Integrated Diagnostic and Prognostic Health Management for Mechanical and Structural Systems

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Friday May 13, 2005

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Facility for Experimental Nonlinear Dynamics and Diagnostics
Overview of Diagnostics and Prognostics
Definitions of Diagnostics & Prognostics
e.g., gas turbine engine (mechanical / electrical components)

Thermo-Mechanical Fatigue,
Foreign Object Impact,
Service-Induced Faults

Life-cycle monitoring enables prognosis
- Sensing
- Data processing

 Loads Identification

Diagnostics
(Detect, Locate, Quantify Faults)

Prognosis
(Predict Fault Evolution and Remaining Life)

Load / Energy

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Trends in Defense and Commercial Sectors
Trends

Needs for diagnostics / prognostics in commercial / defense platforms

- **Defense manufacturers** aim to reduce conservatism, turnaround times, O&S costs and to increase readiness.
  - New materials, new systems, new missions, new requirements, new warfare

- **Commercial manufacturers** aim to increase profits and competitiveness by reducing life-cycle times and costs.
  - New business models (“power by the hour”) and reliability requirements

### New business models

### Operational parameters

- 2% increase in downtime for 20 trucks → $13M losses/year

### Networked military systems (FCS) with new mission requirements
Why Wire Harnesses?

Managing the health of the “nervous system” of an engine

- Technologies for integrated prognosis are needed for wire harnesses in engines because:
  - Faults are difficult to find due to complexity (needle in the haystack)
  - Faults in harnesses lead to removal and unavailability of components
  - Increase equipment availability
  - Decrease pipeline spares and maintenance labor hours

End connectors and harness

Connector, sockets, flange, and wire

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Why Weapon Systems?

*Triage for body armor and vulnerability assessment of missile bodies*

- Technologies for integrated prognosis are needed for *weapon systems (armor, missiles, etc.)* because:
  - Medics must quickly identify if, where, and how armor is penetrated
  - Weapons are stored and then shipped leading to potential damage
  - Increase military readiness
  - Decrease number of fatalities

![Body armor being tested](image1)

![Composite missile casing material being tested](image2)

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Why Suspension Systems?

Reducing conservatism in design and operation

- Technologies for integrated prognosis are needed for **suspension systems** because:
  - Suspensions are conservatively designed (heavy, low performance) by independent suppliers to optimize component life
  - Interacting loads (strut, knuckle, roll bar) lead to complex faults and failure characteristics
  - Integrated suspensions are less conservative and live longer
Product Life-Cycle Management:

Need for Integrated Prognosis Technologies in General
Our Approach to Prognostics at the Component and System Levels
Diagnostic & Prognostic Technical Areas

Interdisciplinary research in modeling, sensing, data interrogation and prediction

**Problem Definition**
- Define subsystem / system
- Define damage / failure modes
- Define life-cycle of system
- Identify existing sensor suites
- Define diagnostic needs
- Define loading environment
- Identify fault initial conditions
- Define duty-cycle / warranty
- Define maintenance history of system
- Define prognostic needs

**Develop Models**
- Evaluate operating environment
- Define infrastructure models
- Define fault / failure models
- Develop system life-cycle model
- Validate system life-cycle model

**Develop Sensor Suite**
- Evaluate data environment
- Specify variables to sense
- Model / calibrate sensing field
- Define sensing infrastructure
- Select / optimize sensor field

**Predict Risk / Reliability**
- Specify loading scenario / statistics
- Select damage and life models
- Update system and fault model
- Predict fault initiation / evolution
- Propagate uncertainty
- Relate fault evolution to life

**Interrogate Data**
- Filter and process signals
- Infer unmeasured state variables
- Extract features with models
- Account for sources of variability
- Detect / locate / quantify loads
- Detect / locate / quantify faults

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Some Applications in Commercial and Defense Systems
Example Applications
Commercial and defense-related systems

- Space Systems and Components
- Weapon Systems
- Future Air Vehicle Tanks and Structures
- Ceramic / Metallic Thermal Protection Systems
- Land and Sea Vehicles
- Marine and Aero Engines
- Machine Tools and Processes

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Identifying Loads

- **Transient impact loads**; dependent on location
- **Nonlinear impact loads**; changes in nonlinear resonance due to preload is indicator of damage
- **Cyclic loads in multi-component system**; Newton’s Law provides restoring forces
Impact Experiments in TPS

Metallic thermal protection system impact apparatus *(data-driven)*

- **Objective:** Identify impact force level and location in a mechanically attached metallic thermal protection system (TPS) panel.

- **Results:** Impact locations and levels were estimated with 90% accuracy in level and 100% accuracy in location.

\[ E = F \times d \]

Magnitude of force versus impact location showing variation

Low velocity impact apparatus showing panel and automatic hammer

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Fuselage Rivet Processing Loads

Identifying process loads early in the life-cycle (physics-based)

- **Objective:** Assess the quality of riveting processes using estimated forces to determine susceptibility of fuselage to future damage near rivet holes.

- **Results:** Poor rivet quality processes due to skewed delivery, extended contact time, etc. were distinguished from good quality processes.
Loads on Suspension

Restoring force within integrated suspension (data-driven)

- **Objective:** Identify forces acting in suspension using measured data on the wheel spindle, strut connection points and knuckle control arm points.

- **Results:** Forces in multiple components were identified in the suspension as a function of motion (displacement/velocity) and frequency.

\[ a = \frac{F}{M} \]

\[ F = F(\Delta x, \Delta v) \]

Quarter-car vehicle instrumented for loads identification

Change in Strut Force with Frequency
Identifying Damage

- Transmission zeros; good for localizing damage

- Detection under load; damage level changes as temperature fluctuates due to thermal expansion

- Nonlinear methods; nonlinearity provides means for quantifying damage in an absolute manner

- Sensitivity methods; quantify damage using only measured frequency response data

- Beamforming; detect and locate global damage

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Damage Detection in FWC
Transmissibility functions (data-driven/local/passive)

- **Objective:** Identify degradation in filament wound canister (FWC) in the form of changes in axial or hoop stiffness.

- **Results:** Transmissibility index shows monotonic increase as damage increases, can be applied using ambient vibration, and is locally sensitive.

\[ T_{pq}(\omega) = \sum_{k=1}^{Ni} \frac{H_{pk}(\omega)}{H_{qk}(\omega)} \]

Filament wound canister with sensors on either end

**Increase in damage**

Change in transmissibility index showing correlation with damage level

<table>
<thead>
<tr>
<th>Damage Index</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1RB@L2</td>
<td>11.3605</td>
</tr>
<tr>
<td>2RB@L2</td>
<td>15.5796</td>
</tr>
<tr>
<td>3RB@L2/1/2/3</td>
<td>21.4412</td>
</tr>
<tr>
<td>3RB@L2/1/2/3</td>
<td>26.4310</td>
</tr>
<tr>
<td>Act. Damage 1</td>
<td>49.1166</td>
</tr>
<tr>
<td>Act. Damage 2</td>
<td>69.8722</td>
</tr>
</tbody>
</table>
**Objective:** Determine if damage can be detected in a metallic thermal protection system (TPS) panel under thermo-mechanical loading.

**Results:** Damage to standoff bolts can be detected more easily if temperature of panel is elevated due to thermal expansion under load.

Panel shown heated and radiated with acoustic loads to simulate launch

Damage index as a function of DOF pair and panel temperature revealing damage

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Nonlinear Passive Damage ID

Identifying loss in joint preload (physics-based/passive/local/nonlinear)

**Objectives** – Develop a diagnostic technique for passively detecting nonlinear damage in mechanical systems.

**Results** – Damage in a three-story frame was quantified directly using a nonlinear feature to detect a discrete transition in a joint with sliding.

Three-story building frame model with seismic excitation and damaged joint

Variation in probability density of nonlinear damage index showing reversal

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**Damage Quantification in Panel**

Active experimental sensitivity functions *(physics-based/local/active)*

- **Objective:** Identify degradation in metallic plate by locating and quantifying loss in stiffness (mass) when fasteners crack (or mass loss).

- **Results:** Changes in stiffness have been located and quantified directly using this approach without need for full analytical model (also in armor).

\[
\frac{\partial H_{pq}}{\partial K_{mn}} = - (H_{pm} - H_{pn})(H_{qm} - H_{qn})
\]

Mechanically attached panel showing fastener and strips to simulate damage

<table>
<thead>
<tr>
<th>Case</th>
<th>Real mass (lb)</th>
<th>Estimated mass (lb)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>2.95e-3</td>
<td>2.80e-3</td>
<td>5.08%</td>
</tr>
<tr>
<td>Case 2</td>
<td>8.85e-3</td>
<td>8.1e-3</td>
<td>5.08%</td>
</tr>
<tr>
<td>Case 3</td>
<td>10.83e-3</td>
<td>8.8e-3</td>
<td>18.7%</td>
</tr>
<tr>
<td>Case 4</td>
<td>2.95e-3</td>
<td>2.0e-3</td>
<td>32.2%</td>
</tr>
</tbody>
</table>

Estimated changes in stiffness/mass

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Damage Detection with Beamforming

*Metal and composite materials (physics-based / active)*

- **Objective:** Identify material damage in large structural components due to changes in mass (corrosion), stiffness (delamination) or damping (crack).

- **Results:** Damage has been detected and located in a steel plate, a FSW Al-Li plate, and a composite plate using phased-sensor arrays.

![Diagram showing actuator and sensor locations](image)

- Defense-relevant specimens
- Transducer array with beamformer and biological inspiration
- Estimated and actual damage locations
Predicting Remaining Useful Life

- Nonlinear effects of damage evolution; damage phase plane diagrams help in prognosis

- Multiple-loads lead to multiple-failure modes; use modified Miner’s rule

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**Physics-Based Prognosis**

*Nonlinear dynamic experiments on beam (physics-based)*

- **Objective:** Develop physics-based models that help to identify milestones in structural material health and predict remaining life in those systems.

- **Results:** Damage phase plane diagrams indicate bifurcations in damage evolution at states that are highly susceptible to damage growth.

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**Diagram:**

- **Crack length [m]**
- **dc/dt [m/s]**

**Graphical Elements:**
- **Transition**
- **Stable growth**

**Text:**

- Damage phase plane with rate of crack growth vs. length showing transitions
- Electrodynmaic shaker and static rotor blade for estimating damage phase plane
Physics-Based Prognosis
Nonlinear models for a valve assembly (physics-based)

- **Objective:** Develop physics-based models to predict remaining valve life.

- **Results:** The predicted failure mode accounts for multiple equilibrium points and accurately reflects the observed multi-mode failures in the field.

\[
M_V \dddot{x}_V + C_V (\dddot{x}_V - \dot{x}_1) + F_{n1}(x_V - x_1, g(\theta)) = 0 \\
I_V \dddot{\theta} + C_T \dot{\theta} + K_T \theta - F_N \cdot c \cos \theta = 0 \\
M_p \dddot{x}_P + C_p (\dddot{x}_P - \dot{x}_2) + F_{n2}(x_P - x_2) + F_T = 0
\]

Butterfly air valve assembly and mechanism with damage due to impacts on bushing

Remaining life as a function of vibration level along valve and angular position

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What Happens When We Try to Implement Prognosis in System of Systems?
Operator’s View of Process Control

- Pump A pumping oil has tripped - **Cause Unknown**
- You switch to Pump B. That also trips - **Cause Unknown**
- Soon hundreds of alarms are going off – **Cause(s) Unknown**
- Within minutes you have an explosion and a fire. Two people are killed and a few hurt at this point.
- It is 10:00 p.m. in the night
- The plant manager is in Aberdeen, Scotland, and not available
- You are on top of an off-shore oil platform in the middle of the North Sea

You are the Shift Supervisor: What do you do?

Piper Alpha Disaster, 1988
164 people killed
$2 Billion in losses

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System of Systems AA587
Emergent, Cascading Failure

JAL – 747
Eddy vortices

AA – A300

Wind

9/11
Ground Zero

JFK Runway

Courtesy: Dr. Nick Lieven, Department of Aerospace Engineering, University of Bristol, UK

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System of Systems AA587
Emergent, Cascading Failure

Wind

JAL – 747
Eddy vortices

AA – A300

JFK Runway

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System of Systems AA587
Emergent, Cascading Failure

JAL – 747
Eddy vortices

AA – A300
Aircraft damage to tail

JFK Runway

Air Traffic Control
Prevailing Winds
Pilot Reaction

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Our Approach
Using
Agent-Based Models
and Information Synthesis
Prognosis Center of Excellence in System of Systems (ProCESS)
*Maintenance and Logistics in Navy ships*

- Develop and continuously validate a ship System of Systems model for assessing the impact of technology insertion on crew and mission using agent-based simulations and prognosis.
Concluding Remarks
Conclusions

- **Business demands** are fueling needs for in situ D&P health management technologies – commercial/defense applications have big payoffs.

- **Integrated sensing, modeling, and data interrogation** are the enabling technologies for prognosis.

- By applying both **data-driven/physics-based models and passive/active sensing methods**, we can develop diagnostic/prognostic methods.

- We must recognize that **prognosis in complex system of systems** brings a new set of challenges that we have not considered in components and systems.