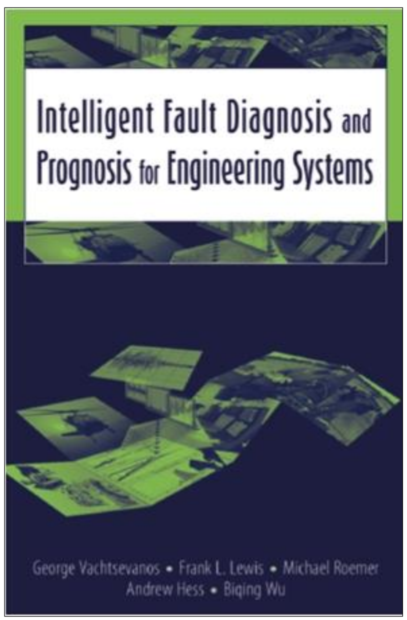
A NOVEL APPROACH TO INTEGRATED VEHICLE HEALTH MANAGEMENT



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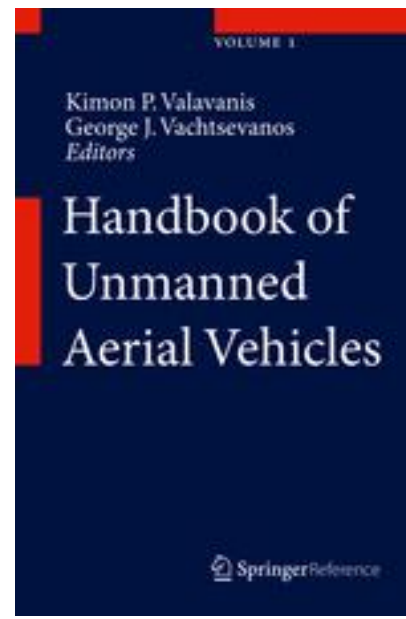
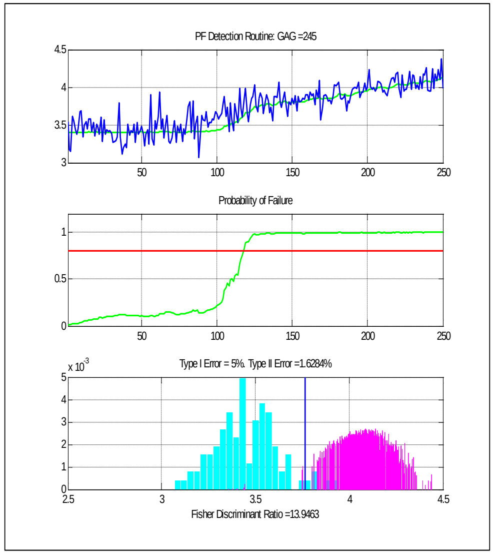
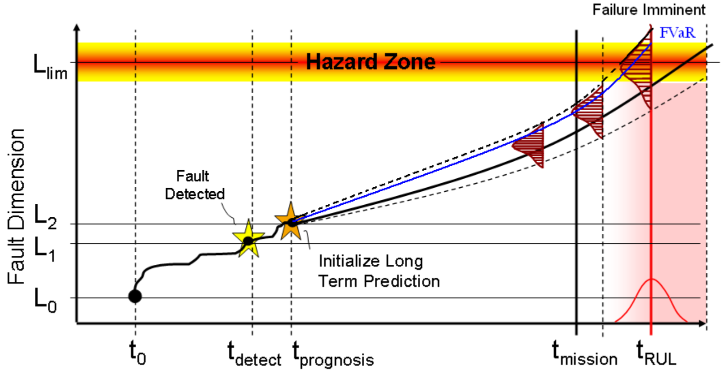
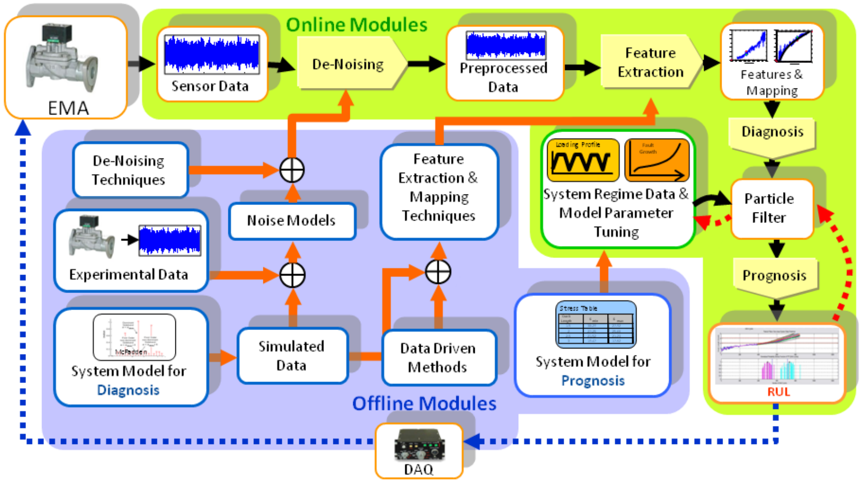


The Technology Base

- ***Prognostics &Health Management Technologies***
- ***Integrated Vehicle Health Management***
- ***Autonomy and Autonomous Systems***
- ***Resilient Design & Operation of Aerospace Systems***
- ***Safety Assessment and Risk Management***
- ***Swarms of Autonomous Systems***
- ***TRL 4-6***







Current Infrastructure Needs

Ability to Predict Future Health Status

MAX SGR

Ability to Anticipate Problems & Req'd Maint Actions

Max Life Usage

Better FD/FI Efficiency

Quick Turn Around Time

Small Logistics Footprint

No RTOK

Performance Based Maint

Accurate Parts & Life Usage Tracking

Low # of Spares

No False Alarms

No Surprises

Maintenance Mgt

Opportunistic Maintenance

Mission Planning

Short & Responsive Supply Pipeline

No/Limited Secondary Damage

No/Min Inspections

Limit Impact of Quality Control Problems

Too Large & Costly

System Performance Feedback

Immediate Access to all Available Information

Prognostics - Definitions

- Health-based vs Usage-based Prognosis
- Prognostics vs Trending
- Uncertainty Representation, Propagation and Measurement
- Performance Metrics – Accuracy, Precision and Convergence

Uncertainty – The Achilles' Heel of PHM

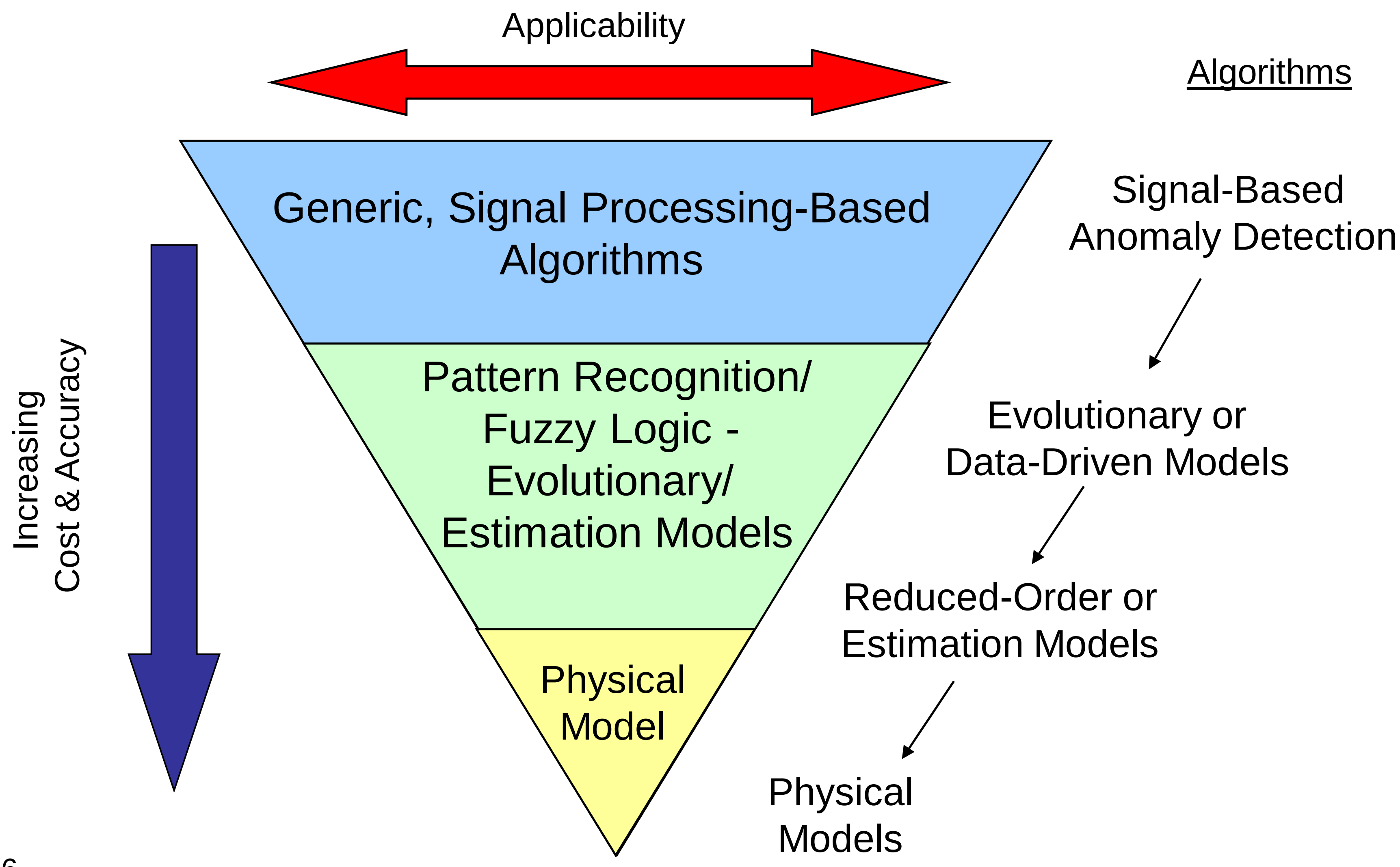
- **Uncertainty representation – the uncertainty tree**
- **Uncertainty propagation – inherent property of prognosis**
- **Uncertainty management: Kernel functions (tails of distributions); Feedback loops for model parameter updating as data is streaming in**

Prognostics and Health Management

- **Why Choose This Technology?**
  - Enable Condition Based Maintenance (CBM) and Asset Management Concepts
  - Enhance Safety
  - Increase Availability and Readiness
  - Eliminate False Alarms
  - Eliminate Cannot Duplicate (CND) and Retest OK (RTOK)
  - Reduce Life Cycle Costs
  - Maximize PHM Benefit from Limited Specialized Sensors
  - Take Max Advantage of the “Smart” Digital Systems

Natural Evolution of Legacy Diagnostic Capabilities Coupled with the Added Functions, Capabilities, and Benefits offered by New Technologies

Select and Develop PHM Algorithms



PHM Technology Needs

What do I need in order to apply PHM technologies to an aircraft?

1. **Data! Data! Data!**
2. **Sensors and Sensing Strategies**
3. **Computing and Communications**
4. **HUMS Equipment – H/S**
5. **Algorithms**
6. **Expert Personnel**
7. **Acceptance by Management**

CBM+/PHM – The Cost

- “There is no free lunch”
- Sensors and sensing requirements
- Health and usage monitoring hardware/software
- Communications and computing requirements
- Land-based data warehouses
- Expert personnel for all phases of CBM+/PHM technologies
- Acceptance by management/decision makers/bean counters

Success Criteria for PHM/CBM+

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

Data Analytics – Novel PHM Technologies

- Data Pre-processing for improved fault signal to noise ratio – filtering, blind deconvolution, PCA, etc.
- Feature or Condition Indicator (CI) extraction and selection – performance metrics
- Novel Deep Learning (DL) methods for feature extraction/selection and classification/control
- Health Indices

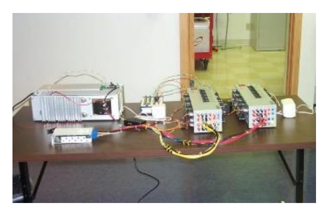
Electronics/Avionics PHM

Failure Mode Analysis
Identify Known Failure Modes

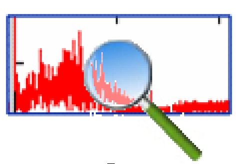
HALT Test
Highly Accelerated Life Testing

$$f_1 = t_0 \sum_{i=1}^{M} \left[\Delta t_i \cdot e^{-\frac{E_a}{kT_j}} \right]$$

Usage Models
Quantify Acceleration Factors



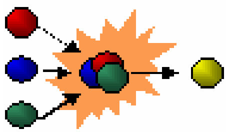
Experiment
Seeded Fault Testing



Analyze
Identify Prognostic Features

$$f_2 = \frac{V_{o,\max} - V_o(t)}{V_{o,\max} - V_{o,\min}}$$

Feature Model
Quantify Failure Precursors



Data Fusion
Combine Evidence Sources

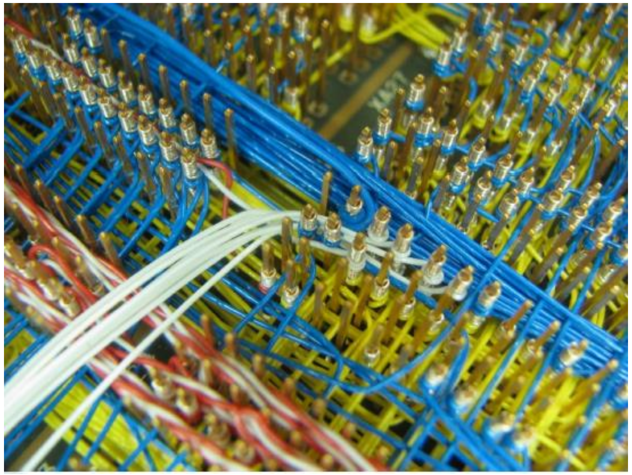
Validation
Confirm prognostic approach

Electronic Prognostics

Wiring Faults

It is the Wiring Stupid!!

It is estimated that about 46% of aircraft faults are attributed to wiring faults/failures



PHM Applications to Rotor Wing Aircraft

- Main transmission gearbox (DARPA Prognosis Program)
- Oil cooler bearing (ARL)
- Intermediate gearbox (ARL)
- Integrated Vehicle Health Management
- Avionics/Electronics (Army advanced diagnostics)
- Corrosion detection and prediction (AF)
- Blades of an HPC Disk-diagnostics/prognostics (P&W)
- Autonomy and Autonomous Systems

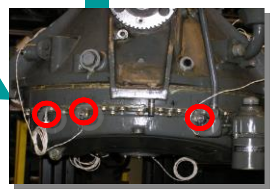
The System

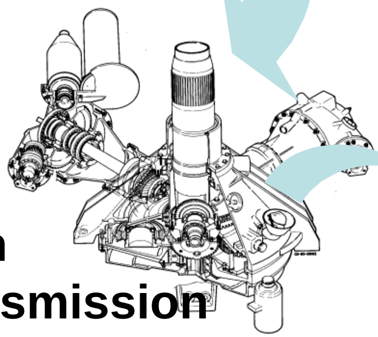
Anomaly Detection Routine

- Prevent unscheduled maintenance

- Assist pilot in making intelligent decisions about air-worthiness

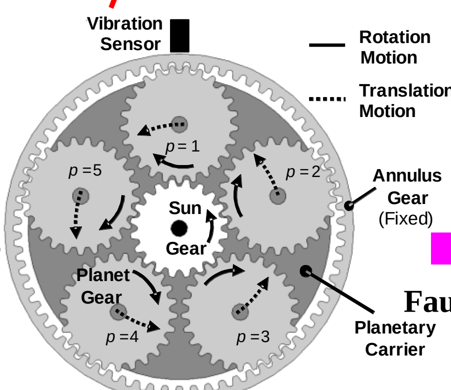
VMEP/HUMS modules



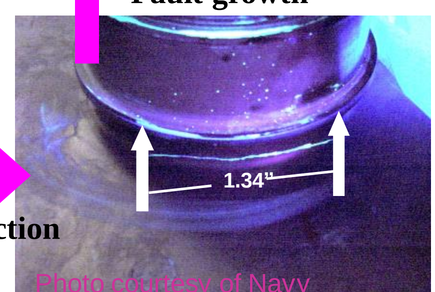


Main Transmission

fitted with **PHM/VMEP sensors** to monitor critical components e.g. **gear plate**



Fault growth

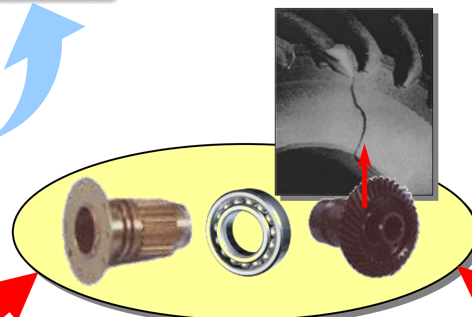


Fault injection

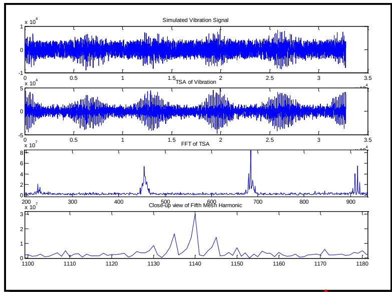
Testing, Modeling, & Reasoning Architecture

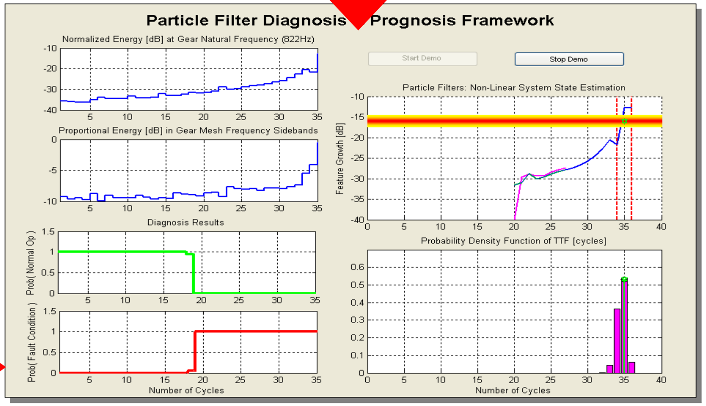
VMEP/ HUMS modules

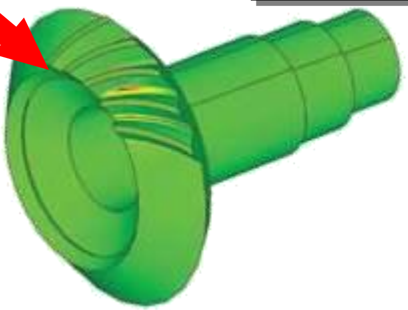
- **Prevent unscheduled maintenance**
- **Assist the pilot in making intelligent decisions about air-worthiness**



Intermediate Gearbox (IGB) fitted with **VMEP sensors** to monitor components





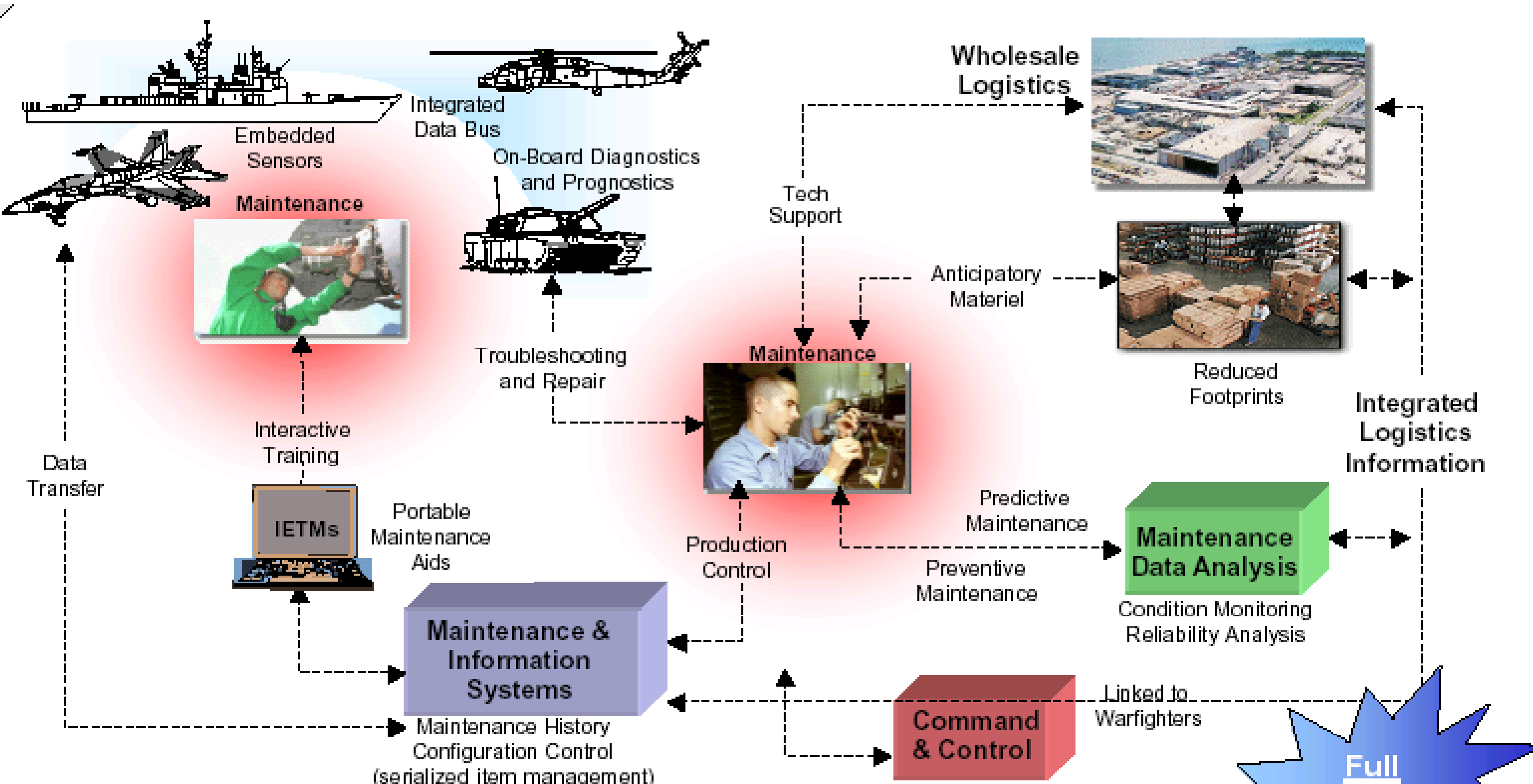


Testing/ Seeded Fault Data

Modeling

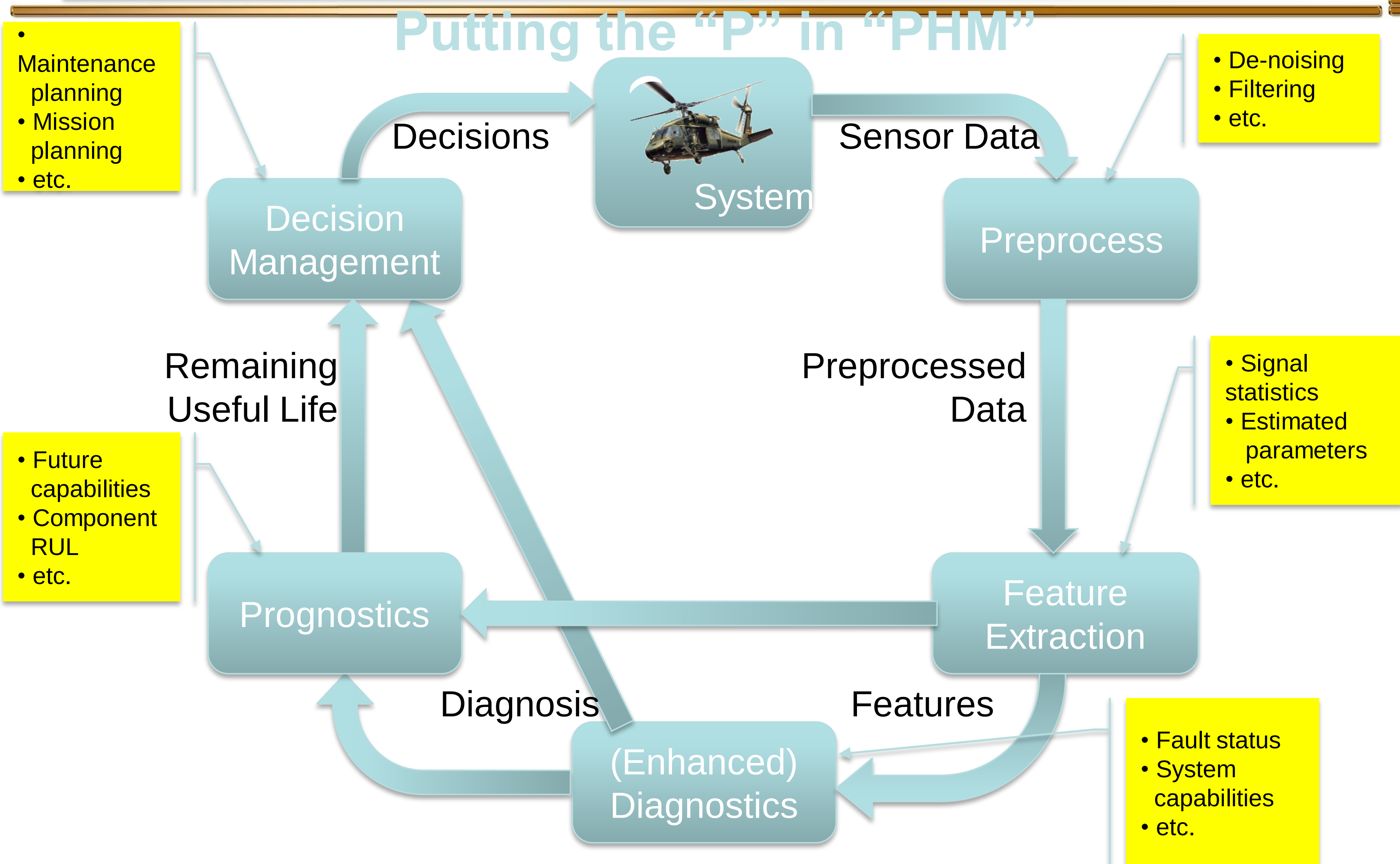
Reasoning Architecture for Diagnosis-Prognosis

CBM+: Maintenance-Centric Logistics Support for the Future



- Real-time status of prime mission equipment
- Minimal maintenance footprint
- Integrated supply/maintenance systems via serial item management

Integrity Management: IVHM



F-35 Prognostic Candidates

Actuator Leakage and Wear

Power and Cooling Turbo Machine Life, Oil Condition, Oil Servicing and Filter Condition

Heat Exchangers

Generator Oil Level Hydraulic Filters, Pump, and Hydraulic Fluid Level

Engine

Battery

Oxygen Generator

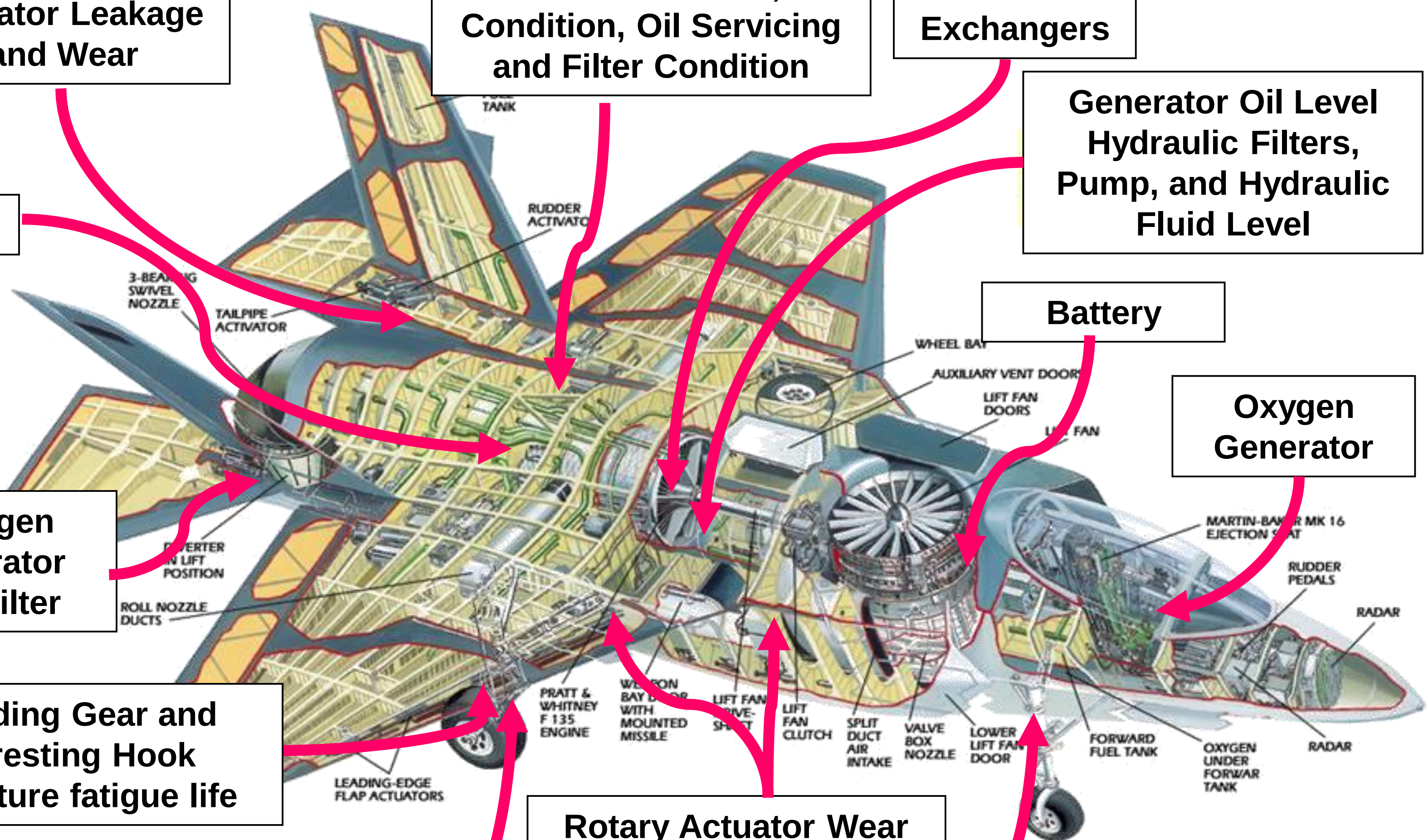
Nitrogen Generator and Filter

Landing Gear and Arresting Hook Structure fatigue life

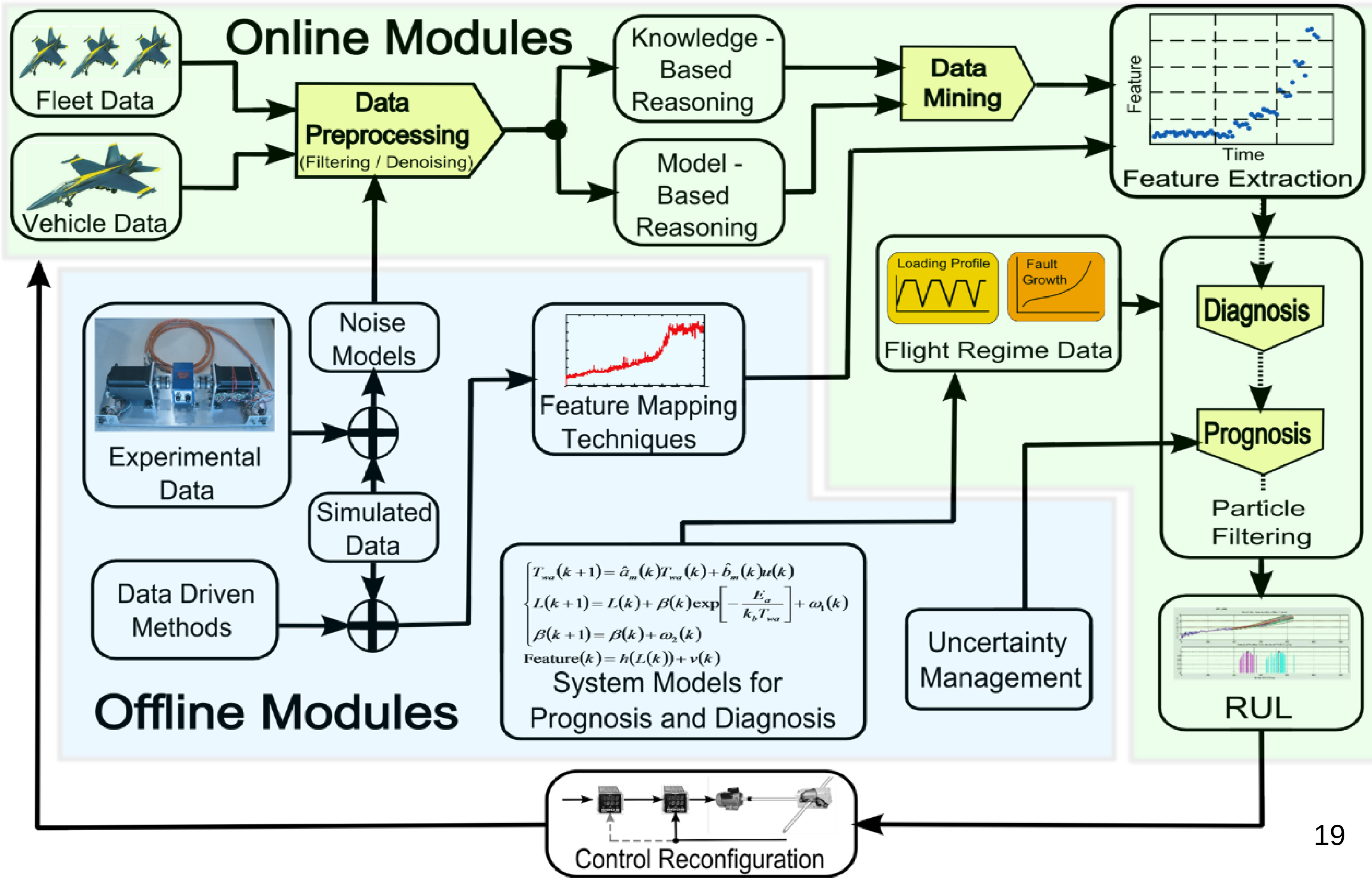
Landing Gear Strut Pressure and Fluid Level

Rotary Actuator Wear

Nose Wheel Stability



The On-Board PHM Architecture



The Particle Filter Framework – A Bayesian Estimation Approach to Prognosis

- **What are Particle Filters?** An application of Bayesian state estimation:
  - Estimation of the posterior *pdf* of a state, x_k, based on all previous measurements, $z_{1:k}$
- The estimation involves two main steps: Prediction step / Update step

❖ **Prognosis: Uncertainty Management**

Corrections on TTF estimates

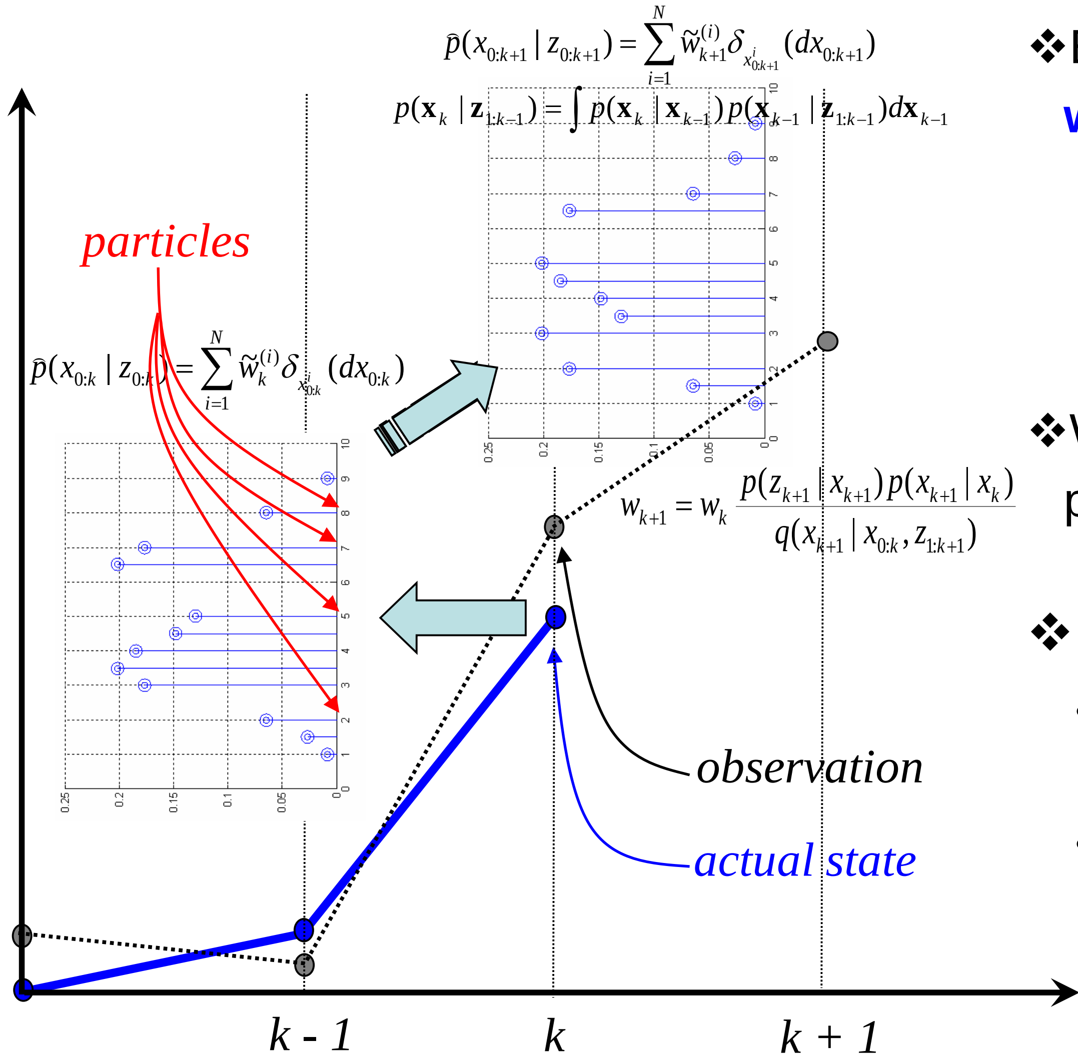
❖ At every time instant t_{o+j}, $j = 0 \ldots k$, the particle filter estimate is updated considering the new observation z_{o+j} and a long term prediction is generated.

❖ The predicted TTF pdf and its expected value T_k are computed.

❖ Define C_j as the set of corrections that were applied to the TTF estimation, given the observations until z_{o+j}.

The Particle Filter Framework

❖ **Particle:** Possible realization of the states of a process.



❖ Every particle is associated with a **weight**

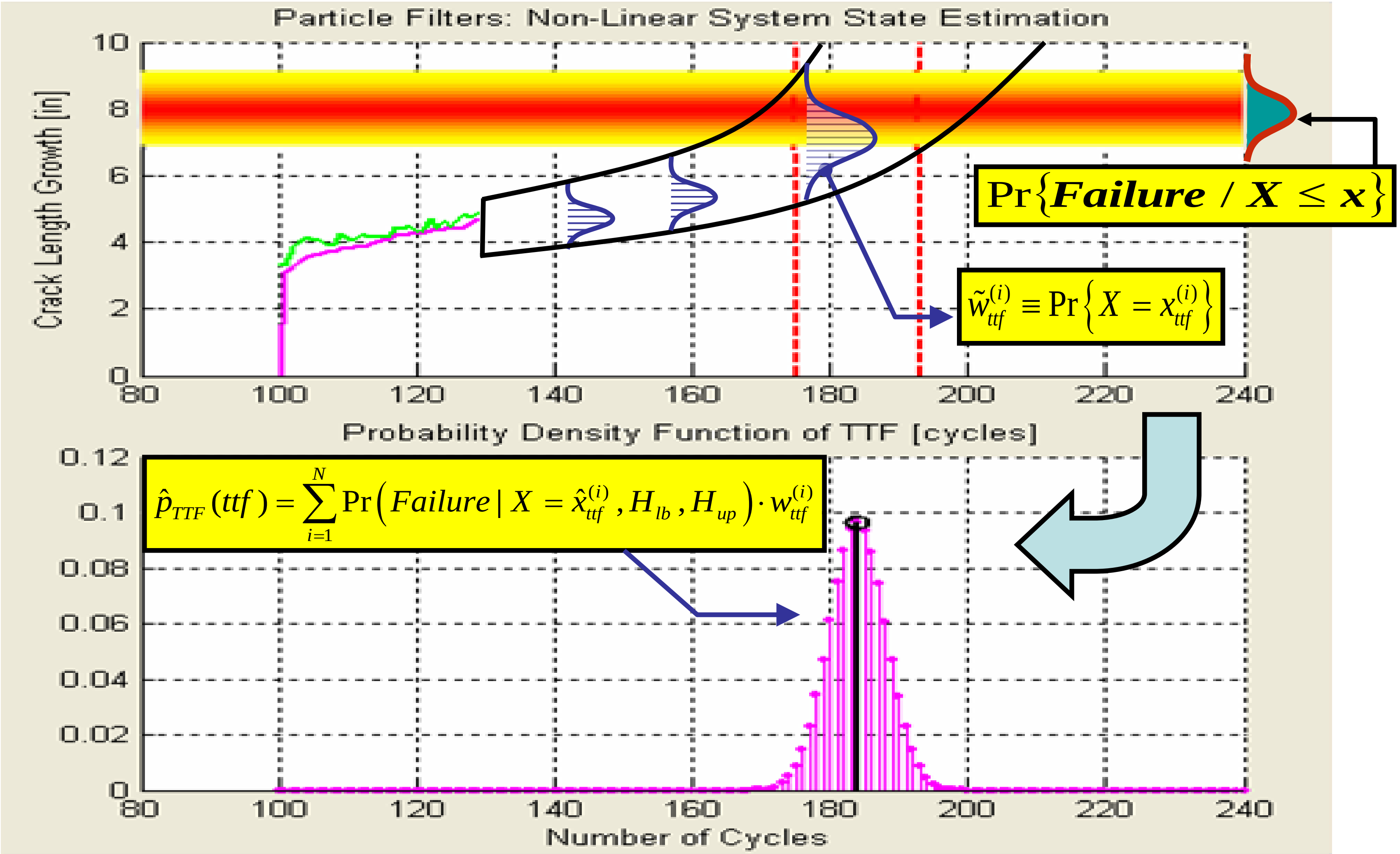
- **Particles, together with their weights, represent a sampled version of the PDF.**

❖ We only need to study the propagation of weights in time!

❖ **Steps**:

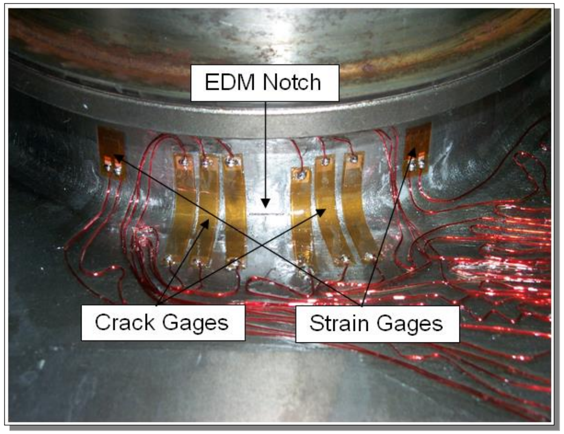
- **Predict the "*a priori*" PDF parameters, using the model**
- **Update parameters, given the new observation**

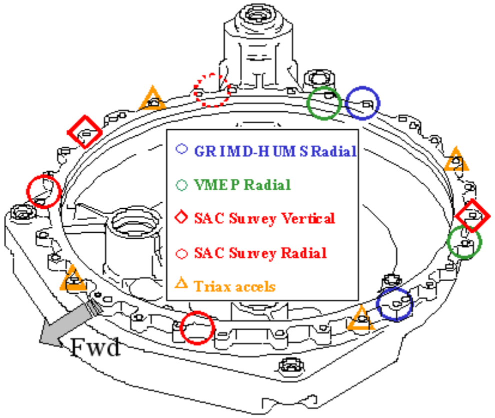
The Particle Filter Framework

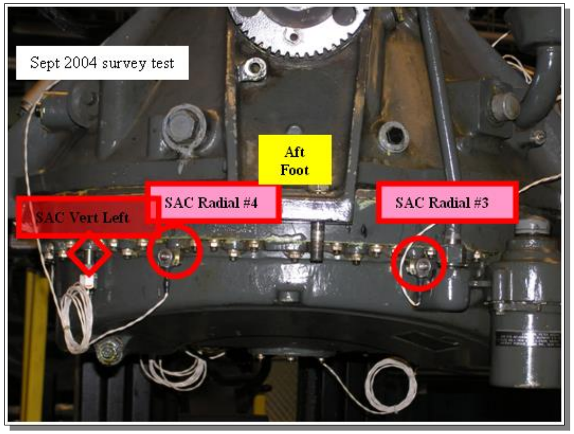


Particle Filtering Fault Detection and Identification Framework

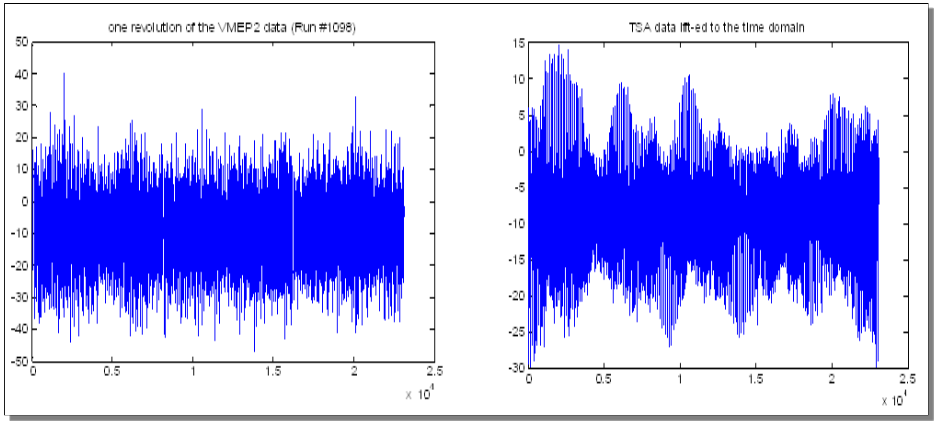
Seeded Fault Test

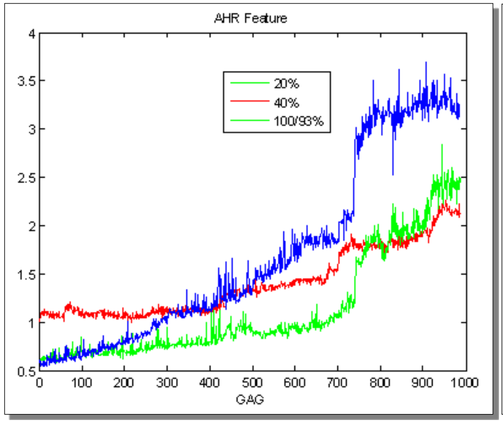


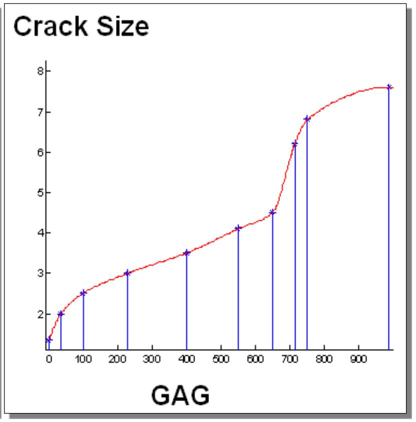




Test Results





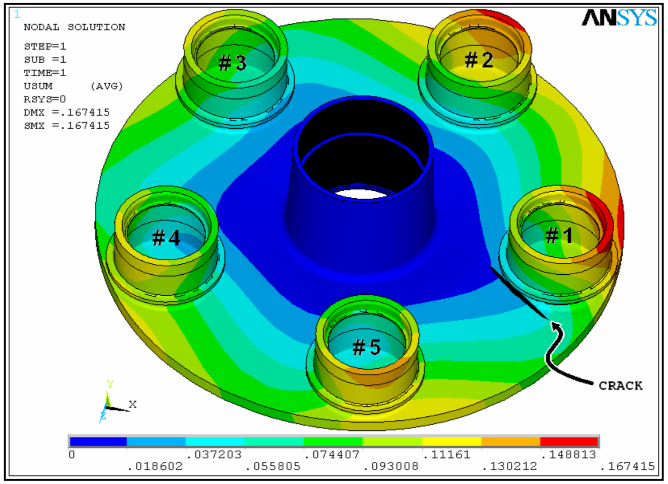


FDI Case Study: Cracks in Planetary Carrier Plate

- <u>Particle Filter Fault Detection Module</u>

  - System: Gear plate of the main transmission of a helicopter
    - Accelerometers mounted on its frame.

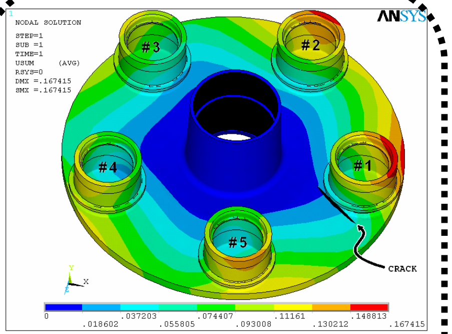
  - Objective: Analyze the growth of a crack in a seeded fault test.
    - <u>*Normal* condition</u>: crack is growing very slowly or not growing at all
    - <u>*Faulty* condition</u>: abrupt change in the growth rate.

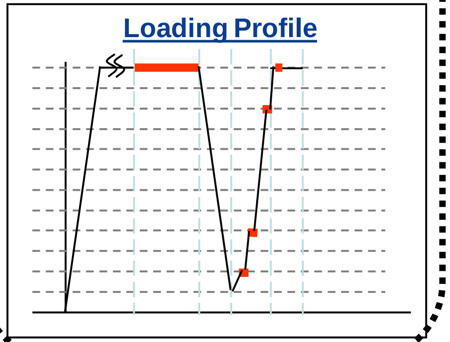


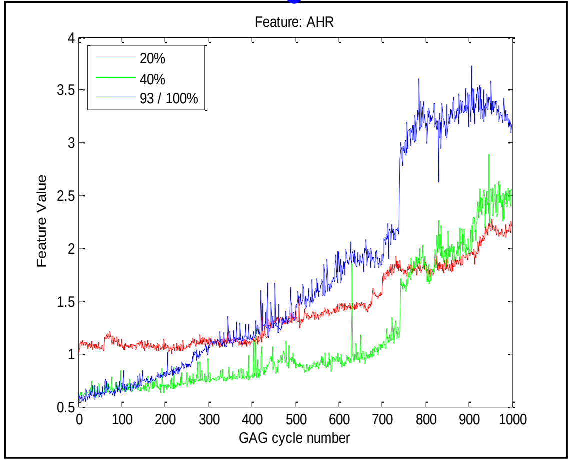
The Particle Filter Framework

$$
\begin{cases}
L(t+1) = L(t) + C \cdot \alpha(t) \cdot \left\{ \left(\Delta K_{inboard}(t) \right)^m + \left(\Delta K_{outboard}(t) \right)^m \right\} + \omega_1(t) \\
\alpha(t+1) = \alpha(t) + \omega_2(t) \\
\Delta K_{inboard}(t) = f_{inboard}\left(\mathrm{Load}(t), L(t) \right) \\
\Delta K_{outboard}(t) = f_{outboard}\left(\mathrm{Load}(t), L(t) \right)
\end{cases}
$$

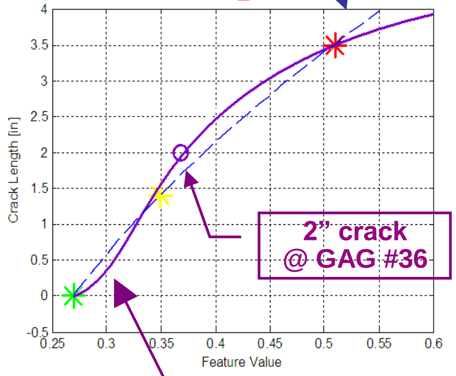
$$
\mathrm{Feature}(t) = h(L(t)) + v(t)
$$







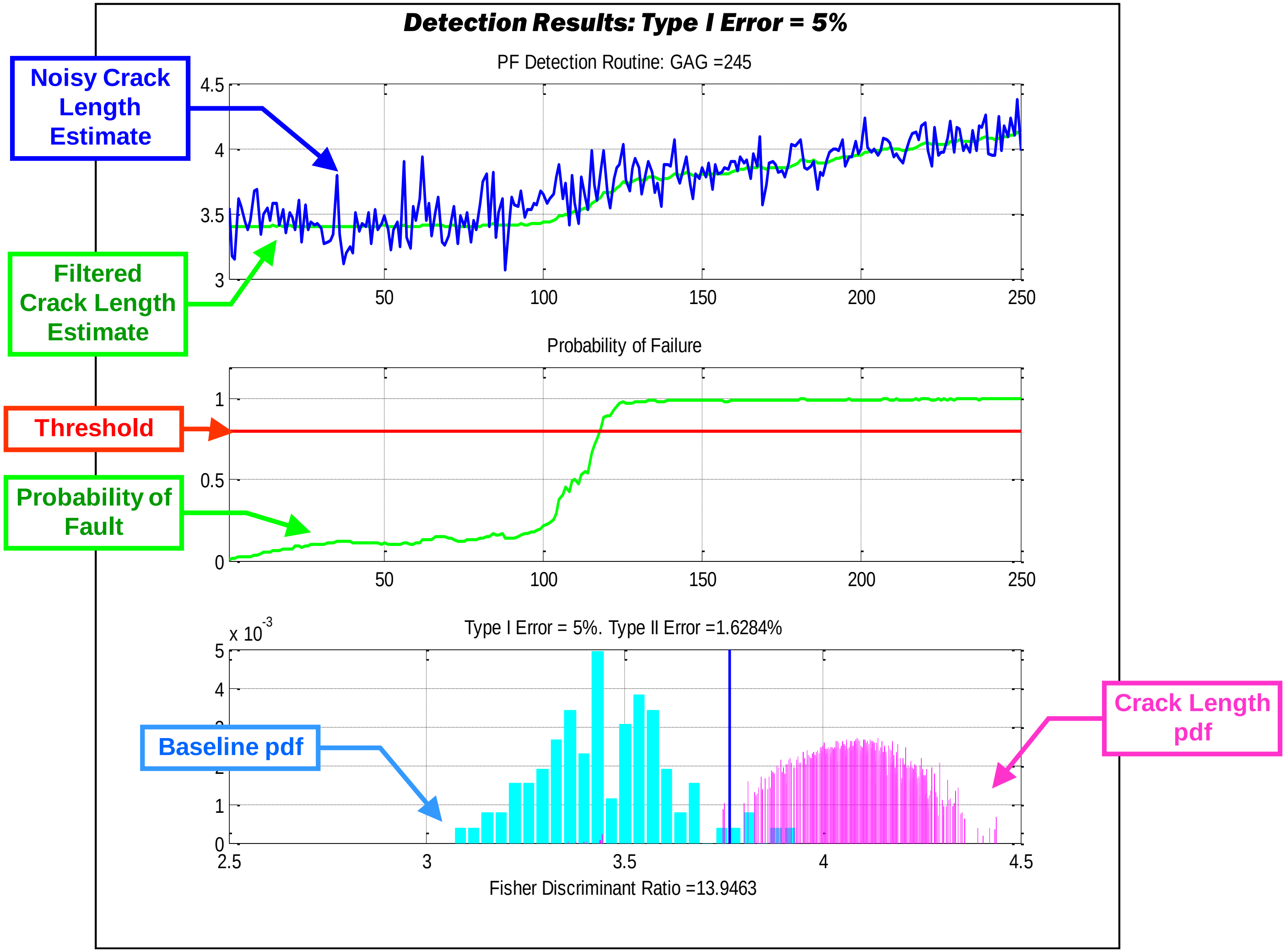
Pretest mapping of Feature→ Crack Length



2" crack @ GAG #36

Updated mapping of Feature→ Crack Length

- [FDI Case Study]: Cracks in Planetary Carrier Plate

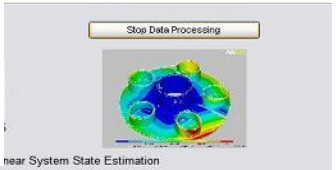


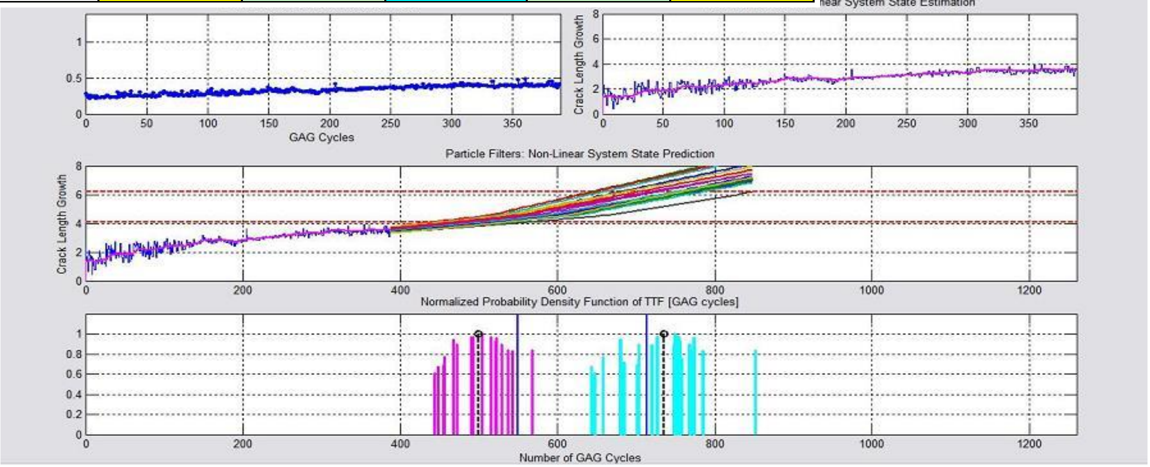
• Prognosis Case Study: Crack in Planetary Carrier Plate

Measured Crack Length		GaTech Predictions				
GAG	Total Crack Length (inches)	-3 sigma	-95%	Mean	+95%	+3 sigma
0	1.34	N/A	N/A	1.34	N/A	N/A
36	2.00	0.74	1.03	1.60	2.17	2.46
100	2.50	1.93	2.09	2.40	2.71	2.87
230	3.02	2.73	2.79	2.90	3.01	3.07
400	3.54	3.41	3.54	3.80	4.06	4.19
550	4.07	3.85	4.11	4.30	4.60	4.75
650	4.52	4.20	4.48	4.71	5.08	5.70
714	6.21	5.27	5.36	5.55	5.74	5.84
750	6.78	6.38	6.42	6.61	6.76	6.84

Initial Prognosis Results:

(No Ground Truth data available)
Hazard Zone around 4.5”

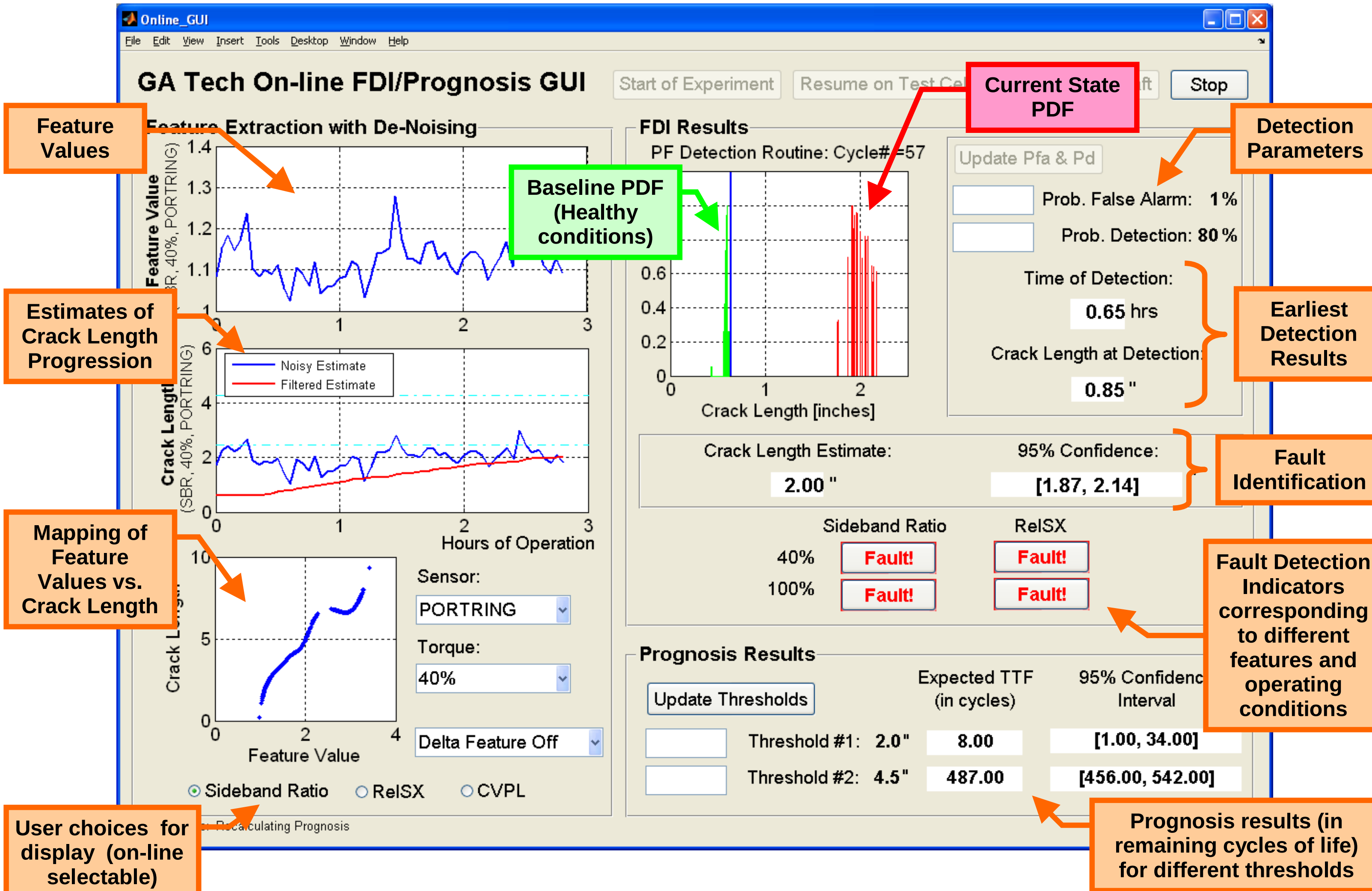




Final Prognosis Results:

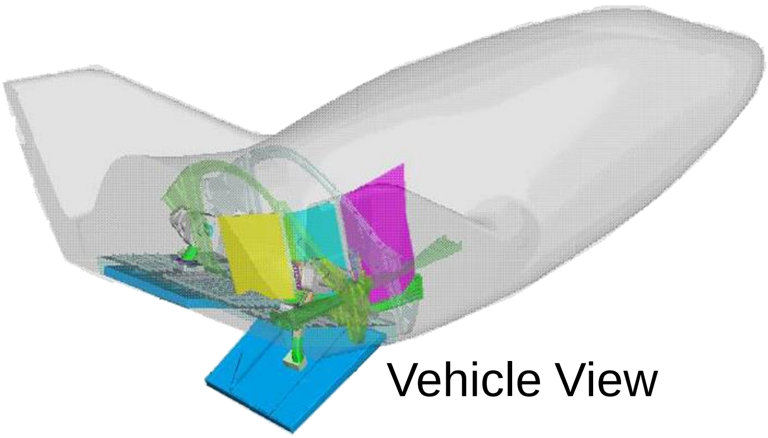
Several Hazard Thresholds i.e. 4.1” 6.2”, etc.

- **Prognosis Case Study: Crack in Planetary Carrier Plate**

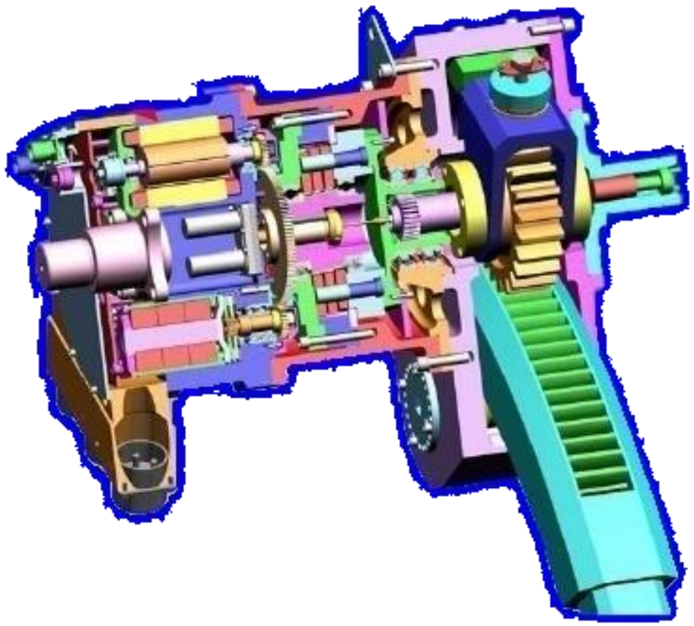


Electromechanical Actuator (EMA) Anomaly Detection

- Avionics flight actuator
- Controls flap and rotor position
- Critical system component
- High reliability required



Vehicle View



Actuator Assembly

Flap Actuator

Case Study: Actuator Fault Modes

<u>Fault Modes Identified</u>

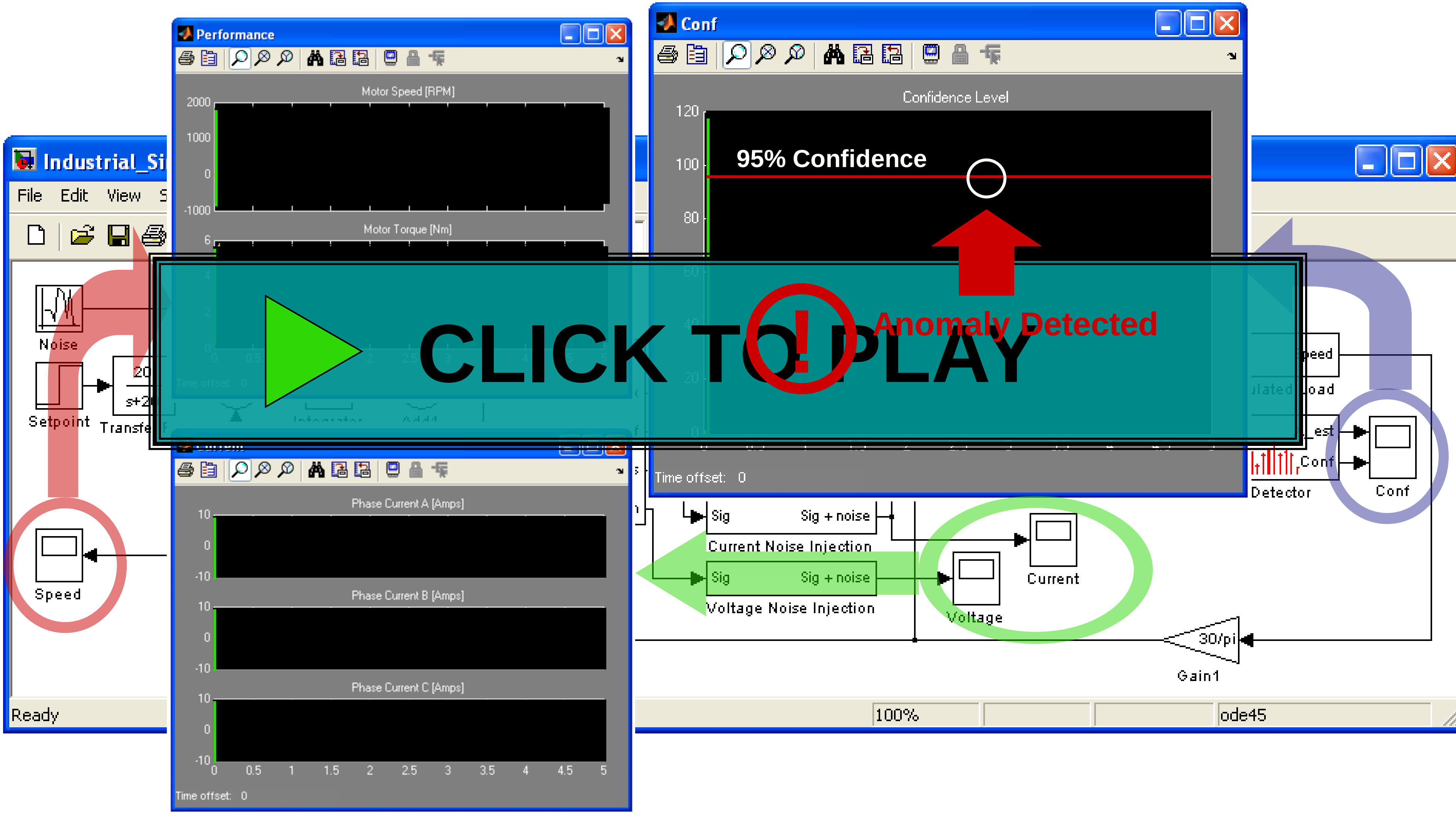
- Stator windings shorts (turn to turn/ turn to ground)/ open faults
- Bearings (friction induced faults), spalling, cracks, etc.
- Resolver winding insulation faults (shorts / open faults)

Brushless Motor

Resolver Sensor (w/ Electronics)

Motor Bearing

Anomaly Detection of EMA Winding Fault (Simulink Demo)



Failure Prognosis

The Opportunity

Condition Based Maintenance (CBM) promises to deliver improved maintainability and operational availability of military assets while reducing life-cycle costs

The Challenge

Prognostics is the Achilles heel of CBM systems - predicting the time to failure of critical systems/components requires new and innovative methodologies that will effectively integrate diagnostic results with maintenance scheduling practices

"Prediction is rather difficult particularly when it concerns the future"
- Niels Bohr

Failure Progression Timeline

Prognostics

Need: To Manage Interaction between Diagnostics and Prognostics

Diagnostics

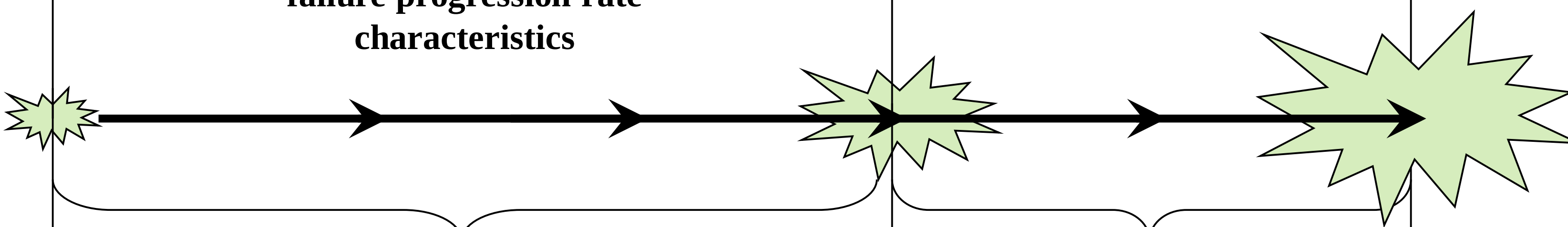
Very early incipient fault

System, Component, or Sub-Component Failure

Secondary Damage, Catastrophic Failure

Proper Working Order - New

Need: Understanding of fault to failure progression rate characteristics



Predicted useful life remaining

Determine effects on rest of aircraft

State Awareness Detection

Desire: Advanced Sensors and Detection Techniques to "see" incipient fault

Develop: Useful life remaining prediction models – physics and statistical based

Need: Better models to determine failure effects across subsystems

The Goal is To Detect "State Changes" as Far to the Left As Possible

Prognosis: A Model-based and Measurements Approach

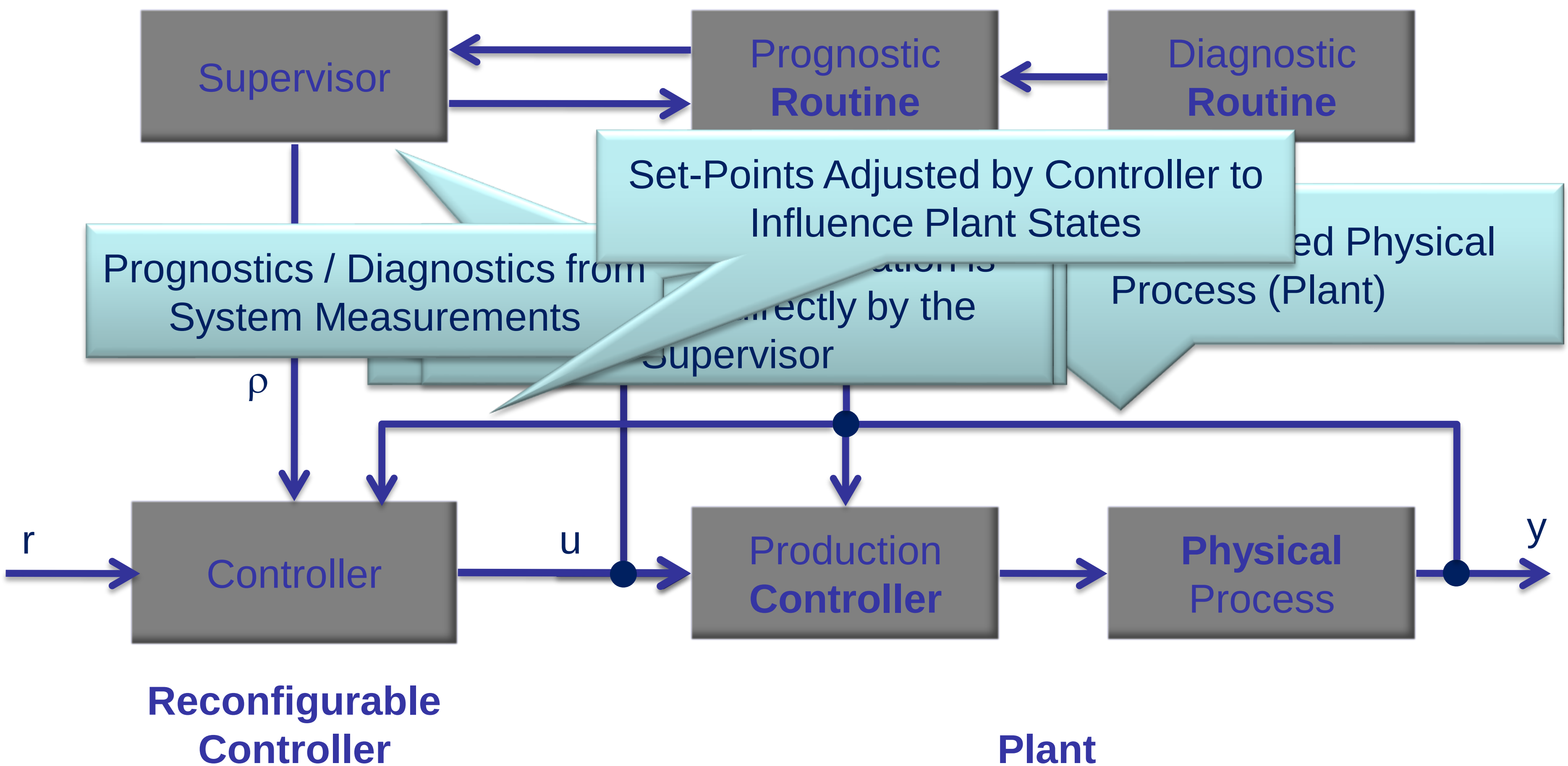
Our Approach:

Utility of a fault model, a feature vs. fault dimension mapping, streaming data and a particle filtering framework (Bayesian estimation) for long-term prediction

Fault Tolerant Control

Designing High-Confidence and Reliable Dynamic Systems

Control Architecture - Reconfigurable Control



The Control Architecture

Optimization Criteria for MPC

Health vs. Performance

Assumptions

RUL Related States vs. Tracking Error

Adaptation parameter ρ adjusts cost

- The cost function:

$$J = \min_{\Delta\mathbf{u}} \int_{t_0}^{t_0+T} [(\mathbf{x}-\mathbf{x}^\star)^\top (\quad \mathbf{Q})(\mathbf{x}-\mathbf{x}^\star) + \Delta\mathbf{u}^\top \mathbf{R} \Delta\mathbf{u}] dt$$

- Subject to the constraints,

$$\begin{cases} \Delta\mathbf{u}_{\min} \leq \Delta\mathbf{u}(t) \leq \Delta\mathbf{u}_{\max} \\ \mathbf{u}_{\min} \leq \mathbf{u}(t) \leq \mathbf{u}_{\max} \end{cases}$$

Complex Systems (Complexity Theory)

- Complex systems can be considered "system of systems" with hierarchical sets of subsystems or components
  - Overall system behavior results from the interaction of subsystems

- Increasing complexity may result in:
  - More unpredictable emergent behaviors
  - Increasing vulnerability to severe disturbances (failures)

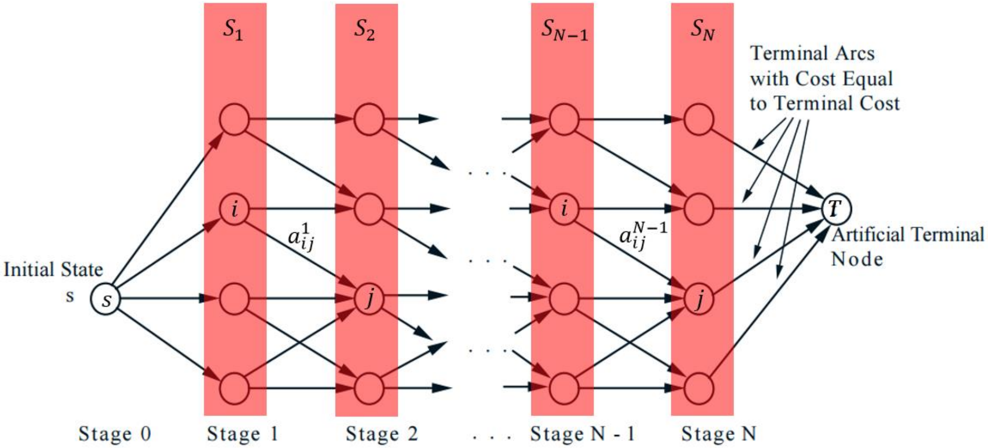
Fleet of Aircraft – the Enterprise Level

- Data acquisition and data analytics from a fleet of aircraft
- Prognostics and Health Management at the fleet level
- Objective: Which assets are ready to fly the next five missions?
- Data aggregation from multiple vehicles
- Data fusion at all levels
- Decision making from multiple asset sources
- Uncertainty representation and management

Dynamic Programming

- The optimal path will be evaluated by finding the path with maximum total expected reward using the Bellman equation in a finite horizon window
  - Value function is defined as:

$$V(s) = \max(R(s,a) + \gamma \sum T(s'|s,a)V(s'))$$



Reliability and Life Cycle Management

- Reliability analysis tools/methods:
- Data and data mining, modeling tools/methods
- Prognosis of remaining useful life or time to failure of failing systems/components
- First order and higher order reliability methods
- Optimization tools
- Risk assessment and management

➢ ***Probabilistic methods for reliability analysis***

Lifecycle Management- The Main Modules

Reliability Analysis (Life Distribution)

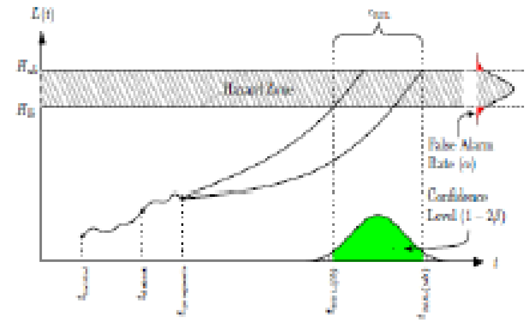
↓

Life Decision (MTBR, etc.)

CBM & PHM

↓

Adjusted Life Decision (Maintenance Options)



Stage I: Long-term Planning

Stage II: Short-term Planning

- Physics-based Life Modeling
- Reliability Analysis

- Condition-based Monitoring
- Risk-based Inspection
- Degradation Prognostics

Maintenance Execution

Past → Present → Future

Safety Assurance - Lifecycle Management

Objective:

- ❖ Given critical component failure(s), build a system lifecycle model for optimizing system performance: lifespan, maintenance cost, safety, etc.

- ❖ Optimize system design on the basis of safety/reliability analysis methods

- ❖ Concepts of envelope protection make use of on-line learning adaptive neural networks to generate on-line dynamic models exploited to estimate limits on controller commands.

Safety Assurance – A Probabilistic Design Approach

- Define safety margins
- Probability of failure
- First-order safety/reliability analysis
- Risk index
- Risk control
- Risk is quantified in terms of the scenario of events leading to hazard exposure, the likelihood of the scenario and a measure of its consequences

Safety Margins

- **Safety Margins -** Safety margins are designed as an automatic envelope protection system.

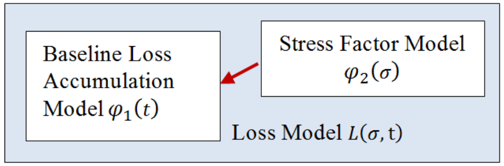
- The system's behavioral modes may escape from the stable region of operation, under severe stress conditions, endangering its safety and survivability.

- Concepts of envelope protection make use of on-line learning adaptive neural networks to generate on-line dynamic models exploited to estimate limits on controller commands.

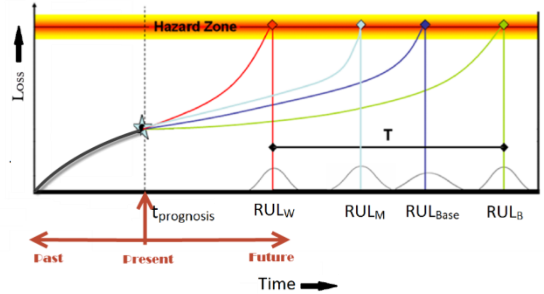
Overall Architecture

Engineering System

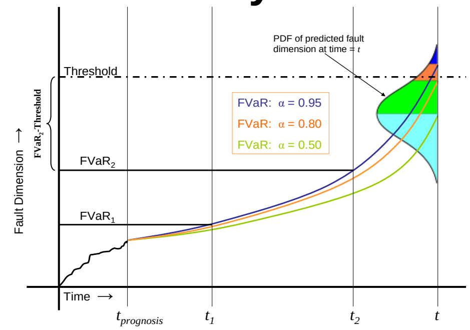
Life Loss Modeling under Stressors



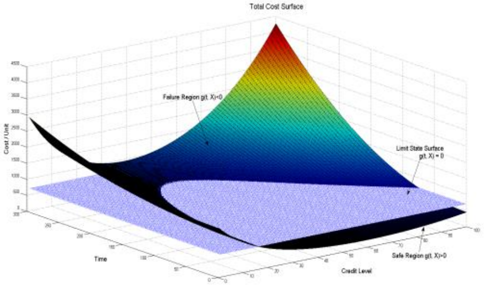
Long-term Prognosis



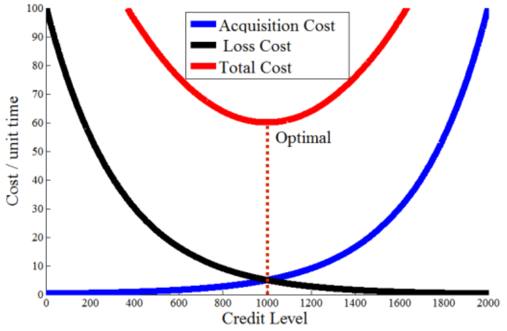
Prognosis-based Risk Analysis



Safety Analysis



Life Cycle Optimization



Potential Benefits

- Provide exactly the functionality needed, exactly when needed
- Optimum life cycle management via tools/methods for modeling, detection, prediction and fault-tolerant control of critical assets
- An open-ended architecture so that it can be improved, upgraded, and reconfigured, rather than replaced
- Application domains: autonomous systems, aerospace assets, industrial and manufacturing processes

A new paradigm in the way we design and operate complex systems

Concluding Comments

- The need: Data! Data! Data!
- Seeded Fault Testing
- Data Warehousing / Knowledge Bases
- Prognosis-The Achilles' Heel of CBM/PHM
- The Expanding Customer Base: Maintainer, Field Commander Manager, Designer
- The Business Case: ROI

Where do we go from here?

- Improved coupling between design, health management and fault-tolerant control
- The human-system interface
- The uncertainty issue
- Probabilistic design methods

- **DESIGN OF FAULT-TOLERANT HIGH-CONFIDENCE SYSTEMS**