Prognostics and Health Management (PHM) for Rotating Systems

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Ridgetop Group, Inc.

Ridgetop Group Facilities in Tucson, AZ

- 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 Europe Facilities in Brugge, Belgium

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of North America

This is to certify that the
Quality Management system of:

Ridgetop Group, Inc.

3580 West Ina Road
Tucson, AZ 85741
US

has been assessed and found complying with the requirements of

ISO 9001:2008 & AS9100C

Approval is hereby granted by Management Certification of North America under its ANAB accreditation and in accordance with the AAQG Program and AS9104 Rev A, provided the certification rules and conditions are observed at all times.

Certification Scope:

Provision of engineering, research & development, electronic prognostics, integrated circuit design.

Certificate Number: 1107004 **Audit Date:** 22-Dec-2011

Issue Date: 27-Jan-2012 **Expiration Date:** 26-Jan-2015

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AS9100C Quality Management System

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CATEGORY 1A

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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

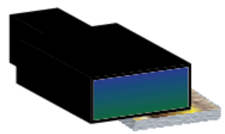
Progression of Electronic Health Solutions

Die Level

- Process-related
- Wear-out/radiation effects

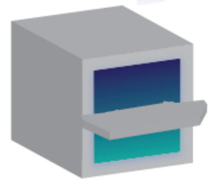
Component Level

- Radiation damage
- Intermittencies
- Degradation



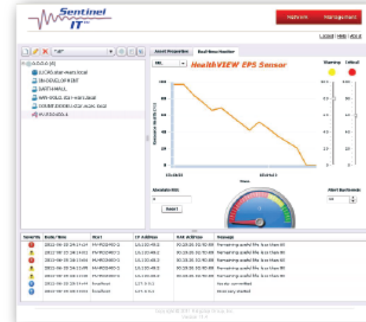
Board Level

- 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

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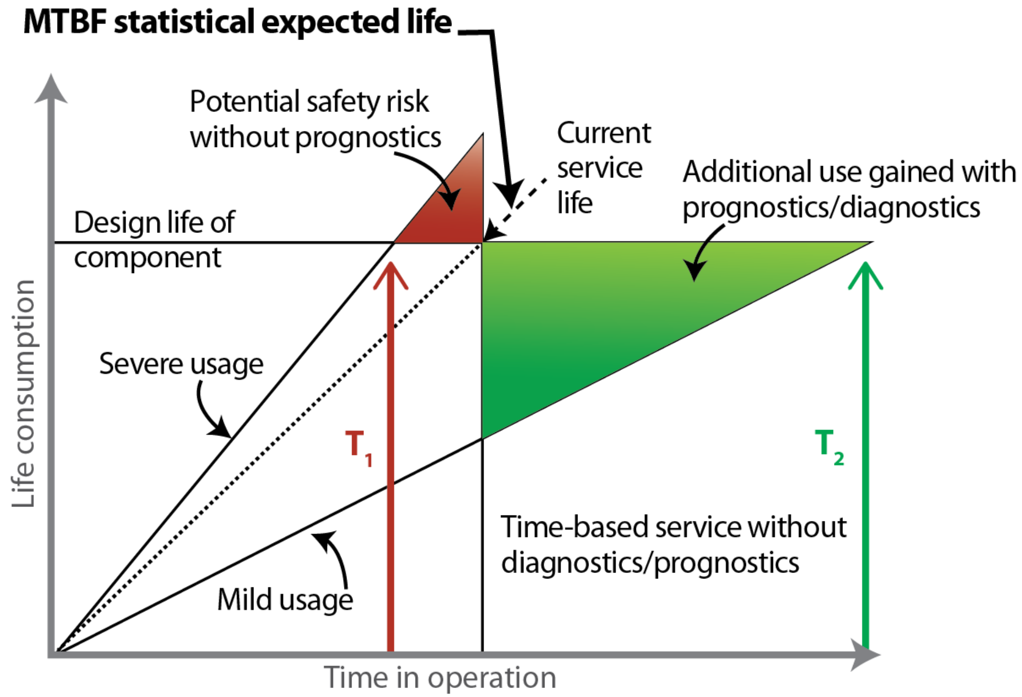
Degradation Rates Dependent on Environmental Conditions

<u>Usage Environment</u>

- 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)**.



Source: Economic and Safety Benefits of Diagnostics & Prognostics (Romero et al. 1996)

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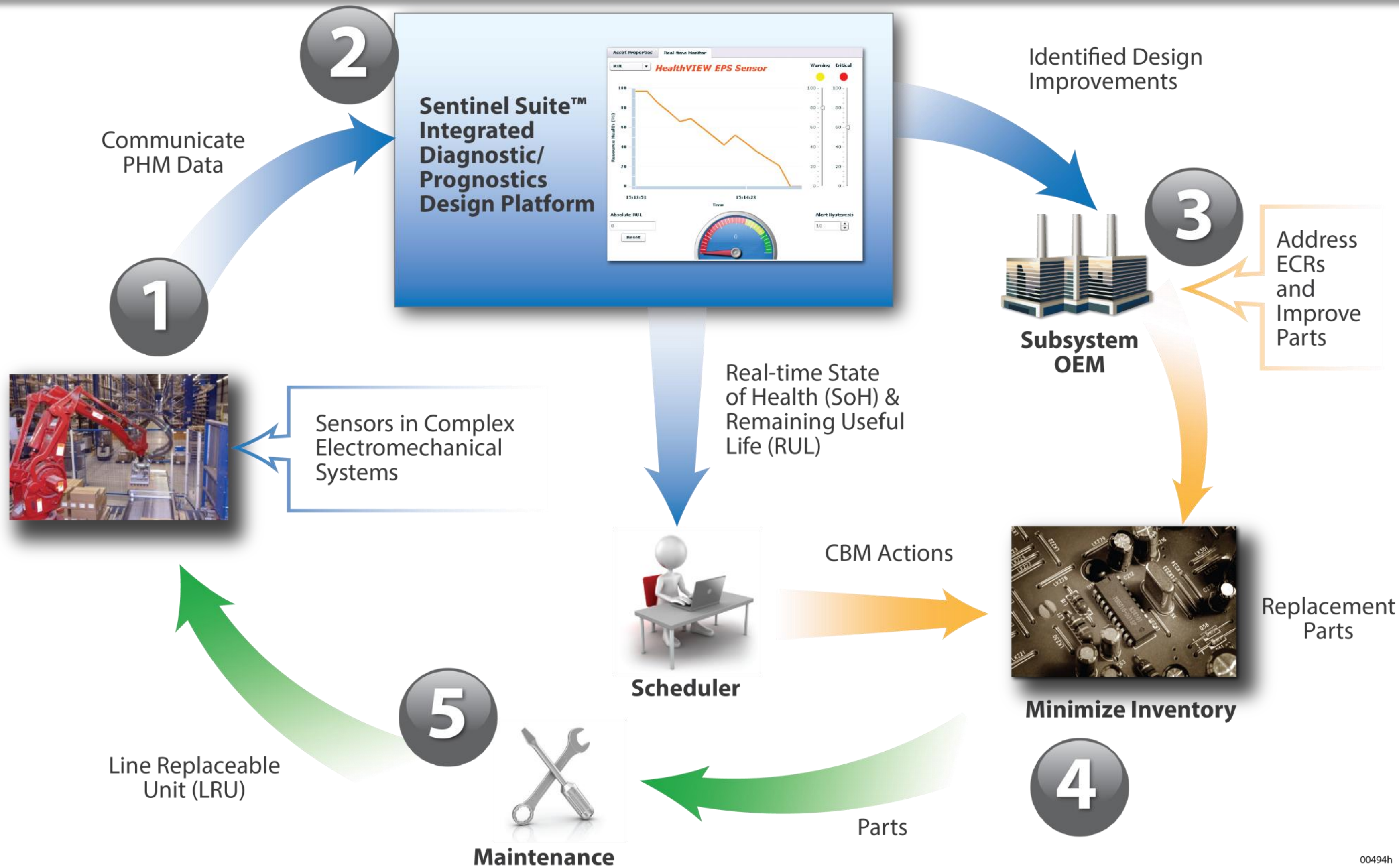
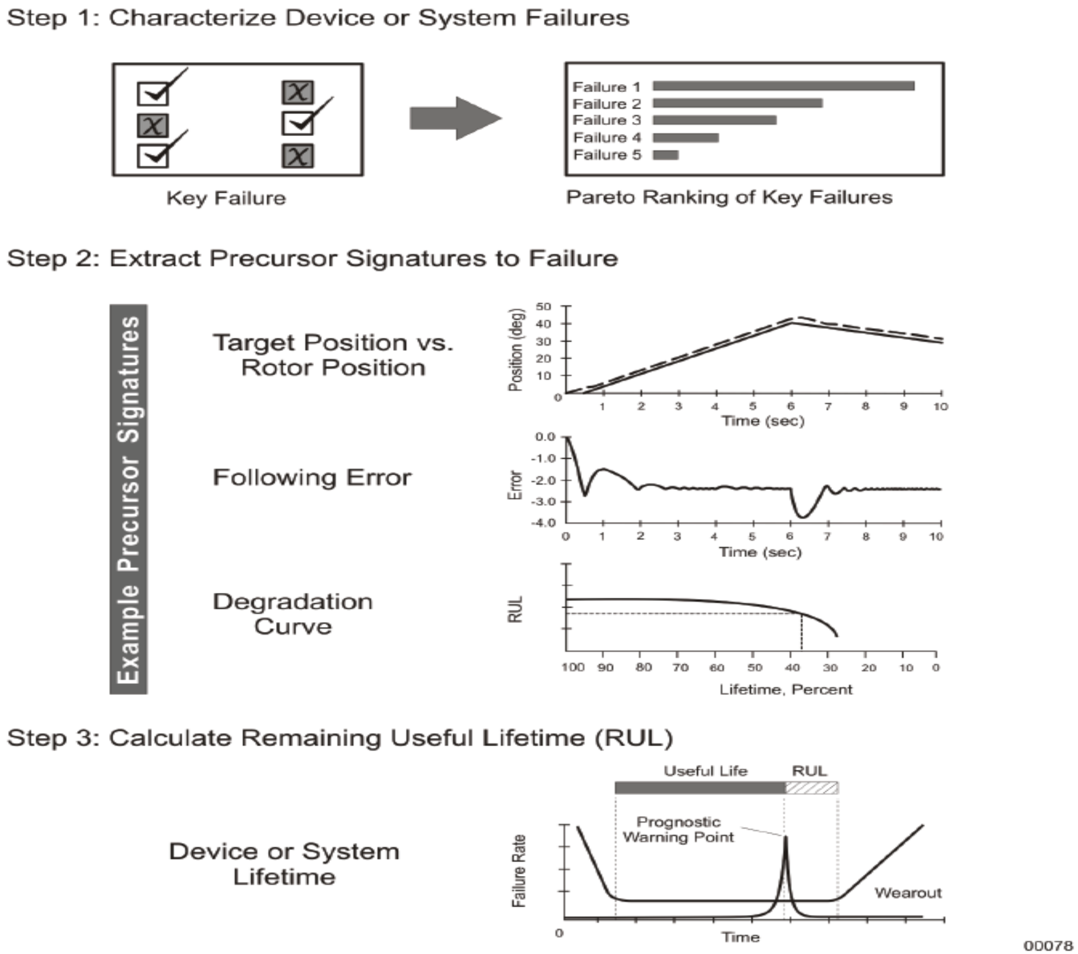
PHM enables replacement only upon evidence of need

Prognostic Health Management (PHM) Ecosystem



Building a Prognostic-Enabled System

Basic Process Steps



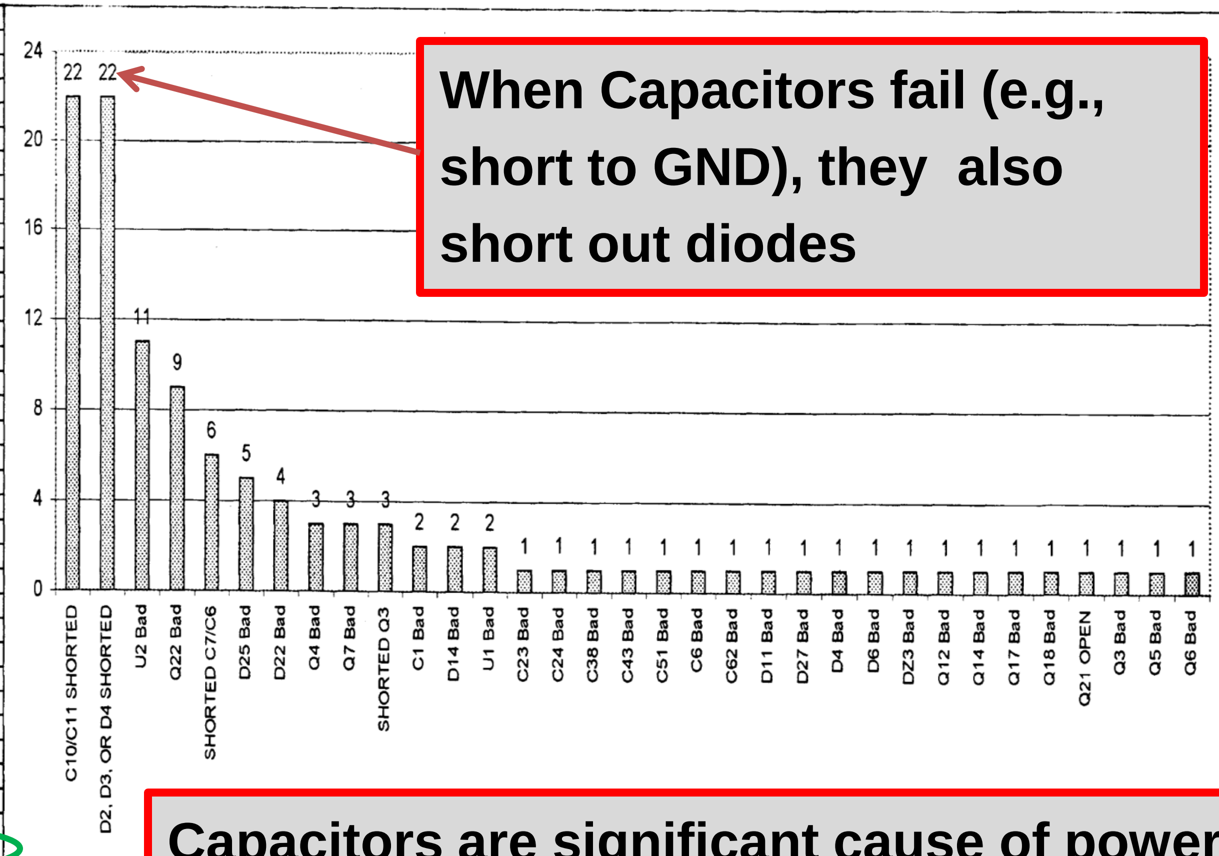
Designing a Prognostic Solution

Pareto Analysis to Prioritize

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

1st Level Root Cause	Quantity
C10/C11 SHORTED	22
D2, D3, OR D4 SHORTED	22
U2 Bad	11
Q22 Bad	9
SHORTED C7/C6	6
D25 Bad	5
D22 Bad	4
Q4 Bad	3
Q7 Bad	3
SHORTED Q3	3
C1 Bad	2
D14 Bad	2
U1 Bad	2
C23 Bad	1
C24 Bad	1
C38 Bad	1
C43 Bad	1
C51 Bad	1
C6 Bad	1
C62 Bad	1
D11 Bad	1
D27 Bad	1
D4 Bad	1
D6 Bad	1
DZ3 Bad	1
Q12 Bad	1
Q14 Bad	1
Q17 Bad	1
Q18 Bad	1
[illegible]	1
[illegible]	1
Q5 Bad	1
Q6 Bad	1
Total Returns	114

Customer returns



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

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)**

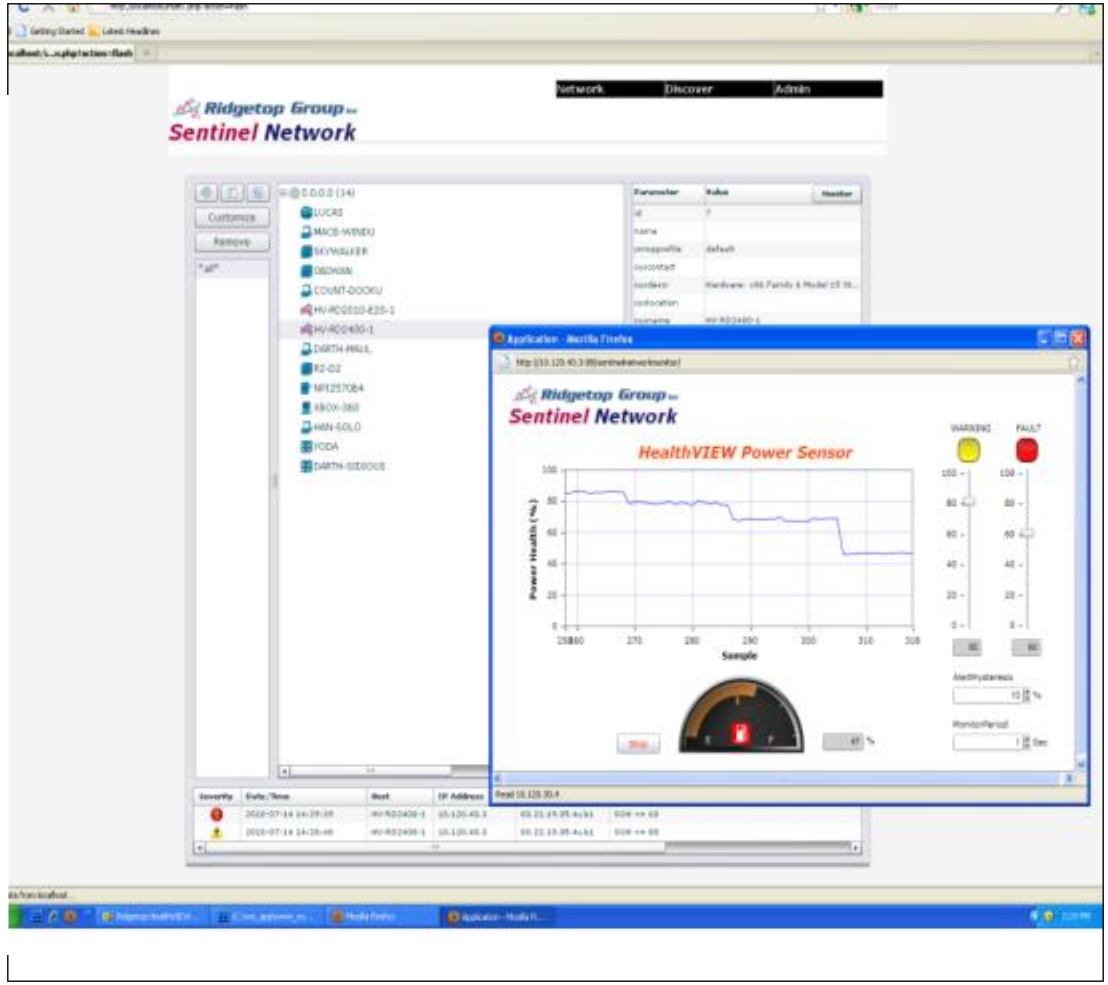
Development Platforms

PHM / Diagnostic Monitoring Scenarios

- 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

Helicopter Gear Box Example

Helicopters suspended as gearbox fault blamed for Super Puma ditching

STV 13 May 2012 12:02 BST

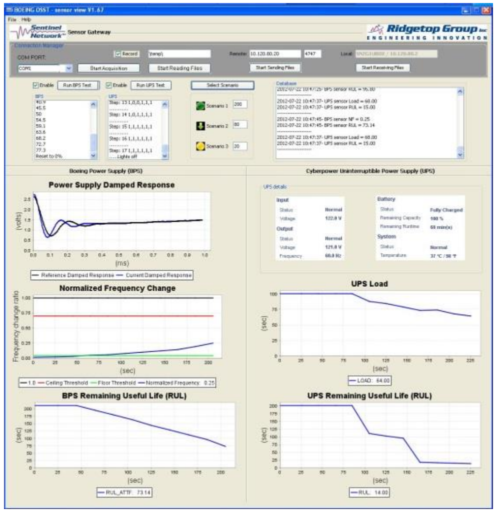
The owners of a helicopter which ditched in the North Sea last week grounded more aircraft today after an early investigation revealed a fault in its gearbox.

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.

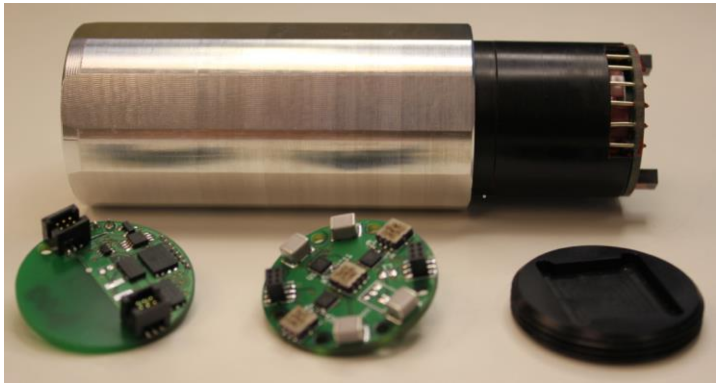
Source: http://news.stv.tv/north/99554-helicopters-suspended-as-gearbox-fault-blamed-for-superpuma-ditching/

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)



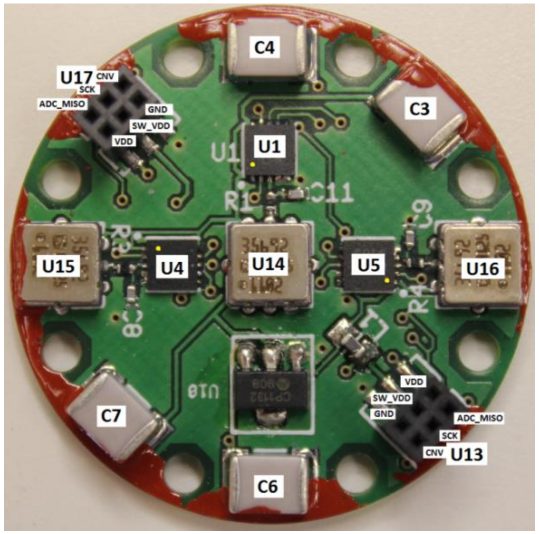
RotoSense™ Module

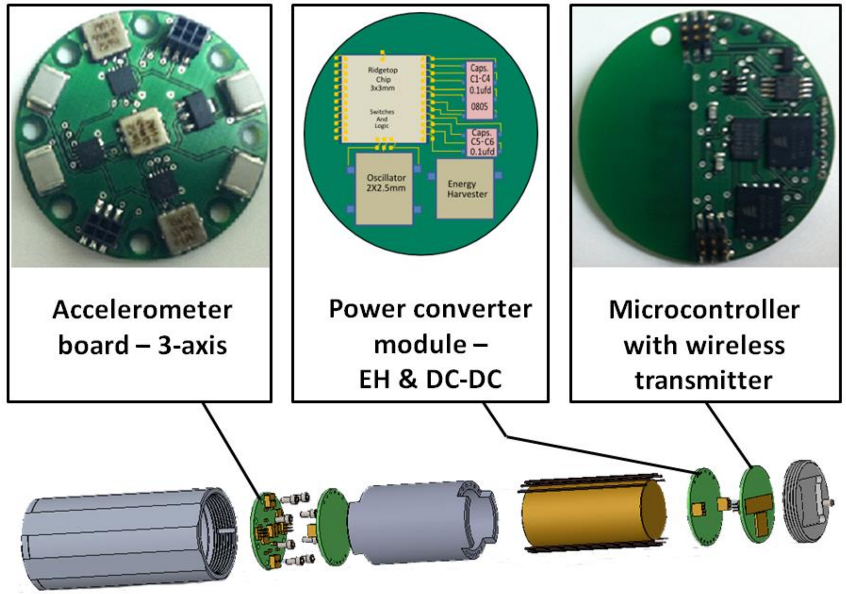


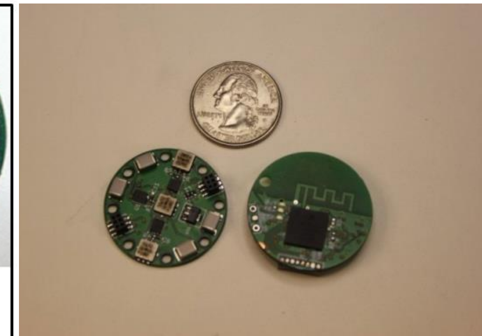
- RotoSense is a wireless rotational vibration sensor
- IEEE 802.15.4 wireless implementation
- Sensing tool wear, chatter, or spindle balance in CNC applications
- Detecting prognostic vibrational signatures in rotating shafts or pinions to give early warning of gear tooth cracking or spalling in wind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

Specification	Value
MEMS accelerometer peak impact	>200 g
Operating temperature	93 °C
Sensor housing	1.5” diameter x 3” length
Sensor data memory	2 Mbits
Accelerometer sensitivity	<20 mV/g at 100 Hz
Wireless data rate	75 kbaud nominal
Battery-powered	3.6 V high-temp battery, 4.5 Ah, 200 °C
Battery life	4 months at a 50% duty cycle
Sensor and signal conditioning bandwidth	20 kHz
ADC resolution	16 bits
ADC sample rate	>250 kHz

RotoSense Configuration

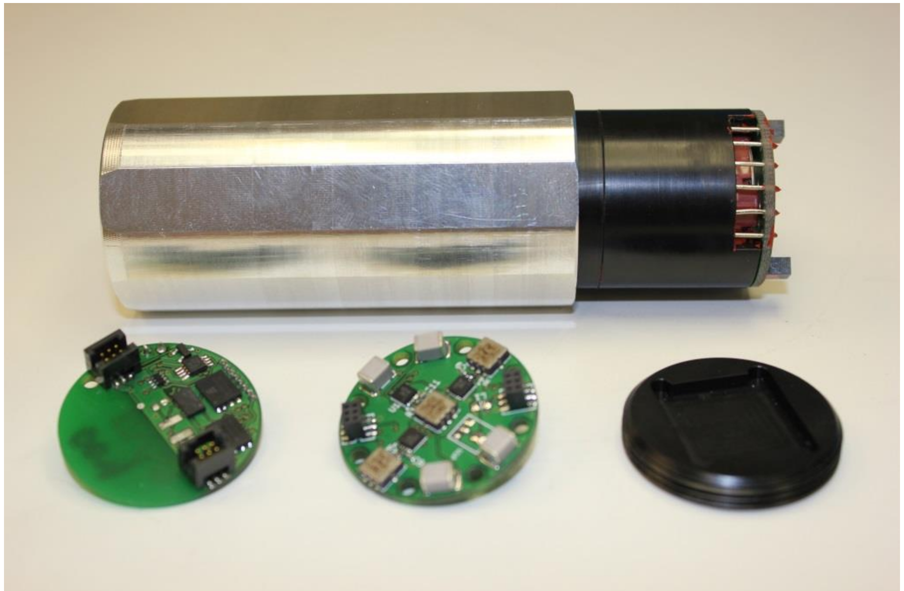


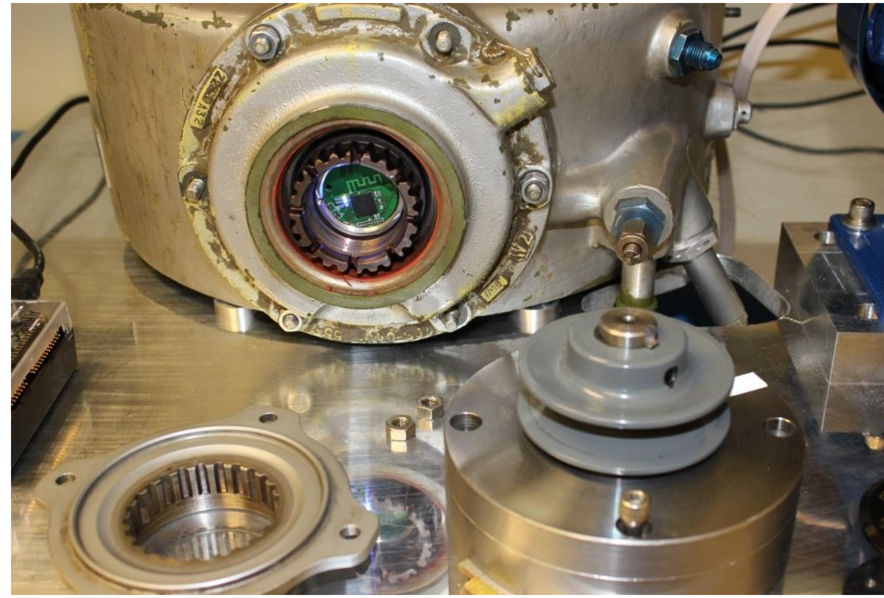




Small size allows the whole system to be mounted in the shaft of the transmission

RotoSense System





Complete module

Module mounted in the shaft of the transmission

NASA Spinoff – RotoSense™

Office of the Chief Technologist

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Spinoff 2012

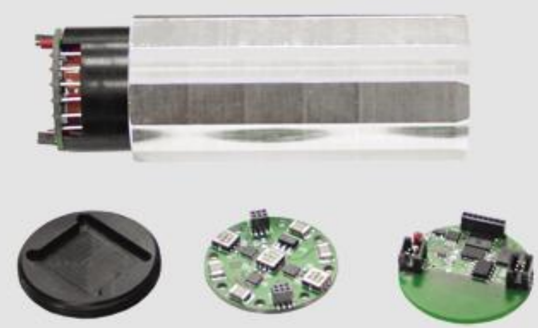
Wireless Sensors Pinpoint Rotorcraft Troubles

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.

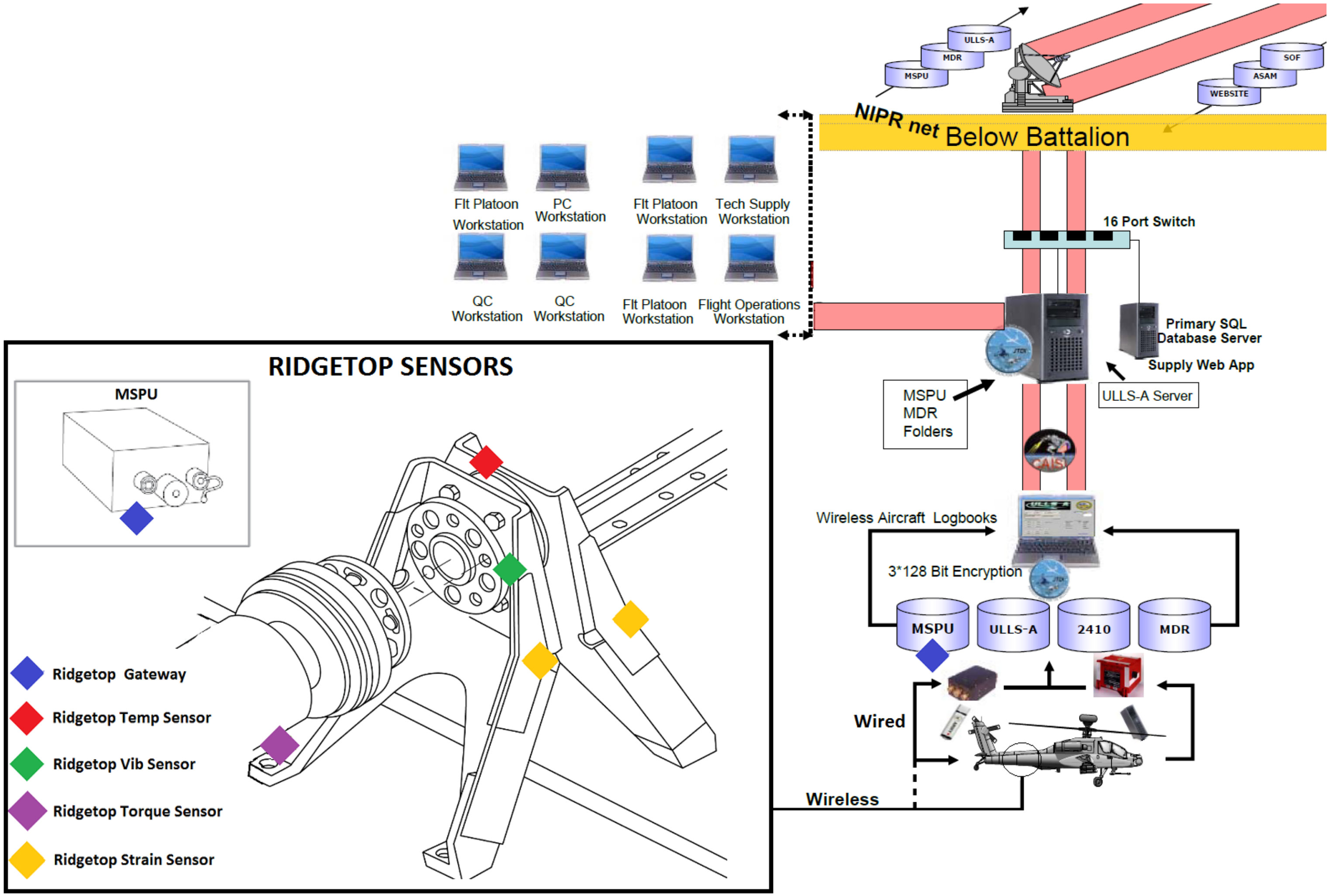


Ridgetop's wireless MEMS accelerometer can gather quality data from spots inaccessible to the sensors typically employed today.

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

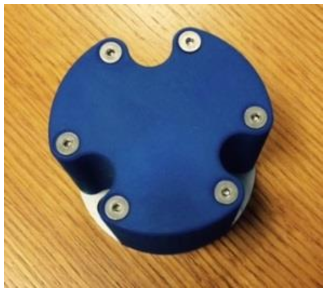


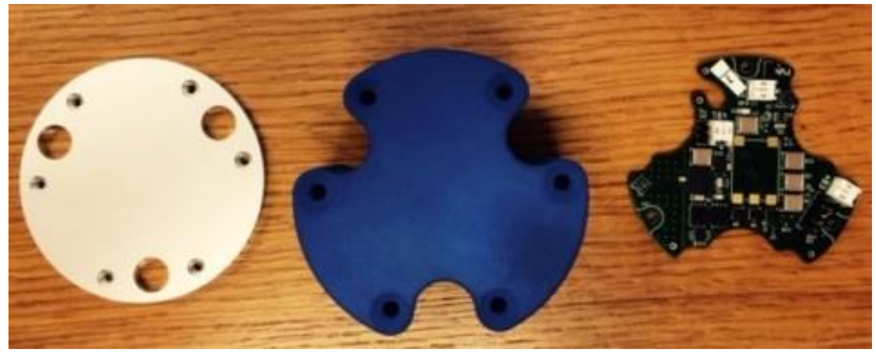
Wheel – Axle Applications

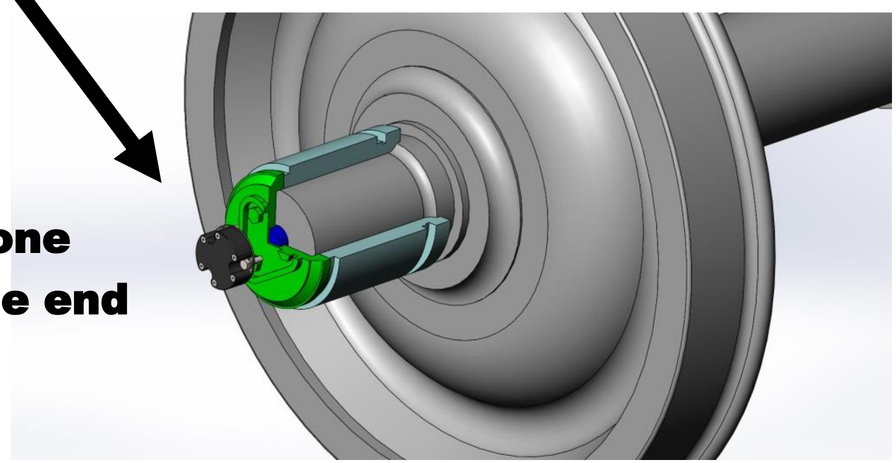
Problem Statement

- 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

RotoSense™ Wireless Rotational Vibration Sensor







Mount two wireless RotoSense™ sensors, one on each side of the axle end caps.

Wireless Testing Conducted at Railroad Test Facility

Standard TCP/IP Implementation

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: 172.0.0.5

Vibration Sensor: 172.0.0.32

Vibration Sensor: 172.0.0.15

Gateway: 172.0.0.1

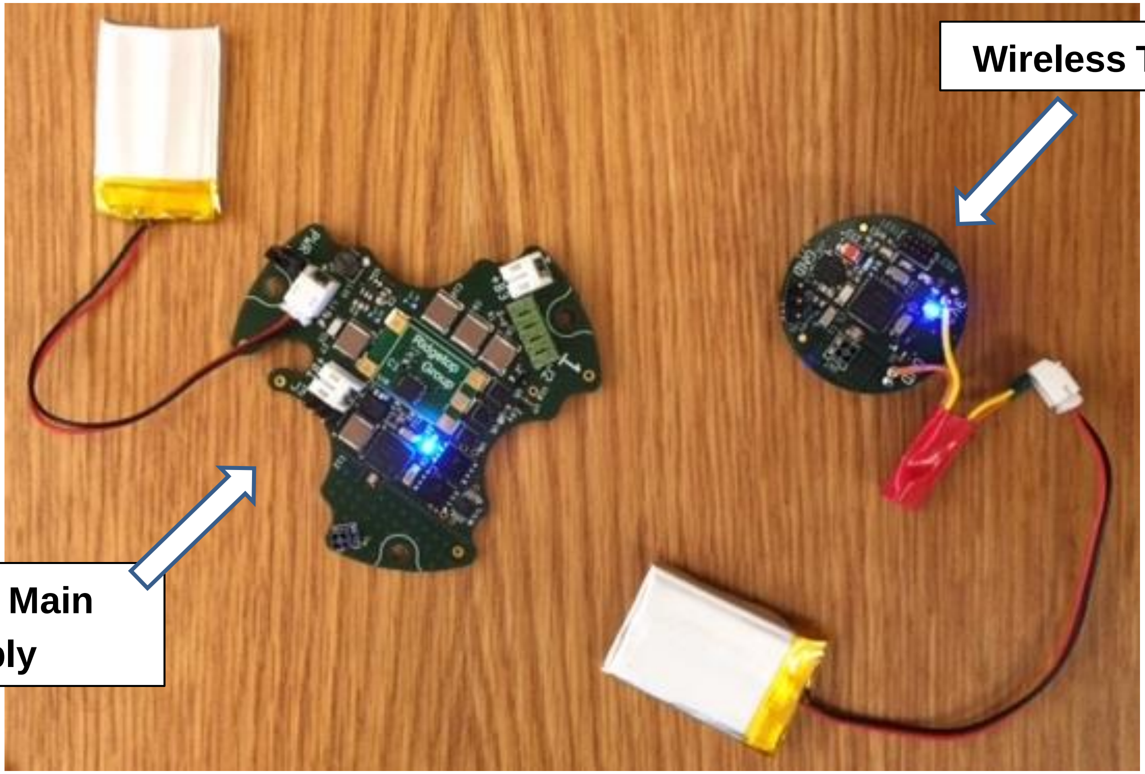
Ethernet

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

RJ45 Ethernet connection using TCP/IP

RotoSense Hardware Components

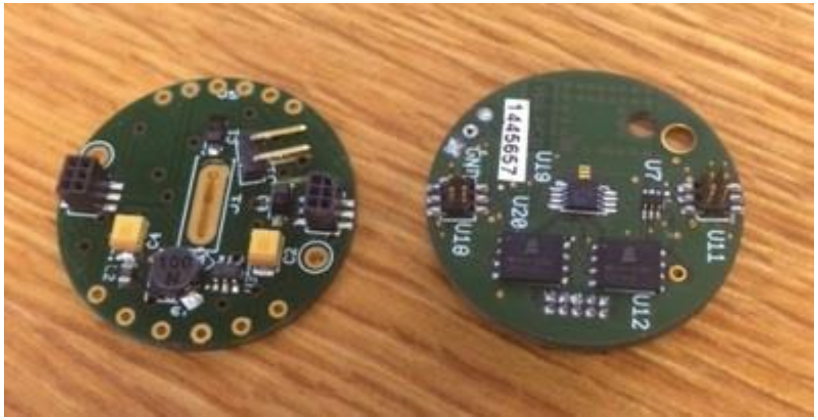
IEEE 802.15.4 low power wireless network standard



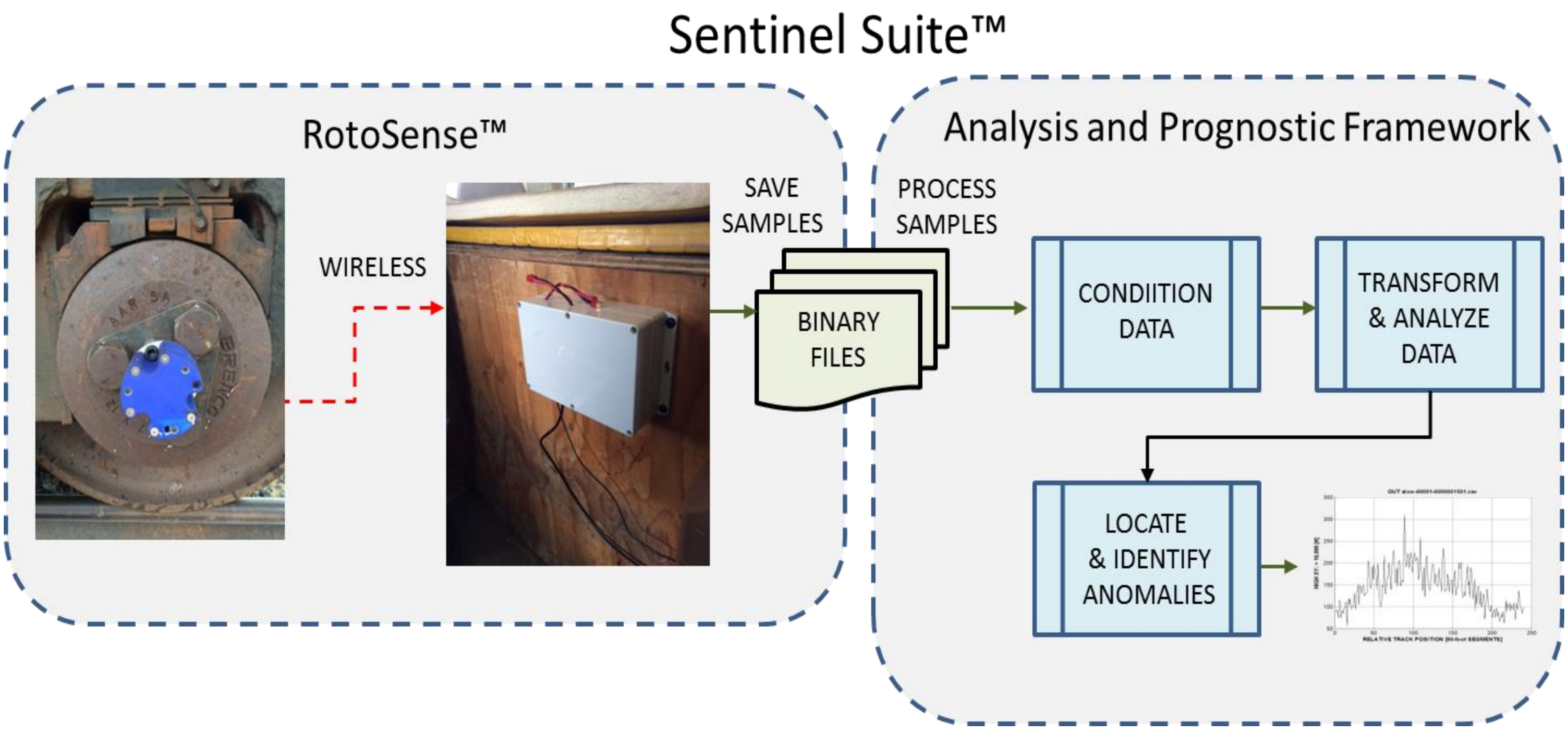
Ridgetop's IoT Sensor Enablement Kit

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

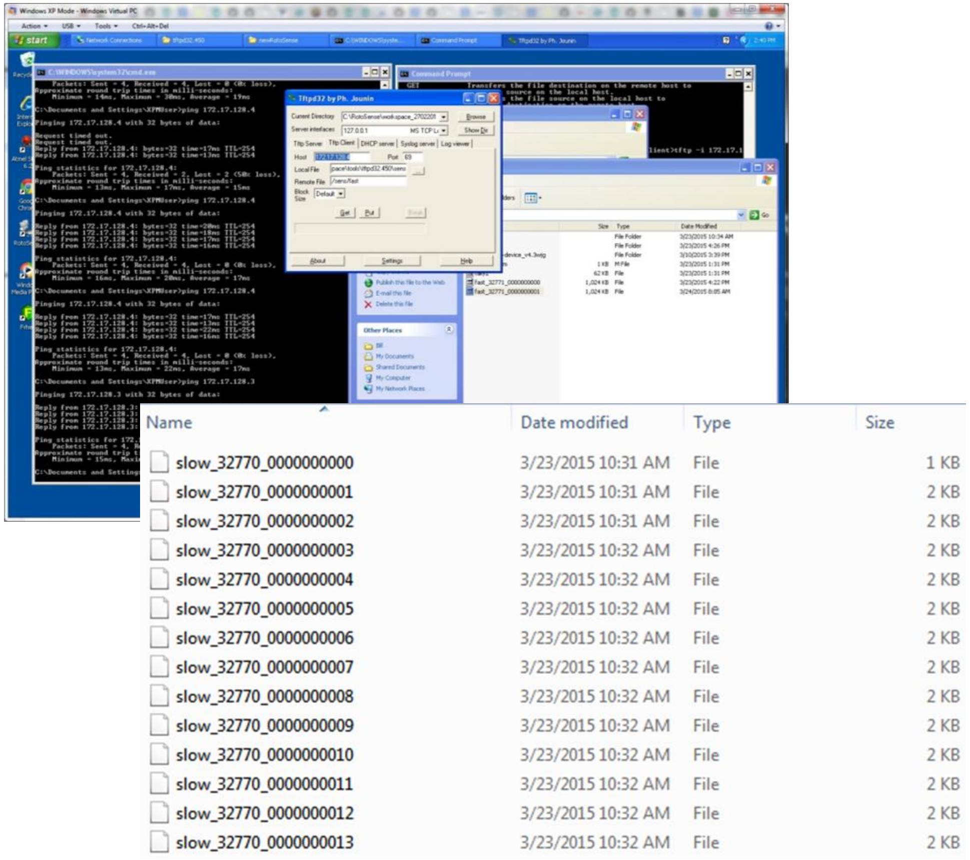
Examples include: light level, temperature measurement, strain/stress/pressure gauges, etc. along with I/O control



Railroad Car Application

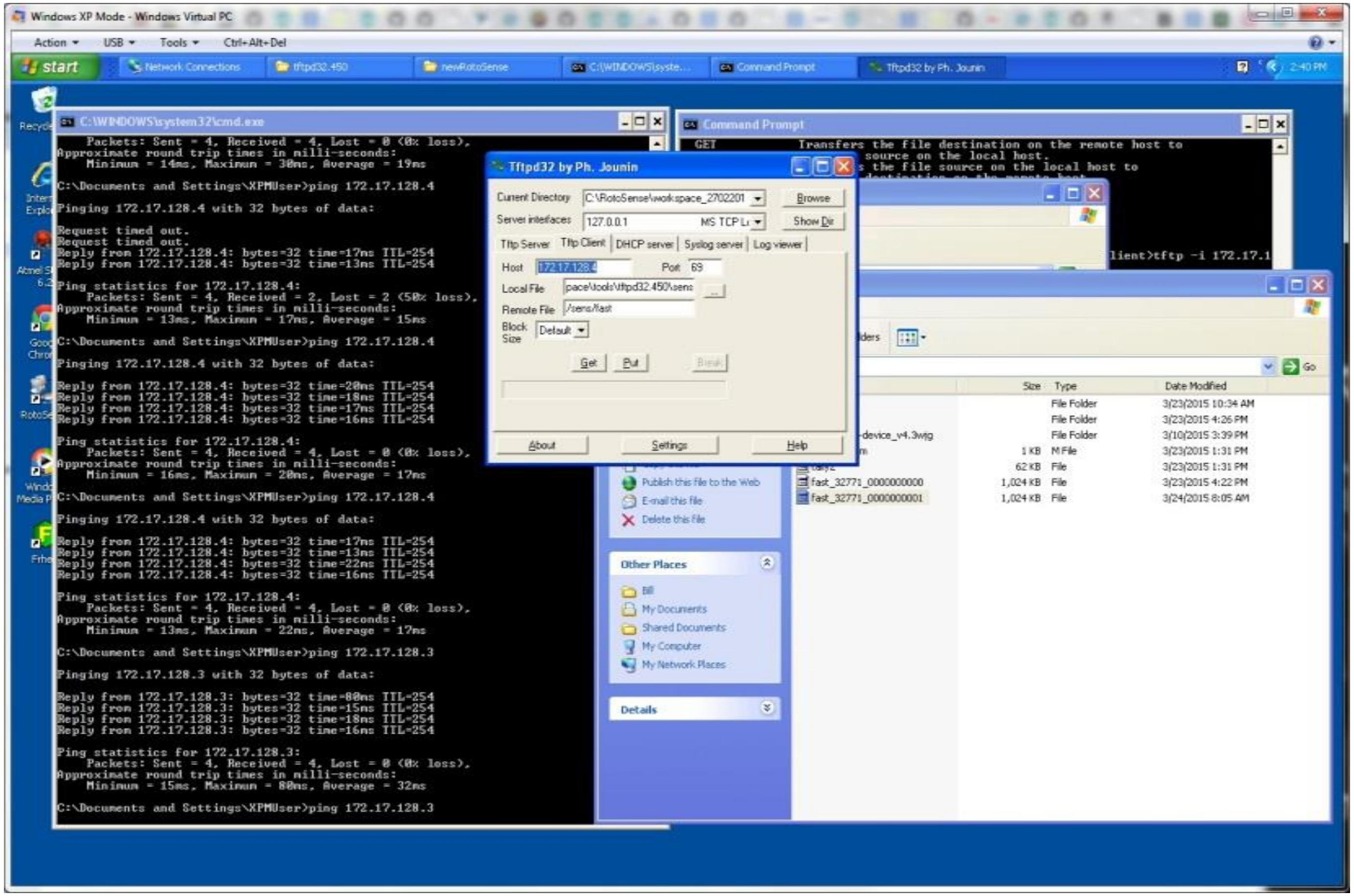


Wireless Real Time Data Transfer

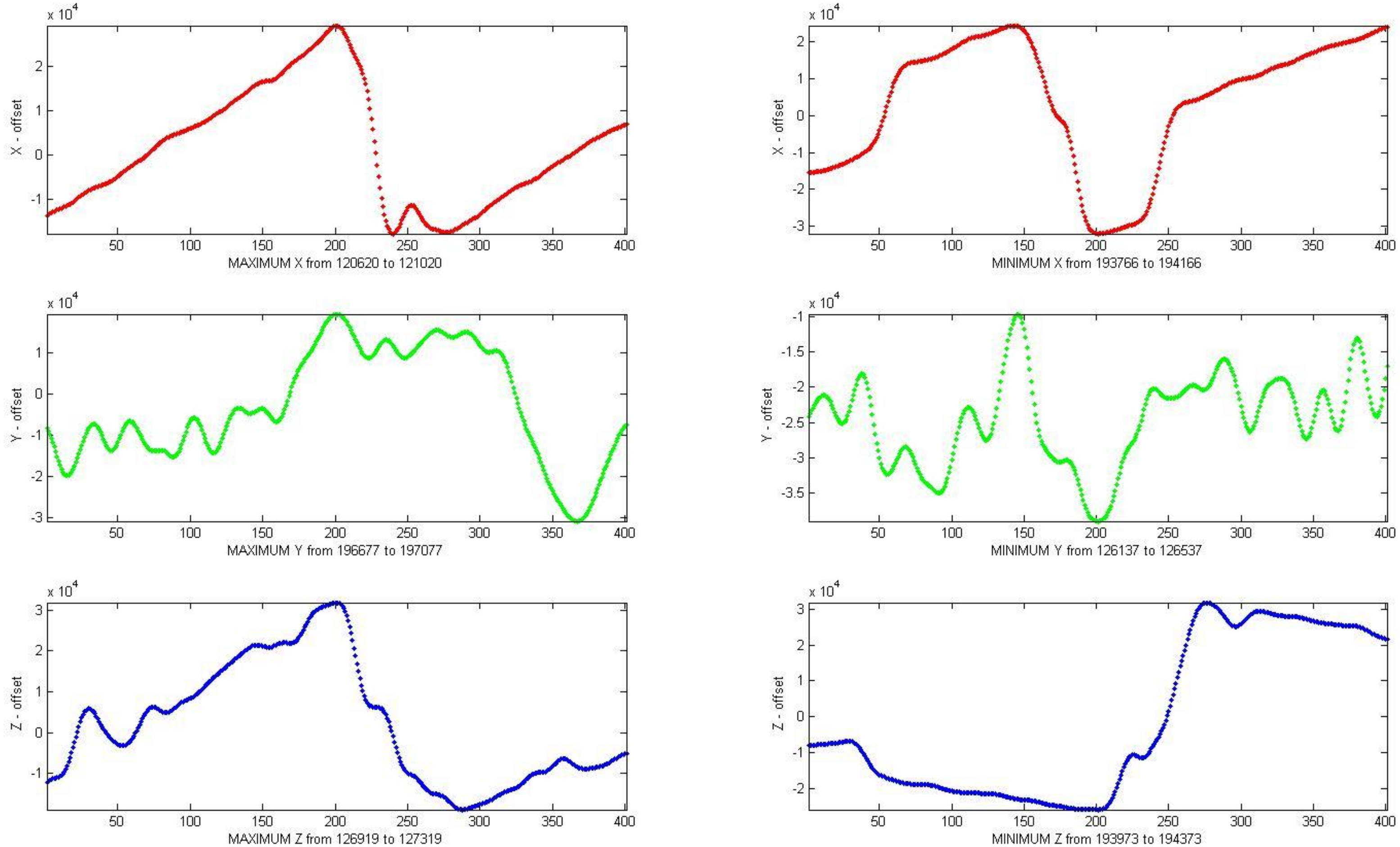


Gateway Data Transfer

Trivial File Transfer Protocol (TFTP) is embedded for reliable multi-node data exchanges with the gateway and sensors



Raw Data Plots



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.

Name	Date modified	Type	Size
slow_32770_0000000000	3/23/2015 10:31 AM	File	1 KB
slow_32770_0000000001	3/23/2015 10:31 AM	File	2 KB
slow_32770_0000000002	3/23/2015 10:31 AM	File	2 KB
slow_32770_0000000003	3/23/2015 10:32 AM	File	2 KB
slow_32770_0000000004	3/23/2015 10:32 AM	File	2 KB
slow_32770_0000000005	3/23/2015 10:32 AM	File	2 KB
slow_32770_0000000006	3/23/2015 10:32 AM	File	2 KB
slow_32770_0000000007	3/23/2015 10:32 AM	File	2 KB
slow_32770_0000000008	3/23/2015 10:32 AM	File	2 KB
slow_32770_0000000009	3/23/2015 10:32 AM	File	2 KB
slow_32770_0000000010	3/23/2015 10:32 AM	File	2 KB
slow_32770_0000000011	3/23/2015 10:32 AM	File	2 KB
slow_32770_0000000012	3/23/2015 10:32 AM	File	2 KB
slow_32770_0000000013	3/23/2015 10:32 AM	File	2 KB

Name	Date modified	Type	Size
fast_32771_0000000000	3/23/2015 4:22 PM	File	1,024 KB
fast_32771_0000000001	3/24/2015 8:05 AM	File	1,024 KB

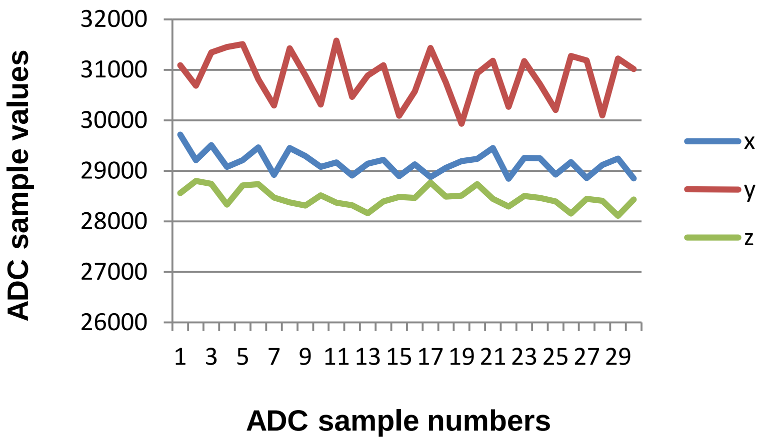
Sensor Data File Format

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

x	y	z
29719	31089	28561
29208	30687	28799
29506	31340	28742
29078	31450	28330
29210	31506	28711
29467	30811	28736
28918	30290	28474
29451	31423	28377
29296	30885	28314
29079	30313	28516
29166	31574	28369



RailSafe™ Integrity Analysis Platform

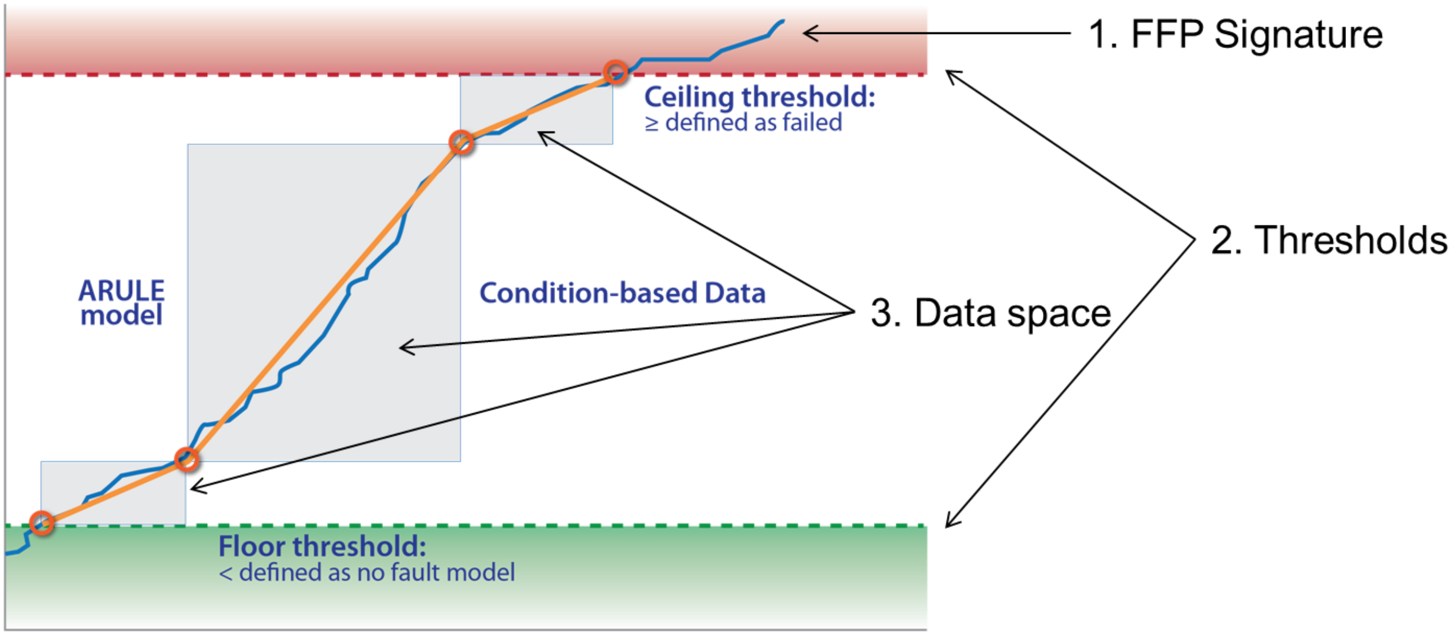
- **Continuous sensor monitoring with analysis using proven PHM algorithms**
- **Provides system-level State of Health (SoH) indication with accurate Remaining Useful Life (RUL) estimates**
- **Results can be integrated with existing CBM systems**

RailSafe™ Complete Solution

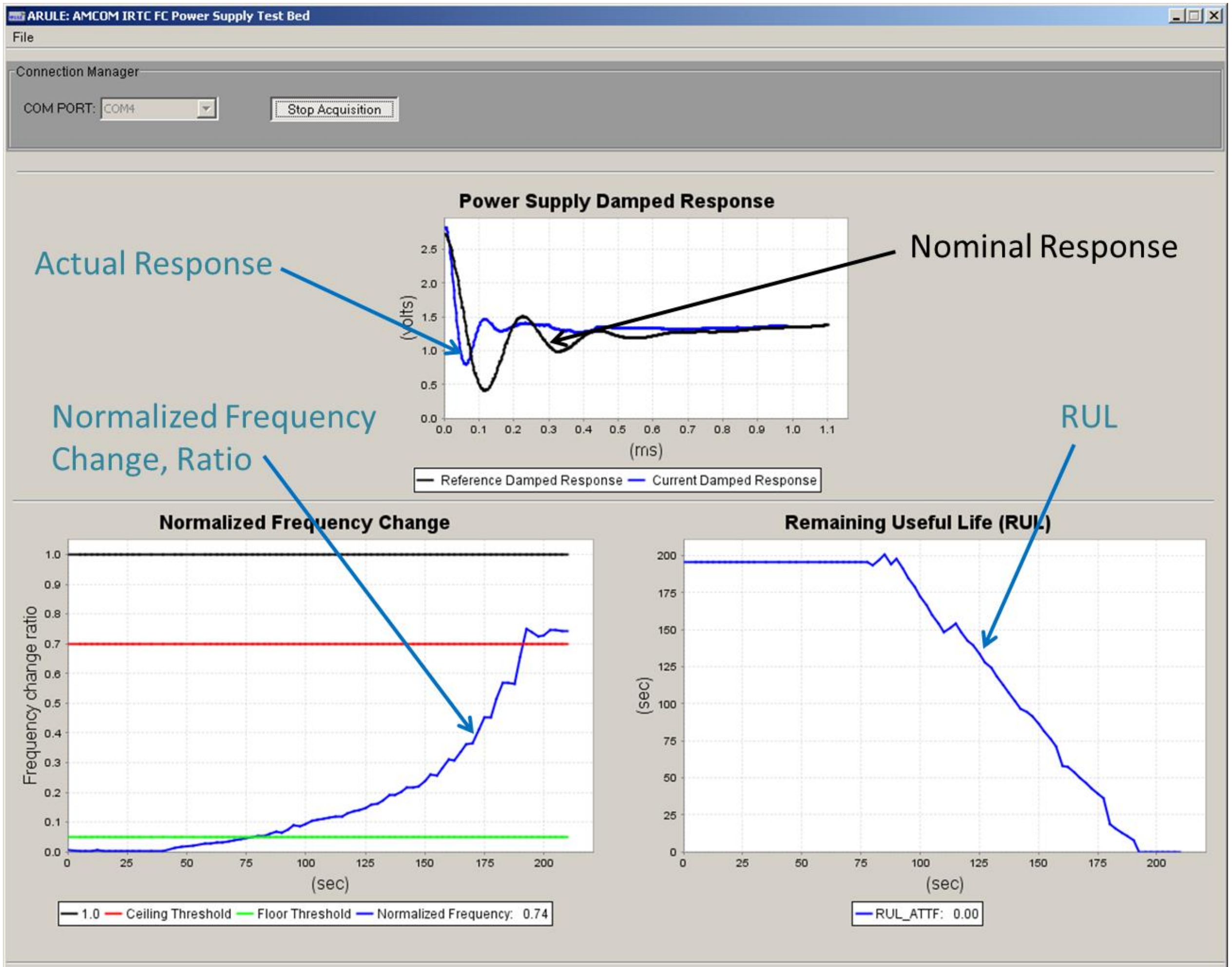
Algorithm Development

Fault to Failure Progression Model

- 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.



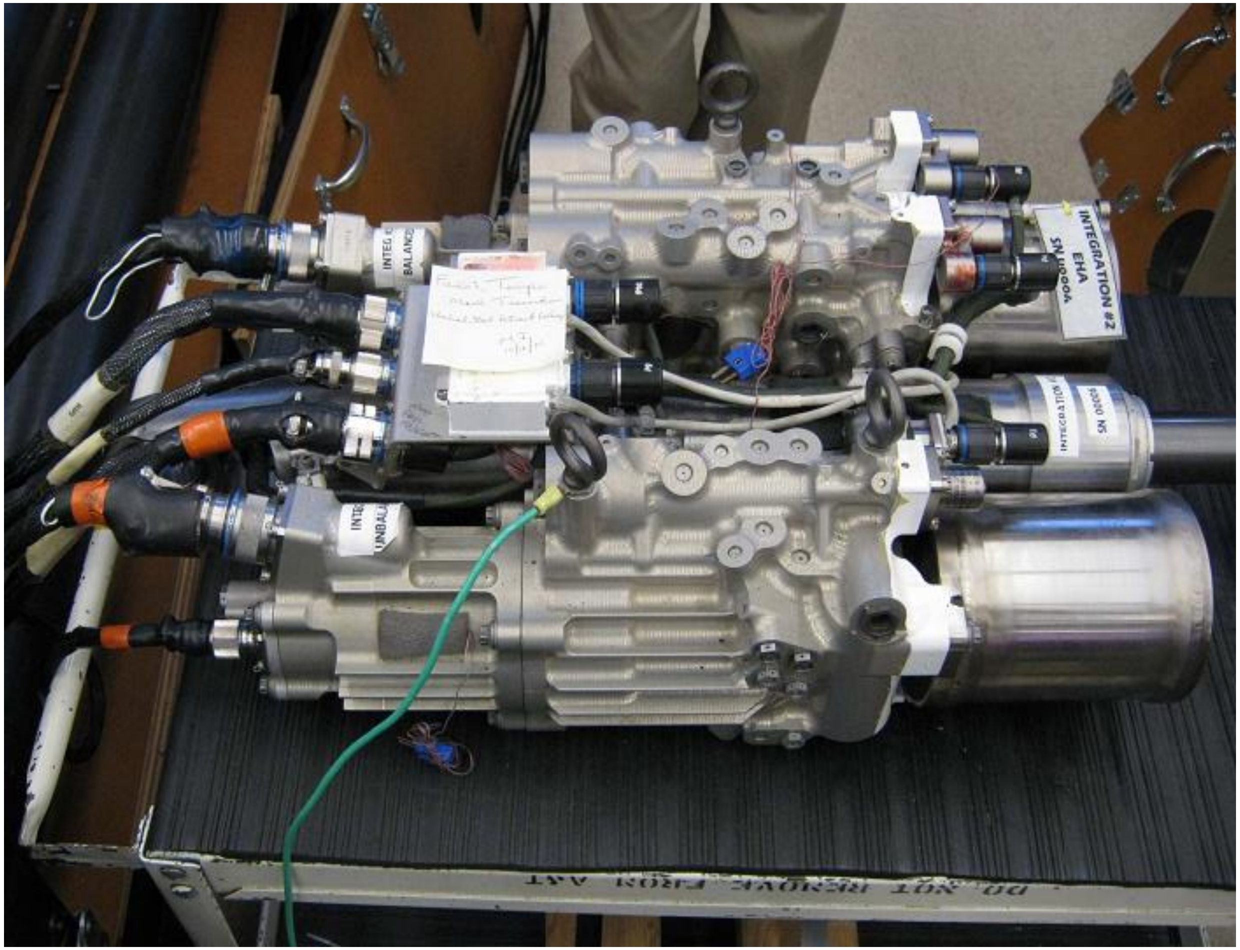
ARULE Algorithm Example



US PATENT 7,619,908; PATENT PENDING

EMA Actuator Prognostics

Actuator Hardware Configuration



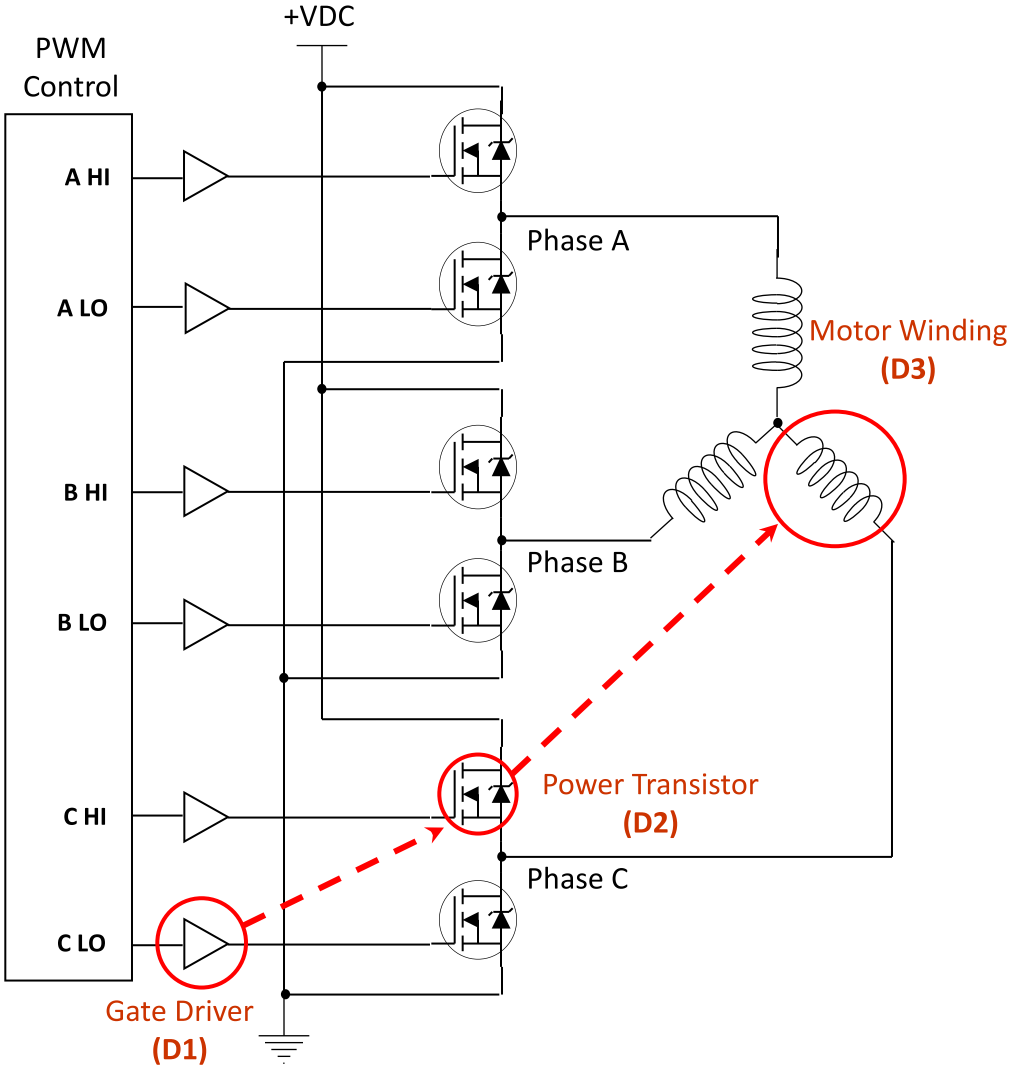
Actuator Power Drive Prognostics

- **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**

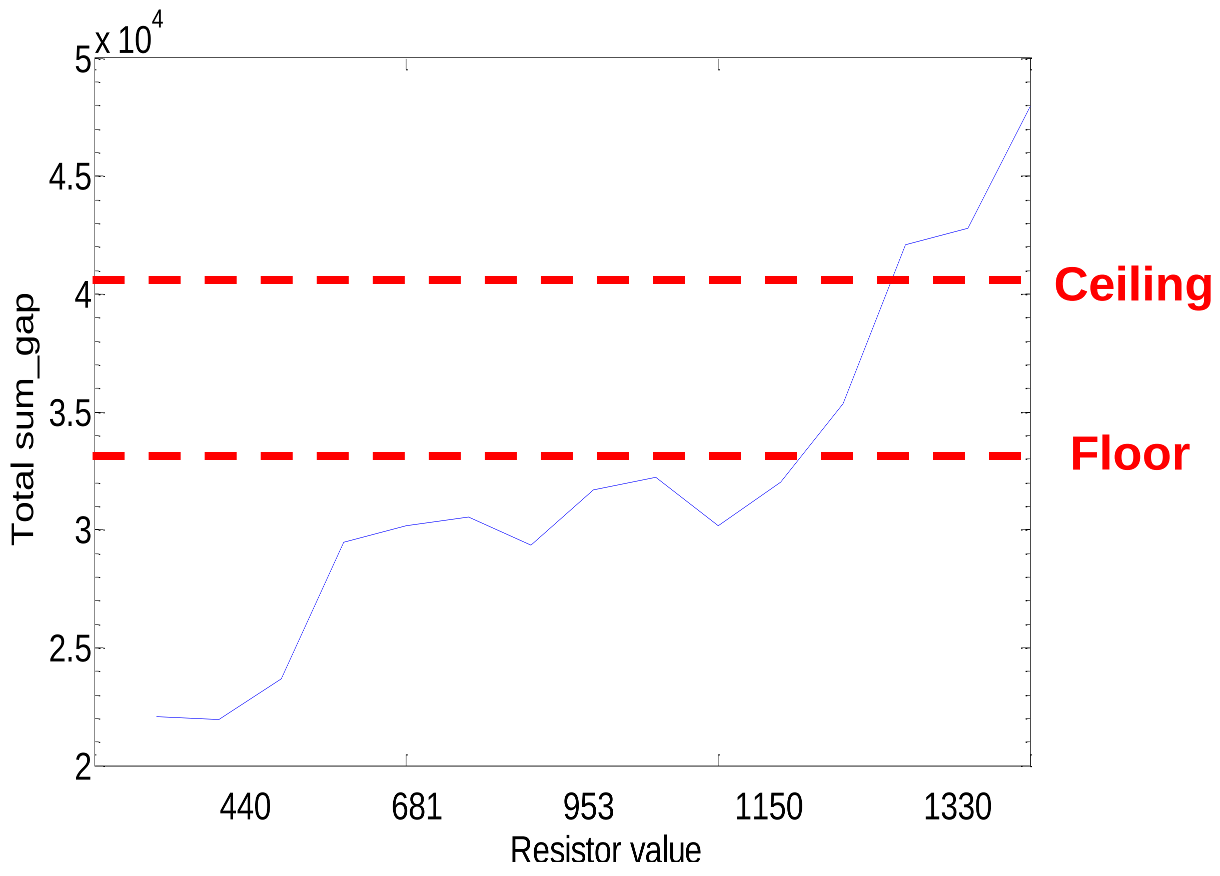
- **Results: Detection of precursor events that mark impending failure of the servo drive subsystem or damage to its individual components**



Analysis

- 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



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

Time	Fault Ref	Location	Description
16:21:02	E213_006	EHA Drive Card	MOSFET Degraded
16:43:02	M166_001	Gear Box A	Broken Tooth
16:45:02	M166_002	Gear Box A	Gear Spalling
17:04:02	H006_001	EHA Hydraulic Valve	Pressure drop

EHA Hydraulic Valve Test

1. Apply test sequence Q_12_DS2
2. Monitor input drive current at test point 13
3. Verify excessive current.
4. Replace part and retest.

Conclusion

- 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!

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