CBM/PHM at Warner Robins ALC

Chris Minnella
Impact Technologies, LLC
Frank Zahiri
USAF WR-ALC

Agenda

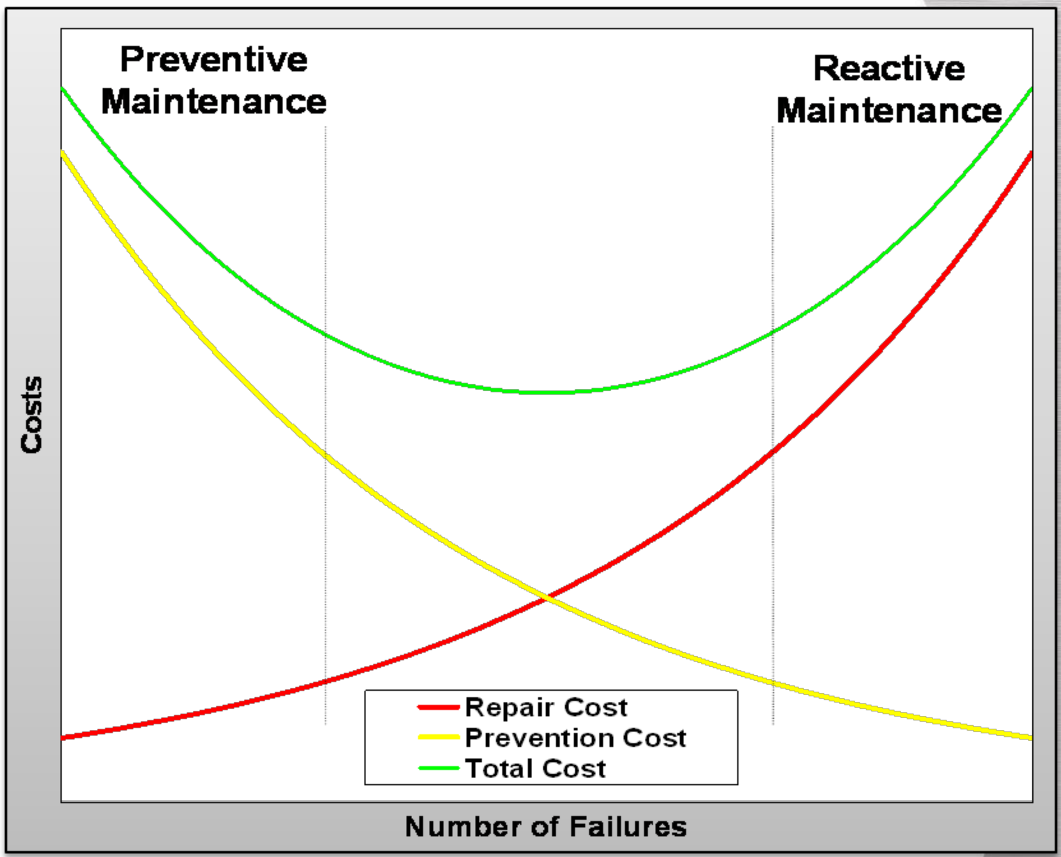
- Background
- The Application Domain: 30V
- Data Acquisition
- Data Analysis
- CBMi Overview
- Benefits
- Lessons Learned
- Going Forward

Background: Motivation

- Department of Defense policy that Condition Based Maintenance (CBM) be implemented to:
  - improve maintenance agility and responsiveness
  - increase operational availability
  - reduce life cycle total ownership costs
- CBM tenets include:
  - need-driven maintenance
  - appropriate use of embedded diagnostics and prognostics through the application of RCM
  - automated maintenance information generation
  - trend based reliability and process improvements
  - integrated information systems providing logistics system response based on equipment maintenance condition

Background: History

- Purely statistical-based preventative maintenance suffers
  - significant useful life remains in many replaced components
  - limited failures continue to occur in some components prior to scheduled replacement
- Condition-based maintenance and health management
  - reduce maintenance costs
  - increase readiness
  - improve product quality



Background: Maintenance Strategies

1930 - 1960

1st Generation
Corrective Maintenance

- Fix when broken
- All life consumed
- High forced outage costs
- Hard to predict
- Poor availability

1960 - 1985

2nd Generation
Preventive Maintenance

- Very popular
- Scheduled replacement
- Low forced outage costs/risk
- Higher scheduled outage costs
- Wasteful

1985 - 2000 / **2000 - 2008**

3rd Generation
Predictive Maintenance

Reliability Centered Maintenance (RCM)

- Interval from reliability bathtub curve
- E.g. B1 life
- Useful for unobserved risks

Condition Based Maintenance (CBM)

- Physics/Empirical Damage accumulation
- Update model w/inspection data
- Risk-Based Inspection (RBI)

Prognostics Health Management (PHM)

- Real-time
- M&D data based
- Fault/Anomaly detection & isolation (FDI)
- Diagnostics & Prognostics

Optimal part life usage, improved reliability, availability maintainability & safety (RAMS), reduced O&M costs

2009+

4th Generation
Intelligent Machine Health Management

- Integrate controls with CBM/PHM
- Optimize asset usage

Background: the Problem

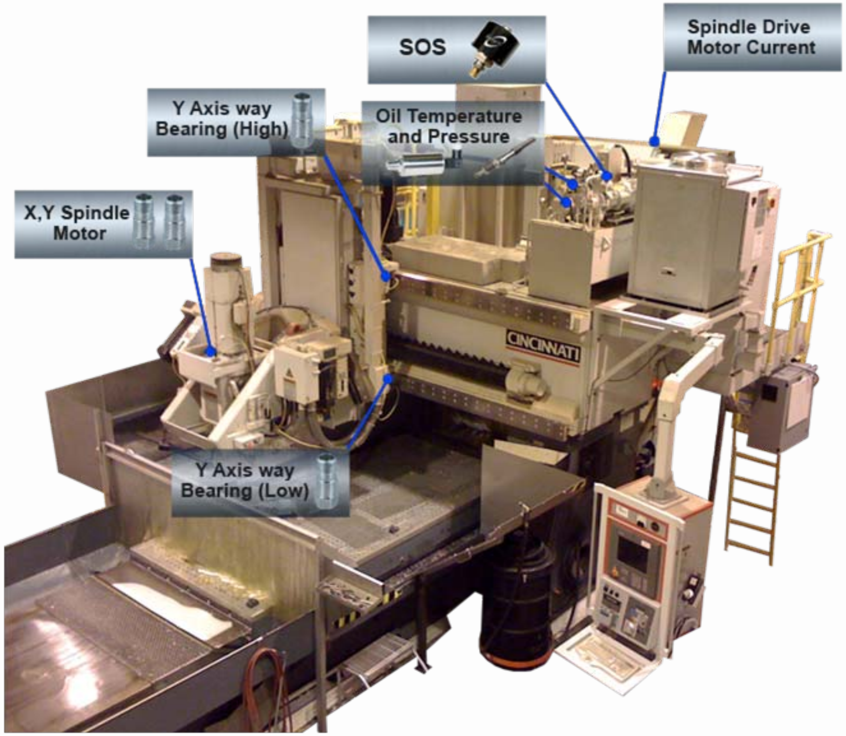
- WR-ALC was looking to transition from a Preventive Maintenance model to a Condition Based Maintenance model.
- Data collection and analysis takes time and experienced personnel.
  - The resources available for analysis are not local
  - Operations personnel are interested in performance indicators
  - Personnel resources are not available to take measurements or analyze the data
- Recent failures on two CNC machines resulted in considerable downtime and cost for critical part replacement.
- In June 2008, it was recommended that these two machines be instrumented and monitored for possible failure modes.

Background: Goals

- Reduce maintenance cost by 30%
- Improve Reliability, Availability, Maintainability and Safety of ground facilities and air platforms
- Reduce time for repair of aircraft by several days
- Increase uptime of critical ALC facilities to 98%
- Achieve JIT practice in inventoried equipment / supplies / spares
- Optimum utilization of ALC personnel / resources – improve productivity by 10%
- Migrate to CBM practices throughout all ALC operations

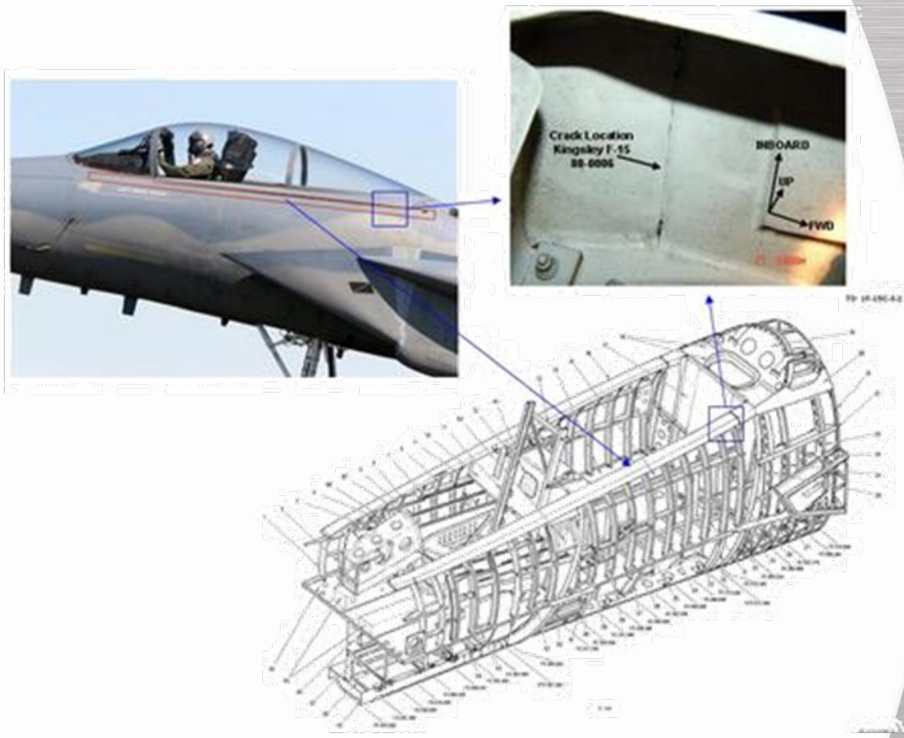
The Application Domain: 30V

- Located at Robins Air Force Base in Warner Robins, GA
- Critical to Air Force operations, supports:
  - C-5 Galaxy
  - C-17 Globemaster III
  - C-130 Hercules (A, E, H, M varients)
  - E-8 Joint STARS
  - F-15 Eagle
  - HH-60 Pave Hawk
  - MH-53 Pave Low
  - RQ-4 Global Hawk
  - U-2 Dragon Lady
  - UH-1 Iroquois
- 5-axis vertical profiler, 30HP Spindle
- Used to manufacture short runs of critical replacement parts used in USAF aircraft



The Application Domain: 30V

- Fatigue cracks started by manufacturing defects in a fuselage longeron caused the in-flight break-up of a Boeing F-15C Eagle on 2 November 2007†
- 30V was tasked with replacing these parts in early 2008
- Impact's instrumentation was to transparently implement all sensing without causing any unnecessary downtime or impeding the machine's operations and operators.



Upper longeron location in F-15 forward fuselage

†Butler, A. (January 10th 2008). Manufacturing Defect Root Of F-15C Crash. *AviationWeek.*

Data Acquisition

- Hardware
  - Transduction TR-5001 PanelPC in NEMA Enclosure

Acquisition Hardware

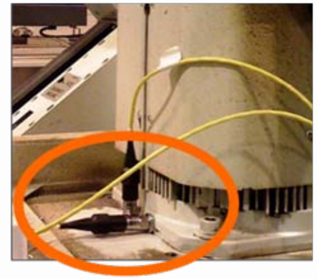
- USB-9234 – 4 channel DSA module
  - 51.2 kS/s per-channel maximum sampling rate
  - ±5 V input, 24-bit resolution
  - 102 dB dynamic range
  - antialiasing filters
- PCI-6023E – 16 channel multifunction DAQ
  - 200 kS/s, 12-bit resolution

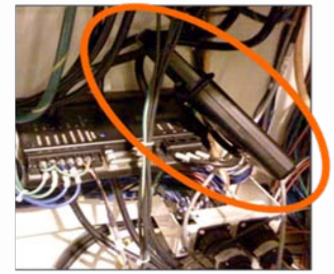
Sensor/Signal Conditioning Hardware

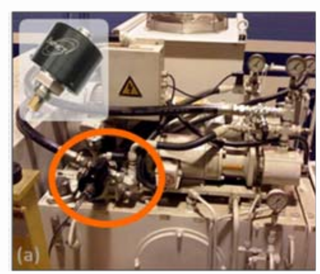
- 4x Wilcoxon General Purpose Accelerometer
- Impact Technologies SmartMon Oil Quality Sensor
- Amprobe CT-600 AC DC Current Transducer
- Omega OMNI-AMP-IV TC Amplifier with K-type Thermocouple
- Omegadyne PX219-100G10V Pressure Transducer

Data Acquisition

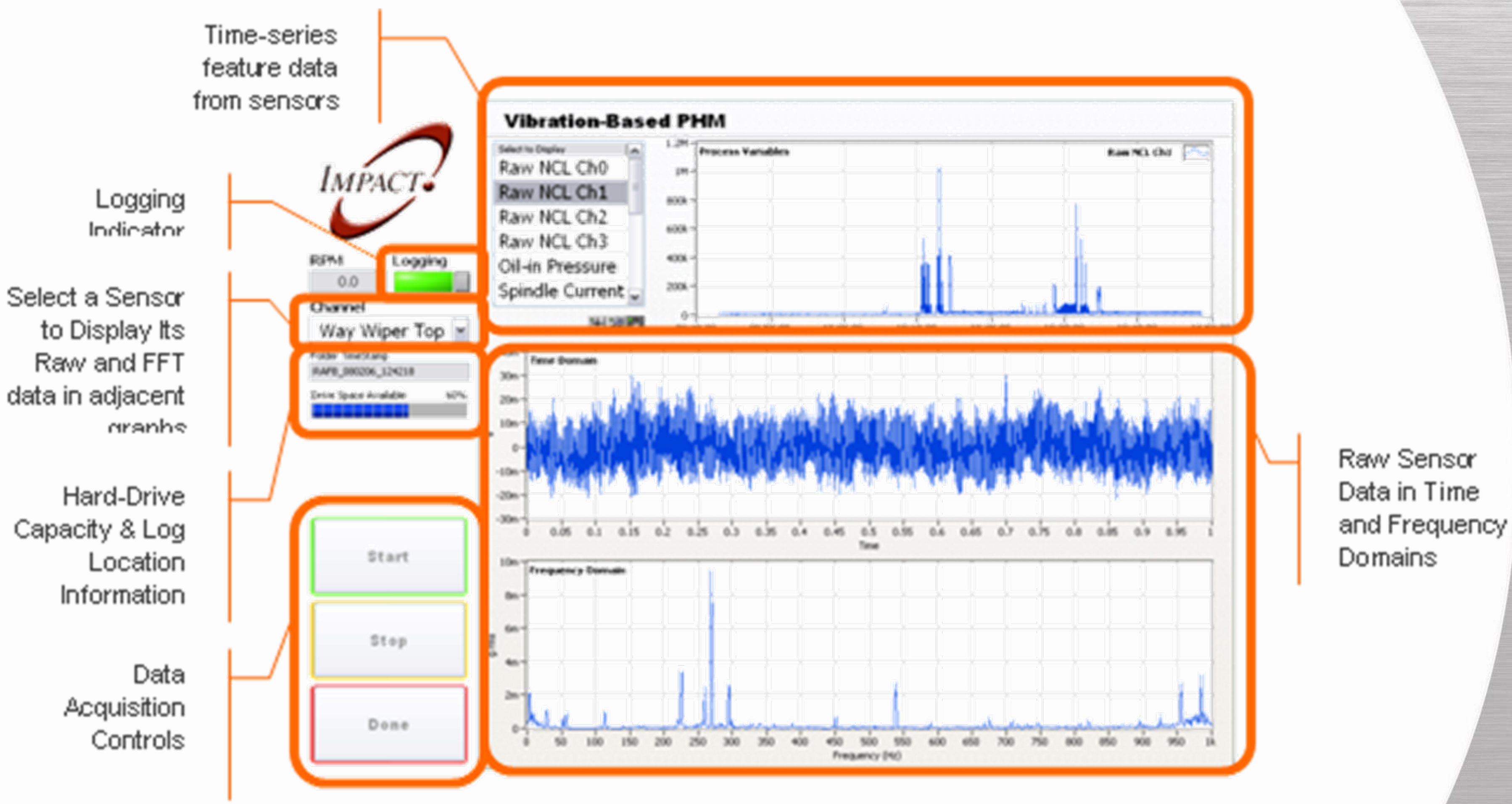
- Axial and Radial Accelerometers Installed on Spindle Motor
- Accelerometers Installed at the Top and Bottom Y-axis Way Bearings
- Current Transducer in Spindle Motor Drive Cabinet
- Impact SmartMon Oil Quality Sensor on the Hydraulic Oil-Return Line
- Temperature and Pressure Transducers on the Hydraulic Oil-In Line





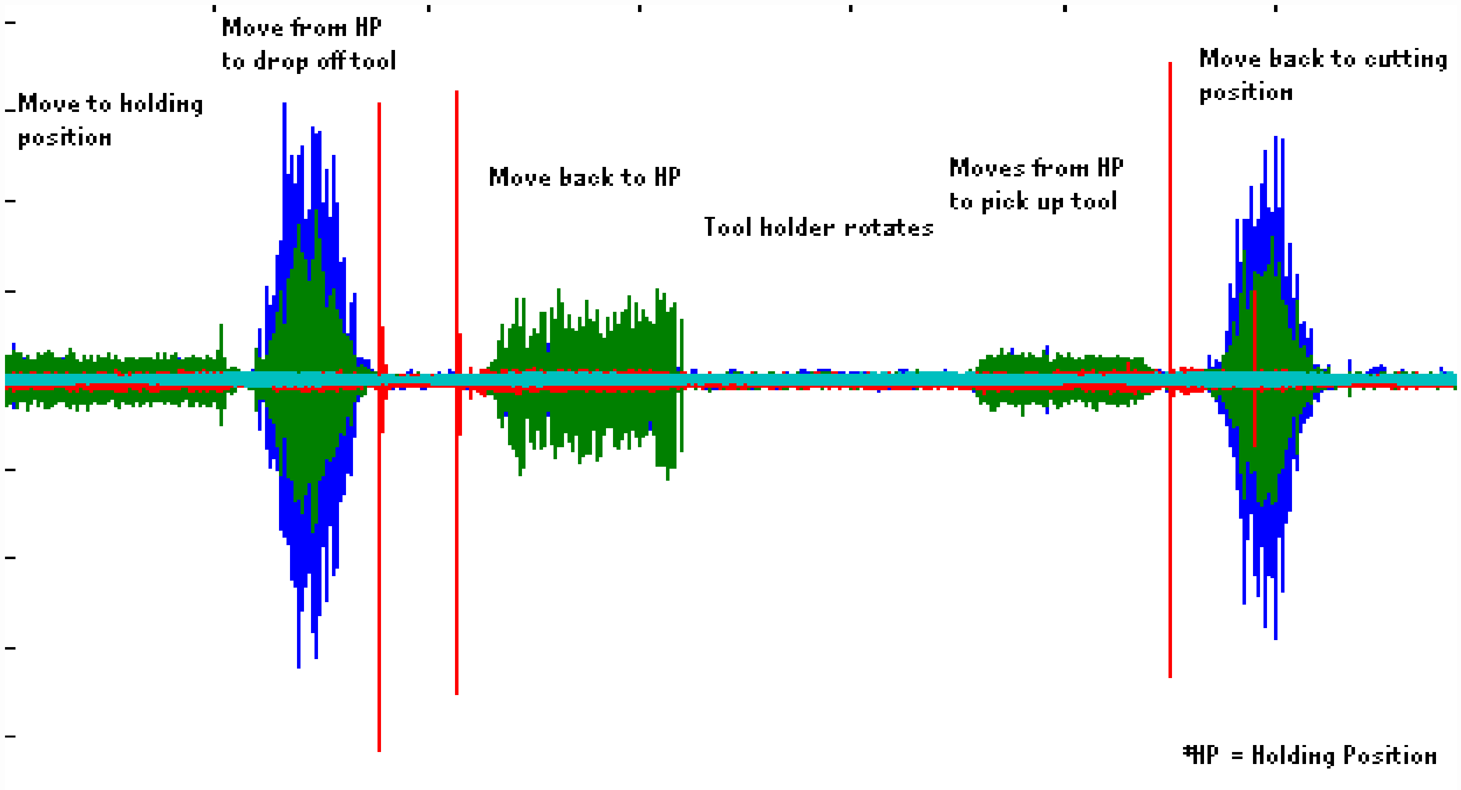


Data Acquisition Interface



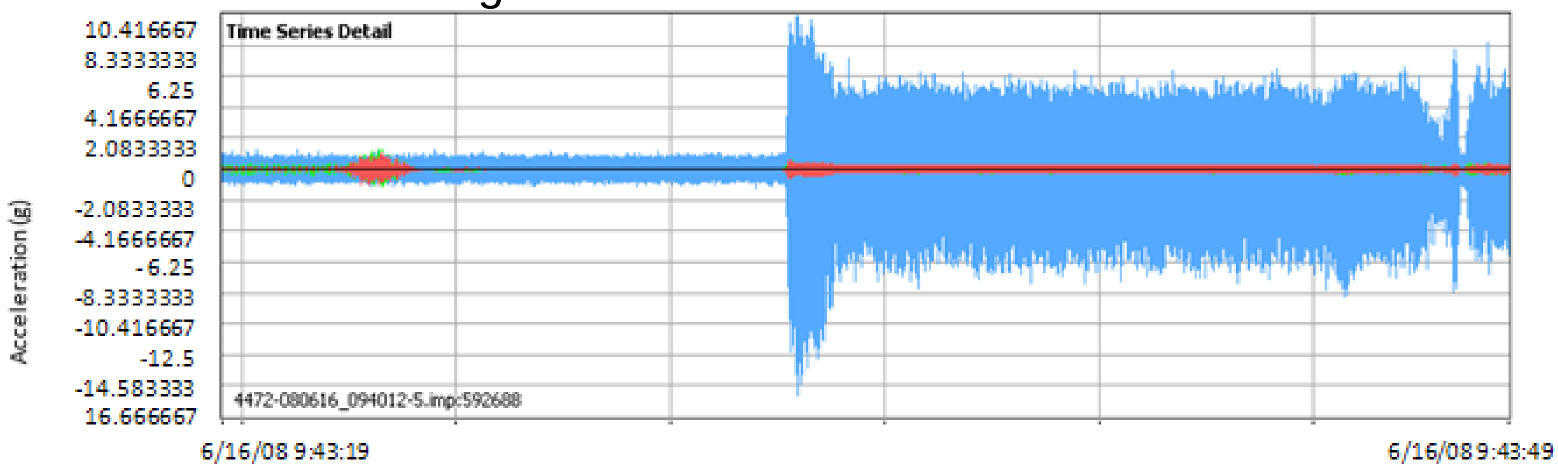
Data Analysis

Tool Change Event – Sequence of Vibration Signatures in Spindle and Way Bearings Accelerometers

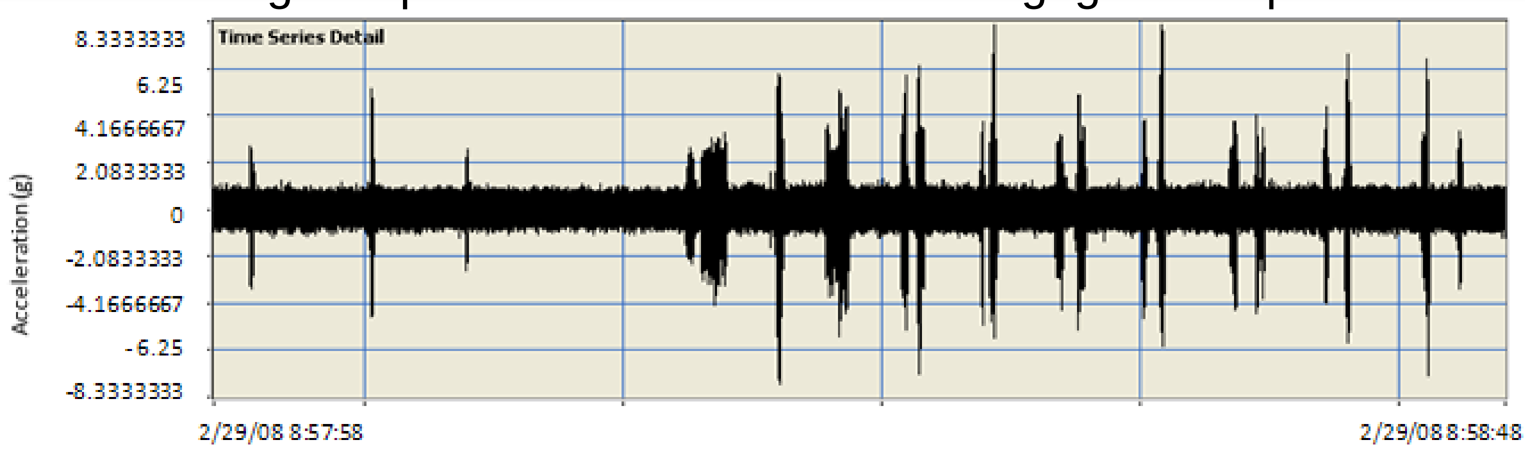


Data Analysis

Tool breakage

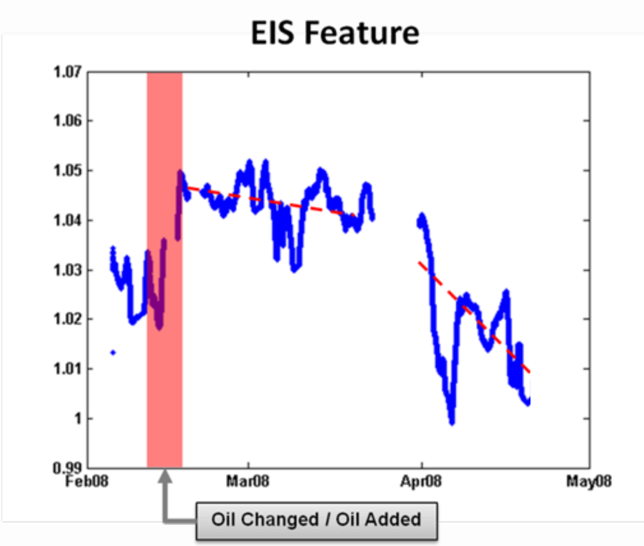


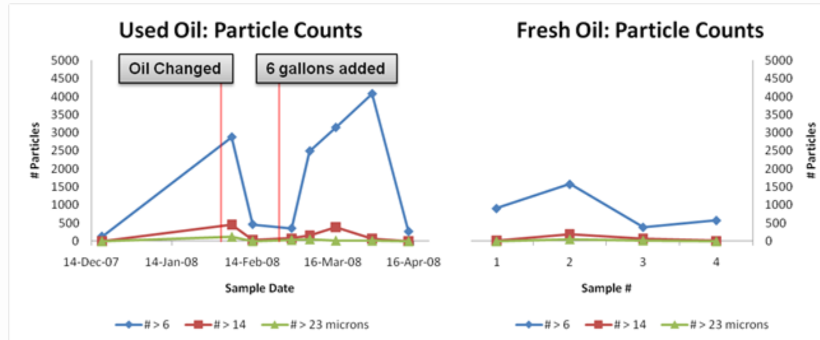
High amplitude vibration when tool engaged with part

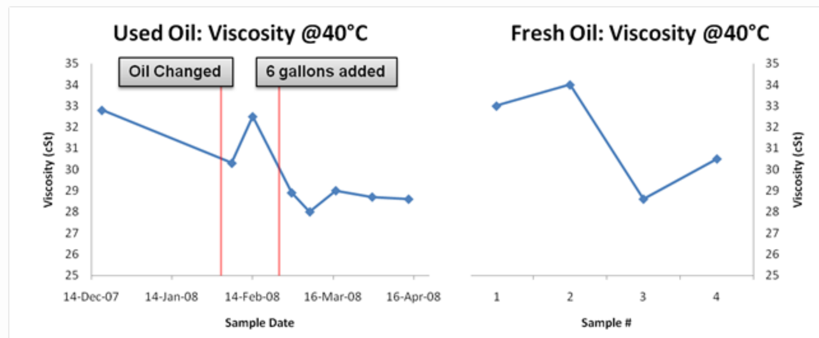


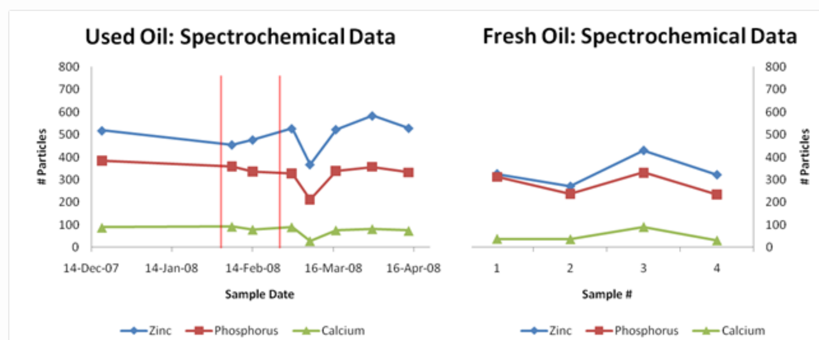
Data Analysis

- The sensor “feature” data appears to show some sensitivity to the oil change, and also appears to generally have a downward trend over time.



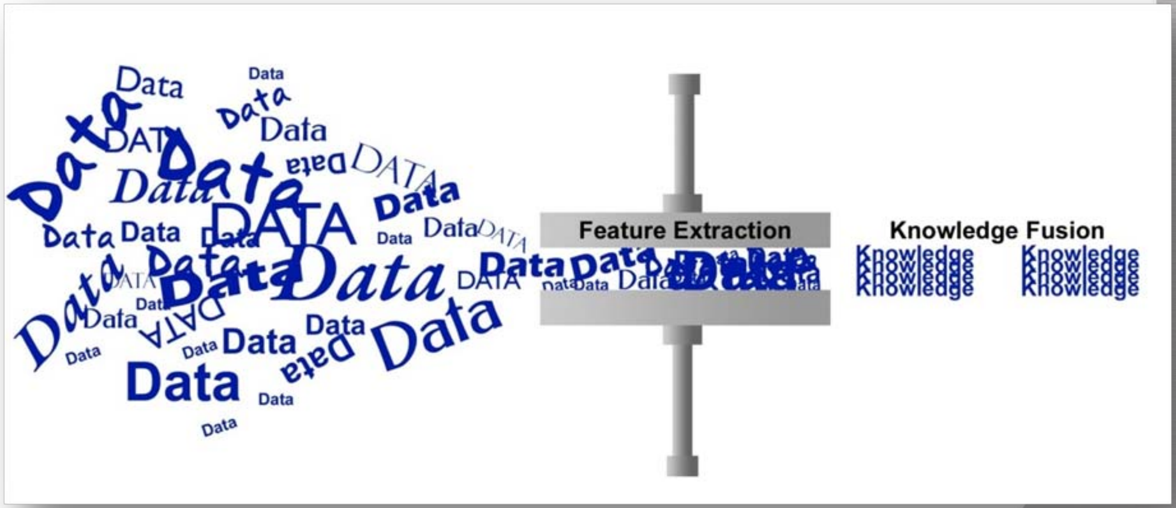




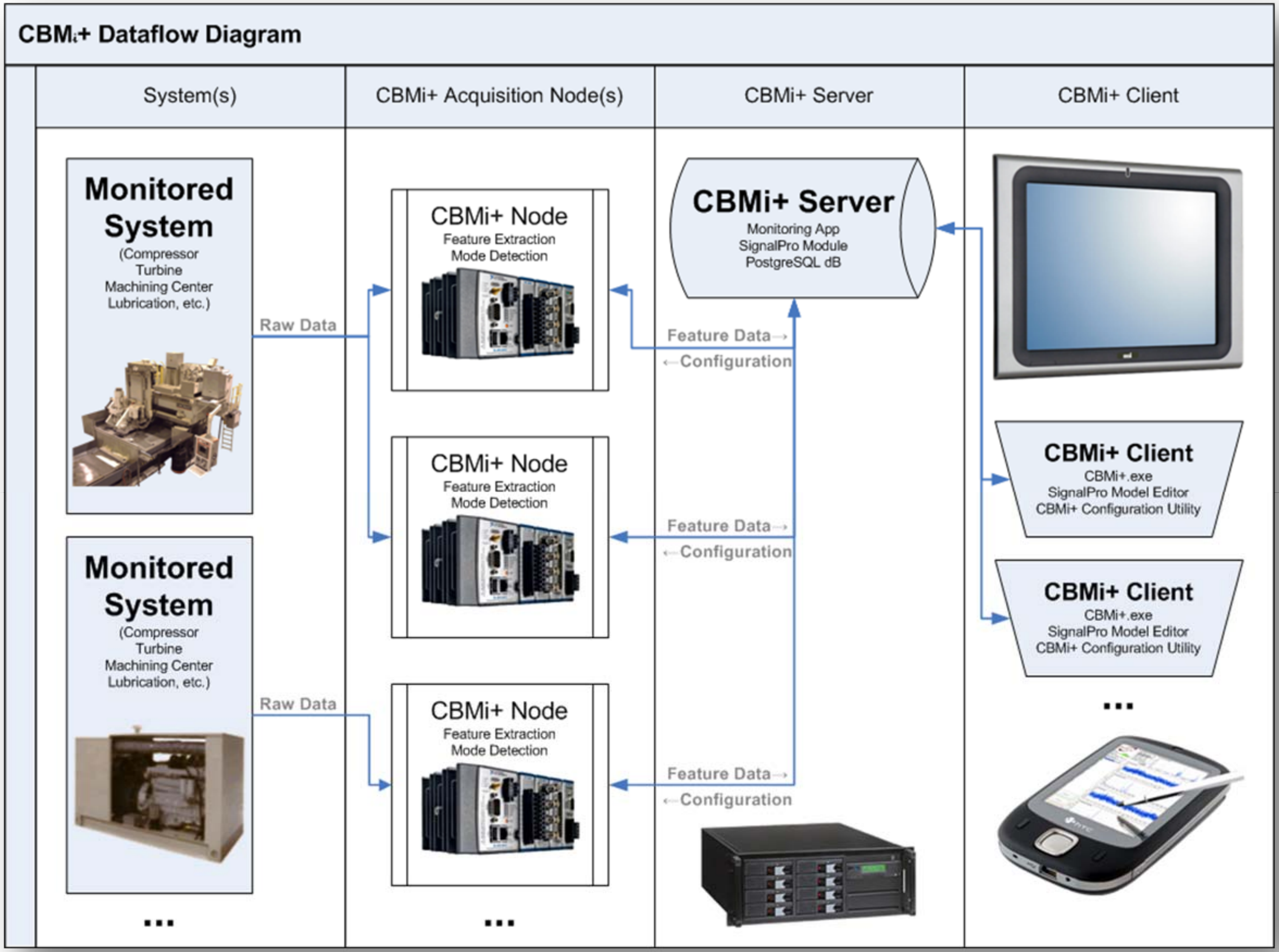


a Solution – CBMi

- Automatically collects, processes, and posts relevant information to a central repository.
- Information is available remotely to all interested users.
- Automatic alarms and notifications based on customizable inference systems, or simple threshold crossings.
- Scales from a single asset, to an entire facility.



CBMi Data Flow Diagram



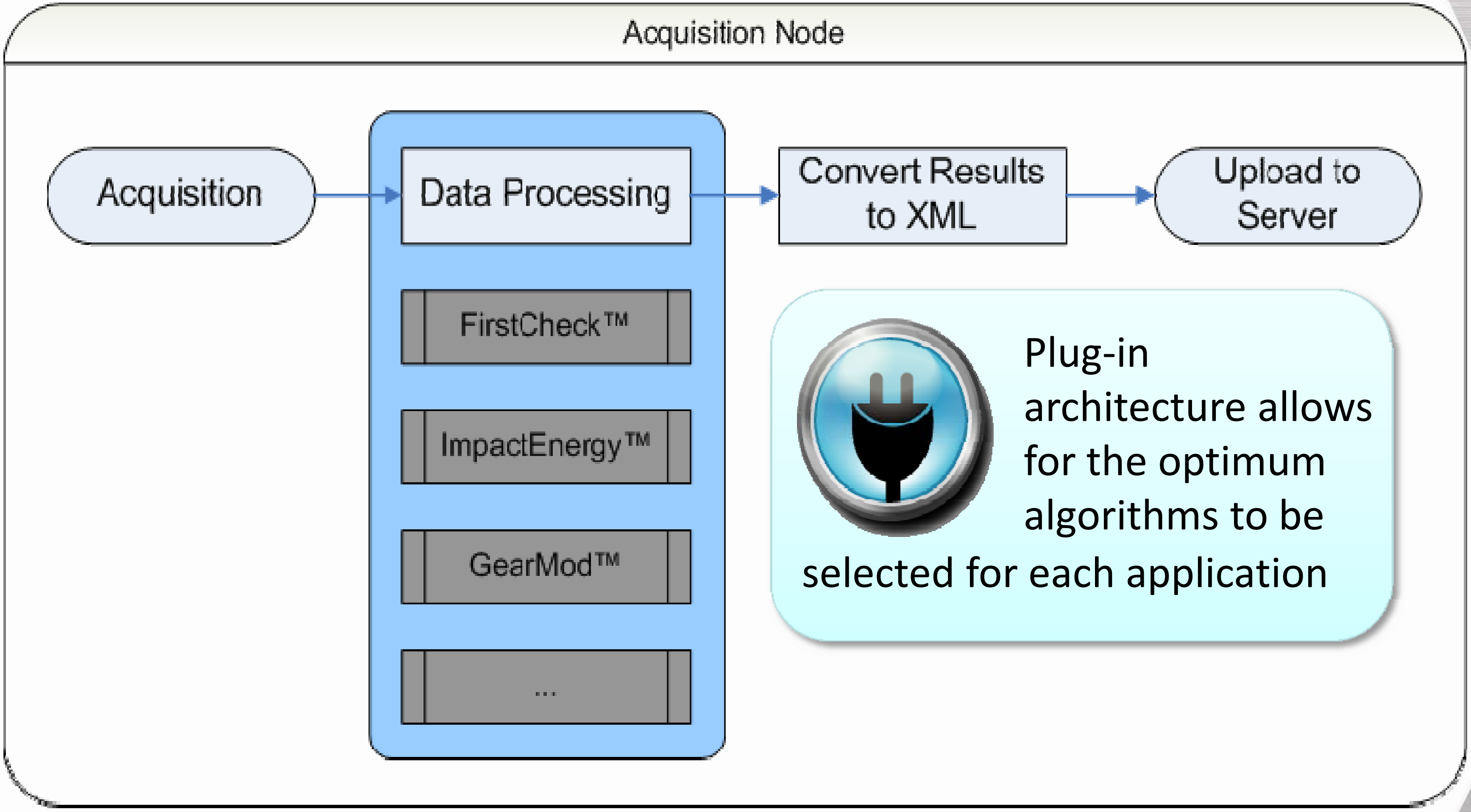
Hardware

Acquisition Node Flexibility

- A variety of 1st and 3rd party devices are available as acquisition nodes

Device		Cost	Expansion Options	Flexibility	Processing Power	Size	Required Power	Robustness
	NI PXI Platform	🔴	🟢	🟢	🟢	🔴	🔴	🔴
	NI Compact RIO	🟡	🟢	🟢	🟡	🟡	🟡	🟢
	Impact-RLW S2NAP	🟢	🟡	🟡	🔴	🟡	🟡	🟢
	Impact-RLW S5NAP	🟢	🔴	🔴	🔴	🟢	🟢	🟢

Acquisition Node Responsibilities



Plug-in architecture allows for the optimum algorithms to be selected for each application

National Instruments CompactRIO

- Small, rugged embedded control and data acquisition system
- Embedded real-time processor for reliable stand-alone operation
- Hot–swappable industrial I/O modules with built in signal conditioning
- Extreme industrial certifications:
  - -40 to 70 °C (-40 to 158 °F) operating temperature
  - Up to 2,300 Vrms isolation (withstand)
  - 50 g shock rating
  - International safety, EMC, and environmental certifications
  - Class I, Division 2 rating for hazardous locations

Software
CBMi with SignalPRO

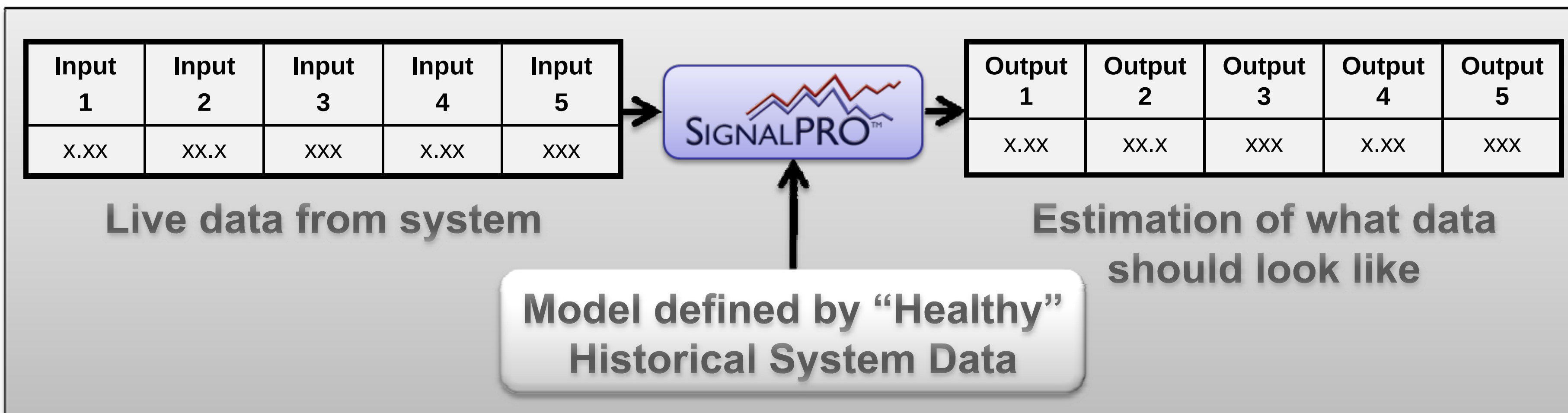
- A widely applicable, data-driven, automated fault detection system for performance & condition monitoring
- Key Concepts:
  - Easy to install / use / maintain
  - Generic Models
    - Models based on existing data → no specialized application specific equations
    - Point & Click interface to build and maintain models
  - Continuous / on-line anomaly detection (“continuous commissioning”)
  - Remote access to diagnostic information
- Combination of CBMi and SignalPRO increases potential application areas
  - Both performance and true condition monitoring

SignalPRO Model

- Multiple ‘snapshots’ in time to characterize the behavior of the system
  - Think of a spreadsheet – columns are sensors, rows are data from different operating points and points in time.
- Can be
  - Historical data
  - Initial installation data
  - Data from models: (e.g. thermal performance codes)
- Best if
  - Covers entire expected range of (healthy) operation
  - Low in random noise
  - All data is related (monitors same process)

SignalPRO Engine
Anomaly Detection

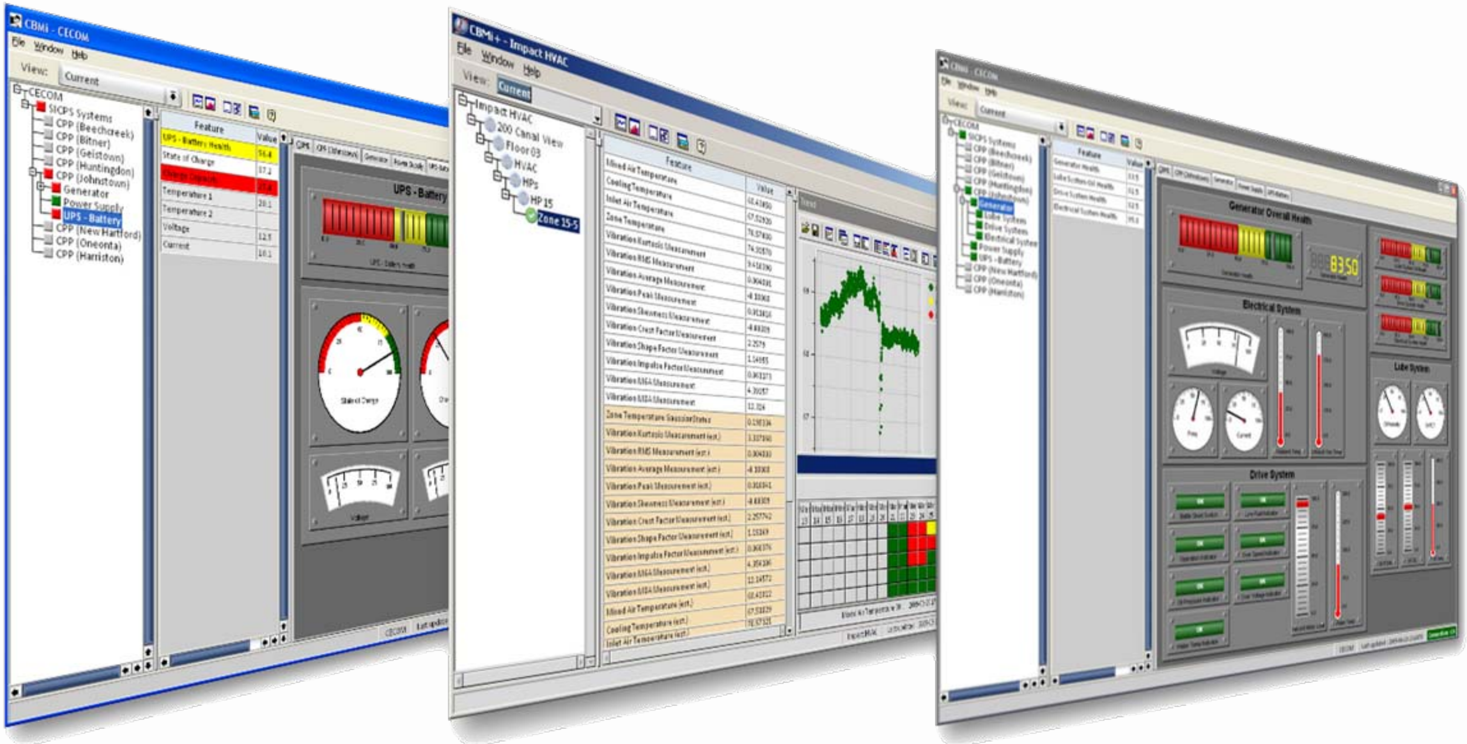
- Data driven system modeling engine
  - Transfer function uses “Similarity techniques”
- Input: Current vector of data & the model
  - Sensor or calculated data (e.g. efficiency)
- Output: Estimated values of the input data, assuming a healthy system.
  - A single point in time



Input 1	Input 2	Input 3	Input 4	Input 5
x.xx	xx.x	xxx	x.xx	xxx

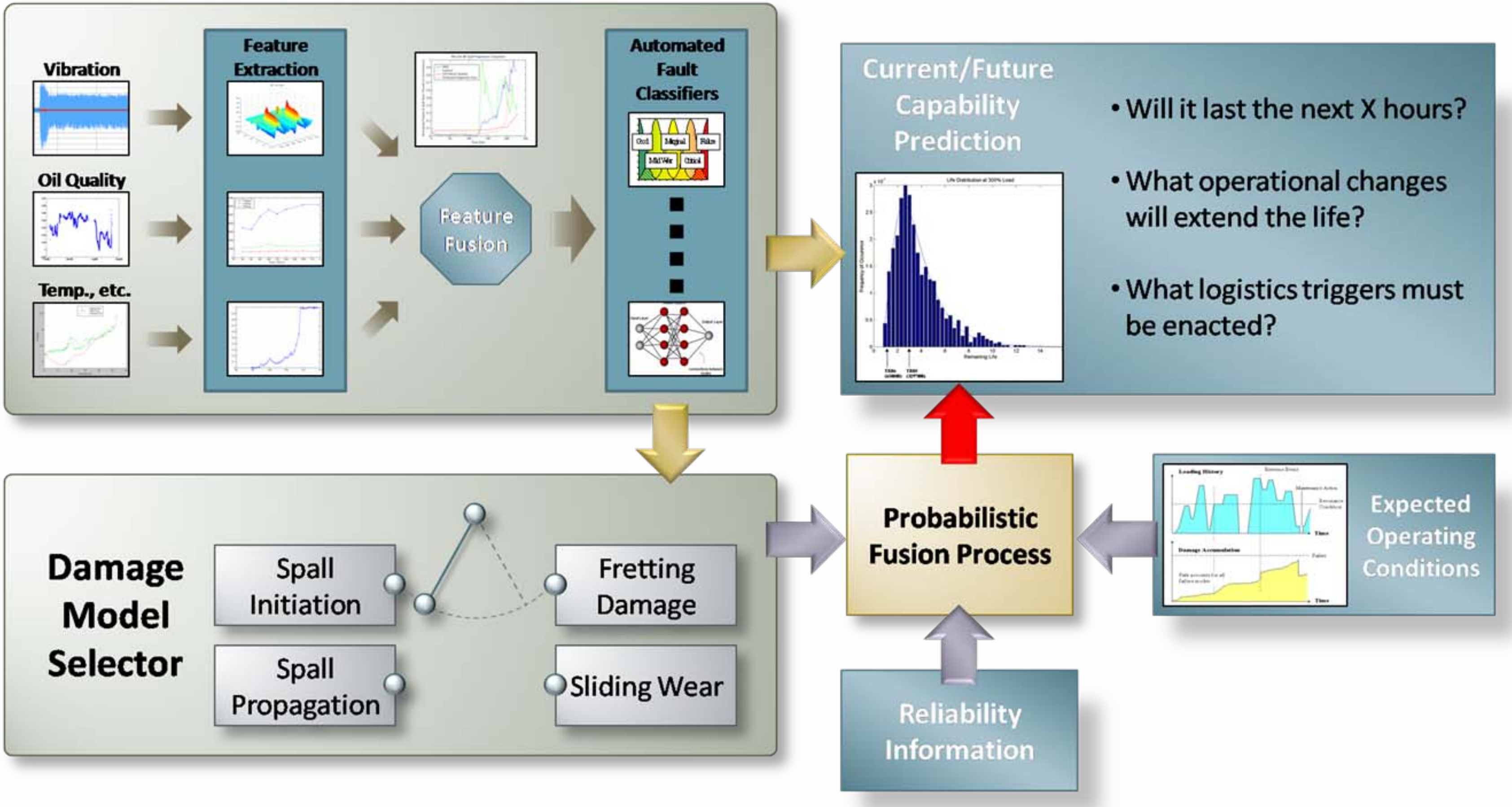
Output 1	Output 2	Output 3	Output 4	Output 5
x.xx	xx.x	xxx	x.xx	xxx

CBMi Client Interface



- Drill-downs
- Roll-ups
- Plant
- Equipment
- Sensor

General Approach to Model-Based Prognostics



Potential Benefits

- Continuous online health monitoring and assessment
- Optimum maintenance overhaul/repair schedules (for spare parts/personnel/ facilities/tools etc)
- Maintenance cost reduction
- Improvement of equipment reliability/safety (avoid catastrophic failures)
- Optimum planning schedules for equipment and facilities for specific missions
- Reduce Unjustified Repair/Removal rates and Increase Justified rates
- Reduced Can Not Duplicate (CND) rates
- Reduced maintenance induced failures
- Reduced numbers of tests to isolate failures
- Reduced repair times (enhanced availability)

30V Machining Center CBM Implementation Results

- Reduced shop maintenance cost of systems monitored to near zero
- *Increased uptime of 30V Machining Center by 80 Hours*
- Improved equipment reliability/safety (avoided any catastrophic failures)
- Enhanced optimum planning schedules for equipment for specific F-15 missions enhanced availability
- Reduce Unjustified Repair/Removal rates
- Reduced maintenance induced failures
- Continuous online health monitoring and assessment

Lessons Learned

- In general, equipment operators should be included in the planning early so that they understand that the monitoring system is designed to monitor the equipment, not them, and it should make their jobs easier.
- A non-real-time (NRT) operating system like Windows XP is not ideal when consistent power may not be available, even when a UPS is utilized to mitigate problems.
- Lack of key parameters such as operating speed and cycle definitions can be overcome with intelligent algorithm development.
- An industrial grade wireless modem can reliably provide network access when local infrastructure is not available, even in a manufacturing environment where large metallic structures and high current power lines are present.
- Extended periods of continuous monitoring may be required before the data required for fault isolation algorithm development is provided, particularly from a machine which is typically reliable.
- High quality 50’ accelerometer cables and superior signal conditioning kept electromagnetic noise from becoming an issue, even though the cabling was run in parallel to the motor drive lines.

Going Forward

- Implement CBMi at WR-ALC
- Fully integrate the general approach to model-based prognostics with CBMi so that it can be leveraged at WR
- Apply advanced algorithms:
  - FirstCheck: sensor validation
  - ImpactEnergy & IE FIS: bearing incipient fault detection
  - GearMod: drivetrain and gearbox diagnostics
- Expand sensing to more machines
- Target problem areas instead of reliable machines to fully realize the ROI