Expanding the Boundaries of Test and Diagnostics :

Prognostics and Health Management (PHM) for Complex Systems

Doug Goodman

May 2015

Ridgetop Group, Inc.

- **Leader in prognostic health management technologies**
- **Published over 80 papers via IEEE, SAE, PHM Society, MFPT and others.**
- **Selected for R&D Partnerships by major government labs such as NASA, DOE, and DoD.**
- **Provider of development and run-time tools for PHM systems.**

Partners and Customers

LOCKHEED MARTIN

AkerSolutions

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BAE SYSTEMS

Prognostics Health Management (PHM)

What is it?

- **Diagnostics – is the process of determining the state of a component to perform its function(s)**

- **Prognostics – is predictive diagnostics which includes determining the remaining life or time span of proper operation of a component**

- **Health Management – is the capability to make appropriate decisions about maintenance actions based on diagnostics/prognostics information, available resources and operational demand.**

PHM turns 'Bad Actors' or 'Intermittents' into scheduled maintenance without affecting the success of the Mission

A. Hess NAVAIR

Evolution of Maintenance Practices

Going from REACTIVE to PROACTIVE

Repair/Replace when Broken → Maintenance as Suggested by Manufacturer → Diagnostic of Components → Condition-based Maintenance (CBM)

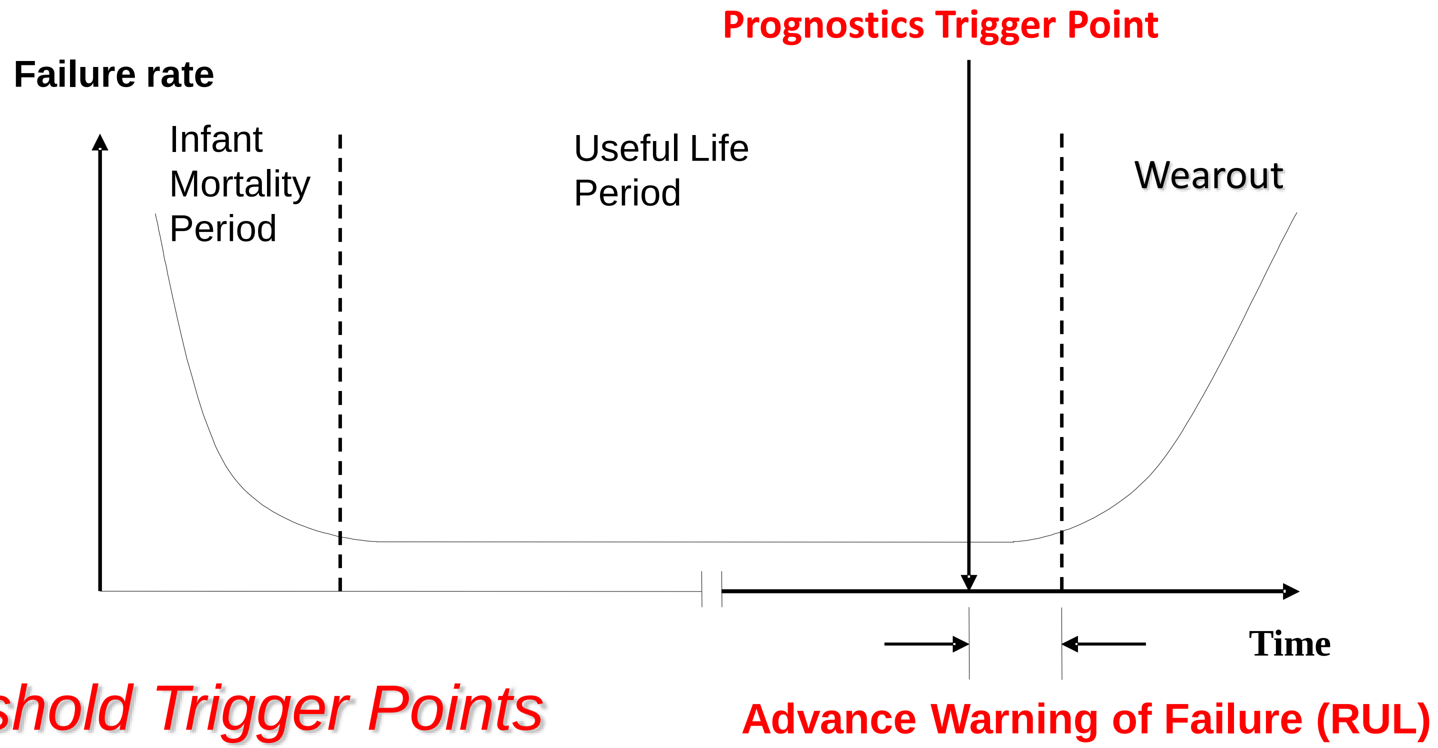
Reactive

Proactive
(Prognostics)

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 reliability methods fall short for critical systems
- Prognostics is key to enabling reliable operations of these systems in the future

Reliability "Bathtub Curve"

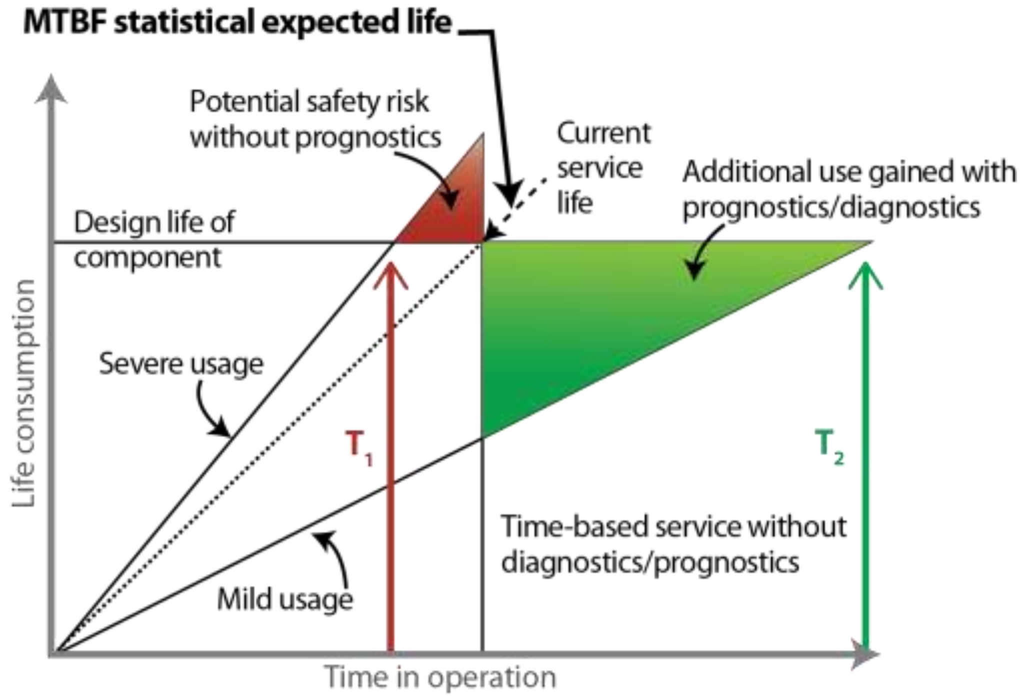


Threshold Trigger Points are selectable

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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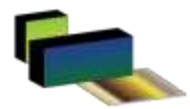
PHM enables replacement only upon evidence of need

System Fault Hierarchy

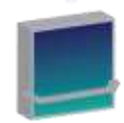
Sensor Solutions for Acquisition of Health Data

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
- 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

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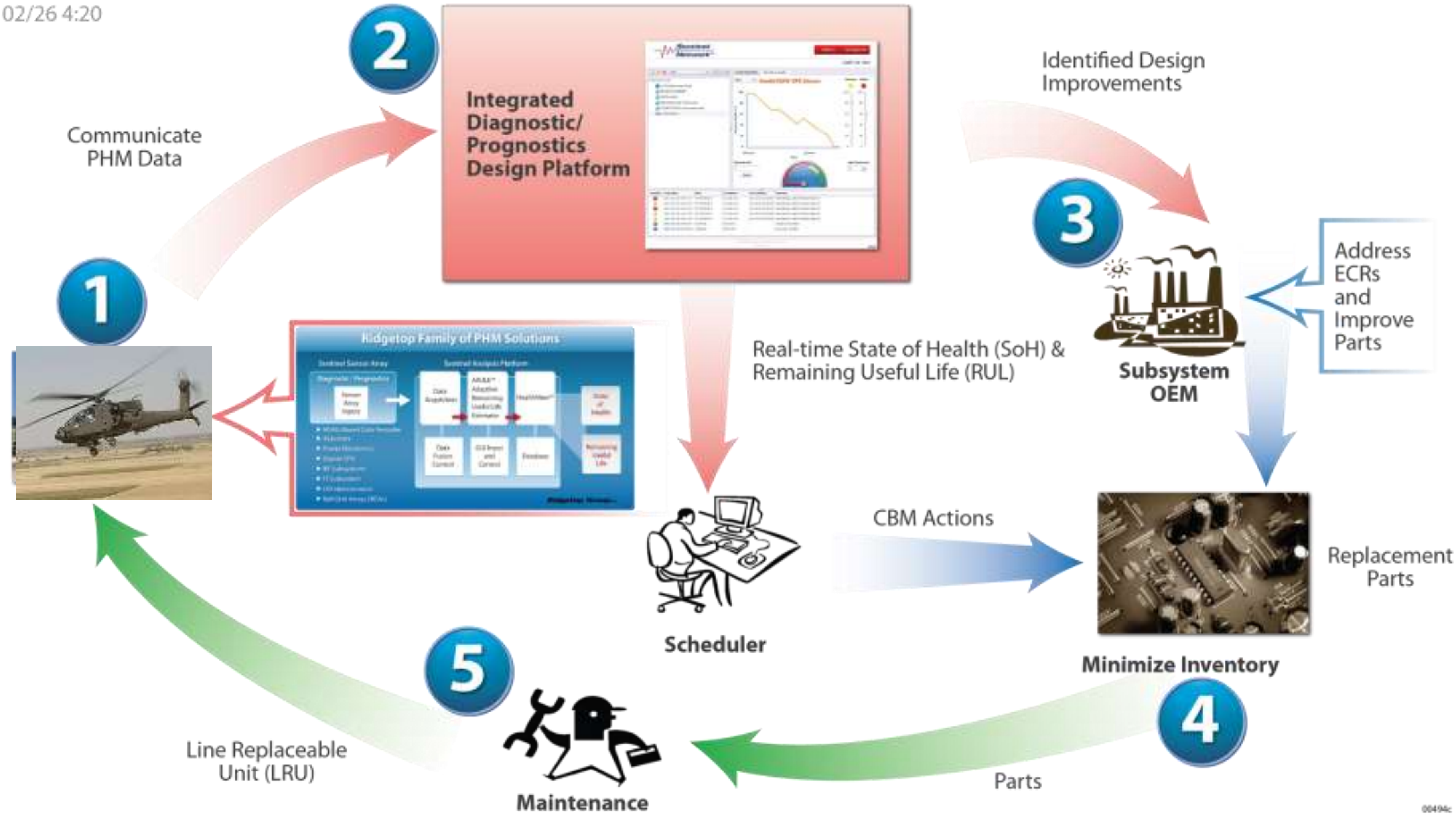
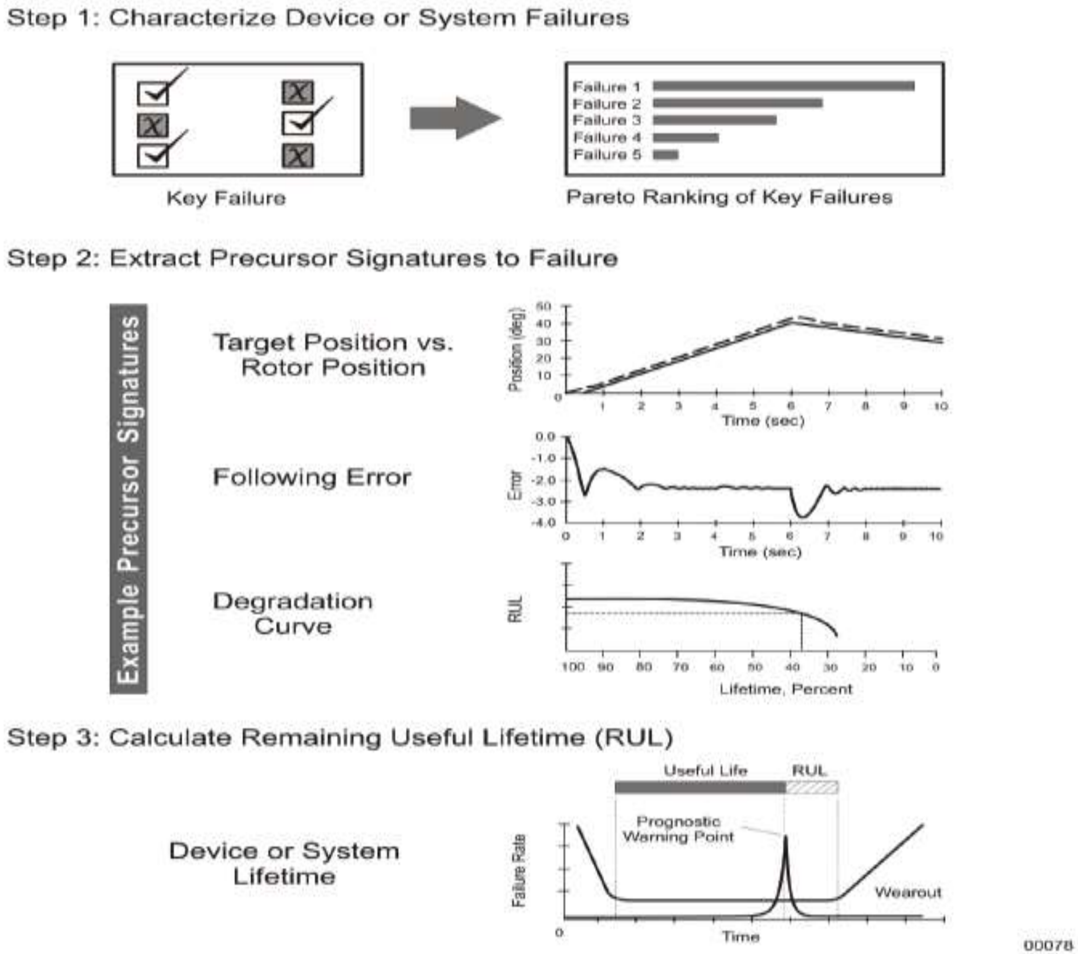
Ecosystem

02/26 4:20



Building a PHM System

Basic Process Steps

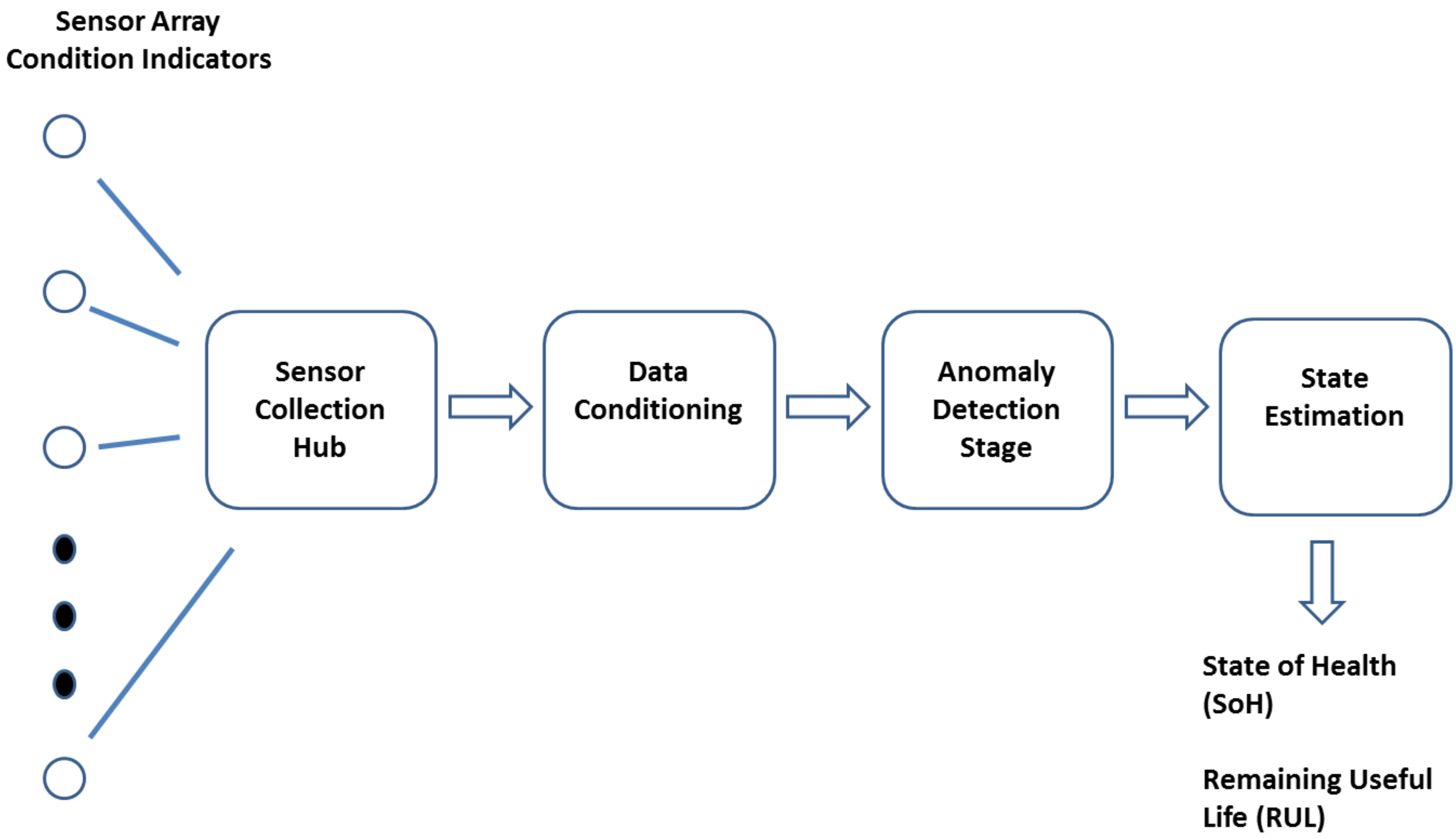


Designing a Prognostic Solution

Process Overview

- Through Pareto Analysis, determine high ranked modules to be monitored.
- Extract signatures for degrading components and modules
- Detect anomalies and appropriate algorithm for prognostic reasoning
- A fault-to-failure progression (FFP) model from the article under test in the system.
- Confirmation and identification of physics-of-failure for detected faults that can propagate into system failures.
- The hardware and software integration involved along with resulting output display and data that can be used to provide dynamic state of health (SoH) and remaining useful life (RUL) estimates.
- Future directions in advanced anomaly detection methods, with fault management methodology are areas of further R&D (self-healing, autonomic operation, …)

PHM Implementation - Prognostics



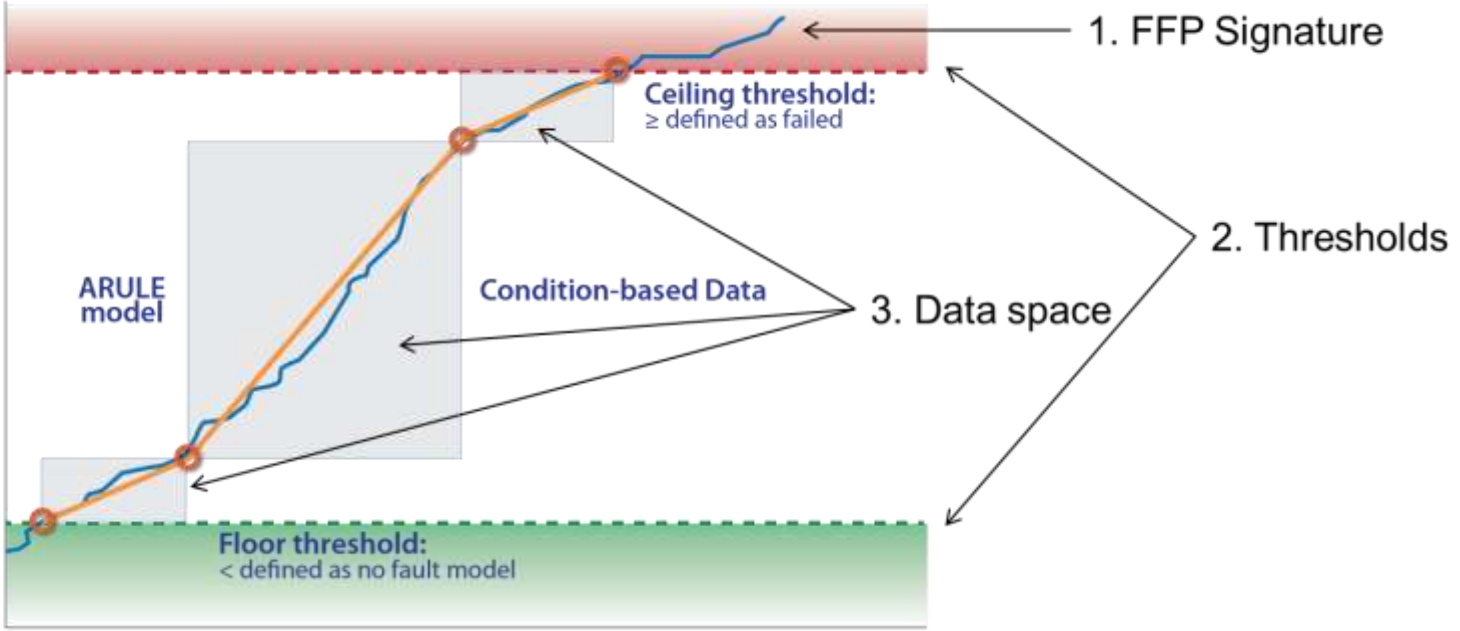
PHM Implementation

- **Advanced Sensing Methods, including wireless IoT (Internet of Things)**
- **Processing Platforms**
- **Anomaly Detection Algorithms**
- **State of Health (SoH) Assessment**
- **Remaining Useful Life (RUL) Projection**
- **Linkages to other tools (Fault Management, Logistics Systems)**

Ridgetop Group Inc 3580 West Ina Road | Tucson AZ | 85741 | 520-742-3300 | ridgetopgroup.com

Adaptive Remaining Useful Life Estimator

- 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.



Advanced Battery and Fuel Cell Systems

Common Battery Problems

- **Battery performance gradually deteriorates due to physical changes in active chemicals**
  - Corrosion consumes some of the active chemicals leading to increased impedance and capacity loss.
- **Chemical loss through evaporation.**
  - Overcharging can cause gaseous products lost to the atmosphere causing capacity loss.
- **Morphology of working chemicals**
  - Crystal formation
  - Dendrite formation
  - Electrode or electrolyte cracks (e.g. Lithium polymer)
- **Temperature variations**

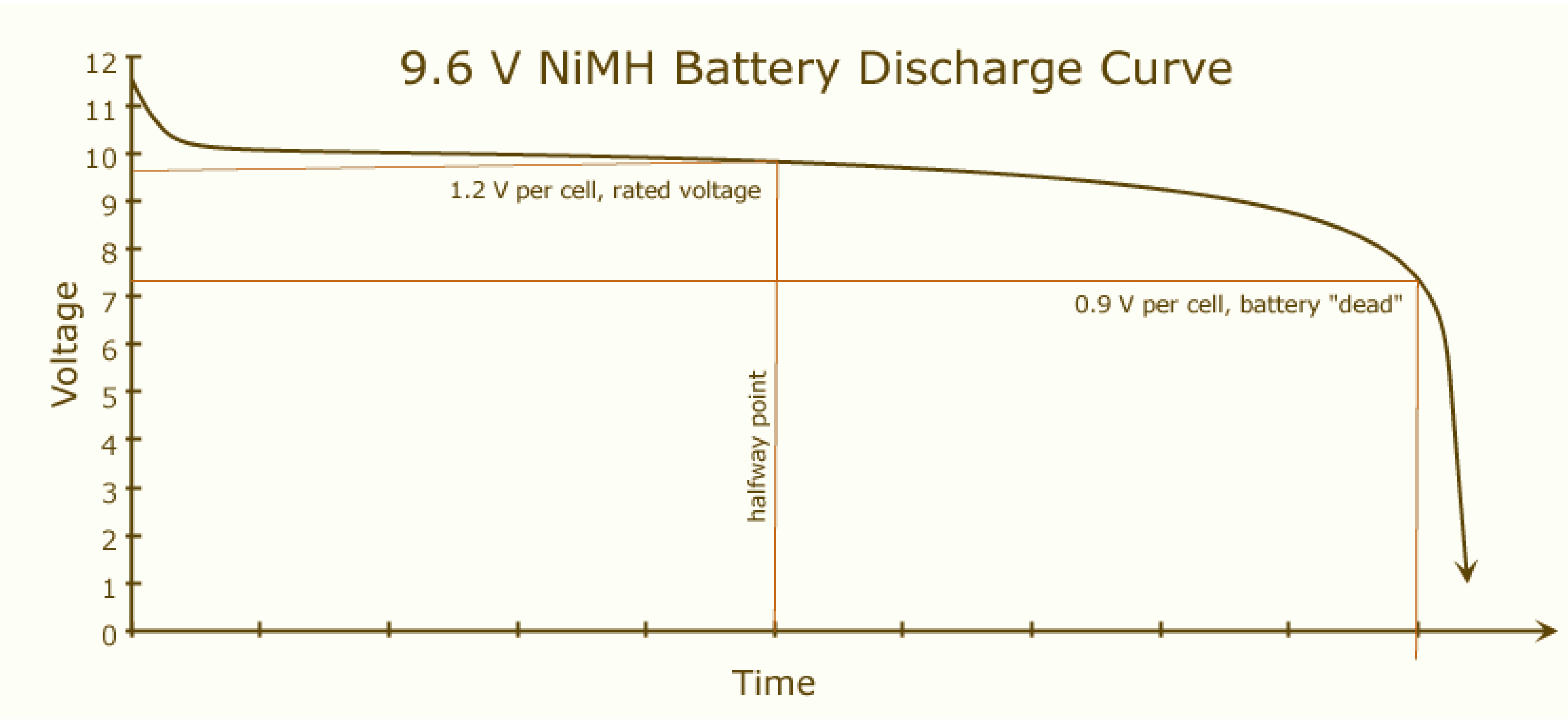
Characterization and correlation mapping is required from the chemical domain to the electrically observable domain.

Battery Chemistries

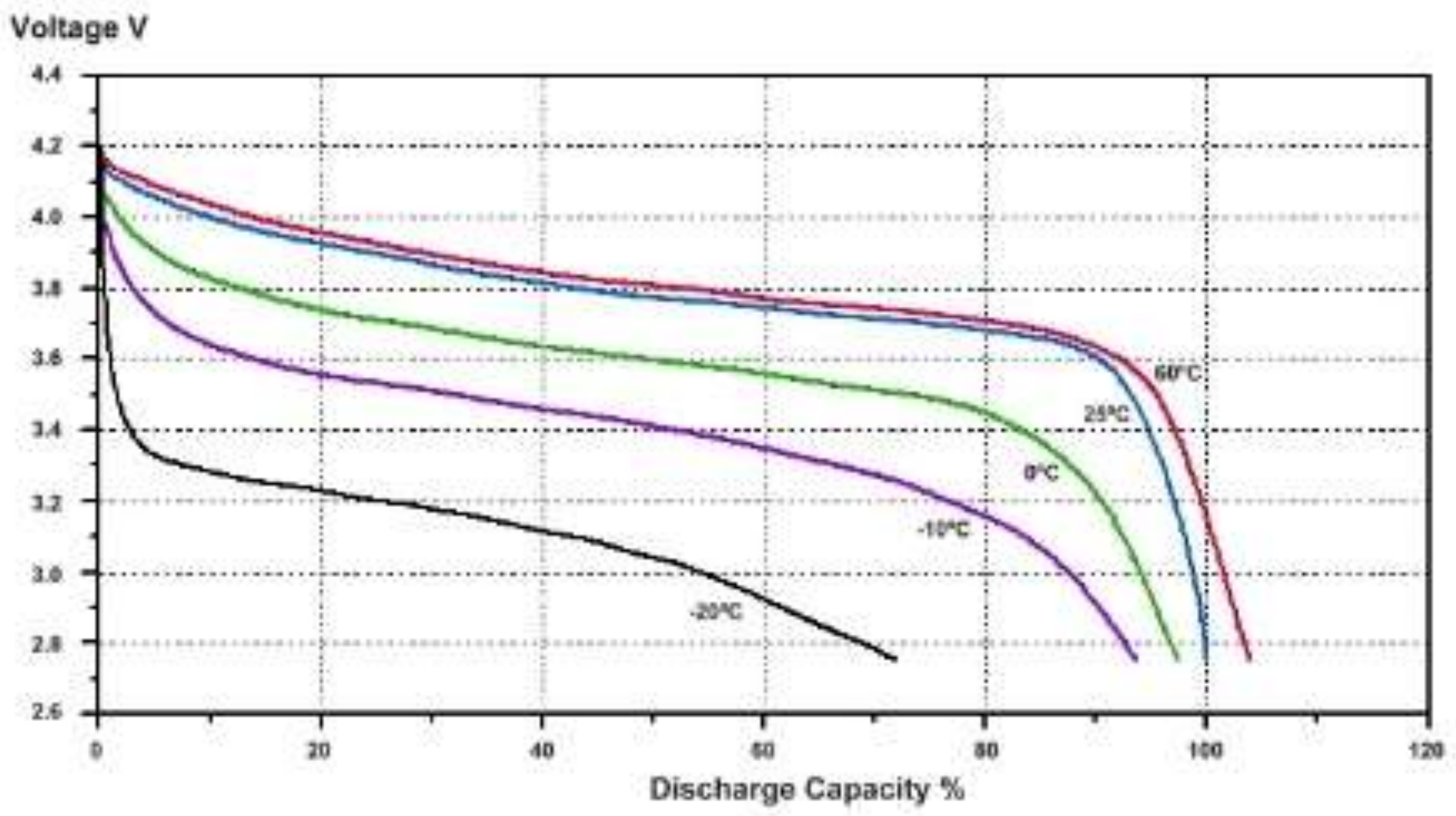
Chemistry	Advantages	Disadvantages
Lithium Ion	Highest energy density Low self-discharge	Protection required Cost 40% higher for cells
Nickle Metal Hydride (NiMH)	No toxic metals	High self-discharge
Nickle Cadmium (NiCd)	Highest number of charge/recharge cycles	High Self Discharge Memory effect
Lead Acid	Well-characterized Larger Power Applications	Weight often a problem Lead is toxic

Specific battery chemistries also have their unique problems

NiMH Discharge Curve



Lithium Ion Discharge Curve



www.ibt-power.com

Battery Technologies

- **From US Navy Sources:**

  "Predicting NiCad cell life expectancy, especially in series-connected multi-cell battery arrays, is a major issue within embedded military applications. Current cost to replace sonar system batteries is upwards of $450,000 each time. Moreover, poor battery reliability has significant intangible impacts to MH-60R fleet readiness "

- **Technical Issue:**

  The weakest cell in the series is vulnerable to reverse bias conditions during deep discharge. Conversely, the strongest cell in the string is vulnerable to over-charging in the charge cycle. This significantly reduces cell lifetimes and reliability.

- **Design solution:**

  Innovative designs that allow individual cells to be monitored for charge and discharge, and optimize each cell so as to maximize battery life and reliability, as well as reduce overall system cost.

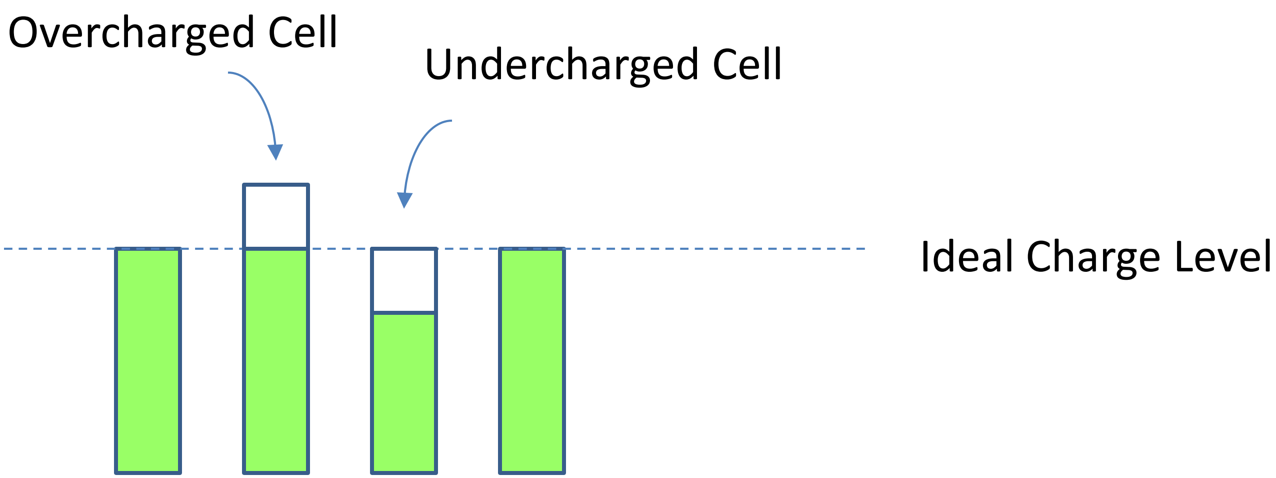
Definitions

- State-of-Charge (SoC)
  - Integrate current flow over time, subtract from known capacity of fully-charged battery
- State-of-Health (SoH)
  - Index of battery-based power source to do its intended purpose
- Remaining Useful Life (RUL)
  - Fault to Failure progression distance from current location, to end of useful life

Cell Diagnostic and Real Time Analysis

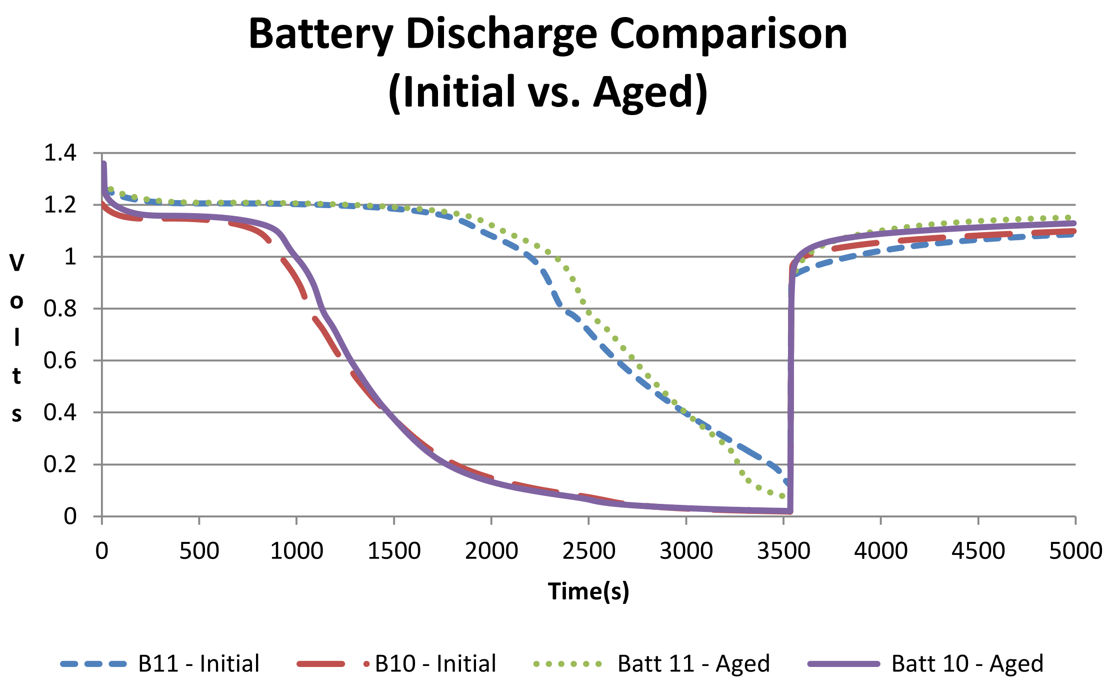
- Key observation parameters which are functions of temperature and cycling
  - Capacity fade
  - Cell conductance fade
  - Power Fade
- Model Based Reasoner (MBR) links operating parameters with nominal performance to provide SoC and SoH
- State estimator provides RUL

Cell Aging Variations in Battery String



Need monitoring of individual cell voltages to adjust for inter-cell parametric differences

Battery Discharge Curves



- Apply this data for accurate State of Charge (SoC), State of Health (SoH), and Remaining Useful Life(RUL) estimates.

Battery Management Systems

- Chemistry-independent solution:
  - Direct cell voltage measurement and control
  - Transformer-based measurement and control

- Provide a well-centered charging protocol
  - Under control of CPU with polling of observation points inside the battery pack

Battery Management Systems (BMS)

- Charge and discharge individual cells
- Read SoC(State of Charge) of individual cells or a stack of cells
- Balance the cells for increased lifetime
- Maintain DC output voltage through SMPS converter

PHM for Battery Power Sources

- Collect cell status data
- Track and store the number of charge and discharge cycles
- Monitor temperature
- Use inferential sensing and model based reasoner (MBR) method for Remaining Useful Life (RUL) determination (K. Gering, INL/DOE)
- Communicate RUL to the system

Main Design Issues of ASIC

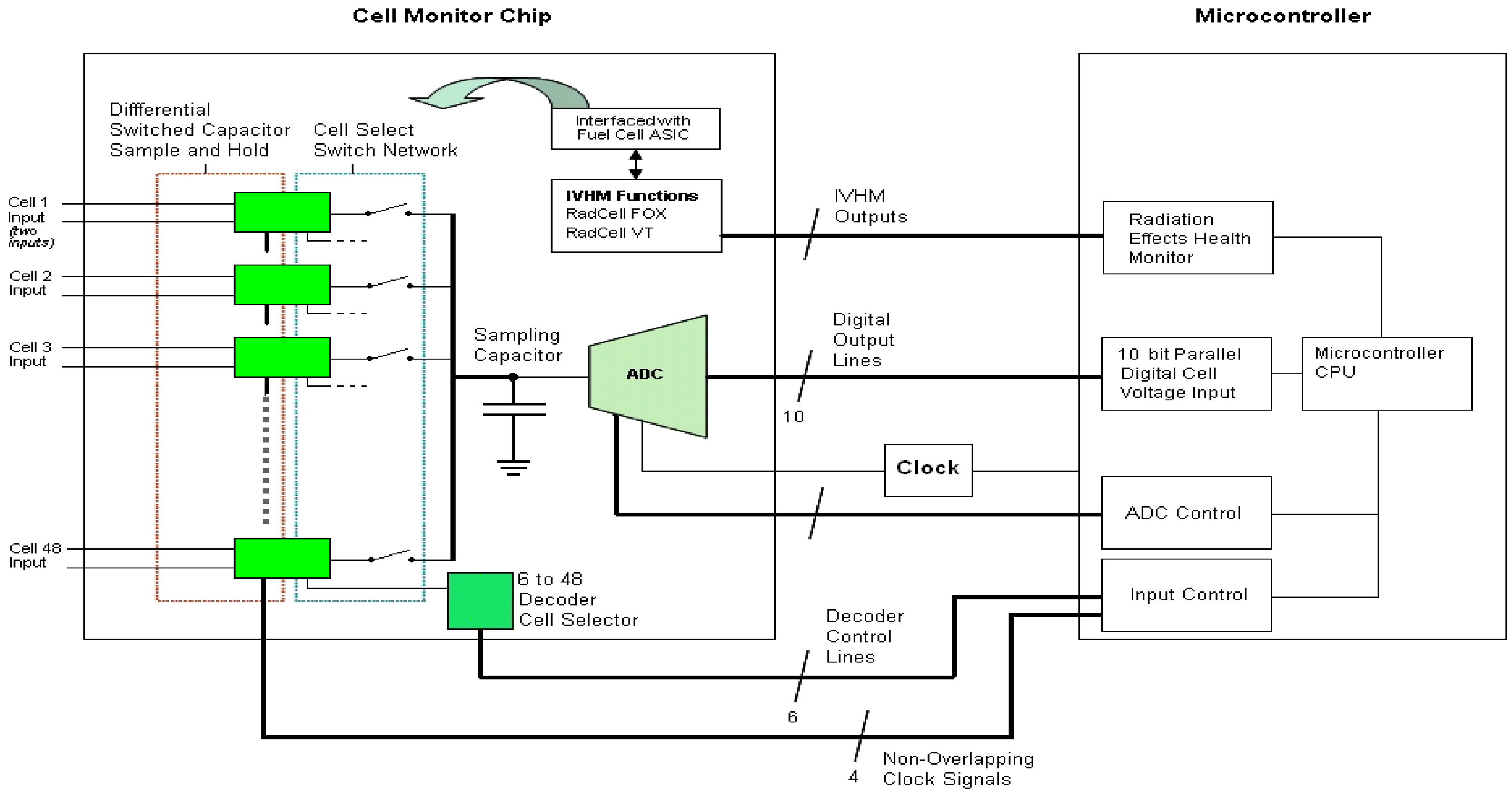
100V Common Mode at the Input Stage:

- CMOS is typically a low voltage process
- 32 volt tolerant, up to 40 volts with extended drain devices
- No isolation between devices
- Higher voltage breaks down the body

Radiation Environment Issues:

- Field oxide is susceptible to ionizing dose
- Causes threshold voltage shift – impacts ADC resolution
- Digital circuits may be upset by single event radiation

Ridgetop Measurement and Control IC

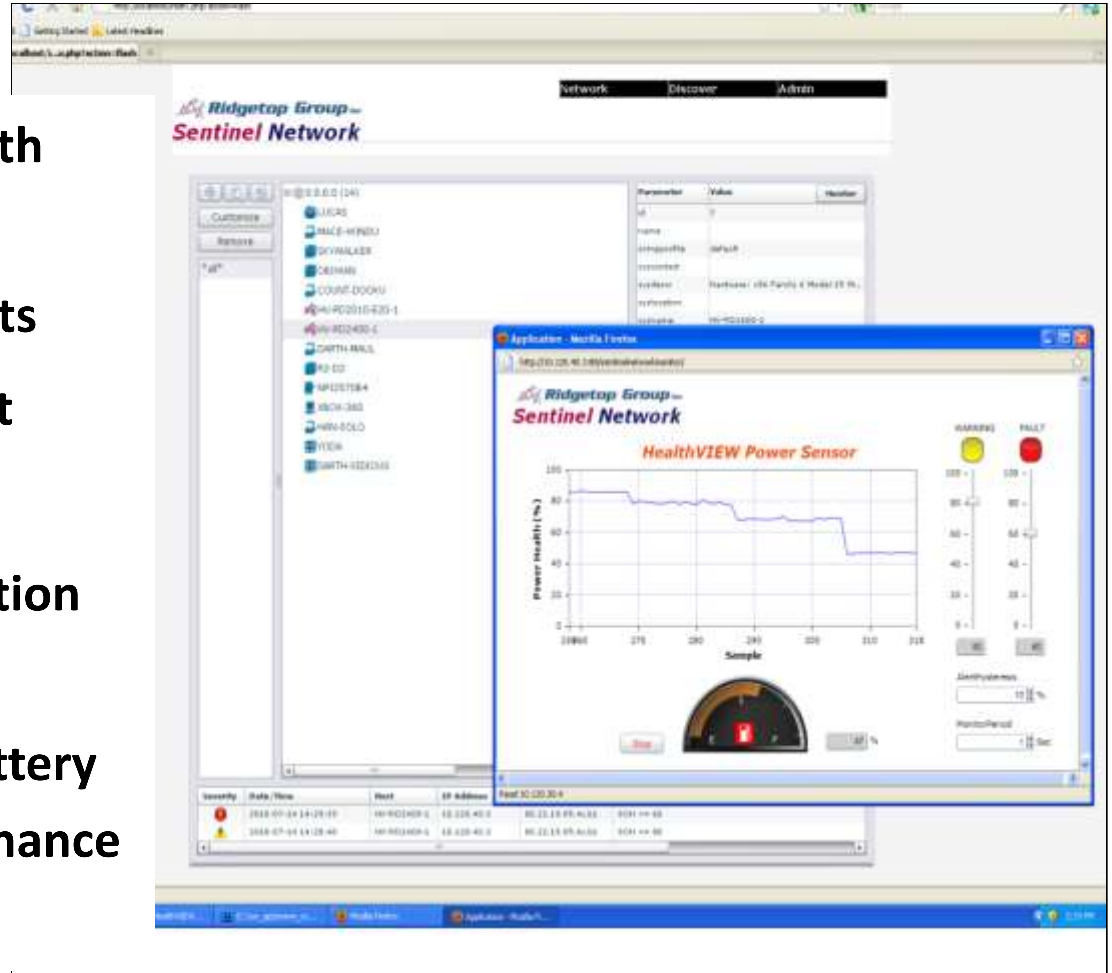


Design

- **A Fuel Cell Stack Monitor Application Specific Integrated Circuit (ASIC) designed to measure individual, 0-2 VDC, cell voltages in up to a 48 cell stack. The analog cell voltages are sampled and converted to digital words with 9 bit resolution. Features include:**
  - **Single chip replaces 48 discrete cell measurement circuits**
  - **Rejection of common mode voltage up to 100VDC**
  - **Integrated Prognostic cells measure cumulative radiation effects and provide early warning of impending failure**
  - **Supports Health Monitoring applications and more precise, closed loop designs of battery management systems (BMS)**

Results Prognostics and PHM

- **Scalable, system level Health Analysis & Prognostics**
- **Network Discovery of Assets**
- **Configuration management**
- **Troubleshooter**
- **System stability cost reduction for tactical networks**
- **On-going monitoring of battery conditions to drive maintenance intervals**



Mechanical Prognostics

Helicopters suspended as gearbox fault blamed for Super Puma ditching

STV 13 May 2012 12:02 BST

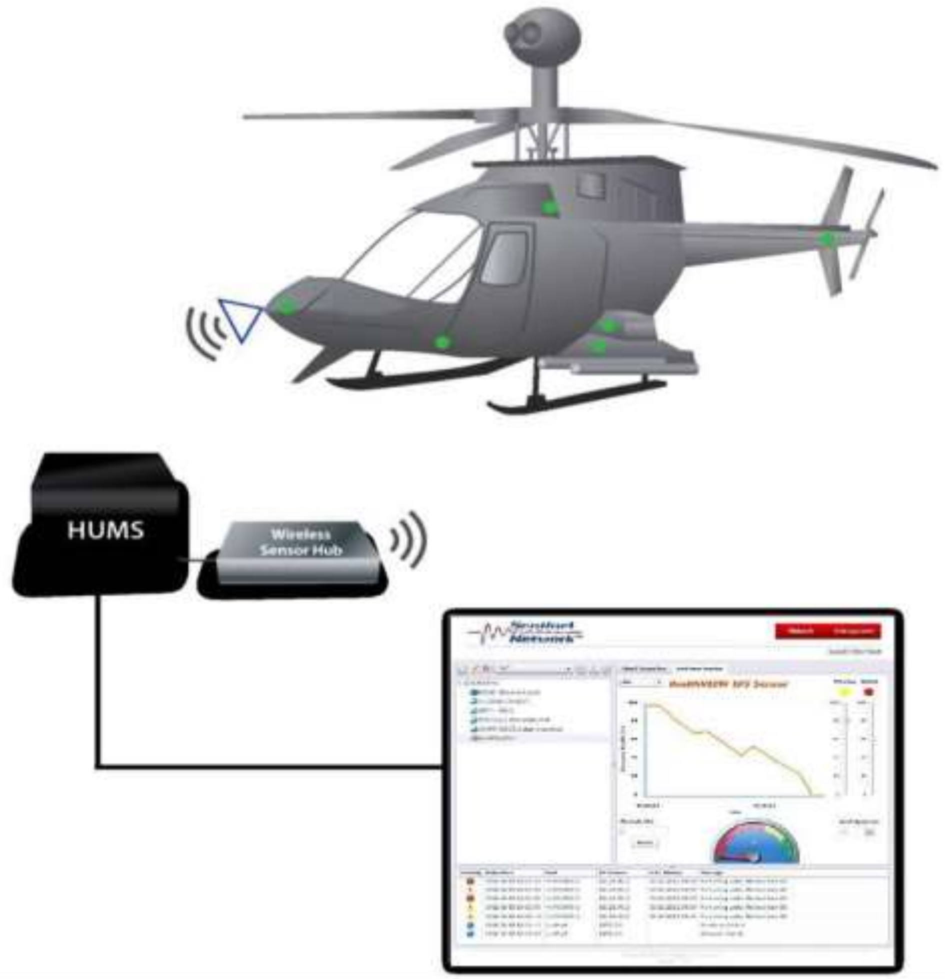
The owners of a helicopter which ditched in the North Sea last week grounded more aircraft today after an early investigation revealed a fault in its gearbox.

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/

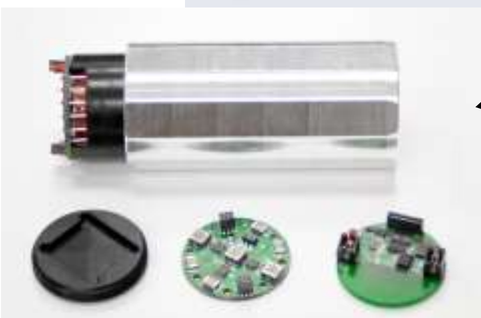
Rotorcraft Wireless Implementation

- Wireless Sensor nodes are placed in the gear box to collect both rotation and vibration data
- Onboard Health and Usage Management System (HUMS) integrates the SoH and RUL for immediate notification
- All data can be downloaded for CBM interactions with ground station equipment

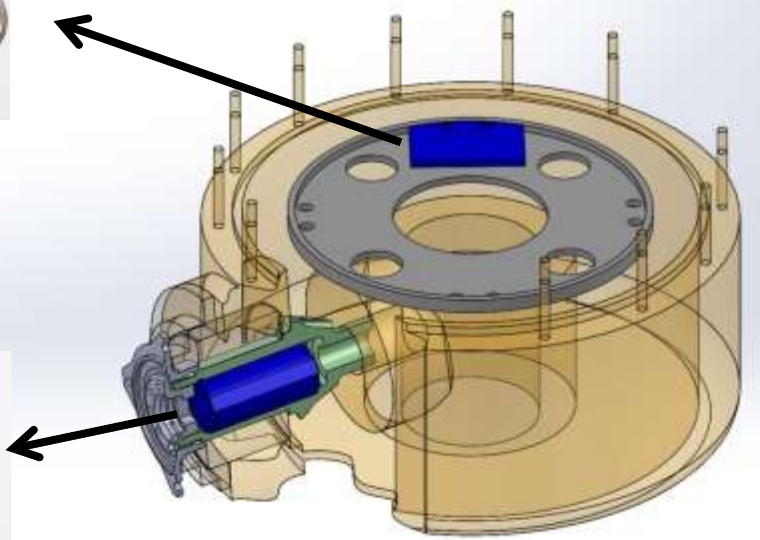


Helicopter Gear Box Health Monitoring

Sun gear wireless sensor



Pinion gear wireless sensor



OH-58 Gearbox

NASA Spinoff – RotoSense™

Office of the Chief Technologist
Value for NASA, Benefits for the Nation
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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.

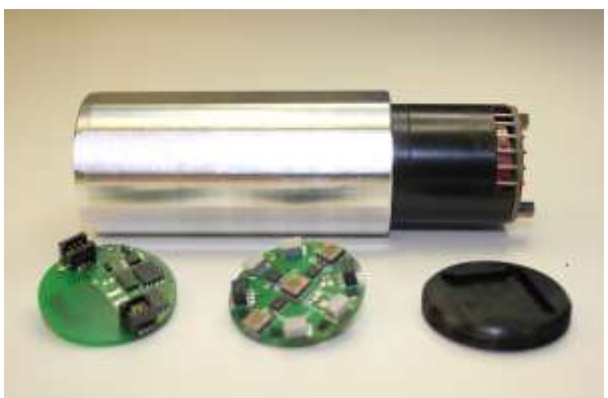
For example, one persistent issue in helicopter maintenance and operation is that their components are subject to high amounts of wear compared to fixed-wing aircraft. In particular, the rotor drive system that makes flight possible undergoes heavy vibration during routine performance, slowly degrading 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.

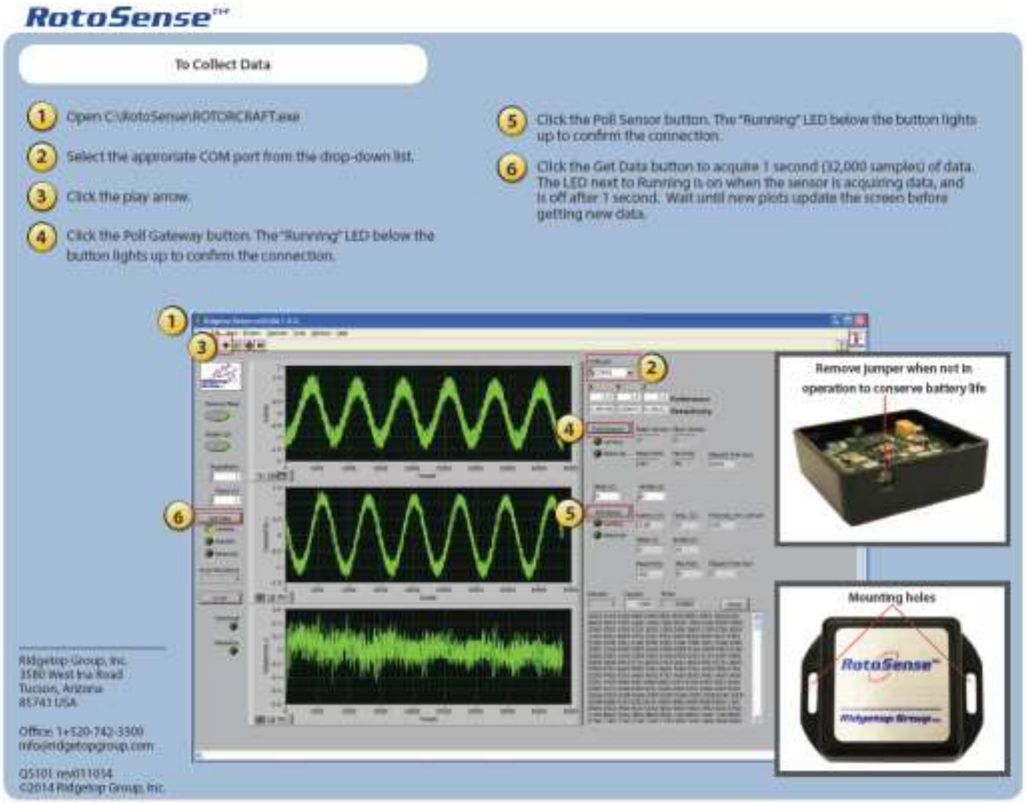
Ridgetop's wireless MEMS accelerometer can gather quality data from spots inaccessible to the sensors typically employed today.

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.

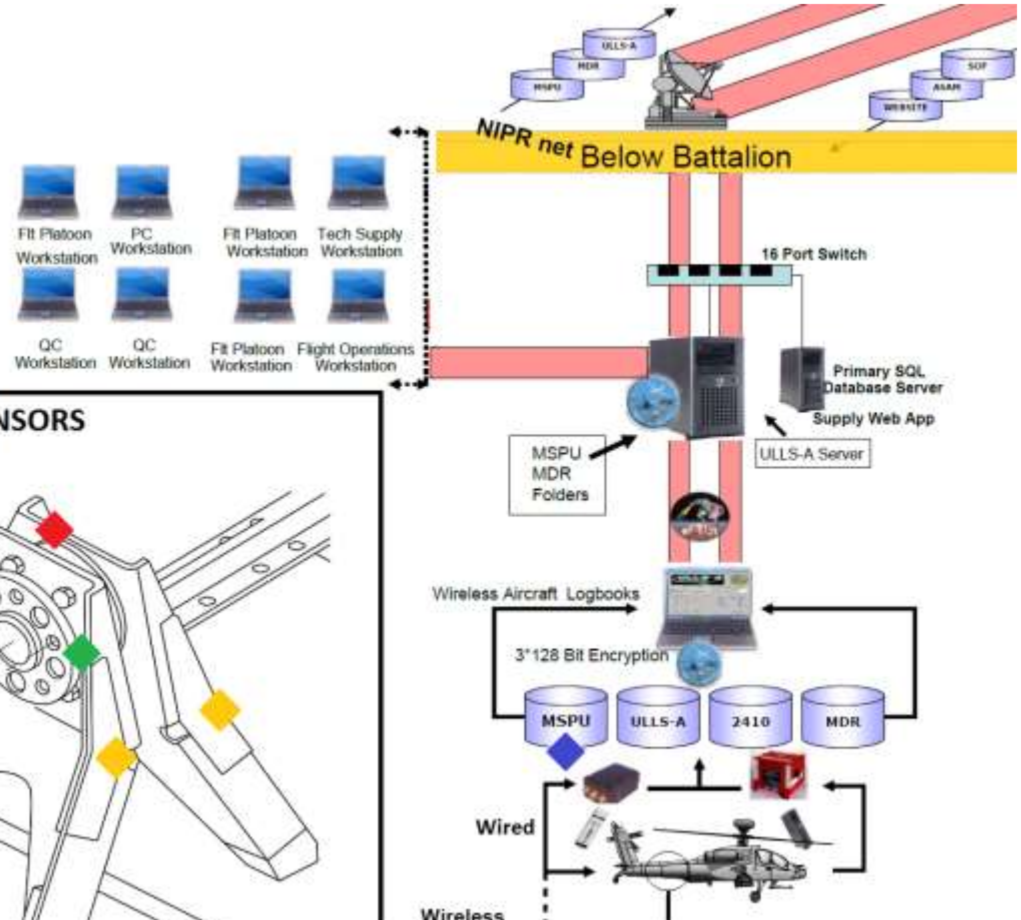
Full article here: http://spinoff.nasa.gov/Spinoff2012/t_6.html

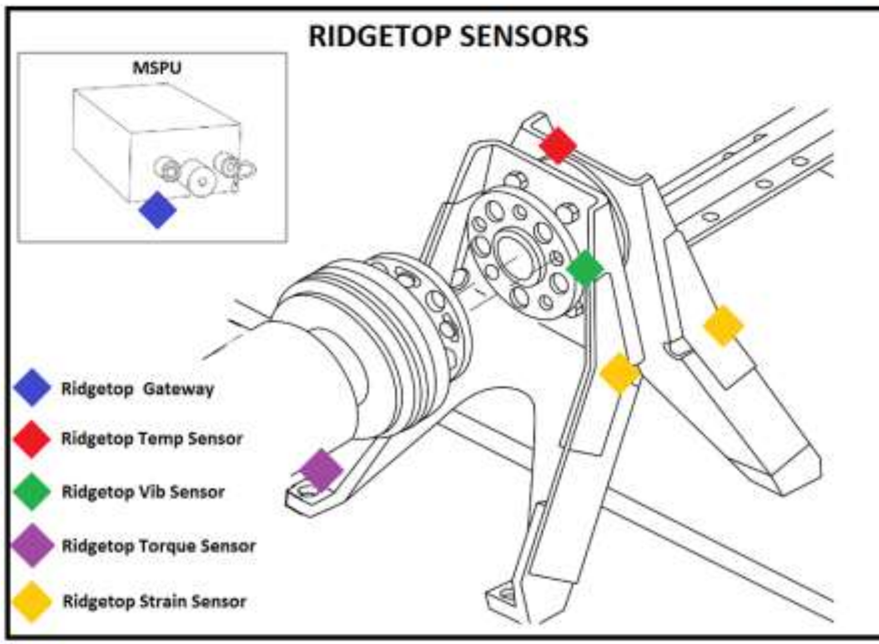
RotoSense Development kit





Additional Sensors





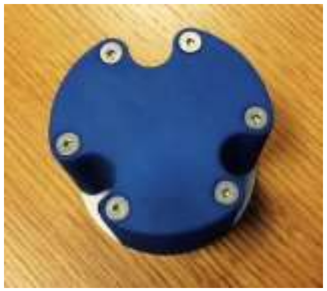
PHM Complete Solution

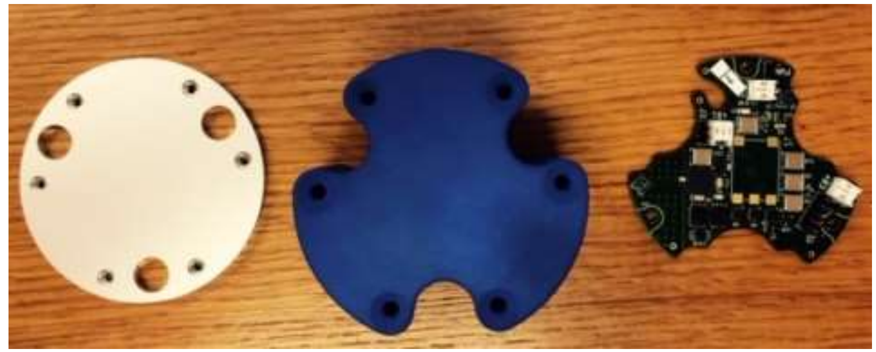
- Continuous sensor monitoring with analysis using proven algorithms
- Provides system-level state of health (SoH) indication with accurate remaining useful life (RUL) estimates
- Results can be integrated with existing CBM systems

Example Application – Train Systems

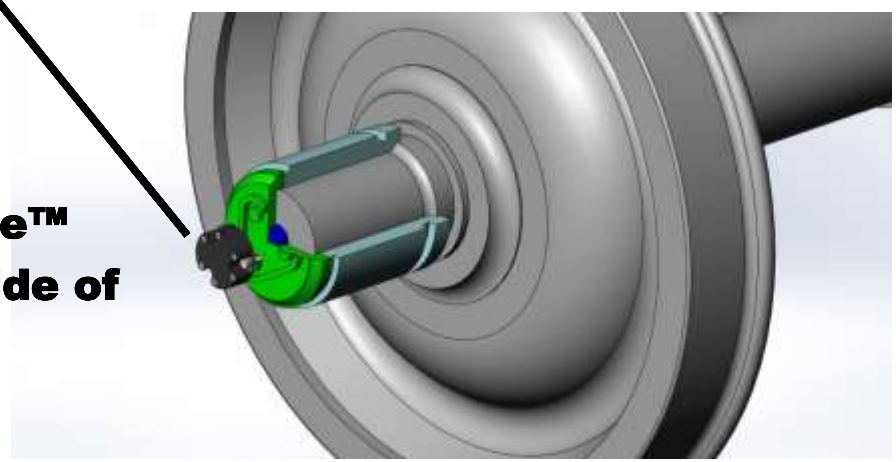
- Decaying Railroad Infrastructure; track, rolling stock, bridges
- Transportation of Dangerous materials such as flammable liquids and gases
- Passenger traffic safety is critical

RotoSense™ Railway Safety Analysis

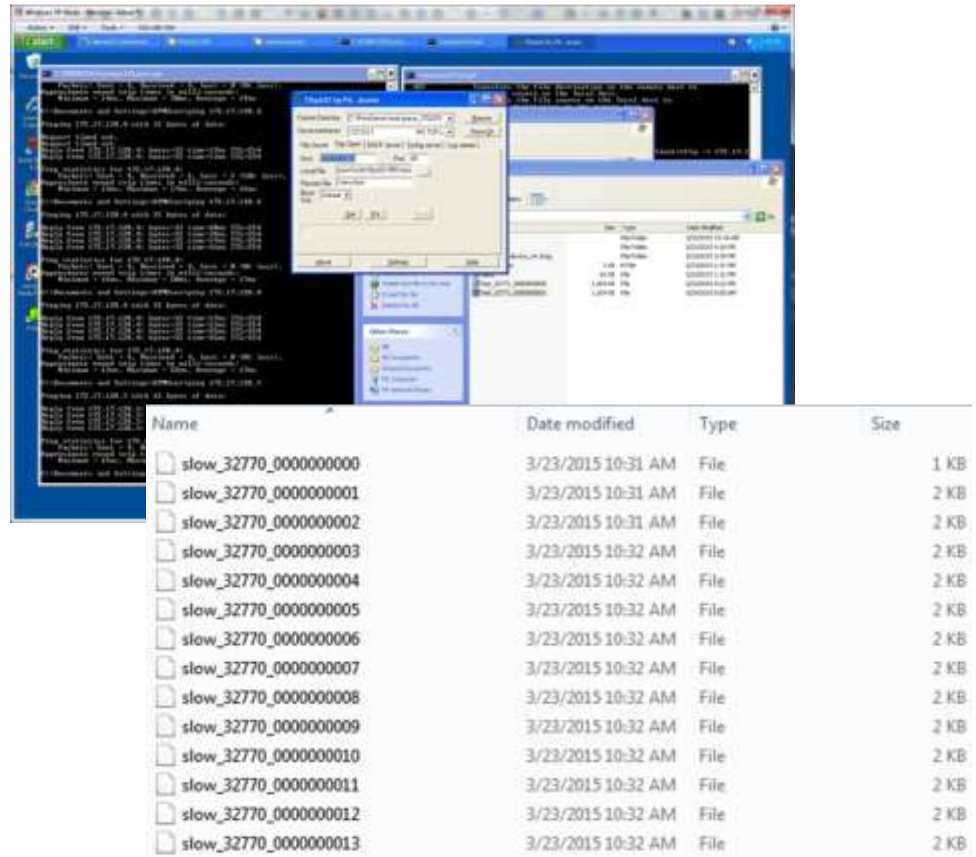




Two wireless RotoSense™ sensors, one on each side of the axle end caps.



Wireless Real Time Data Transfer



Testing Conducted at Railroad Test Facilities

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

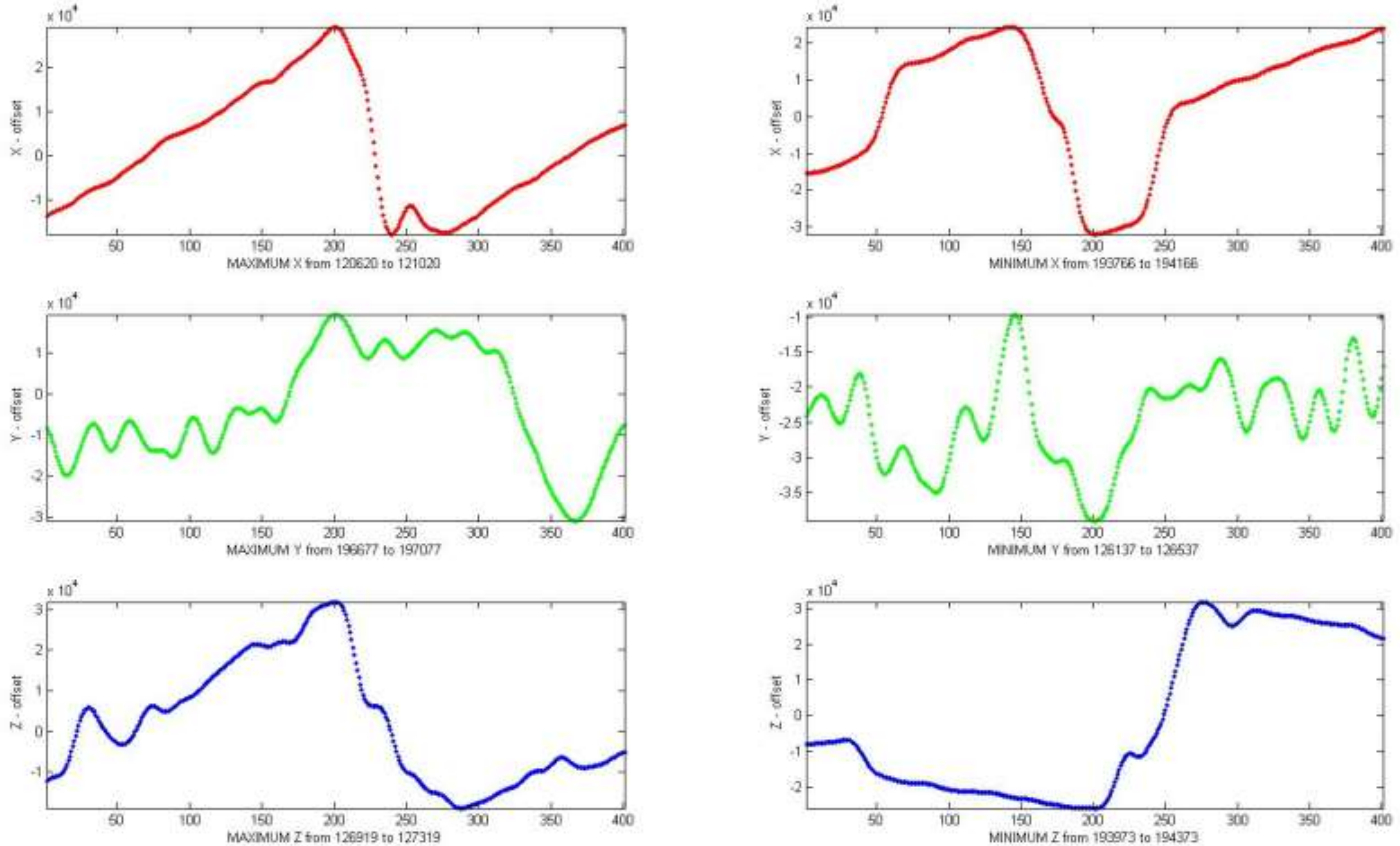
IEEE 802.15.4 low power wireless network standard.
10m / ~32' range

RJ45 Ethernet connection using TCP/IP

Gateway: 172.0.0.1

Ethernet

Raw Data Plots



Red = X = Horizontal motion
Green = Y = Vertical motion
Blue = Z = Lateral motion

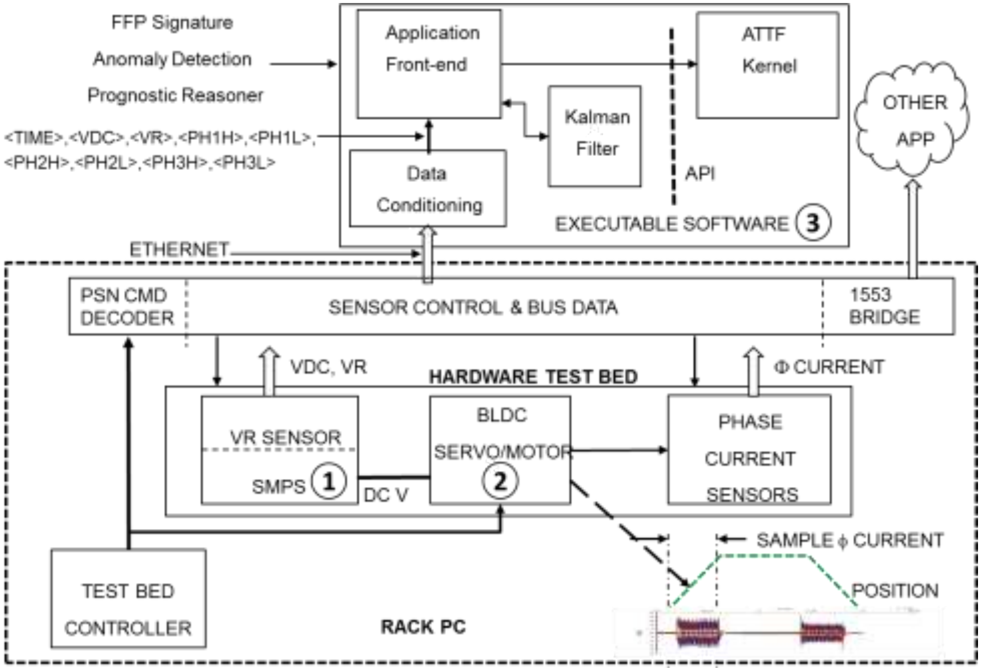
Process Raw Data into a Solution

- 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 PHM or Condition Based Maintenance (CBM) systems

Power System Prognostics

Example Application – Actuator System

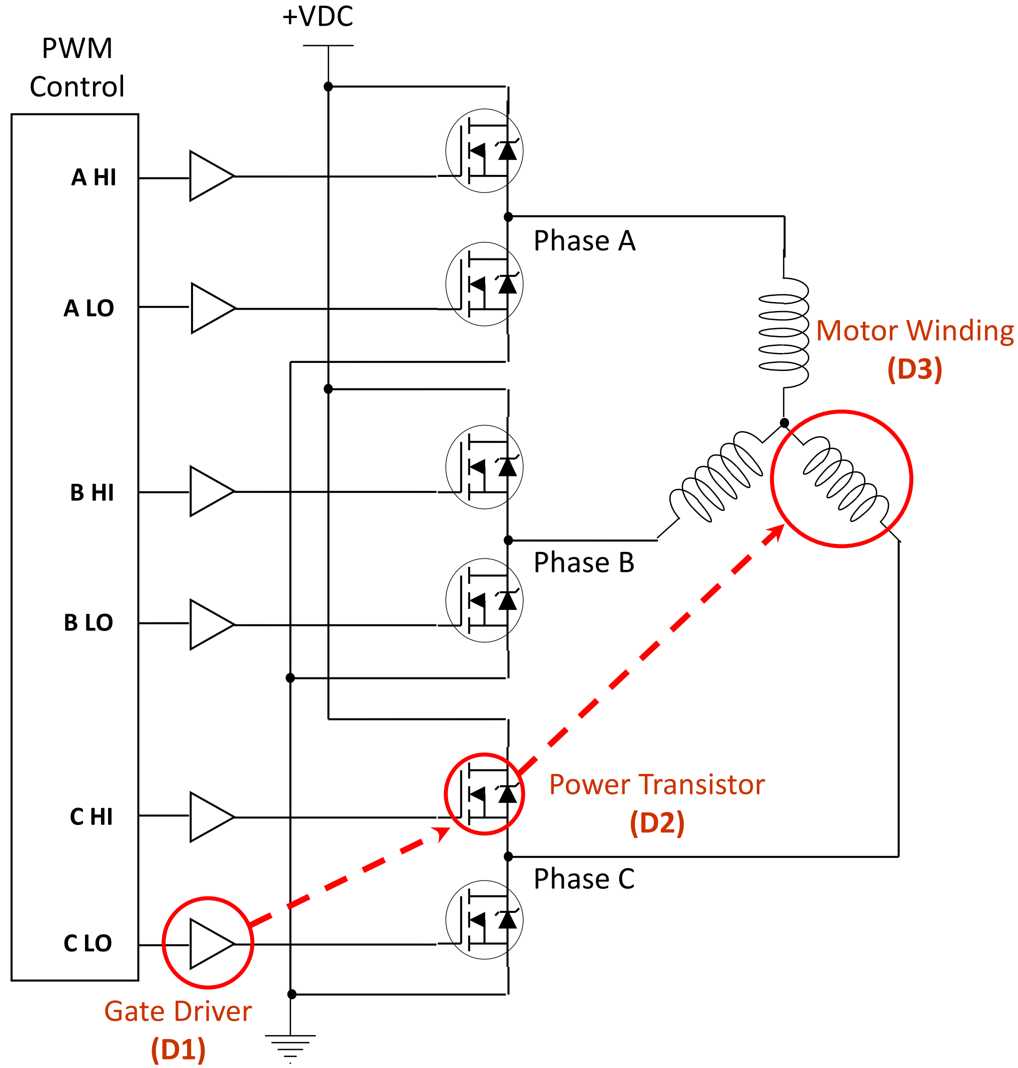
Electromechanical System



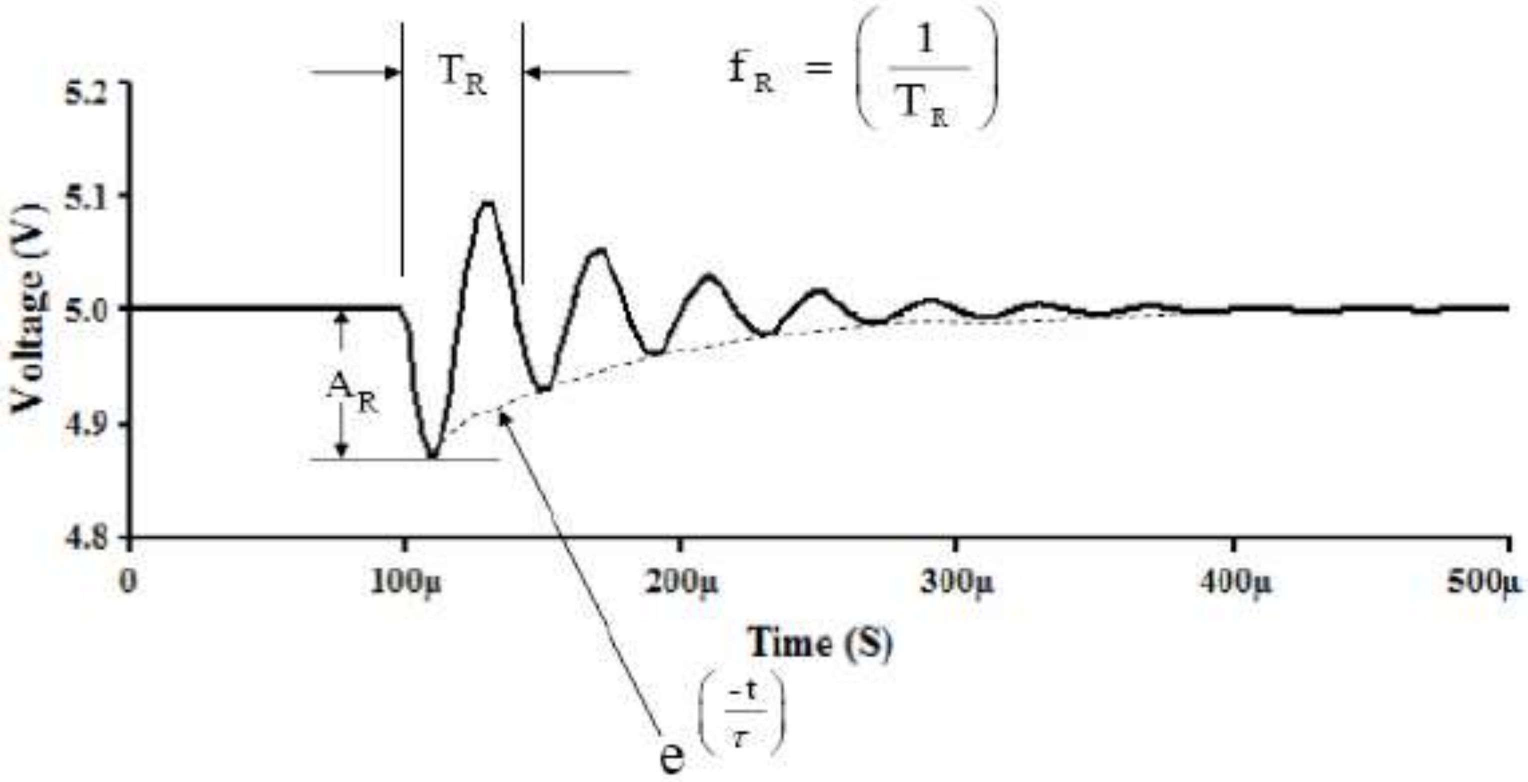
- Select monitoring observation points from Pareto Ranking or heuristics
- Seeded faults to examine effects
- Build fault dictionary

Power System Actuator Prognostics

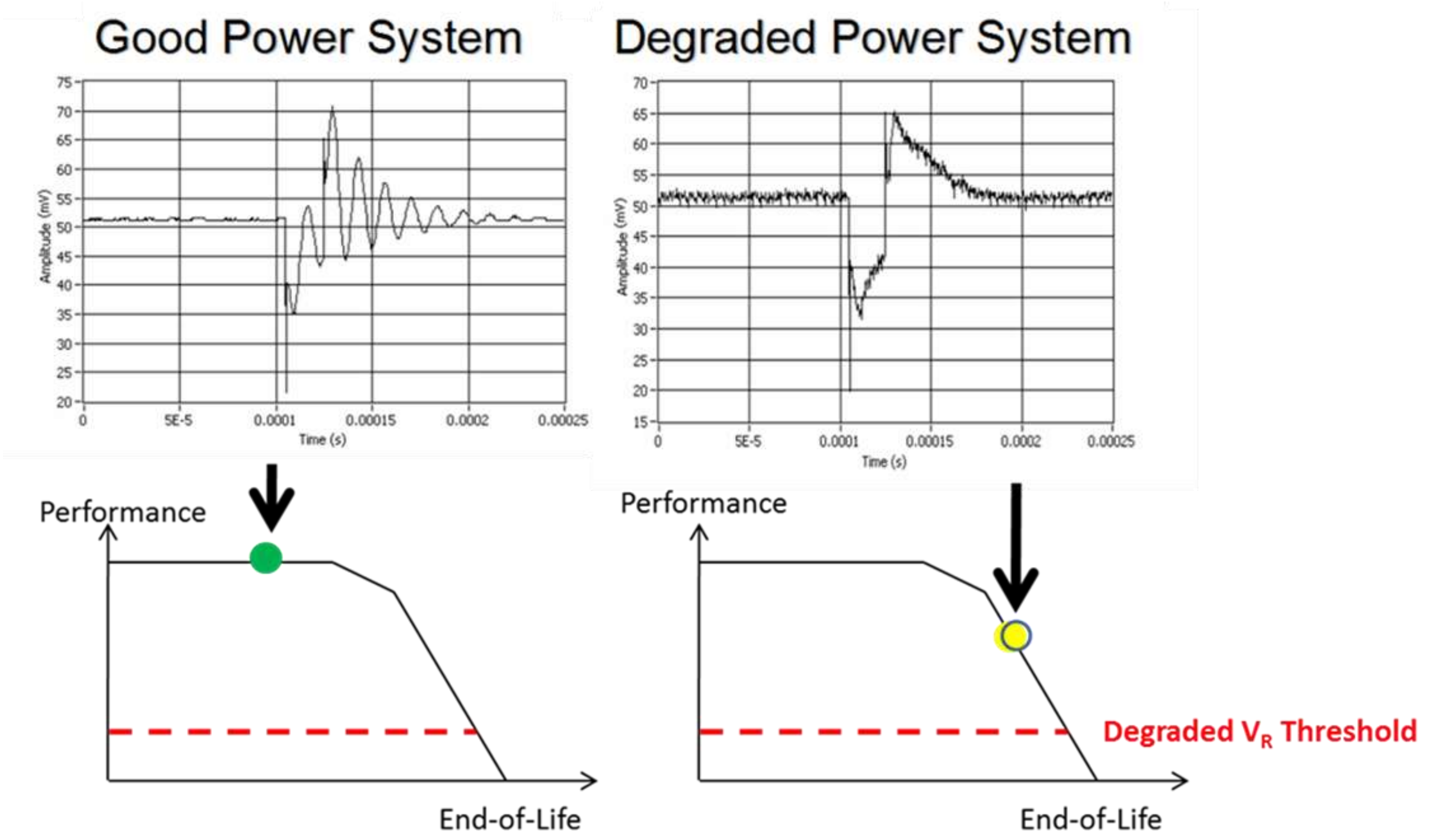
- **Typical Problem: Gate drive (D1) fault with progression to the power transistors (D2) and motor windings (D3) of each phase.**
- **Acquire and characterize the pertinent multivariate servo drive data associated with each fault condition (both electrical and mechanical) and the resulting stress effect 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.**



RingDown Relationship

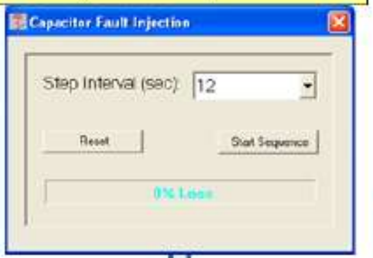


Anomaly Detection – RingDown™



Monitoring Results

Graphical interface to specify fault-injection step interval

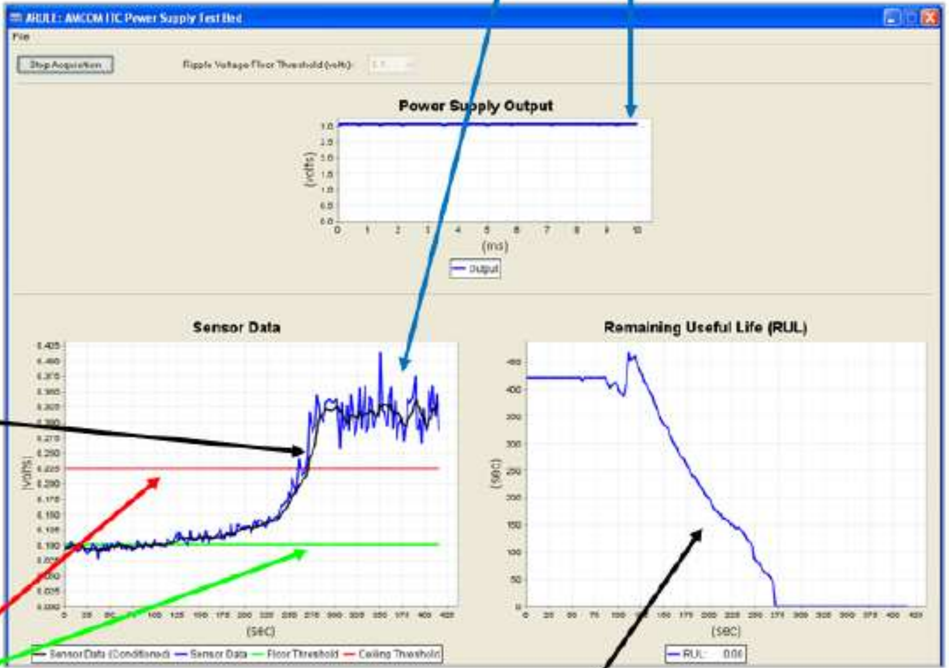


Fault injection stops after 90.9% loss of capacitance

Thresholds set by Degradation FMEA:

- exceeds predefined spec
- defined as good as new

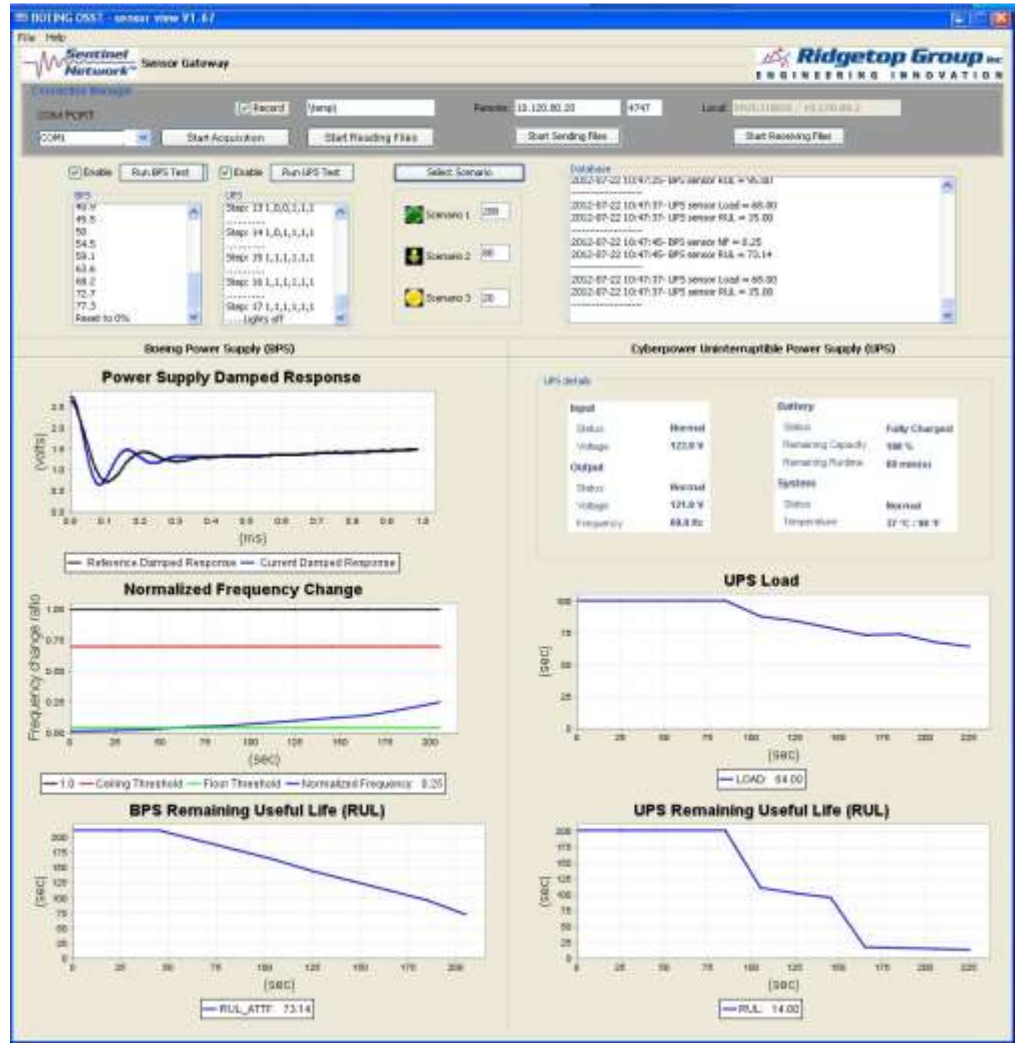
Power supply has failed (91% degraded)
- Output is still being regulated
- But noise is too large



RUL declines as degradation damage progresses: becomes zero once degradation reaches FMEA predefined failure threshold

Complex PHM System Analysis

- PHM applied to power systems in harsh environment
- Helicopter application where vibration, heat, shock all can reduce lifetime of deployed systems
- Extracts and processes data as a metric of health



Remaining Useful Life Estimator

- 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.
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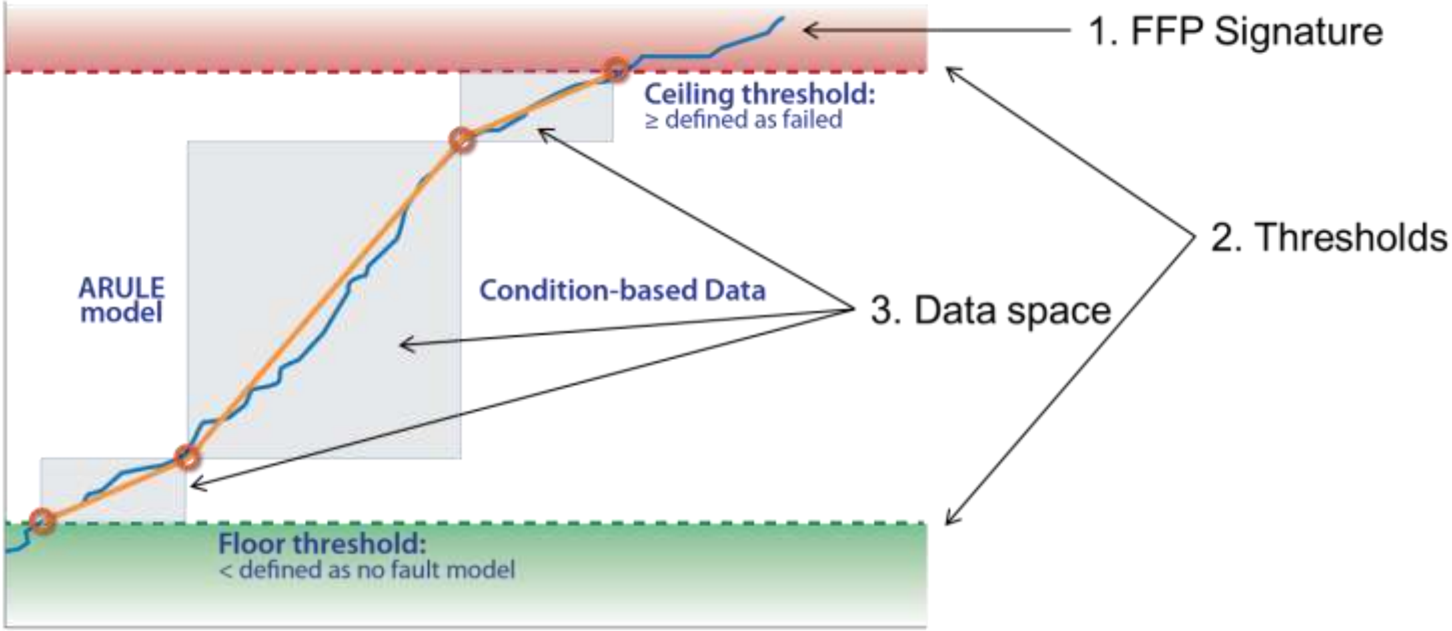
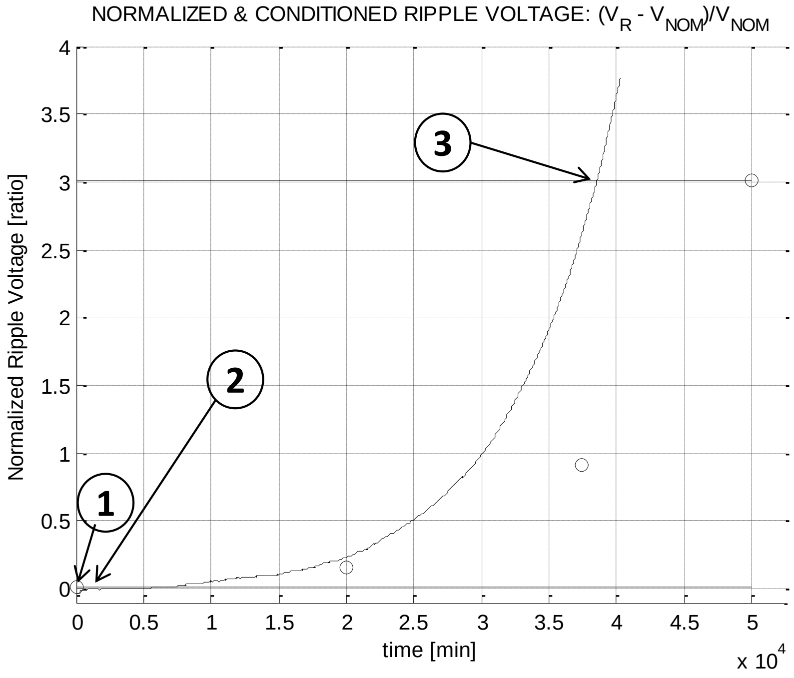


Fault-to-Failure Progression (FFP) Example

- In monitoring a power system, the observation point can be the ripple voltage from a regulated power supply.
- At (1), the ripple voltage is below a defined “no damage” value (the low horizontal threshold); at (2) the ripple voltage has increased above a defined “no damage value” and degradation is detectable; and at (3) the ripple voltage has increased to a defined “failed” value and the power supply has reached the effective end of its useful life.
- Other monitored points can be considered, with non-invasive being most favored.



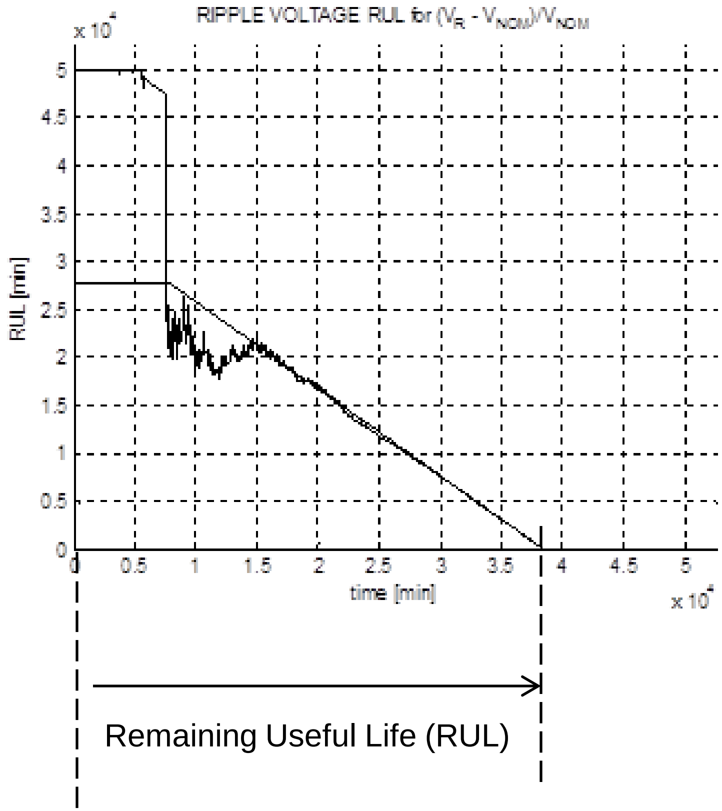
Remaining Useful Life (RUL)

Fault to Failure (FFP) Signature Modeling

- The creation of an FFP signature model
  - Create a representative curve using a set of normalized, dimensionless FFP signature data
  - Measure the amplitudes at specific time points;
  - Specify the four model points using an application programming interface (API).

Noise and Kalman Filtering

- Sampled data can be noisy, especially if the ripple voltage of a power system is sampled once every 30 minutes over a time span in the tens of thousands of minutes. Kalman filtering is used to remove noise to produce "clean" FFP signatures.
- Development system tools and libraries are available to help with implementation.



Enabling Technology - IoT

- Data captured by Internet of Things (IoT) devices exceeded 200 Exabytes in 2014
- Annual total to increase 7x by 2020 to 1.6 Zettabytes
- Cloud computing, edge computing, … , all is revolutionizing the landscape rapidly
- New system deployments are evolving
- More Research and Development is needed across multiple disciplines

*** ABI Research, High Frequency Electronics, May 2015**

Example Application – Wind Turbines

- RotoSense sensor is installed in the gearbox of wind turbines
- The sensor will gather data on the performance of the equipment
- The data will be transmitted wirelessly to a gateway in order to be processed and analyzed

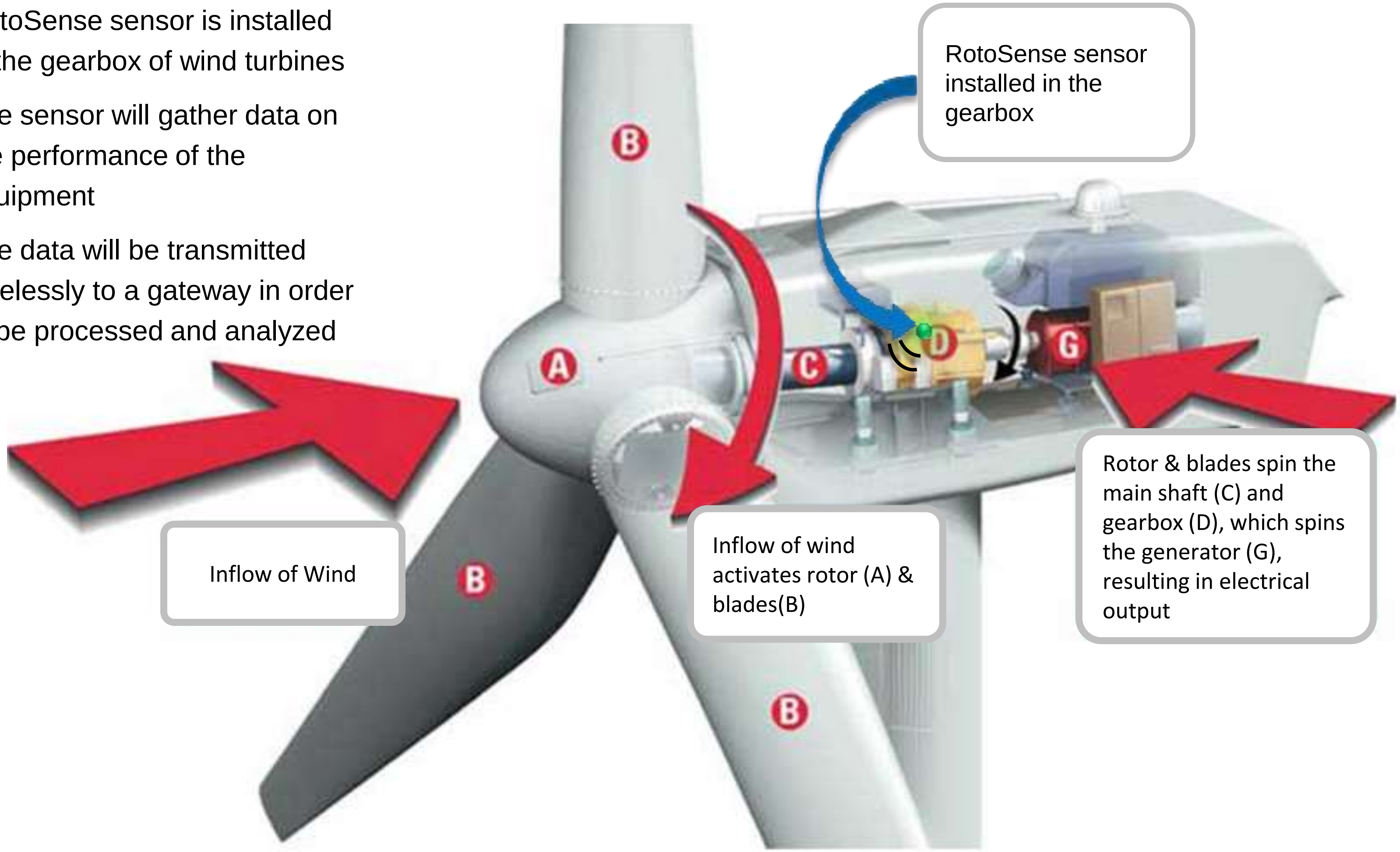
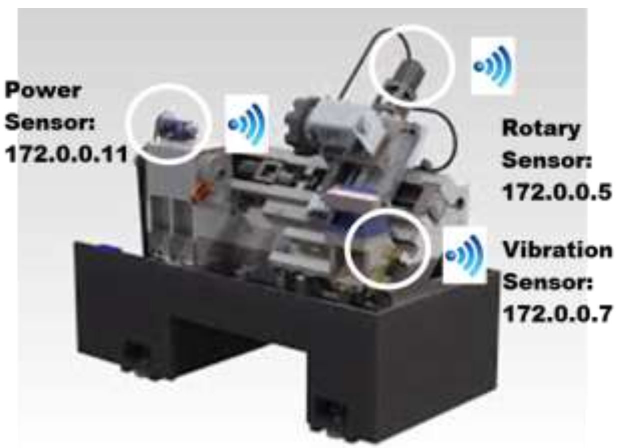


Image source: http://www.techienation.com/2008/08/14/understanding-wind-power-wind-generators-turbines/

Example Application – Equipment Monitoring

Which factory assets need maintenance?



Industrial Ethernet

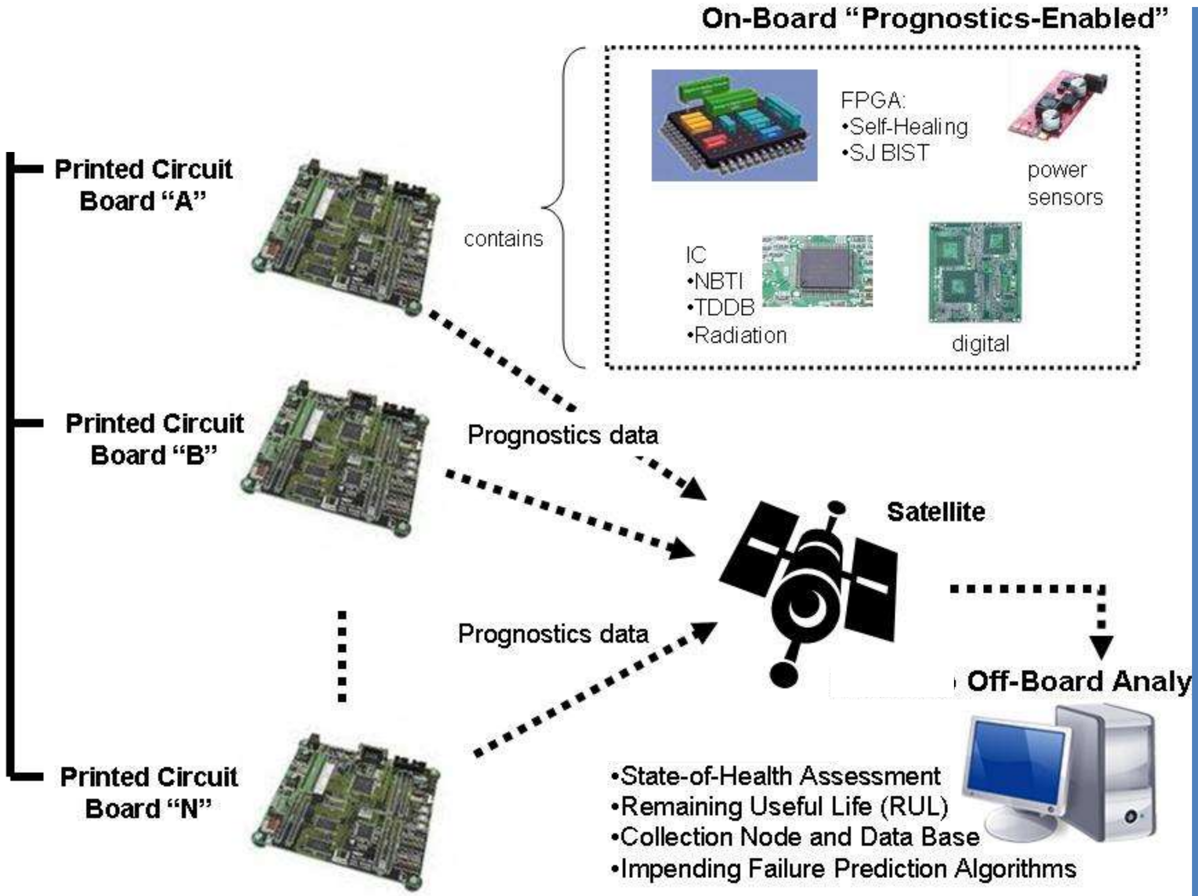
Gateway 172.0.0.1

Individual Equipment Monitoring

Sentinel Suite:

- **Equipment State-of-Health (SoH)**
- **Remaining Useful Life (RUL)**

Example Application - Distributed Assets



- Digital prognostics for autonomous systems
  - Detect impending failures at the IC level
  - Detect impending failures at the board level
- Links to Off-Board logistics network
  - Collection node and central database
  - RUL assessment

Return on Investment (RIO) Example

Assumptions for this scenario are as follows:

- **Grid power may be lost at any time**
- **A UPS failure constituting less than necessary time to safely power down attached equipment occurs about three times per year on average**

- **Only a single UPS will be replaced per incident**

In order to calculate the ROI of an electronic prognostics implementation for this scenario, the equation,

ROI = (Cost of Outage without PHM) – (Cost of Implementing PHM).

PHM Return on Investment (ROI)

Cost of new UPS procurement ~$10,000
Information Technology (IT) UPS & Power Supply Systems

Cost of installation during network outage ~$5,000 which includes:

o Expedited product handling and shipping
o Network expert consultant(s)
o Time required to get systems back online

Lost revenue from unscheduled network down time (2 hours) ~$40,000

ROI Calculation

The cost for prognostics-enabling a non-network UPS over the network is estimated to be on the order of ~$50,000

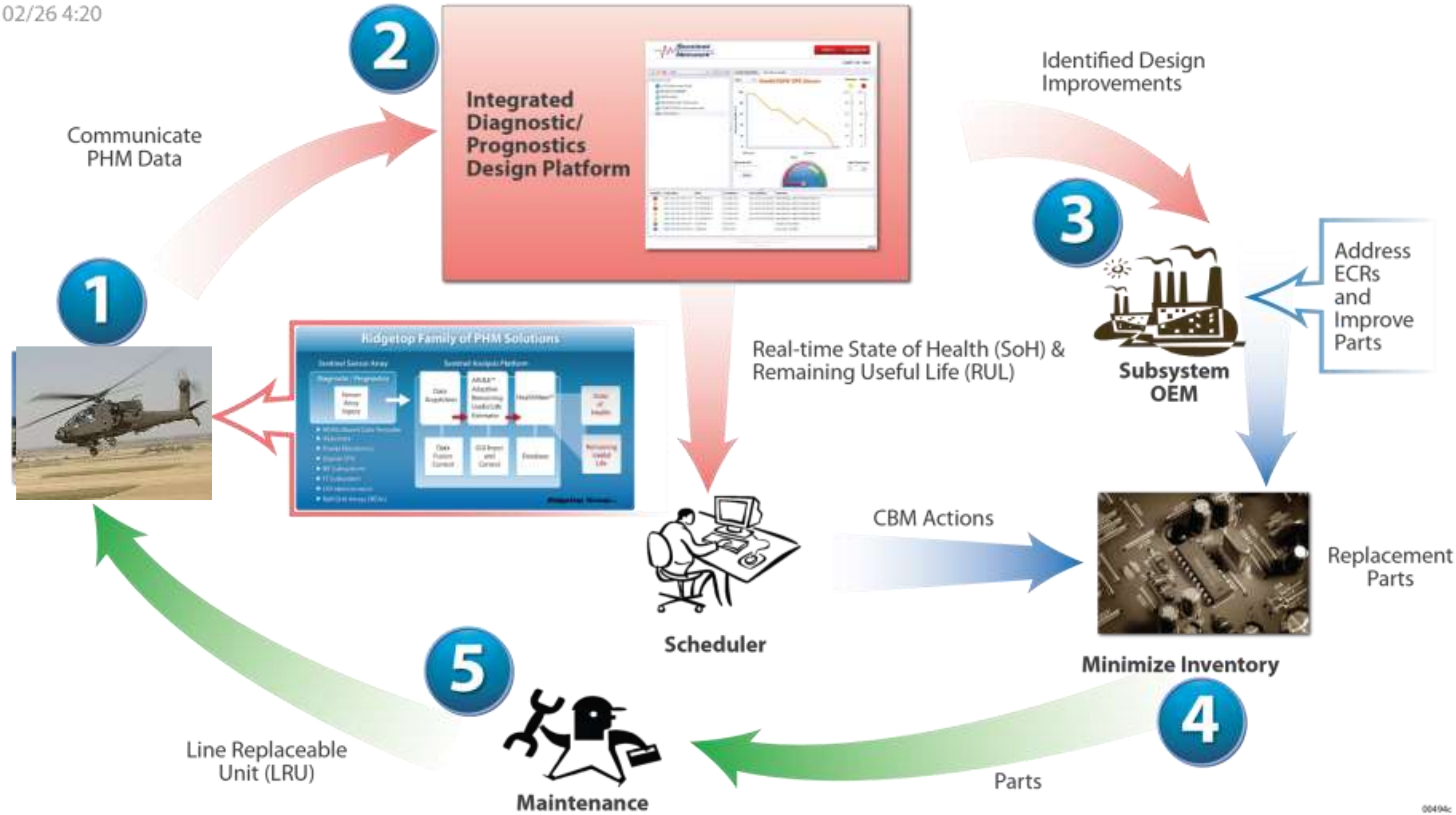
A basic ROI calculation follows:

ROI = (Cost of Outage without PHM) – (Cost of Implementing PHM)
ROI = (3 x $55,000) - $50,000
ROI = $115,000

In terms of percentage the ROI calculations are as follows:
ROI = (Cost of Outage without PHM – Cost of Implementing PHM)/ (Cost of Implementing)
ROI = ($165,000-$50,000)/$50,000
ROI = 230%

Cost-saving Ecosystem

02/26 4:20



Major Issues in Adopting PHM

- Technical Issues
  - PHM technology has been refined and deployed over the last 10 years.
  - Prioritization of observation points in complex systems.
  - Development system and modeling functions are available.
  - Many excellent areas for further Research and. Development
- Management Issues
  - Selection of Pilot Program to demonstrate functionality.
  - Management of various functions; design engineering, maintenance, logistics and support, manufacturing.
  - Quantifying results in cost savings across several departments.

Summary Benefits of PHM

- Prognostics provides advance warning of impending failure conditions on critical systems and avoidance of expensive system downtime.
- In some cases, safety can be improved.
- Electrical evidence of degradation is the basis for maintenance on the component or system, not an arbitrary time interval.
- PHM can reduce support costs through optimized timing of service and parts replacement.
- An Autonomic Logistics Information System (ALIS) can be established, placing spare parts and provisions where needed.

Thank you!

Example Application - Semiconductor

Characterizes deep submicron (DSM) processes (bulk CMOS, SiGe, SOI) reliability and variability effects

Test Coupon

- Low cost
- Easily ported
- Small as 1 mm x 1 mm area
- Easily controlled: Fully programmable test conditions cover DC and AC stress cases
- Highest throughput: Test time reduced from months to hours
  - Tests from hundreds to over a thousand devices
  - Local heaters elevate temperatures up to over 300 °C

ECTC

- Environmental chamber test cable for placing test articles in radiation test chamber

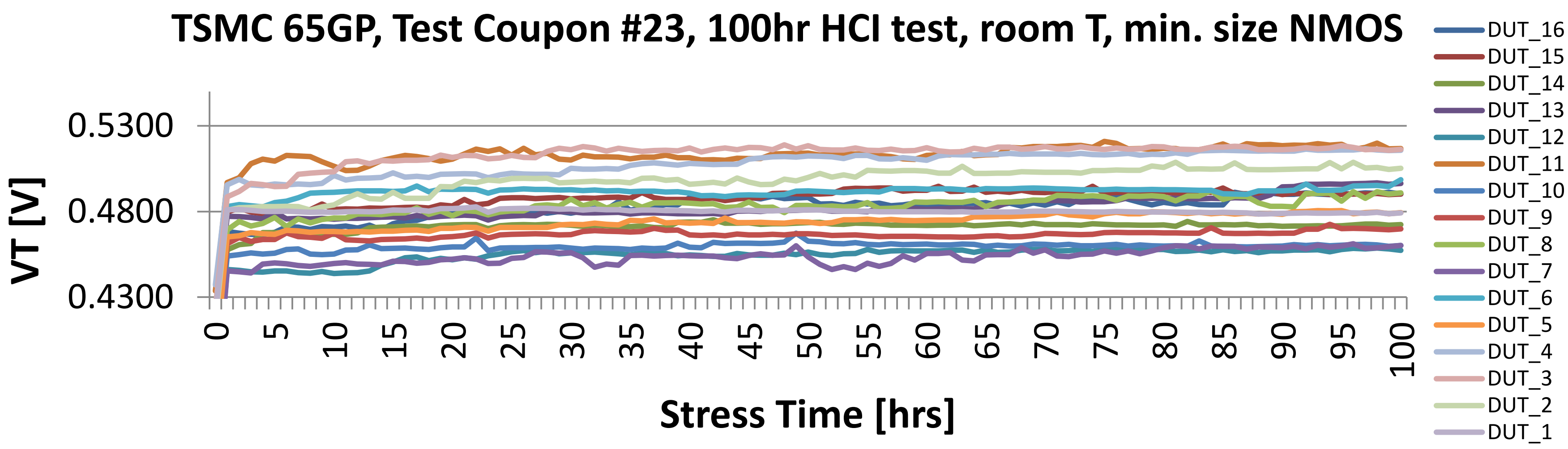
Host Controller

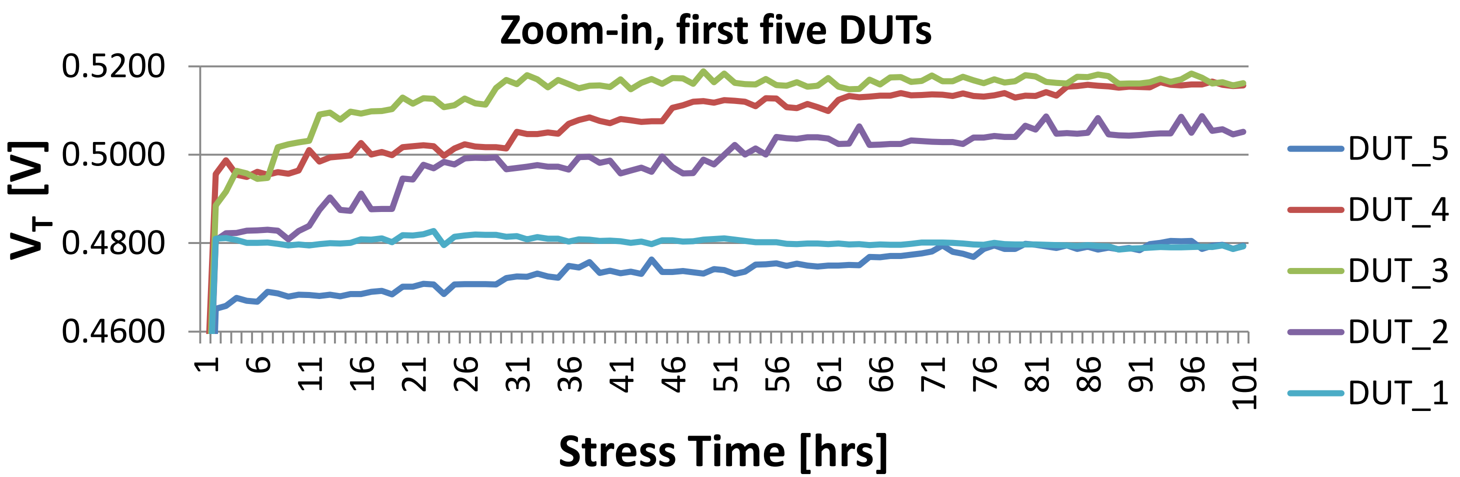
- Easy-to-use software interface
- Local data processing

Benchtop Tester

- Universal: Supports all test coupons
- Low cost: No "big iron" ATE or oven required
- Contains/controls all stress and measurement instruments

ProChek Results





Example - Stacked Die Monitoring

- Input (Control)
  - Clock, Enable & Reset
- Dedicated Test Pins
  - 2 bidirectional I/O pins: TP0 & TP1
- Output (to supervisor)
  - Failure Flags (fault was detected on TP0/TP1)
  - Active fault flags (fault is active on TP0/TP1 at the moment of interrogation of SJ BIST)
  - Failure counts (2 8-bit values related to number of faults detected on TP0 and TP1 respectively)