Introduction to Advanced Engine Control Concepts

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 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. The key enabling technologies for an Intelligent Propulsion System are the increased efficiencies of components through active control, advanced diagnostics and prognostics integrated with intelligent engine control to enhance operational reliability and component life, and distributed control with smart sensors and actuators in an adaptive fault tolerant architecture. This presentation describes the current activities of the Controls and Dynamics Branch in the areas of active component control and propulsion system intelligent control, and presents some recent analytical and experimental results in these areas.

Fundamentals of Aircraft Engine Control Design Course

Lesson 16: Advanced Control Concepts

Guest Lecture:
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NASA Glenn Research Center

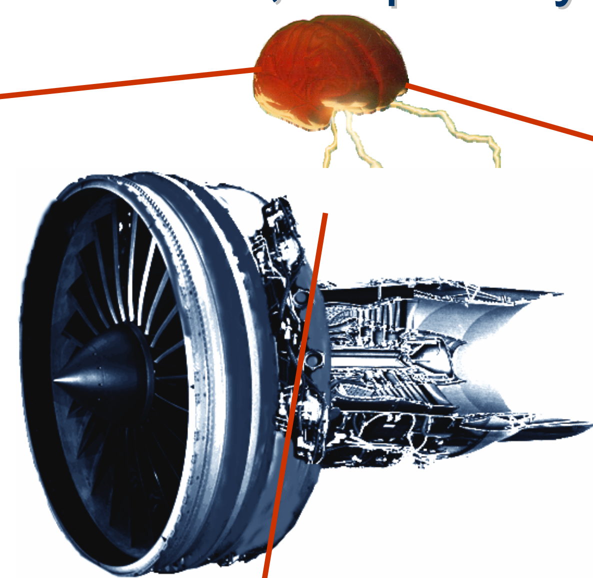
Lesson 16: Introduction to Advanced Engine Control Concepts

- Agenda:
  - Intelligent Engine Concept – from a controls perspective
  - Intelligent Engine Control
    - Model-Based Controls and Diagnostics
    - Life Extending Control
    - Performance Deterioration Mitigating Control
  - Active Component Control
    - Flow Control to improve compressor efficiency
    - Combustion Control for enabling reduced emissions
    - Higher bandwidth turbine tip Clearance Control
  - Distributed Engine Control
  - Lesson summary

INTELLIGENT ENGINES
Control System perspective

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

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



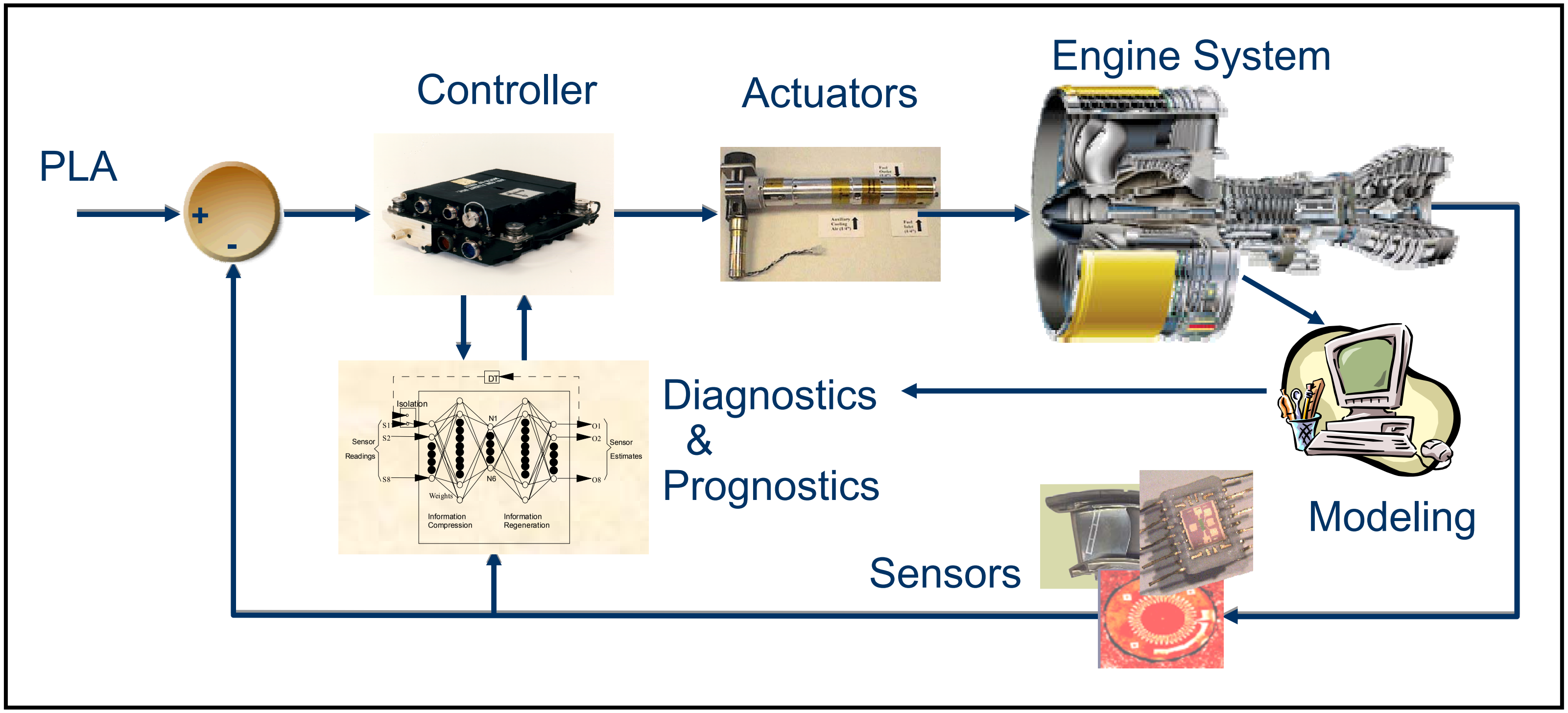
Advanced Health Management technologies for self diagnostic and prognostic propulsion system
- Life usage monitoring and prediction
- Data fusion from multiple sensors and model based information

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

NASA GRC Contronls and Dynamics Branch (CDB) 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

Intelligent Engine Technologies
- A Systems Viewpoint -



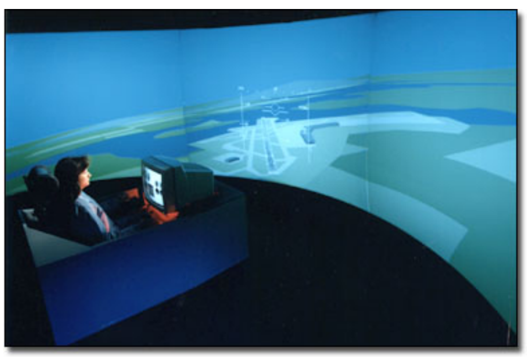
- Components such as actuators, sensors, control logic, & diagnostic systems have to be designed with overall system requirements in mind.

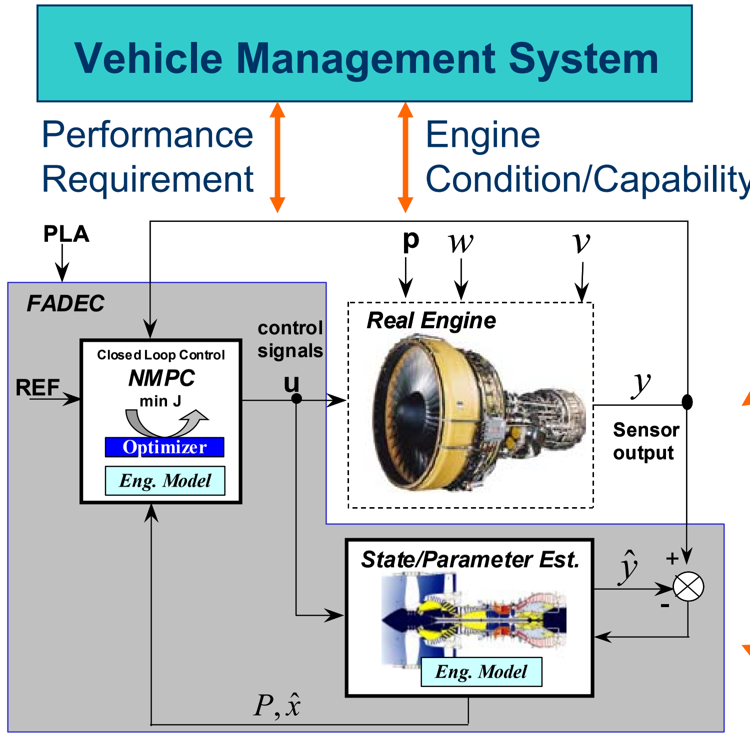
- Simplified models are essential for controller design. Understanding the physics of the phenomena is required to capture critical system dynamics in these models.

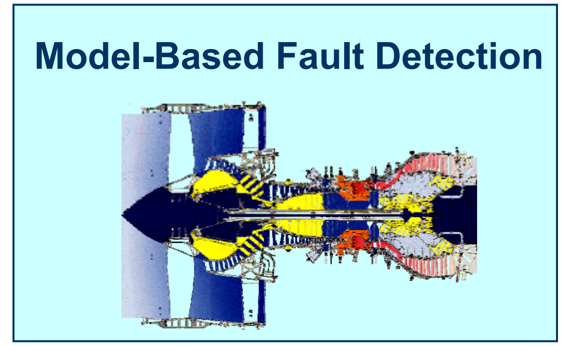
Autonomous Propulsion System Technology

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

Demonstrate Technology in a relevant environment







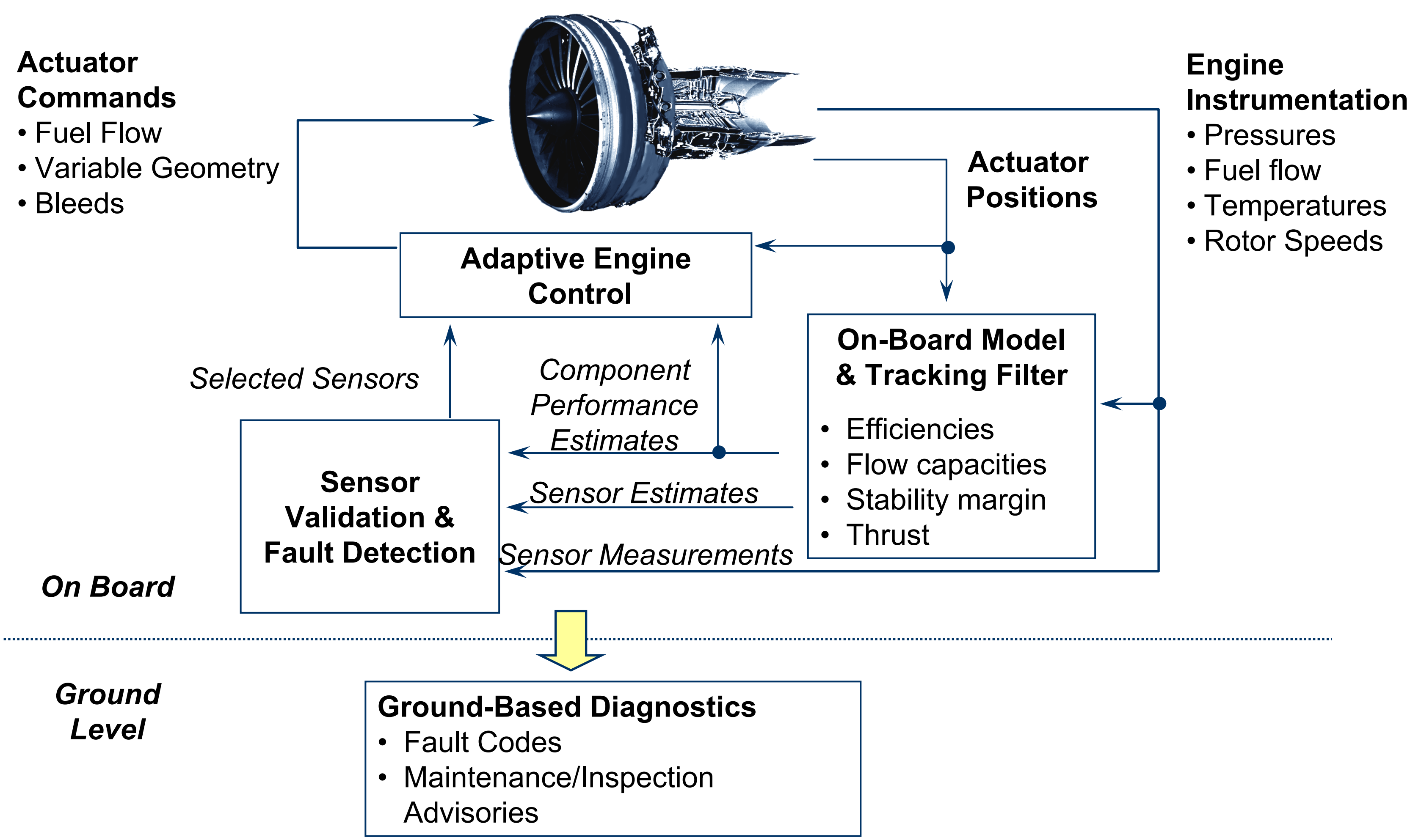
Diagnostics/Prognostics Algorithms Are Being Developed

Data Fusion

Self-Diagnostic Adaptive Engine Control System

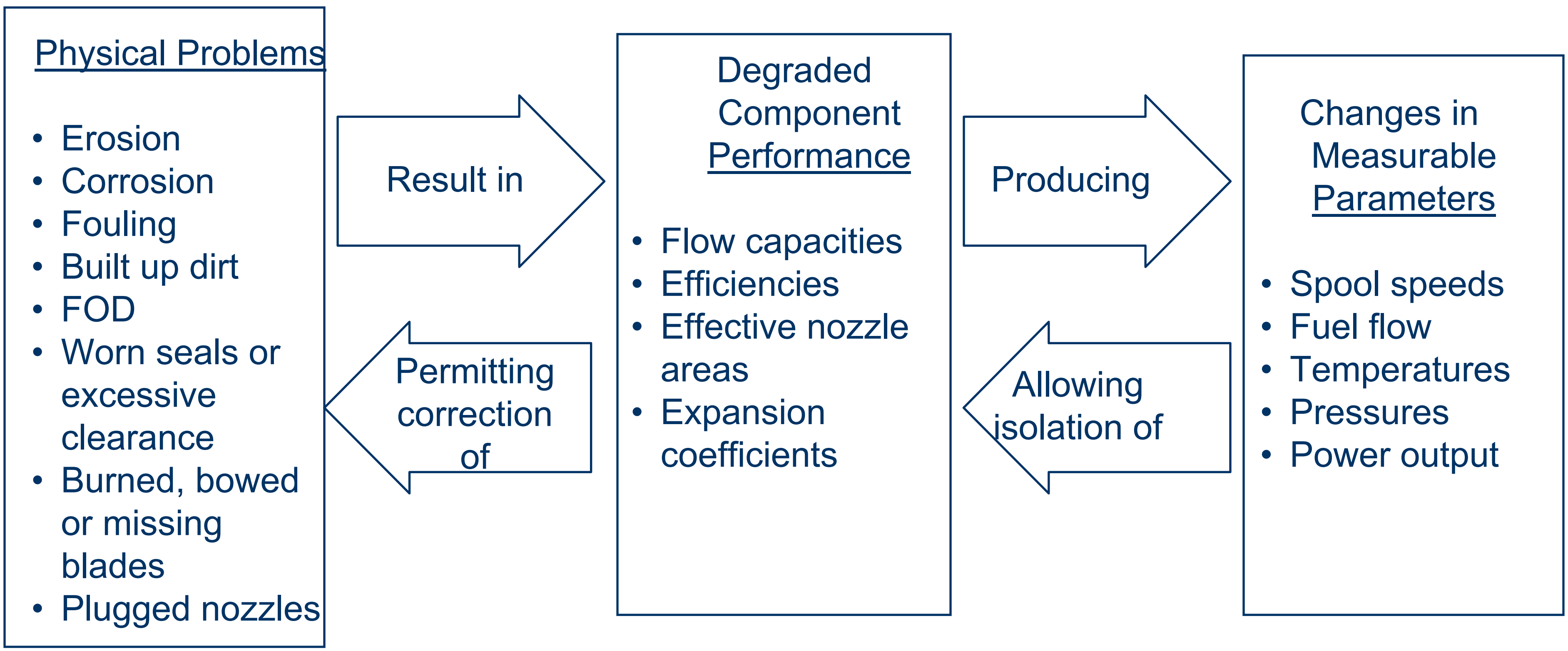
- Performs autonomous propulsion system monitoring, diagnosing, and adapting functions
- Combines information from multiple disparate sources using state-of-the-art data fusion technology
- Communicates with vehicle management system and flight control to optimize overall system performance

Model-Based Controls and Diagnostics



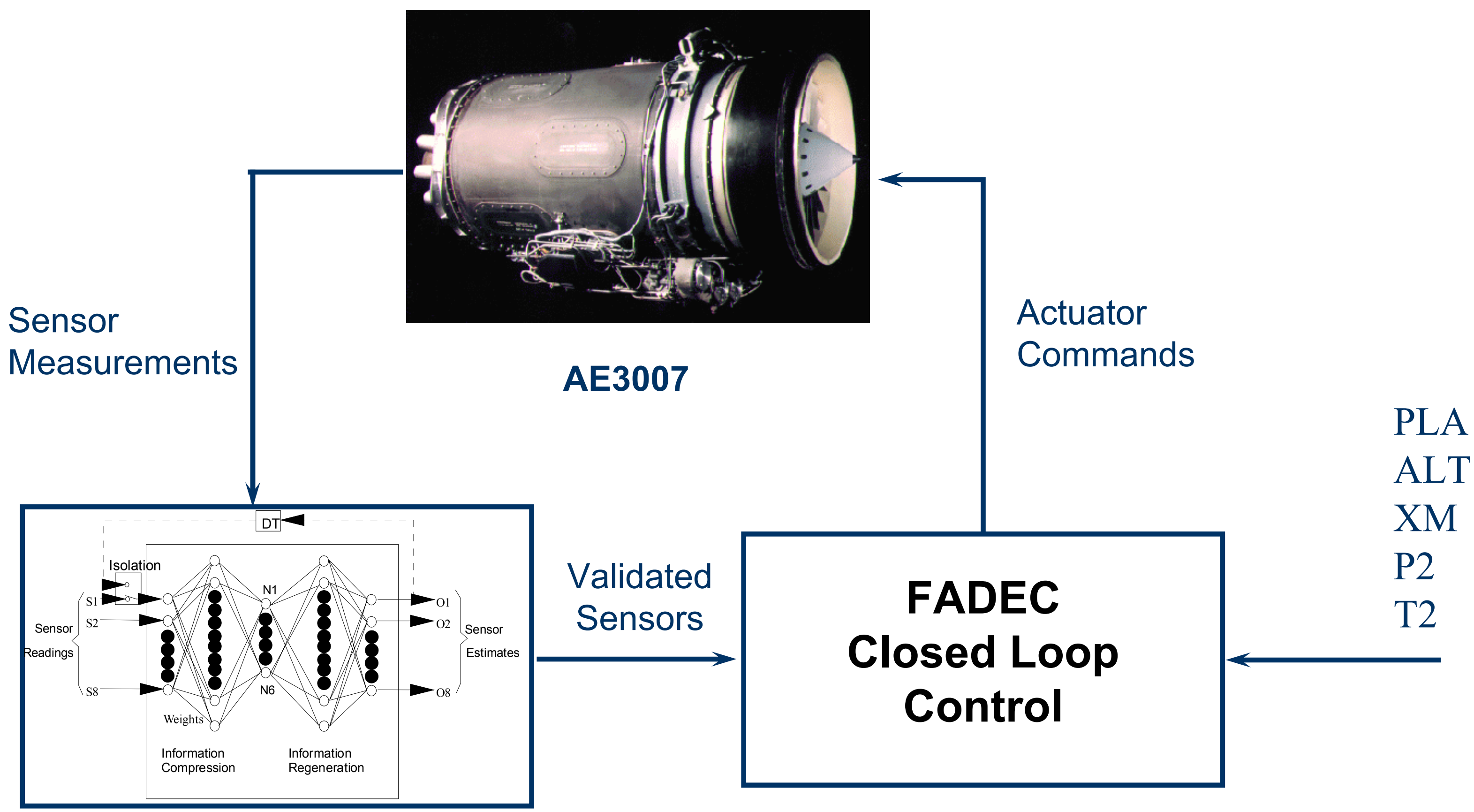
Gas Path Analysis Engine Fault Isolation Approach *

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.



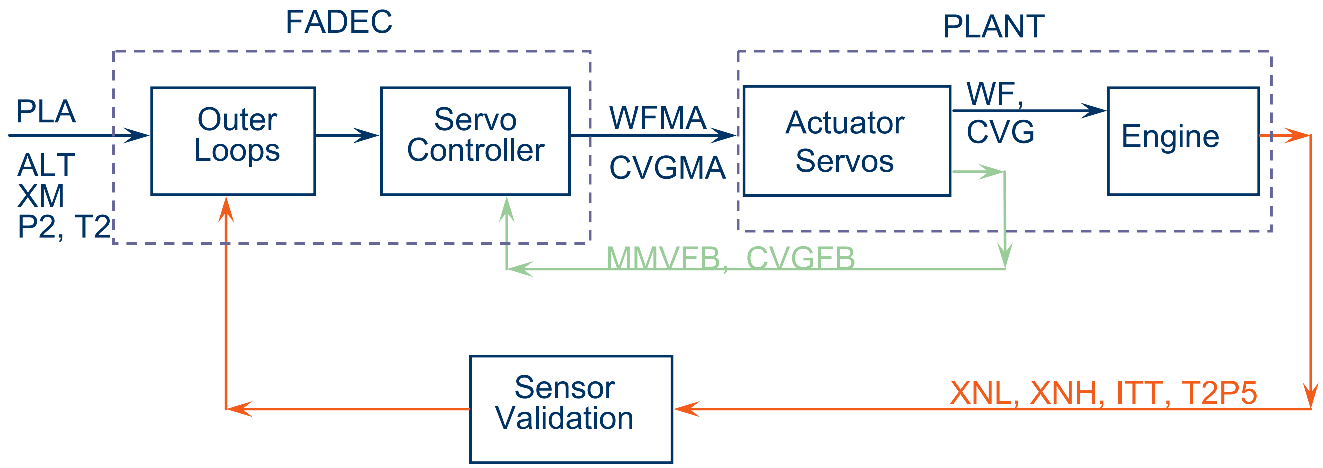
* From “Parameter Selection for Multiple Fault Diagnostics of Gas Turbine Engines” by Louis A. Urban, 1974

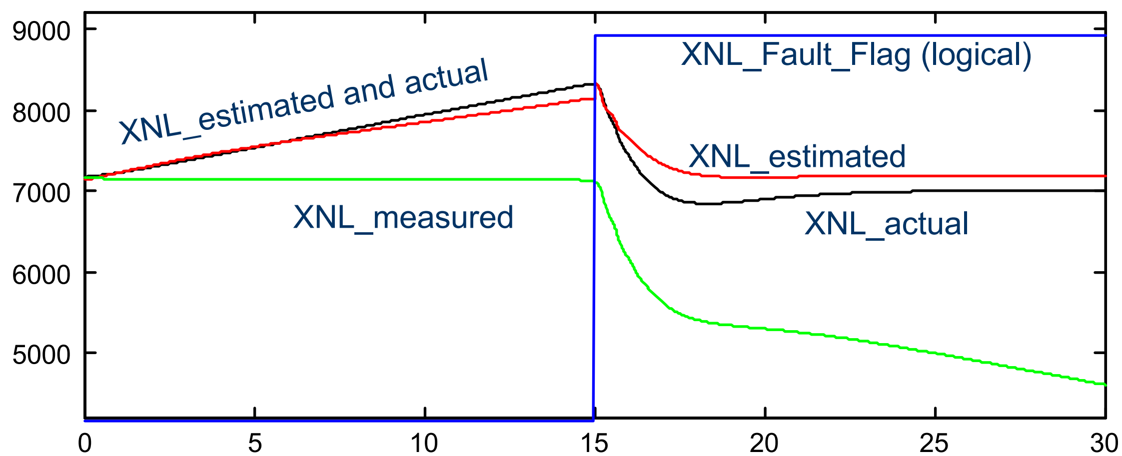
High Reliability Engine Control



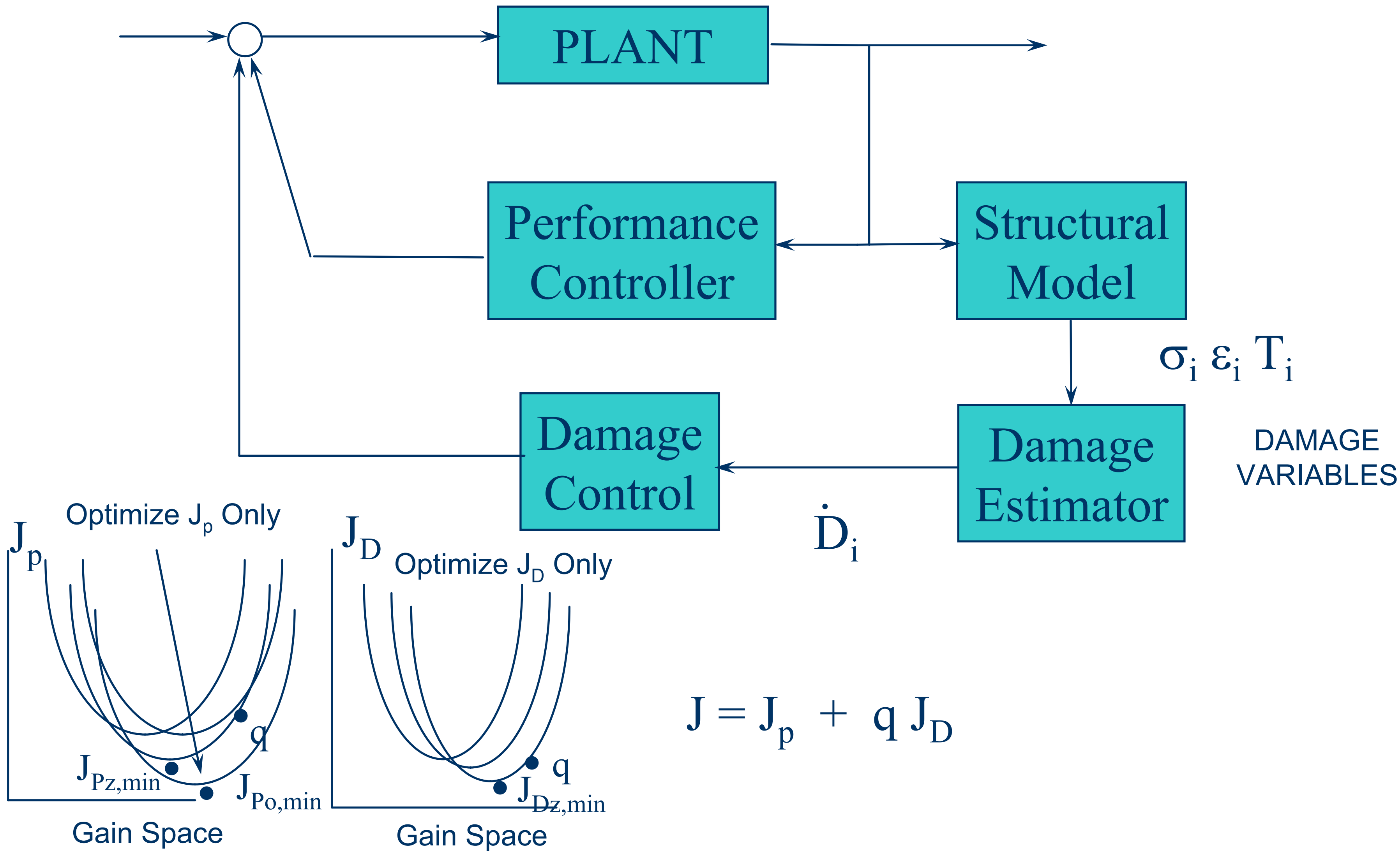
Neural Network Based Sensor Validation
- Sensor Estimates
- Failed Sensor Detection and Isolation

HREC - Closed Loop Control of System with Sensor Validation





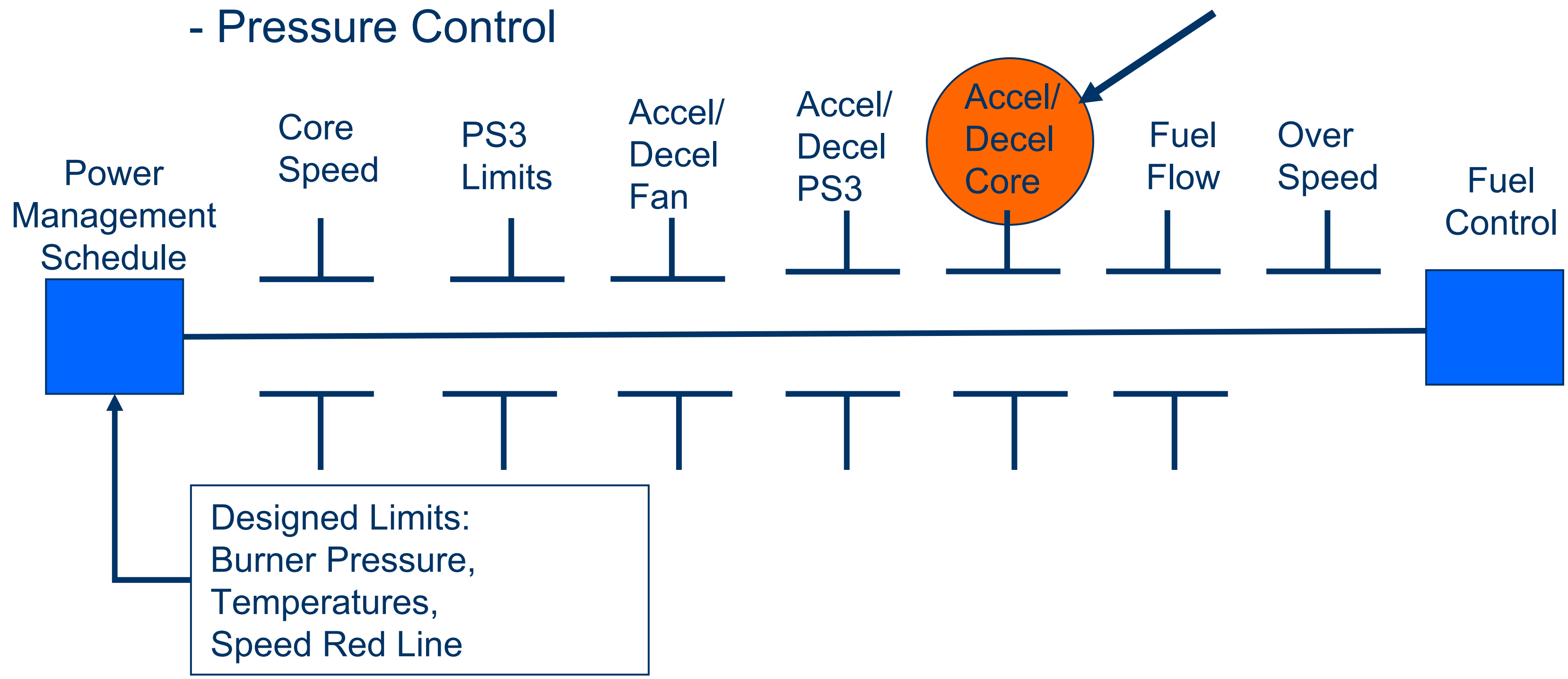
Life Extending Control



$$J = J_p + q\,J_D$$

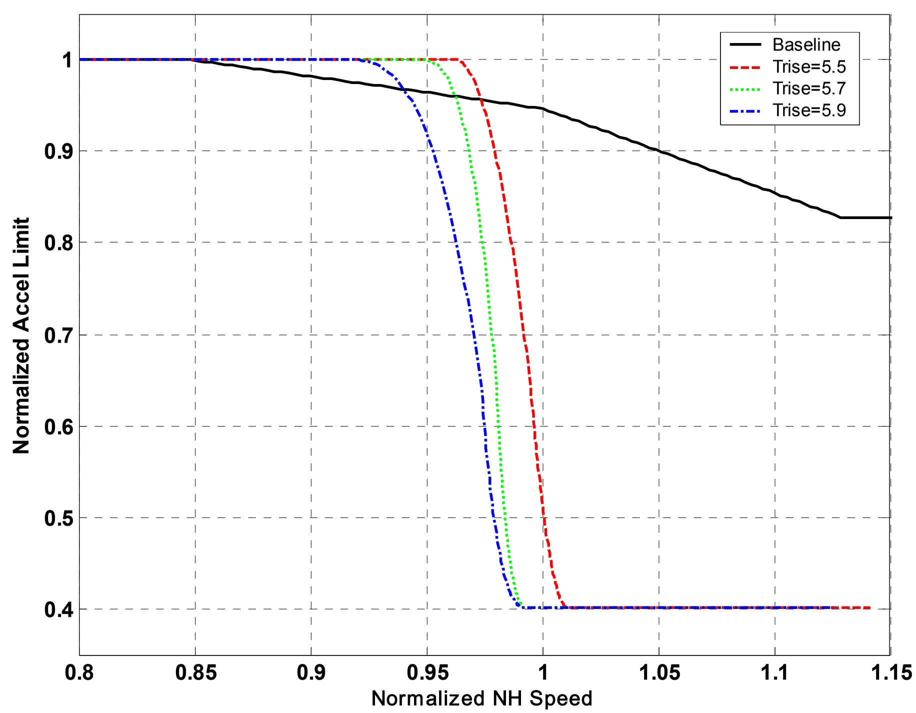
Typical Engine Control

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

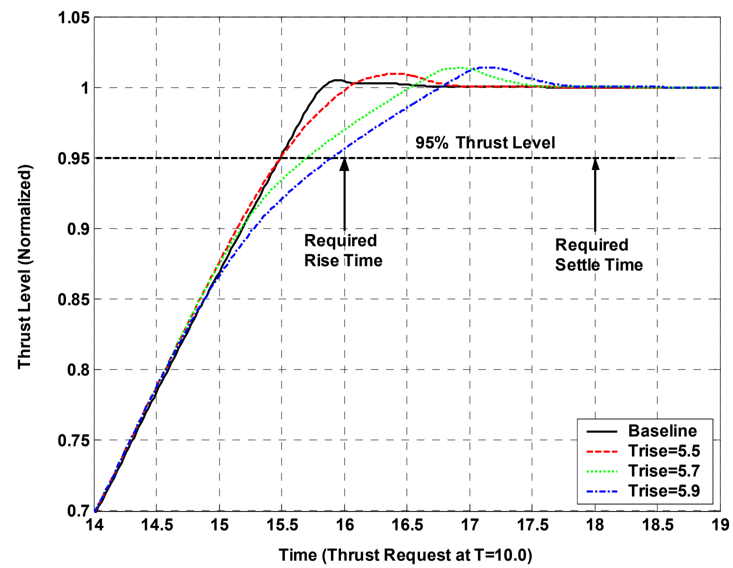


Effect of Optimizing Core Accel Schedule

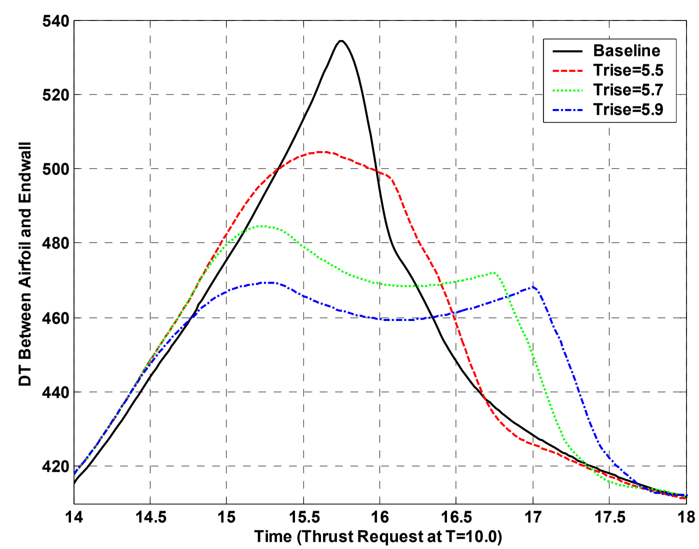
Acceleration Schedule Optimized for various Rise Time Constraints



Thrust Response



DT between Airfoil & Endwall



Smart Life Extending Control

Engine Simulation Demonstration Using Stochastic Based Life Models

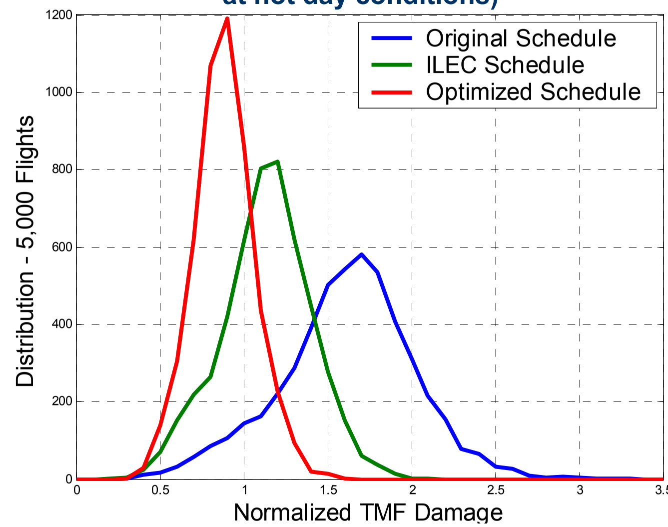
Comparison of Average TMF Damage Accumulation

(With Varying Ambient Condition and Control Mode)

Operating Condition \ Control	Original Control Schedule	ILEC Control Schedule	Optimized Control Schedule
Design Condition	1.0	0.725 (-27.5%)	0.628 (-37.2%)
With Typical Operating Conditions	1.132	0.826 (-27.0%)	0.718 (-36.6%)
Hot Day Bias	1.668	1.181 (-29.2%)	0.931 (-44.2%)
Cold Day Bias	0.609	0.500 (-17.9%)	0.481 (-21.0%)

TMF Damage Accumulation

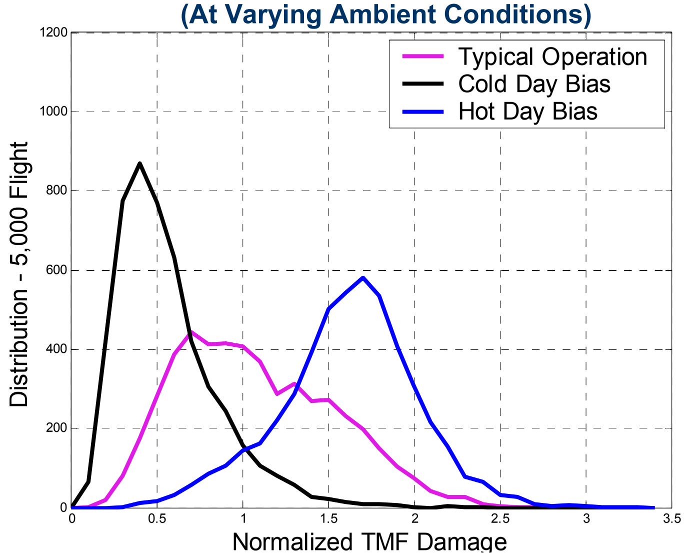
(Comparison of Original, ILEC, and Optimized Control at hot day conditions)



3. Optimized control results in significant component life savings

TMF Damage Accumulation w/ Original Control

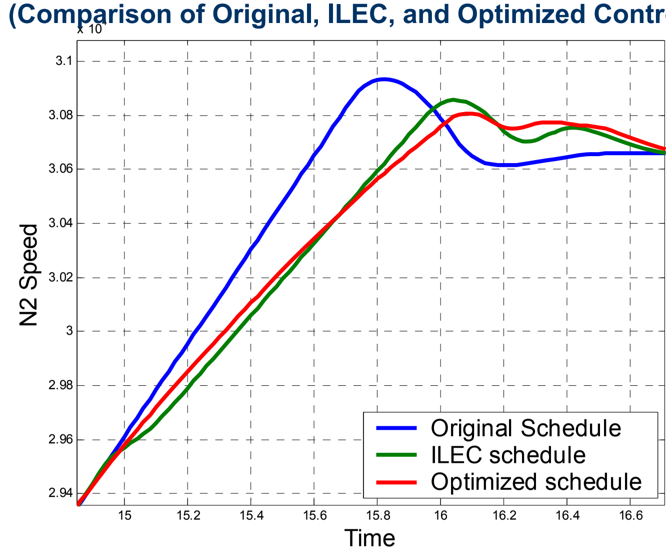
(At Varying Ambient Conditions)



1. Component damage accumulation is a function of ambient operating condition

Engine Core Speed Acceleration Response

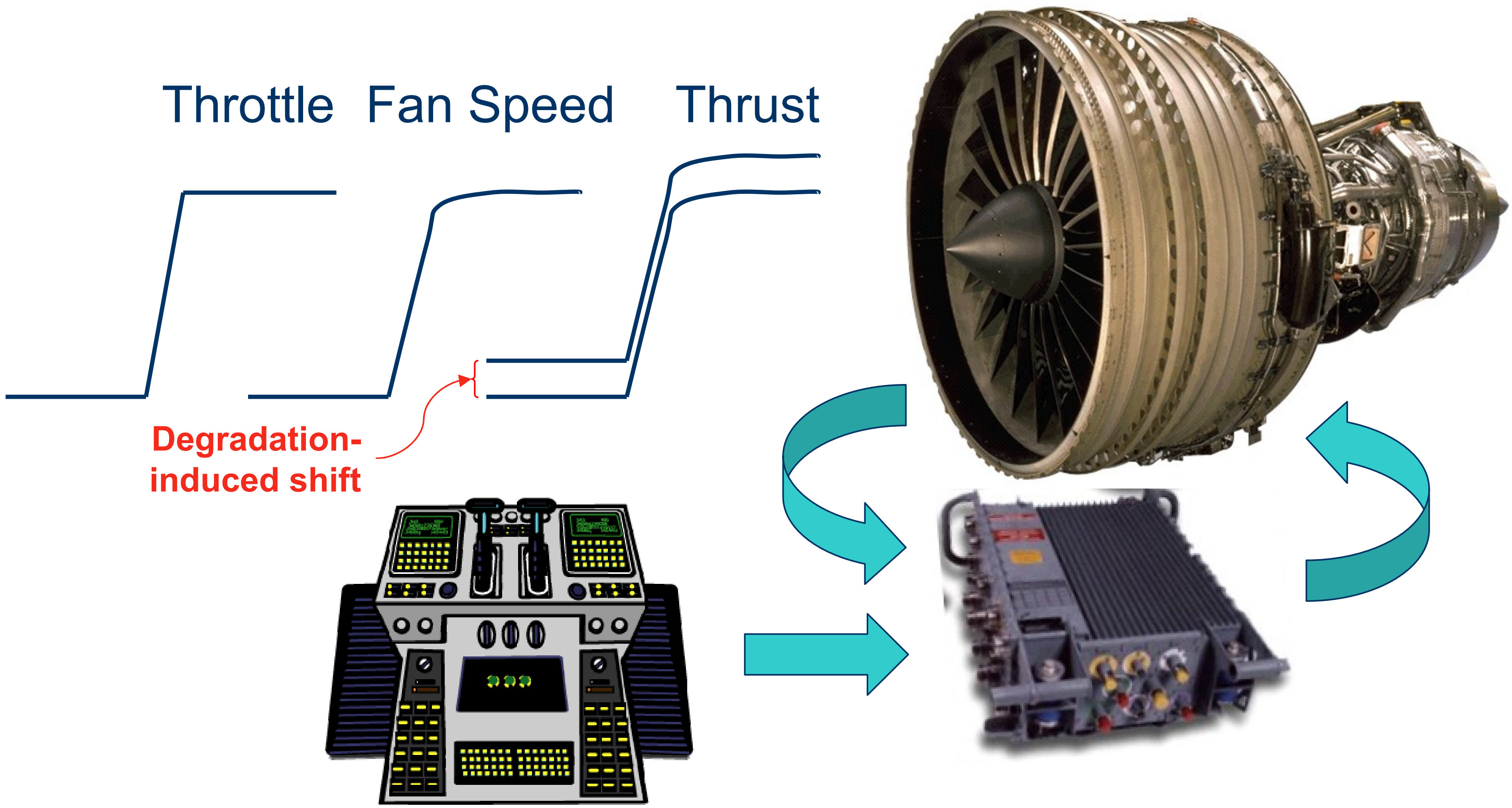
(Comparison of Original, ILEC, and Optimized Control)



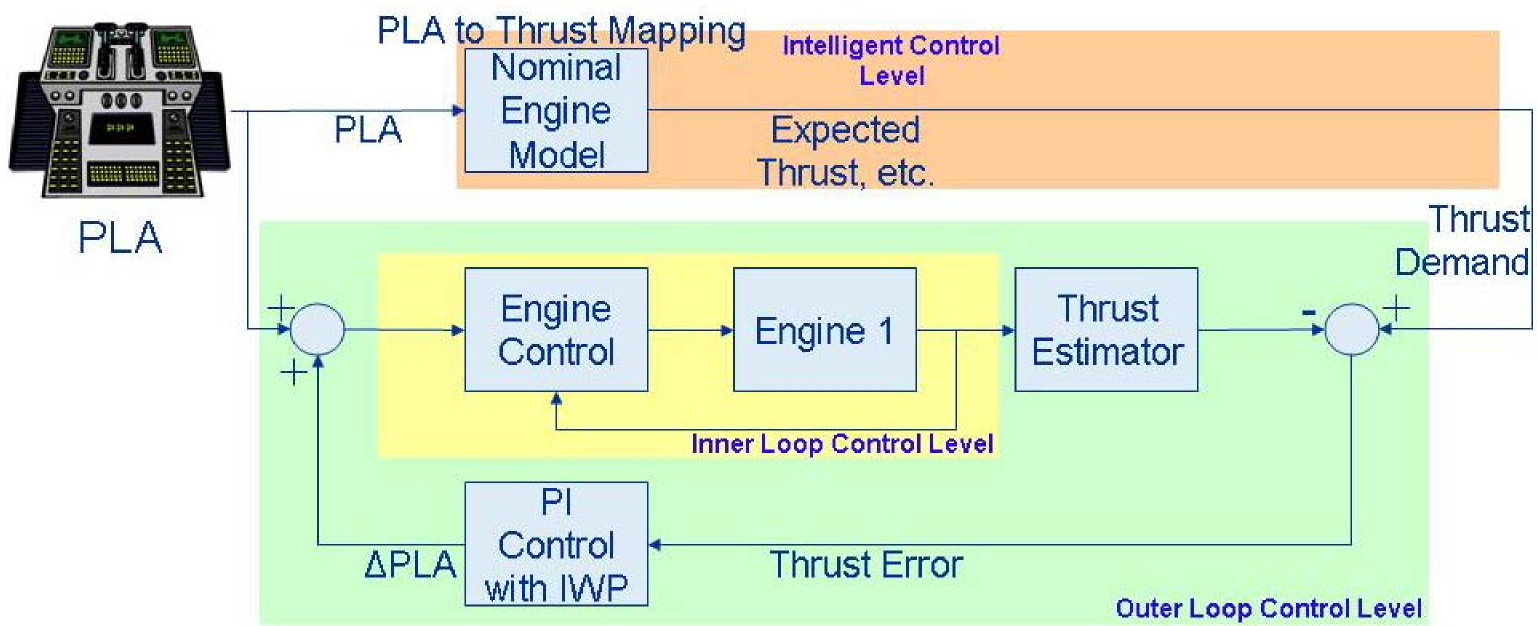
2. Engine control logic can be optimized to minimize damage while maintaining desired engine performance

Engine Performance Deterioration Mitigation Control

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



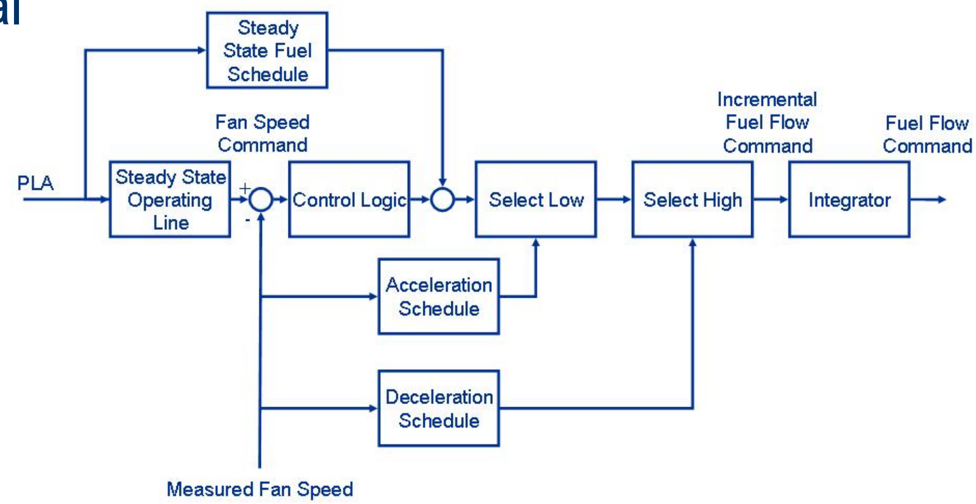
Control Architecture



- Leverages existing FADEC Control logic based on a Fan Speed Control
- Adds the following logic/software elements:
  - A simplified model of the engine which matches the “nominal” PLA to Thrust response
  - A Thrust estimator
  - A PI control to modify the PLA to Fan Speed command

Parts of the Testbed Architecture

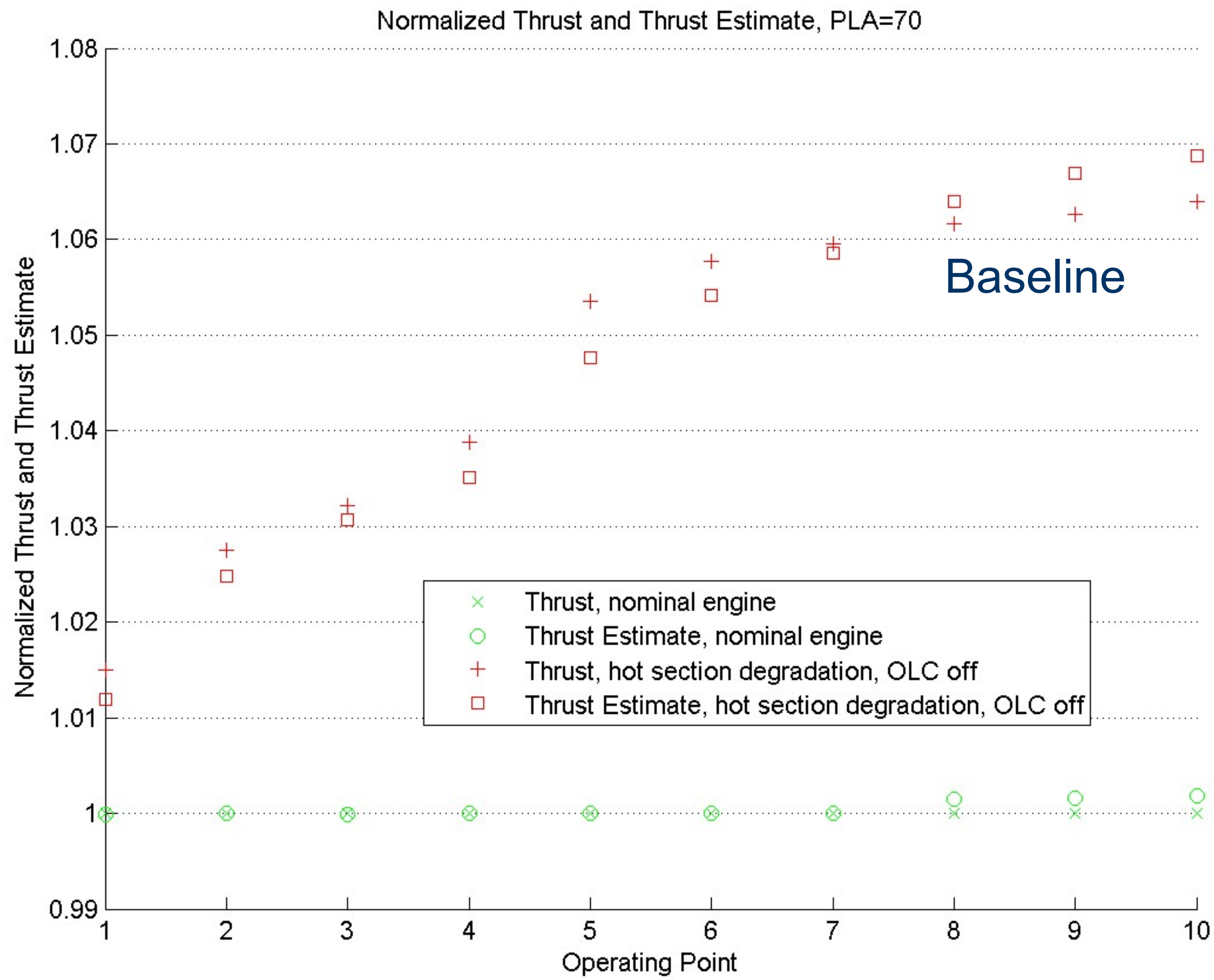
- **Engine Control**
  - Typical Full Authority Digital Engine Control (FADEC) type controller
  - PLA in, fuel flow out
  - Fan speed is controlled



- **Nominal Engine Model**
  - Piecewise linear model
  - Scheduled on percent corrected fan speed

- **Thrust Estimator**
  - Piecewise linear Kalman filter
  - Based on Nominal Engine Model
  - Provides optimal estimation of variables in a least squares sense subject to sensors selected

Steady State Evaluation

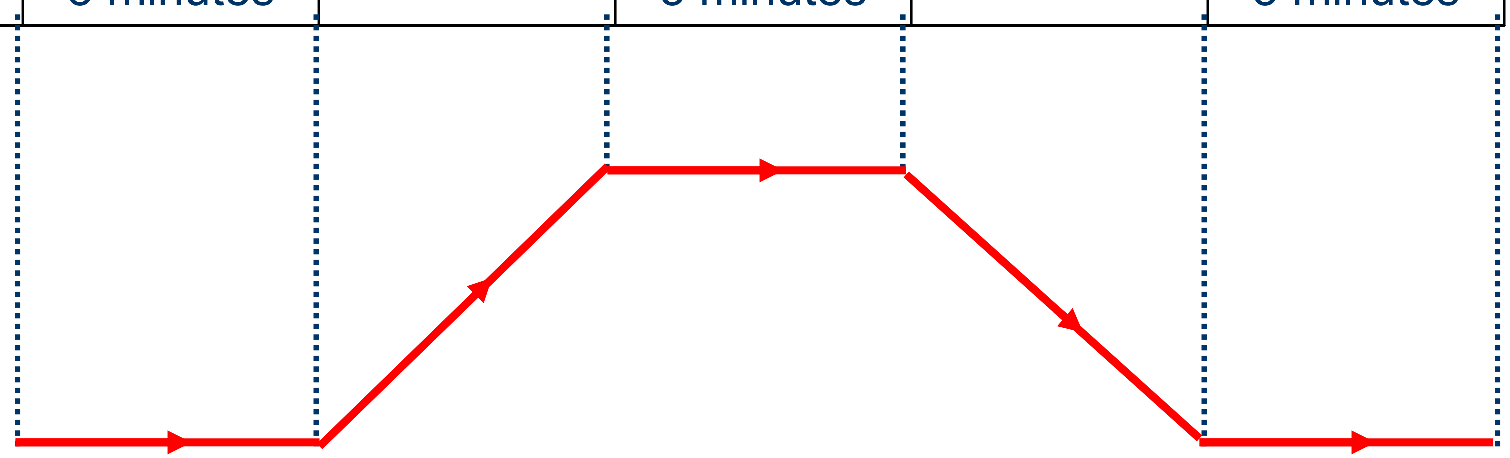


Outer Loop
Control On

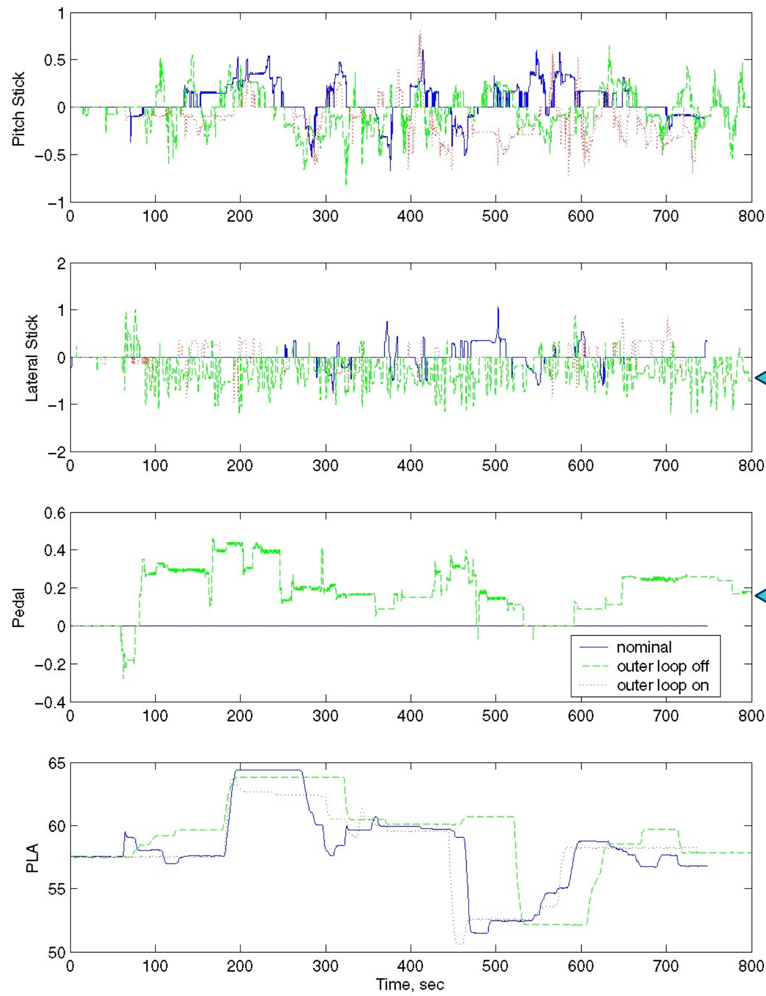
Transient Evaluation of Architecture

- Pilot-in-the-loop in a fixed-base simulator
- Maintain airspeed and heading while following profile
  - Three cases: Nominal, 1 engine degraded – OLC Off/On

Segment	1	2	3	4	5
Fan Speed	86%	90%	88%	82%	86%
Indicated Airspeed	290 knots	290 knots	290 knots	290 knots	290 knots
Heading	270º	270º	270º	270º	270º
Altitude	32,000 feet	Climb	33,000 feet	descend	32,000 feet
Duration	3 minutes	-	3 minutes	-	3 minutes

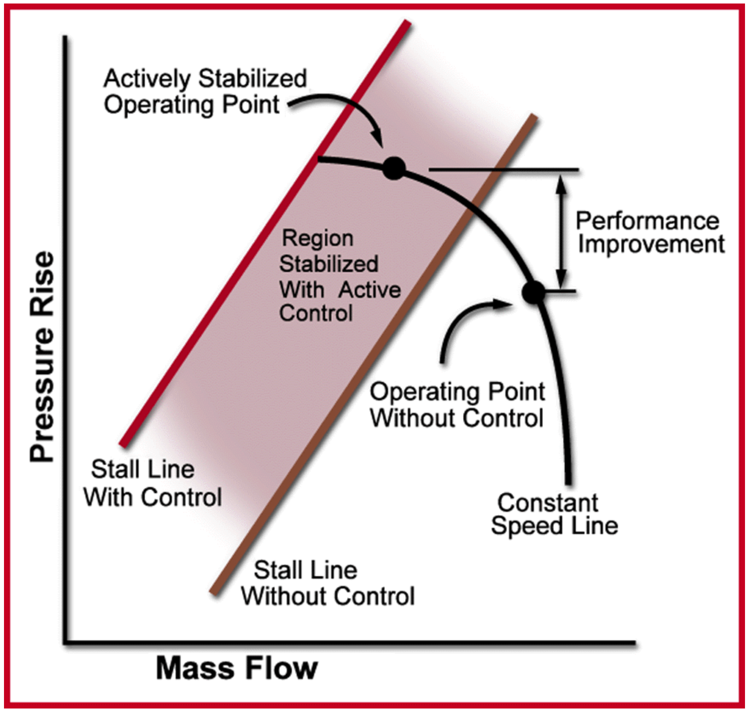


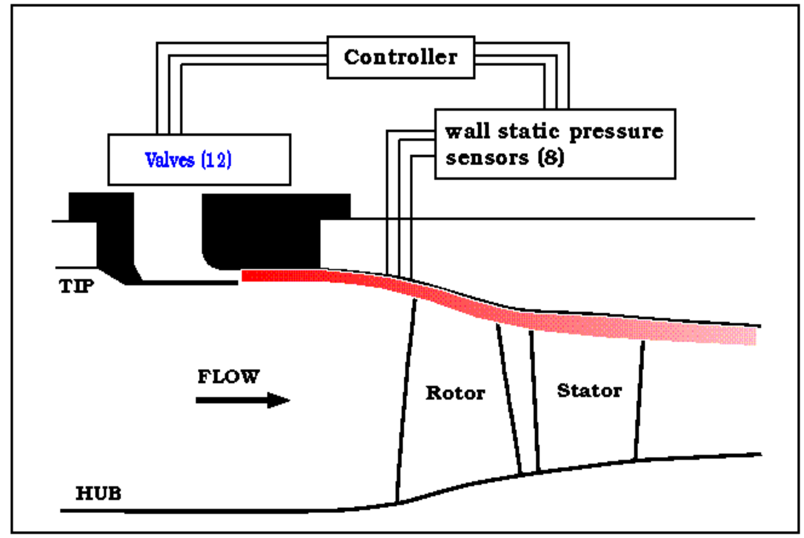
Pilot Workload During Transient Flight

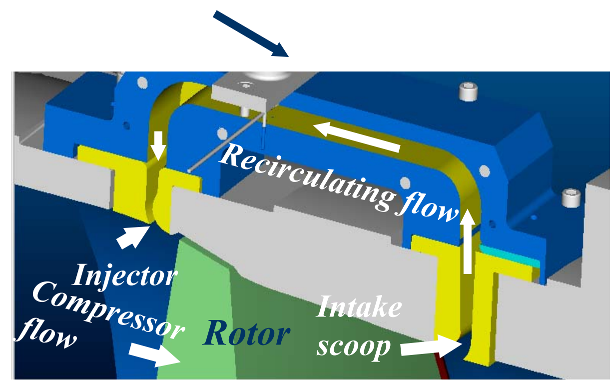


Very Clear Increase in Workload With Outer Loop Control Off

Active Stall Control







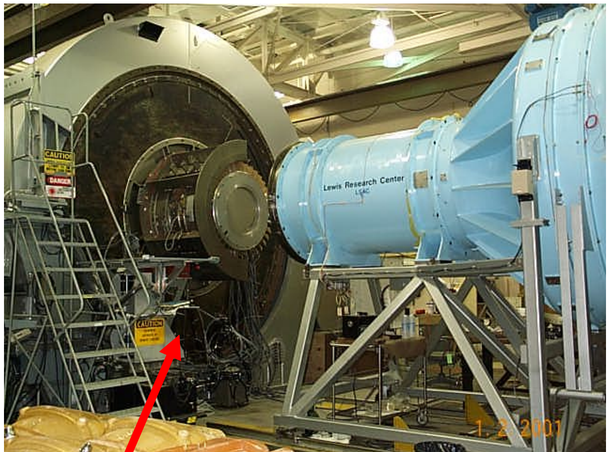
Compressor Stability Enhancement Using Recirculated Flow

- 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.

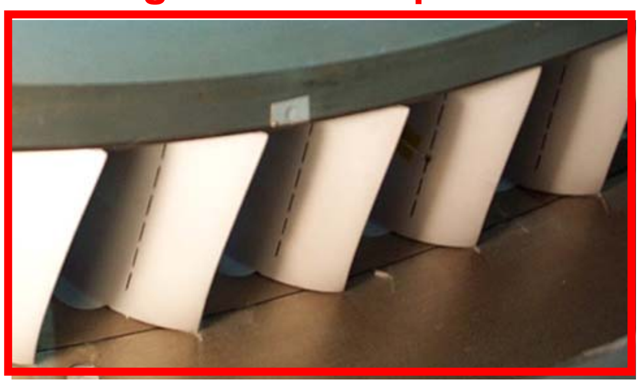
- Demonstrated significant performance improvement with an advanced high speed compressor in a compressor rig with simulated recirculating flow

Active Flow Control - Compressors

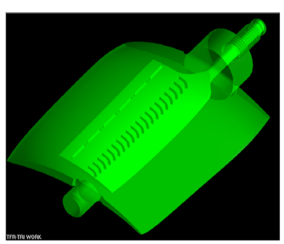
Compressor Stator Suction Surface Separation Control



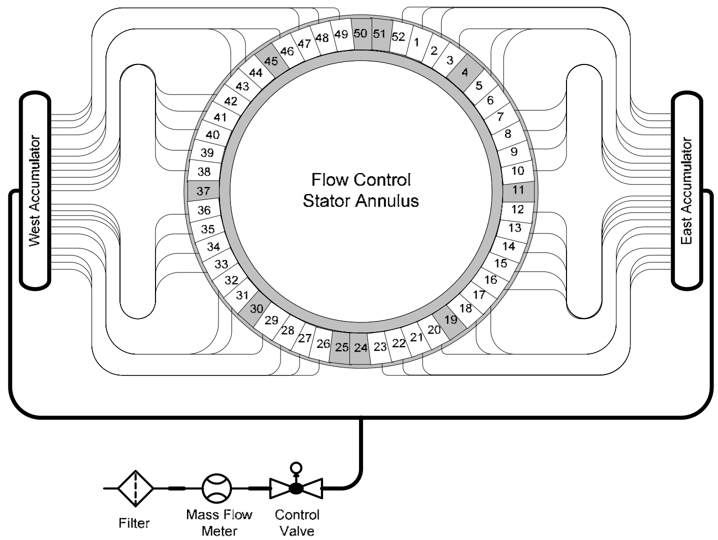
Multistage Axial Compressor



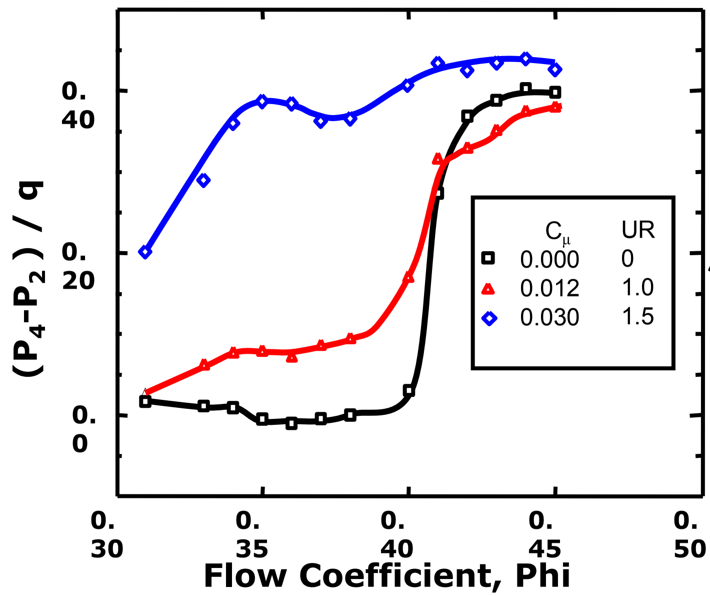
Installed Smart Vane Stators

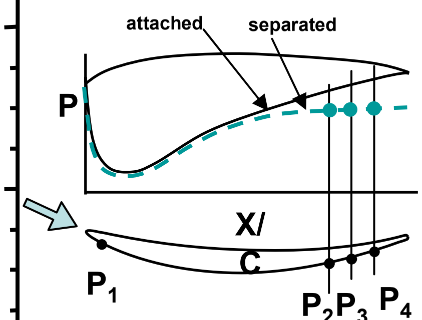


Rapid Prototype Flow Control Vane



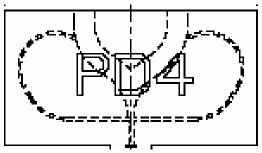
Flow Delivery System

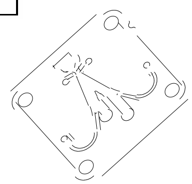




Sensing Separation from Blade Surface Pressures

Flow Control Actuation Development



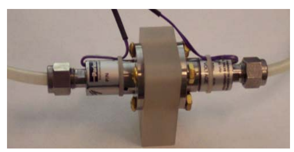


FLUIDIC
- **Passive**
- **Active**
  - **–Variable frequency**
  - **–Variable duty cycle**

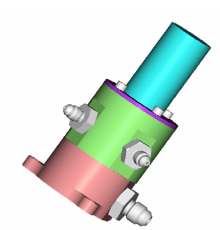
Inlet-Fan-Compressor
- Stator suction surface injection for separation control
- Rotor tip injection for stability control
- Lightweight, low power hybrid actuation

Hot Gas Path
- Active cooling control for mass flow reduction
- Film cooling efficiency enhancement
- Separation control

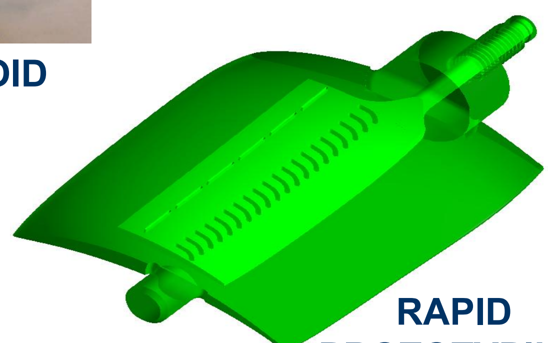
VOICE COIL



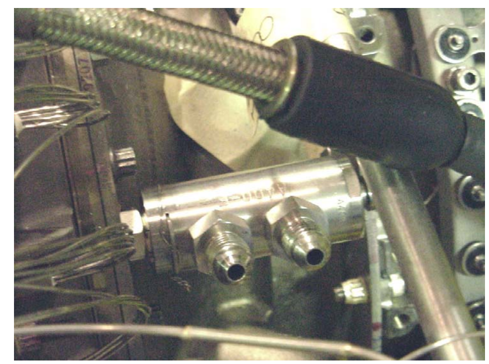
SOLENOID



ROTARY

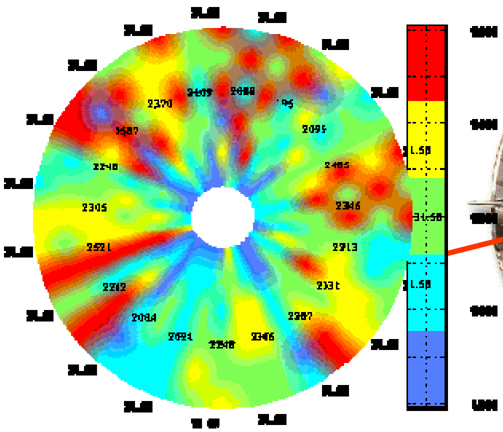


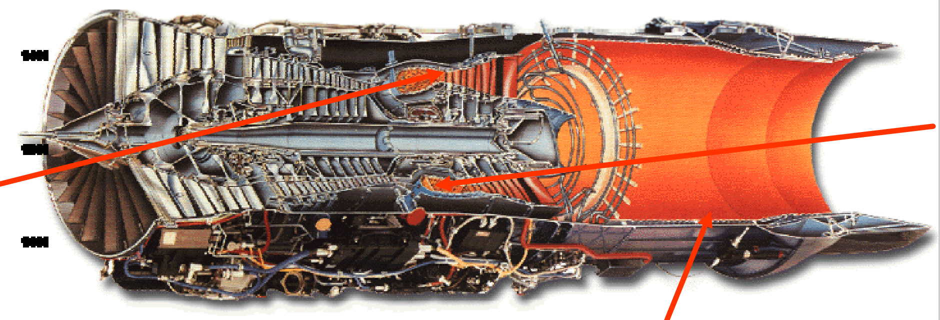
RAPID PROTOTYPING

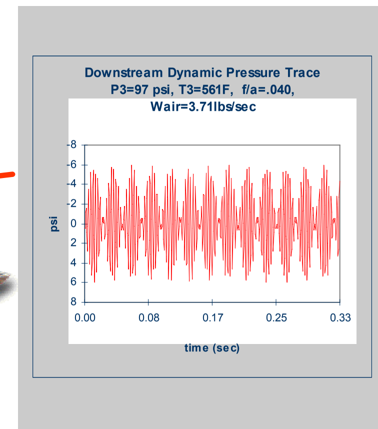


HYBRID
- **Based on high temperature shape memory alloy**

Active Combustion Controls



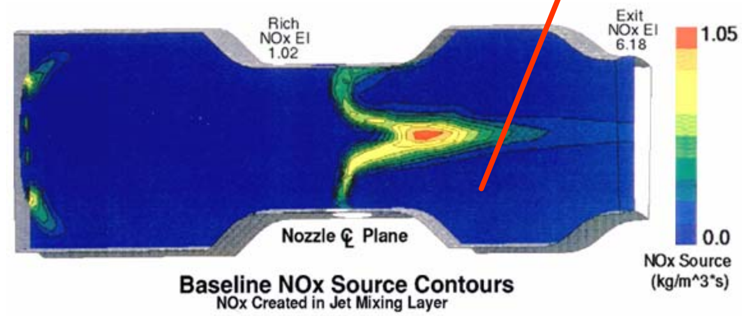




Pattern Factor Control

Objective: actively reduce combustor pattern factor

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



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.

Combustion Instability Control

Objective: actively suppress thermo-acoustic driven pressure oscillations

Status: Continuing research under the Smart Efficient Components project

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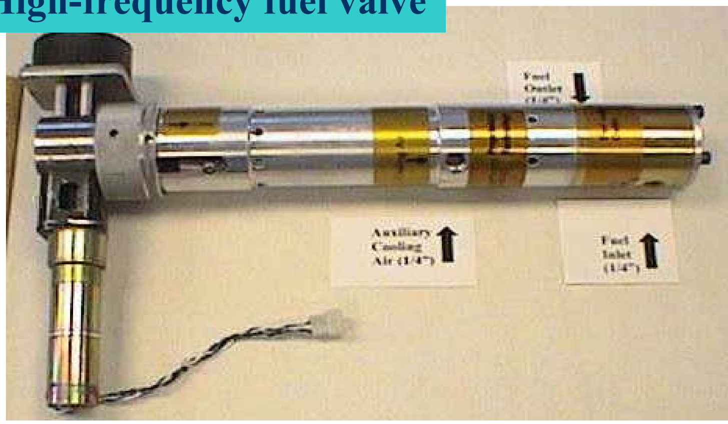
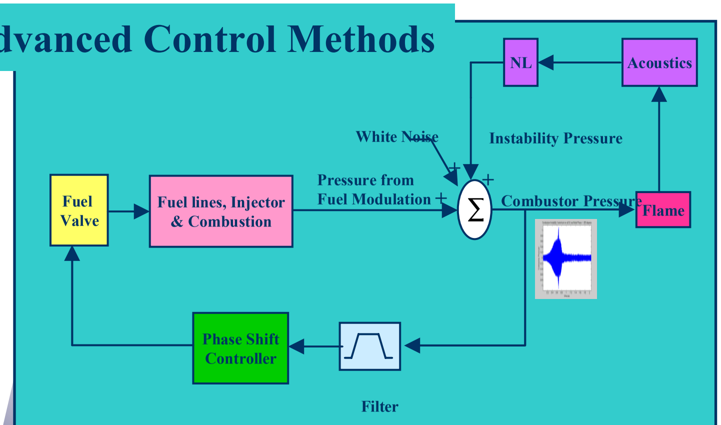
Active Control of Combustion Instability

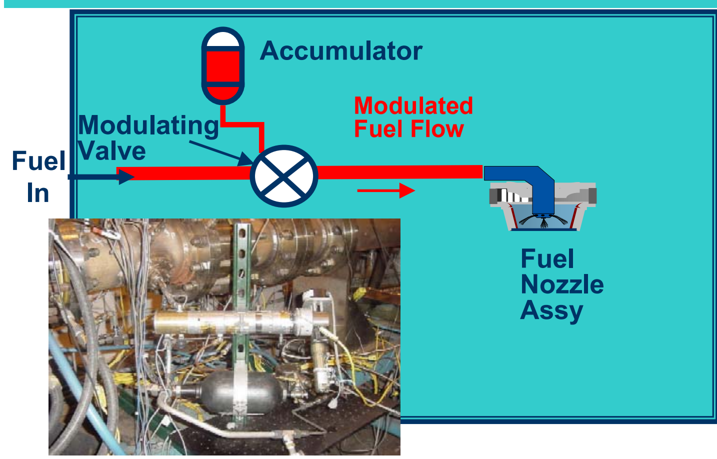
High-frequency fuel valve

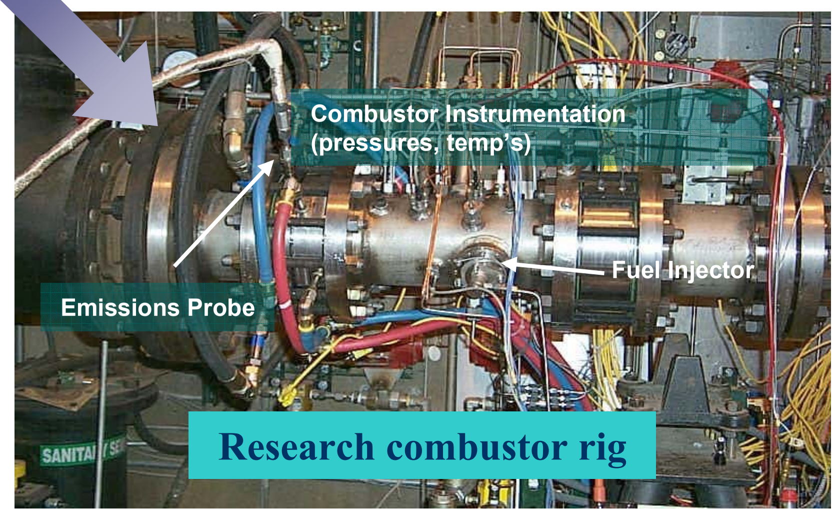


Advanced Control Methods



Fuel delivery system model and hardware

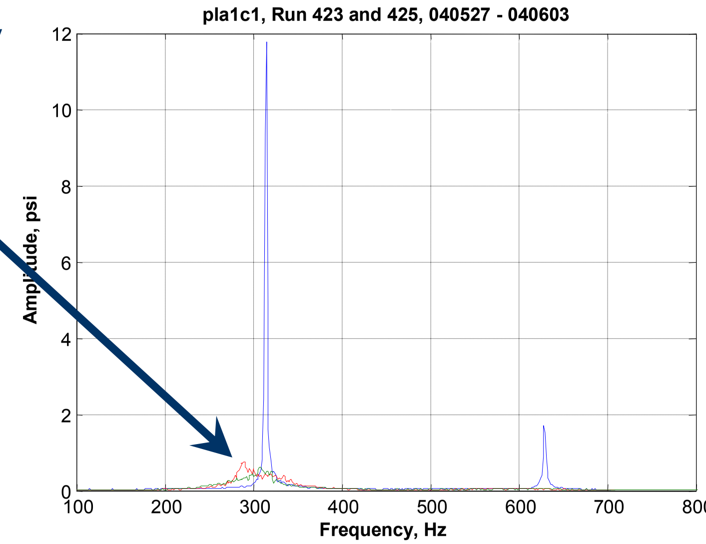


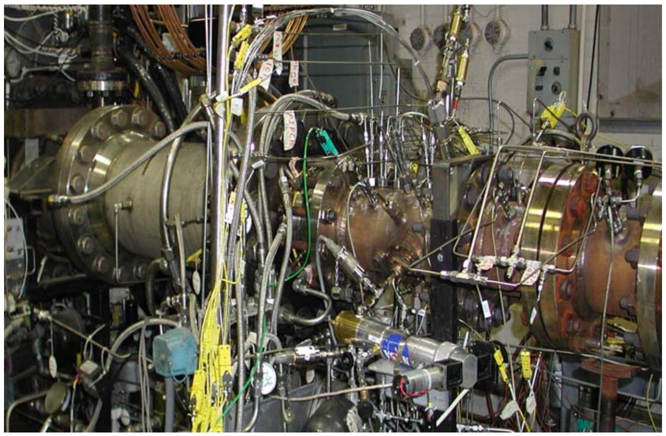


Research combustor rig

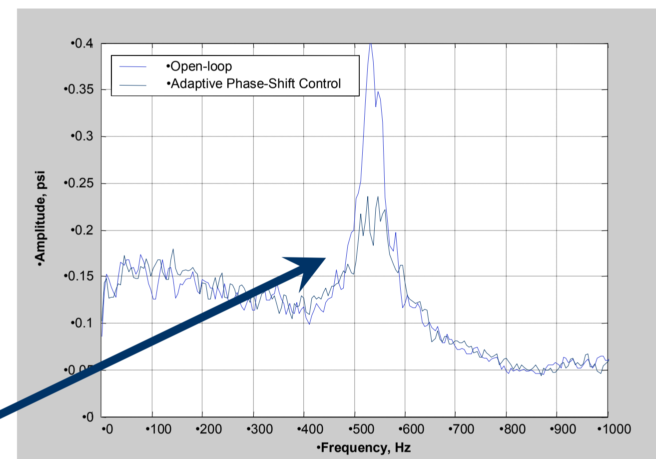
Active Combustion Control of Instability Recent Experimental Results

Large amplitude, low-frequency instability suppressed by 90%





Liquid-fueled combustor rig emulates engine observed instability behavior at engine pressures, temperatures, flows

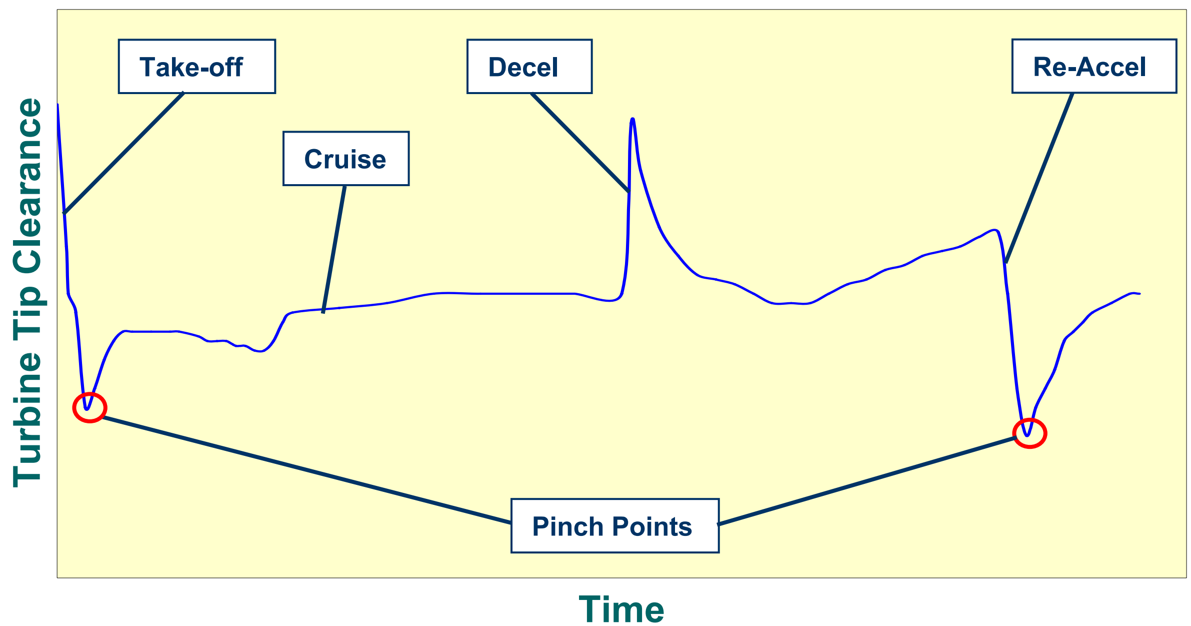


High-frequency, low-amplitude instability is identified, <u>while still small</u>, and suppressed almost to the noise floor.

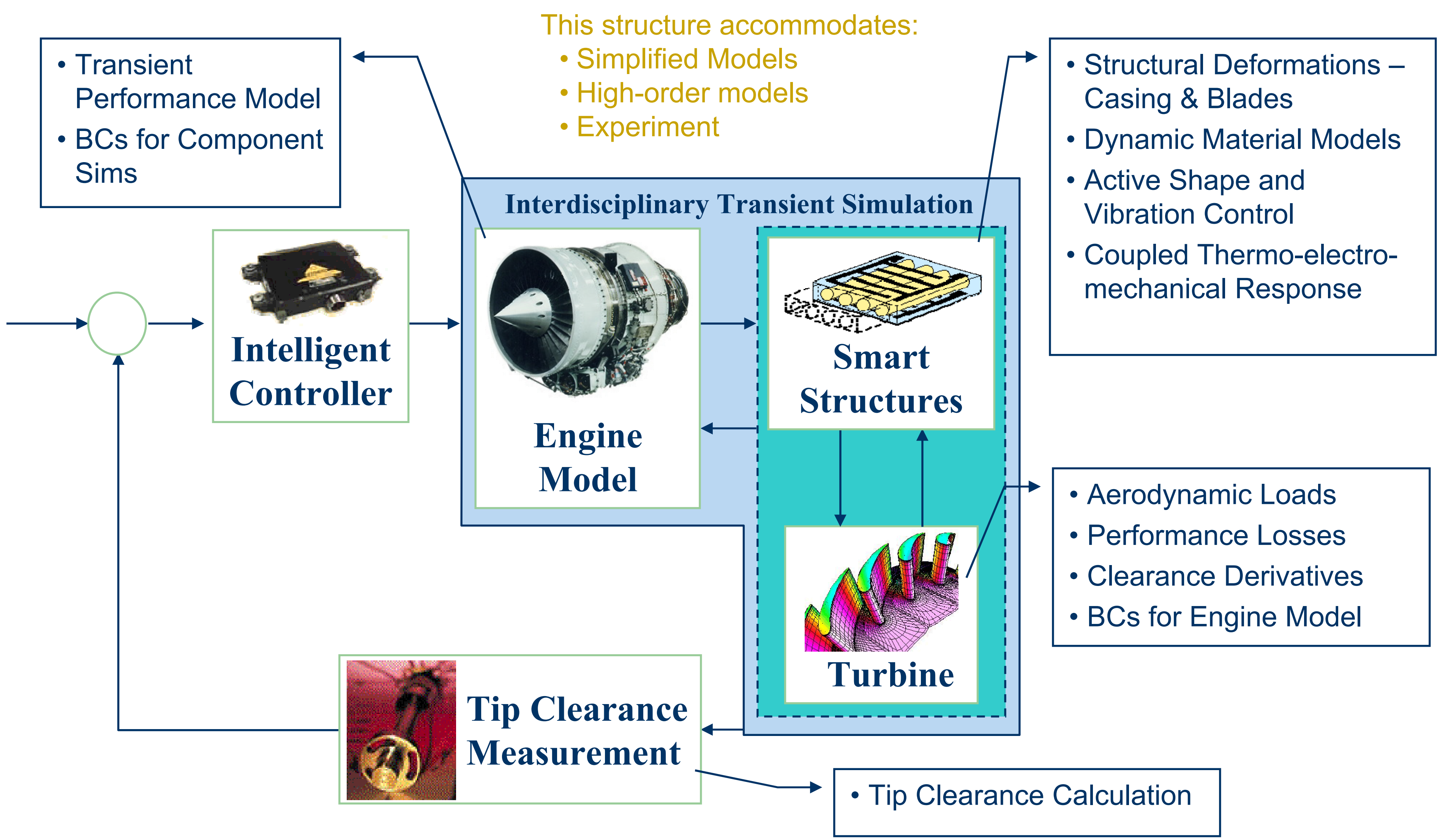
Intelligent Turbine Tip Clearance Management

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

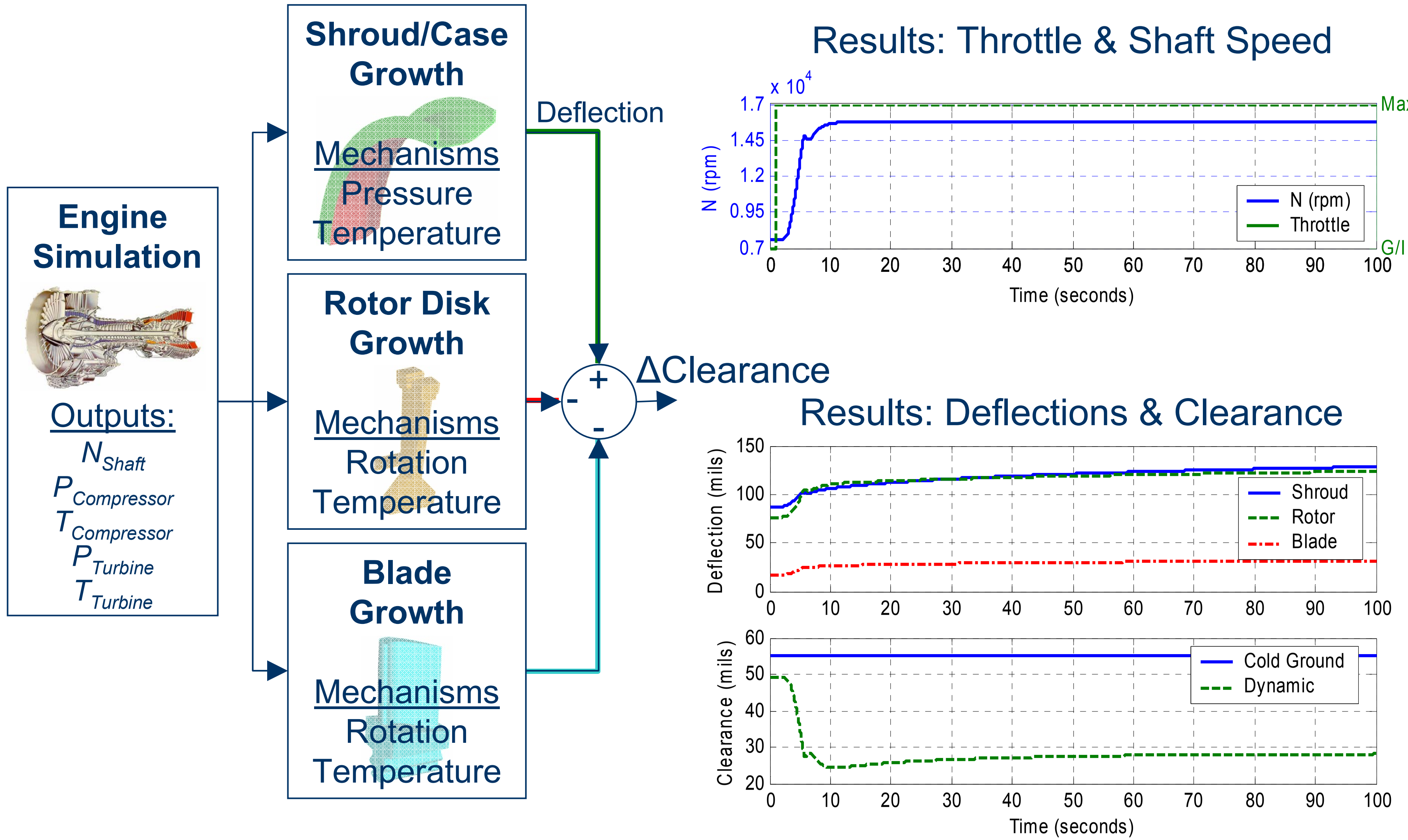
Notional Mission Profile



Intelligent Control of Turbine Tip Clearance

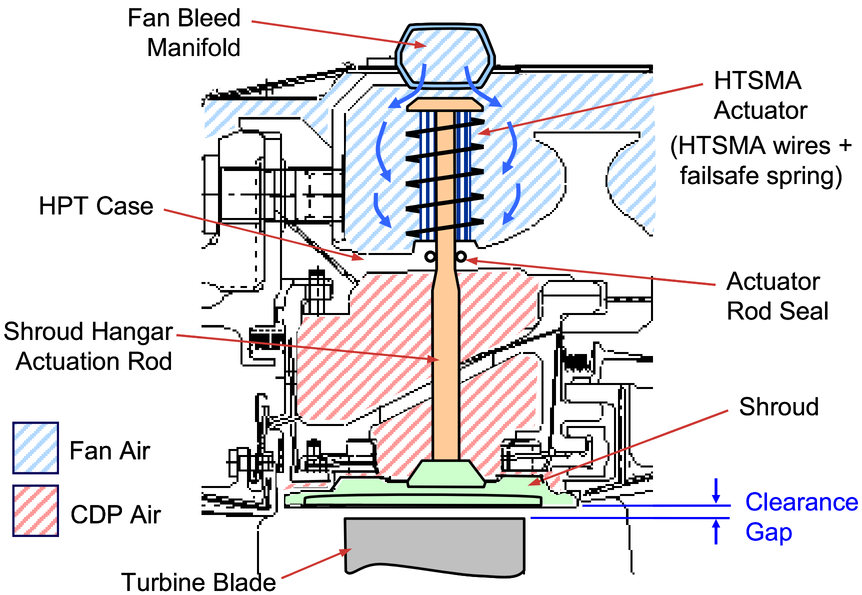


First Principles Based Clearance Model



High-Temperature Shape Memory Alloy Actuator for Active Turbine Tip Clearance Control

HTSMA Design

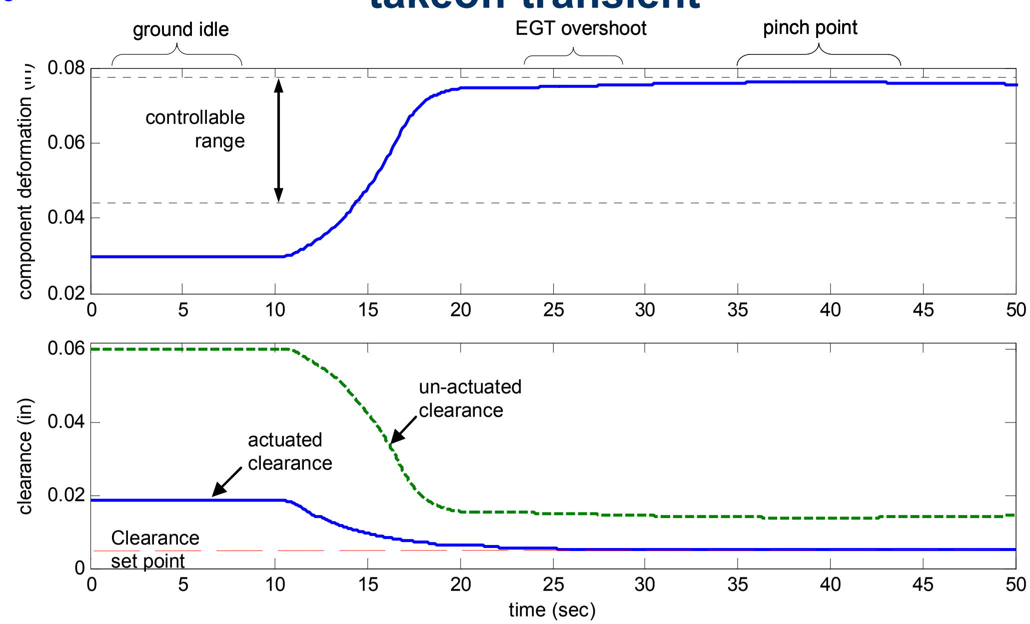


- **SMA actuator consists of wire bundle**
  - Facilitates heat transfer, Provides failure redundancy, Lowers fabrication costs
- **Engine fan bleed air utilized to cool actuator below transition**
- **Design ensures rub-free failsafe operation that improves and preserves performance and extends turbine life**

Results of System Simulation

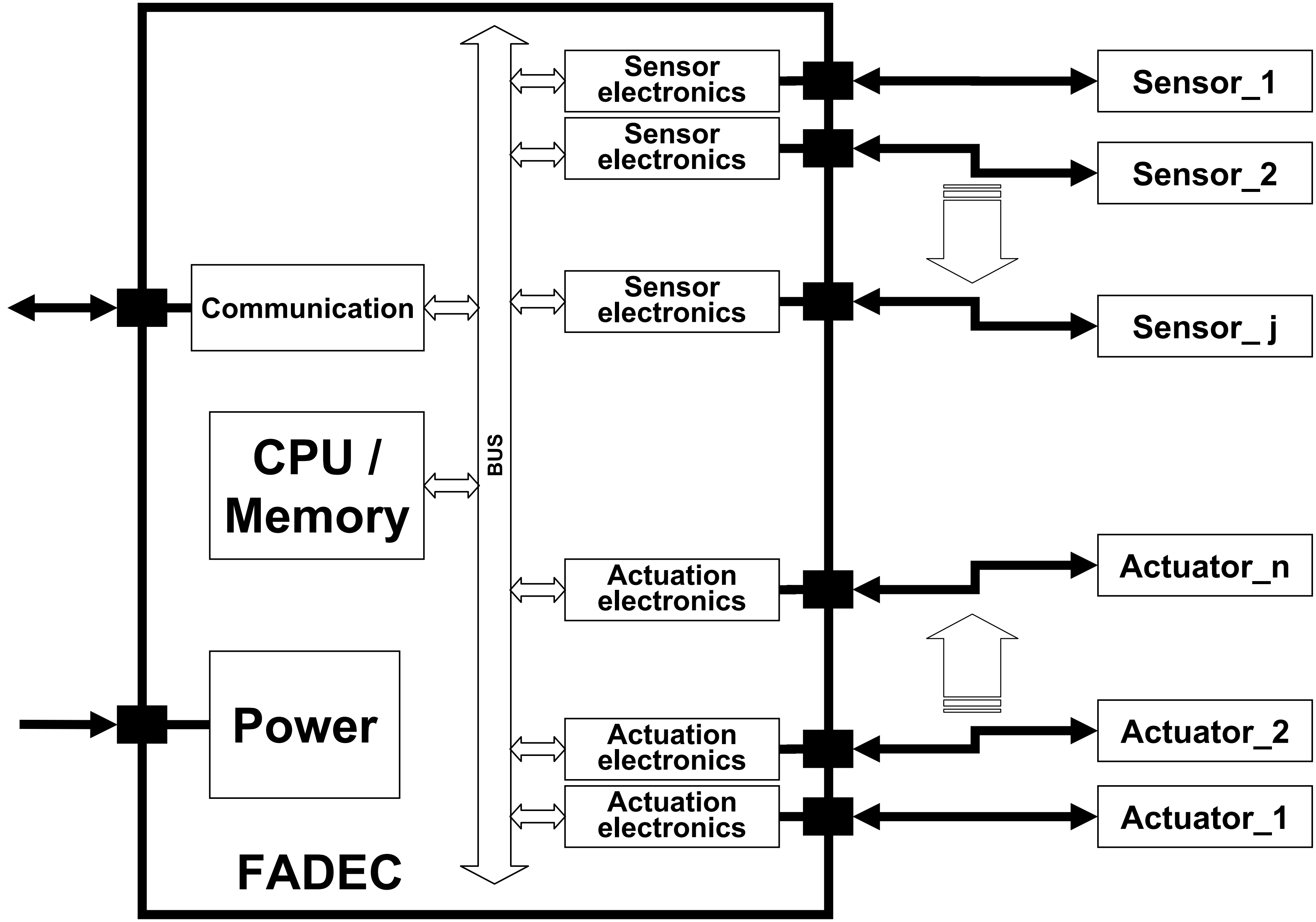
- Generated by incorporating HTSMA actuator model & control with detailed turbofan engine simulation
- Demonstrated clearance control at a 5-mil set point, at takeoff, and other operating points
- Optimized design operates with little fan bleed air
- Shows significant reduction in EGT and SFC

Rub-free clearance control during a takeoff transient



Current Engine Control Architecture

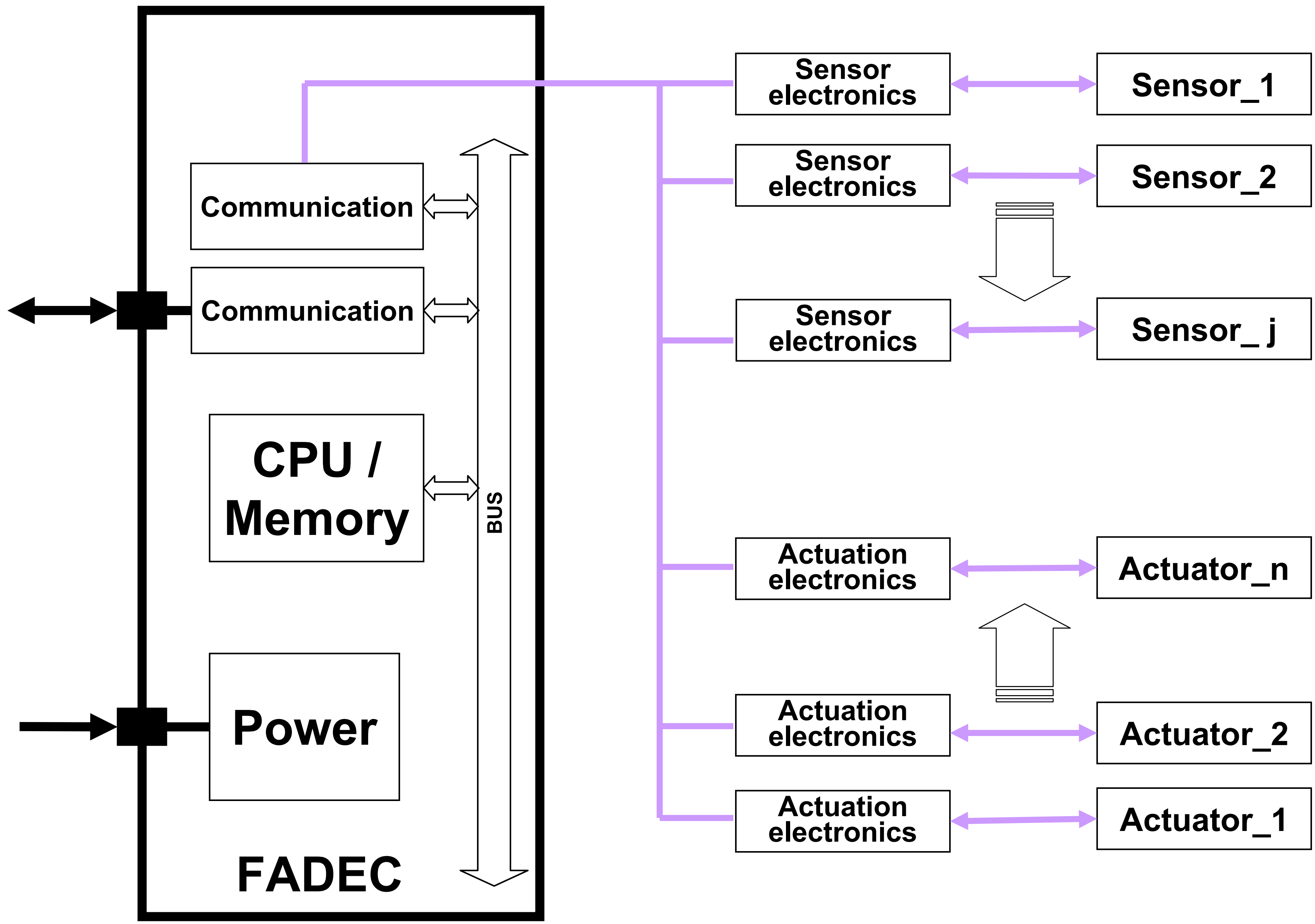
- Centralized with each sensor/actuator directly connected to FADEC



Centralized Engine Control

- **Pros:**
  - Works, reliable, well-understood, experience, comfort level
- **Cons:**
  - Expensive, inflexible, in the future will become a limiting factor in engine performance
  - Wire harness weight forces the FADEC to be co-located on the engine structure
  - Co-located FADEC requires environmental hardening (thermal, mechanical) further increasing weight and cost.
  - Complicates fault detection and isolation

Distributed Engine Control



Distributed Engine Control

- **Topologies:**
  - Star (point to point), Ring or bus (daisy chain)
  - Wired or wireless
- **Pros:**
  - Known to work well in other industries, much less expensive (initial and overall cost), very flexible
- **Cons:**
  - Communication unknowns and deterministic behavior
  - Overall increased complexity
  - Requires new technologies, i.e., high temperature electronics

Lesson 16 Summary

- There are tremendous opportunities to improve and revolutionize aircraft engine performance through “proper” use of advanced control techniques
  - 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 reduce “control system” weight, increase operational reliability and flexibility to easily incorporate new and improved capabilities