Smart Sensors for Distributed Event-Triggered System Health Monitoring

Ridgetop Group, Inc.
Doug Goodman, President & CEO
Kyle Ferrio, VP Advanced Research
Agenda

- Quick Introduction to Ridgetop Group
- Event-Driven Inspection
- Smart Sensors
Ridgetop Group, Inc.

- Arizona-based firm, founded in 2000, with focus on electronics for critical applications
- Two divisions: Semiconductor & Precision Instruments (SPI) and Advanced Diagnostics & Prognostics (ADP)
- 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
Ridgetop Accreditations

ISO9001:2008 Quality Management System

AS9100C Quality Management System

Microelectronics Trusted Supplier
(Defense Microelectronics Activity)
Partners and Customers
Faults Occur at Multiple Levels in Systems

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 intermittenocs

- **Module Level**
  - CNI prognostics
  - Digital boards
  - Power/analog boards
  - Connectors

- **System Level**
  - Embedded Sentinel Network™ with HealthVIEW™ software
  - System-level state-of-health (SOH) analysis & prognostics
  - Remaining useful life (RUL)
  - On-board monitors
  - Communicate with ground-based systems
Evolution of Maintenance Practices

Going from REACTIVE to PROACTIVE

1. Repair/Replace when Broken
2. Scheduled Inspection & Maintenance
3. Event-Triggered & On-Demand Inspection
4. Condition-based Maintenance (CBM)
Evolution of Maintenance Practices

Going from REACTIVE to PROACTIVE

- Repair/Replace when Broken
- Scheduled Inspection & Maintenance
- Event-Triggered & On-Demand Inspection
- Condition-based Maintenance (CBM)

Reactive maintenance plans are unacceptable for critical systems.
Evolution of Maintenance Practices

Going from REACTIVE to PROACTIVE

1. Repair/Replace when Broken
2. Scheduled Inspection & Maintenance
3. Event-Triggered & On-Demand Inspection
4. Condition-based Maintenance (CBM)

Preemptive maintenance may increase risk to crew and vehicle.
Evolution of Maintenance Practices

Going from REACTIVE to PROACTIVE

- Repair/Replace when Broken
- Scheduled Inspection & Maintenance
- Event-Triggered & On-Demand Inspection
- Condition-based Maintenance (CBM)

Event-triggered maintenance is based on *timely and actionable* information.
Evolution of Maintenance Practices

Going from REACTIVE to PROACTIVE

- Repair/Replace when Broken
  - Reactive
- Scheduled Inspection & Maintenance
  - Preemptive
- Event-Triggered & On-Demand Inspection
  - Actionable
- Condition-based Maintenance (CBM)
  - Proactive (Prognostics)

Smart sensors and algorithms provide the prognostic horizon for CBM.
The Challenge: Situational Awareness

- Cannot be in all places at all times
- Slow, dangerous work
- High risk to crew and vehicle
- Autonomous monitoring should be the norm

NASA STS-116
Sensors, Everywhere?

- Sensors improve situational awareness
  - But data is not the same as information!

- New challenges
  - Big Data
  - Proliferation of sensors implies growth of data
  - Extracting actionable information from big data is hard, even on earth
    - Compute burden
    - Power draw
    - Cooling load

Google press release
http://www.google.com/about/datacenters/
Smart Sensors Ease Data Burden

- Big Data in Space can borrow from Big Data on Earth
  - Don’t move (much of) the data to the algorithms
  - Move routine computation to the data
  - Monitor *locally* and persistently with low-power sensors
  - Reduce data to events *locally*, at the sensor
  - Communicate *events* over low-bandwidth, low-power channel
  - Stream *data* at full (or fractional) bandwidth only when commanded

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**Mode & program**

- **Smart Sensor**
  - Continuous measurements;
  - *Raw Data are high-bandwidth*

- **High-Level Reasoning Algorithms**
  - Events and heartbeats;
  - *Information is low-bandwidth*

- **Crew Dashboard**

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Big Data in Space can borrow from Big Data on Earth: Don’t move (much of) the data to the algorithms. Move routine computation to the data. Monitor *locally* and persistently with low-power sensors. Reduce data to events *locally*, at the sensor. Communicate *events* over low-bandwidth, low-power channel. Stream *data* at full (or fractional) bandwidth only when commanded.
Smart Sensors Ease Data Burden

- Smart Sensors transform data into information by combining...
  - Physical instruments
  - Dynamic data acquisition scheduling
  - First-order data reduction → event detection
  - Low-bandwidth communication and control
  - Remotely reconfigurable algorithms
  - Integrate (except transducer) in a rad-hard ASIC
RotoSense™
Full article here: http://spinoff.nasa.gov/Spinoff2012/t_6.html
Problem Statement

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.

Solution: RotoSense

- RotoSense is a wireless rotational vibration sensor
- IEEE standard 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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>MEMS accelerometer peak impact</td>
<td>&gt;200 g</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>93 °C</td>
</tr>
<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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<tr>
<td>Wireless data rate</td>
<td>75 kbaud nominal</td>
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<tr>
<td>Battery powered</td>
<td>3.6 V high-temp battery, 4.5 Ah, 200 °C</td>
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<tr>
<td>Battery life</td>
<td>4 months at a 50% duty cycle</td>
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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>
</tr>
<tr>
<td>ADC sample rate</td>
<td>&gt;250 kHz</td>
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• Electrical based intermittent/No Fault Found (NFF) issues are amongst the most difficult to identify and deal with in complex systems.

• Ridgetop’s unique approach to addressing this will be critical to enabling reliable system performance for years to come
With present technology, reported electronic system problems in the field cannot be duplicated at the service point or in the lab.

“Three/Four-letter” words (CND, NTF, RTOK)
- Could Not Duplicate (CND)
- No Trouble Found (NTF)
- Retest OK (RTOK)

50 to 80% of these CND/NTF/RTOK problem categories are reported by service personnel.

Major culprits – Solder joint intermittencies, connectors, and NBTI effects in deep submicron ICs
Solder Balls, Cracks and Fractures

IC / SOC / SiP

Printed Circuit Board

Solder Balls

Typical Failure Points

Lall 2005 IEEE

Fractures

100µm x 140
Mechanisms of Failure

- Fatigue fractures (cracks) are caused by thermo-mechanical stress/strain.
- During periods of high stress, fractured bumps tend to momentarily open and cause intermittent faults of high resistance for periods of ns to µs.
- Over time, contamination and oxidation films occur on the fractured faces: the effective contact area becomes smaller and smaller.
- Transient opens can be detected by event detectors.
Mechanics of Failure

HALT results - Pulled FPGA – Damaged Solder Balls

- Undamaged
- Damaged: Cracked
- Cracked, not detectable
- Fractured, detectable
Intermittent Faults

- Faults are intermittent: confirmed by CAVE, Auburn Univ., German automobile manufacturer, BAE Systems and other firms
  - Occur during periods of increasing strain
  - Multiple occurrences per cycle
  - Industry standard: 200 ohms +, 200 ns +
SJ BIST™ Objectives & Features

- **Objectives**
  - Detection of impending interconnect failures
  - Unique in-situ testing in operating circuits
  - Technology-independent

- **Feature and Benefits**
  - Detects ball fractures prior to catastrophic failure of circuit
  - Provides actionable maintenance data
  - Independently tested and verified
  - Endorsed by leading automotive and aerospace customers
SJ BIST Operation

Healthy Solder Joint

 Writes a “1” and reads a “1”
Faulty Solder Joint

 Writes a “1” but reads a “0”
SJ BIST Summary

- Available as:
  - Verilog or VHDL core for FPGA
  - Microcontroller code
- Requires dedicated I/O + capacitor
- Runs concurrently
- Interconnect reliability verification
  - Process qualification
  - Lifetime observation
SJ BISTView GUI

B1: SJ BIST View
B2: Ridgetop Group Inc
B3: SJ BIST
B4: SJ BIST View
R1: SJ BIST View
R2: SJ BIST View

FPGA BGA grid

About
Reset Errors

Frequency: 10000000 Hz

Disconnect
COM4

00 00 00 00

00 00 00 00

00 00 00 00

00 00 00 00
Contact Information

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SJ BIST Demo Kit Hardware

- The SJ BIST Demo Kit, built into an impact-resistant case, contains a control board that is connected to a 324-pin test integrated circuit (Xilinx XC6SLX16-2CSG324C FPGA) in a fine-pitch ball grid array package.

- SJ BIST is designed and programmed to monitor the health of the solder balls in 12 I/O ports that have been configured to form six groups of two pairs of pins.

- There are four push buttons used for manual fault injection, and two dials that adjust the resistance between the FPGA pins in order to demonstrate the sensitivity of SJ BIST to resistance changes.
Demonstration Kit Hardware
**Hardware**

- **Assigned I/O Pins**
  - In the test board, pairs of I/O pins are wired together to form test groups for monitoring by SJ BIST. The pins being monitored are configured as six groups of two pins each, for 12 pins total.

- **SJ BIST Fault Injection**
  - To simulate a failure, the SJ BIST Demo Kit has fault injection push buttons and dials that allow to inject various types of faults into six of the FPGA pin pairs.
  - Faults injected by pushing the SJ BIST Demo fault injection push buttons (B1, B2, B3, or B4) or by adjusting the dials (R1 or R2), are being monitored by SJ BIST cores and can lead to detection depending on the selected observation frequency.