Detection, Isolation, and Recovery of Sensor Performance Degradation

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Objectives
• An ever-increasing number of sensors have been employed in dynamic systems to ensure correct control functionalities and diagnosis.
• Nevertheless, a sensor itself degrades and fails, just as any other dynamic system.
• A faulty sensor may cause undesirable system performance, process shut down, or even a fatal accident.

State-of-the-Art
Instrument Fault Detection and Isolation Techniques

- Hardware Redundancy
  Desai and Ray (1984)
  Glockler et. al (1989)

- Analytical Redundancy
  Model-based method
  Glockler et al. (1989)
  Luenberger observer and Kalman filter
  Van Dijk (1994)

- Knowledge-based System
  Expert system
  Lesi et al. (1992)

- Process history based method
  History network
  Betta et al. (1992)

- Instrument Fault Detection
  and Isolation Techniques
  Multivariate statistical methods
  Harque (1996)
  Bayesian belief networks
  Napolitano et al. (1994)
  Process history analysis
  Betta et al. (1998)

Approaches

- Fit a proper model to the data within the moving window by subspace model based method
  \[ x(t+T) = A(x(t))+B(u(t)+K(w(t)+e(t))) \]
  \[ y(t) = C(x(t))+D(u(t)+e(t)) + e(t) \]

- Extract the time constants of the monitored system and the sensor from the poles of the corresponding transfer function

Detection and Isolation of Dynamic Changes

Assumption 1: There is no nonlinearity included in the system
Assumption 2: Sensor dynamics is much faster than that of the plant
Assumptions 3: The process disturbances and measurement noise are white noise

Future Work
• Develop methods for the case when the process disturbances and measurement noise are colored noise processes.
• Extend this method to detect and isolation degraded sensors in presence of nonlinearities in the monitored system

For more information, contact Prof. J. Ni; Phone: 734-936-2918; Email: junni@umich.edu
Objectives

- The Watchdog Agent™ Toolbox is a software program that has been created to assess and predict system performance in various conditions and easily assess which combination of algorithms is the best fit for a particular application.

State-of-the-Art

- Modularization of the toolbox allows different methods of signal processing, feature extraction, performance evaluation, and sensor fusion to be used in any combination.

Approaches

- The software takes as input sensor data from the current, normal, and faulty operation of the equipment, and outputs the current level of degradation of the system, an ARMA prediction of future degradation, and a sensitivity analysis, or measure of affinity, for the chosen algorithms.
- The Watchdog Agent™ Toolbox has several functional layers, shown below, compliant with the Open System Architecture for Condition Based Maintenance (OSA-CBM).

<table>
<thead>
<tr>
<th>Data Acquisition</th>
<th>National Instruments PXI system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Manipulation</td>
<td>Time frequency, wavelet, FFT analysis</td>
</tr>
<tr>
<td>Condition Monitor</td>
<td>Not currently integrated</td>
</tr>
<tr>
<td>Health Assessment</td>
<td>Statistical pattern recognition, logistic regression, sensor fusion</td>
</tr>
<tr>
<td>Prognostics</td>
<td>ARMA modeling</td>
</tr>
<tr>
<td>Decision Support</td>
<td>Not currently integrated</td>
</tr>
<tr>
<td>Presentation</td>
<td>Graphical user interface (GUI)</td>
</tr>
</tbody>
</table>

- The following picture shows the National Instruments PXI system which is used for data acquisition.

Sponsors

- NSF Industry/University Collaborative Research Center on Intelligent Maintenance Systems
- National Instruments

Accomplishments

- Several interchangeable tools have been developed in Matlab and compiled into a standalone application. The tools that have been integrated can be seen below in the main window of the Watchdog Agent™ Toolbox.

- Shown below is the degradation analysis from 1100 cycles of a boring tool at DaimlerChrysler; two methods of performance assessment are compared.

Future Work

- A method for analysis of discrete event data will be added to the toolbox.

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**Objectives**
- Provide diagnostic & predictive information in a networked industrial automation system at the device level.
- Develop a methodology to evaluate effects of device-level embedded prognostics.
- Create methods to minimize maintenance-related costs through strategic allocation of failure risks associated with basic embedded prognostics.

**State-of-the-Art**
- Due to bandwidth limitations, limited amount of maintenance related information is available in an industrial networked automation systems.
- Inherent intelligence of networked devices is not utilized for maintenance purposes.

**Approaches**
- The Embedded Watchdog Agent™ solution
  - The risk allocation problem

**Accomplishments**
- Defined 3 levels of EWA complexity
  - Level 1: Operation/cycle counter
  - Level 2: Operation/cycle counter AND Cycle Timer
  - Level 3: Trending and data streaming

**Future Work**
- Conduct and improve dynamic optimal risk allocation using Basic Embedded Watchdog Agent™ Prognostics in complex industrial automation systems.
- Conduct industrial test and cost effect analysis of basic prognostics Embedded Watchdog Agent™.
**Motivation**
- Nearly 54% of failures in a networked industrial automation system occur due to faults on the network itself.
- There is need to create a predictive agent for assessment and prediction of performance of an industrial automation network.
- Current tools are not designed to provide such capabilities.

**Objectives**
- Develop and evaluate novel network health monitoring tools for industrial automation systems.
- Develop methodology that could assess and predict the performance of industrial automation networks.

**Approaches**
- Proposed data acquisition system

**Accomplishments**
- Identified key failure modes that occur in the networked industrial automation systems.
  - Connection problems, including loose connection of cable connectors and terminating resistors.
  - Corrupt frames, including damaged transceivers, grounding problems, electrical Magnetic Interference (EMI).
- Identified key parameters that affect the performance of networked industrial automation systems.
  - Bus voltage and current.
  - Common Mode Signal features.
  - Waveform of Digital signal.
- Preliminary results of one lost terminating resistor.

**Future Work**
- Develop NWA for the data link layer.
- Develop diagnosis methodology using data from both data link layer and physical layer.
- Testbed validation and demonstration for NWA.

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**Framework of the Network Watchdog Agent™**

- **Data collection system**
  - National instruments digital oscilloscope.
  - SST DeviceNet interface card.

**Performance Assessment**

**Failure mode Database**

**Performance Prediction**

**Network**

**Feature Extraction**

**Feature cluster under normal condition and with one lost terminating resistor**

**Comparison of DeviceNet signals under normal condition and with one lost terminating resistor**

**Measurement of key parameters of DeviceNet**

**PC**

**Statistic Data**

- Error Frame Ratio
- Bus load
- Bus Voltage
- Overshoot
- Signal-To-Noise Ratio

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Objectives

- Detecting and localizing unknown faults i.e. anomalies
- Sensing gradual performance degradation of controlled dynamic system
- Discriminating whether the performance deviation is caused by control software or plant (hardware)
- Developing effective diagnostics that can be applied comprehensively from product design through design validation, manufacturing testing on-board monitoring and finally repair service operating

State-of-the-Art

- With the growing complexity of both plants and control systems, effective diagnostics for all possible failures has become increasingly difficult and time consuming.
- As a result, many systems rely on limited diagnostic coverage provided by a diagnostic strategy which test only for known or anticipated failures, and presumes the system is operating normally if the full set of tests is passed.
- In addition, these tests are often developed separately and at large costs in terms of time and resources after hardware and the control system have been produced and are available for analysis.

Approaches

Method Overview

- The new anomaly detection method relies on the use of Self-Organizing Maps (SOM) for regionalization of the system operating conditions, followed by Time-Frequency Analysis (TFA) and Principal Component Analysis (PCA) for anomaly detection and fault isolation
- The proposed approach consists of two elements: anomaly detection which identifies whether a deviation from normal operation has occurred and fault isolation, which isolates the problem, as best as possible, to the specific component or subsystem that has failed

Accomplishments

- Ability to detect gradual changes of the system parameters as the dynamic system operates.
- Ability to detect faults that were not observed before (i.e. detect anomalies) using the same generic approach.
- No prior assumptions were made about the system behavior and the model of system behavior was learnt from a normal driving profile.
- Ability to detect and isolate of controller (software) anomalies from the plant (hardware) anomalies.

Future Work

- Development of effective method for intermittent fault detection

Sponsors

- This project is supported in part by Center for Intelligent Maintenance System at University of Michigan, Ann Arbor and ETAS Inc., Ann Arbor
Objectives

- To develop system modeling and decision support tools that integrate different data domains in a semiconductor fabrication facility into coherent performance information that will facilitate rapid and proactive countermeasures for any problem that will adversely affect the yield and uptime.

- To coordinate and synthesize the integrated information from all stations into system level information that will be used to make dynamic, accurate and cost-effective maintenance scheduling and product routing decisions.

Approaches

- Improved yield prediction from integrated information flow using enhanced Bayesian networks.

- Enhanced maintenance decision support tools based on improved yield estimation model.

- Validation of results in an industrial testbed.

State-of-the-Art

- Many yield models based on defect detection and critical area analysis have been developed, in which, however, only defect inspection data are utilized.

- Researchers have attempted to predict yield using localized in-line data or in-situ measurements of particle contamination, which only give a partial picture of the process degradation.

- Majority of maintenance operations are still based on either historical reliability of equipment, or diagnostic information from equipment performance signatures extracted from in-situ sensors.

Future Work

- Performing case study using semiconductor dataset.

- Handling incomplete data without compromising inference accuracy.

- Periodically updating inference structure when real inspection becomes available.

Sponsors

Semiconductor Research Corporation (SRC)
Objectives

- Shift the maintenance policy from reactive to proactive
- Assess current performance of a railroad bogie bearing

Condition Based Maintenance

- **Condition based maintenance policy**

Approach

- **Life Cycle unit and diagnostic/prognostic algorithms**
- **Feature extraction – Time-frequency distribution**

Classification Method

- **Support Vector Machine (SVM)**
  - Training vectors are mapped into a higher dimensional space with help of a kernel
  - SVM algorithm creates a maximum-margin hyperplane that separates data into two classes

Measurement

- **Testbed**
  - **Measured vibrations**
  - RPM was varied with a sinusoidal input
  - Sinusoid has a period of T=60s
  - Experiment was conducted with five different loads acting on the bogie cage

Expected Results

- High identification rate of functional and defective bearing
- Improved maintenance policy through condition based maintenance

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Objectives

- Develop novel approach to realize "immune systems" functionalities in automated systems
- Robustly detect abnormal behaviors, isolate its source, and compensate for negative effects to achieve desired performance in spite of the presence of an anomaly

State-of-the-Art

- Nonlinear plant is regionalized into several local linear models through “divide and conquer” methodology
- Local models are analyzed for fault detection and isolation
- Adaptive local controllers are applied per region to achieve desired performance

Approach

Model using Growing Structure Multiple Model System (GSMMS) algorithm
- Identify anomalies via Anomaly Detection Agents
- Diagnose and isolate faults
- Reconfigure control system to restore desired performance
- Are modeling errors large?
  - NO: Continue control with current GSMMS model
  - YES: Reconfigure control system to restore desired performance

Accomplishments

Benchmark Problem

- Continuously Stir Tank Reactor (CSTR) Model is used to serve as the plant for preliminary study
- Inputs (flow rate, $q$, and heat transfer removal rate, $Q_C$) are used to control output (concentration $C_b$)

Modeling Results

- Recursive Learning for both GSMMS and Fuzzy Logic have been performed on CSTR model
- The index, variance accounted for (VAF), has been used to quantify the deviation of the models from the actual plant (Note: the VAF of two equal signals is 100%)

Comparison of Results

<table>
<thead>
<tr>
<th></th>
<th>GSMMS</th>
<th>Fuzzy</th>
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</thead>
<tbody>
<tr>
<td>Computation Time</td>
<td>2.01 sec</td>
<td>29.87 sec</td>
</tr>
<tr>
<td>VAF</td>
<td>99.1833 %</td>
<td>99.7115 %</td>
</tr>
</tbody>
</table>

Results using GSMMS and Fuzzy

Future Work

- Apply local adaptive controller to the local models
- Vary parameters to simulate anomalies
- Achieve desired performance despite anomalies
- Apply same approach to practical data (i.e. automotive engine)

Sponsors

National Science Foundation

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