Prognostics and Health Management (PHM) for Rotating Systems

Doug Goodman

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Ridgetop Group, Inc.

- Arizona-based firm, founded in 2000, with focus on electronics for critical applications
- Advanced Diagnostics & Prognostics (ADP) and PHM/IVHM Expertise
- Technology leader in precision test structures for QA and prognostic applications
- Wide range of commercial and government customers

- Worldwide nanotechnology R&D partners in industry and academia
- Foundation and focus in physics-of-failure for electronic systems
- Custom Engineering Services

Ridgetop Group Facilities in Tucson, AZ

Ridgetop Europe Facilities in Brugge, Belgium
Ridgetop Accreditations

ISO9001:2008 Quality Management System

AS9100C Quality Management System

Microelectronics Trusted Supplier (Defense Microelectronics Activity)

Alliance Partner
Partners and Customers

- Lockheed Martin
- Aker Solutions
- Dell
- General Atomics
- Boeing
- UTC Aerospace Systems
- Rolls-Royce
- Ingenium Aerospace
- Raytheon
- Moog
- Honeywell
- Astronics Corporation
- BAE Systems
Why Prognostics?

- Complex systems such as aircraft, radar systems, oil drilling equipment, etc., are being called upon to extend their useful service life
- "Black Swan" event mitigation.
- Statistical and model-based reliability methods fall short for critical systems
- Prognostics is key to enabling reliable operations of these systems in the future
Reliability Issues in Complex System

Ridgetop Five-level Model
Progression of Electronic Health Solutions

Die Level
- Process-related
- Wear-out/radiation effects

Component Level
- Radiation damage
- Intermittencies
- Degradation

Board Level
- IC, capacitors
- FPGA/CPU
- Solder joint intermittencies

Module Level
- Prognostics
- Digital boards
- Power/analog boards
- Connectors

System Level
- Embedded hardware and software monitors
- System-level state of health (SOH) analysis & prognostics
- Remaining useful life (RUL)
- Communicate with ground-based systems

00394d
Usage Environment

- Usage monitoring would provide a safety benefit if actual usage is more severe than predicted (see the red region, $T_1$).
- Service life can be extended beyond normal replacement time if the actual usage severity is known (see the green region, $T_2$).

PHM enables replacement only upon evidence of need

Source: Economic and Safety Benefits of Diagnostics & Prognostics (Romero et al. 1996)
Prognostic Health Management (PHM) Ecosystem

1. Communicate PHM Data

2. Sentinel Suite™ Integrated Diagnostic/Prognostics Design Platform

3. Identified Design Improvements
   - Address ECRs and Improve Parts

4. Scheduler
   - Minimize Inventory
   - Replacement Parts

5. Maintenance
   - Line Replaceable Unit (LRU)

Sensors in Complex Electromechanical Systems

Real-time State of Health (SoH) & Remaining Useful Life (RUL)

CBM Actions

Parts
Building a Prognostic-Enabled System
Basic Process Steps

Step 1: Characterize Device or System Failures

Key Failure

Pareto Ranking of Key Failures

Step 2: Extract Precursor Signatures to Failure

Example Precursor Signatures

Target Position vs. Rotor Position

Following Error

Degradation Curve

Step 3: Calculate Remaining Useful Lifetime (RUL)

Device or System Lifetime

Designing a Prognostic Solution
Pareto Analysis to Prioritize

Root Cause Analysis used for Failure Modes and Effects Analysis (FMEA)

When Capacitors fail (e.g., short to GND), they also short out diodes.

Customer returns

Capacitors are significant cause of power supply failures as reported here.
Implementation Elements

- Advanced Sensing Methods
- Processing Platforms
- Anomaly Detection
- State of Health (SoH) Assessment
- Remaining Useful Life (RUL) Projection
- Linkages to other tools (Fault Management, Logistics Systems)
Development Platforms
Decisions are based on fault severity levels

- On-Board for critical faults
- Off-Board, single system or subsystem, for less critical faults
- Mix of On- and Off-board, depending on fault severity

- Net-centric monitoring, off-board, multiple systems with geographic separation
Sentinel Motion™ Platform

- Collection and analysis hub for prognostics
- Scalable, system level state of health (SoH) analysis & prognostics
- Automatic Sensor Network Discovery mode
- Anomaly detection
- Remaining useful life (RUL) algorithms
PHM for Rotating Systems
Examples of Rotating Mechanisms

- Helicopter Gear Boxes (pinion gear, planetary gears)
- Railroad Rolling Stock (wheels, axles)
- Electromechanical Actuators
- Industrial Equipment and Machine Tools
- Automotive Transmissions
- Wind Turbines
Special Problems with Rotating Systems

- Spinning shafts degrade with eccentricities from wear patterns
- Bearings that suspend spinning shafts can wear out
- Direct measurements are difficult to make due to rotation effects
- Slip rings are not always possible and they add noise
- Cabling is impractical and adds weight
Helicopters suspended as gearbox fault blamed for Super Puma ditching

STV 13 May 2012 12:02 BST

The owners of a helicopter which ditched in the North Sea last week grounded more aircraft today after an early investigation revealed a fault in its gearbox.

The move comes after an initial Air Accidents Investigation Branch examination of the EC225, which went down while carrying 12 passengers and two crew, showed it suffered a crack to a gearbox shaft.

Helicopter Gear Box Health Monitoring

- Strategy is to place a self-contained sensor to monitor operating data of the pinion gear
- A separate sensor monitors a planetary gear for the helicopter transmission
- Sensor is a MEMS-based rotational vibration and speed sensor designed by Ridgetop
- Transmit vibration and speed data wirelessly using IEEE 802.15.4 to collection hub
- Analyze data stream for anomalies, and determine state of health (SoH) and remaining useful life (RUL)
RotoSense™ Module

- RotoSense is a wireless rotational vibration sensor
- IEEE 802.15.4 wireless implementation
- Sensing tool wear, chatter, or spindle balance in CNC applications
- Detecting prognostic vibrational signatures in rotating shafts or pinions to give early warning of gear tooth cracking or spalling in wind turbines and transmissions
- Applications include:
  - CNC
  - Down-hole oil & gas drilling
  - Wind turbines and transmissions

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<th>Value</th>
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<tr>
<td>Operating temperature</td>
<td>93 °C</td>
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<tr>
<td>Sensor housing</td>
<td>1.5” diameter x 3” length</td>
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<tr>
<td>Sensor data memory</td>
<td>2 Mbits</td>
</tr>
<tr>
<td>Accelerometer sensitivity</td>
<td>&lt;20 mV/g at 100 Hz</td>
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<td>Wireless data rate</td>
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<td>Battery-powered</td>
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<tr>
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<tr>
<td>Sensor and signal conditioning bandwidth</td>
<td>20 kHz</td>
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<tr>
<td>ADC resolution</td>
<td>16 bits</td>
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<tr>
<td>ADC sample rate</td>
<td>&gt;250 kHz</td>
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RotoSense Configuration

Small size allows the whole system to be mounted in the shaft of the transmission
RotoSense System

Complete module

Module mounted in the shaft of the transmission
NASA Spinoff – RotoSense™

Wireless Sensors Pinpoint Rotorcraft Troubles

Transportation

NASA Technology

Helicopters present many advantages over fixed-wing aircraft: they can take off from and land in tight spots, they can move in any direction with relative ease, and they can hover in one area for extended periods of time. But that maneuverability comes with costs.

For example, one persistent issue in helicopter maintenance and operation is that their components are subject to high amounts of wear compared to fixed-wing aircraft. In particular, the rotor drive system that makes flight possible undergoes heavy vibration during routine performance. Slowly degrading components in a way that can cause failures if left unmonitored. The level of attention required to ensure flight safety makes helicopters very expensive to maintain.

As a part of NASA’s Fundamental Aeronautics Program, the Subsonic Rotary Wing Project seeks to advance knowledge about and improve prediction capabilities for rotorcraft, with the aim of developing technology that will meet future civilian requirements like higher efficiency and lower noise flights. One of the program’s goals is to improve technology to detect and assess the health of critical components in rotorcraft drive systems.

Full article here: http://spinoff.nasa.gov/Spinoff2012/t_6.html
Expanded Monitoring System

RIDGETOP SENSORS

- Ridgetop Gateway
- Ridgetop Temp Sensor
- Ridgetop Vib Sensor
- Ridgetop Torque Sensor
- Ridgetop Strain Sensor
Wheel – Axle Applications
Problem Statement

- Decaying railroad infrastructure: tracks, rolling stock, bridges
- Wheel cracks, defective bearings and connections to axles
- Transportation of dangerous materials such as flammable liquids and gases
Mount two wireless RotoSense™ sensors, one on each side of the axle end caps.
Wireless Testing Conducted at Railroad Test Facility
Each Gateway along with each sensor node has discoverable IP addresses

- **Rotary Sensor:** 172.0.0.20
- **Rotary Sensor:** 172.0.0.7
- **Rotary Sensor:** 172.0.0.5
- **Rotary Sensor:** 172.0.0.20
- **Vibration Sensor:** 172.0.0.32
- **Vibration Sensor:** 172.0.0.15
- **Gateway:** 172.0.0.1

IEEE 802.15.4 low power wireless network standard. 10m / ~32' range

RJ45 Ethernet connection using TCP/IP
IEEE 802.15.4 low power wireless network standard
Ridgetop’s IoT Sensor Enablement Kit

Flexible plugin board for additional sensors for IoT development with digital and analog sensors

Examples include: light level, temperature measurement, strain/stress/pressure gauges, etc. along with I/O control
Railroad Car Application

Sentinel Suite™

RotoSense™

Analysis and Prognostic Framework

SAVE SAMPLES

PROCESS SAMPLES

BINARY FILES

CONDITION DATA

TRANSFORM & ANALYZE DATA

LOCATE & IDENTIFY ANOMALIES

WIRELESS
Wireless Real Time Data Transfer
Gateway Data Transfer

Trivial File Transfer Protocol (TFTP) is embedded for reliable multi-node data exchanges with the gateway and sensors.
Red = X = Horizontal motion
Green = Y = Vertical motion
Blue = Z = Lateral motion
Sensor Data

Two types of captured data files can be produced. Slow fixed rate streaming and fast variable length are supported. Multiple gateways and sensor nodes can produce these concurrently.

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The data file format is raw 16bit ADC samples arranged as X, Y & Z values of the supported mems sensor type integrated with these sensor devices.

The format header allows the data files to have system independence after collection and distribution for post processing analysis and visualization. This arrangement coupled with various types of sensor hardware provides an extensible sensor network system approach.

Sample output of the data shown exported to a CSV file and plotted in MS Excel

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
<th>z</th>
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<tr>
<td>29719</td>
<td>31089</td>
<td>28561</td>
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<td>29208</td>
<td>30687</td>
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</table>

![Graph showing ADC sample values for x, y, and z](graph.png)
RailSafe™ Integrity Analysis Platform

- Continuous sensor monitoring with analysis using proven PHM algorithms
- Provides system-level State of Health (SoH) indication with accurate Remaining Useful Life (RUL) estimates
- Results can be integrated with existing CBM systems
RailSafe™ Complete Solution

RailSafe
RotoSense™ Wireless Sensors

Sentinel
Gateway™
Data Collection Hub

RailSafe
ToolBox™
Analysis

Actionable
Real-time
Maintenance
Data

Legend:
- Bridge
- Tunnel
- Line ref
- Railroad line
- Sidings
- Yard track
- Spar
- Crossover track
- Branch line
- Main line
- Highspeed line
- Industrial line
- Industrial service track
- Preserved track
- Track under construction
- Proposed track

Map showing railroad infrastructure.
Algorithm Development
Ridgetop developed software that takes advantage of the fact that failure modes produce predictable degradation signatures.

Each input data sample is used to adapt an Fault to Failure Progression (FFP) signature definition to the data.

The adapted FFP signature definition is then used to produce accurate RUL and SoH estimates that can be used to generate diagnostic and prognostic information: messages, plots, thermometers and so on.
ARULE Algorithm Example

![Graphs showing ARULE Algorithm example](image)

- **Actual Response**
- **Nominal Response**
- **Normalized Frequency Change, Ratio**
- **Remaining Useful Life (RUL)**

**US PATENT 7,619,908; PATENT PENDING**
EMA Actuator Prognostics
Actuator Hardware Configuration
Actuator Power Drive Prognostics

- **Typical Problem:** Gate drive (D1) fault with progression to the power transistors (D2) and motor windings (D3) of each phase

- Acquire and characterize the pertinent multivariate servo drive data associated with each fault condition (both electrical and mechanical) and the resulting stress effect on other components in the system

- Develop the fault-to-failure progression (FFP) signatures of the acquired multivariate data to populate fault dictionary

- **Results:** Detection of precursor events that mark impending failure of the servo drive subsystem or damage to its individual components
The goal of our data analysis methodology is to create a signature that can be used to compute the level of degradation of any future test runs of a motion profile.

Data collected with a threshold level is used to define ‘healthy’ data.

This methodology computes differences from the golden signature and sums the differences over time.

The summed differences relate to fault degradation.

The fault degradation is used to determine a fault to failure progression.
Fault to Failure Progression (FFP) Signature

Resistor value vs. Total sum_gap

Ceiling: 4
Floor: 3

Graph showing the trend of Total sum_gap against Resistor value.
Actuator Results

- Defined EMA Actuator Health Management System

- Identified additional observation points for prognostics of the electronic unit (EU) of an EHA

- Provided SoH and RUL for complex system
### Fault Dictionary Development

#### Prognostic / Diagnostic Fault Dictionary

<table>
<thead>
<tr>
<th>Time</th>
<th>Fault Ref</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:21:02</td>
<td>E213_006</td>
<td>EHA Drive Card</td>
<td>MOSFET Degraded</td>
</tr>
<tr>
<td>16:43:02</td>
<td>M166_001</td>
<td>Gear Box A</td>
<td>Broken Tooth</td>
</tr>
<tr>
<td>16:45:02</td>
<td>M166_002</td>
<td>Gear Box A</td>
<td>Gear Spalling</td>
</tr>
<tr>
<td>17:04:02</td>
<td>H006_001</td>
<td>EHA Hydraulic Valve</td>
<td>Pressure drop</td>
</tr>
</tbody>
</table>

#### EHA Hydraulic Valve Test

1. Apply test sequence O_12_DS2
2. Monitor input drive current at test point 13
3. Verify excessive current.
4. Replace part and retest.
Rotating / moving systems pose a difficult challenge for monitoring, diagnosis, and prognosis

- Wear out and degradation effects are difficult to observe, especially for internal components
- They can be subject to a very wide range of environmental conditions
- Sensor data is often very noisy
- Statistical and model-based predictive analytical methods often fall short

Ridgetop’s Sentinel Suite

- Sensors
  - Designed to be close or inside the monitored component for optimal sensitivity
  - Designed to withstand harsh environments
- Advanced diagnostic and prognostic software
  - Effectively extract the signal from the noise
  - Efficiently compute key diagnostic and prognostic metrics, e.g., SoH, RUL
Questions?

- Slides and recording of the webinar will be available shortly via an e-mail from Ridgetop.

- E-mail follow-up questions & comments to Doug Goodman at dgoodman@ridgetopgroup.com

- Please fill out our brief feedback survey at: https://www.surveymonkey.com/r/57NDFVP
Questions?

Thank you!

Ridgetop Group, Inc.

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