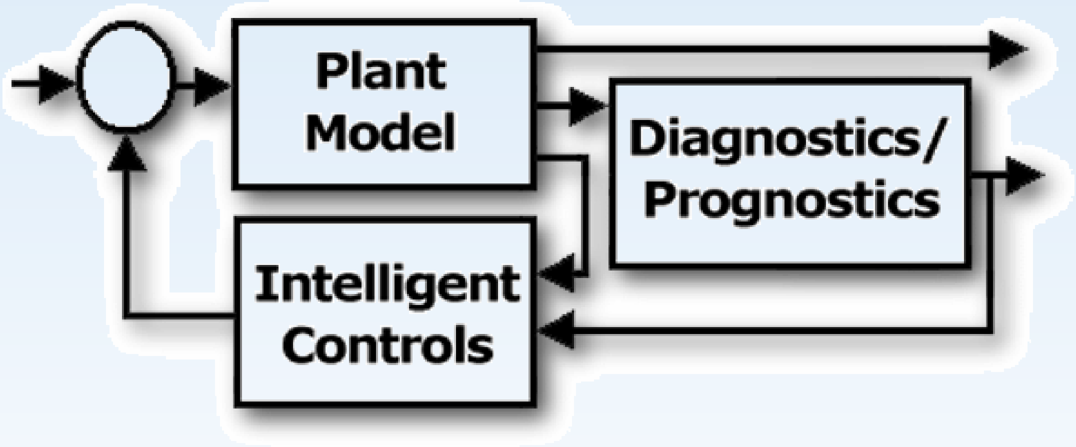
Challenges in Aircraft Engine Control and Gas Path Health Management


Plant Model

Diagnostics/ Prognostics

Intelligent Controls

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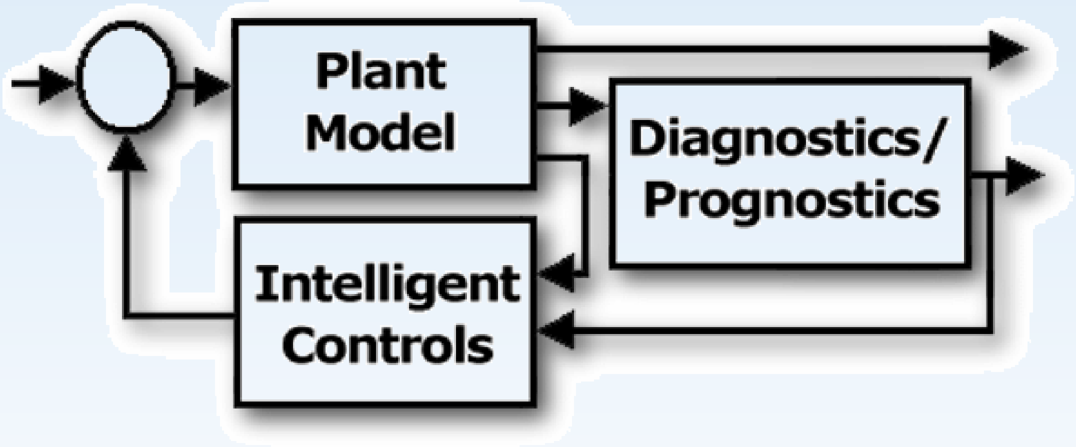
Challenges in Aircraft Engine Controls



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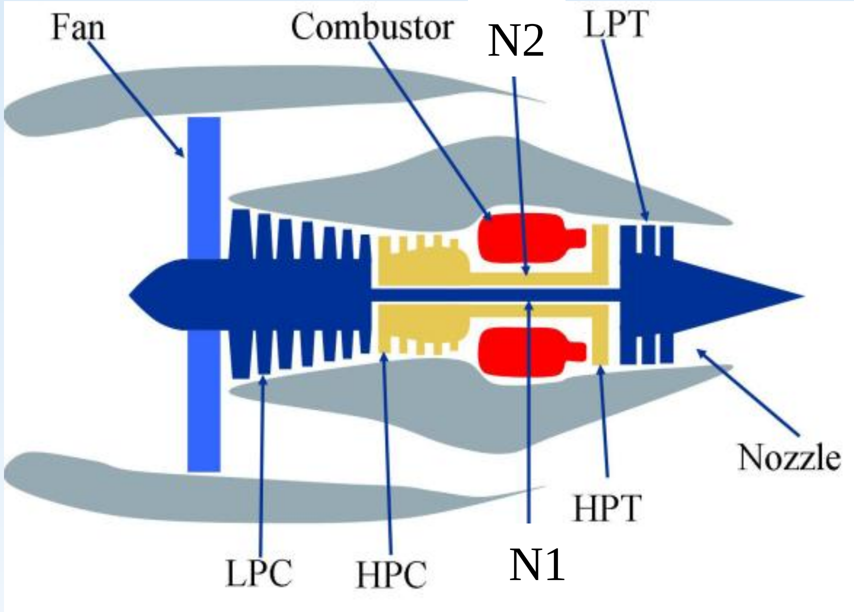
Outline

- Fundamentals of Aircraft Engine Control
- Intelligent Engine Concept – from a controls perspective
- Advanced Engine Control Logic
- Active Component Control
- Distributed Engine Control
- Summary

Turbofan Engine Basics



LPC - Low Pressure Compressor
HPC - High Pressure Compressor
HPT - High Pressure Turbine
LPT - Low Pressure Turbine
N1 - Fan Speed
N2 - Core Speed

- Dual Shaft – High Pressure and Low Pressure
- Two flow paths – bypass and core
- Most of the thrust generated through the bypass flow
- Core compressed air mixed with fuel and ignited in the Combustor
- Two turbines extract energy from the hot air to drive the compressors

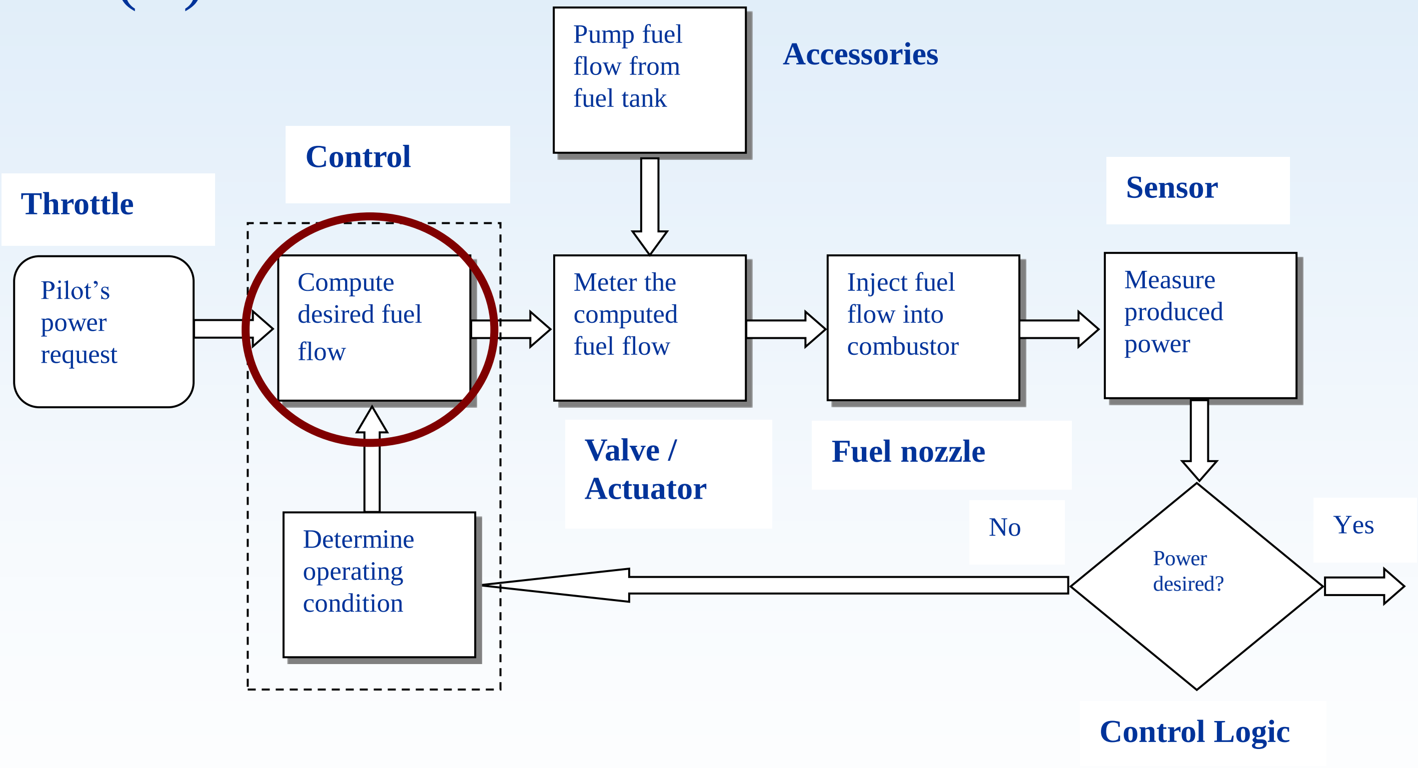
Basic Engine Control Concept

- **Objective:** Provide smooth, stable, and stall free operation of the engine via single input (PLA) with no throttle restrictions
  - Reliable and predictable throttle movement to thrust response

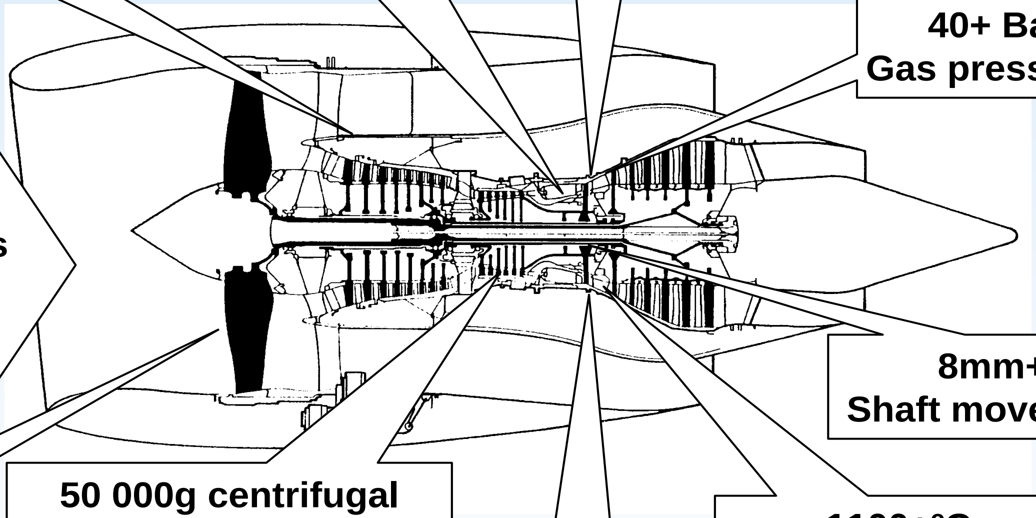
- **Issues:**
  - Thrust cannot be measured
  - Changes in ambient condition and aircraft maneuvers cause distortion into the fan/compressor
  - Harsh operating environment – high temperatures and large vibrations
  - Safe operation – avoid stall, combustor blow out etc.
  - Need to provide long operating life – 20,000 hours
  - Engine components degrade with usage – need to have reliable performance throughout the operating life

Basic Engine Control Concept

- Since Thrust (T) cannot be measured, use Fuel Flow WF to Control shaft speed N
  - T = F(N)



Environment within a gas turbine



Aerodynamic Buffeting 120 dB/Hz to 10kHz

2000+ºC Flame temperature - 40ºC ambient

Cooling air at 650+ºC

20000+ hours Between service

40+ Bar Gas pressures

Foreign objects Birds, Ice, stones Air mass flow ~2 tonne/sec

8mm+ Shaft movement

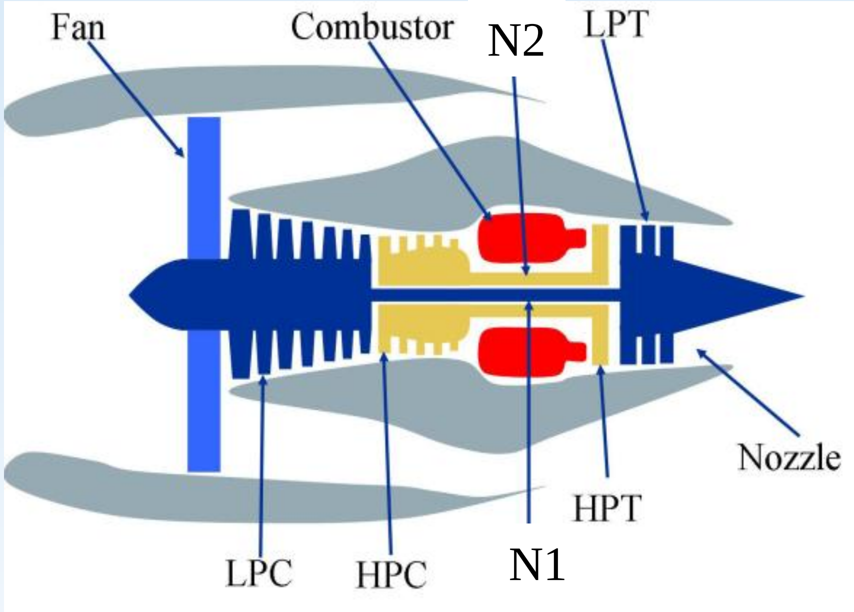
2.8m Diameter

50 000g centrifugal acceleration >100g casing vibration to beyond 20kHz

1100+ºC Metal temperatures

10 000rpm 0.75m diameter

Operational Limits



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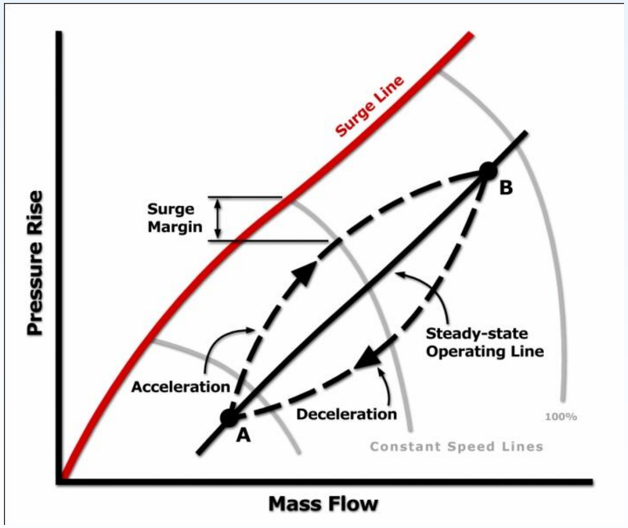
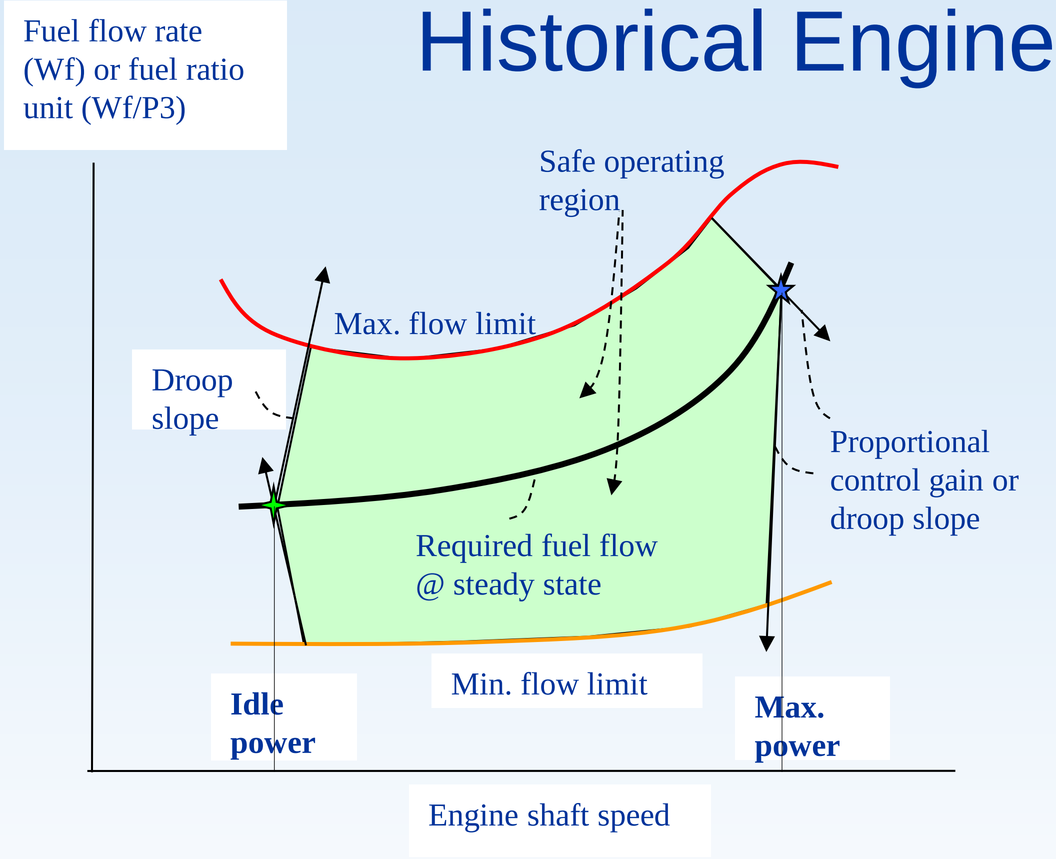
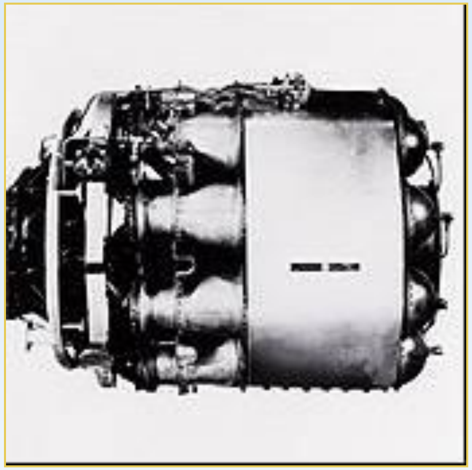


- **Structural Limits:**
  - Maximum Fan and Core Speeds – N1, N2
  - Maximum Turbine Blade Temperature
- **Safety Limits:**
  - Adequate Stall Margin – Compressor and Fan
  - Lean Burner Blowout – minimum fuel
- **Operational Limit:**
  - Maximum Turbine Inlet Temperature – long life

Historical Engine Control





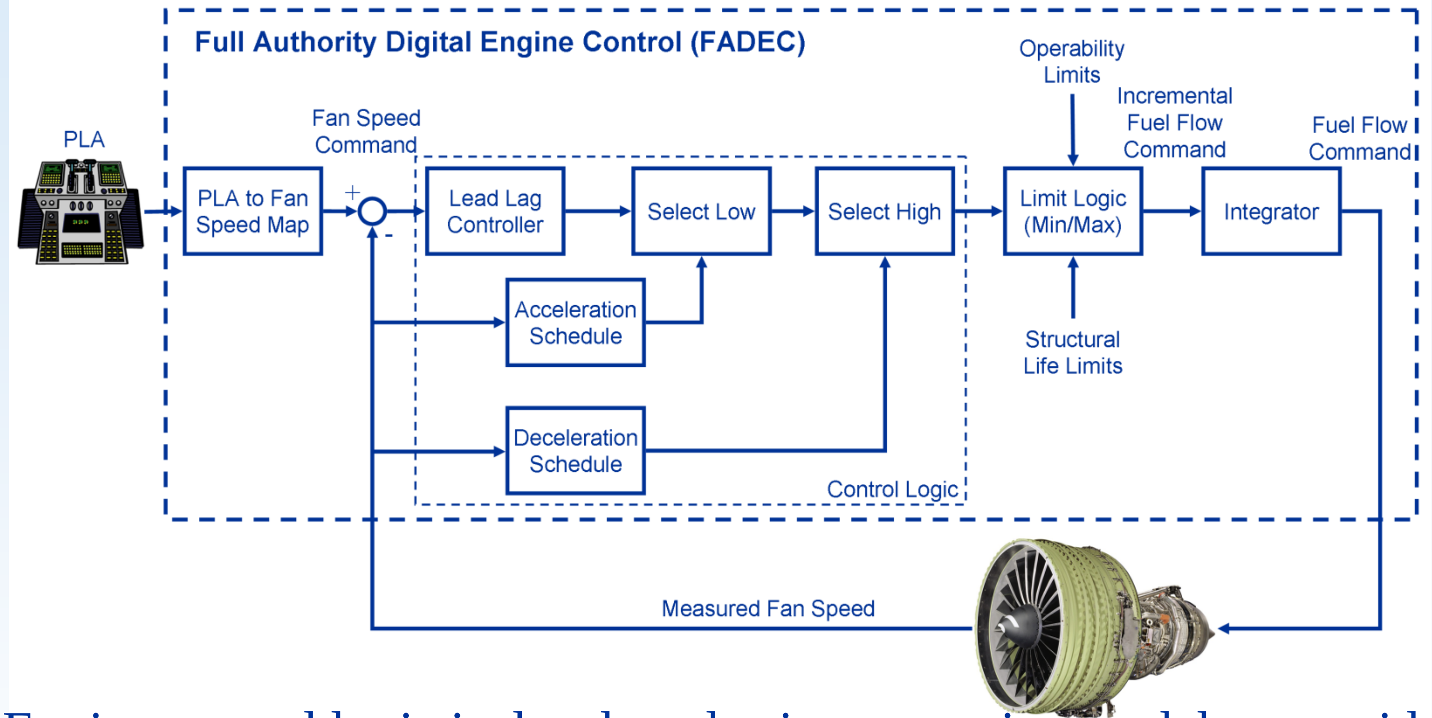
GE I-A
(1942)

- Fuel flow is the only controlled variable.
  - Hydro-mechanical governor.
  - Minimum-flow stop to prevent flame-out.
  - Maximum-flow schedule to prevent over-temperature

- Stall protection implemented by pilot following cue cards for throttle movement limitations

Typical Current Engine Control

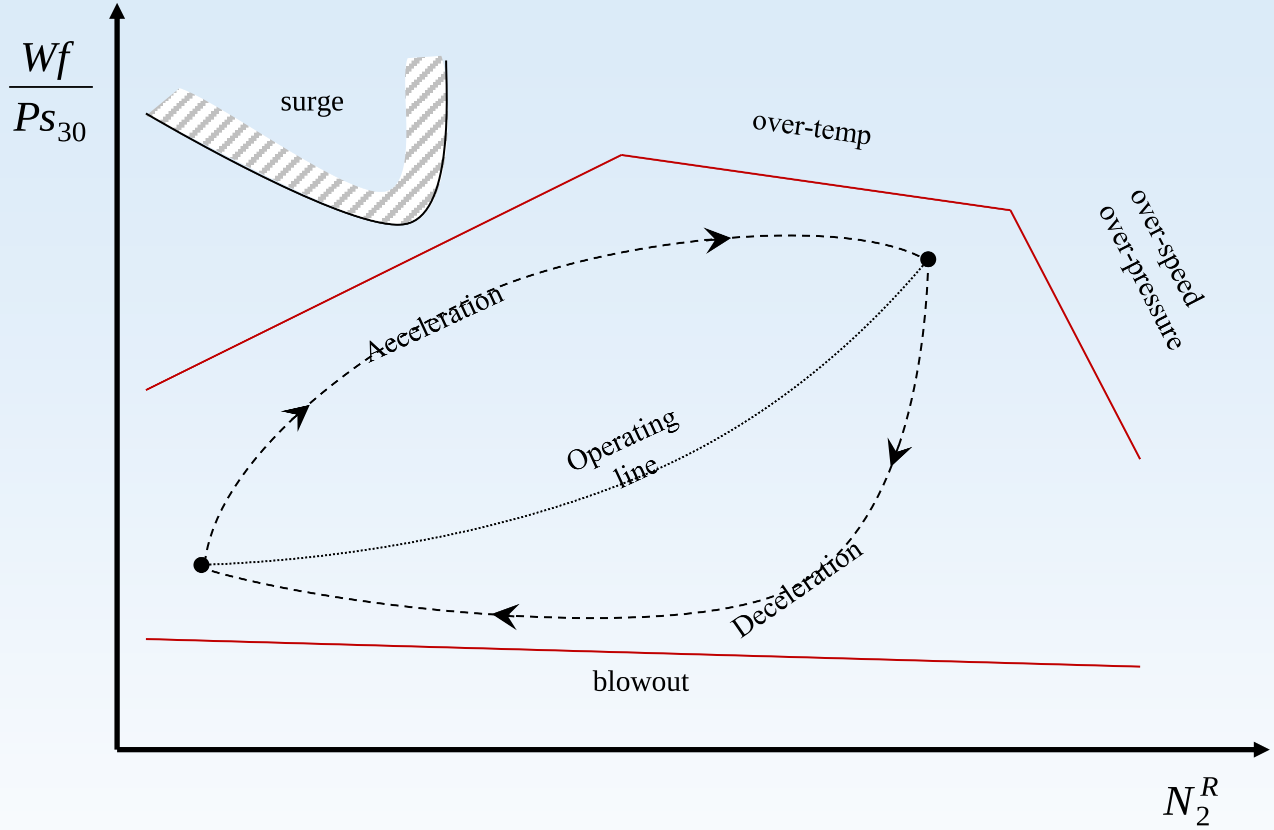
- Allows pilot to have full throttle movement throughout the flight envelope
  - There are many controlled variables – we will focus on fuel flow



- Engine control logic is developed using an engine model to provide guaranteed performance (minimum thrust for a throttle setting) throughout the life of the engine

  - FAA regulations provide a maximum allowable rise time of 5 sec to reach 95% and a maximum settling time for thrust from idle to max

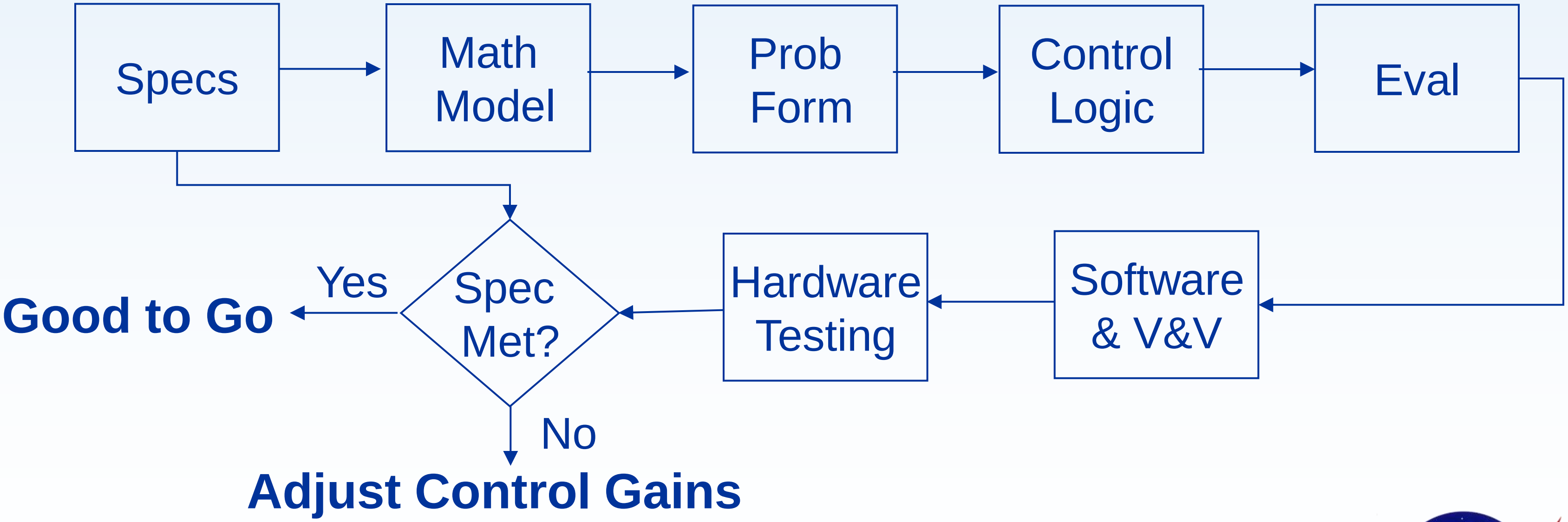
Implementing Limits for Engine Control



- Limits are implemented by limiting fuel flow based on rotor speed
  - Maximum fuel limit protects against surge/stall, over-temp, over-speed and over-pressure
  - Minimum fuel limit protects against combustor blowout
- Actual limit values are generated through simulation and analytical studies

Control Law Design Procedure

- The various control gains K are determined using linear engine models and linear control theory
    - Proportional + Integral control provides good fan speed tracking
    - Control gains are scheduled based on PLA and Mach number
- Control design evaluated throughout the envelope using a nonlinear engine simulation and implemented via software on FADEC processor
- Control gains are adjusted to provide desired performance based on engine ground and altitude tests and finally flight tests


Specs

Math Model

Prob Form

Control Logic

Eval

Software & V&V

Hardware Testing

Spec Met?

Yes

Good to Go

No

Adjust Control Gains

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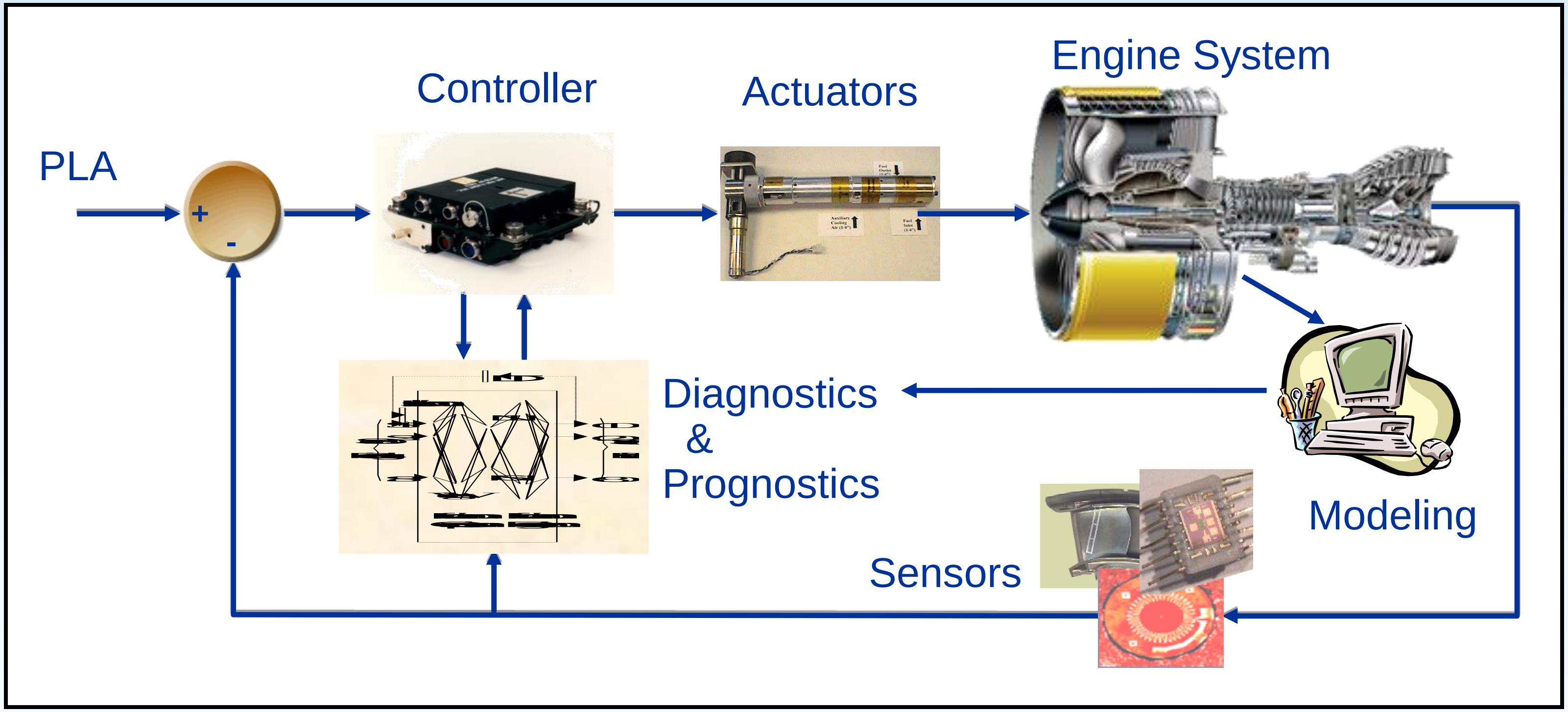
Intelligent Engine Technologies

- A Systems Viewpoint -



PLA

Controller

Actuators

Engine System

Diagnostics
&
Prognostics

Modeling

Sensors

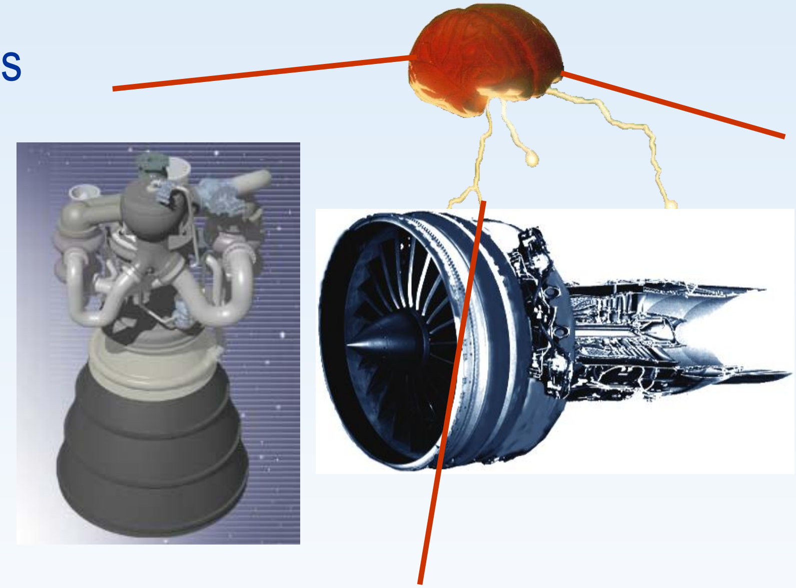
- Components such as actuators, sensors, control logic, & diagnostic systems have to be designed with overall system requirements in mind.

- Simplified models are essential for controller design. Understanding the physics of the phenomena is required to capture critical system dynamics in these models.

Intelligent Propulsion Systems
Control System perspective

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

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

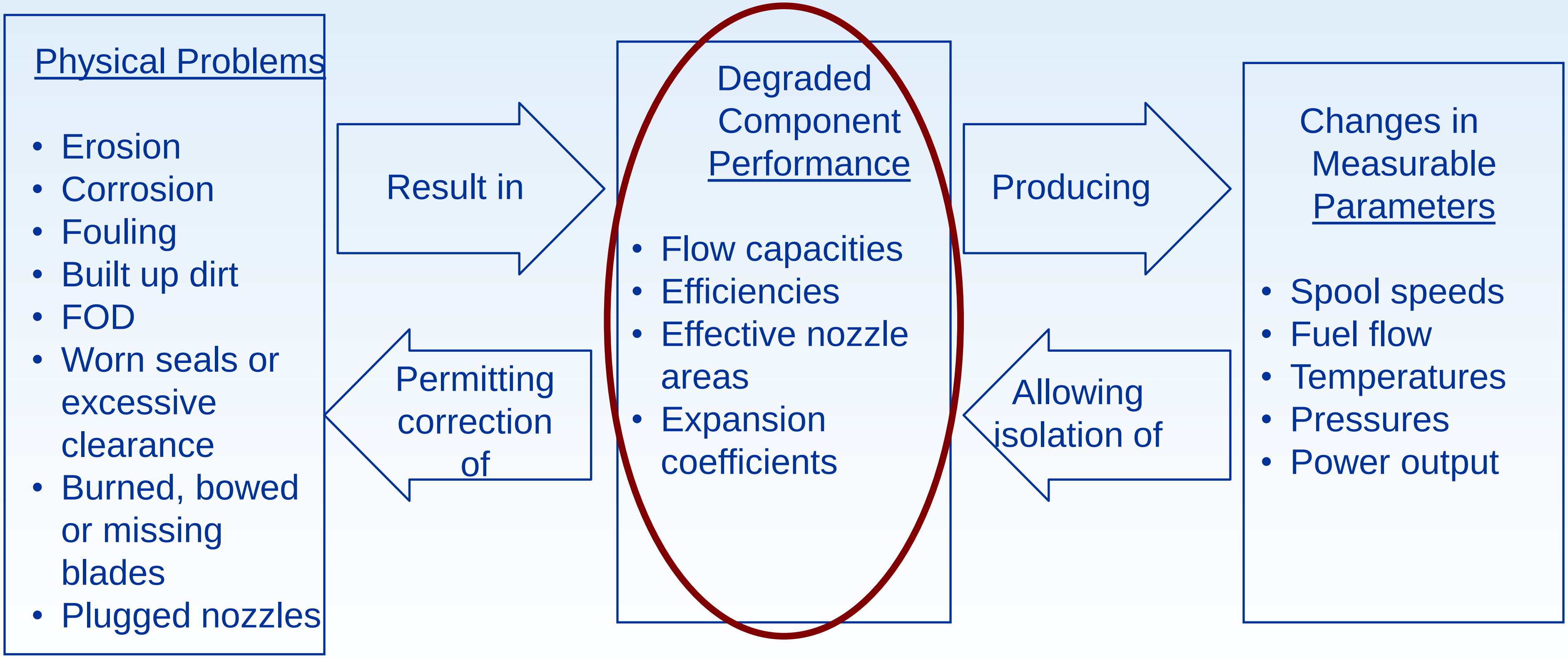


Advanced Health Management technologies for self diagnostic and prognostic propulsion system
- Life usage monitoring and prediction
- Data fusion from multiple sensors and model based information

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

Modeling Engine Faults and Performance Deterioration*

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.



Physical Problems

- Erosion
- Corrosion
- Fouling
- Built up dirt
- FOD
- Worn seals or excessive clearance
- Burned, bowed or missing blades
- Plugged nozzles

Result in

Degraded Component Performance

- Flow capacities
- Efficiencies
- Effective nozzle areas
- Expansion coefficients

Producing

Changes in Measurable Parameters

- Spool speeds
- Fuel flow
- Temperatures
- Pressures
- Power output

Allowing isolation of

Permitting correction of

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

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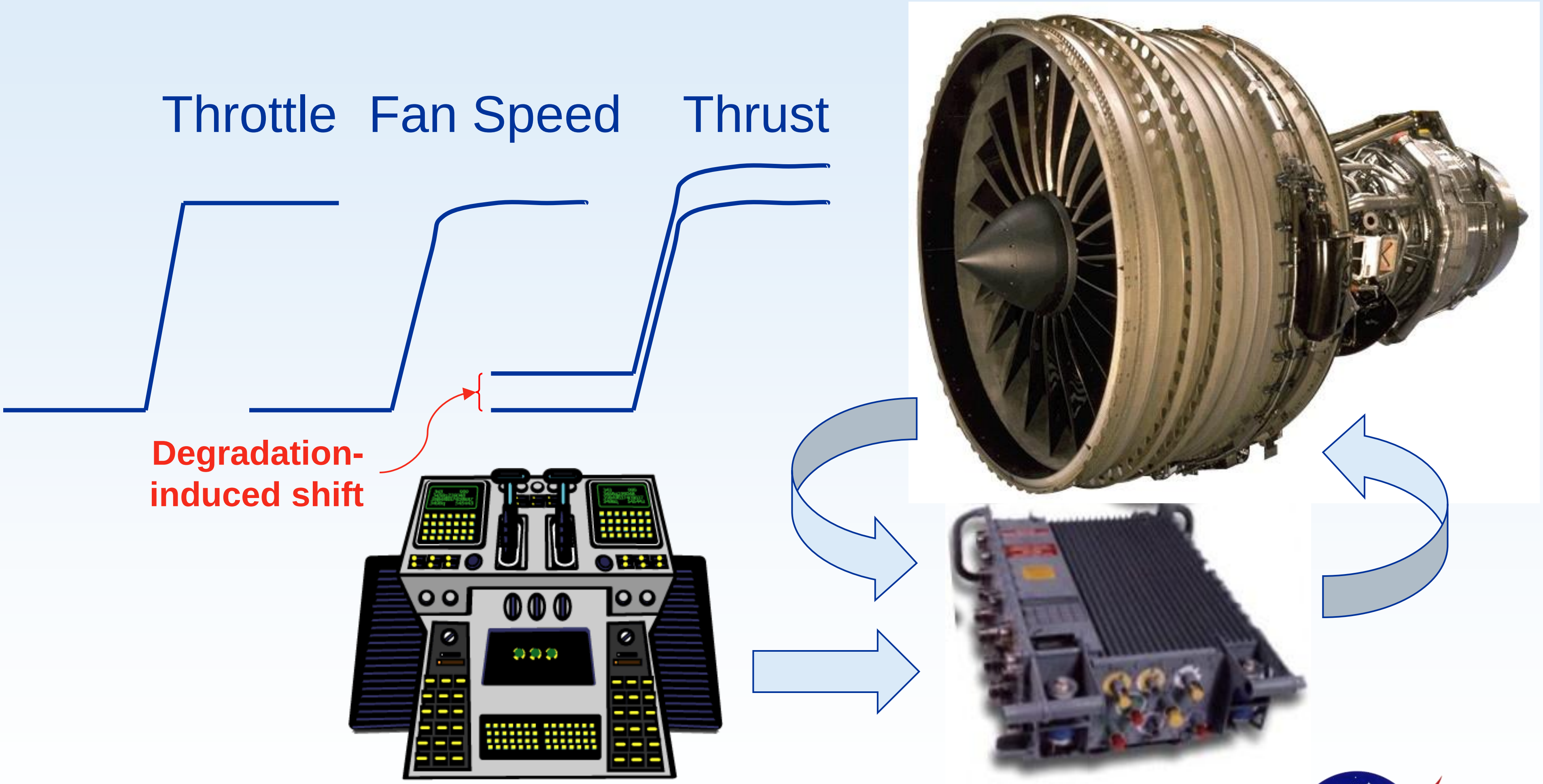
Advanced Engine Control Logic

- Multi-variable Control (MVC) – extensive research on engine application in the mid1970s-90s
  - LQR based MVC demonstrated on F-100 engine at NASA GRC in 1979
  - LQG/LTR based engine control studies in mid 1980s with engine test in UK
  - H-infinity based robust engine control studies at NASA GRC in mid 1990s
- Life Extending Control demonstrated in simulation studies at GRC in early 2000s
  - Modify the acceleration logic to increase on-wing life while still meeting the performance requirements
- Various research studies on Sensor Fault Detection, Isolation and Accommodation

Engine Performance Deterioration Mitigation Control

- Motivation—Thrust-to-Throttle Relationship Changes with Degradation in Engines Under Fan Speed Control



Throttle

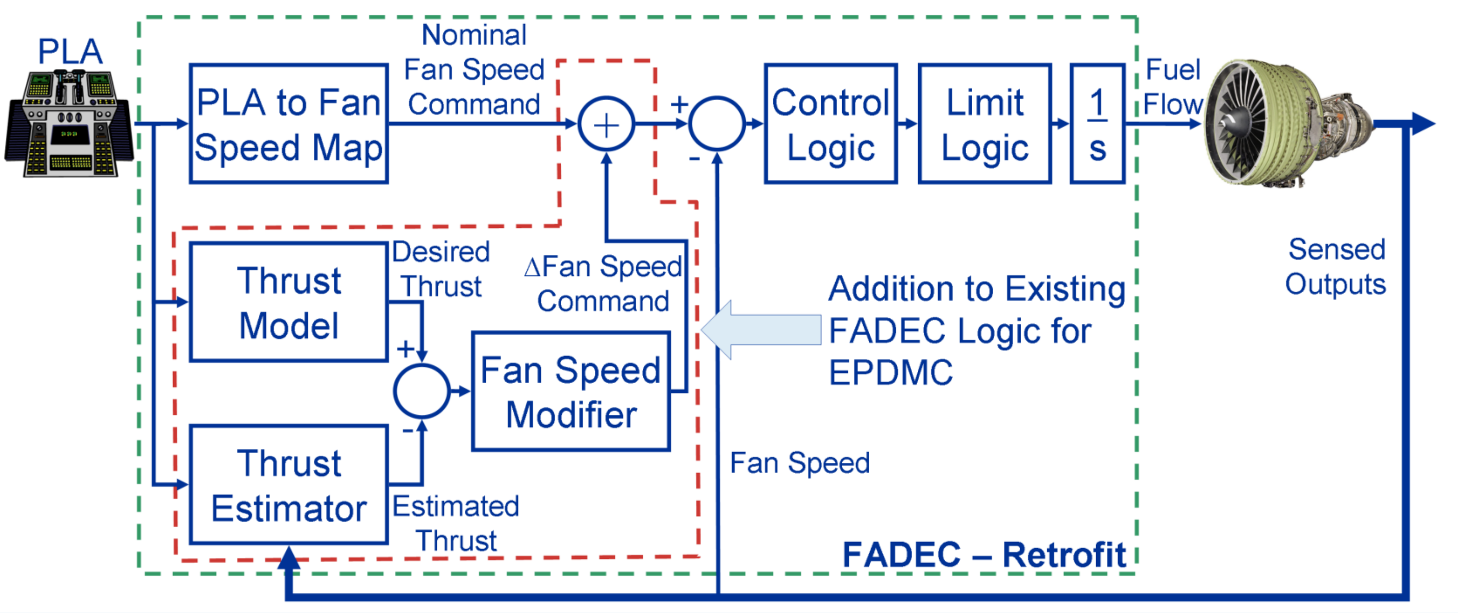
Fan Speed

Thrust

Degradation-induced shift

EPDMC Architecture

- The proposed retrofit architecture:

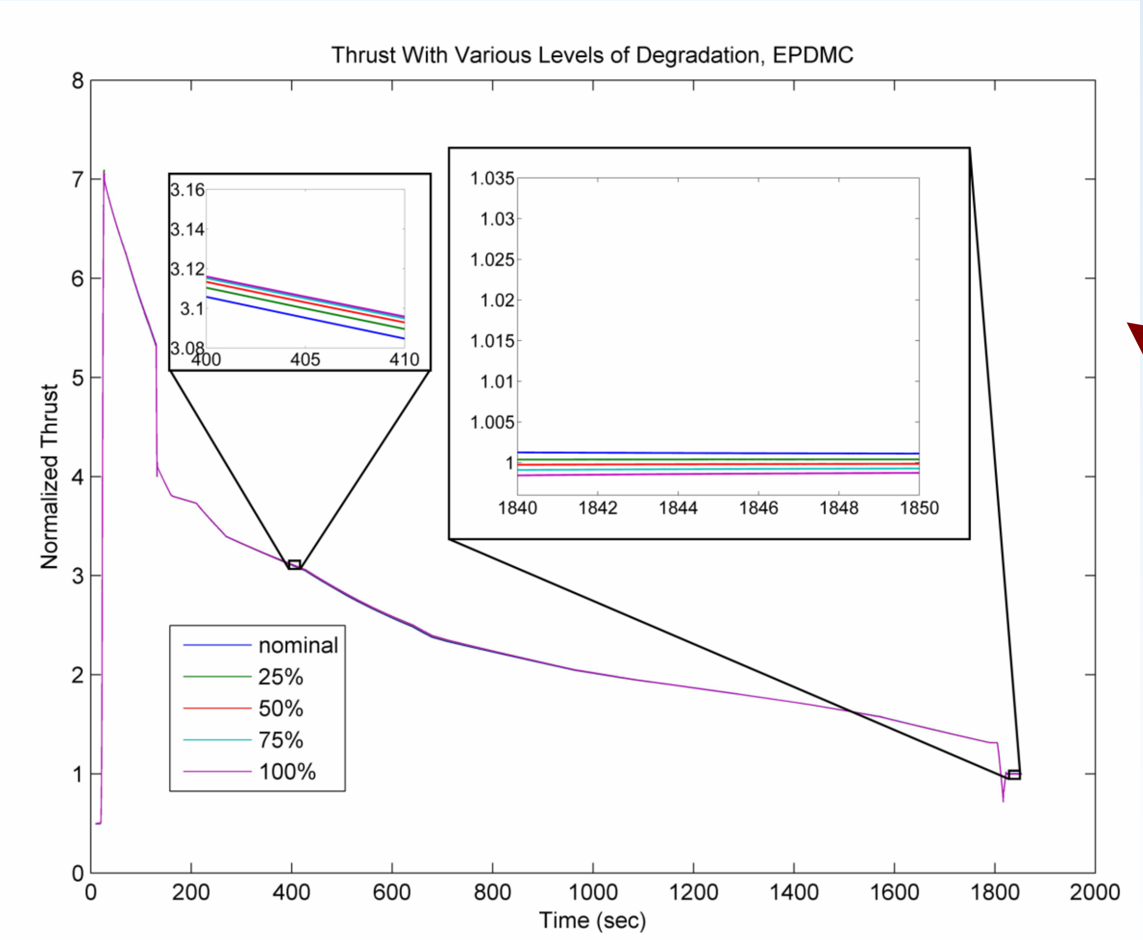


- Adds the following “logic” elements to existing FADEC:
  - A model of the nominal throttle to desired thrust response
  - An estimator for engine thrust based on available measurements
  - A modifier to the Fan Speed Command based on the error between desired and estimated thrust
    - Since the modifier appears prior to the limit logic, the operational safety and life remains unchanged

EPDMC Evaluation

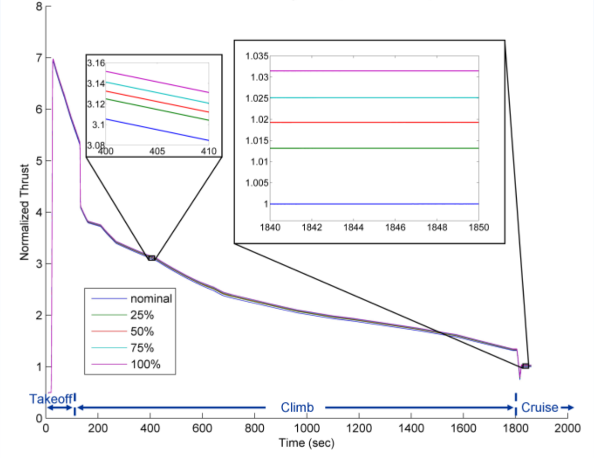
Thrust response for Typical Mission

With EPDMC

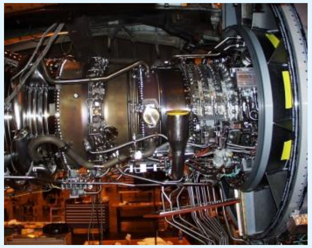


- **Throttle to thrust response is maintained – no “uncommanded” thrust asymmetry**

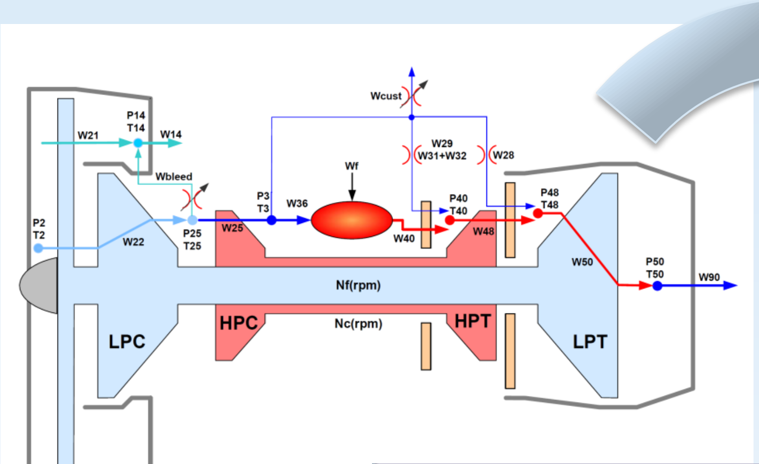
Without EPDMC



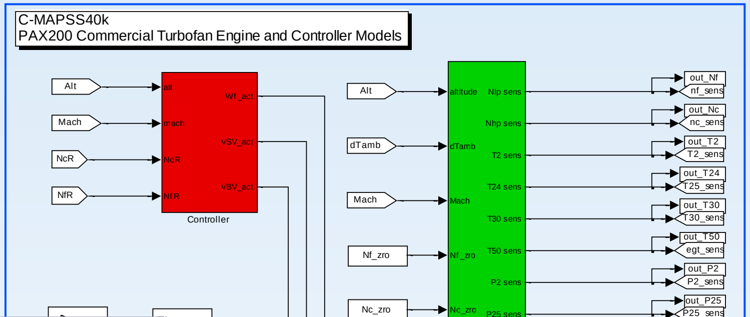
Commercial Modular Aero-Propulsion System Simulation 40k



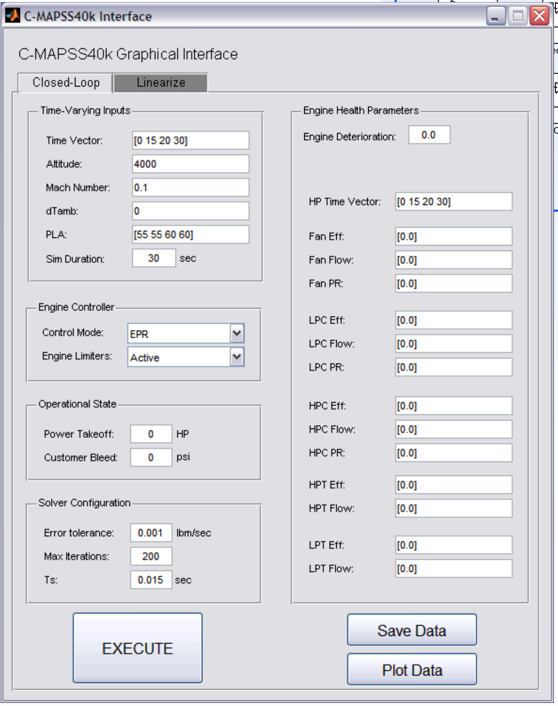
Engine flight data used to tune physics-based model



Simulation programmed in graphical language



Plotting and graphical analysis capability



C-MAPSS40k Interface

C-MAPSS40k Graphical Interface

Time-Varying Inputs

Time Vector: [0 15 20 30]
Altitude: 4000
Mach Number: 0.1
dTamb: 0
PLA: [55 55 60 60]
Sim Duration: 30 sec

Engine Controller

Control Mode: EPR
Engine Limiters: Active

Operational State

Power Takeoff: 0 HP
Customer Bleed: 0 psi

Solver Configuration

Error tolerance: 0.001 lbm/sec
Max Iterations: 200
Ts: 0.015 sec

Engine Health Parameters

Engine Deterioration: 0.0

HP Time Vector: [0 15 20 30]

Fan Eff: [0.0]
Fan Flow: [0.0]
Fan PR: [0.0]

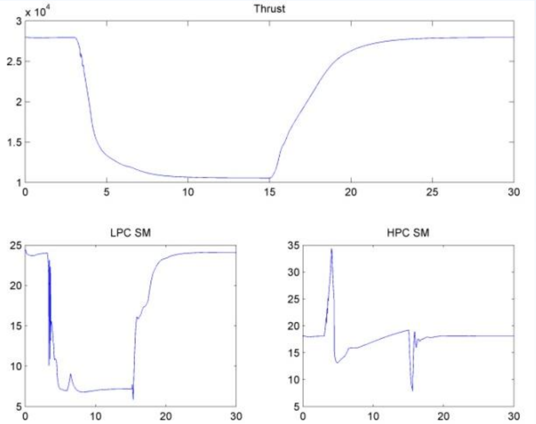
LPC Eff: [0.0]
LPC Flow: [0.0]
LPC PR: [0.0]

HPC Eff: [0.0]
HPC Flow: [0.0]
HPC PR: [0.0]

HPT Eff: [0.0]
HPT Flow: [0.0]

LPT Eff: [0.0]
LPT Flow: [0.0]

GUI driven operation

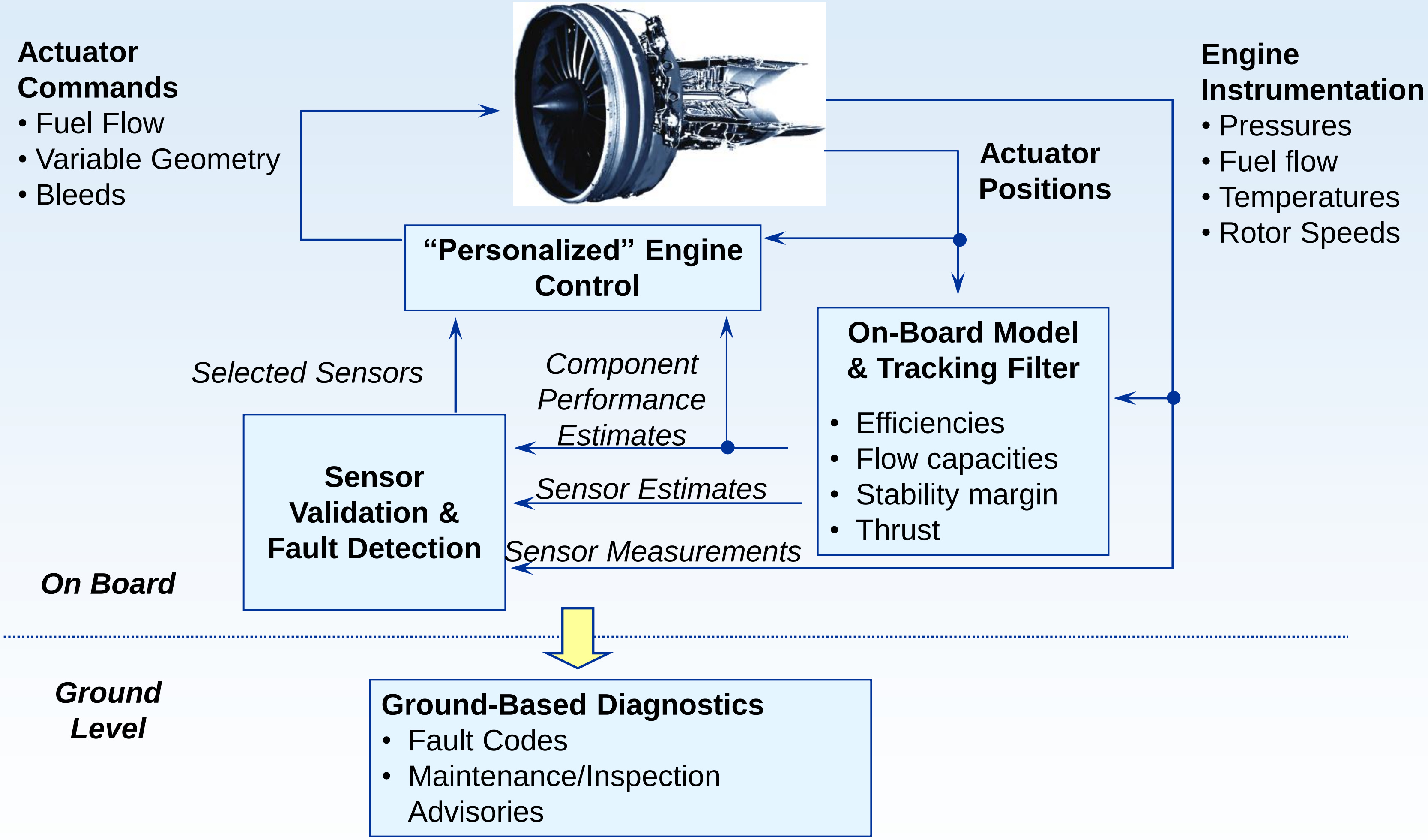


C-MAPSS40k thrust and stall margin response to throttle movements

Glenn Research Center

at Lewis Field

Model-Based Control and Diagnostics Concept



Actuator Commands
- Fuel Flow
- Variable Geometry
- Bleeds

Engine Instrumentation
- Pressures
- Fuel flow
- Temperatures
- Rotor Speeds

Actuator Positions

"Personalized" Engine Control

On-Board Model & Tracking Filter
- Efficiencies
- Flow capacities
- Stability margin
- Thrust

Selected Sensors

Component Performance Estimates

Sensor Estimates

Sensor Measurements

Sensor Validation & Fault Detection

On Board

Ground Level

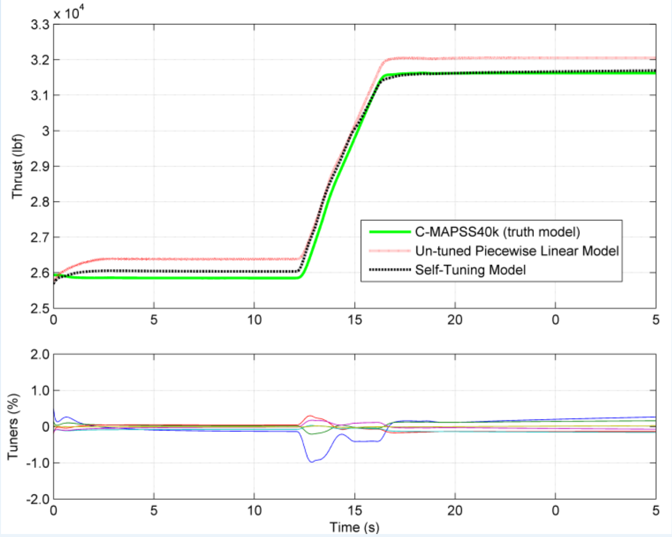
Ground-Based Diagnostics
- Fault Codes
- Maintenance/Inspection Advisories

Model-Based Engine Control

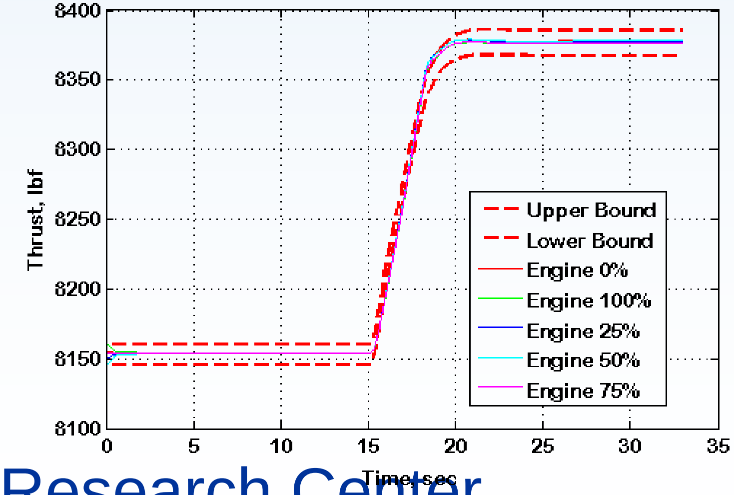
Objective: Develop and demonstrate the capability to provide more efficient engine control using an on-board real-time model.

Approach:

- Develop a self-tuning engine model for the C-MAPSS40k engine simulation – using the optimal tuner approach
- Validate the self-tuning model's ability to track changes in engine gas path performance parameters
- Develop direct thrust and limited variable control using model based estimated value



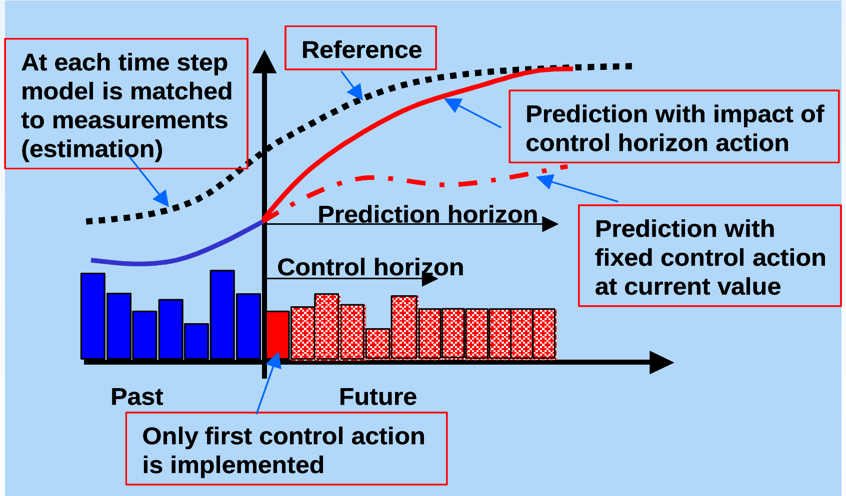
Self-tuning engine model vs. "un-tuned" piecewise linear model response (top), and corresponding model tuning parameter adjustments (bottom)



Tight control of Thrust achieved – preliminary linear design

Adaptive Engine Control

- The traditional engine control logic consists of a fixed set of control gains developed using an average model of the engine
- Having an on-board engine model which "adapts" to the condition of the engine, opens up the possibility of adapting the control logic to maintain desired performance in the presence of engine degradation or to accommodate any faults while obtaining best achievable performance
- An emerging technique for such an adaptive engine control is the Model Predictive Control (MPC)



At each time step model is matched to measurements (estimation)

Reference

Prediction with impact of control horizon action

Prediction horizon

Control horizon

Prediction with fixed control action at current value

Past

Future

Only first control action is implemented

- MPC solves a constrained optimization problem online to obtain the "best" control action - based on a tracked engine model, constraints, and the desired optimization objective

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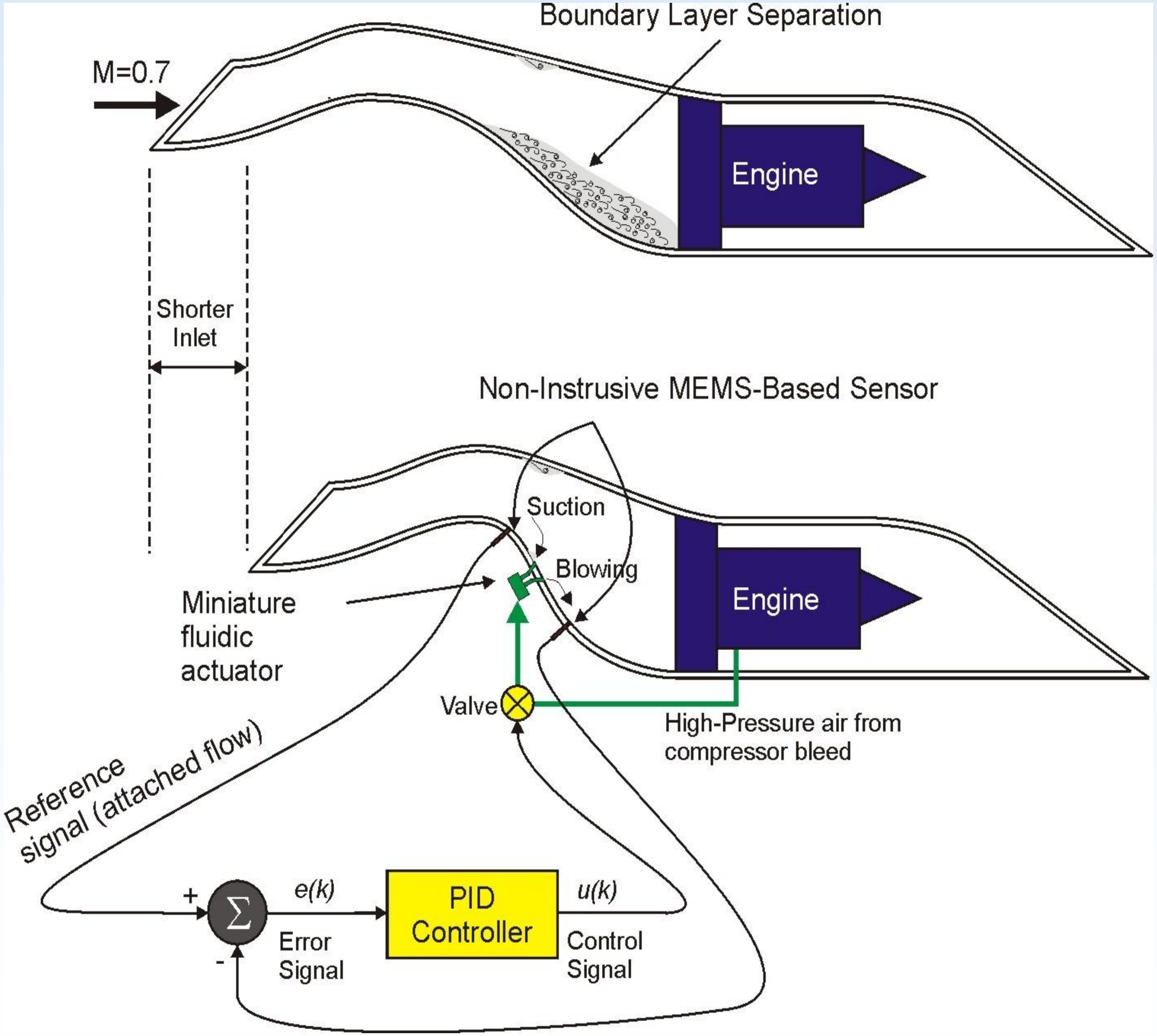
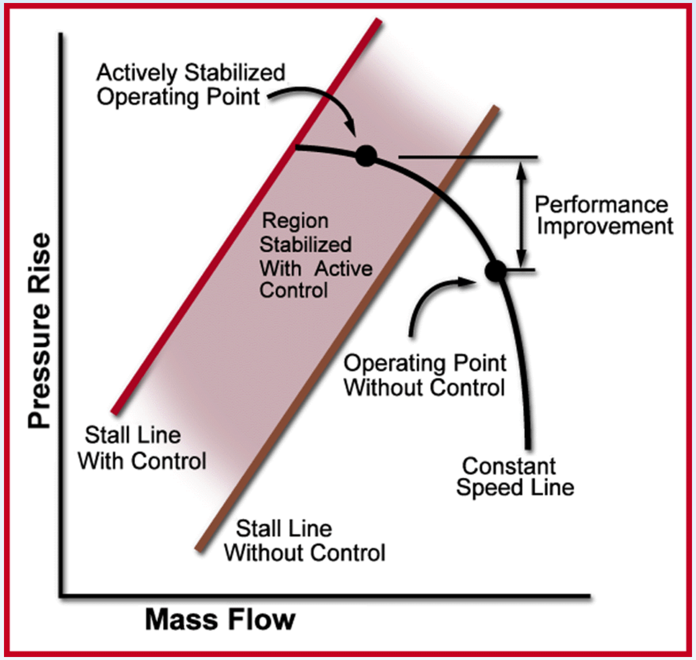
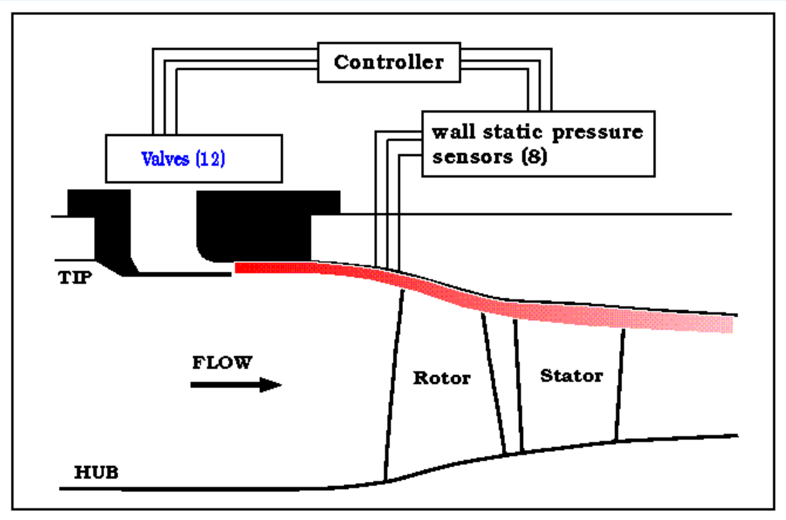
Separation Control in Intake Ducts

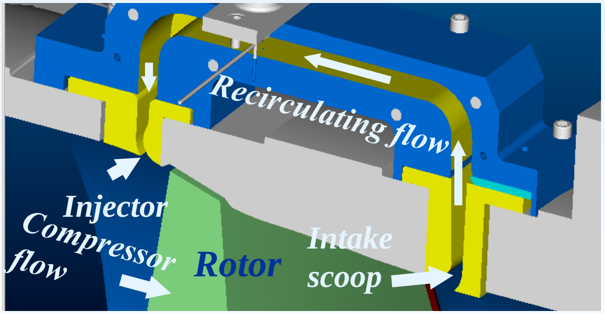


Active Stall Control



- Detect stall precursive signals from pressure measurements.
- Develop high frequency actuators and injector designs.
- Actively stabilize rotating stall using high velocity air injection with robust control.



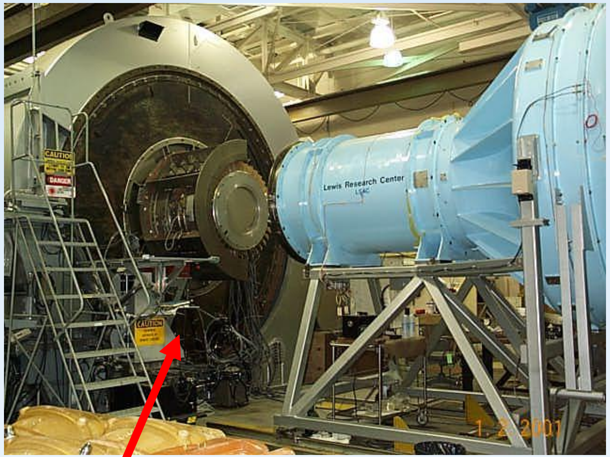


Compressor Stability Enhancement Using Recirculated Flow

- Demonstrated significant performance improvement with an advanced high speed compressor in a compressor rig with simulated recirculating flow

Active Flow Control - Compressors

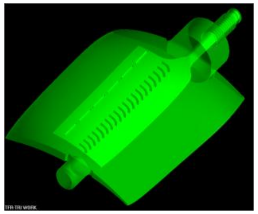
Compressor Stator Suction Surface Separation Control

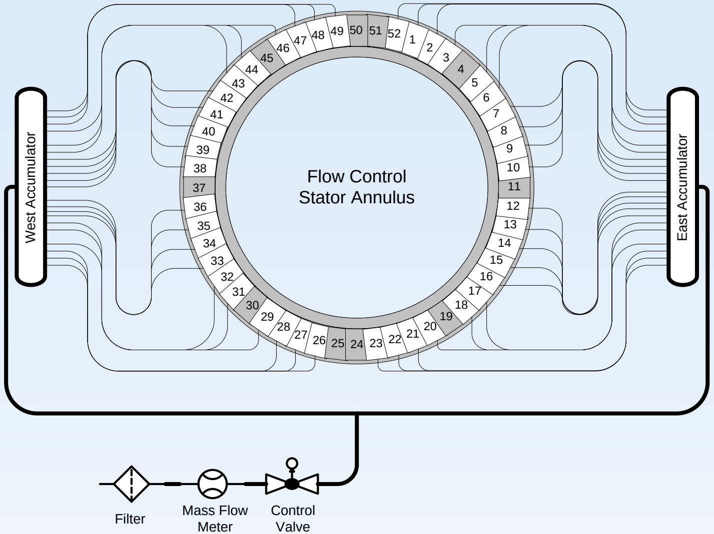


Multistage Axial Compressor

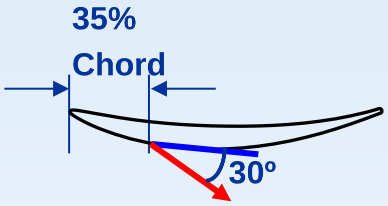
Installed Smart Vane Stators

Rapid Prototype Flow Control Vane

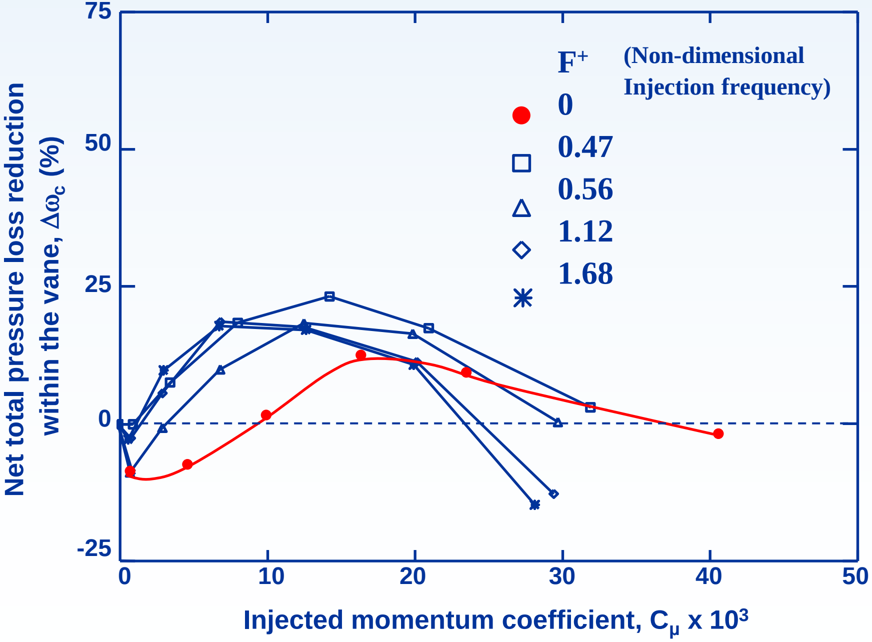




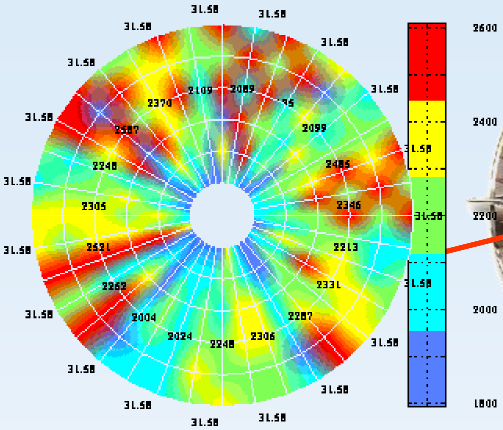
Flow Delivery System

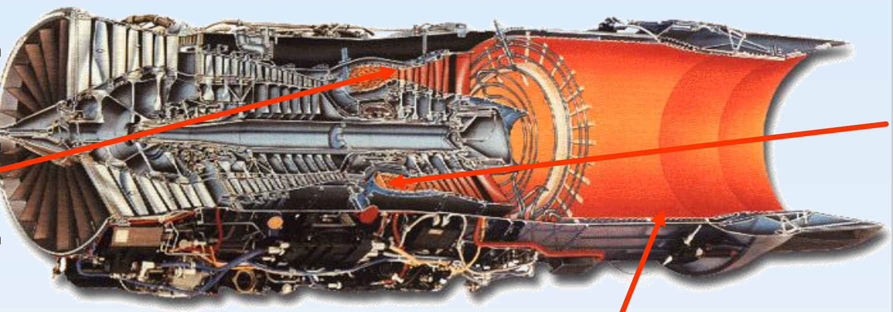


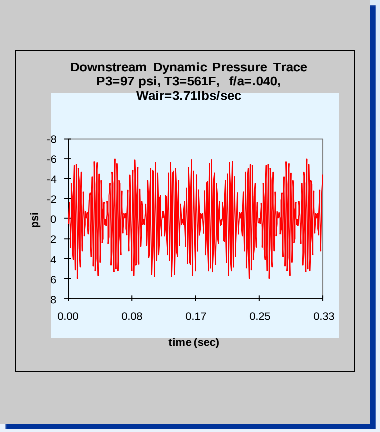
Flow Injection



Active Combustion Controls



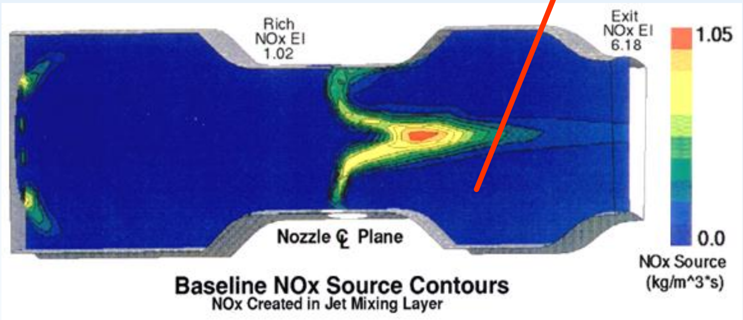




Pattern Factor Control

Objective: Actively reduce combustor pattern factor

Status: Concept demonstrated in collaboration with Honeywell Engines under the AST program - 2000.



Emission Minimizing Control

Objective: Actively reduce NOx production

Status: Fuel actuation concept and hardware developed under AST program. Preliminary low order emission models developed under the HSR program 2000.

Combustion Instability Control

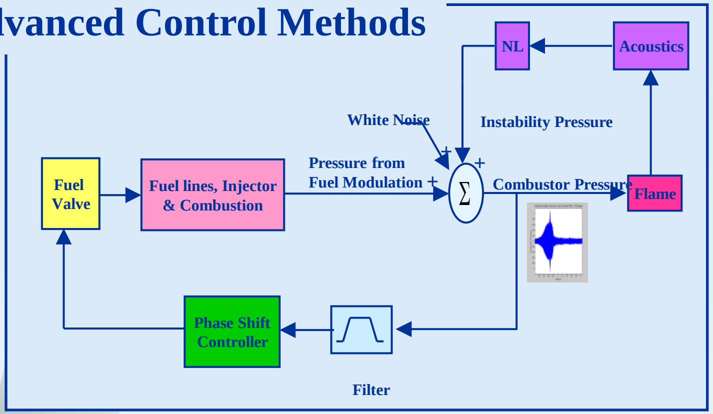
Objective: actively suppress thermo-acoustic driven pressure oscillations

Status: Concept demonstrated on a single combustion rig in 2003. Continuing research under current projects.

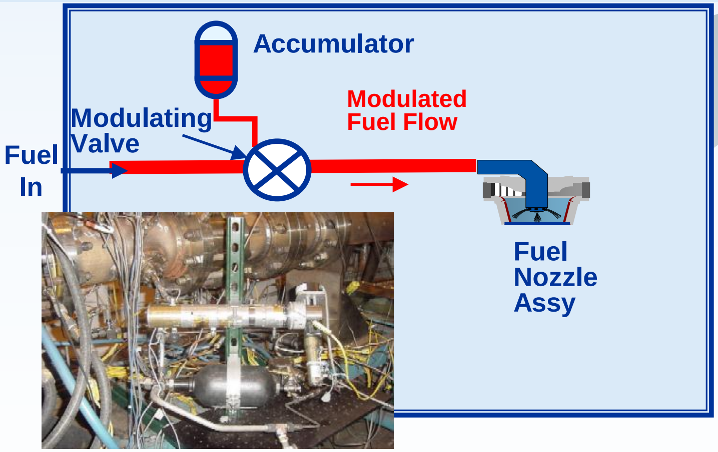
Active Control of Combustion Instability

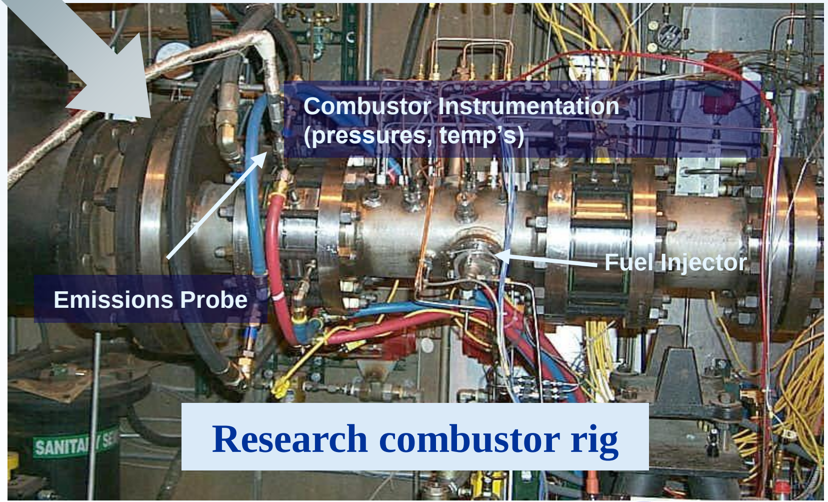
High-frequency fuel valve

Advanced Control Methods



Fuel delivery system model and hardware

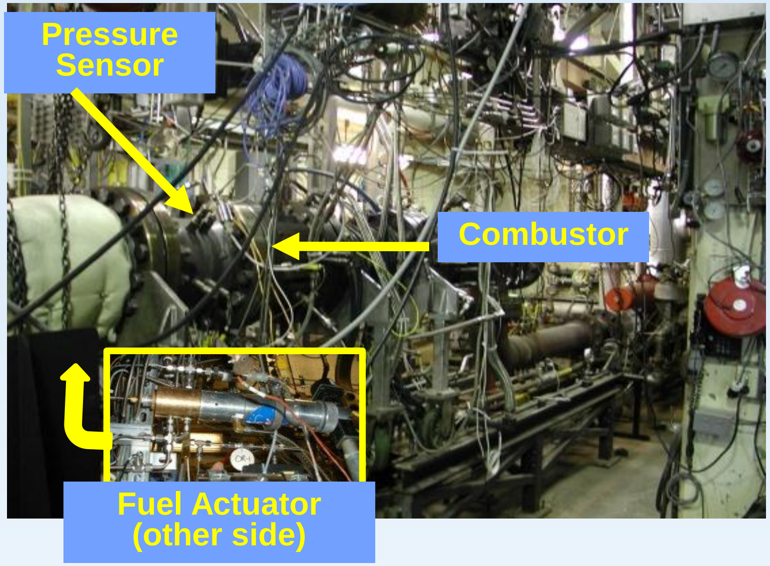


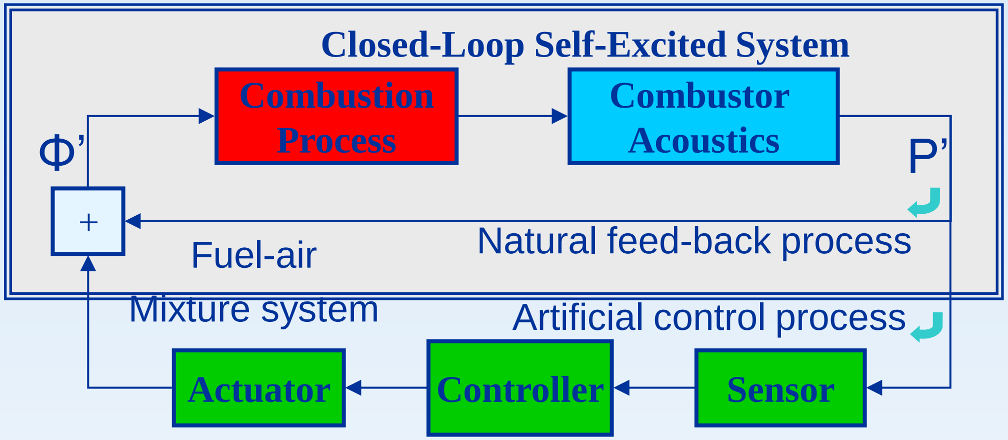


Research combustor rig

Active Instability Control on a Low Emission Combustor Prototype

Results from testing Oct-Nov 2011





Closed-Loop Self-Excited System

Combustion Process

Combustor Acoustics

Φ'

P'

+

Natural feed-back process

Fuel-air

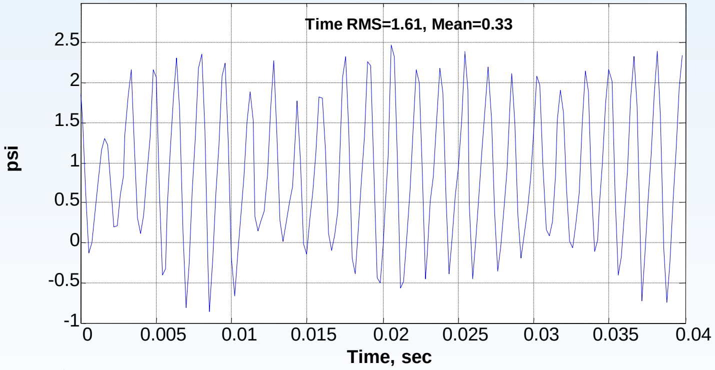
Mixture system

Artificial control process

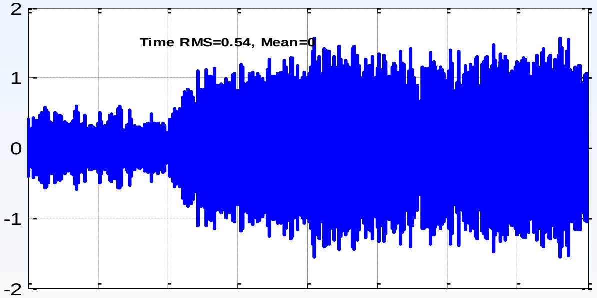
Actuator

Controller

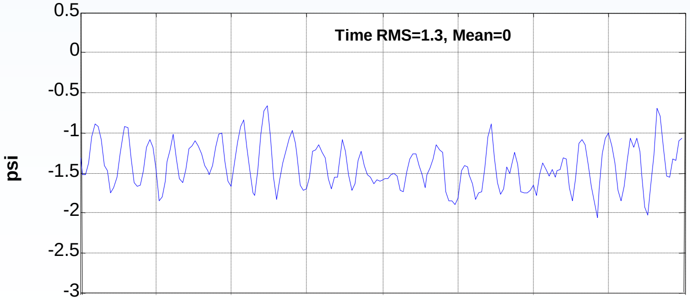
Sensor



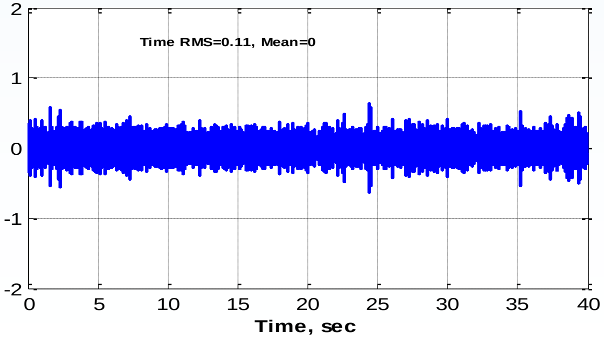
Controller Off



Instability Prevention



Controller On

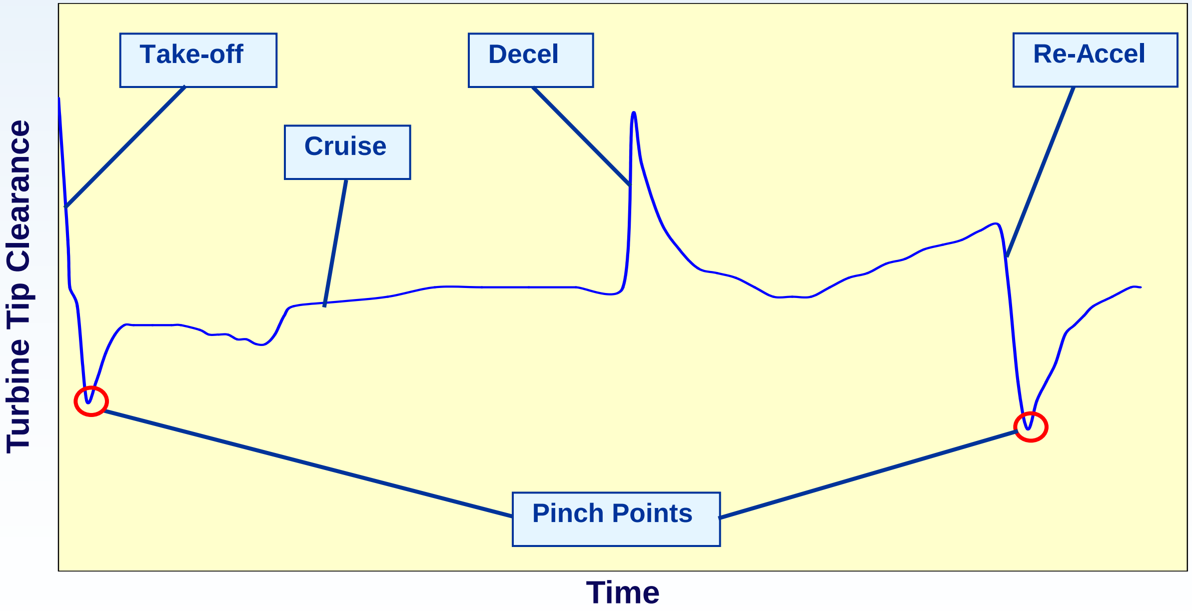


Instability Suppression

Intelligent Management of Turbine Tip Clearance

Time Scales:	Flights	Minutes	Seconds	Milliseconds
Problem:	Engine Wear	Cruise Clearance	Pinch Points	Eccentric Shaft Motion
Approach:	Regen. Seals	Case Cooling	Case Actuation	Magnetic Bearings

Notional Mission Profile



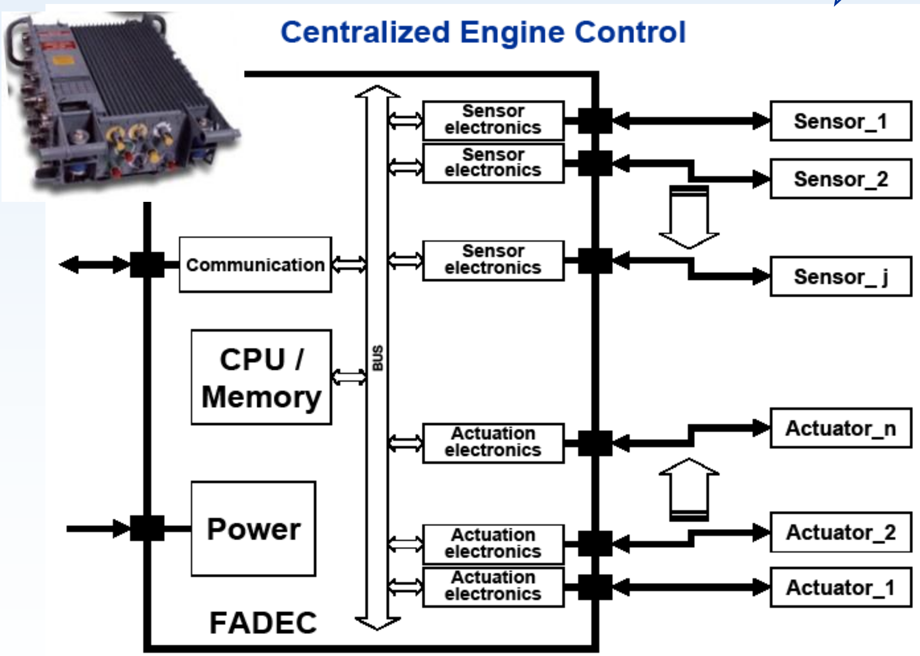
Outline

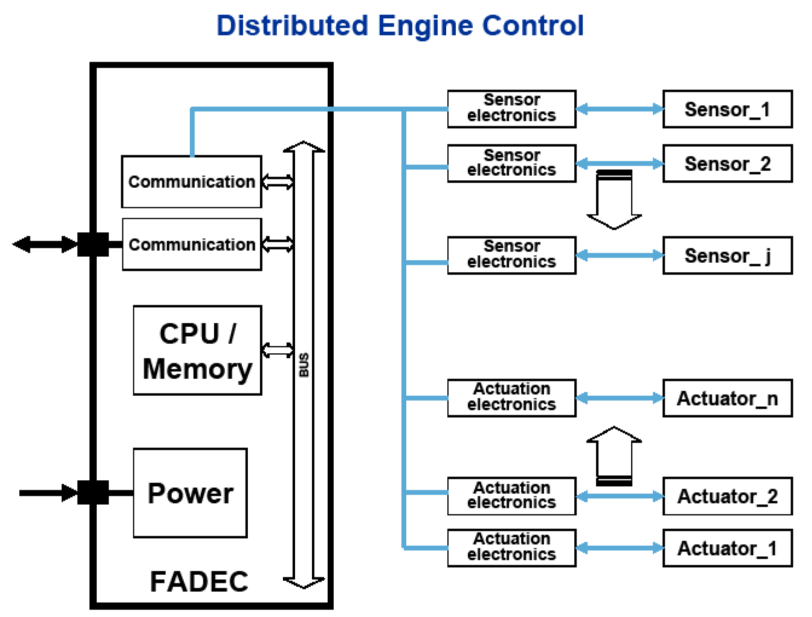
- Fundamentals of Aircraft Engine Control
- Intelligent Engine Concept – from a controls perspective
- Advanced Engine Control Logic
- Active Component Control
- **Distributed Engine Control**
- Summary

Distributed Engine Control

Objectives:

- Enable new engine concepts
- Enable new engine performance enhancing technologies
- Improve reliability
- Reduce overall cost
- Reduce control system weight


Centralized Engine Control


Distributed Engine Control

Challenges:

- High temperature electronics
- Communications based on open system standards
- Control function distribution

Government – Industry Partnership

Distributed Engine Control Working Group

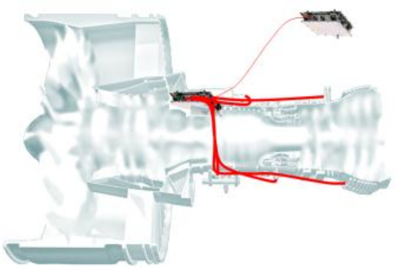
Distributed Control Technology Roadmap

T=0 years 5 10 15 20

CORE I/O

Core-Mounted :
Data Concentrator
Digital Communications
Distributed Power

SOI µP, logic, analog
SiC power

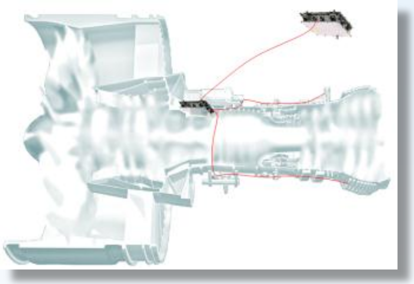


Hardware-in-the-Loop Facility

NETWORKED CONTROL

Engine Network
Smart System Devices
>300 Celsius Electronics

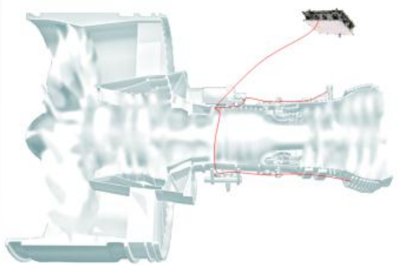
SOI µP, logic, analog
Medium Scale Integration SiC µP, logic, analog
SiC power



FULLY DISTIBUTED

Common Network Communications (Wireless)
Embedded Control Law
Embedded Power Harvesting

SOI µP, logic, analog
Large Scale Integration SiC µP, logic, analog
SiC power



Summary

- There are tremendous opportunities to improve and revolutionize aircraft engine performance through “proper” use of advanced control technologies
  - Intelligent engine control integrated with reliable condition monitoring and fault diagnostics to extend on-wing operating life, maintain performance with aging, safely accommodate faults while maintaining best achievable performance etc.
  - Active control of engine components to provide the desired performance characteristics throughout the flight envelope and enable low emission higher performance components
  - Distributed engine control to enable new engine concepts, reduce “control system” weight, increase operational reliability, and flexibility to easily incorporate new and improved capabilities

References

- H. Austin Spang III and Harold Brown, “Control of Jet Engines”, *Control Engineering Practice, Vo. 7,* 1999, pp. 1043-1059
- Link Jaw and Jack D. Mattingly, “Aircraft Engine Controls,” AIAA Education Series Book
- Jonathan A. DeCastro, Jonathan S. Litt, and Dean K. Frederick, “A Modular Aero-Propulsion System Simulation of a Large Commercial Aircraft Engine”, NASA TM 2008-215303.
- Jeffrey Csank, Ryan D. May, Jonathan S. Litt, and Ten-Huei Guo, “Control Design for a Generic Commercial Aircraft Engine”, NASA TM-2010-216811
- Sanjay Garg, “Propulsion Controls and Diagnostics Research in Support of NASA Aeronautics and Exploration Mission Programs,” NASA TM 2011-216939.

NASA TMs are available for free download at:
http://ntrs.nasa.gov/search.jsp

Engine Simulation Software C-MAPSS40k – available to U.S. citizens
http://sr.grc.nasa.gov/public/project/77/

Challenges in Aircraft Engine Gas Path Health Management

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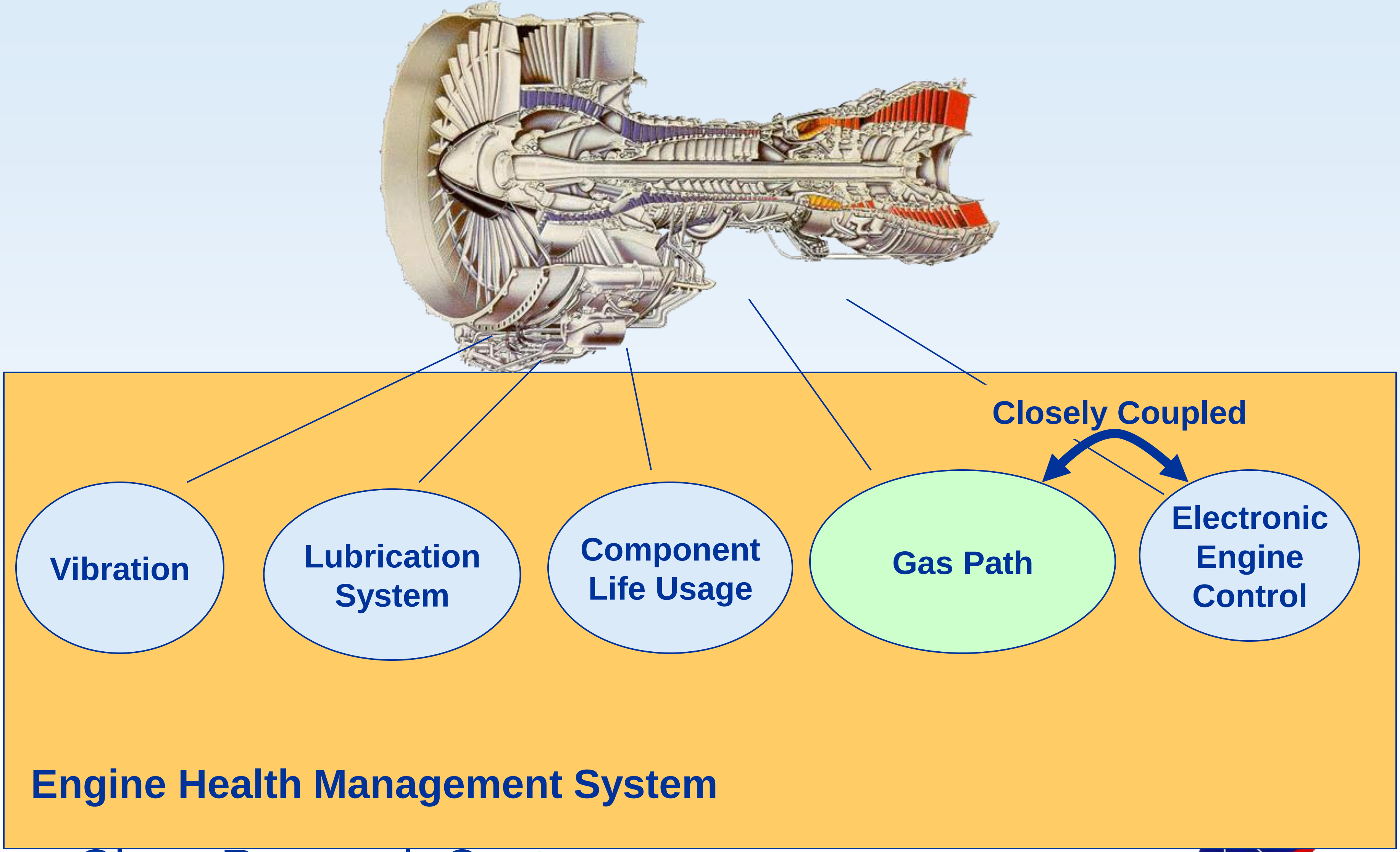
Outline

- Aircraft Engine Gas Path Health Management Background
  - Goals and Benefits
  - Approaches
- Future Challenges
  - Data quantity, data access, and data sharing
  - New sensor suites
  - Benchmarking and verification & validation methods
  - Models and model-based controls & diagnostics
  - Engine fault testing
  - Information fusion
  - Practical design considerations
- Summary

Challenges in Aircraft Engine Gas Path Health Management

Background

Gas Path Health Management is a Critical Element of an Aircraft Engine Health Management System



Closely Coupled

Vibration

Lubrication System

Component Life Usage

Gas Path

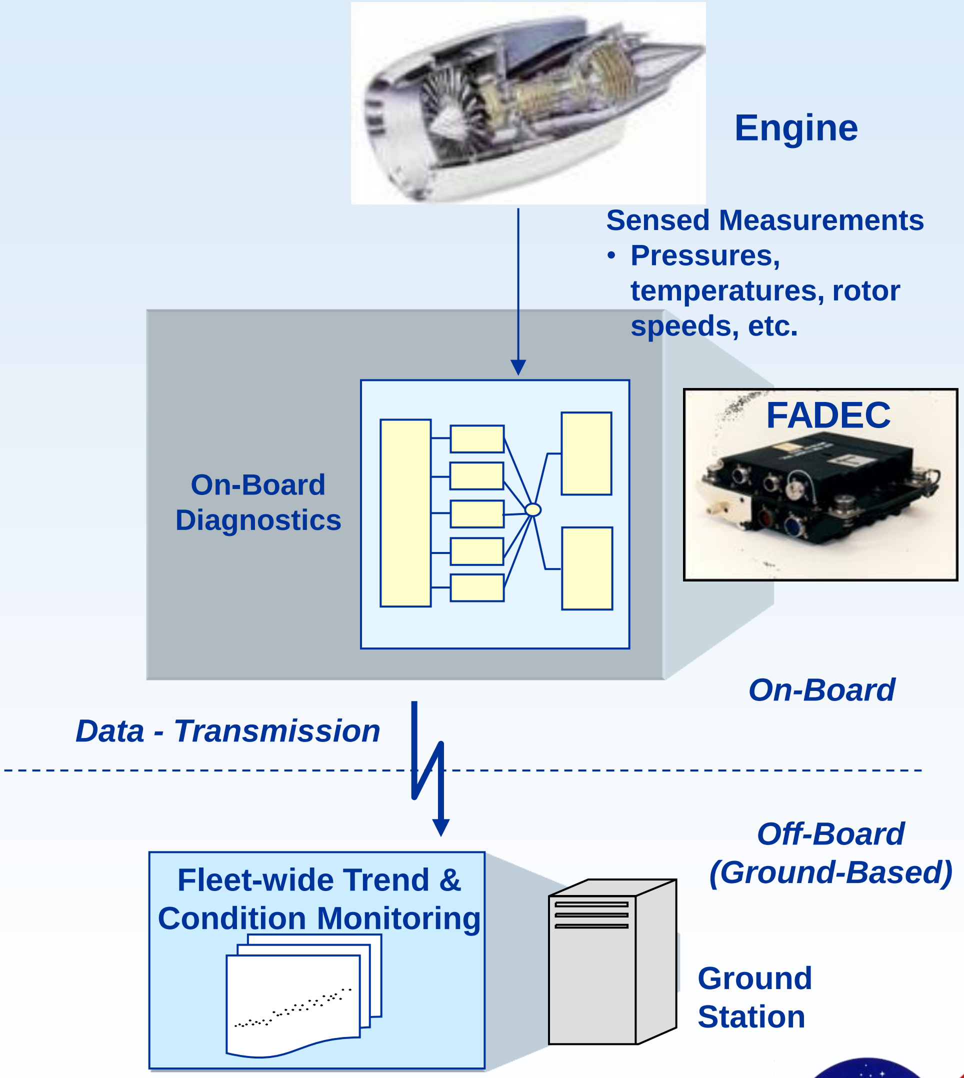
Electronic Engine Control

Engine Health Management System

Aircraft Engine Gas Path Diagnostics Architecture

- **Enabled by digital engine controls and data acquisition systems**

- **Both on-board and off-board functionality**



Engine

Sensed Measurements
- **Pressures, temperatures, rotor speeds, etc.**

On-Board Diagnostics

FADEC

On-Board

Data - Transmission

Off-Board (Ground-Based)

Fleet-wide Trend & Condition Monitoring

Ground Station

Aircraft Engine Gas Path Health Management

Goal: **Through the interpretation of measured aircraft engine gas path parameters…..**

- **Accurately assess engine component performance deterioration over an engine's lifetime of use**

- and -

- **Accurately detect and isolate any engine system and/or instrumentation malfunctions that occur**

Benefits: **Inherently tied to …**

- **Safety**

- and -

- **Affordability**

Reduced in-flight malfunctions

Reduced maintenance-related delays and cancellations

Reduced fuel burn and operating costs

Aircraft Engine Gas Path Deterioration and Fault Examples

Turbomachinery Deterioration

- Fouling
- Corrosion
- Erosion

Turbomachinery Faults

- Foreign object damage
- Blade/Vane failure

Controls and Accessories Faults

- Sensor faults
- Actuator faults
- Wiring harness faults

Aircraft Engine Maintenance Actions

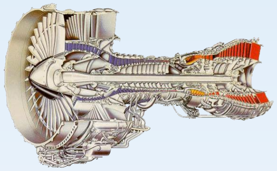
On-Wing Maintenance

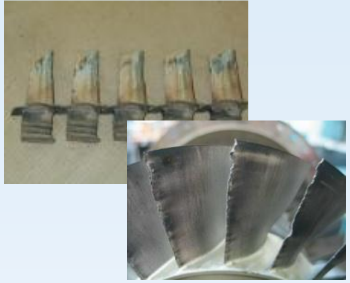
Engine Water Wash

Engine Overhaul

Gas Path Diagnostics Engine Fault Isolation Approach *

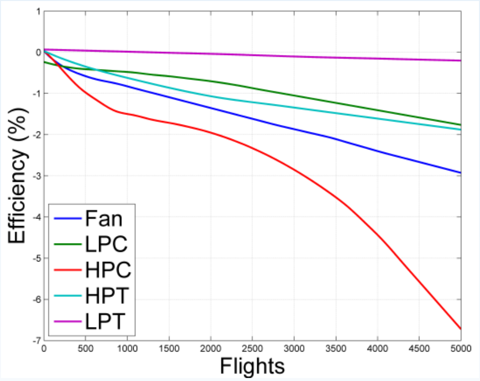
Deteriorated Turbomachinery and Gas Path Faults





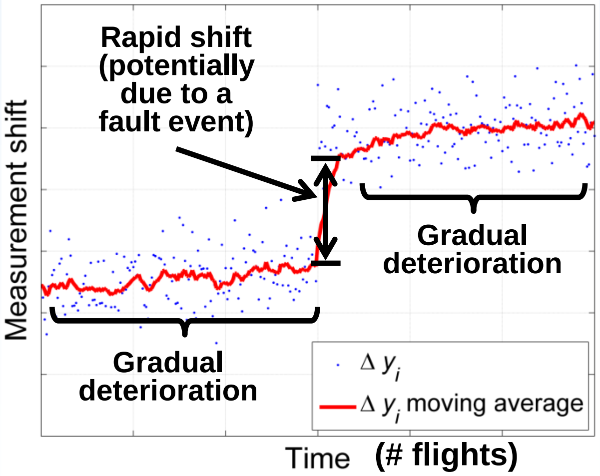
Resulting in

Degraded module performance



Producing

Changes in measured parameters

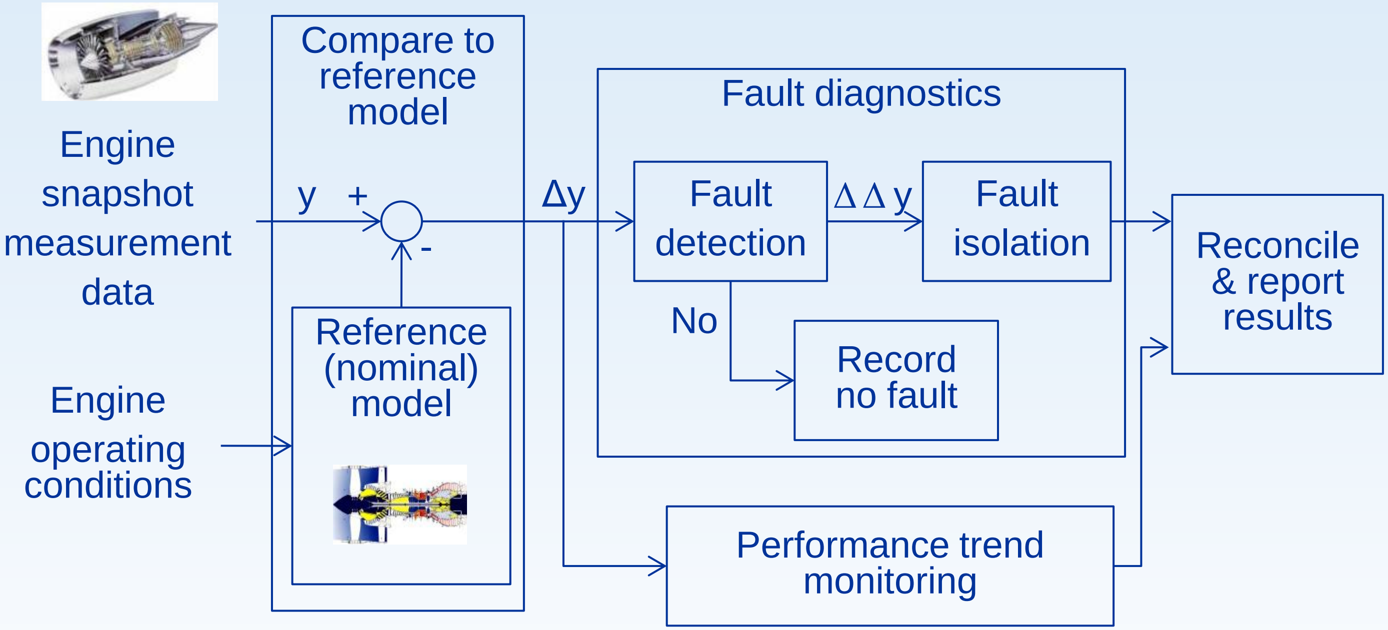


Allowing isolation of

Permitting correction of

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

Ground Station Performance Trend Monitoring and Gas Path Fault Diagnostic Process*



Engine snapshot measurement data

Engine operating conditions

Compare to reference model

y +

-

Reference (nominal) model

Δy

Fault diagnostics

Fault detection

Δ Δ y

Fault isolation

No

Record no fault

Performance trend monitoring

Reconcile & report results

* Reference: Volponi, A., Wood, B., (2005), “Engine Health Management for Aircraft Propulsion Systems,” The Forum on Integrated System Health Engineering and Management (ISHEM) in Aerospace, November 7-10, Napa, CA.

Conventional Performance Estimation and Gas Path Fault Diagnostics (based on “snapshot” measurements)

Performance Estimation

Steady-state measurement process:

$$\Delta y = H\Delta h + v$$

Δy	sensed output vector
Δh	health parameter vector
H	influence coefficient matrix
v	measurement uncertainty (N(0,σ) with covariance *R*)

Performance estimation:

$$\Delta\hat{h} = \left(P_h^{-1} + H^T R^{-1} H\right)^{-1} H^T R^{-1} \cdot \Delta y$$

P_h	health parameter covariance matrix (defined *a priori*)

Gas Path Fault Diagnostics

Steady-state measurement process:

$$\Delta\Delta y = H_f \Delta f + v$$

H_f	fault influence coefficient matrix
Δf	fault vector

Diagnostics performed applying a single fault assumption:

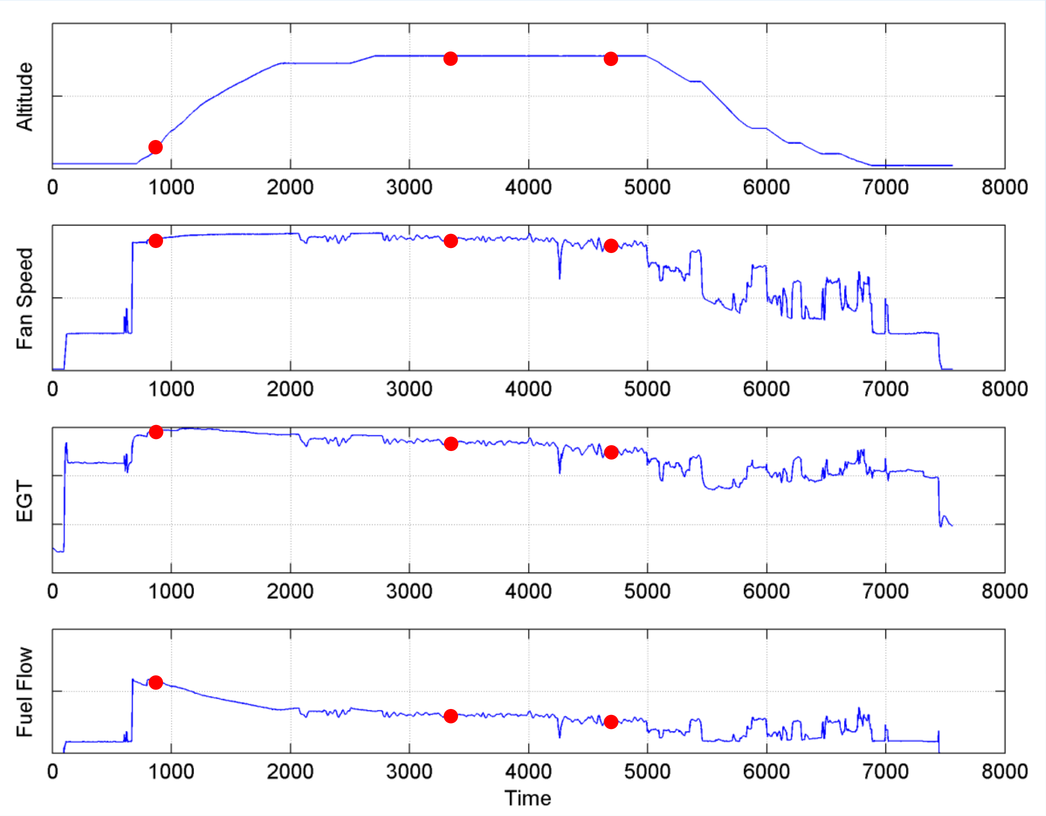
- Assumes that rapid/abrupt performance change is most likely due to a single root cause
- Weighted least squares estimation applied to produce an estimated fault magnitude for each fault type.
- Estimated fault that best matches observed fault signature is classified as fault type.

Challenges in Aircraft Engine Gas Path Health Management

Expanding Quantity of Available Data

Example Commercial Aircraft Engine Flight Data

● Denotes conventional “snapshot” measurement point



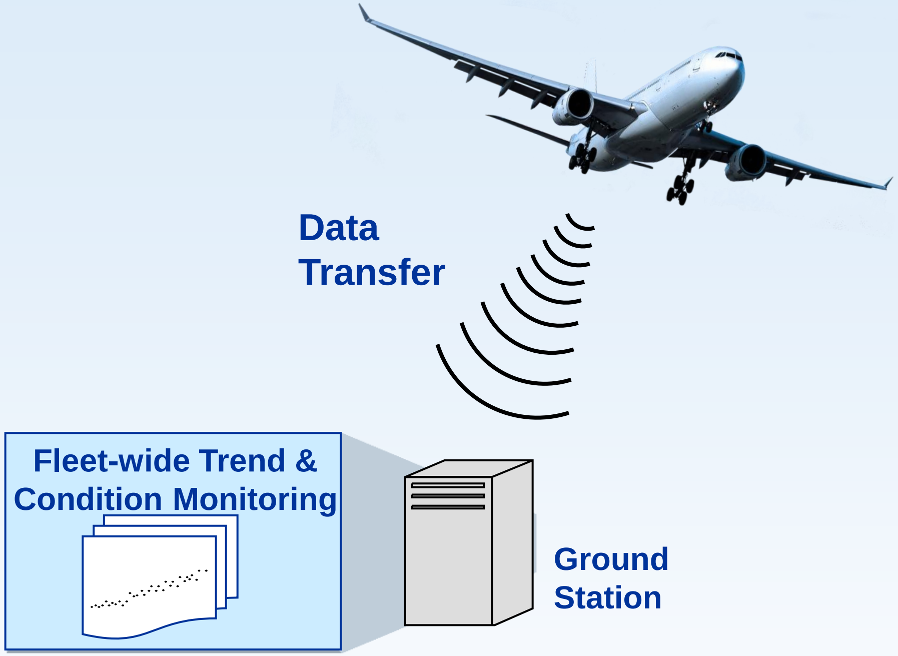
Data Transfer

Emerging Trends

- Increasing flight data recording capabilities
- Flight Operations Quality Assurance (FOQA) programs provide operators access to full-flight data
- Dedicated processors for analyzing data on-board

Expanded Data Quantity Provides both Challenges and Opportunities!

Expanding Quantity of Available Data (cont.)



Data Transfer

Fleet-wide Trend & Condition Monitoring

Ground Station

Potential Benefits:

- Reduced diagnostic latency
- Improved fault detection and isolation capabilities
- Improved prognostics and remaining useful life calculations
- Applied for development of improved engine models

Challenges:

- Streaming data analysis capabilities
- Transient diagnostic techniques
- Data mining techniques for information discovery and extraction
- Efficient data compression and data management strategies
- Effective leveraging of redundant sensor measurement information

Data Access and Data Sharing

- Access to aircraft engine data is often limited due to proprietary issues and liability concerns

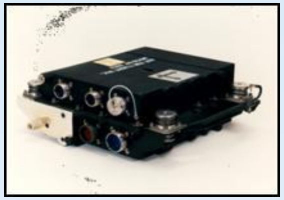
- Access to faulty engine data is rare
  - Engine faults occur infrequently, and when they do occur “ground truth knowledge” of actual fault condition is not always available

- Mechanisms to sanitize and share data between “data owners” and solution providers are desired
  - NASA Ames DASHlink (Discovery in Aeronautics System Health) provides an online resource for data and algorithm development and sharing

DASH*link* is a virtual laboratory for scientists and engineers to disseminate results and collaborate on research problems in health management technologies for aeronautics systems.

New Sensor Suites

- Gas path methods primarily rely upon the sensors installed for engine control purposes
  - In some cases the trend is to reduce the number of control sensors in order to reduce cost and weight and increase reliability
  - Health management benefits of sensors is often a secondary consideration



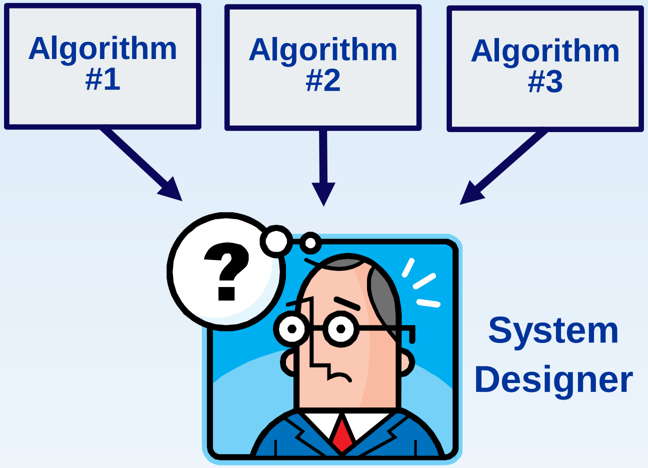
- It is difficult to justify adding additional engine sensors solely for health management purposes
  - Reduce cost/weight and increased reliability of existing sensors is desired
  - Additional sensors must have strong cost-benefit justification
  - Often dual-use functionality is necessary

- New sensors added for advanced control purposes can potentially be leveraged for health management benefits
  - Examples: tip clearance sensors, active control sensors, etc.
  - Requires new feature extraction and data synchronization techniques
  - Must relate any new information back to engine health

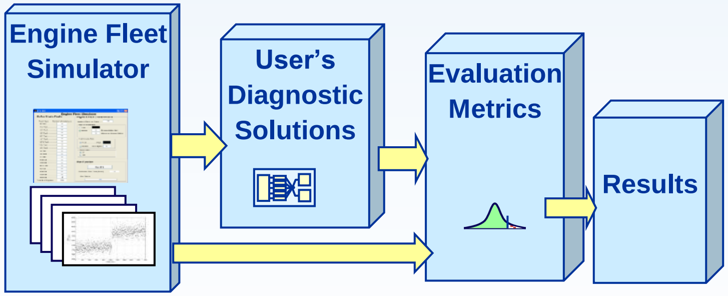
- Effective sensor selection tools are necessary to help end users assess the health management consequences of adding/removing sensors

Benchmarking and Comparison of Candidate Health Management Methods

- Engine Health Management (EHM) related R&D activities have increased significantly since the late 1990's. However, due to the use of different terminologies, applications, proprietary data, and metrics there is no basis of comparison



- Standardized metrics can enable diagnostic method performance to be reflected in a common format
  - SAE Committee E32 Aerospace Propulsion Systems Health Management publication ARP5783, "Health and Usage Monitoring Metrics: Monitoring the Monitor"
- Public benchmarking problems can facilitate the development and comparison of candidate health management methods against a common problem
  - The Prognostics and Health Management (PHM) Society Conference puts forth a data challenge problem annually
  - NASA's Propulsion Diagnostic Method Evaluation Strategy (ProDiMES) enables gas path benchmarking



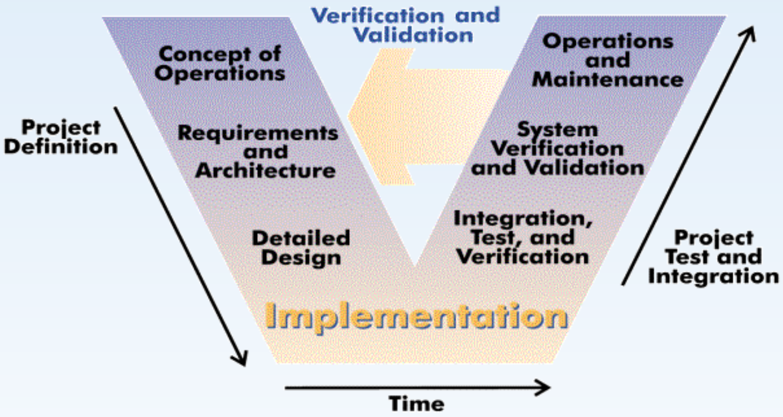
ProDiMES Architecture

Verification and Validation Tools and Techniques

Engine health management technology is growing in its breadth of application and its complexity

Presents a need for improved verification and validation tools and techniques to reduce development time and cost

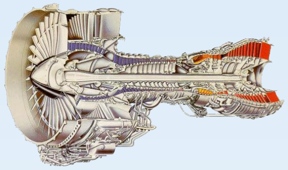
- Certification applicants must adhere to regulatory agency certification requirements
  - DO-178C, Software Considerations in Airborne Systems and Equipment Certification, will be the primary document by which the certification authorities will approve all commercial software-based aerospace systems
  - SAE E32 will soon publish ARP 5987, Guidelines for Engine Health Management System Software and Airborne Electronic Hardware Assurance Levels



Verification and Validation Process

Models for Health Management Applications

- Algorithm developers must keep in mind that engine models are imperfect
  - Engine models are 1D; actual engine is multi-dimensional
  - No two engines are the same
  - Sensors aren’t modeled correctly
  - Model accuracy during transients and at off-design operating conditions is notoriously poor
  - Models developed during engine design phase aren’t necessarily updated once engine goes into production; design changes aren’t always modeled



Engine

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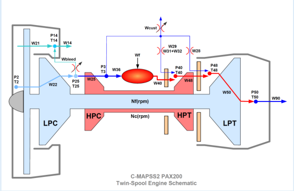
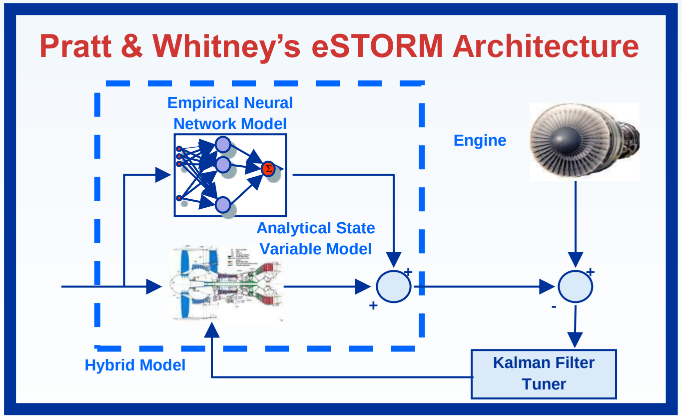


Engine Model

- Model-based health management algorithms must be robustly designed to account for model imperfections

- Cost effective techniques to update/maintain models over an engine type’s lifetime of use are desired

- Hybrid modeling (analytical + empirical) techniques hold promise for capturing engine-model mismatch



Pratt & Whitney’s eSTORM Architecture

Empirical Neural Network Model

Engine

Analytical State Variable Model

+

+

+

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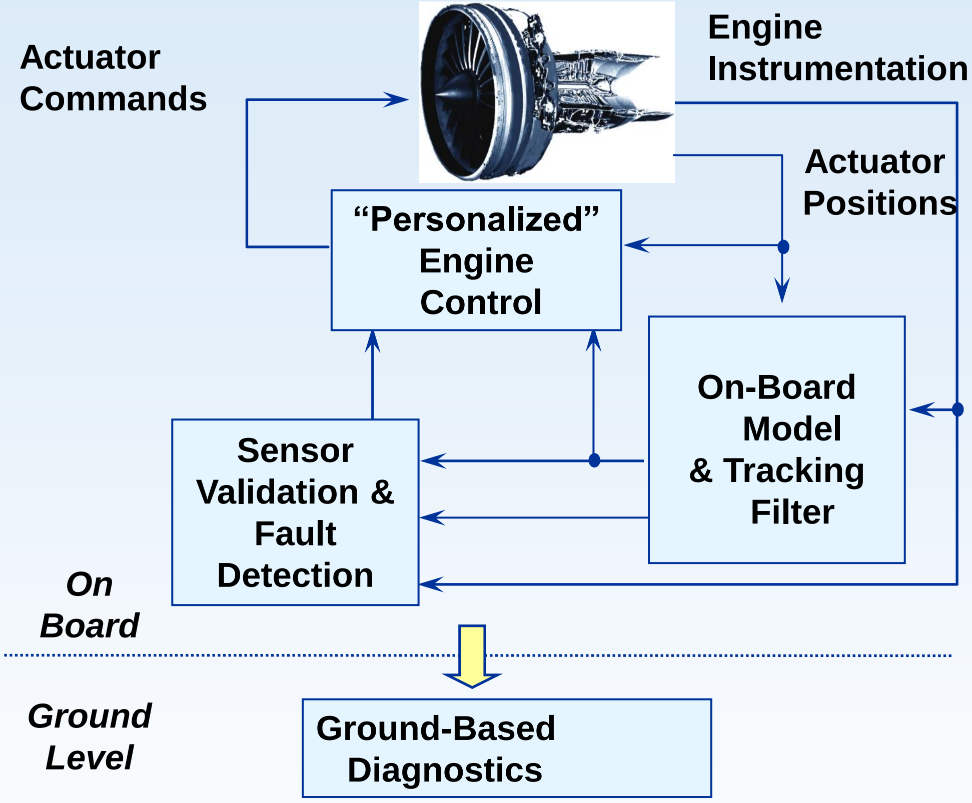
Hybrid Model

Kalman Filter Tuner

Model-Based Control and Diagnostics Concept



Actuator Commands

Engine Instrumentation

Actuator Positions

“Personalized” Engine Control

On-Board Model & Tracking Filter

Sensor Validation & Fault Detection

On Board

Ground Level

Ground-Based Diagnostics

Model-Based Control and Diagnostics Architecture

Related Technology Challenges:

- Model Accuracy
  - At steady-state and transient operation
  - Sensor dynamics
  - Ability of tuning parameter adjustments to reflect engine performance deterioration effects in engine outputs
  - Hybrid modeling (e.g., eSTORM) helps address engine-model mismatch
- Verification and Validation
  - Coupling with control necessitates higher level of software assurance
- Underdetermined estimation problem (fewer sensors than unknown health parameters reflecting deterioration)
  - NASA-developed optimal tuner selection methodology provides systematic design approach for minimizing error

Kalman Filter-Based Performance Estimation (based on streaming measurement data)

Performance Estimation

Dynamic measurement process:

$$x_{k+1} = Ax_k + Bu_k + Lh_k + w_k$$
$$y_k = Cx_k + Du_k + Mh_k + v_k$$

k	discrete time index
y	sensed output vector
h	health parameter vector
x	state vector
u	actuator command vector
v	measurement noise (*N*(0,σ) with covariance *R*)
w	process noise (*N*(0,σ) with covariance *Q*)

Full-order state space equations:

$$\begin{bmatrix} x_{k+1} \\ h_{k+1} \end{bmatrix} = \begin{bmatrix} A & L \\ 0 & I \end{bmatrix} \begin{bmatrix} x_k \\ h_k \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u_k + \begin{bmatrix} w_k \\ w_{h,k} \end{bmatrix}$$
$$y_k = \begin{bmatrix} C & M \end{bmatrix} \begin{bmatrix} x_k \\ h_k \end{bmatrix} + Du_k + v_k$$

Reduced-order state space equations (replacing h with q)

$$\begin{bmatrix} x_{k+1} \\ q_{k+1} \end{bmatrix} = \begin{bmatrix} A & L^* \\ 0 & I \end{bmatrix} \begin{bmatrix} x_k \\ q_k \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u_k + \begin{bmatrix} w_k \\ w_{q,k} \end{bmatrix}$$
$$y_k = \begin{bmatrix} C & M^* \end{bmatrix} \begin{bmatrix} x_k \\ q_k \end{bmatrix} + Du_k + v_k$$

Optimal tuner selection

- *Define* $q = V^* h$
- V^* *is selected through an optimal iterative search to minimize Kalman filter mean squared estimation error in the parameters of interest**
- *Health parameter estimation:*

$$\hat{h} = V^{*\dagger} \hat{q}$$

*Reference: Simon, D.L., Garg, S., (2010), "Optimal Tuner Selection for Kalman Filter-Based Aircraft Engine Performance Estimation," *Journal of Engineering for Gas Turbines and Power*, Vol. 132 / 0231601-1.

Engine Fault Test Opportunities

EHM technology development is challenging:

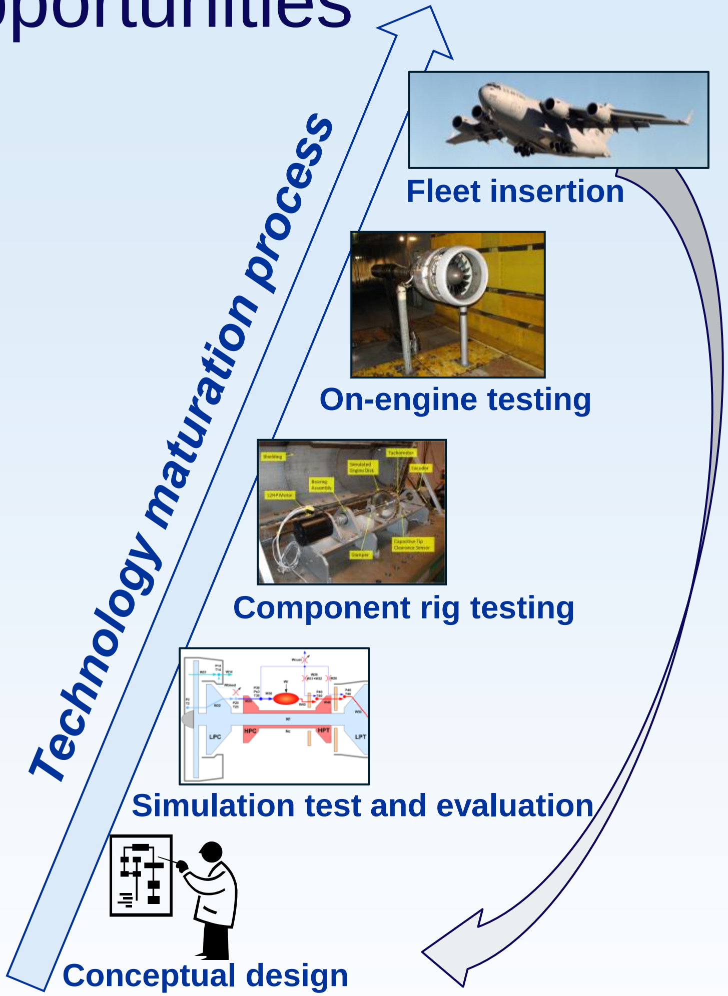
- Expensive to intentionally fault/fail aircraft engines
- However, dedicated testing is desired to demonstrate technology against known system “ground truth” state

Partnerships often make it possible:

- Sharing of costs, results and benefits
- “Piggy-backing” on related tests such as mission endurance testing, acceptance testing, etc.

Examples of past engine fault testing:

- Australian DSTO fault testing on F404 Engine (1990’s)
- Joint Strike Fighter (JSF) Program F100 engine seeded fault testing (1998-1999)
- FAA/Navy/NASA TF-41 engine seeded disk crack testing
- NASA Vehicle Integrated Propulsion Research (VIPR) engine testing (2011-current)



Technology maturation process

Fleet insertion

On-engine testing

Component rig testing

Simulation test and evaluation

Conceptual design

Engine Test Opportunities are Rare. When they do arise, they should be leveraged as much as possible in order to derive maximum benefits

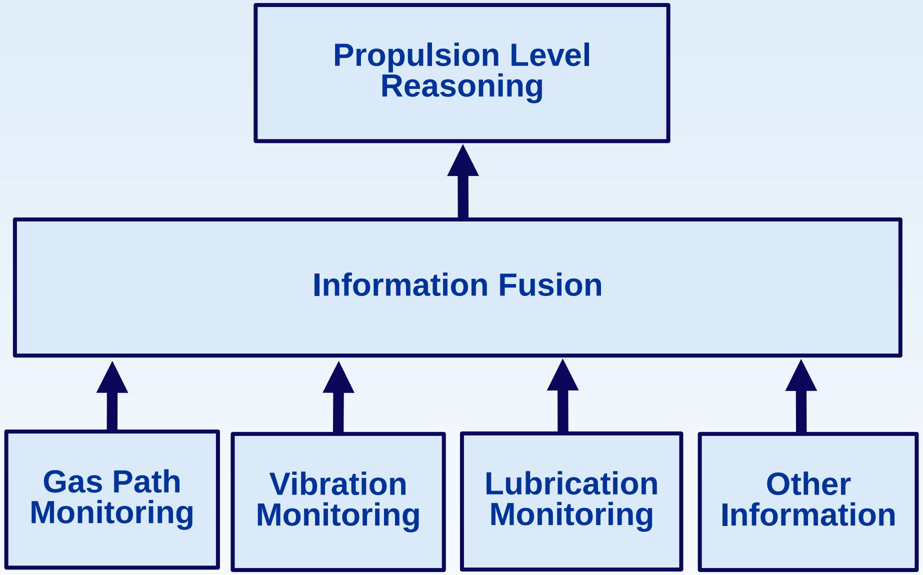
Testing is a necessary and challenging component of Engine Health Management (EHM) technology development

Information Fusion

Leverage all available information

Health inferences do not have to be based solely on gas path measurements!

- Other subsystem health information (e.g., vibration, lubrication, etc.)
- Recent maintenance actions
- Opposite engine health information
- Control information—fault codes, limit activation
- Fleet-wide engine statistics
- Domain expert knowledge / heuristics
- Negative information (the absence of information can be significant)


Propulsion Level Reasoning

Information Fusion

Gas Path Monitoring

Vibration Monitoring

Lubrication Monitoring

Other Information

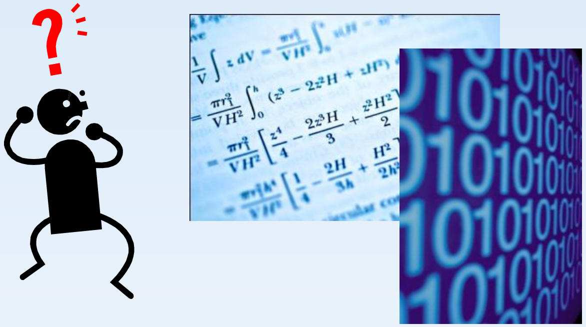
Information Fusion Architecture

Practical Design Considerations

Keep end user in mind

- Keep in mind that the skill of individual end users may vary considerably, and not all users will be proficient in computers or engineering terminology.
- Humans are not infallible. Consideration must be given to the fact that they may misinterpret or ignore information.
- If the user cannot operate the system, or lacks confidence in its capabilities, it may lose credibility.
- Provide quality documentation and training.

Keep maintainer of tool in mind



- Keep in mind verification and validation requirements.
- Keep expense to develop, update and maintain tool at a minimum.
- Avoid the need for substantial redesign each time the engine undergoes a hardware change or maintenance.
- Avoid the need to manually tailor the tool for each individual engine.
- Keep in mind that tool will probably be integrated into existing architecture

Try to keep the tool simple!

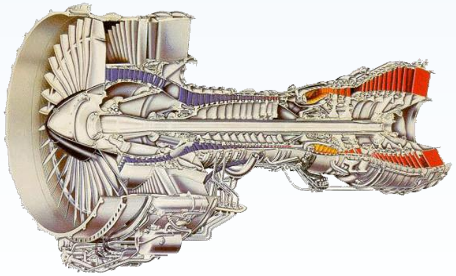
Summary

Aircraft propulsion gas path health management is a key element of an overall engine health management system, providing …

- Improved safety
- Improved affordability

Challenges:

- Techniques to take advantage of expanding quantity of data including the processing, mining, and sharing of data
- New sensor suites
- The need for improved models/modeling
- Engine fault test opportunities
- Leverage all available information
- Keep the design practical



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