Detecting, Diagnosing and Controlling Process Variations: A Review of Modeling Options

Venkat Venkatasubramanian

Laboratory for Intelligent Process Systems
School of Chemical Engineering
Purdue University
W.Lafayette, IN 47907
Outline

- Introduction
  - Exceptional Events (Abnormal Events) Management (AEM/EEM)
  - Intelligent Control
  - Challenges and Issues
- Model based and Process History-based methods
- Emerging Trends
- Future Directions
Lecture Philosophy

- Broad overview
  - Not a detailed, in-depth review
  - Identify key concepts, issues, challenges
  - Compare and contrast different approaches
Introduction

- Intelligent Control deals with Exceptional Events in Process Plants
- Exceptional Events are deviations in process behavior from normal operating regime
  - Safety problems
  - Environmental concerns
  - Quality problems and Economic losses
- Why do exceptional events occur?
  - Human errors
  - Equipment degradation and failures
- This is really a Process Control Problem
Process Fault Detection and Diagnosis

- First Step in Exceptional Events Management
  - Find out what is wrong
- Interpreting current status of process
  - Utilizing sensor data & process knowledge, isolate abnormal situations

```
Process → Sensor Readings → Diagnostic System
  → Process Knowledge
```

- Infer Process State - Detection: Normal/Abnormal
  & Isolation of abnormality

- Problem Size and Complexity
  - As many as 1500 variables monitored every few seconds
  - Integrated Process Operations
- Broad scope of the task: Variety of Process Failures
  - Parametric Faults, Structural faults, Malfunctioning Sensors/Actuators
- Process Measurements may be
  - Insufficient, Incomplete, Unreliable

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Diagnostic Approaches – Brief Review

- Process Fault Diagnosis: First Step in Intelligent Control
- Diagnostic Philosophies
  - Source of Process knowledge
    - Process Model
    - Process History
  - Form of Process knowledge
    - Qualitative
    - Quantitative
- Process Model: Deep, Causal or Model-Based knowledge
- Process History: Shallow, Compiled, Evidential knowledge

Transformations

- **Diagnostic Decision Process**
  - View as a series of transformations or mappings on process measurements

- **Important Components in the process:**
  - *a priori* process knowledge and search technique

Sets of measurements input to the diagnostic system

Useful features extracted as a function of measurements using *a priori* problem knowledge

Map feature space to decision space to meet some objective - minimizing misclassification e.g. using discriminant function/threshold function

Class space: fault classes, final interpretation of the system delivered to the user. By threshold functions, template matching, symbolic reasoning
Example

- Neural Network based classifier
  - Input Nodes: Measurement Space
  - Hidden Nodes: Feature Space
  - Output Nodes: Decision Space
  - Interpretation of Outputs: Class Space

**Input layer**
- Measurement Space

**Hidden layer**
- Feature Space

**Output layer**
- Decision Space

**Class Space**

Neural Network based classifier:
- Input Nodes: Measurement Space
- Hidden Nodes: Feature Space
- Output Nodes: Decision Space
- Interpretation of Outputs: Class Space

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Classification of Diagnostic Methods: Options

- Diagnostic Methods
  - Model-Based
    - Quantitative
      - Observers
      - EKF
      - Parity Space
      - Digraphs
      - Fault Trees
      - Causal Models
  - Qualitative
    - Abstraction Hierarchy
      - Structural
      - Functional
  - Process History Based
    - Qualitative
      - Expert systems
      - QTA
      - Statistical Physics
      - Qualitative Physics
    - Quantitative
      - PCA/PLS
      - Statistical Classifiers
      - Neural Networks

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QUANTITATIVE MODEL-BASED
**Model-based Detection and Diagnosis**

**Residual Generation**
*Unknown fault modes, uncertain nominal model, system/measurement noise*

**Residual Analysis**
*Statistical testing of residuals to arrive at a diagnostic conclusion*

**Consistency Checking (Analytical Redundancy):** Compare actual behavior with a nominal fault-free model driven by same inputs, using *residuals.*

**Residuals:** Functions accentuated by faults representing this inconsistency

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Quantitative Models

- Key idea is to check the parity (consistency) of plant models by using actual measurements - sensor outputs (measurements) and process inputs.

- **Observer-based Methods**
  - Develop a set of observers each sensitive to set of faults while being insensitive to the other faults/unknown inputs.
  - Observers for nonlinear systems: Elegant approach for fault-affine (Frank, 1990)
  - Bilinear nonlinearity (Ding et. al. 1995); Differential geometric methods (Yang and Saif, 1995)
  - Good Reviews by Frank (1990, 1994); Patton & Chen (1997)

- **Parity-Space Approaches**
  - Rearranged/transformed variants of the input-output/state-space models
  - Chow and Willsky (1984) provided a general scheme for both direct and temporal redundancy
  - Once residual properties have been selected all parity and observer based designs are fundamentally equivalent (Gertler, 1991)
  - Reviews of parity space by Patton and Chen (1991); Gertler (1997)
Quantitative Models

- **Kalman Filters**
  - Stochastic version of observers: Estimating $x$ based on $u$ and $y$; with gaussian white noises
  - Kalman filter in state space model is equivalent to an optimal predictor for a linear stochastic system in the input-output model.
  - Single Filter (Mehra and Peshon, 1971, Clark 1978)
  - Bank of filters (Wilbers and Speyer, 1989)
  - Extended Kalman Filter (Chang and Huang, 1998; Huang et. al., 2000)

- **Parameter Estimation Techniques**
  - Alternative Approach: Not based on state estimation
  - Faults of a dynamic system are reflected in the physical parameters
  - Detect faults via estimation of the parameters (Isermann, 1984)
  - Different estimation techniques: least squares, nonlinear optimization
Issues in Model-Based Diagnosis

- Modeling uncertainty: Availability of a ‘decent’ model
  - Perfectly accurate/complete model of a physical system is rarely available
  - Uncertainty: Mismatch between actual process and its math model
  - Effect of modeling uncertainties is very crucial

- Sensitizing/Desensitizing & Robustness
  - Decoupling fault effects, system/measurement noise
  -Insensitive to modeling uncertainty, noise, disturbances with increased sensitivity to faults

- Online speed: Computations Vs Performance

- Theory
  - Well developed for linear systems, nonlinear systems’ still not mature
Quantitative Model-Based

- **Merits**
  - Mathematical approach based on first principles
  - Estimation of fault magnitude, multiple fault identifiability
  - Handling novel situations

- **Demerits**
  - Requirement of a good model
  - Effect of modeling uncertainties is very crucial
  - Need robustness to shifts in normal regimes, noise
  - Linear Vs Nonlinear systems
  - Procedural nature: No explanation facility

- **Online speed:** Computations Vs Performance
Classification of Diagnostic Methods

- Diagnostic Methods
  - Model-Based
    - Quantitative
      - Observers
      - EKF
      - Parity Space
    - Qualitative
      - Causal Models
      - Abstraction Hierarchy
  - Process History Based
    - Qualitative
      - Expert systems
      - QTA
    - Quantitative
      - Statistical
        - Neural Networks
      - Statistical Classifiers

- Quantitative
  - Structural
  - Functional
- Qualitative
  - Physics

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QUALITATIVE MODEL-BASED
Qualitative Models

- **Fault Trees**
  - Qualitative cause-effect relationships represented as a tree
  - Fault Trees (Lapp & Powers, 1977)
    - Top-down, symptom-driven approach
    - Qualitative ambiguities

- **Signed Digraphs and Causal Models**
  - Qualitative cause-effect relationships as a directed graph with nodes and arcs
  - Bottom-up, cause-driven approach
  - Qualitative ambiguities
  - Single fault diagnosis (Iri et.al., 1979; Kramer and Palowitch, 1987; Wilcox and Himmelblau, 1994)
  - Multiple fault diagnosis (Morales and Garcia, 1990; Vedam and Venkatasubramanian, 1999)

- **Abstraction Hierarchy**
Qualitative Model Based

- **Merits**
  - Qualitative nature facilitates their development without exact model equations
  - Completeness: Enumerates all possible root causes

- **Demerits**
  - Need to develop and maintain SDG
  - Qualitative nature results in poor resolution
  - Number of spurious solutions
Model based Framework: Challenges

- **Appropriate level of modeling**
  - Too Coarse: Not very useful results
  - Too Fine: Too complex and buried in details
  - Quantitative vs Qualitative

- **ALL MODELS ARE WRONG, SOME ARE USEFUL**
  -- George Box
PROCESS
HISTORY-BASED
Process History Based Techniques

*Process-History Data from normal/abnormal operation*

- **Quantitative Methods**
  - **Neural Networks**: Easy learning & interpolation capabilities leading to numerous diagnostic applications (Venkatasubramanian et. al. 1989, 93, 94)
  - **Statistical Techniques**:
    - Univariate SPC based on limit-checking
    - Multivariate PCA/PLS based monitoring (MacGregor et. al., 1994)

- **Qualitative Methods**
  - **Qualitative Trend Analysis**: Sensor Trend Information
    - Process History enters the antecedent and consequent of rules
    - Lack of generality; Poor handling of novel situations
Qualitative Trend Analysis: Representation

- **Primitives Representation**
  - Each segment is represented by a quadratic polynomial equation and is characterized by its first and second derivatives

Desirable Features of an Intelligent Control System

- Early detection & diagnosis
- Isolability: discriminate between failures
- Robustness: to noise & uncertainties
- Novelty Identifiability: novel malfunction
- Explanation facility: Fault propagation
- Adaptability: Processes change & evolve
- Reasonable storage & computational requirement
- Multiple Fault Identifiability: Difficult requirement
Comparison of Different Diagnostic Methods

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</table>

No single method achieves all !!!

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Hybrid Framework

- No single method meets all the criteria of a ‘good’ diagnostic method

A Hybrid Framework
- Involving different methodologies
- Based on a collective and synergistic approach to problem solving seems most promising (Mylaraswamy & Venkatasubramanian, 1997)
- Compensate one method’s weakness with the strengths of another’s

DKit implemented in G2
- Effectiveness demonstrated on Model IV FCCU by successfully diagnosing wide varieties of faults
- Combined causal model-based diagnosis with statistical classifiers
- Basis for the prototype of the ASM Consortium
- Licensed to Honeywell by Purdue University

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Hybrid Methods: All methods have advantages and disadvantages. Combining methods allows us to capitalize on the advantages and make up for the disadvantages.

**Signed Directed Graphs (SDG)**

1. Data from Process
2. Obtain SDG based on equations governing the process
3. Obtain IRT based on SDG
4. Obtain Measured IRT
5. Compare IRT
6. Obtain Set of Possible Candidate Faults
7. Represent faults as sequences of basic shapes
8. Compare sequences
9. Most Probable Fault Determined

**Qualitative Trend Analysis (QTA)**

- Simple Unimodals
- Knowledge Base of Fault Patterns

Event: No powder entering roll region

Causes:
- No powder in hopper
- Blockage in hopper
- Jam in nip region
Roller Compactor

Governing Equations of Roller Compaction Process

\[ \rho_{in} \cdot \cos \theta_{in} \cdot \left( \frac{1}{R} \frac{h_0}{R} - \cos \theta_{in} \right) \cdot \left( \frac{u_{in}}{\omega \cdot h_0} \right) = \rho_{exit} \]

\[ F = \frac{C_1 \cdot (\rho_{exit})^K}{1 + \sin \delta} \int_0^{u_{in}} \left[ \frac{h_0}{R} \frac{h_0}{R} \cos \theta \cdot \cos \theta \right]^K \cos \theta \cdot d\theta \]

Qualitative Simplification of Mathematical Model

\[ \frac{h_0}{R} \sim + u_{in} \rho_{in} - \rho_{exit} - \omega \]

\[ \rho_{exit} \sim - \frac{h_0}{R} + F \]

In the absence of models that capture abnormal behavior, expert and/or operator knowledge of exceptional events can be incorporated into initial response table

Signed Directed Graph and Initial Response Table

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</table>
Qualitative Trend Analysis: Hybrid Methods

**Fault Detection & Diagnosis: SDG**

First Level of Diagnosis

**Fault Detection & Diagnosis: QTA**

Second Level of Diagnosis

EEM Mitigation Strategy

Exceptional Event in Roller Compactor

No powder entering the roll region possibly due to jamming in the nip region. Minimize hydraulic pressure and feed speed. Maximize roll speed.

Figure 2

Roller Compactor Roll Gap

Roller Compactor Hydraulic Pressure

Roller Compactor Feed Screw Speed

Roller Compactor Roll Speed
Real-Time EEM Implementation

- EEM detected and diagnosed exceptional within 10 seconds of its inception
- EEM detected and diagnosed before feedback controller reacted to decrease in roll gap by increasing feed screw speed
  - **Incipient** detection & diagnosis
- Currently, exceptional event and mitigation strategy appear as warning
Continuous Manufacturing Line

Partially Continuous Dry Granulation Line

- **Feeder A**
  - Powder Weight (kg)
  - Feed Rate (kg/hr)
- **Feeder B**
  - Powder Weight (kg)
  - Feed Rate (kg/hr)

- **Blender**
  - Blender Mix Speed (rpm)

- **Roller Compactor**
  - Roll Gap (microns)
  - Hydraulic Pressure (bar)
  - Feed Screw Speed (rpm)
  - Roll Speed (rpm)

- **Ribbons**

- **API**

- **Excipients**
Integrated Intelligent Control Systems

- **Regulatory Control (MPC)**
- **Data Acquisition**
- **Intelligent Monitoring**
- **Fault Diagnosis**
- **Supervisory Control and Fault Administration and RTO**
- **Operator**

**Processes**:
- Manipulated Variables
- Controller Settings
- Setpoints
- Sensor Trends
- Reconciled Data
- Data
- Faults
- Information
- Specifications
- FDD Design
- Parameter Estimates
- Controller Settings
- Setpoints
- Sensor Trends
- Reconciled Data
- Data
- Faults
- Information
- Specifications
- FDD Design
- Parameter Estimates

**Data Flow**:
- Data Acquisition
- Fault Diagnosis
- Data Reconciliation Parameter Estimation

**Information**:
- Fault Diagnosis
- Data Reconciliation Parameter Estimation
- Sensor Trends
- Reconciled Data
- Data
- Faults
- Information
- Specifications
- FDD Design
- Parameter Estimates

**Control**:
- Regulatory Control (MPC)
- Data Acquisition
- Intelligent Monitoring
- Fault Diagnosis
- Supervisory Control and Fault Administration and RTO
- Operator

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Summary

- Reviewed the approaches, challenges, and emerging trends in Intelligent Control Systems
  - Model based and Process history based approaches
  - Hybrid Systems

- Intelligent control systems can make a substantial improvement to current practices

- Considerable challenges remain but good progress has been made in recent years

- Future potential is enormous and exciting
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