PRESENTATION ONLY

Fundamental Technology Development for Gas-Turbine Engine Health Management

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Integrated vehicle health management technologies promise to dramatically improve the safety of commercial aircraft by reducing system and component failures as causal and contributing factors in aircraft accidents. To realize this promise, fundamental technology development is needed to produce reliable health management components. These components include diagnostic and prognostic algorithms, physics-based and data-driven lifing and failure models, sensors, and a sensor infrastructure including wireless communications, power scavenging, and electronics. In addition, system assessment methods are needed to effectively prioritize development efforts. Development work is needed throughout the vehicle, but particular challenges are presented by the hot, rotating environment of the propulsion system. This presentation describes current work in the field of health management technologies for propulsion systems for commercial aviation.

Fundamental Technology Development for Gas-Turbine Engine Health Management

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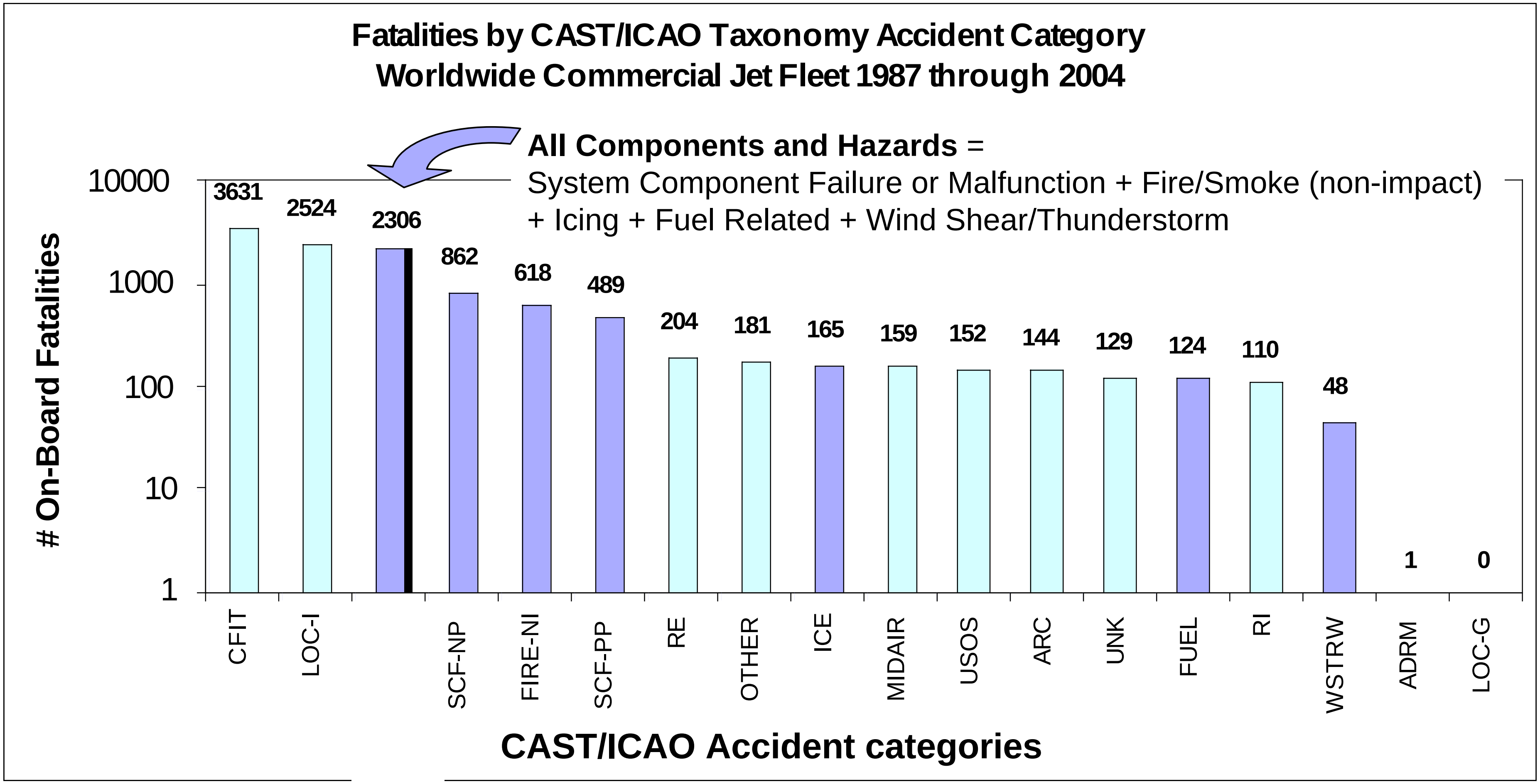
Outline:

- Motivation for health management technology development from a commercial aircraft perspective
- Technology gaps for gas-turbine engine health management
- Fundamental technology development for gas-turbine engine health management
- Summary

Health Management Motivation: Commercial Aircraft Safety

Component failure/malfunction plus hazards contribute to 24% of on-board fatalities. IVHM technologies can reduce system and component failures as causal and contributing factors in aircraft accidents and incidents.



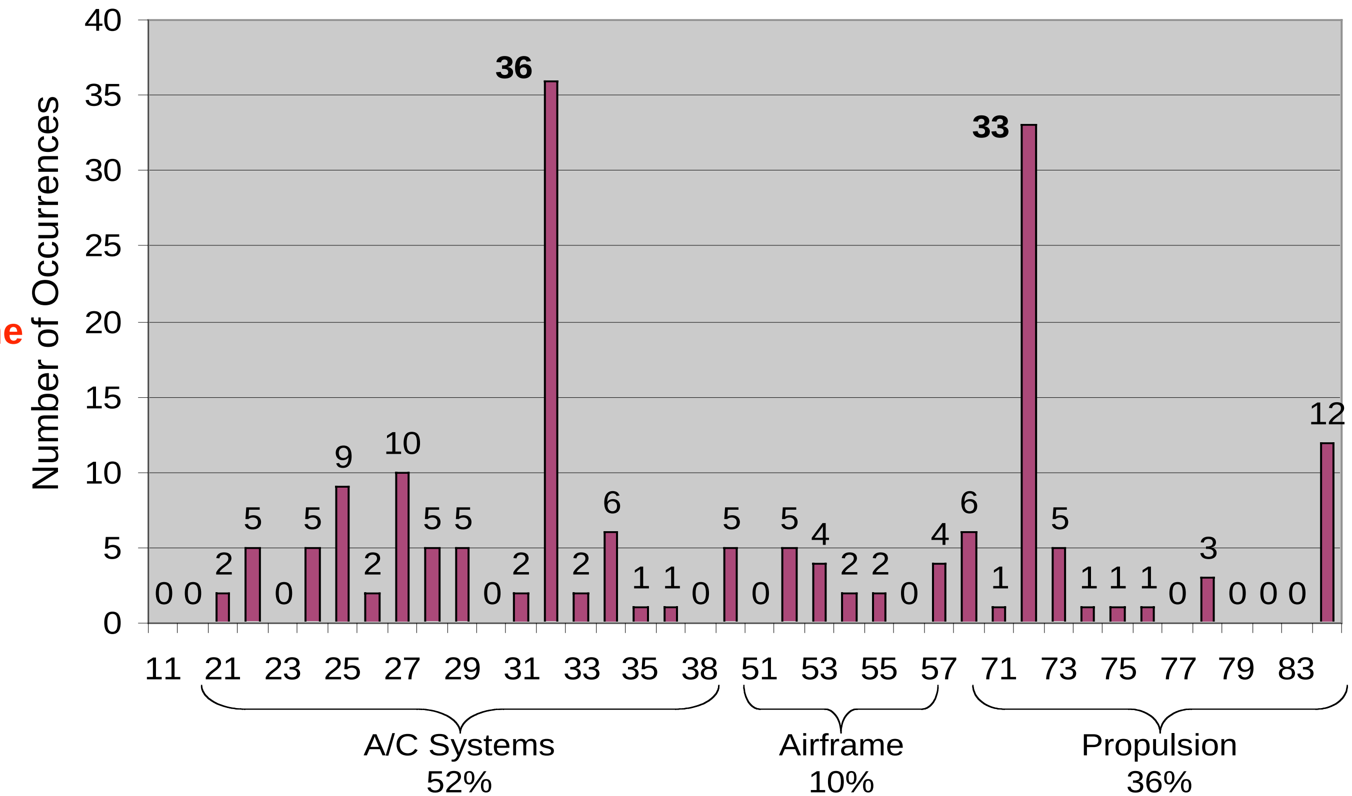
Source: 2004 Statistical Summary, Boeing Commercial Airplanes, May 2005

Health Management Motivation: Commercial Aircraft Safety - Mechanical Malfunctions

<u>ATA Component Codes</u>

21: Air conditioning
22: AutoFlight
24: Electrical Power
25: Equipment/Furnishings
26: Fire Protection
27: Flight Controls
28: Fuel
29: Hydraulic Power
31: Instruments
32: Landing Gear
34: Navigation
61: Propellers/Propulsors
71: Powerplant
72: Turbine/Turboprop Engine
73: Engine Fuel & Control
74: Ignition
75: Air
76: Engine Control
77: Engine Indicating
78: Engine Exhaust
79: Engine Oil
80: Starting
83: Accessory Gearboxes
85: Reciprocating Engine

Coded Breakdown of US Transport Airplane Accidents due to Mechanical Malfunctions.
Covers 7,571 U.S. registered airplanes (31 models) from 1980 - 2001.



Source: Air Transport Association of America

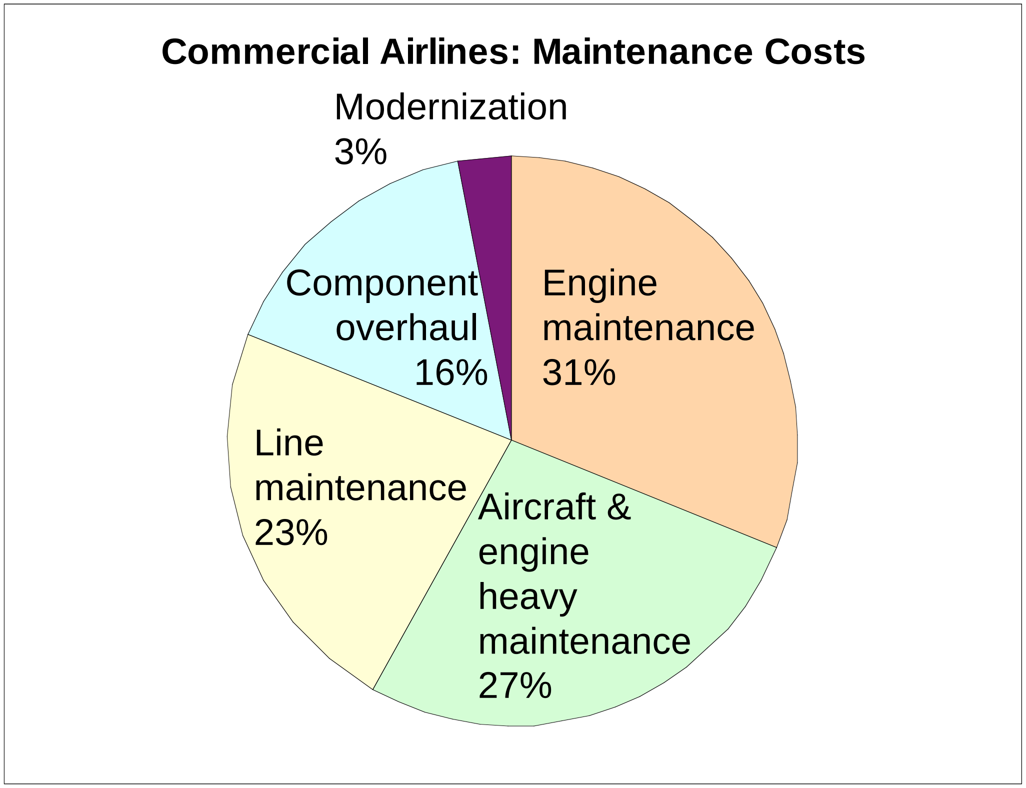
Health Management Motivation: Economic Drivers

- **The airline industry faces severe economic pressures,** posting $32B in cumulative net losses between 2001 and 2004.
  - Ownership costs (purchase price, financing, depreciation, insurance) and operating costs (fuel, fees, maintenance, and labor) directly impact profitability.
  - Of these, health management technologies directly impact maintenance costs, and can indirectly impact fuel costs and fees by providing enabling adaptive technologies that can be used to reduce fuel burn and fee-invoking emissions.

- **Worldwide, airlines spend $31B per year on aircraft maintenance.**
  - In addition, 5-10% of all flights are cancelled for un-scheduled maintenance.

- **Airlines are demanding increased time on wing and reduced engine shop visits** in terms of A-checks. On-condition engine maintenance is becoming more prevalent than scheduled maintenance. The cost of engine overhaul depends on engine size, age and operating profile; 70% of the cost is for hot section repairs.

- **Engine maintenance is the #1 factor in military force readiness.**
  - The DoD spends $3.5B yearly on sustainability vs. $1.3B on acquisition.
  - Their goal is to substantially lower repair costs, and they recognize health management technologies as critical to achieving that goal.



Health Management Motivation: Technology Gaps

Joint Strike Fighter Prognostics: What is missing
-- Andrew Hess, ISHEM Forum, November 2005

- Better Understanding of Physics of Failure
- Condition Based Performance Predictions
- Better State Awareness Techniques
- Better Understanding of Incipient Crack Growth
- Better Understanding of Fault/Failure Progression Rates
- Better Understanding of Material Properties Under Different Loading Conditions
- Better Data Fusion Methods
- Cost Benefit Models to Determine Practicality of Prognostics
  - Risk vs. Reward
- Better Knowledge of Effects of Failures Across the Air Vehicle
- Study to Determine What Components to Perform Prognostics On

Gas-Turbine Engine Health Management: Technology Gaps (1/2)

Monitoring (detect)

- Stainless and Silicon-Nitride bearing monitoring
- Journal bearing monitoring for fan drive gears
- Oil debris and vibration monitoring

Diagnostics (diagnose)

- Fan case damage diagnostics and control
- Diagnostics for static parts
- Rotorcraft drivetrain diagnostics, prognostics and testing
- Damage detection algorithms
- Non-destructive inspection and evaluation of metals (fatigue, corrosion, and cracking)
- Database of defect signatures

Lifing & Damage Models (predict)

- General life prediction models
- Corrosion and combined effects models
- Turbine blade life prediction
- Mixed-mode cracking models for high pressure turbine blade life prediction
- Microstructure behavioral models for Nickel-based alloys
- Low-cycle- and high-cycle-fatigue mechanisms for airfoils
- Combustor lifing
- Spallation models for bearings
- Physics-based prognosis
- Consumed fatigue life indication for prognosis
- Combined gas-path/component usage analysis

Gas-Turbine Engine Health Management: Technology Gaps (2/2)

All sensors and associated electronics must be reliable, low-cost, and minimally intrusive.

Combustor and high-pressure turbine environment is particularly challenging, as is application in rotating components.

Gas Path Sensors
- Emissions (chemical)
- Planar gas path temperature
- High-temperature dynamic pressure
- Fuel nozzle pressure and temperature
- High-pressure turbine temperature

Structural Sensors
- Strain
- Turbine Temperature
- Hot section surface temperature mapping
- Hot section dynamic rotating strain gauges
- Crack/Damage
- Blade tip time-of-arrival
- Vibration
- Load monitoring
- Bearing/rotor thrust

Power Sources
- Self-powered sensors

Communications, Electronics and Packaging
- Wireless sensors
- High temperature packaging
- High temperature electronics

Gas-Turbine Engine Health Management: Technology Development

Integrated Vehicle Health Management

Develop technologies to determine system/component degradation and damage early enough to prevent or gracefully recover from in-flight failures

Propulsion Health Management

Develop and employ virtual and real sensors to assess subsystem states,

Couple state awareness data with physics-based and data-driven models to diagnose degradation and damage,

Integrate sub-system information to provide diagnostics and prognostics for the entire vehicle, including using data from one subsystem to provide information for another.

- Gas Path Health Management
- Structural Health Management
- High Temperature Sensing
- Propulsion Condition Monitoring via Integrated Propulsion and Aircraft measurements – Thrust Asymmetry

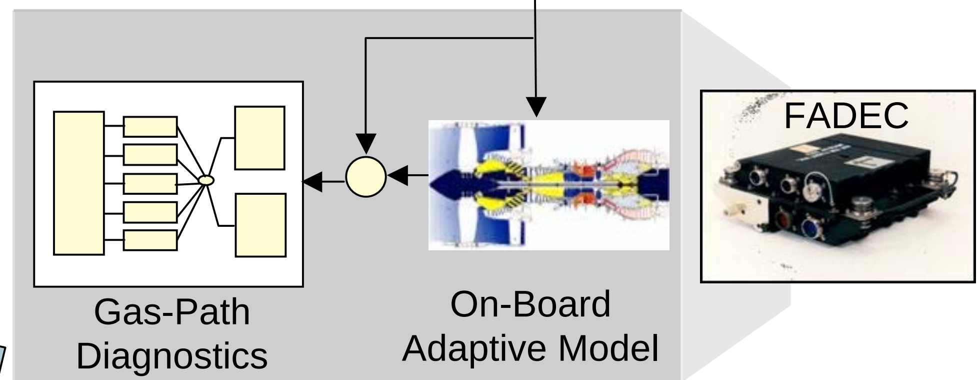
Propulsion Health Management Technology Development: Gas Path

Focuses on health of engine …
- Flow-path turbo-machinery
- Control sensors
- Control actuators

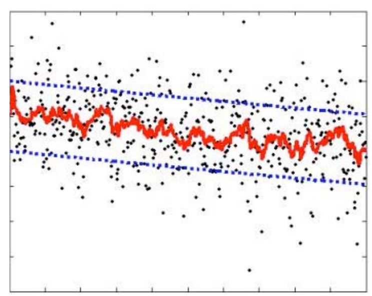
Engine

Sensed Measurements
Pressures, temperatures, rotor speeds, etc.

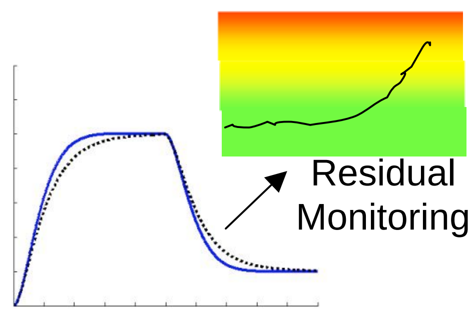
Technical Approach:
- Establish benchmark diagnostic problems and metrics
- Develop enhanced adaptive modeling techniques to track engine performance deterioration
- Develop & combine steady-state and transient diagnostic techniques for robust, reliable fault detection
- Collaboration/Integration
  - Coordinated with industry and DoD partners
  - NRA partnering on fault isolation and prognostic trending techniques
  - Integrated with high temperature sensors, electronics, and communications IVHM technology
  - Inclusion within NASA IVHM test-bed



Model-Based Diagnostics Architecture



Performance Trend Monitoring



Transient Diagnostics

Propulsion Health Management Technology Development: Structures

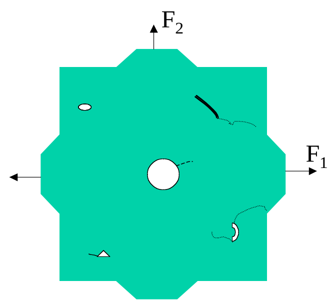
Diagnostic & Prognostically Challenging

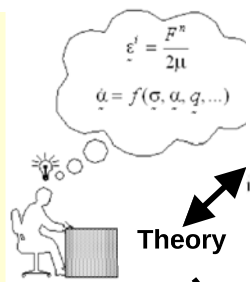
Focuses on verifying prognosis of hot structural parts …

- High temperature, time-dependent material behavior
- Complex multi-axial load histories (e.g. over-loads, biaxial)
- Geometric imperfections and/or stress risers

Technical Approach:

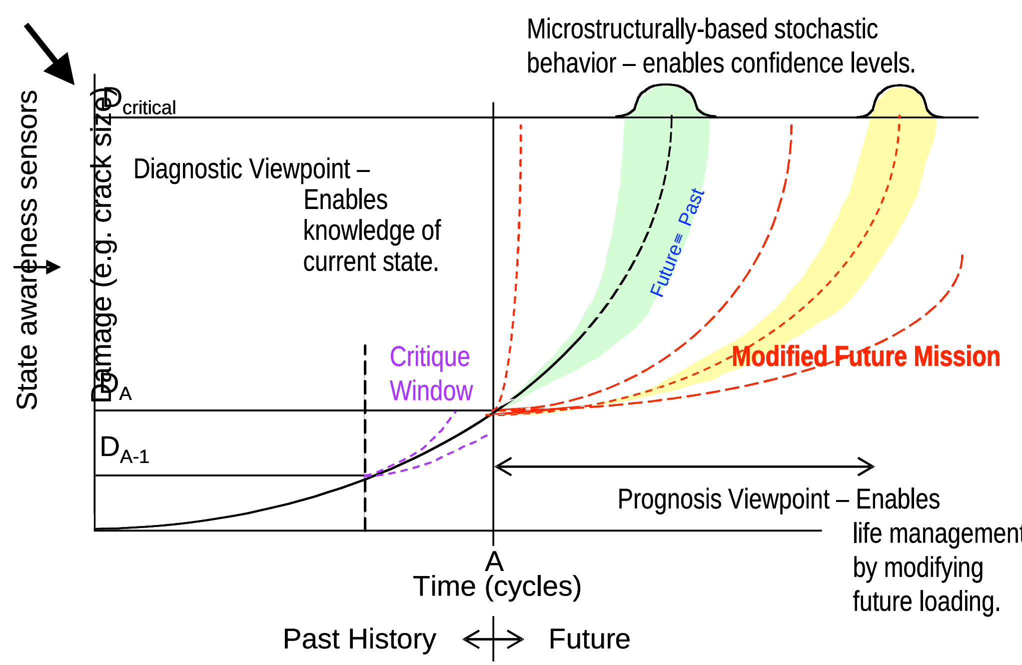
- Select material system and identify prognostically challenging benchmark problems
- Establish experimental database for characterization and validation of both diagnostic and prognostic models
- Characterize deterministic deformation and damage model for selected material system
- Demonstrate accuracy and capability of prognostic model within ABAQUS FEA environment:
  - GVIPS-class coupled deformation and damage methodology.





Biaxially Ratio		Uniaxial	Biaxial	Simple Cyclic		Biaxial Creep, Combustor Linear	Complex Cyclic F1 – Fixed F2 - Variable	Cyclic – Discrete Overload		Stepped Cyclic	Thermal
		0	2	1	2	2	V	V	2		
Inflicted Defect Configuration	Baseline	✓	✓		✓						
	B/PC			✓	✓	✓	✓	✓	✓	✓	✓
	DC		✓		✓					✓	✓
	DPC		✓	✓		✓	✓	✓	✓	✓	✓

☐ = Room Temp. ☐ = Room & Elevated Temp. ☐ = Elevated Temp.



Propulsion Health Management Technology Development: High Temperature Sensing

Enable New Capabilities …

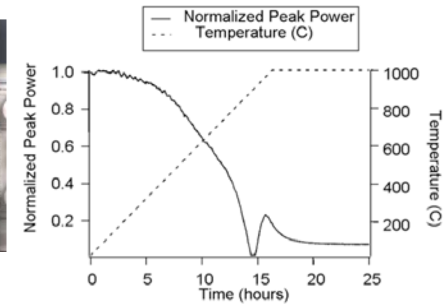
- Propulsion Structural Health Monitoring
- High-temperature Pressure Sensors and
- High-temperature Wireless Communications And Energy Harvesting Technologies

Technical Approach:

- Propulsion structural health monitoring including smart accelerometers, and optical strain and blade tip-timing sensors.
- Pressure sensors for incorporation into gas-path trending and fault diagnostic models to infer turbine health.
- Integration of sensor technology with high temperature wireless communications and energy harvesting to enable smart systems operable at high temperatures.
  - ➢ High-temperature wireless communications based on SiC electronics and rugged RF passive components
  - ➢ Energy harvesting systems focusing thermo-electric and photo-voltaic materials for generation of power for remote sensors.

High Temperature Pressure Sensor

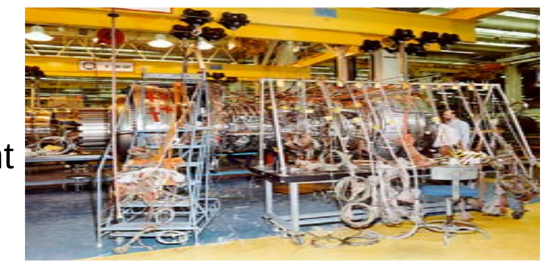
Self Diagnostic Accelerometer



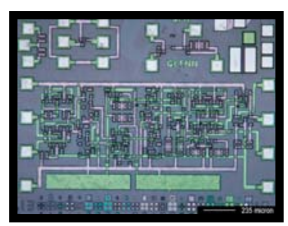
High Temp Fiber Sensor Operation

Provide a New Generation of Sensor Technology

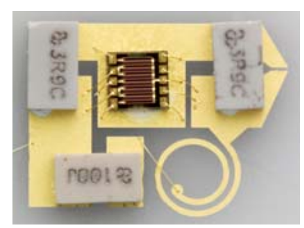
Significant wiring exists with present sensor systems



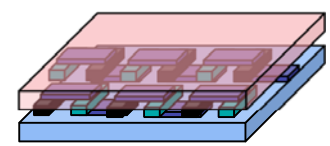
Allow Sensor Implementation by Eliminating Wires



World Record High Temperature Electronics Device Operation



High Temperature RF Components



Energy Harvesting Thin Film Thermoelectrics

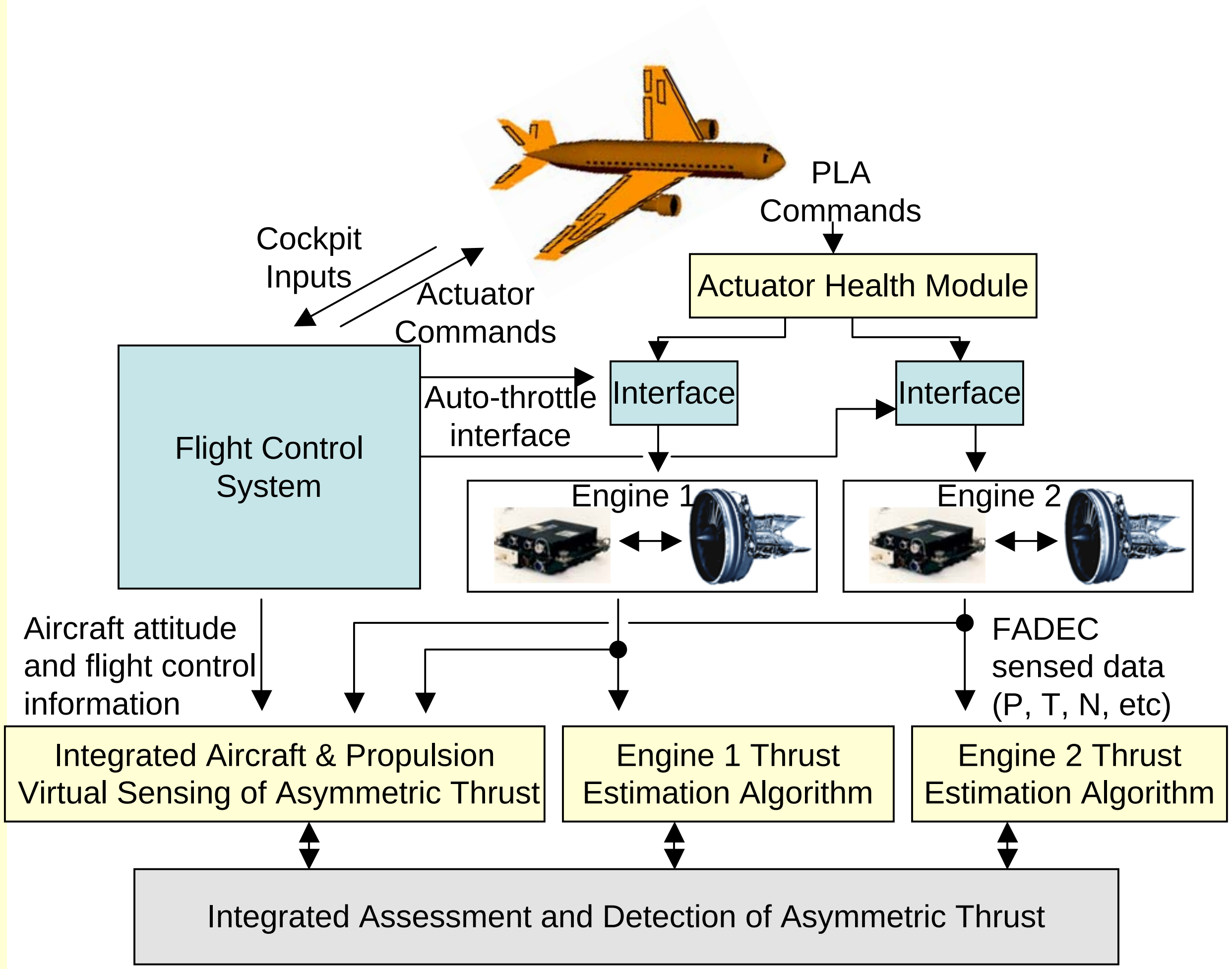
Propulsion Health Mangement Technology Developement: Asymmetric Thrust Diagnosis

Background: Asymmetric thrust conditions, if large enough and undetected, can compromise vehicle safety

Objective: Develop a reliable "integrated" approach for the detection of asymmetric thrust

Approach:

- Apply thrust estimation techniques at the individual engine level
  - Regression techniques & model based approaches
- Apply vehicle wide "virtual" asymmetric thrust estimation
- Apply actuator health monitoring to assess the condition of throttle interface servo-actuator
- Perform high-level fusion of engine thrust & thrust asymmetry assessments



Notional Asymmetric Thrust Detection Architecture

Gas Turbine Engine Health Mangement: Summary

- Health management technologies address key commercial aircraft requirements: safety, cost, and performance.

    Component malfunctions are contributing factors in 24% of accidents, of which 36% are related to propulsion.

    $31B is spent worldwide on maintenance, 31% on engine maintenance plus more on engine heavy maintenance (schedule C & D checks).

    Adaptive technologies can reduce fuel burn (emissions).

- Technology needs for gas turbine engine health management include detection, diagnosis, and prognosis.

- Fundamental technology development is underway for engine health management including gas path health management, structural health management, and high temperature sensing technologies. Asymmetric thrust is being addressed as an integrated propulsion/vehicle diagnostic problem.