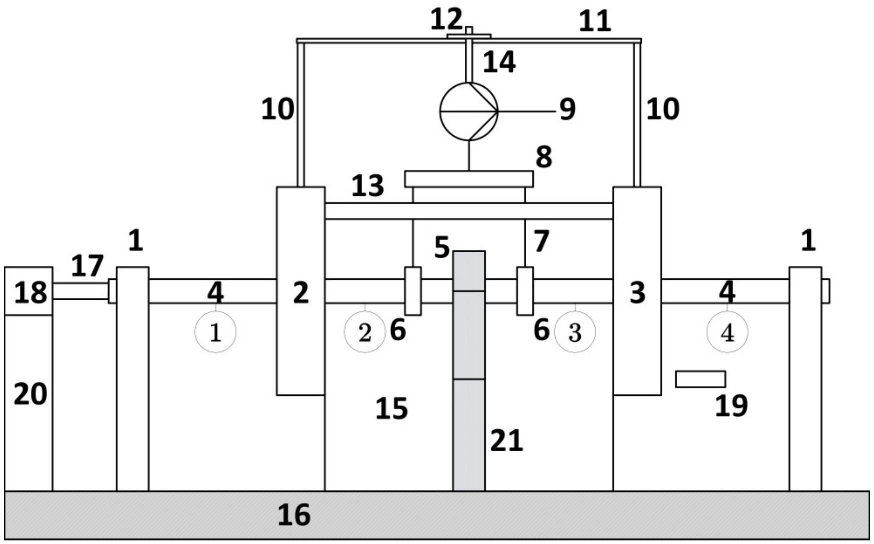
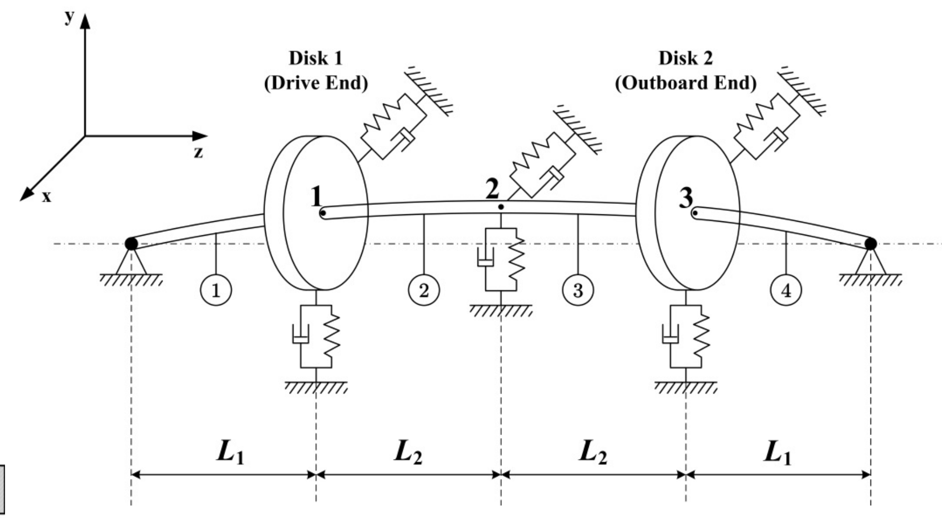
Journal Bearing Test Rig

Physical test rig and 24 state nonlinear model





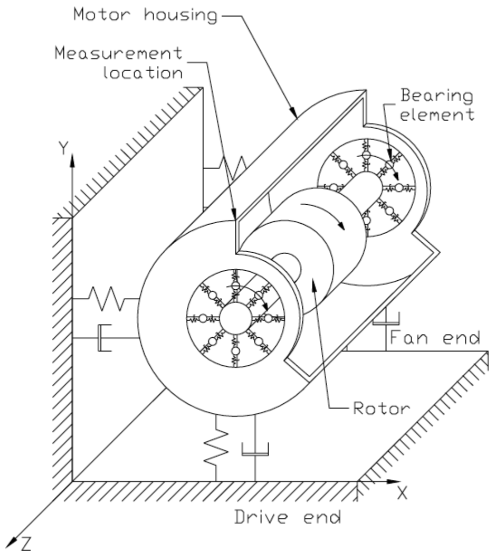
Legend:

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

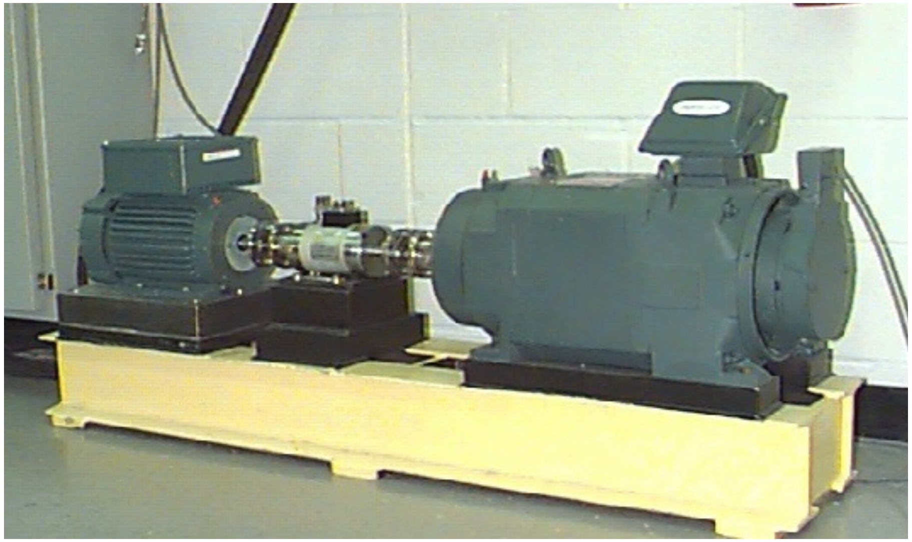
- Refurbished bearing test rig with controllable shaft preload, shaft speed, and disk unbalance.
- Key phasor and Bentley-Nevada proximity probes located at journal bearing.
- 24 state simulation implemented with nonlinear bearing models.

Rolling Element Test Rig

Instrumented bearings and motor



- 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.

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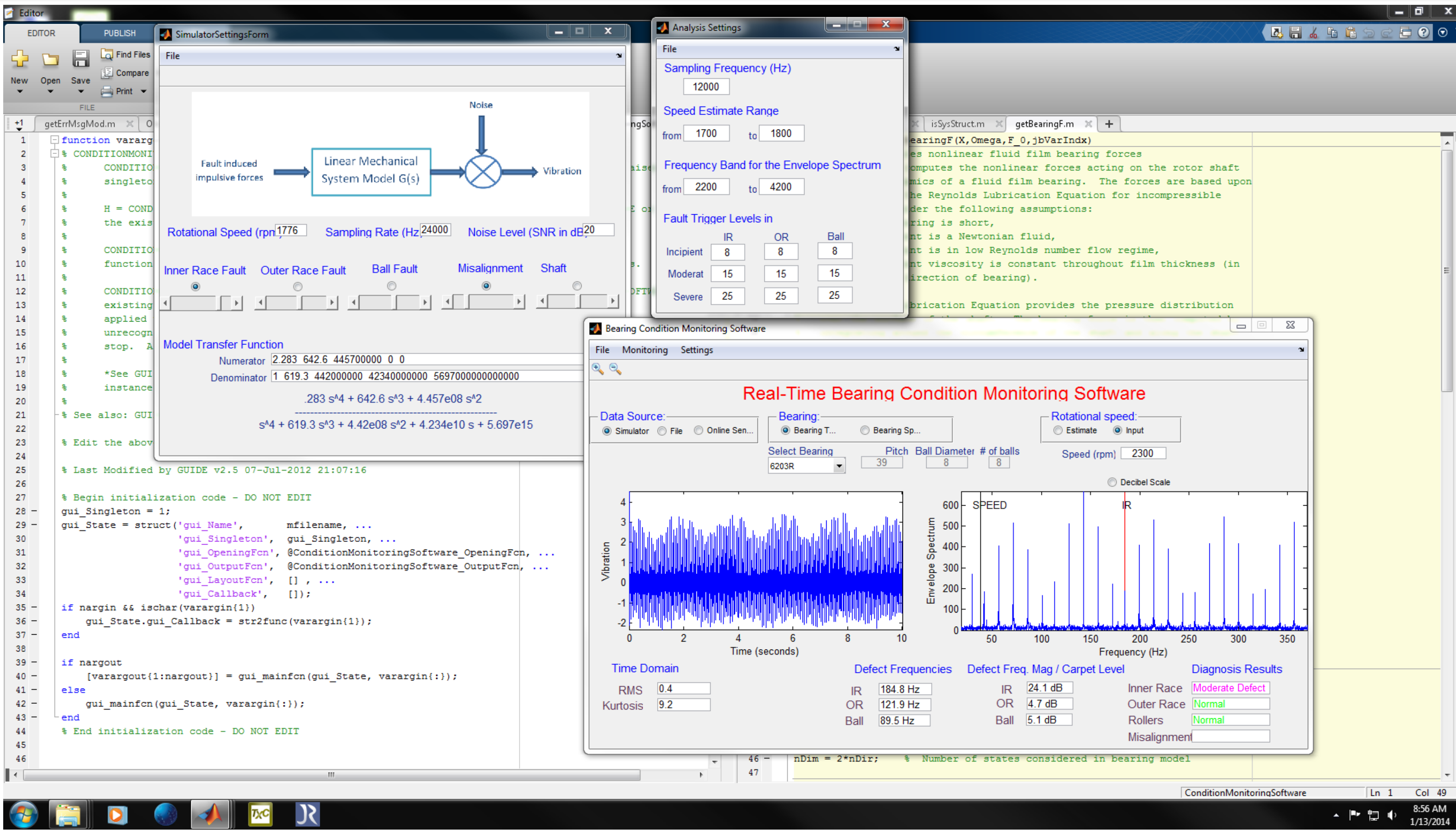
Bearing Condition Simulator

Matlab-based simulation and diagnostic software



Bearing Fault Simulator

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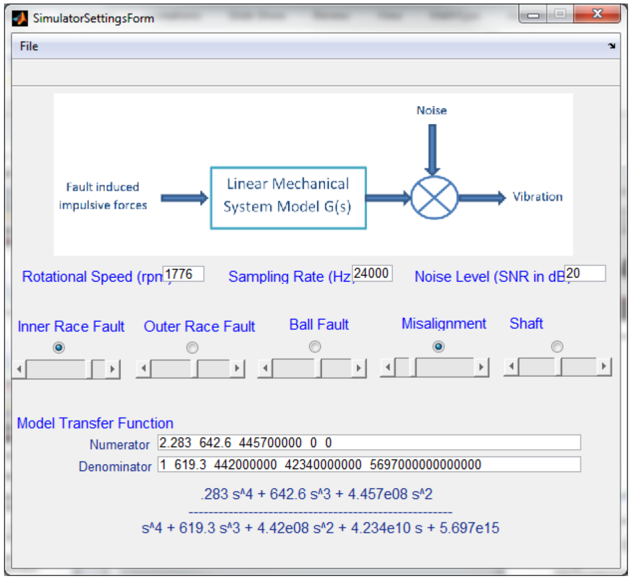
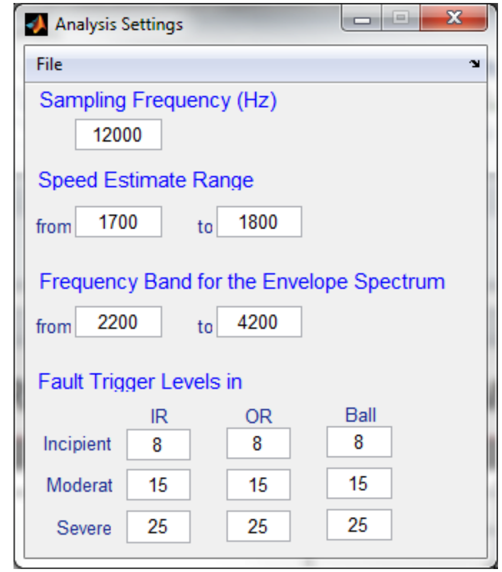
Two modes of operation



(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 if 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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