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The University of Texas at Arlington  

CBM IV – Prognostics and Maintenance Scheduling  

http://ARRI.uta.edu/acs
The CBM/PHM Cycle

Required Background Studies

- Identify sensors
- Identify important features
- Fault Mode Analysis

Machine Sensors

Data → Pre-Processing → Feature Extraction → Fault Classification → Prediction of Fault Evolution → Perform Required Maintenance

Systems & Signal processing

Diagnostics

Prognostics

Maintenance

CBM → PHM

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CBM Fault DIAGNOSTICS Procedure

Sensing → Systems, DSP & Data Fusion → Fault Feature Extraction → Reasoning & Diagnosis

Inject probe test signals for refined diagnosis

- Sensor outputs
  - Math models: $\dot{x} = f(x,u,\pi)$, $y = h(x,u,\pi)$
  - Physics of failure
  - System dynamics
  - Physical params. $\pi$

- Models-Based Diagnosis
- Feature extraction - determine inputs for Fault Classification

- Feature vectors
  - Vibration Moments, FFT
  - Feature Vectors - Sufficient statistics
  - Physical Parameter estimates & Aero. coeff. estimates
  - Feature vectors

- Fault Classification
  - Feature patterns for faults
  - Decision fusion could use:
    - Fuzzy Logic
    - Expert Systems
    - NN classifier

- Fault Classification
  - Decision fusion could use:
    - Fuzzy Logic
    - Expert Systems
    - NN classifier

- Fault Pattern Library
- Stored Legacy Failure data
- Statistics analysis

- More info needed?
- Set Decision Thresholds:
  - Manuf. variability data
  - Usage variability
  - Mission history
  - Minimize $Pr\{false\ alarm\}$
  - Baseline perf. requirements

- Inform pilot
- Request Maintenance
- Current Fault Condition
## Fault Pattern Library

<table>
<thead>
<tr>
<th>Condition</th>
<th>Fault Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF (leakage coeff. L is large)</td>
<td>THEN (fault is hydraulic system leakage)</td>
</tr>
<tr>
<td>IF (motor damping coeff. B is large) AND (piston damping coeff. (B_p) is large)</td>
<td>THEN (fault is excess cylinder friction)</td>
</tr>
<tr>
<td>IF (actuator stiffness K is small) AND (piston damping coeff. (B_p) is small)</td>
<td>THEN (fault is air in hydraulic system)</td>
</tr>
<tr>
<td>Etc.</td>
<td>Etc.</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Condition</th>
<th>Fault Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF (base mount vibration energy is large)</td>
<td>THEN (fault is unbalance)</td>
</tr>
<tr>
<td>IF (shaft vibration second mode is large) AND (motor vibration RMS value is large)</td>
<td>THEN (fault is gear tooth wear)</td>
</tr>
<tr>
<td>IF (third harmonic of shaft speed is present) AND (kurtosis of load vibration is large)</td>
<td>THEN (fault is worn outer ball bearing)</td>
</tr>
<tr>
<td>Etc.</td>
<td>Etc.</td>
</tr>
</tbody>
</table>

## Fuzzy Logic Rulebase
The CBM/PHM Cycle

Required Background Studies

Who really knows??

Available resources
RUL
Mission due dates

Machine legacy failure data

Current fault condition

Data

Pre-Processing  Feature Extraction  Fault Classification  Prediction of Fault Evolution  Prescribe Maintenance  Schedule Required Maintenance

Systems & Signal processing

Diagnostics

Prognostics

Prescription

Maintenance Scheduling
PHM Maintenance Prescription and Scheduling Procedure

Prescription-Based Health Management System (PBHMS)

- Prescription Library
  - Stored Prescription Library
  - Medical Health Prescriptions
- Prescription
  - Prescription modes
trends
side effects
Rulebase expert system
Fuzzy/Neural System
Prescription decision tree
Bayesian
Dempster-Shafer

- Diagnostics and Fault condition

- Prescription Library
  - RUL
  - Estimated time of failure
  - Adaptive integration of new prescriptions

- Maintenance Requirements Planning
  - Maint. Planning & Scheduling
  - weight maint. Requests
  - Computer machine planners
  - HTN, etc.

- Scheduling
  - Maintenance Priorities
  - Mission Due Dates
  - Guaranteed QoS

- Performance Priority Measures
  - earliest mission date
  - least slack repair time
  - due date

- Priority Costs
  - safety risk cost

- Resource assignment
  - and dispatching
  - priority dispatching
  - maximum % utilization
  - minimize bottlenecks

- Dispatching
  - opportunity convenience
  - resources

- Manufacturing
  - On-Line Resource Dispatching
  - Manufacturing MRP

- User interfaces for Decision assistance
  - Decision Support

- Communications System Scheduling & Routing
  - Guaranteed QoS

- User interfaces for Decision assistance
  - Decision Support

- Prioritized Work Orders assigned to Maint. Units
  - Generate: optimized maint. tasks
  - (c.f. PMS cards)
Prognostics - Why?

I. Fault Propagation & Progression

Fault detection threshold

- Replace subsystem
- Replace component
- Replace entire system

Fault development trend:
Progressive escalation of required maintenance

N. Viswanadham

-II. Time of Failure & Remaining Useful Life (RUL)

Scheduling Removal From Service and Start of Repair in terms of ETF and Mission Due Date

RUL

- Estimated time of Failure (ETF)
- Mission due date
- Repair time
- Start repair
- Remove from service
- Present time

Mission Criticality Impacts the Scheduling

Progressive Escalation Impacts the Prescription
Four Stages of CBM/PHM

- Diagnostics
- Prognostics & RUL
- Maintenance Prescription
- Maintenance Scheduling

Two Phases of Prognostics & RUL

- **Off Line**- Background Studies, RUL Analysis
- **On Line**- Perform real-time Prognostics & RUL
Phase I- Preliminary Off-Line Studies

PHM – Fault Prognostics & RUL Background Studies

- **Fault Mode Time Analysis** - Identify MTTF in each fault condition
- Identify the best **Feature Combinations** to track for effective prognosis & RUL
- Identify **Best Decision Schemes** to compute the feature combinations
- Build **Failure Time Pattern Library**

Deal with Mean Time to Failure in each Fault condition. ALSO require **Confidence Limits**
PROGNOSTICS

Legacy Data Statistics gives MTBF, MTTF etc.

Estimate Remaining Useful Life with Confidence Intervals

Hazard Function-
Probability of failure at current time
- H. Chestnut

Based on legacy failure data

Fault tolerance limits found by legacy data statistics

Trend Analysis & Prediction-
Track Feature vector trends
Study $\phi(t)$ and $\dot{\phi}(t)$
Stored Legacy Failure data Statistics analysis

Statistical Regression Clustering Neural network classification

Find MTTF for given fault condition and find confidence limits
Estimation of Failure Probability Density Functions

Gives best estimate of RUL (conditional mean) as well as confidence limits

A priori failure PDF

A posteriori conditional failure PDF given no failure through present time

Expected remaining life

Removal From Service-Just In Time Point (JITP) avoids 95% of failures
RUL PDFs as a Function of Time

RUL estimates become more accurate and precise as RUL decreases

95% confidence limits
Fault Trend Analysis

Kalman Filter is the optimal estimator for the conditional PDF for linear Gaussian case - gives estimate plus covariance

Minimize $\text{Pr}\{\text{false alarm}\}$
$\text{Pr}\{\text{miss}\}$

Model-Based Predictive Methods
- Mike Grimble

Fault tolerance limits

Normal operating region

Confidence limits

Estimated feature

Failure

Alarm

$\phi(t)$
Prescription of Maintenance

Fault condition → Decision-Making Prescription → Maintenance Prescription

Fault Trend??

Prescription may change if fault worsens

Model-Based Reasoning (MBR) for Fault Progression?

Who really knows??

Stored Prescription Library

Neural networks
Fuzzy logic
Expert system rulebase
Bayesian
Dempster-Shafer
## Prescription Library

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Prescription</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF (leakage coefficient is excessive)</td>
<td>THEN (Replace hydraulic pump)</td>
</tr>
<tr>
<td>IF (piston friction is excessive)</td>
<td>THEN (Replace hydraulic pump)</td>
</tr>
<tr>
<td>IF (excessive bearing wear)</td>
<td>THEN (replace motor)</td>
</tr>
<tr>
<td>IF(exc. piston friction) AND (exc. bearing wear)</td>
<td>THEN (replace hydraulic pump/motor assembly)</td>
</tr>
</tbody>
</table>

## Fuzzy Logic Rulebase!

### Side Effects?
- Equipment down time
- Impact on related systems
- Mission failure
- Use of critical maintenance resources or parts
Maintenance Requirements Planning
c.f. Manufacturing Requirements Planning - MRP

Assembly Schedule

Assembly Tree

- Product
- Subassembly 12
  - SA 11
  - SA 12
    - SA 111
    - SA 112
    - SA 121
    - SA 122
    - SA 123

Assembly time For SA 112
Assembly time For SA 11

Product due date

Work backwards to get schedule

RUL
Estimated time of Failure (ETF)

Mission due date

Repair time

Present time
Remove from service
Start repair

Scheduling Removal From Service and Start of Repair in terms of ETF and Mission Due Date

Maint. is more complex – more constraint times
Maintenance Dispatching & Resource Assignment

The maintenance prescription and schedule is assigned **off-line**

The maint. action is dispatched with available resources **on-line**

Use manufacturing dispatching and resource assignment techniques
- first-in / first-out (FIFO)
- last buffer first serve (LBFS)
- earliest due date (EDD)
- least slack (LS)

Discrete Event Supervisory Controller
A new matrix formulation