Prognostics and Health Management: From Solder Joints to Systems

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Unexpected Failures

Unexpected failure of critical systems can have severe consequences in terms of unavailability of services, loss of life or property, and economic costs.

- Jan. 17, 2008: BA 038 crash landed at Heathrow after electronics failure caused loss of all power; 18 people hospitalized

- Aug. 1, 2007: Mississippi River bridge collapse; the bridge was “structurally deficient” due to corrosion
Prognostics and Health Management

• **Prognostics** is the process of predicting the remaining useful life (RUL) of a product by assessing the extent of deviation or degradation from its expected state of health in its expected usage conditions.

• **Health Management** utilizes prognostic information to make decisions related to safety, condition-based maintenance, ensuring adequate inventory, and product life extension.

• PHM permits the evaluation of a system’s reliability in its actual life-cycle conditions.
Why PHM?

- Reliability estimations are based on anticipated use conditions.
  - If actual conditions are known, a more accurate assessment of lifetime can be achieved.
- Remaining life can be predicted from the state of health of a system or product
  - Real-time health monitoring enables informed and timely life cycle management decisions.

![Anomaly Graph]

Anomaly
Traditional PHM: Monitoring of Structures (e.g., Pressure Vessels)
Provide a knowledge and resource base to support the development and sustainment of competitive electronic products and systems in a timely manner.
Areas of Research:

• Physics of Failure
• Design for Reliability
• Accelerated Qualification
• Supply-chain Management
• Prognostics
• Cost Modeling
CALCE PHM Applications

Batteries

Gear-bearing Systems

PCBs

Wind Turbines

Analog Circuits

IGBTs

LEDs

Avionics

Unmanned Ground Vehicle
Health Monitoring and Fusion Prognostics

1. Identify Parameters
2. Identify Historical Database and Standards
3. Identify In-situ Monitoring
4. Identify Data Analysis: Anomaly?
   - Yes: Alarm
   - No: Proceed to next step
5. Identify Physics-based Models
6. Identify Failure Definition
7. Identify Remaining Useful Life Estimation
8. Identify Parameter Isolation
9. Identify Data-Driven Models
10. Identify Health Management

Health Monitoring and Fusion Prognostics

- Identify Parameters
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- Identify Health Management
Early Detection of Degradation in Electronics

• Failure of a single interconnect or component could cause a circuit to lose functionality.

• Early detection allows reduction of:
  – **risks** associated with adoption of new materials, processes, or technologies;
  – **uncertainties** regarding actual usage conditions;
  – **likelihood of unanticipated failure** in safety- or mission-critical applications;
  – **costs** associated with a product’s operation and maintenance.

• Health monitoring can also enable life prediction.
Interconnect Failure Mechanisms and Challenges

Solder Joint Cracking

High Density Interconnect Microvia Voiding

Solder ball

Copper pad

Pad cratering

Metallization Corrosion

Wirebond Crack

Plated Through Hole Crack
The Role of the Interconnect Surface in Early Stages of Degradation

Interconnect degradation often starts from the surface and propagates inward.

The skin effect suggests the use of high frequency signals for early detection of degradation, such as cracking.

Time Domain Reflectometry (TDR)

- TDR reflection coefficient ($\Gamma$) is the ratio of the incident and reflected voltage due to impedance discontinuities in the circuit.
- In the time domain, any discontinuities due to impedance mismatches within the circuit are seen as discrete peaks.

\[ \Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \frac{Z_L - Z_0}{Z_L + Z_0} \]

- $Z_L$: the impedance of device under test
- $Z_0$: characteristic impedance of the circuit

![Diagram showing Agilent E8364A Vector network analyzer (VNA) and SMT low pass filter (LPF) on 50 Ohm controlled impedance board with TDR response graph.]
Comparison of Detection Sensitivity

- Toward the end of the tests, the TDR reflection coefficient provided failure precursors as a gradual increase.
- The event detector did not trigger any alarms until an open circuit occurred.
Application of TDR Monitoring to Detection of Degradation

- The response is well-behaved and directly correlated to crack growth, providing a real-time, non-destructive monitoring tool.

- In this example, the geometry and the localized changes to the microstructure strongly suggest the future crack path.

SnPb Solder Joint (During High Temperature Creep)
Prediction of Remaining Useful Life

- Regression analysis was performed on the normalized TDR responses.
- The regression curve from 70% to 98% lifetime was used to predict the remaining life of the solder joints with high accuracy.
Testing of High I/O Count Separable Interconnects

- This technology provides higher reliability for large devices.
- Little insight exists on interconnect failure mechanisms, or degradation of high frequency performance prior to loss of continuity.
- CALCE has applied TDR monitoring to this effort.

7296 I/O Land Grid Array, partially populated
Electrolytic Capacitors

- Liquid aluminum electrolytic capacitors are commonly a life-limiting component in power electronics.

- Degradation of the electrolyte (evaporation, chemical reaction) raises the power dissipation and increases the core temperature of the capacitor.
Health Monitoring and Reliability Assessment of Electrolytic Capacitors

• Lot-to-lot variability, unreported process changes, and counterfeit parts all represent risks associated with electrolytic capacitors, as they can cause early life failures.
  ➢ PHM based on known failure mechanisms can reduce these risks.

• CALCE has also developed a variety of rapid assessment tests, based on critical-to-reliability factors, which can be used to perform lot acceptance testing and screening.

Other parameters of interest: ripple on DC power output; leakage current; time constant; strain on case.
Challenges for Bearing PHM

- Although bearings have been the focus of Condition-Based Maintenance (CBM) for many years, a number of challenges remain.
- CALCE has focused on the development of methods to address:
  - **Complexity of sensor information**: dozens of features could be extracted from different types of sensors: accelerometer, acoustic emission transducer, electrical current probe, speed sensor, and microphone.
  - **High rates of false positives and negatives in anomaly detection**: methods are needed for parameter optimization and improved decision-making.
  - **Inaccuracy of predicted remaining life**: the bearing degradation process is stochastic. Reliable health indicators and prognostic models are needed.
Prognostics and Health Management of Bearings

• Bearing failure is one of the main causes of downtime for rotating machinery.

• Potential impact of the research:
  – Prevent unscheduled maintenance of equipment such as wind turbines, motors and generators.
  – Improve PHM of rotating machines including vehicles.
  – Reduce the time needed for qualification and/or screening of electromechanical hardware such as cooling fans.
Trend in Bearing Degradation

- Features were extracted from both accelerometer and acoustic emission data.
- The Mahalanobis distance (MD) was used for combining these features, allowing detection of degradation at only 30% of the life of the bearing.
In-situ Temperature Monitoring of Laptop Computer

• Temperatures were monitored at multiple locations
  – Microprocessor heat-sink
  – Hard Disk Drive (HDD)
  – Ambient

• Laptop was continuously monitored in all stages including power on/off, operating and non-operating conditions, handling and travel.
Anomaly Detection in Laptop Computers

- Multi-parameter data from 10 new computers was used to form the baseline.
- Utilizing the correlations between the measured parameters Mahalanobis Distance (MD) reduces the multivariate data to univariate data.
- A No-Trouble-Found (NTF) computer (Abnormal) was tested and the same parameters were recorded as for the baseline computers.
- The MD values for the Abnormal system showed faulty behavior at time zero.

<table>
<thead>
<tr>
<th>Stats (Model A)</th>
<th>Normal</th>
<th>Abnormal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean of MD</td>
<td>0.83</td>
<td>10.72</td>
</tr>
<tr>
<td>Std.dev of MD</td>
<td>1.16</td>
<td>3.13</td>
</tr>
</tbody>
</table>
Wind Turbine Failures

• Failures can be categorized as
  – Failures with high frequency of occurrence
    • Electrical system failures
    • Sensor failures
    • Control system failures
  – Long downtime and high risk failures
    • Gearbox failures
    • Bearing failures
    • Rotor and blade assembly failures

• Early detection of faults can increase availability by:
  – reducing the lead time for replacement of faulty equipment.
  – providing greater flexibility in scheduling maintenance operations

Health monitoring helps to avoid catastrophic failures and increase availability of wind turbines for power generation.
Dynamic System Modeling and Health Monitoring

• **Approach**
  - Dynamic modeling of the electrical and mechanical components using a lumped parameter approach is carried out for *fault simulation and diagnostics*.

• **Advantages**
  - Guidance for sensor selection: identifies system level parameters to be monitored which are sensitive to a certain fault condition.
  - Enables *optimization of sensor placement*.

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**Current Research Work**

- **Monitor Electrical Parameters**
- **Predict Health of System**
- **Various Sensors for monitoring**
- **Health Monitoring**

**Conventional System**

- **Electrical System (Motor, Generator)**
- **Mechanical System (Gearbox, Turbine)**
- **Mechanical Work**

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**Energy Flow**

- **System example**
  - Electric cars
  - Wind turbine

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Dynamic System Modeling Approach

Input torque from the wind

Lumped parameter modeling of all mechanical components

Dynamic modeling of the doubly-fed induction generator (DFIG)

Gearbox

- Sun gear
- Planet gear
- Sun-and-planet gears

Hub and blades

- Shaft 1
- Stage 1 gears
- Stage 2 gears
- 1
- 2a
- 2b
- 3

Generator

Double Tooth Contact

Center for Advanced Life Cycle Engineering
“Condition Based Maintenance Plus”
Advanced Fault Diagnostics

• CALCE is providing support in developing improved fault detection and diagnostics capabilities for rotary aircraft.

• CALCE is evaluating algorithms for
  – denoising,
  – dimensional reduction,
  – feature recognition,
  – classification, and
  – prognostics.
Benefits of PHM

• Improved understanding of application conditions – knowing the customer

• Condition-based maintenance – enhanced system availability

• Reduced life cycle costs by decreasing inspections, repairs, downtime, and inventory – product support cost avoidance

• Proactive maintenance to forestall failures – reduced failure rate

• Reduced qualification time

• Extension of operational life

• Improved product/system design

• Improved warranty management

• Intelligent repair/re-use/refurbishment/recycle decisions
Any Questions???

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