NASA Glenn Research in Controls and Diagnostics for Intelligent Aerospace Propulsion Systems

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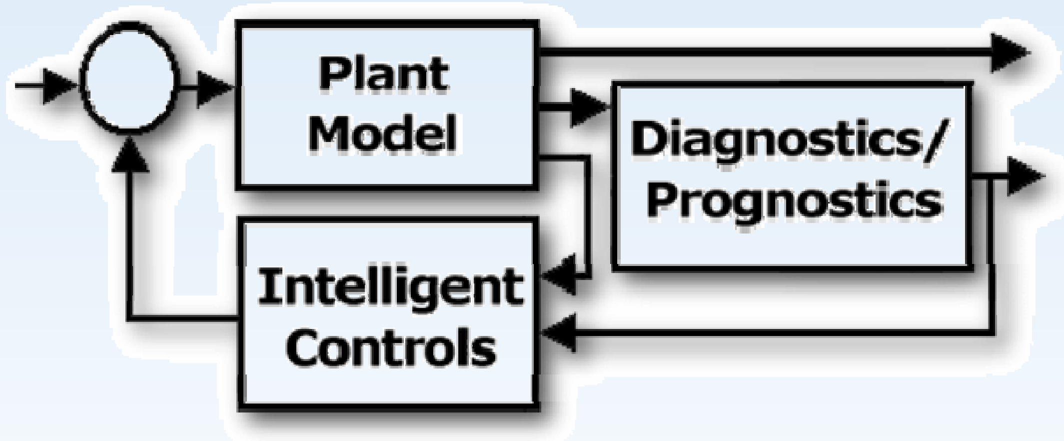
Abstract

With the increased emphasis on aircraft safety, enhanced performance and affordability, and the need to reduce the environmental impact of aircraft, there are many new challenges being faced by the designers of aircraft propulsion systems. The Controls and Dynamics Branch (CDB) at NASA (National Aeronautics and Space Administration) Glenn Research Center (GRC) in Cleveland, Ohio, is leading and participating in various projects in partnership with other organizations within GRC and across NASA, the U.S. aerospace industry, and academia to develop advanced controls and health management technologies that will help meet these challenges through the concept of Intelligent Propulsion Systems. This presentation describes the current CDB activities in support of the NASA Aeronautics Research Mission, with an emphasis on activities under the Integrated Vehicle Health Management (IVHM) and Integrated Resilient Aircraft Control (IRAC) projects of the Aviation Safety Program. Under IVHM, CDB focus is on developing advanced techniques for monitoring the health of the aircraft engine gas path with a focus on reliable and early detection of sensor, actuator and engine component faults. Under IRAC, CDB focus is on developing adaptive engine control technologies which will increase the probability of survival of aircraft in the presence of damage to flight control surfaces or to one or more engines. The technology development plans are described as well as results from recent research accomplishments.

NASA Glenn Research in Controls and Diagnostics for Intelligent Aerospace Propulsion Systems



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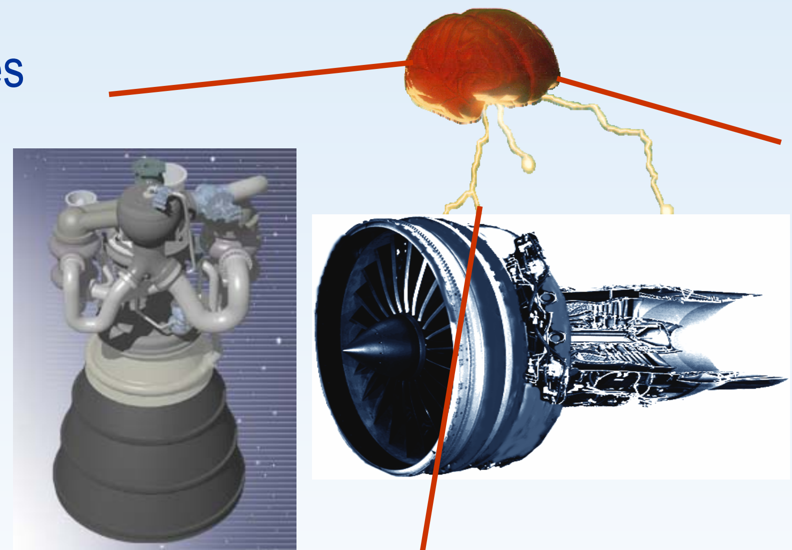
Intelligent Propulsion Systems - Control System perspective

Multifold increase in propulsion system Affordability, Safety, Reliability, Capability, and Environmental Compatibility

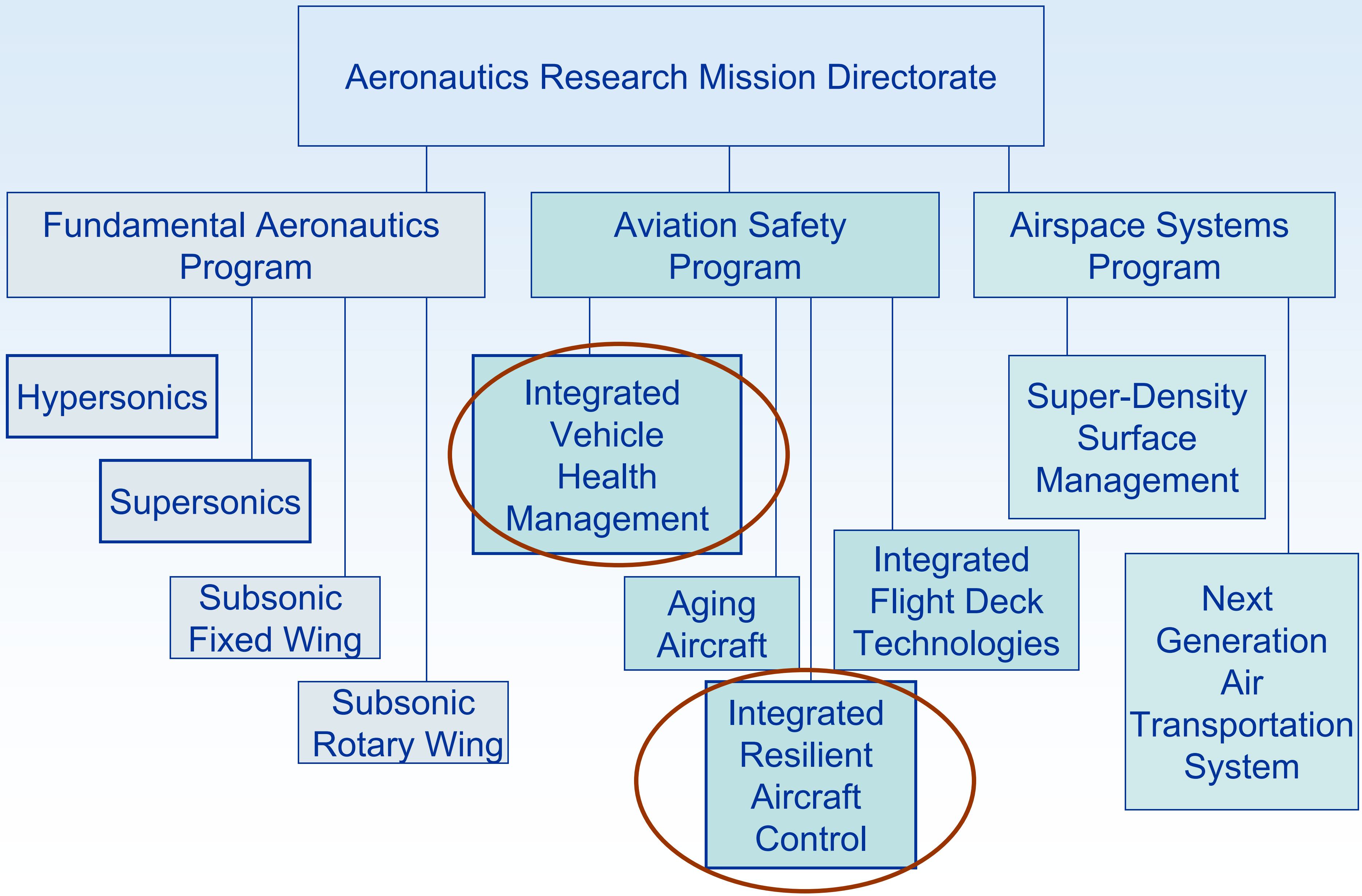
Active Control Technologies for enhanced performance and reliability, and reduced emissions
- active control of combustor, compressor, vibration etc.
- MEMS based control applications



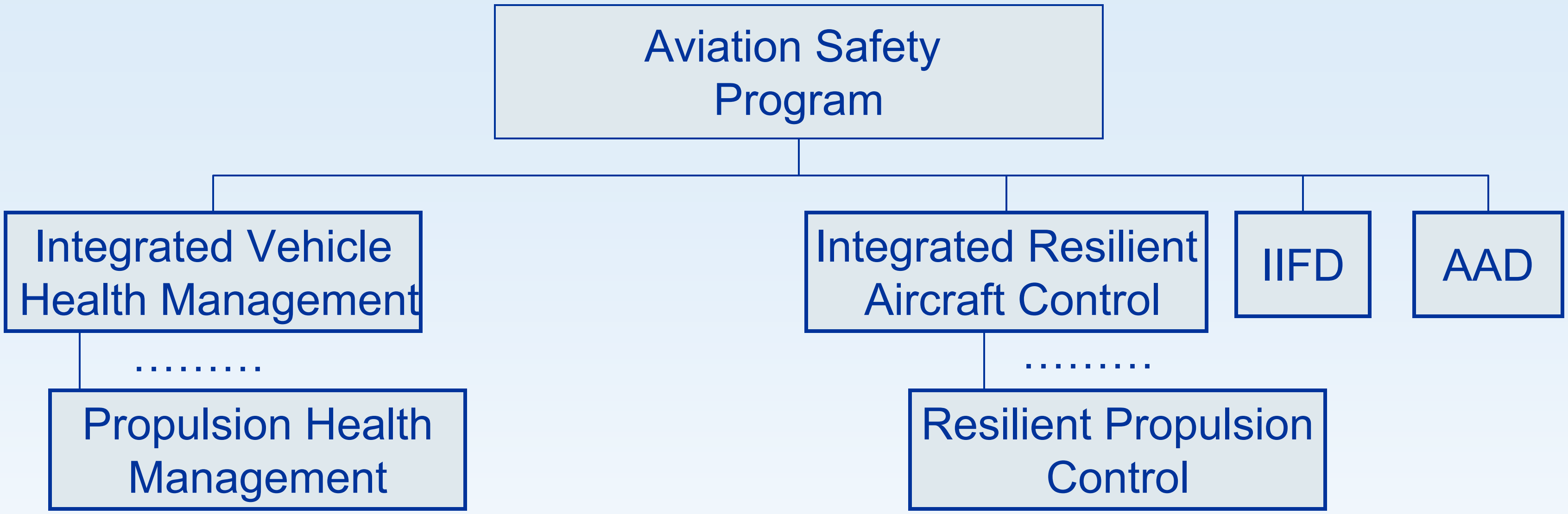
Advanced Health Management technologies for self diagnostic and prognostic propulsion system
- Life usage monitoring and prediction
- Data fusion from multiple sensors and model based information

Distributed, Fault-Tolerant Engine Control for enhanced reliability, reduced weight and optimal performance with system deterioration
- Smart sensors and actuators
- Robust, adaptive control

NASA Aeronautics' Program Structure



Propulsion Control and Diagnostics for Aviation Safety



- Self awareness and prognosis of gas path, combustion, and overall engine state; fault-tolerant system architecture
  - Gas Path health management
  - .....

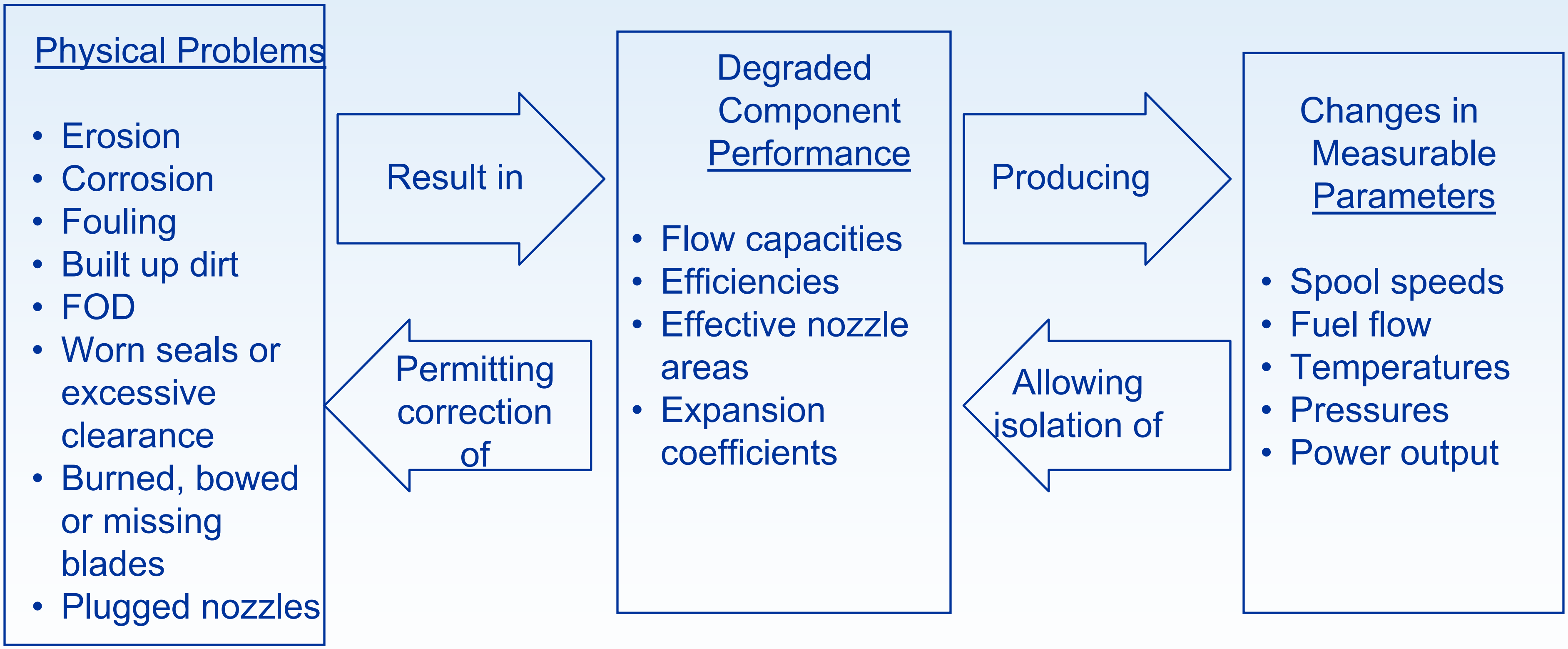
- Damage tolerance and design for extended envelope operation; onboard hazard effects assessment, mitigation and recovery

Controls & Dynamics Branch Overview

- Mission
  - Research, develop and verify aerospace propulsion dynamic modeling, health management, control design and implementation technologies that provide advancements in performance, safety, environmental compatibility, reliability and durability
  - Facilitate technology insertion into the mainstream aeropropulsion community
- Capabilities
  - 20+ engineers and scientists - most with advanced degrees and extensive experience in aeropropulsion controls related fields
  - Extensive computer-aided control design and evaluation facilities including real-time and man-in-the-loop simulation facility
  - Strong working relationship with controls technology groups in the aerospace propulsion industry, academia and other agencies

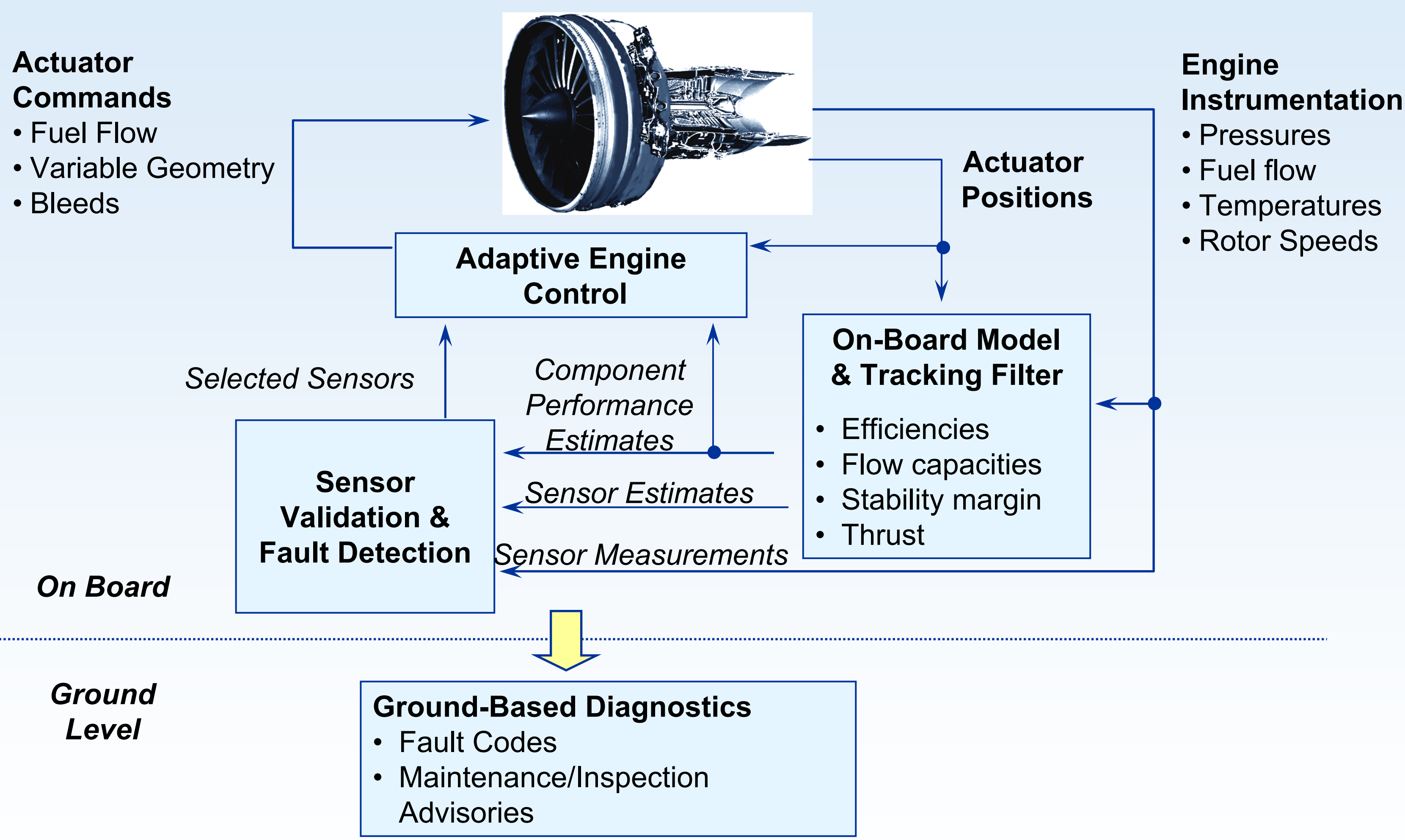
Gas Path Analysis Engine Fault Isolation Approach *

A general influence coefficient matrix may be derived for any particular gas turbine cycle, defining the set of differential equations which interrelate the various dependent and independent engine performance parameters.



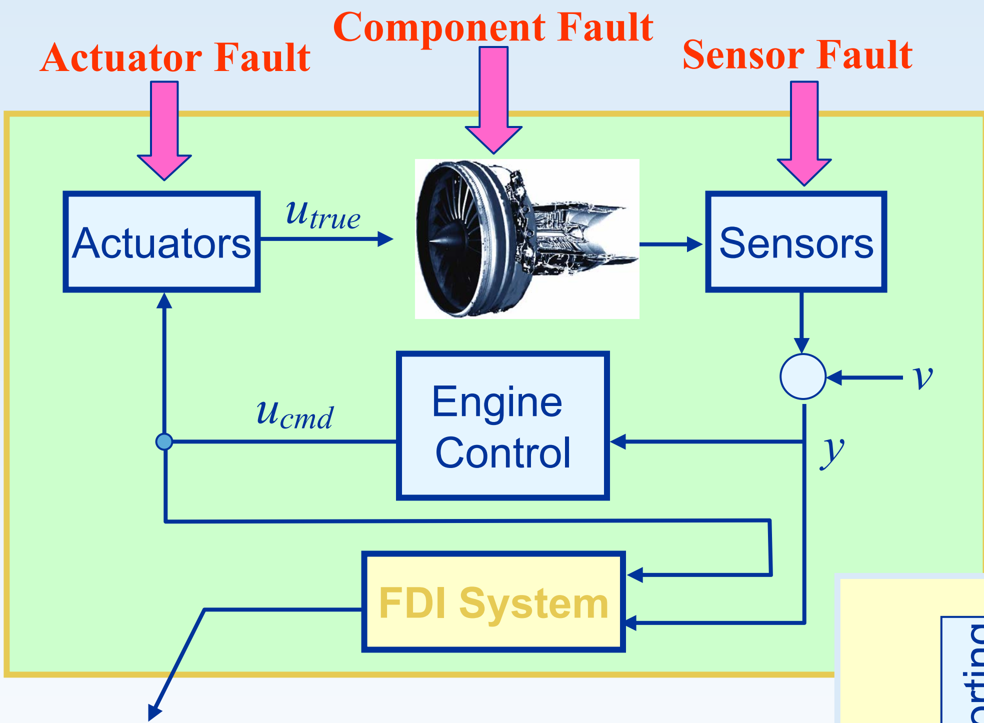
* From “Parameter Selection for Multiple Fault Diagnostics of Gas Turbine Engines” by Louis A. Urban, 1974

Model-Based Controls and Diagnostics



Model-Based Controls and Diagnostics

Bank of Kalman Filters for Aircraft Engine Fault Diagnostics



Approach

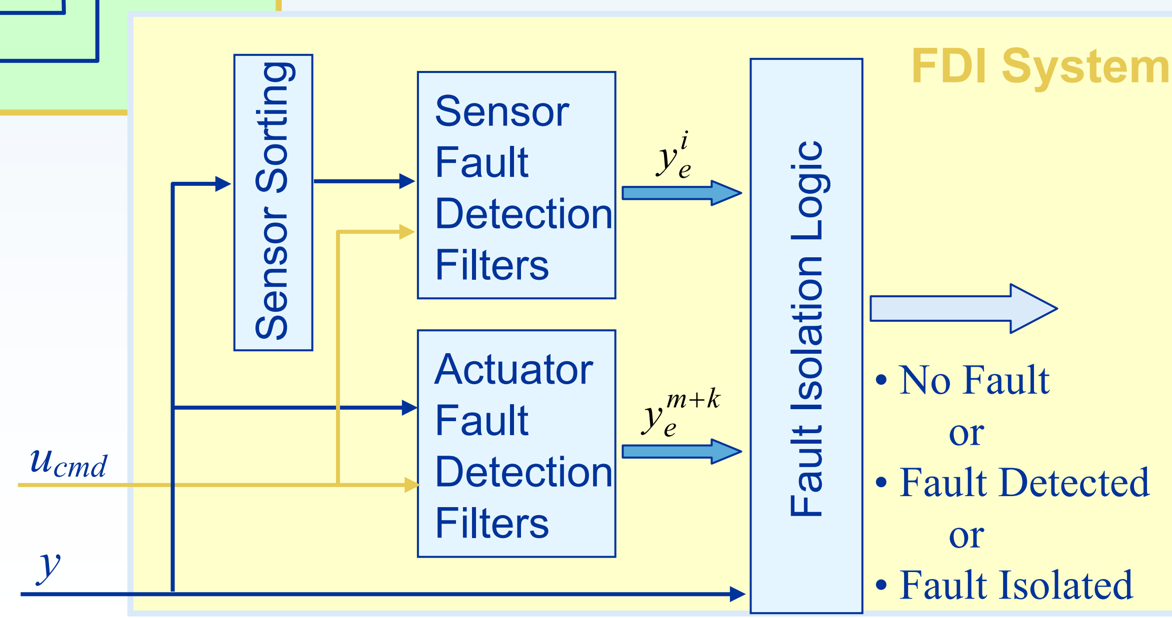
- Application of a Bank of Kalman Filters for Aircraft Engine Fault Diagnostics
- Each Filters Designed with a Specific Fault Hypothesis
- Filters are Updated to Account for Component Degradation

Significance

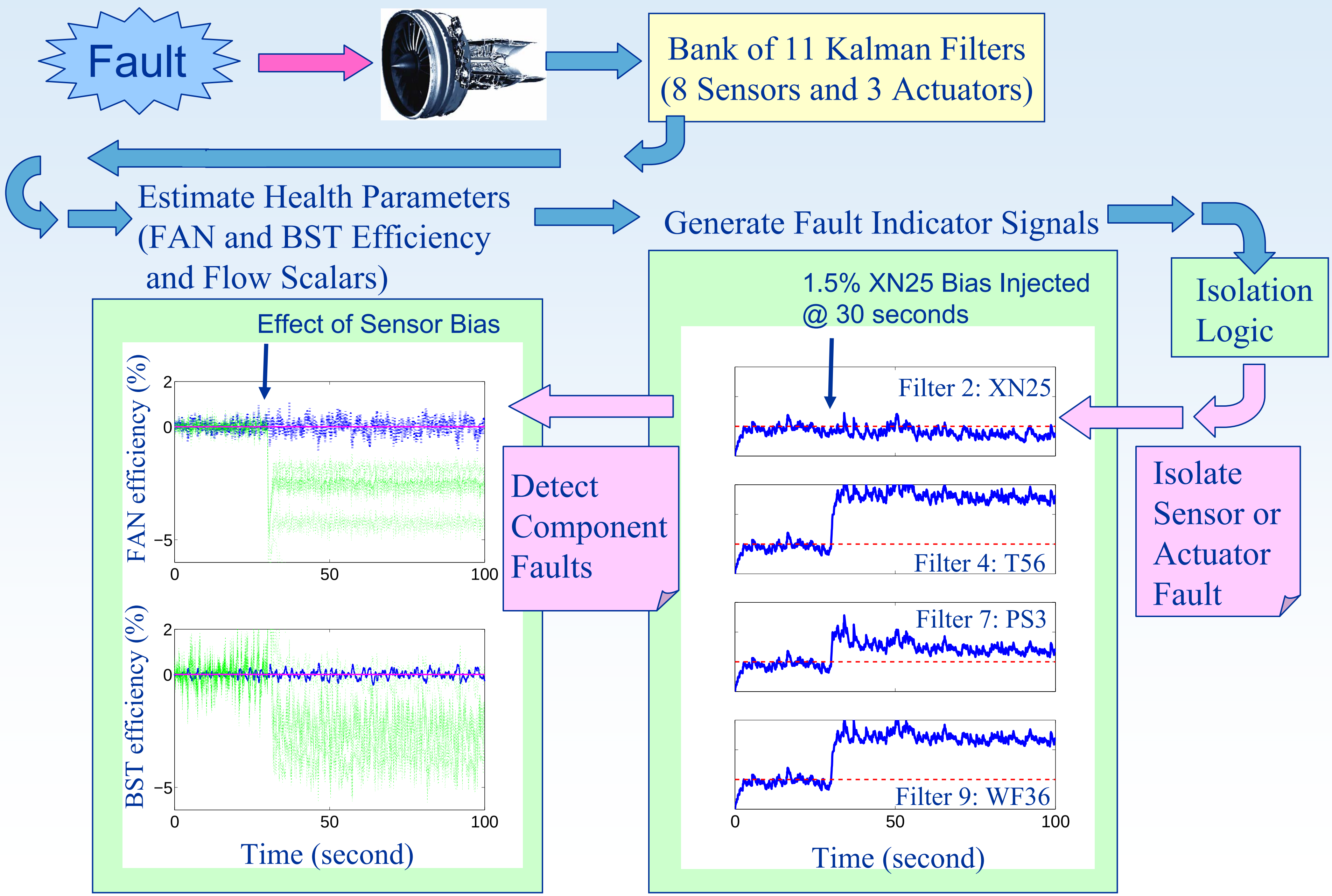
- Detection of Smaller Magnitude Faults
- Reduced False Alarms

Capability

- Sensor/Actuator Fault Detection and Isolation
- Detection of Component Faults by Estimating Health Parameters



Simulation Case: 1.5% XN25 Sensor Bias Injected at 30 Seconds



Enhanced Bank of Kalman Filters for Sensor Fault Detection (Application to an Aircraft Engine Simulation)

Monte Carlo simulation studies were performed to evaluate the system's robustness to various combinations of component and actuator faults

Types and Magnitude of Faults Evaluated

Fault Event		Delta Range	# of Cases
Single Component Fault	**FAN**	[1%, 4%]	50
	LPC	[1%, 4%]	50
	HPC	[1%, 4%]	50
	HPT	[1%, 3%]	100
	LPT	[1%, 3%]	100
Multiple Component Fault	**FAN** **LPC**	[2%, 4%] [1%, 3%]	100
	LPC **HPC**	[2%, 4%] [1%, 3%]	100
	FAN **LPC** **HPC**	[2%, 4%] [1%, 3%] [0.5%, 2%]	100
	HPT **LPT**	[1%, 3%] [1%, 3%]	200
Single and Multiple Actuator Fault	**WF36** **VBV** **VSV**	5% 5% 5%	150

of Fault Misclassifications

	With Filter #(m+1)	Without Filter #(m+1)
PLA 50	0	97
PLA 60	0	113
PLA 68	0	108

- **1000 cases evaluated at three power levels**
- **No fault misclassifications with enhanced approach!**
- **~10% misclassification rate with standard approach**

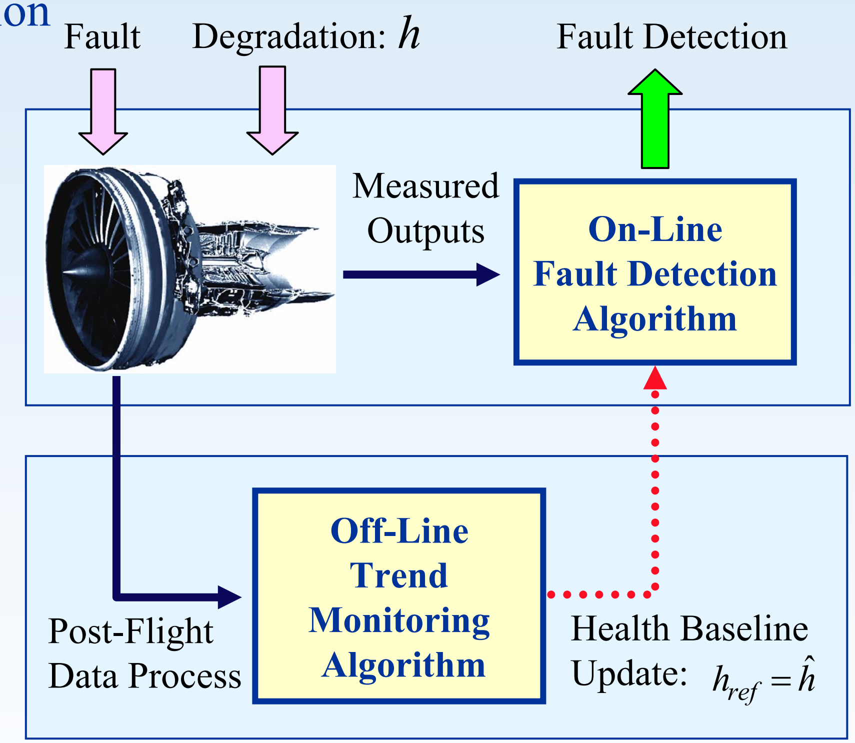
Integration of On-Line and Off-Line Diagnostic Algorithms

Off-Line Trend Monitoring Algorithm

- Diagnostics for normal event: health degradation
- Non-real-time process
- Utilize steady-state flight data
- Estimate engine health degradation: $\hat{h} \approx h$

On-Line Fault Detection Algorithm

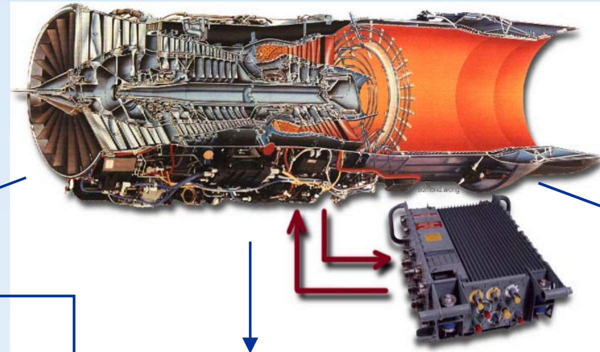
- Diagnostics for abnormal event: faults
- Real-time process during flight
- Utilize measured engine outputs
- Detect faults, avoid false alarms
- Operate at reference health baseline: h_{ref}



Integration

- Periodically update health baseline of the on-line algorithm: $h_{ref} = \hat{h}$
- Benefit: On-line algorithm maintains its diagnostic effectiveness while the engine continues to degrade over time

Data Fusion for Propulsion Health Management



Gas Path Measurements

- Temperatures
- Pressures
- Speeds
- Fuel Flow
- Variable Geometry Positions
- Bleed Positions

Mechanical Measurements

- Vibration
- Oil Pressure
- Oil Temperature
- Oil Quantity
- Fuel Pressure

Advanced Diagnostic & Prognostic Instrumentation

- Electrostatic Inlet Debris Monitor
- Engine Distress Monitor
- Eddy Current Blade Sensor
- Oil Condition Monitor

Model & Tracking Filter

- Data Correction and Component Performance Estimates

Maintenance, Overhaul & Operating History

Data Fusion

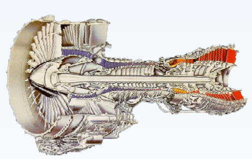
- Data Validation
- Expert System
- Neural Network
- Model Based Diagnostics
- Automated Reasoning
- Statistical Correlation
- Signal Processing

Maintenance and Inspection Advisories, Operating Advisories

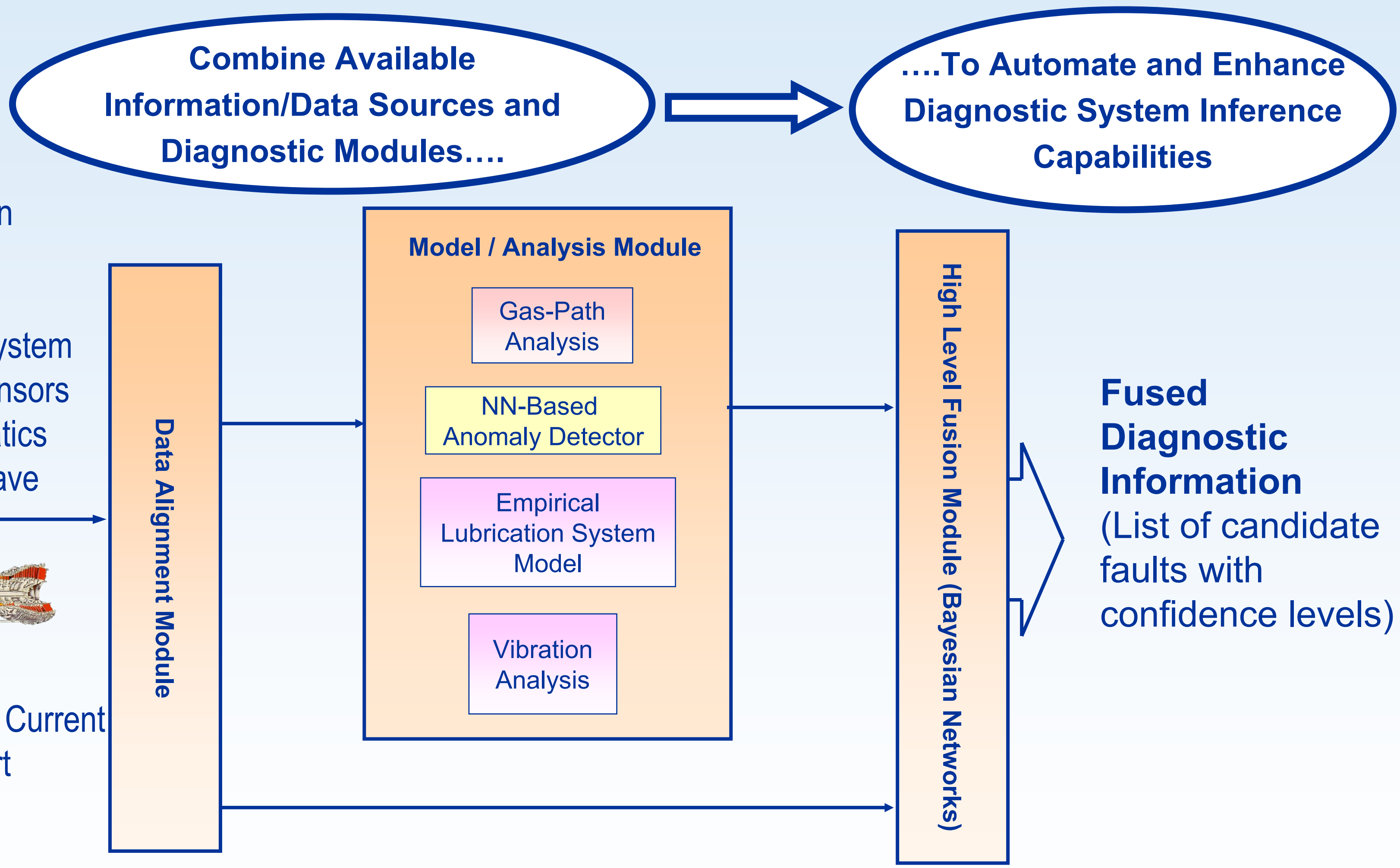
Engine Diagnostic Data / Information Fusion

(Applied to Pratt & Whitney F117 Engine – C17 Aircraft)

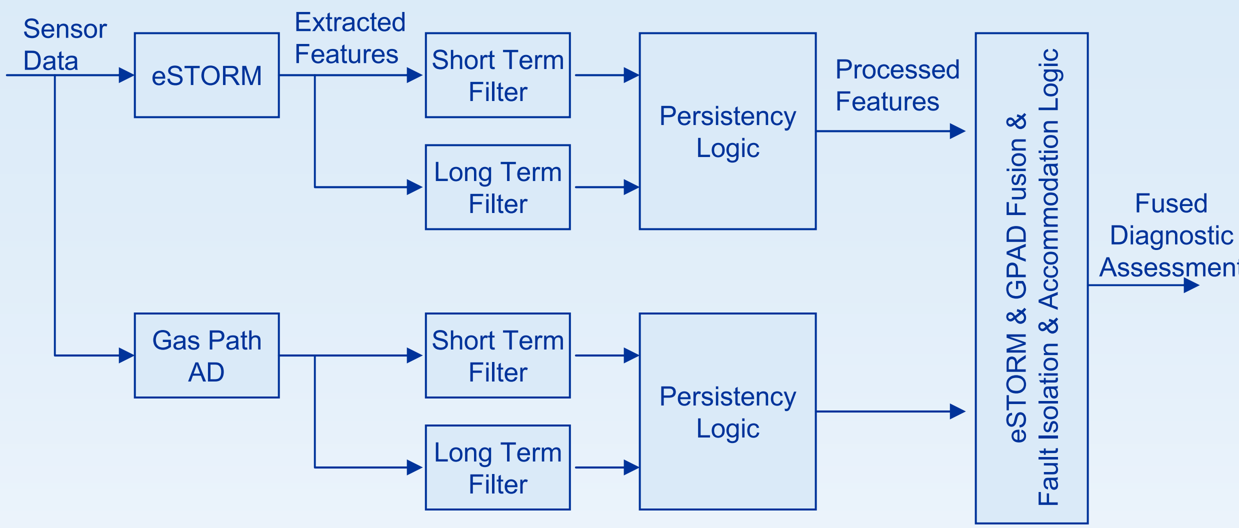
Engine Instrumentation
- •Gas Path
- •Vibration
- •Lubrication System
- •Advanced Sensors
  - –Electrostatics
  - –Stress Wave



Not Used Under Current Research Effort
- • Maintenance Information
- • FADEC Fault Codes



Algorithmic Fusion for Extended Gas Path Analysis Capability



Algorithmic Fusion Architecture

Architecture:

- Fuses Enhanced Self-Tuning Onboard Real-time Model (eSTORM) and Gas Path Anomaly Detector (GPAD)
- Persistency logic enables system to distinguish between faults and noise
- Fuzzy logic fusion approach combines algorithm outputs

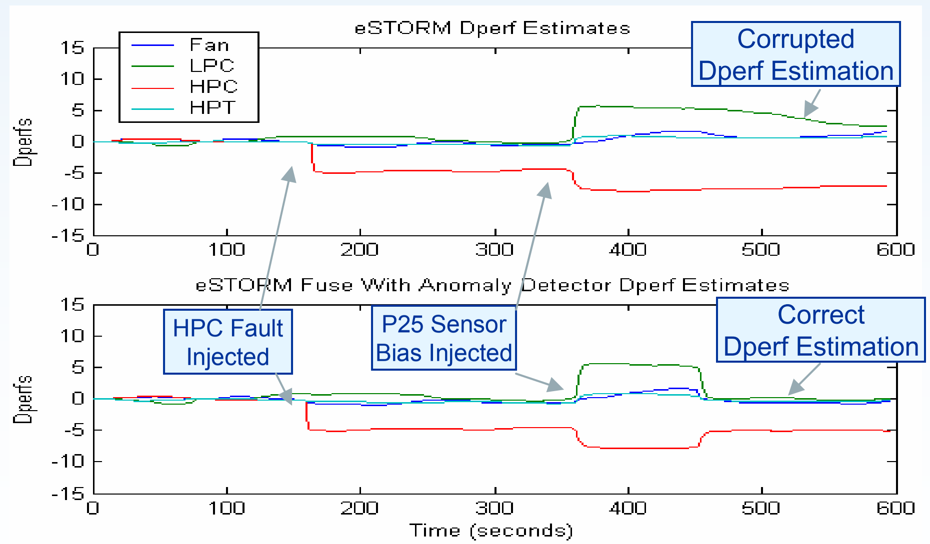
Simulation Results:

eSTORM:

- Sensor faults corrupt eSTORM's ability to accurately estimate component health

Fused eSTORM + GPAD:

- Sensor faults are automatically diagnosed and accommodated
- eSTORM is able to accurately estimate component health in the presence of a sensor fault



Engine Health Management Industry Review

EHM R&D activities have significantly increased in recent years

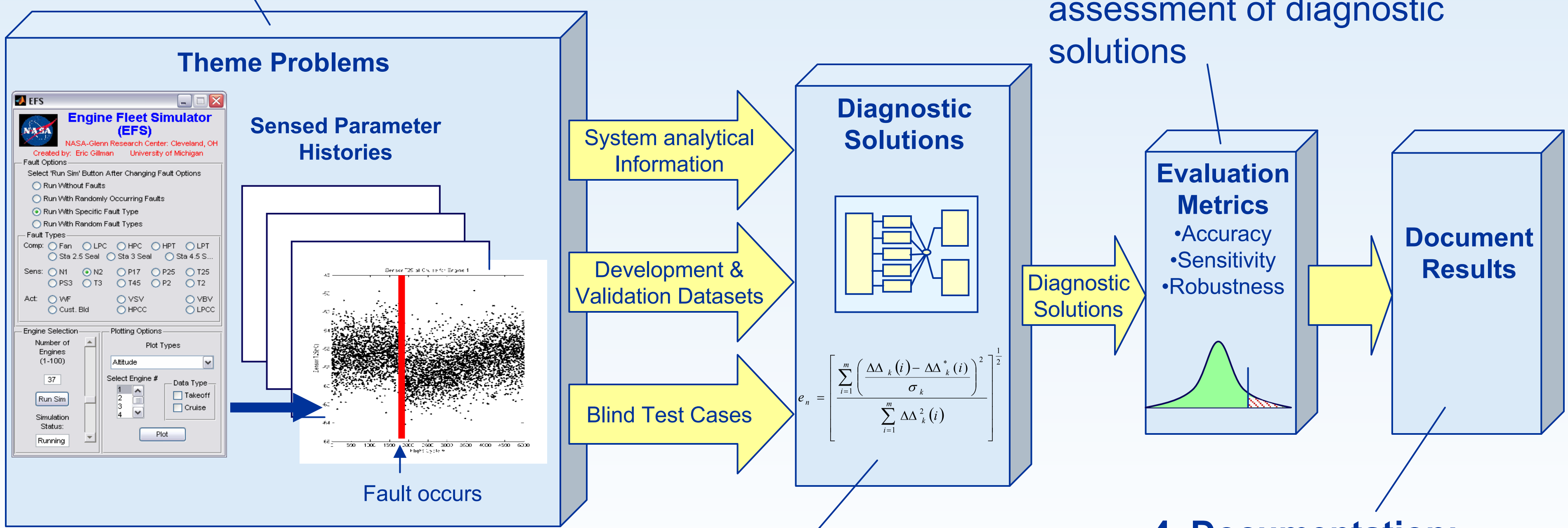
However due to the use of different terminologies, metrics, and applications there is no basis of comparison.

- **Objective**: Provide publicly available benchmark diagnostic problems and metrics to facilitate the development and comparison of candidate diagnostic algorithms
- **Status & Plans:**
  - Established as a collaborative project under The Technical Co-operation Program (TTCP) Propulsion & Power Systems Panel
  - Sub-teams are formulating theme problems & metrics in three EHM areas:
    - Gas Path Diagnostics
    - Vibration Diagnostics
    - Life Usage Monitoring
  - Once problems are completed an invitation will be extended to academic/industry experts to provide problem solutions
  - A conference to present results will be held
  - Results will be documented

Engine Health Management Industry Review Approach

1. Theme problems: Relevant problems constructed from publicly available models and datasets

3. Evaluation Metrics: Defined and applied to provide a uniform assessment of diagnostic solutions



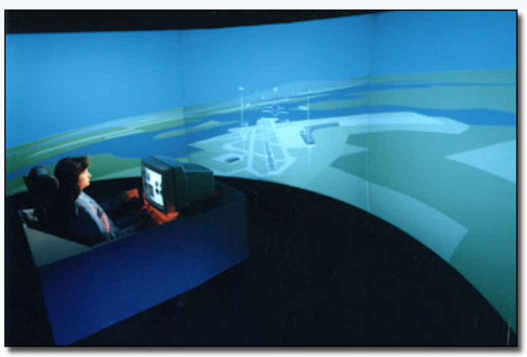
2. Solution providers given:
- Diagnostic requirements
- System analytical information
- Development & validation datasets
- Blind-test cases
- Example solutions

4. Documentation:
- Conference held to present results
- Proceedings published

Autonomous Propulsion System Technology

Reduce/Eliminate human dependency in the control and operation of the propulsion system

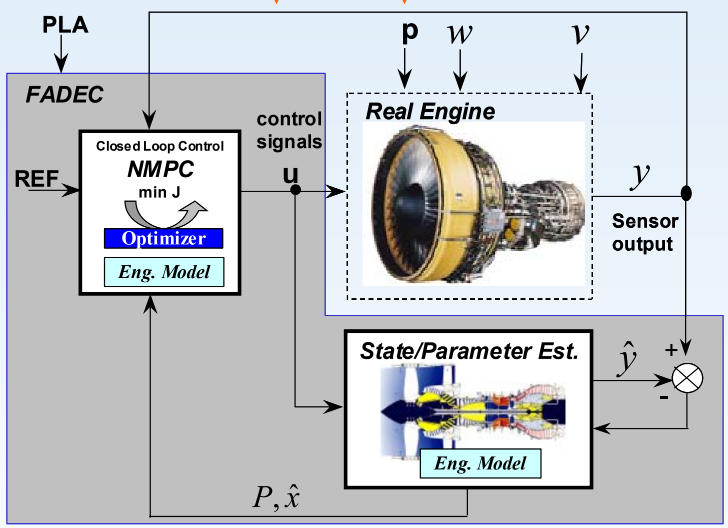
Demonstrate Technology in a relevant environment



Vehicle Management System

Performance Requirement

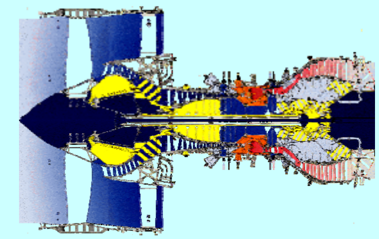
Engine Condition/Capability



Self-Diagnostic Adaptive Engine Control System

- Performs autonomous propulsion system monitoring, diagnosing, and adapting functions
- Combines information from multiple disparate sources using state-of-the-art data fusion technology
- Communicates with vehicle management system and flight control to optimize overall system performance

Model-Based Fault Detection



Diagnostics/Prognostics Algorithms Are Being Developed

Fuzzy Belief Network

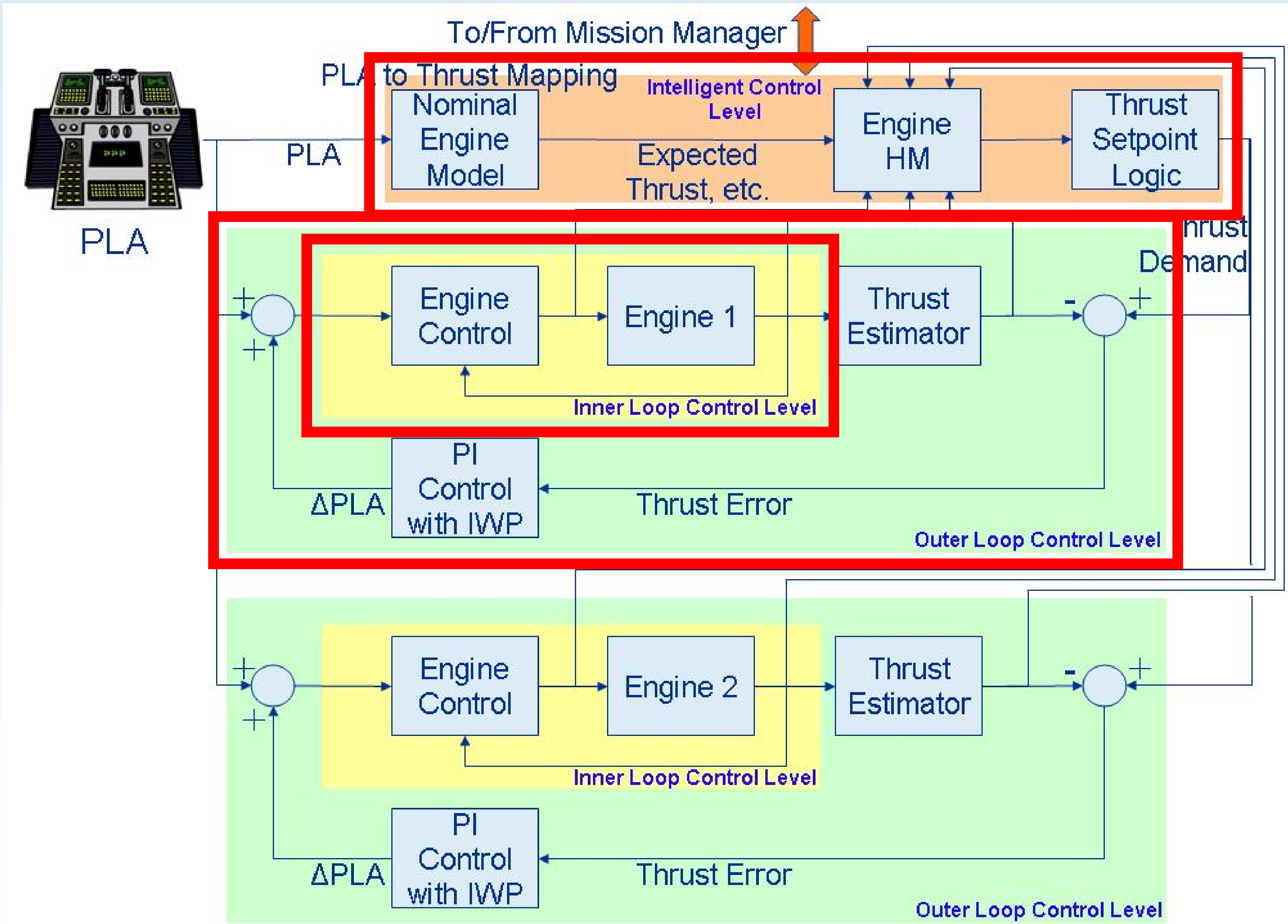
Data Fusion

Glenn Research Center

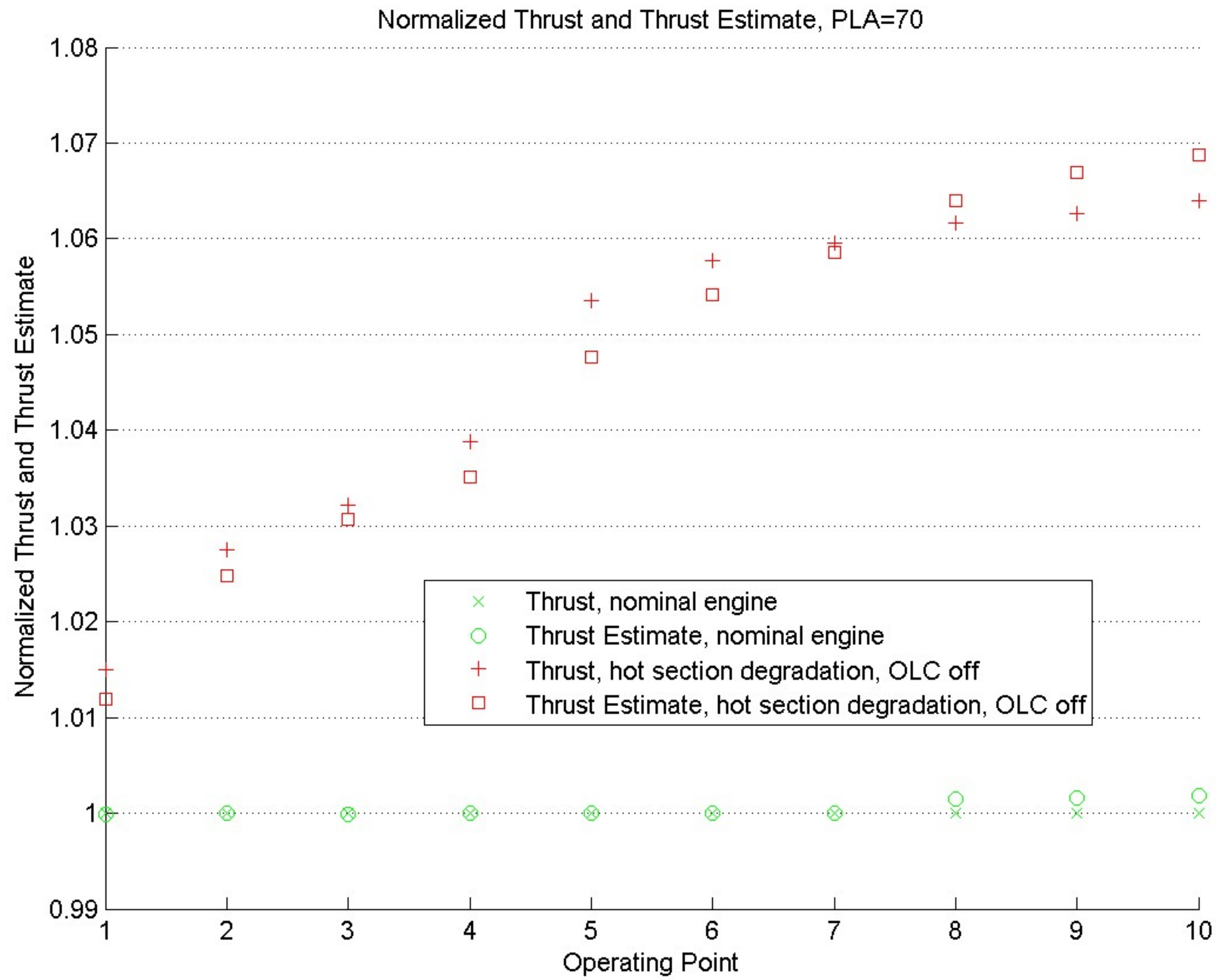
Controls and Dynamics Branch

at Lewis Field

Intelligent Retrofit Architecture



Retrofit Architecture - Steady State Evaluation

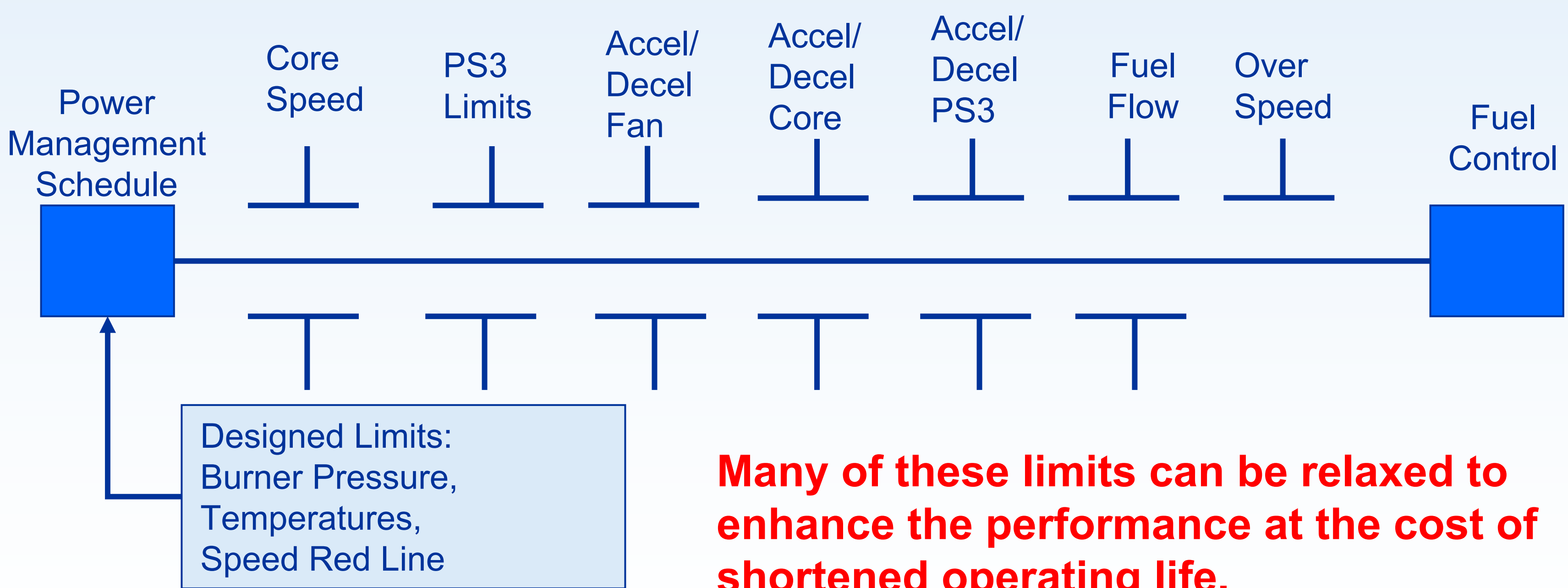


IRAC – Resilient Propulsion Control

- **Objective**
  - To provide adaptive engine control to maximize the probability of survival to damaged aircraft
- **Approaches:**
  - **Damaged Engine Scenario:**
    - damage detection and isolation
    - damage mitigation and partial power recovery
  - **Damaged Aircraft Scenario:** Past research and experience (eg. TOC – Thrust only Control) showed that propulsion systems can be very effective tools to save airplanes from adverse conditions. This capability can be further enhanced by:
    - Independent engine thrust control capability
    - Over-the-limit engine operation for maximum thrust and response

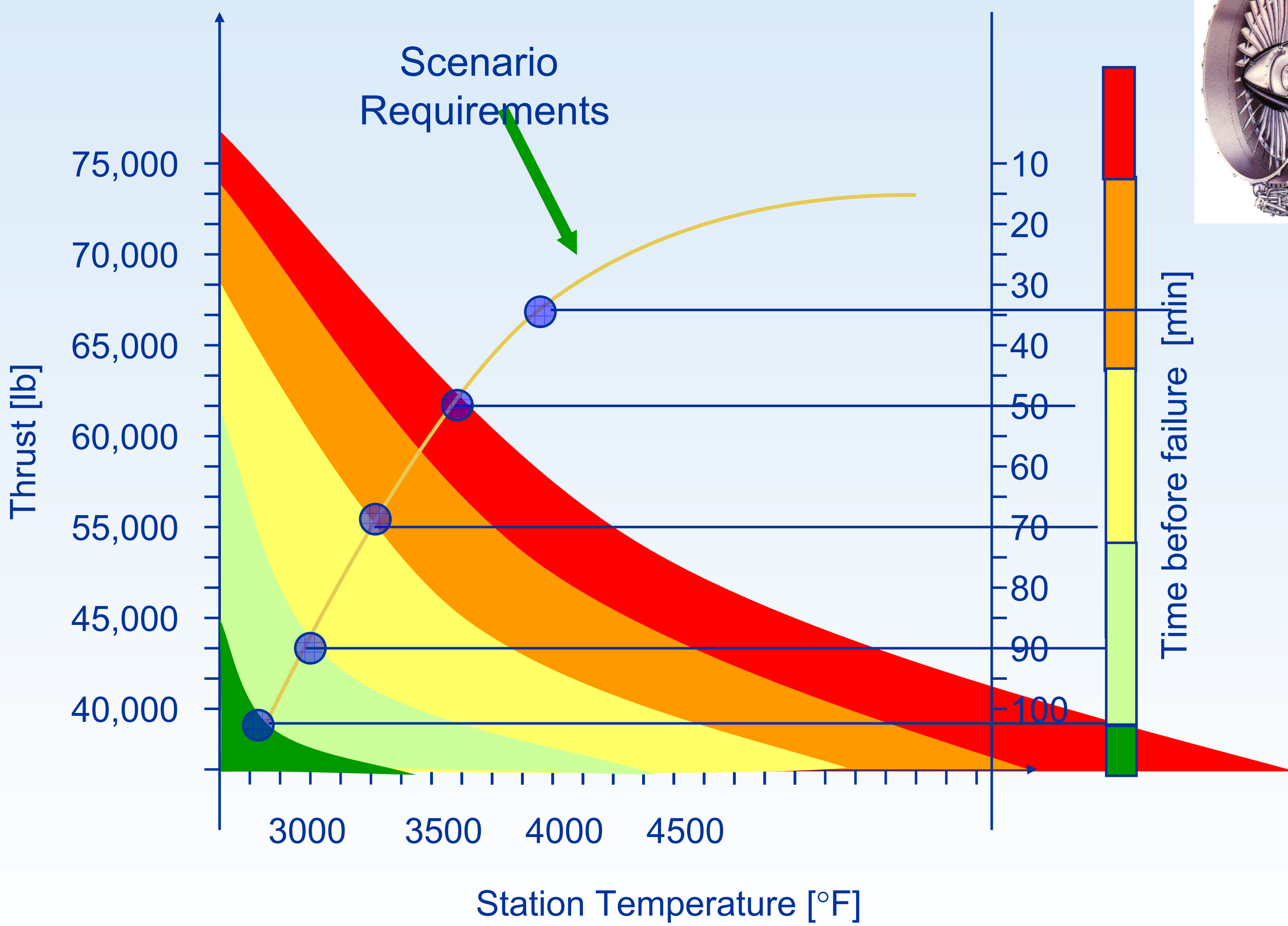
Typical Engine Protection Limits

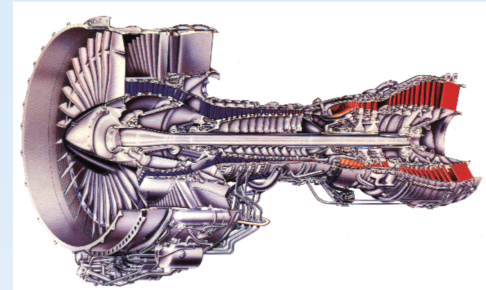
- FADEC system adjusts fuel flow to set power management
  - Speed Control limits
  - Acceleration/Deceleration speed limits
  - Fuel Flow limits
  - Pressure Control



Many of these limits can be relaxed to enhance the performance at the cost of shortened operating life.

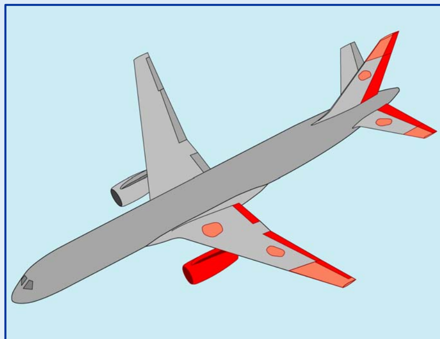
Thrust vs Life Trade-Off





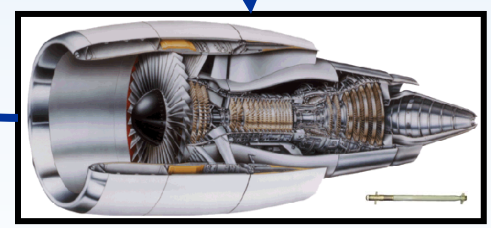
Example : Thrust → Station Temperature → Sustainable Time Duration

IRAC – Airframe Propulsion Control Integration

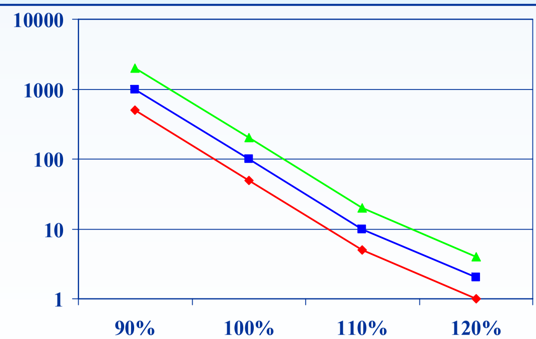


Adaptive Flight Control
- Decision Based on Damage, Engine capabilities, Risks

Flight Control Commands
-Engine Operation Mode
-Engine Performance Requirements



Engine Status Report
- Engine Damage Condition
- Engine Performance Limits
- Performance/Life Trade-off Curve



- Engine Damage Assessment
- Survival Operation Mode for Damaged Engine
- Optional Operation Beyond Designed Envelope

Resilient Propulsion Control – Research Tasks

- Extended Engine Control Development:
  - Baseline Engine and Control Models
  - High Level Requirements
  - Engine Model Improvements
  - Engine Dynamic Models
  - Operability Study for Extended Operation
  - Failure Mode Study
  - Life Modeling
  - Enhanced Engine Control Development
  - Flight Simulator Testing
  - TOC/PCA Testing

Systematic Sensor Selection Strategy (S4)

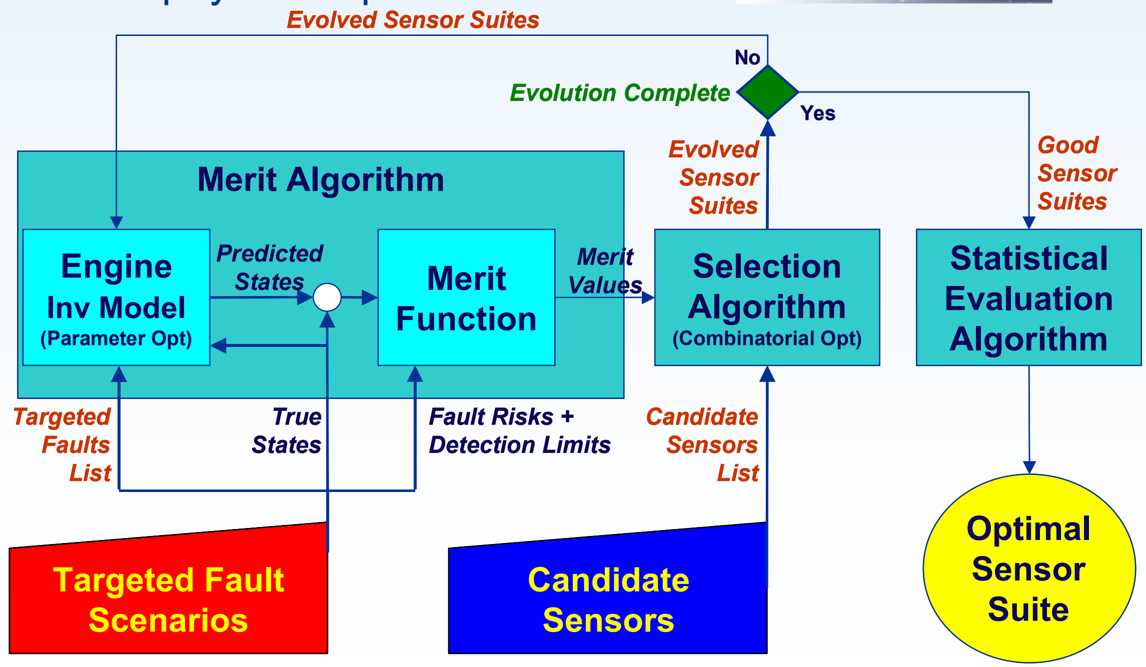
Background: Developed under NASA Space IVHM efforts

Approach:

- Selects sensors (type/location) to optimize the fidelity and response of engine health diagnostics
- Targets high risk engine anomaly types/classes at detection thresholds and assigns quantitative sensor suite value based on
  - –Overall risk reduction
  - –Diagnostic speed
  - –Probability of correct type/class isolation
- Accommodates various types of models/physical inputs

Systematizes Use of Design and Heritage Experience Base:

- Uses critical FMEA identified modes and risk assessments
- Considers sensor response and system/signal noise effects
- Accommodates fault scenarios from correlated test data and/or model simulations



Conclusion

- Controls and health management technologies play a critical role in making “Intelligent Engines” a reality.
- NASA has a well defined research program to advance the state-of-the-art in aircraft engine control and diagnostics to enable:
  - Safer aircraft operation through enhanced engine capabilities and higher confidence fault detection and isolation
  - Reduced life cycle cost through improved diagnostics and prognostics resulting in condition-based maintenance and increased on-wing engine life.
- A multidisciplinary cross-organizational collaborative approach is essential for successful development and demonstration of Intelligent Engine technologies
  - NASA is working collaboratively with industry/academia/DoD
- It is essential that the controls and diagnostics expertise be integrated early into the system concept development to enable system intelligence in the design.