Using Prognostic Information for Reconfigurable Control

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PHM 2009 Conference Tutorial
We have 1 GAL left in the tank.

THE NEAREST STATION IS 30 MI AWAY!!!
Can We Close The Loop?
Fault – Tolerant Control
(Fault Mitigation, Fault Accommodation, Reconfigurable Control)

The Caveat: With Prognostic Information

The Link between PHM and Control
The Problem
Case Study

- Identify the Fault
  Fault Detection and Identification
- Stabilize the Vehicle
  Active System Restructuring
  Reconfigurable Flight Control
- Continue the Mission
  Reconfigurable Path Planning
  Mission Adaptation


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Fault Tolerant Control
Conceptual Illustration

Conventional Control Algorithms

Collective Pitch Saturation
Loss of Tail Rotor Effectiveness
Stuck Swashplate Actuator

CRASH!
Overall Architecture for Implementation of Fault Diagnosis and Failure Prognosis Algorithms
Testing, Modeling, and Reasoning Architecture

Electromechanical Actuator

Components

HUMS modules

Modeling

Testing / Seeded Fault Data

Reasoning Architecture for Diagnosis-Prognosis

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Understanding the Physics of Failure Mechanisms

Feature Selection and Extraction

- Optimum Feature Selection
- Mapping of Features vs. Fault Dimension
- Utility in Diagnosis / Prognosis

Optimum mapping of CI’s to Fault Dimension

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System Background
Fault Hierarchy (Top–Down)

Critical Component

Crew Return Vehicle

Fault Mode

Triplex Redundant Actuator

Failure Mechanism
Insulation Breakdown

Brushless DC Motor
Objective: Detect a fault (without isolating the faulty component; without assessing the severity of the fault) as early as possible with specified confidence level and given false alarm rate.

The routine is implemented online in real time.
Anomaly Detection
Anomaly Detection Results
Failure Prognosis

• Objective
  – Determine time window over which maintenance must be performed without compromising the system’s operational integrity
  – Estimate time-to-failure and provide information to operator/pilot

• Enabling Technologies:
  – Data Driven
  – Model-Based

• A Model/Measurements Based Approach
Prognosis: Fault Growth Characterization

Fault Dimension

Loading Profile

Fault Growth Equation

\[ \frac{dL}{dt} = f(t, L, u) \]

Fault Dimension Estimate as obtained from Physics-based Model

Feature Selection and Extraction

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**Particle**: Possible realization of the states of a process.

\[
p(x_{0:k+1} | z_{0:k+1}) = \sum_{i=1}^{N} w_{k+1}^{(i)} \delta_{x_{0:k+1}^{(i)}} (dx_{0:k+1})
\]

\[
p(x_k | z_{1:k}) = \int p(x_k | x_{k-1}) p(x_{k-1} | z_{1:k}) dx_{k-1}
\]

Every particle is associated with a **weight**

- Particles, together with their weights, represent a sampled version of the PDF.
- We only need to study the propagation of weights in time!

**Steps:**

- Predict the “a priori” PDF parameters, using the model
- Update parameters, given the new observation
The Particle Filter Framework

\[ P_{TTF}(ttf) = \sum_{i=1}^{N} Pr\{Failure / X \leq x^{(i)}\} \cdot \tilde{w}_{\text{ttf}}^{(i)} \]

\[ Pr\{\text{Failure} / X \leq x\} \]

\[ \tilde{w}_{\text{ttf}}^{(i)} \equiv Pr\{x = x^{(i)}\} \]
Prognosis: Fault Growth Characterization

Fault Dimension

Loading Profile

Fault Growth Equation
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Fault Dimension Estimate as obtained from Physics-based Model

Feature Selection and Extraction

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Prognosis
Preliminary Simulation Results

Insulation Prognosis Demo

Features from Motor Current

Probability of Failure 96.00%

Type I Error = 5%, Type II Error = 36.54%

Insulation Prognosis

Fault Dimension

Particle Filters: Non-Linear Estimation

Fisher Discriminant Ratio = 1.516

Fisher Discriminant Ratio = 1.516

Detection Prob. = 96.00%

Estimate TTF = 584

Backup

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• LQR design methodology using long-term prediction as a design constraint.

• Single parameter $\rho$ used to trade-off importance between tracking error and control effort.

\[ J = \int_{0}^{\infty} \left( (x - x^*)^T Q (x - x^*) + (\rho R) u^2 \right) dt \]

• Feedback gain computed solving the Algebraic Riccati Equation:

\[
P A x + A^T P - P B_u \left( \rho R \right)^{-1} B_u^T P + Q = 0
\]

\[ u^* = -\left( \rho R \right)^{-1} B_u^T P \left( \rho \right) x \]


Model-based Adaptive Flight Control

- NNs for modeling and system identification.
- Online model corrections using the adaptation scheme.
- Structure learning modeling algorithm.
- Receding horizon optimal control to maximize performance and safety.
- Modified least squares for model parameter identification.

Reconfigurable Control – State of the Art
Other Significant Work

- Artificial intelligence
- Active (Direct) adaptive control
- Expert systems
- Intelligent controls (NNs and Neuro-Fuzzy)
- Model Reference Adaptive Control (MRAC)
- Robust control design
- Robust adaptive control
- Supervisory / Hierarchical control
What is missing?

Control reconfiguration with prognostic information →
real-time implementation issues.

• Computational Complexity
• Latency
• Satisfy Performance Requirements
• Stability
• Optimality
• Uncertainty Representation and Management
• Rigorous fault (or degradation) modeling and particle filtering for fault detection and diagnosis
• Early diagnosis and accurate prognosis with uncertainty management
• Optimization using MPC with constraints
Reconfigurable Control Architecture

Functional Relation in the Hierarchy

- **High-Level Control**
  - Supervisor
  - Monitors mission objectives
  - Defines subsystem objectives
  - Responsible for mission adaptation
  - Restructures subsystems
  - Ensures system stability

- **Mid-Level Control**
  - Supervisor
  - Interface between the system and components
  - Monitors subsystem objectives
  - Defines component objectives (RUL and performance)
  - Redistributes control authority among components
  - Path replanning
  - Ensures subsystem stability

- **Low-Level Control**
  - Supervisor
  - Interfaces the subsystem
  - Monitors component objectives
  - Reconfigures set-points
  - Ensures component stability

Components of Subsystem-1

Components of Subsystem-n

Components of Subsystem-N

Components of Subsystem-n

Components of Subsystem-N

System with PHM Based Reconfigurable Control

Reconfigurable Control Architecture

Functional Relation in the Hierarchy
The High-Level:

- Mission adaptation – adapt mission profile (way points in aircraft case, control objectives in EMA case) to meet hard mission objectives under impairment constraints.

**Methodology:** Minimize the following objective function

\[ J(\bar{u}) = f^T \left| \bar{y} - \bar{y}_c \right| \]

where

- \( \bar{y}_c \) = Flight path generated from waypoints
- \( \bar{y} \) = Desired flight path
- \( f^T \) = Weighting vector
The Middle-level:

- Trajectory re-planning: Find optimal path (trajectory), in least cost sense, that meets mission objectives under system impairment conditions. Example: Aircraft trajectory re-planning

- Re-distribution of control authority: Re-distribute available control authority (under impairment constraints) to meet hard mission objectives. Example: EMA with triple motor redundancy; or, flight control re-distribution.
Reconfigurable Control
Low Level – State Transition Transition Diagram

Component Supervisor
- Set Performance and RUL Requirements
- Initialize Soft Constraints
- Define Cost Function Parameters
- Interface with Subsystem Supervisor

Production Controller (Nominal Operation)
- No Fault Detected
- Fault Detected
- No Need for Reconfiguration

Fault Detection
- Request Fault Status
- Restructure Model
- Evaluate Performance and RUL

Fault Accommodation
- Fault Mitigation
- Redistribute Control Authority
- Reconfigure Control

Subsystem Supervisor
- Interface to Mid-Level Supervisor
- Request Control Redistribution
- Redistribute Control Authority

Subsystem Supervisor

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Evaluation Platform / Validation
The EMA – Nominal system
The Actuator Testing Configuration
The Model Predictive Control Framework
Technical Approach
Control Reconfiguration Architecture

- Supervisory controller
  (mission objective/constraints)
- Adaptation Law
- Model Predictive Control
- Diagnostics/Prognostics
- EMA
- Model Identification

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Minimize the cost function $J$ subject to control offsets $\Delta u(k|k)$, ..., $\Delta u(m-1+l|k)$,

$$
\min_{\Delta u(k|k), \ldots, \Delta u(m-1+k|k)} J(\Delta u, r, y)
$$

where $J$ is defined as,

$$
J(\Delta \tilde{u}_p, \tilde{r}_p, \tilde{y}_p) = (\tilde{y}_p - \tilde{r}_p)^T W_y^2 (\tilde{y}_p - \tilde{r}_p) + \Delta \tilde{u}_p^T W_{\Delta u}^2 \Delta \tilde{u}_p + \rho_s \varepsilon^2
$$

where

\[
\begin{align*}
\tilde{y}_p &= \begin{bmatrix} y(1|0) & y(2|0) & \ldots & y(p|0) \end{bmatrix}^T & \text{– Predicted plant outputs} \\
\tilde{r}_p &= \begin{bmatrix} r(1) & r(2) & \ldots & r(p) \end{bmatrix}^T & \text{– Desired set-points} \\
\Delta \tilde{u}_p &= \begin{bmatrix} \Delta u(0) & \Delta u(1) & \ldots & \Delta u(p-1) \end{bmatrix}^T & \text{– Reconfigured set-points}
\end{align*}
\]
Fault Growth Model for Prognosis

Outline

• Describes how the primary feature evolves with the turn-to-turn winding fault

• Principle assumptions
  • Time rate of growth ($dL/dt$) increases with the current fault dimension ($L$)
  • Time rate of growth ($dL/dt$) increases with winding temperature ($T_{wa}$)
  • Current ($i$) is related to winding temperature ($T_{wa}$)

![Diagram showing the process of data processing, feature extraction, thermal model, growth rate, feature mapping, and prognosis.]

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Step 1. Initialization

- Load initial fault dimension $L_0$
- Define fault detection criteria for diagnosis
Step 2. Fault Detection

- Continuously monitor for fault
Step 3. Initialize Prognosis

- Initialize long term prediction
Step 4. Calculate RUL

- Predict fault dimension using fault-growth model
- Project hazard-zone crossing onto the time axis for RUL
Step 5. Compute $u_{RUL}$

- Find constant control input $U_{RUL}$ required to achieve the desired $t_{RUL}$
- If performance and RUL restraints cannot be satisfied request control reconfiguration
Triplex Redundant Actuator Model

Load Torque Redistributed

Feedback gain adjusted

Simulink Triplex Actuator Model

Motor Current [A]
Motor Position [deg]
Motor Speed [RPM]
Load Position [deg]
Load Speed [RPM]
Preliminary Results
Various Fault Dimension / Constant $T_{\text{mission}}$

Simulation results for the fault growth model

<table>
<thead>
<tr>
<th>Operating Current [A]</th>
<th>Expected RUL [min]</th>
<th>RUL Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2200</td>
<td>2444</td>
</tr>
<tr>
<td>25</td>
<td>310</td>
<td>344.4</td>
</tr>
<tr>
<td>30</td>
<td>41.0</td>
<td>45.56</td>
</tr>
<tr>
<td>35</td>
<td>6.00</td>
<td>6.667</td>
</tr>
<tr>
<td>40</td>
<td>0.90</td>
<td>1.000</td>
</tr>
</tbody>
</table>
Reconfigurable Control
Benefits of Reconfigurable Control with PHM

• Capability to enhance mission effectiveness in the presence of contingencies
• Means to complete mission while satisfying performance constraints and assuring system stability
• Ability to optimize reconfigurable control and PHM algorithm requirements for specific components / subsystems under degraded operation in order to meet mission objectives
• Full functionality for reconfiguration / fault tolerance via an intelligent hierarchical architecture
• Ability to perform failure prognosis and reconfigurable control in almost real-time avoiding latency problems
• Uncertainty representation and management through a particle filtering approach.
• Mission capability updates through the integration of reconfigurable control and Integrated Adaptive Guidance and Control Systems

• Ability to provide engineering justification for adding new reconfiguration, control and communication system upgrades with technical and economic benefits clearly identifiable

• Provision of feedback to system designers of design information that will lead to fault-tolerant high-confidence systems.
CONCLUSIONS – FUTURE WORK

– Linking PHM To Controls – The Added Value
– Need To Mature Prognostic Algorithms
– Computational Issues
– V&V – Qualification
– Opportunity For New R&D