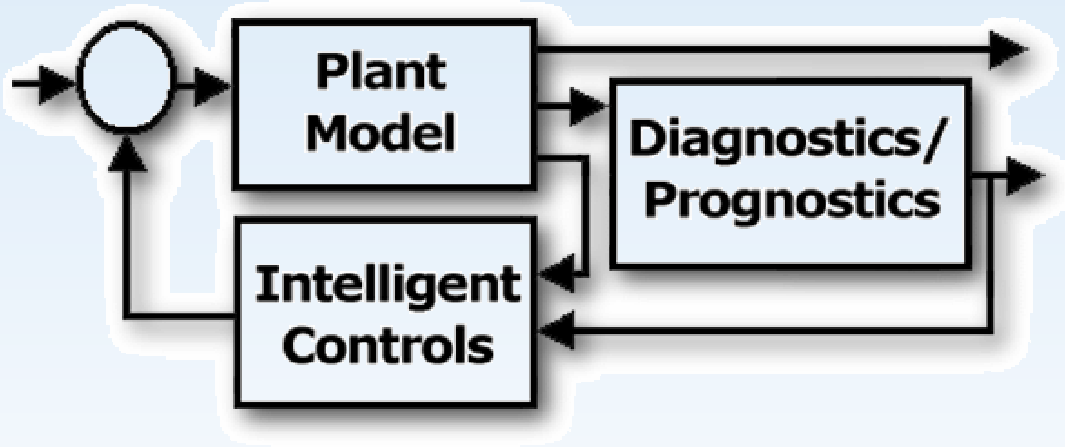
Fundamentals of Aircraft Turbine Engine Control

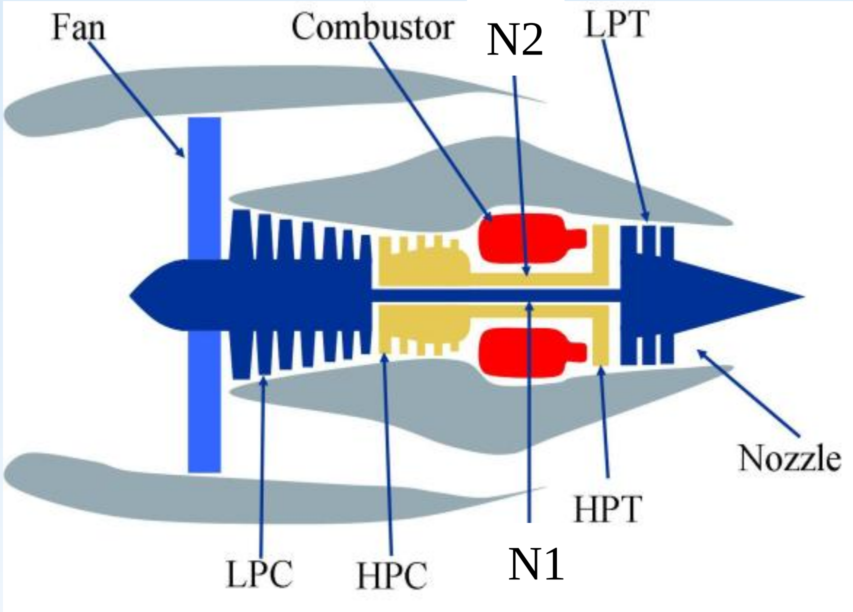


Dr. Sanjay Garg
Chief, Controls and Dynamics Branch
Ph: (216) 433-2685
FAX: (216) 433-8990
email: sanjay.garg@nasa.gov
http://www.lerc.nasa.gov/WWW/cdtb

Outline

- The Engine Control Problem
- Safety and Operational Limits
- Historical Engine Control Perspective
- Modeling and Simulation
- Basic Control Architecture
- Advanced Concepts

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

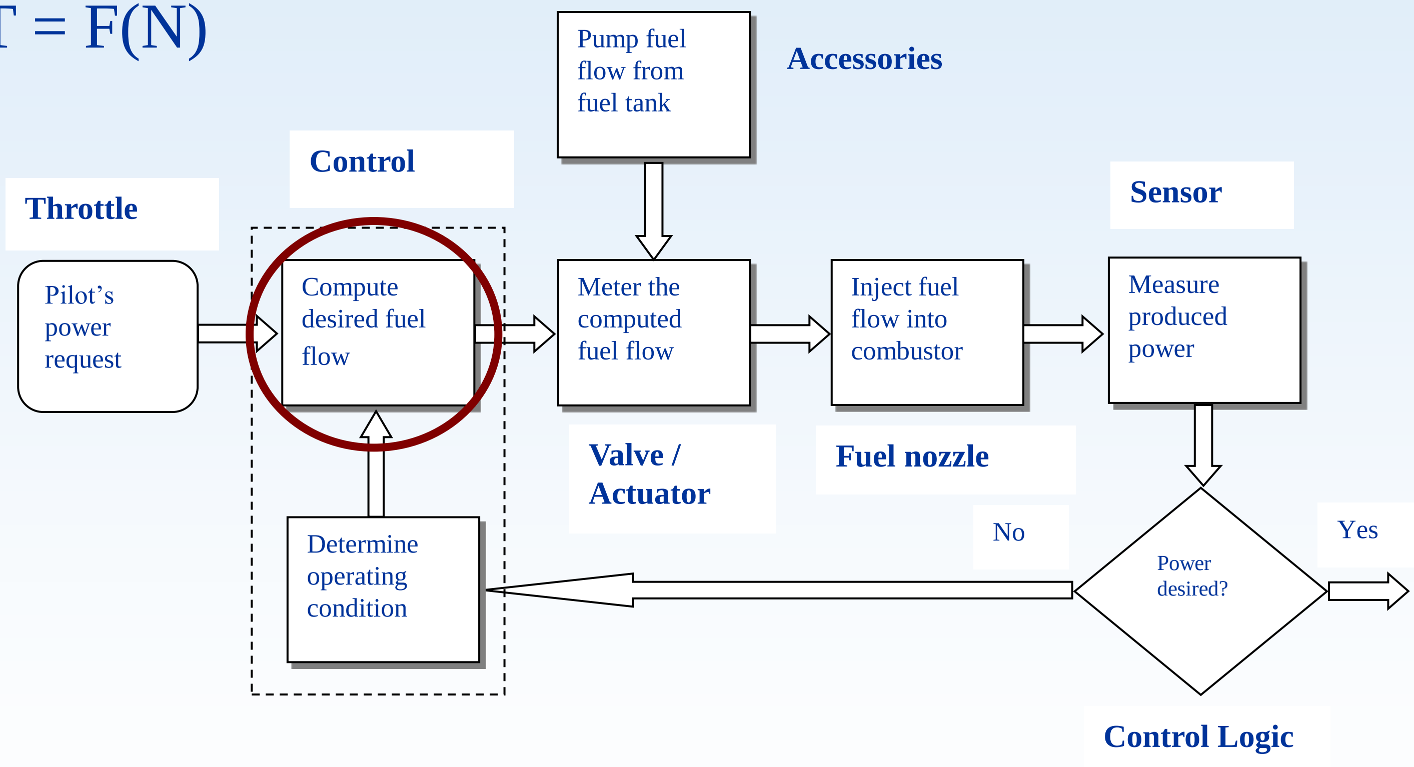
Basic Engine Control Concept

- **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

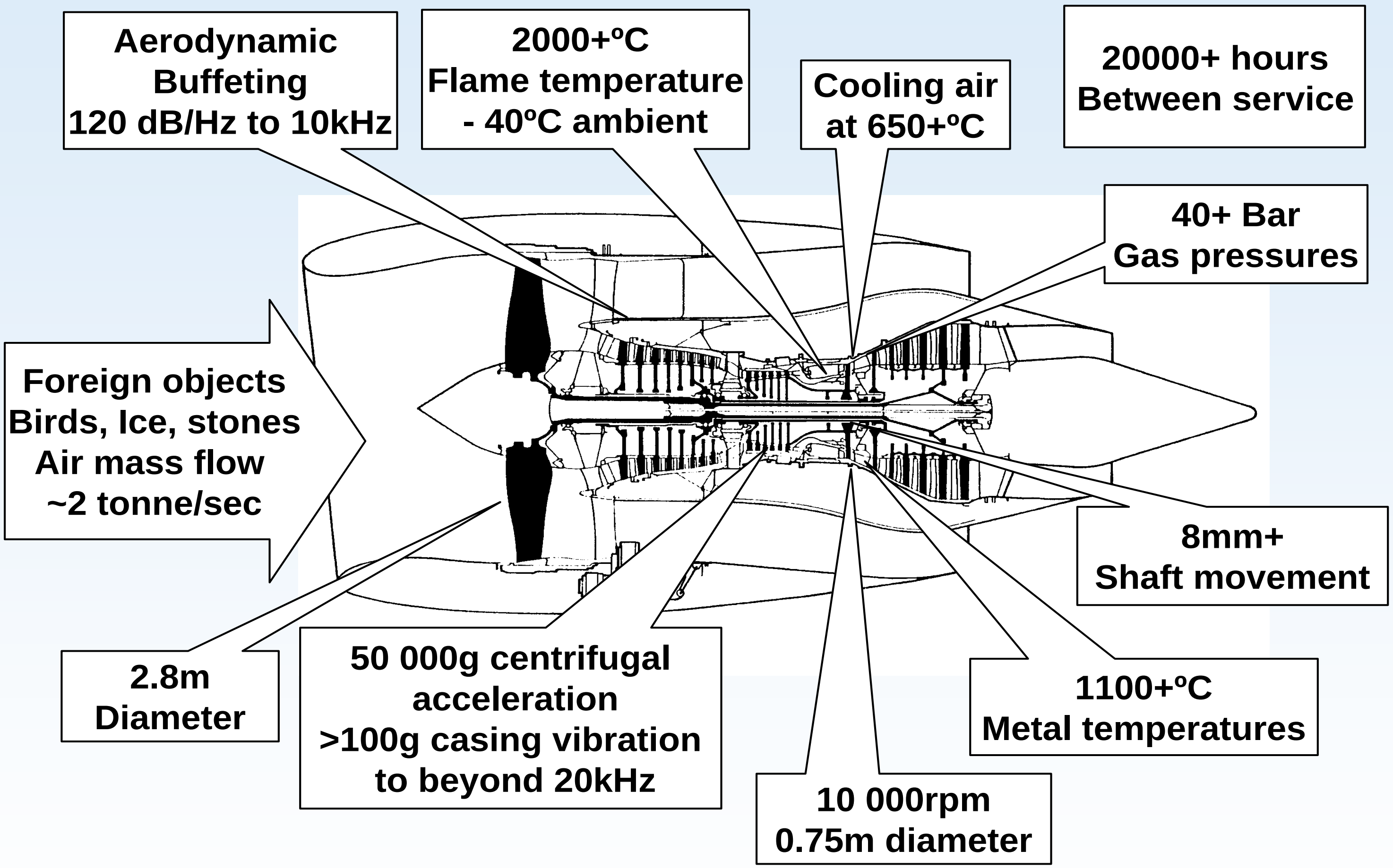
- **Issues:**
  - Thrust cannot be measured
  - Changes in ambient condition and aircraft maneuvers cause distortion into the fan/compressor
  - Harsh operating environment – high temperatures and large vibrations
  - Safe operation – avoid stall, combustor blow out etc.
  - Need to provide long operating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

Basic Engine Control Concept

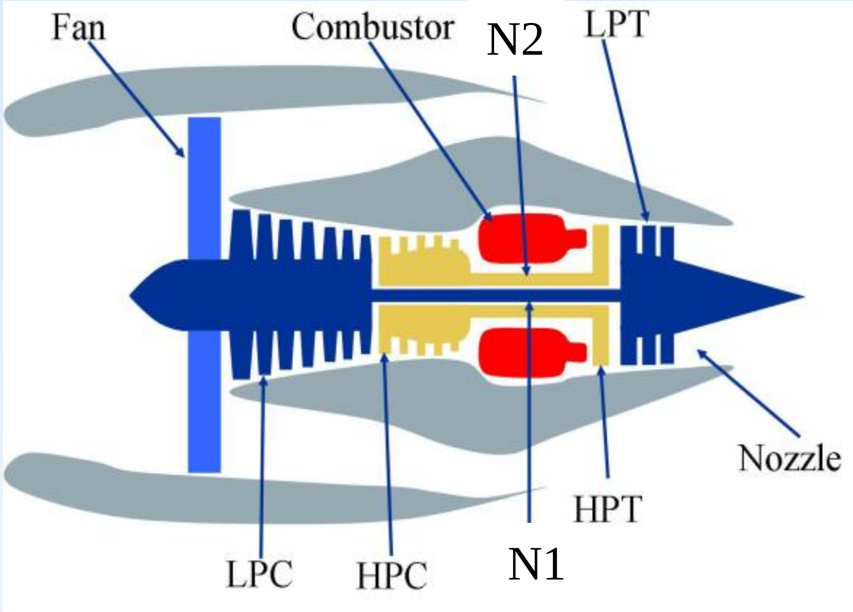
- Since Thrust (T) cannot be measured, use Fuel Flow WF to Control shaft speed N (or other measured variable that correlates with Thrust
  - T = F(N)



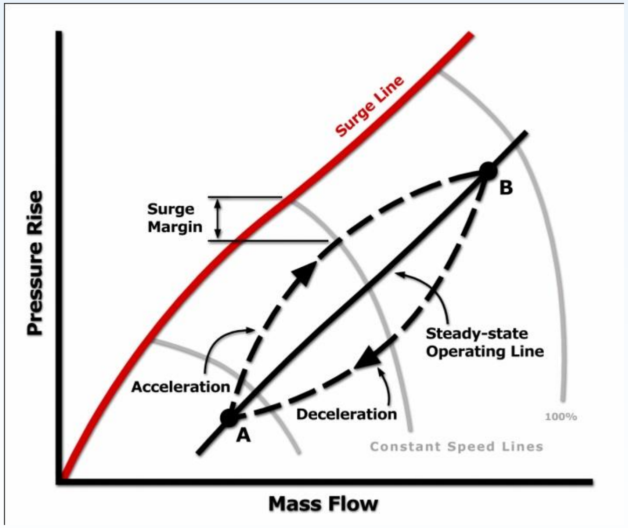
Environment within a gas turbine



Operational Limits

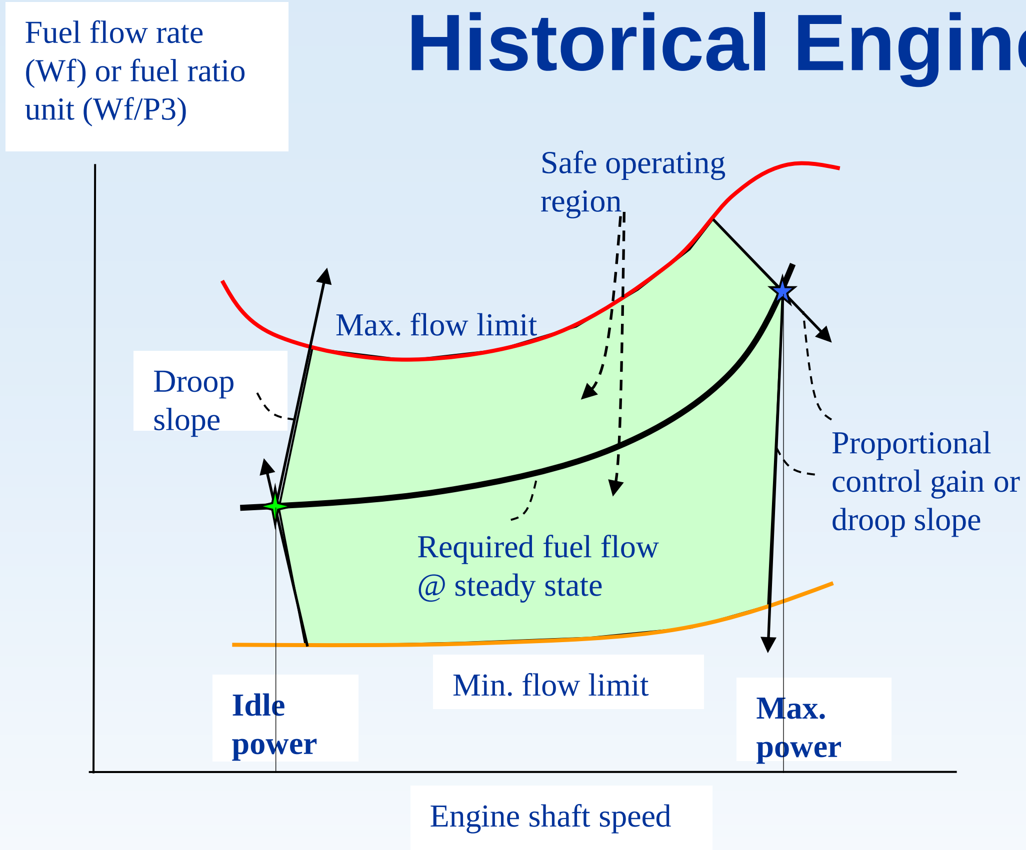


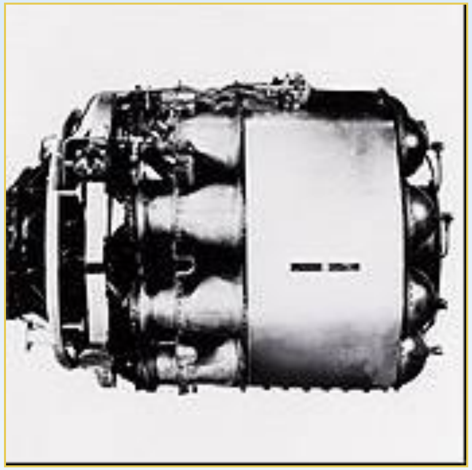
LPC - Low Pressure Compressor
HPC - High Pressure Compressor
HPT - High Pressure Turbine
LPT - Low Pressure Turbine
N1 - Fan Speed
N2 - Core Speed



- **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





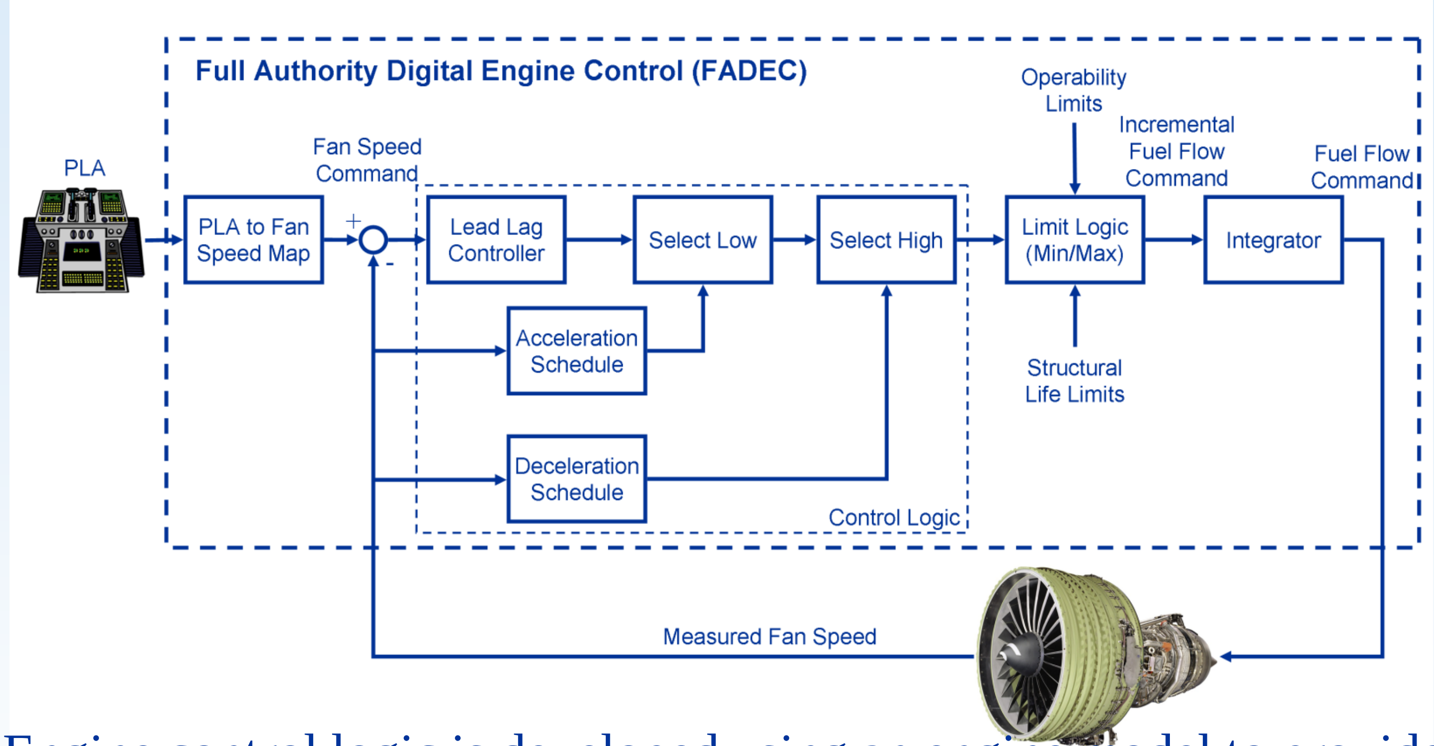
GE I-A
(1942)

- 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

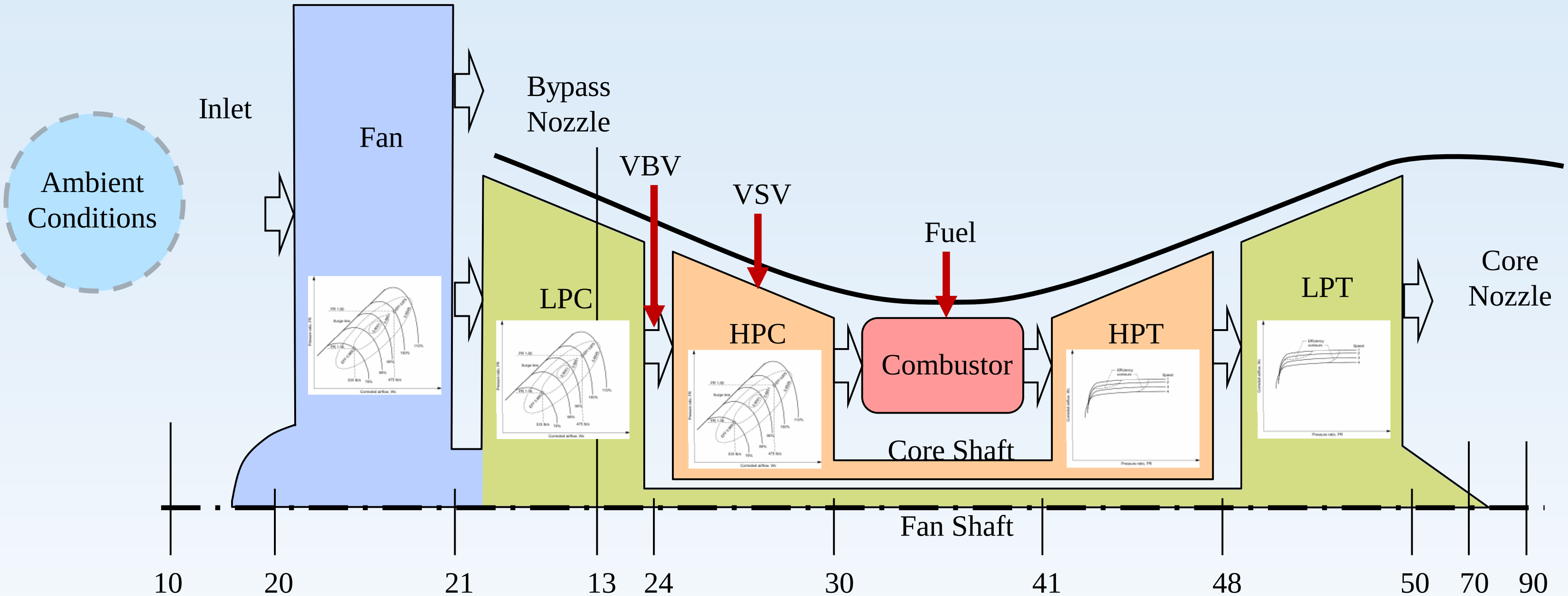


- Engine control logic is developed using an engine model to provide guaranteed performance (minimum thrust for a throttle setting) throughout the life of the engine
  - FAA regulations provide a minimum rise time and maximum settling time for thrust from idle to max throttle command

Engine Modeling

- Steady State performance obtained from cycle calculations derived from component maps obtained through detailed component modeling and component tests
  - Corrected parameter techniques used to reduce the number of points that need to be evaluated to estimate engine performance throughout the operating envelope
- Dynamics modeled through inertia (the rotor speeds), combustion delays, heat soak and sink modeling etc.
  - Computationally intensive process since it is important to maintain mass/momentum/energy balance through each component
- Detailed thermo-dynamic cycle decks developed and parameters adjusted to match engine test results
- Simplified models generated to develop and evaluate control design

Engine Component Modeling – Modern Turbofan Engine



Aero-Thermodynamics

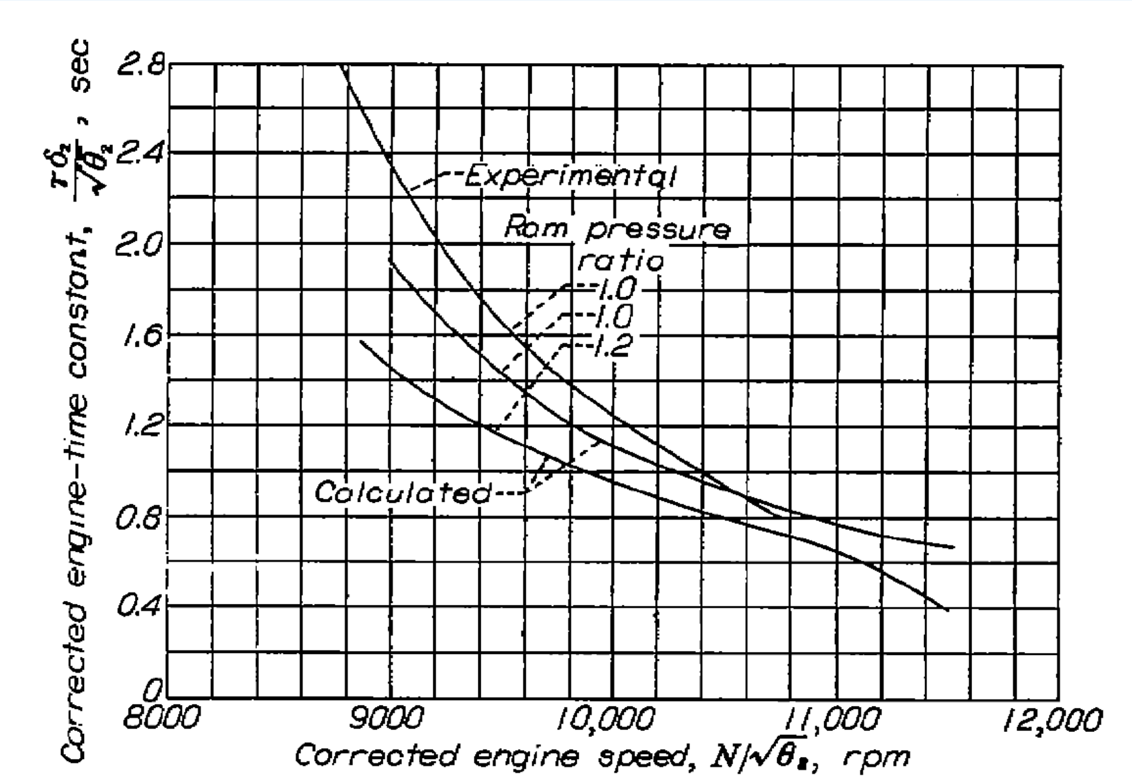
- Compressor/Fan Maps: **PR**, **Corr. Flow** & Efficiency as functions of **Shaft Speed** & **R-line**
- Turbines: **Corr. Flow** and **Efficiency** as functions of **Shaft Speed** & **PR**

Dynamics

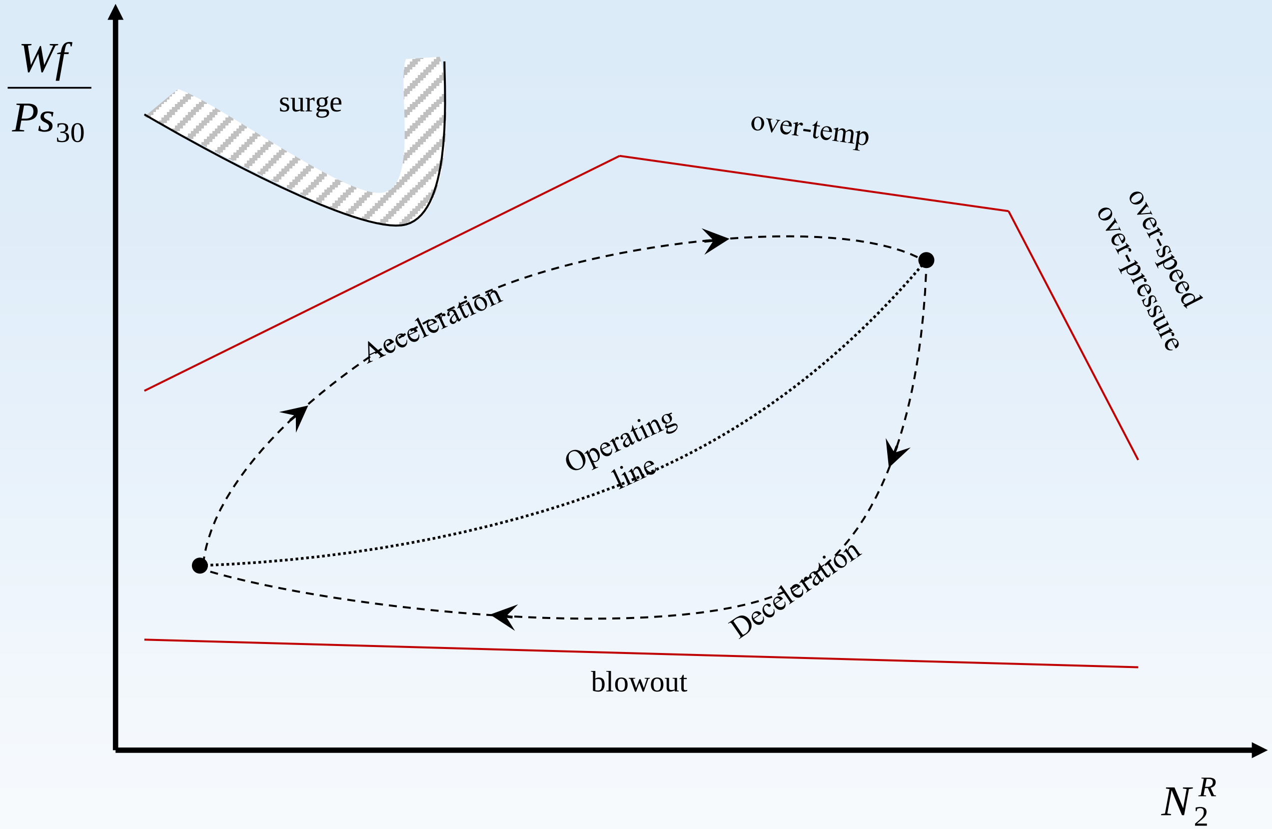
- Two physical states: fan speed, core speed
- Actuator/sensor dynamics: first-order lags
- Combustion delay

Engine Dynamic Modeling – Historical Perspective

- Dynamic behavior of single-shaft turbojet first studied at NACA Lewis Laboratory in 1948
- The study showed that the transfer function from fuel flow to engine speed can be represented by a first order lag linear system with a time constant which is a function of the corrected fan speed: N(s)/WF(s) = K/(as+1) with a=f(N)

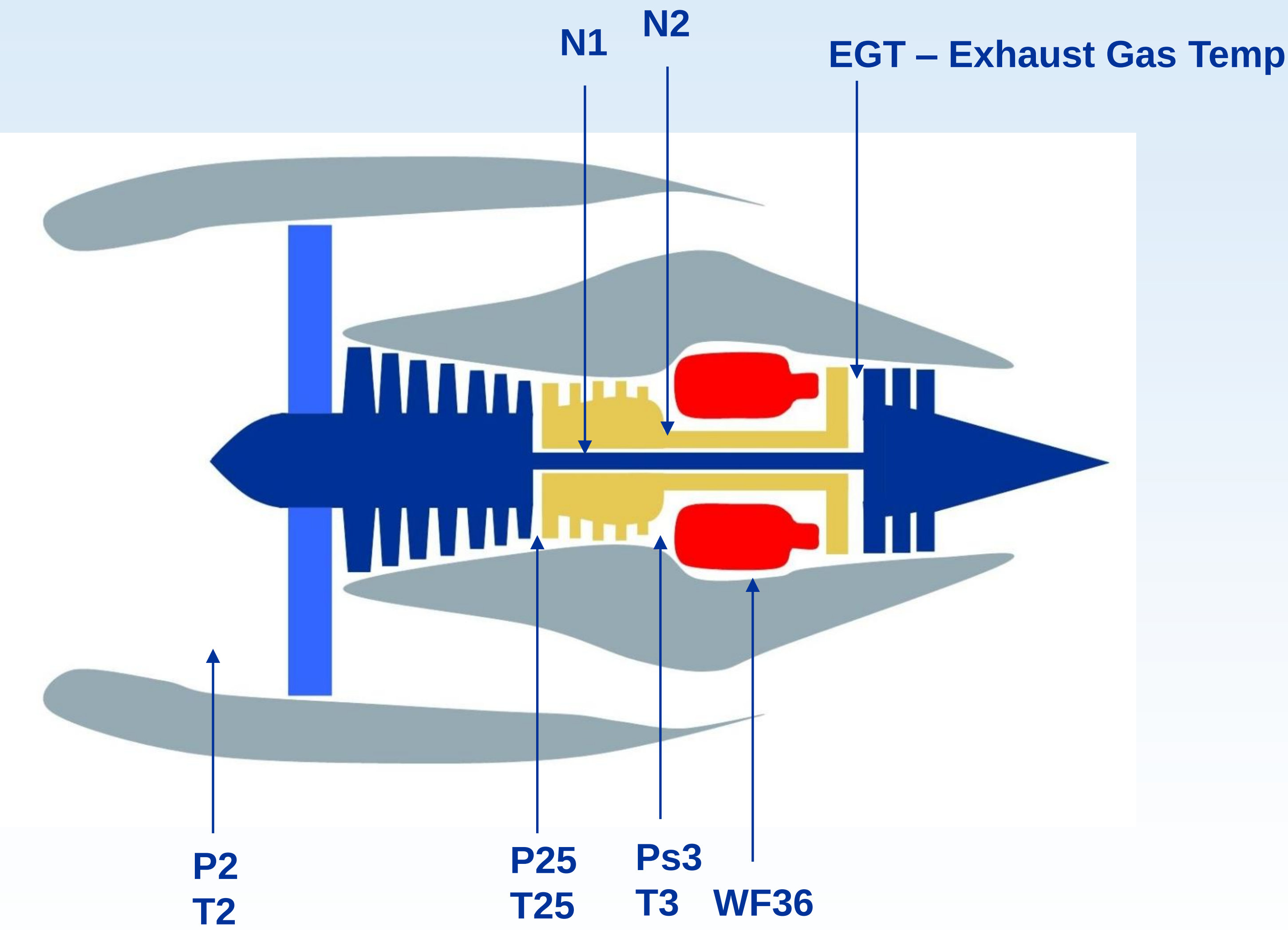


Implementing Limits for Engine Control



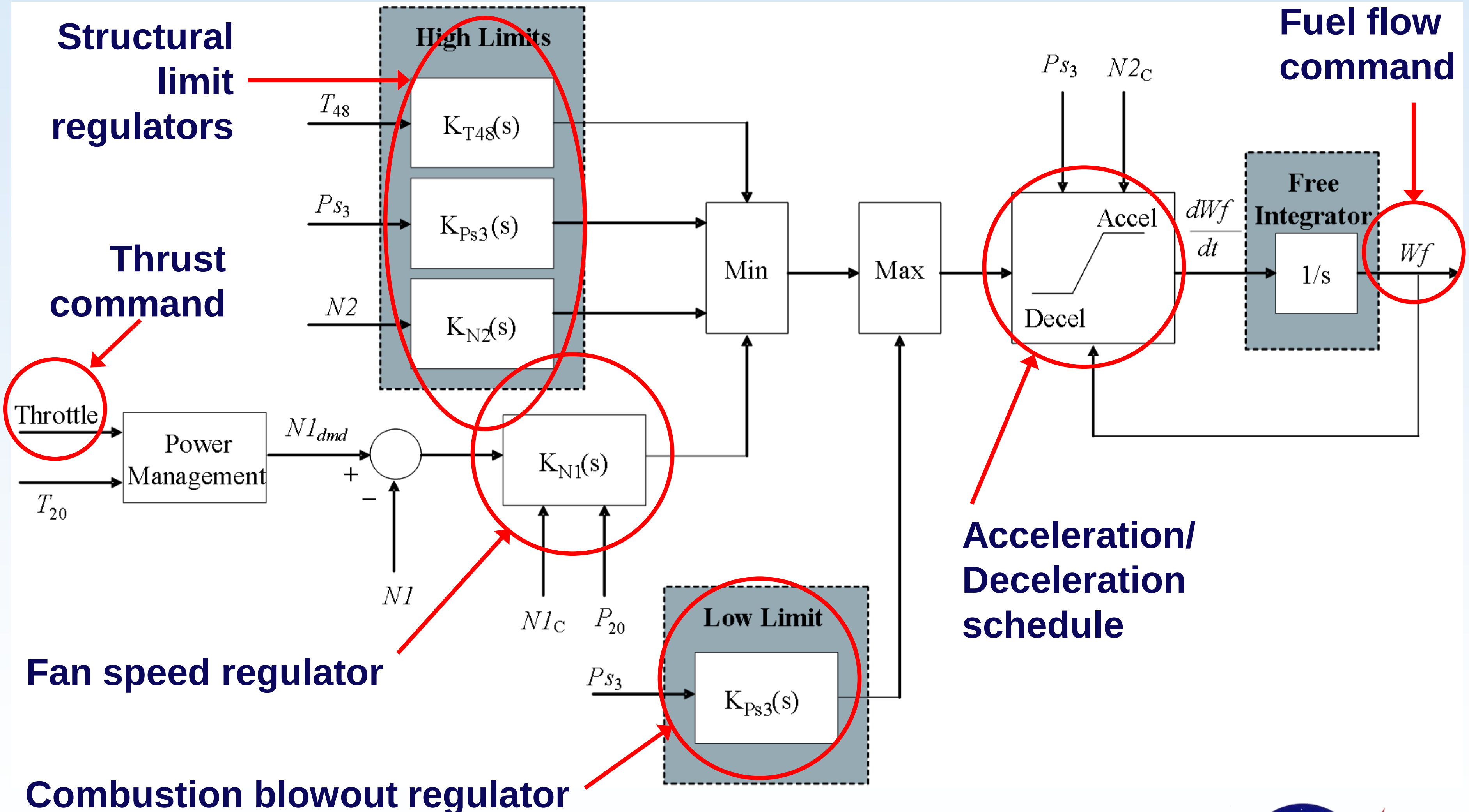
- Limits are implemented by limiting fuel flow based on rotor speed
  - Maximum fuel limit protects against surge/stall, over-temp, over-speed and over-pressure
  - Minimum fuel limit protects against combustor blowout
- Actual limit values are generated through simulation and analytical studies

Typical Sensors Used for Engine Control



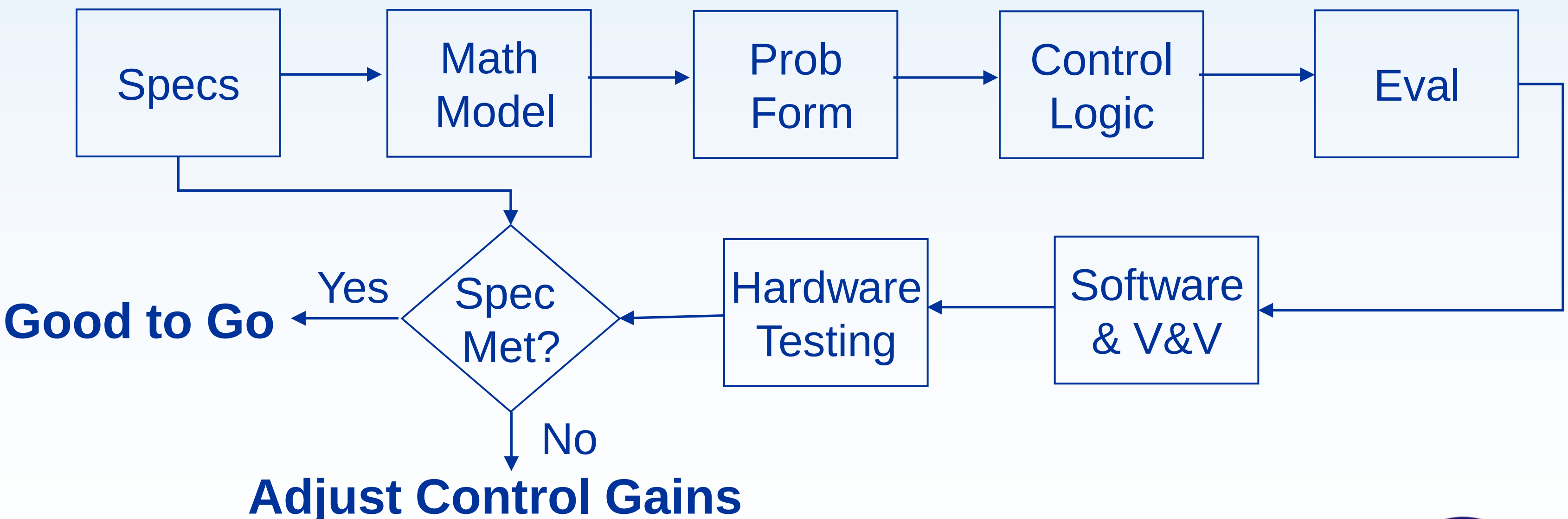
Typical Modern FADEC Control Architecture

All regulators produce incremental fuel flow commands

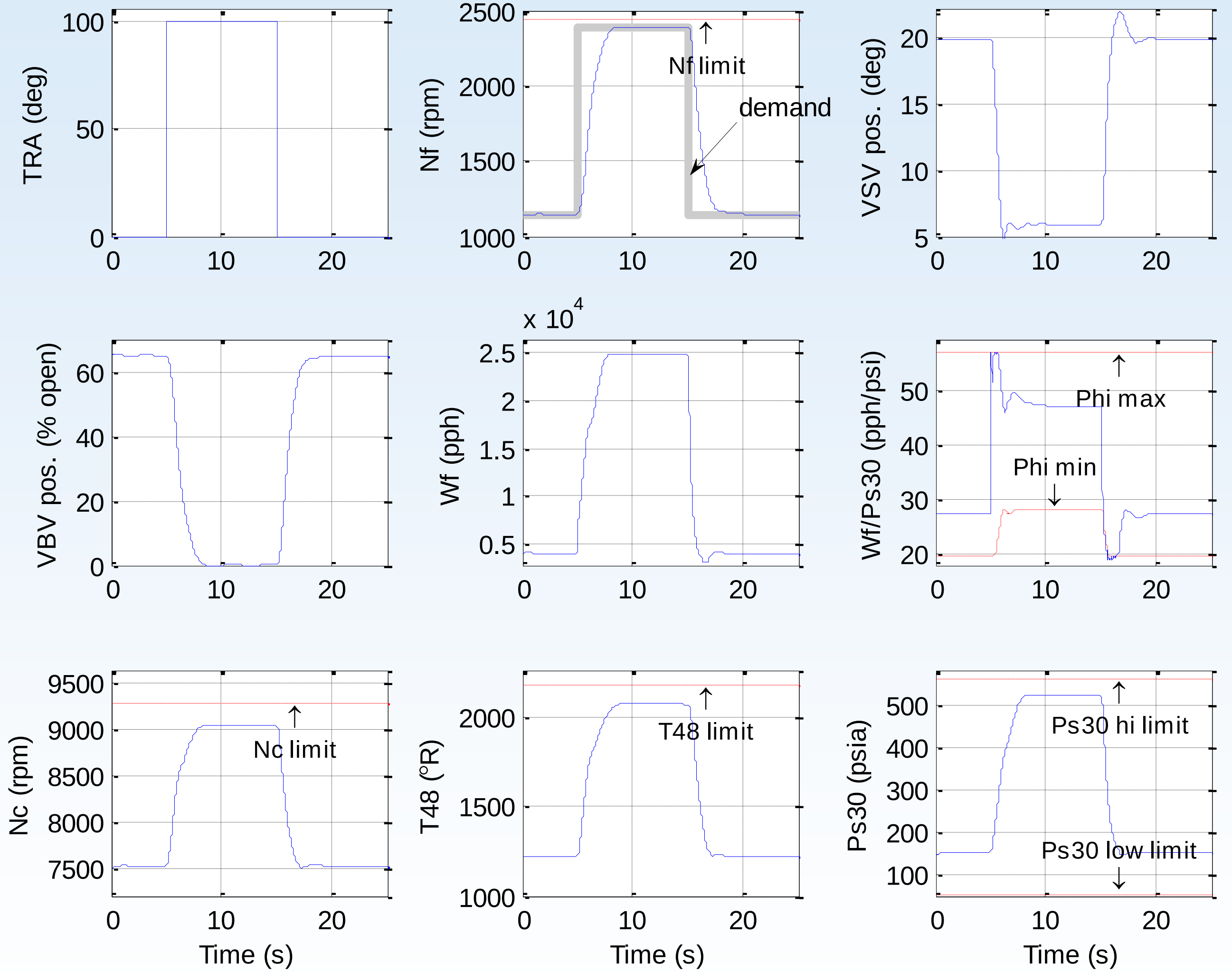


Control Law Design Procedure

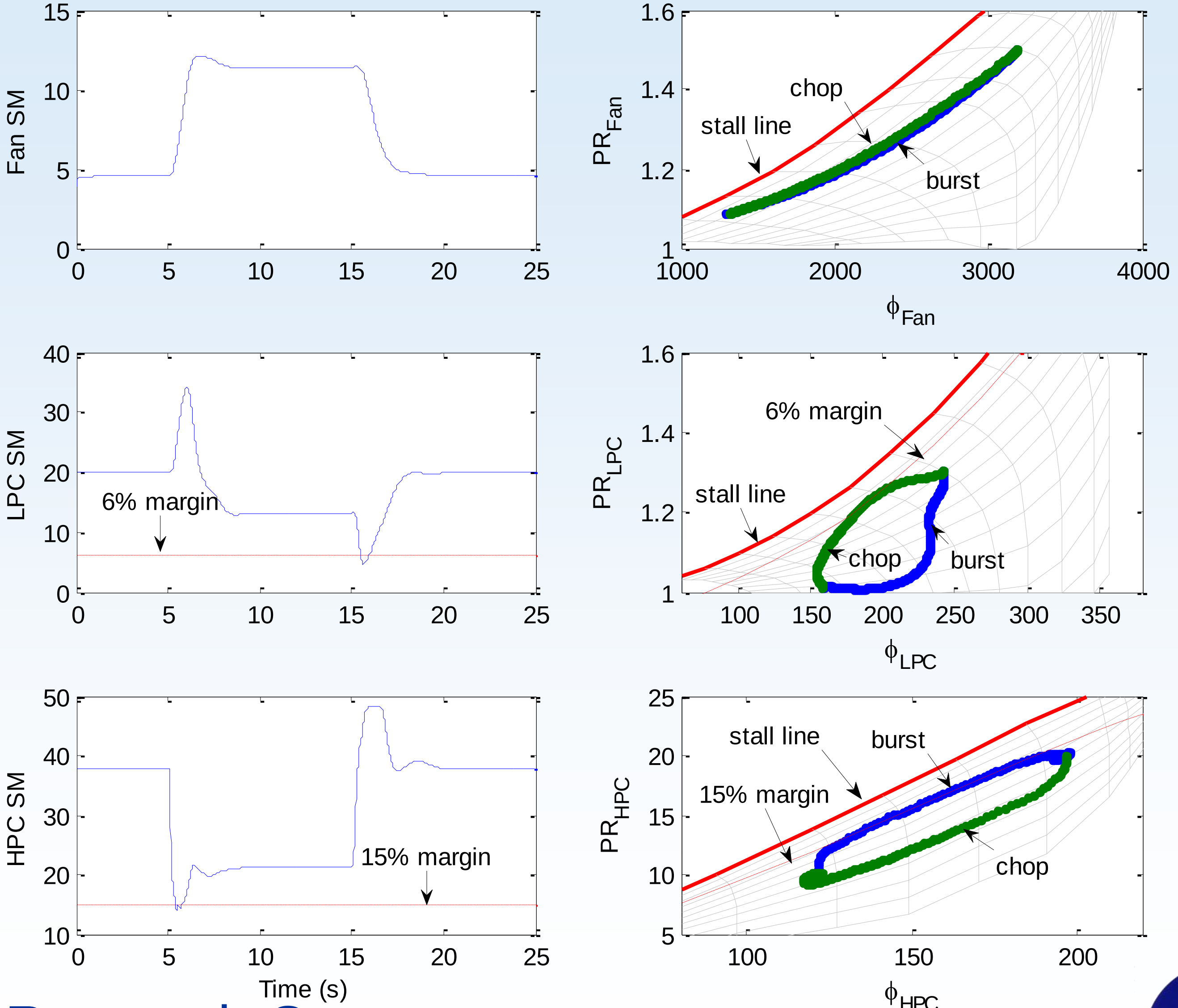
- The various control gains K are determined using linear engine models and linear control theory
    - Proportional + Integral control provides good fan speed tracking
    - Control gains are scheduled based on PLA and Mach number
- Control design evaluated throughout the envelope using a nonlinear 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



Burst-Chop Example – Inputs/Outputs



Burst-Chop Example - Stall Margins

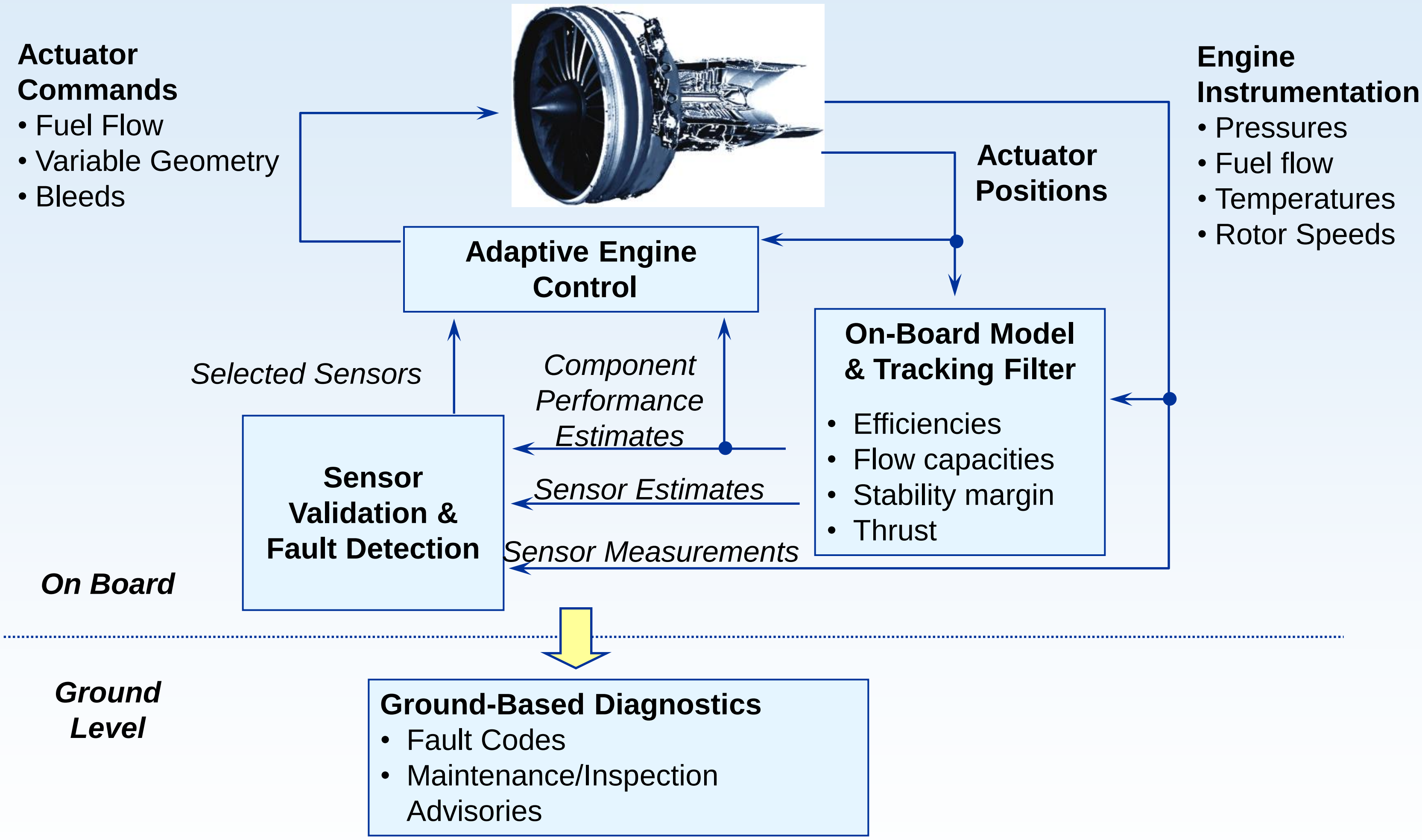


Engine Simulation Software Packages

The following engine simulation software packages, developed in Matlab/Simulink and useful for propulsion controls and diagnostics research, are available from NASA GRC software repository

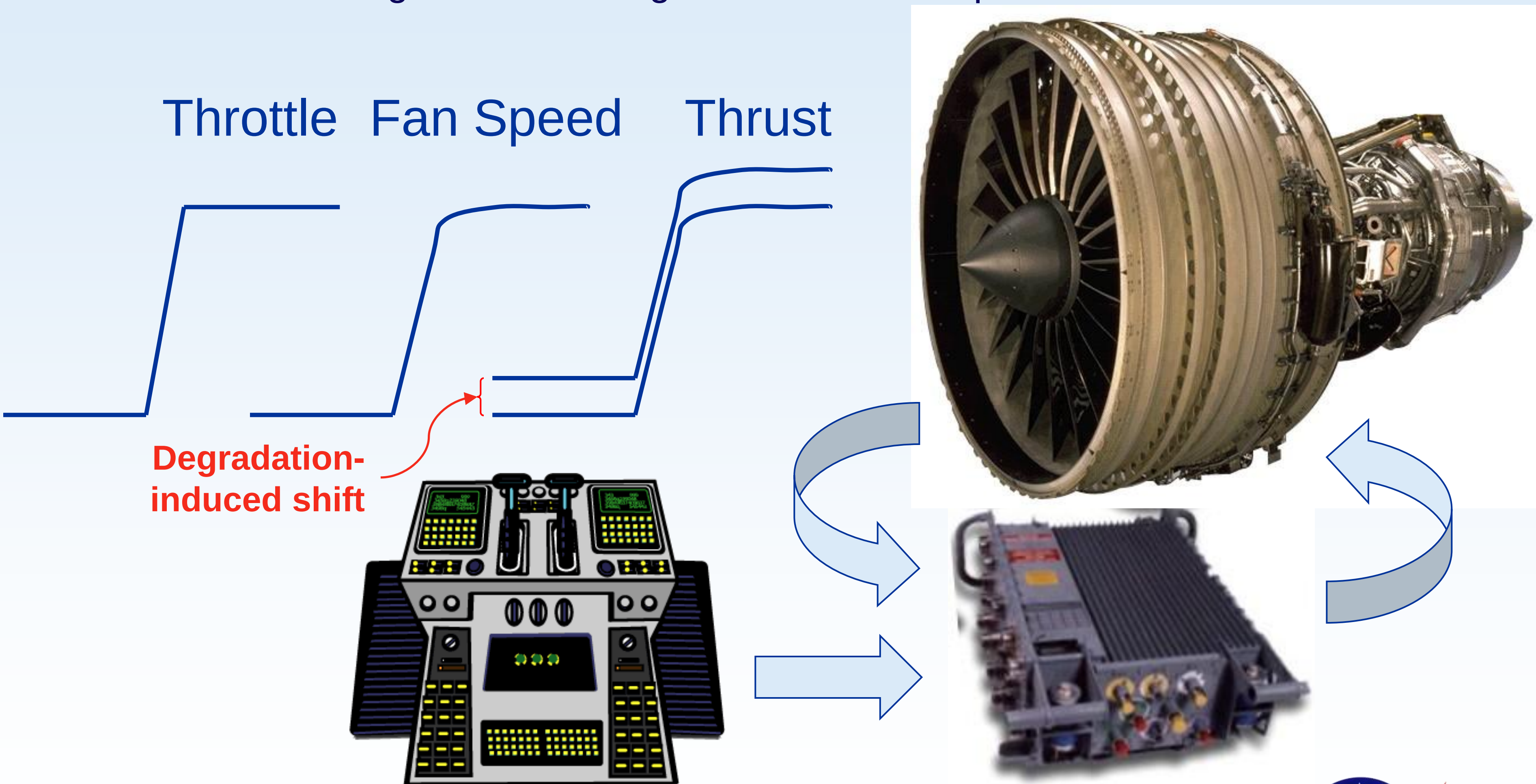
- **MAPSS** – Modular Aero-Propulsion System Simulation
  - Simulation of a modern fighter aircraft prototype engine with a basic research control law: http://sr.grc.nasa.gov/public/project/49/
- **C-MAPSS** – Commercial Modular Aero-Propulsion System Simulation
  - Simulation of a modern commercial 90,000 lb thrust class turbofan engine with representative baseline control logic: http://sr.grc.nasa.gov/public/project/54/
- **C-MAPSS40k**
  - High fidelity simulation of a modern 40,000 lb thrust class turbofan engine with realistic baseline control logic: http://sr.grc.nasa.gov/public/project/77/

Model-Based Controls and Diagnostics



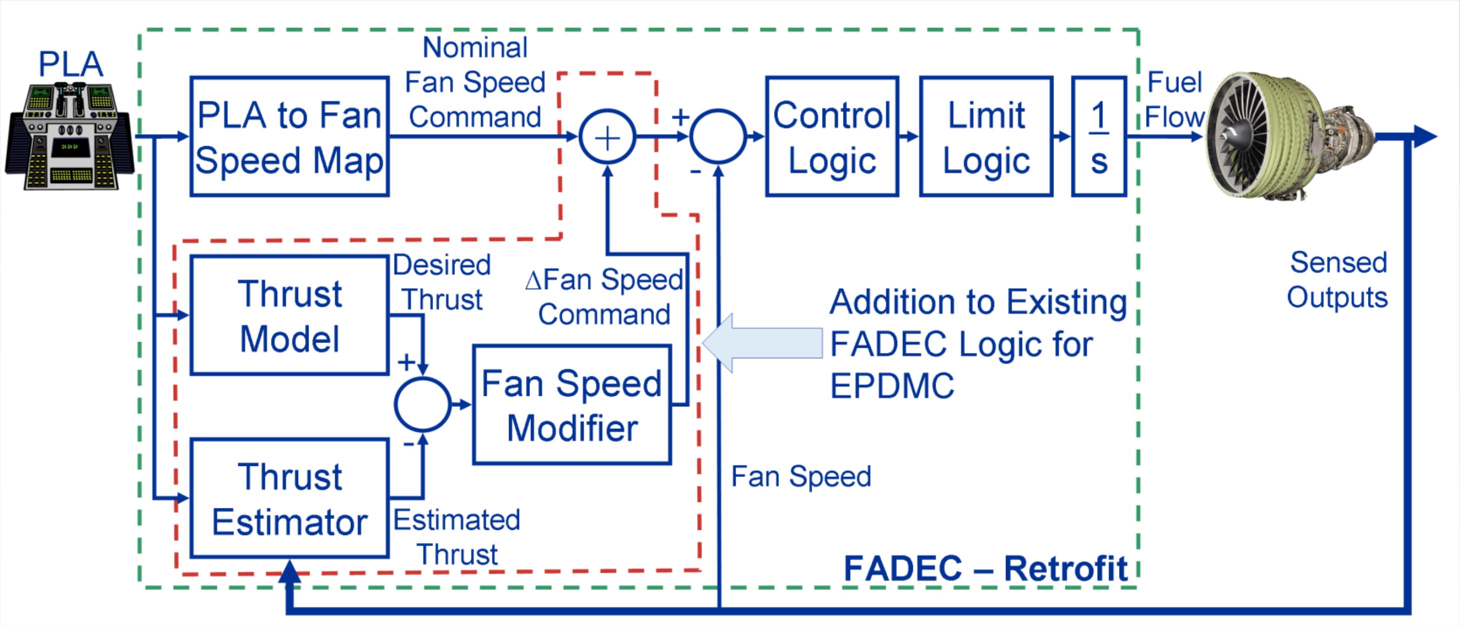
Engine Performance Deterioration Mitigation Control

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



Engine Performance Deterioration Mitigation Control (EPDMC)

- The proposed retrofit architecture:

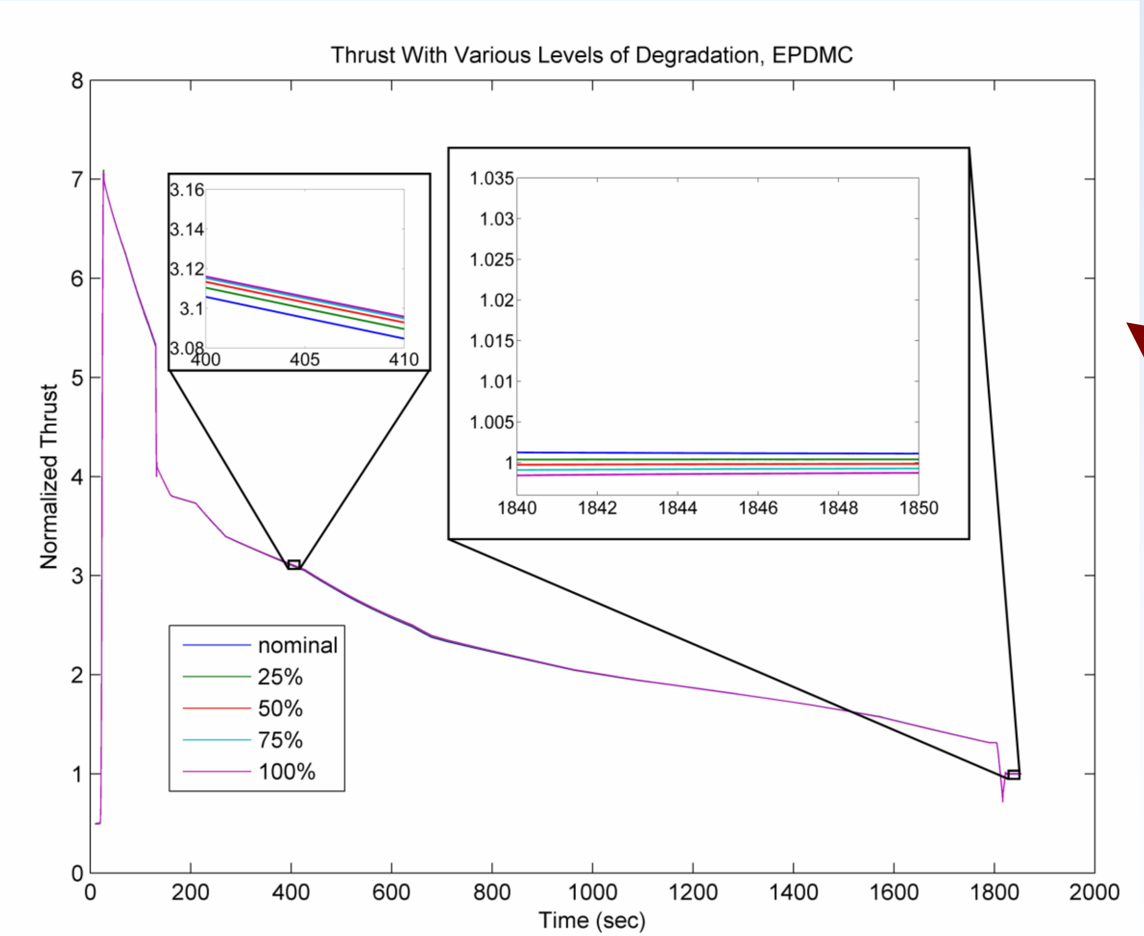


- Adds the following “logic” elements to existing FADEC:
  - A model of the nominal throttle to desired thrust response
  - An estimator for engine thrust based on available measurements
  - A modifier to the Fan Speed Command based on the error between desired and estimated thrust
    - Since the modifier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

EPDMC Evaluation

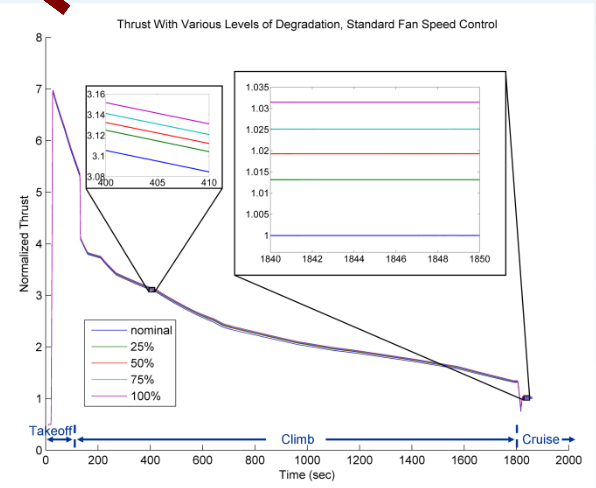
Thrust response for Typical Mission

With EPDMC

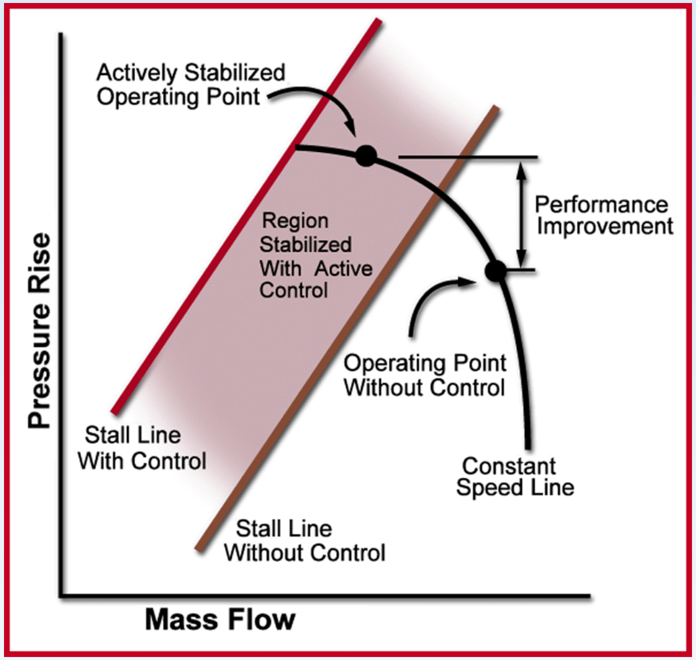


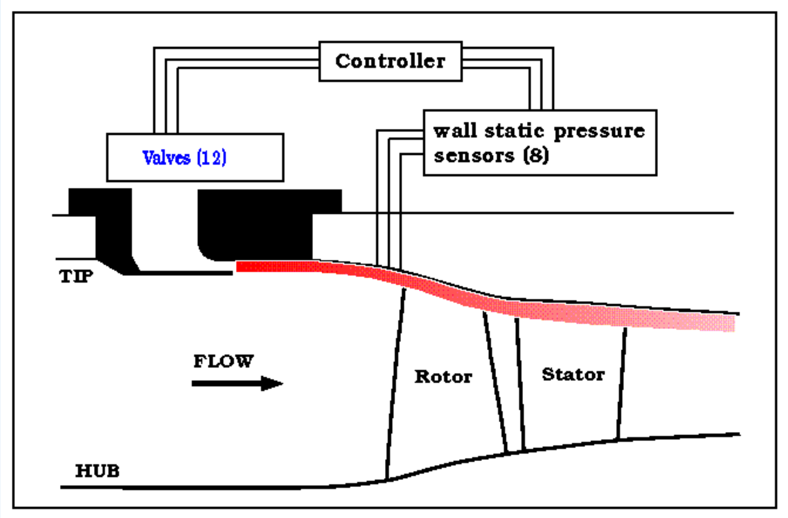
- Throttle to thrust response is maintained
  – no "uncommanded" thrust asymmetry

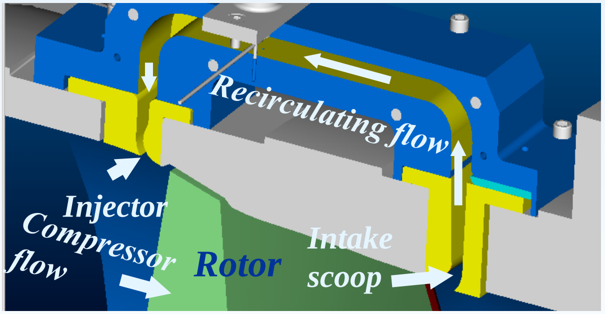
Without EPDMC



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

Summary

- Provided an overview and historical perspective of engine control design
- The control design enables smooth and safe operation of the engine from one steady-state to another through implementation of various limits
- There are tremendous opportunities to improve and revolutionize aircraft engine performance through "proper" use of advanced control technologies

References

- H. Austin Spang III and Harold Brown, “Control of Jet Engines”, *Control Engineering Practice, Vo. 7,* 1999, pp. 1043-1059
- 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://gltrs.grc.nasa.gov/