Session 6
Dynamic Modeling and Systems Analysis

1:00 – 1:05p	Overview – Jeffrey Csank
1:05 – 1:30p	Dynamic Systems Analysis – Jeffrey Csank
1:30 – 1:55p	T-MATS (Toolbox for the Modeling and Analysis of Thermodynamic Systems) – Jeffryes Chapman
1:55 – 2:20p	Reducing Conservatism in Aircraft Engine Response Using Conditionally Active Min-Max Regulators – Ryan May

4th Propulsion Control and Diagnostics Workshop
Ohio Aerospace Institute (OAI)
Cleveland, OH
December 11-12, 2013

Dynamic Systems Analysis

- Preliminary Engine Design
  - Systems Analysis (Steady state)
  - Lack of dynamic performance information
    - Historical data (past experiences)
    - Additional conservatism in the design
- Dynamic Systems Analysis
  - Better predict/account for dynamic operation in PED
  - Allow for trade-offs between performance and operability margins to meet future engine performance requirements
  - Enabled through the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)

T-MATS (Toolbox for the Modeling and Analysis of Thermodynamic Systems)

- Simulation System designed to give a user a library containing building blocks that may be used to create dynamic Thermodynamic systems. Includes:
  - Iterative Solving capability
  - Generic Thermodynamic Component models
    - Turbomachinery components (compressor, turbine, burner, nozzle, etc.)
  - Control system modeling (controller, actuator, sensor, etc.)
- MATLAB/Simulink Based
- Open Source (free of proprietary and export restrictions)
- Development of T-MATS is being led by NASA Glenn Research Center
  - NASA's focus for this project is on the modeling of aerospace applications, however the T-MATS framework is extremely general and can be applied to any thermodynamic model.

Reducing Conservatism in Aircraft Engine Response Using Conditionally Active Min-Max Limit Regulators

- Typical aircraft engine control is based on a Min-Max scheme
- Designed to keep the engine operating within prescribed mechanical and operational safety limits
  - Compares fuel flow to determine the limit that is closest to being violated
  - Conservative
- Improve engine performance by allowing the limit regulators to only be active when a limit is in danger of being violated.

Dynamic Systems Analysis

Jeffrey Csank

NASA Glenn Research Center

4th Propulsion Control and Diagnostics Workshop
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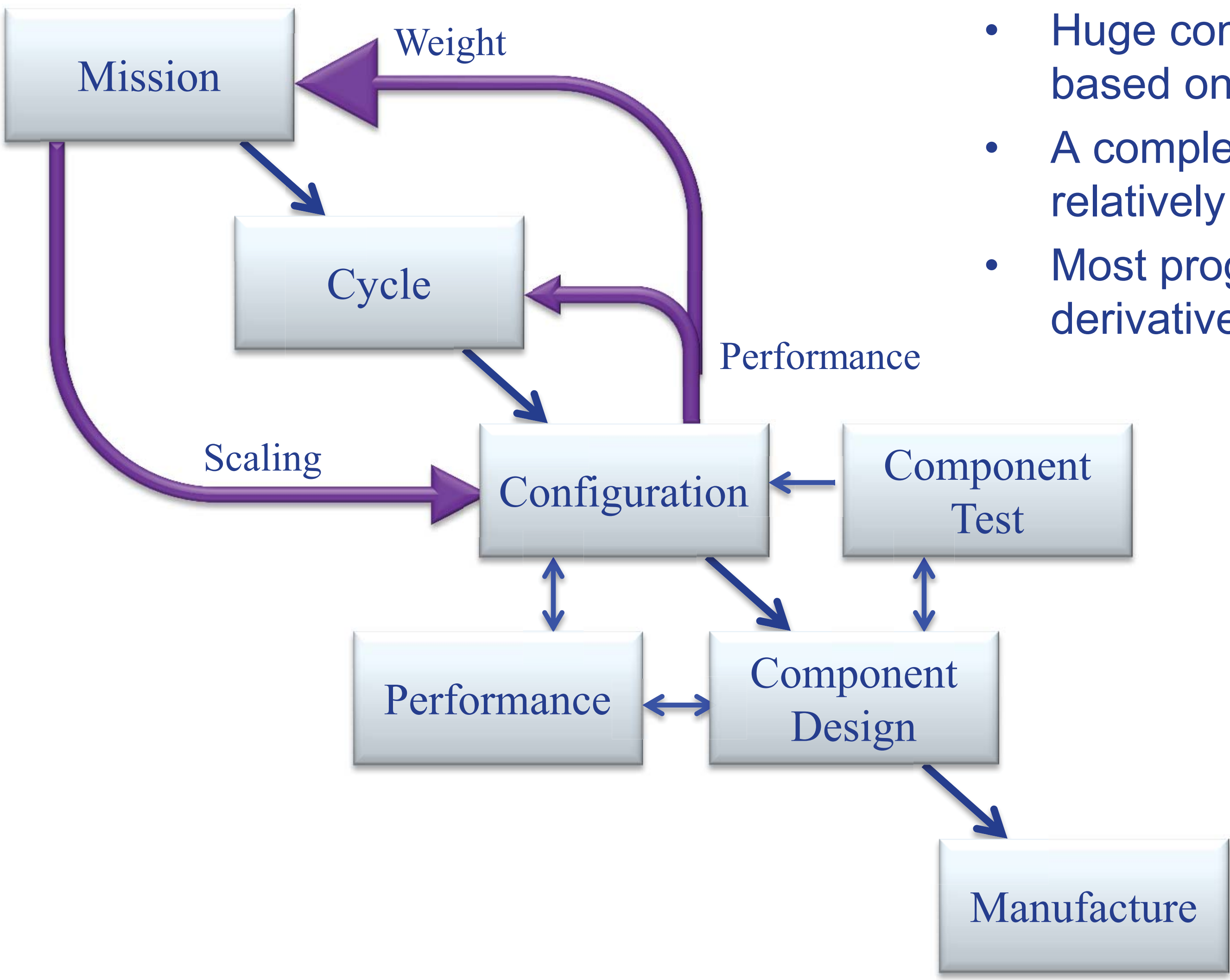
Team Members

- Jonathan Seidel, NASA Glenn Research Center/RTM
- Jeffrey Chin, NASA Glenn Research Center/RTM
- Alicia Zinnecker, N&R Engineering
- Georgia Institute of Technology

Outline

- Preliminary Engine Design
- Systems Analysis
- Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)
- Dynamic Systems Analysis
- Conclusion

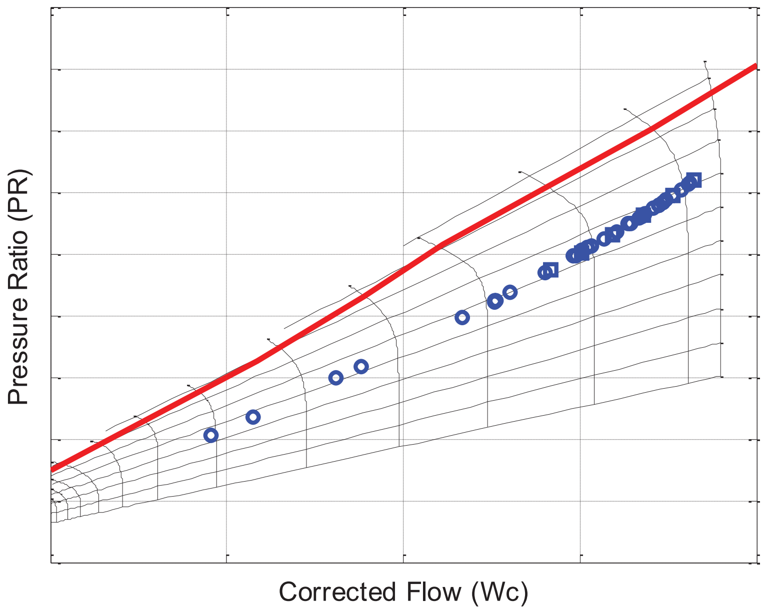
Preliminary Engine Design



- Huge commitments are made based on results
- A completely new engine is relatively rare
- Most programs focus on derivative engines

Systems Analysis

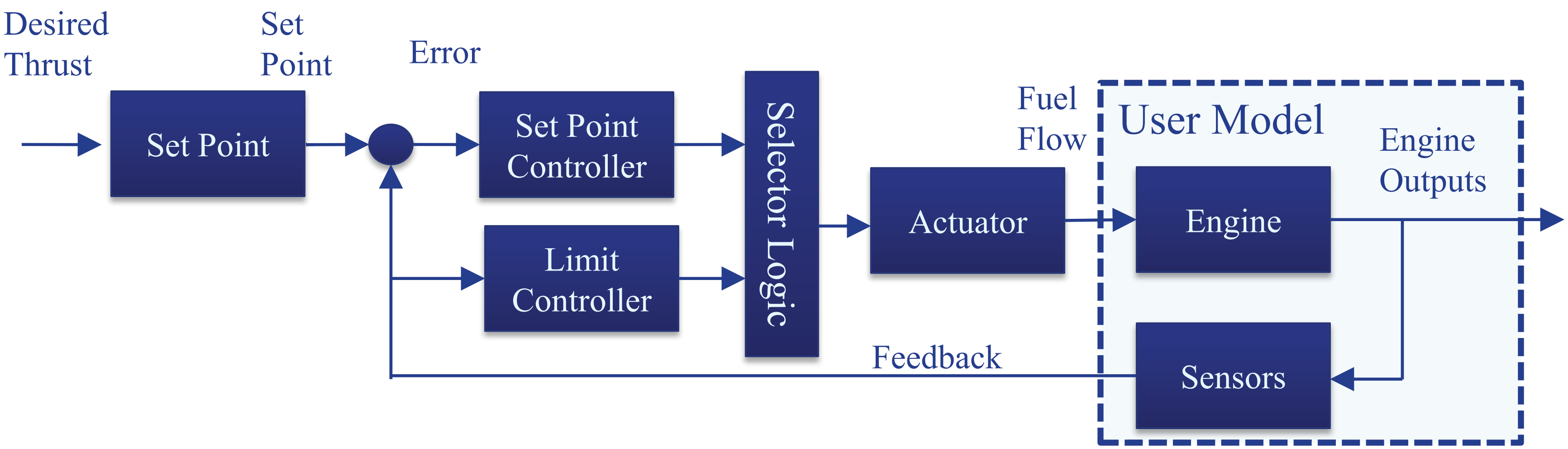
- Complex process that involves system-level simulations to evaluate system-level performance, weight, and cost (optimize system, compromise component)
- Focus on steady-state design cycle performance
- Dynamic considerations and issues are incorporated through the use of operating margins
  - Stall margin



Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)

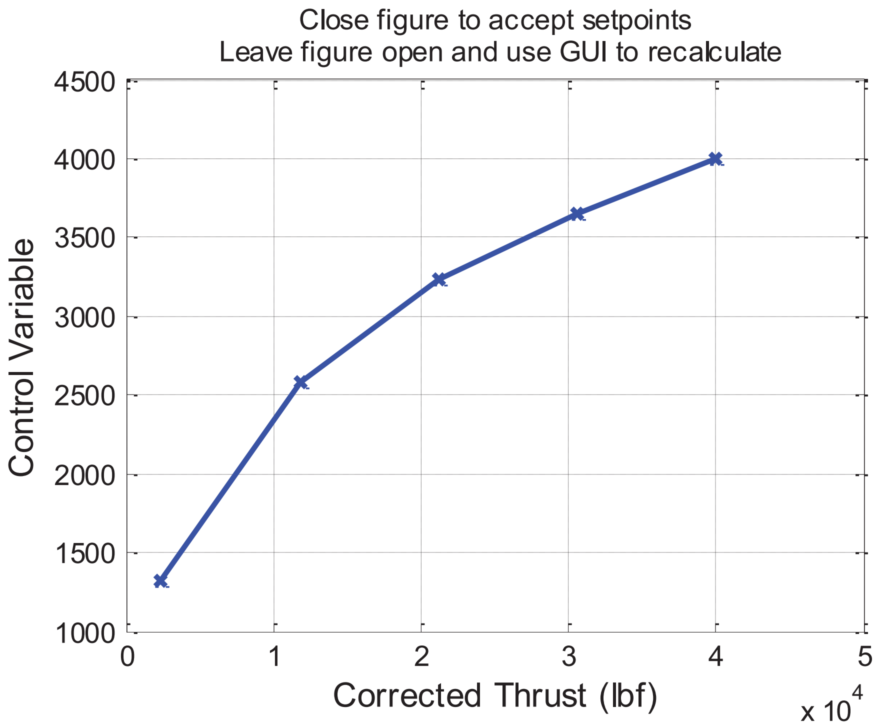
- Capable of automatically designing a controller
- Easily integrates with users engine model in MATLAB/Simulink environment
- Provide an estimate of the closed-loop transient performance/capability of a conceptual engine design
- Requirements:
  - MATLAB®/Simulink® (Release R2012b or later)
    - MATLAB® Version 8.0 (R2012b)
    - Simulink® Version 8.0 (R2012b)
    - Control Systems Toolbox® Version 9.4 (R2012b)
  - Engine Model compatible with Simulink
  - State space linear model in MATLAB

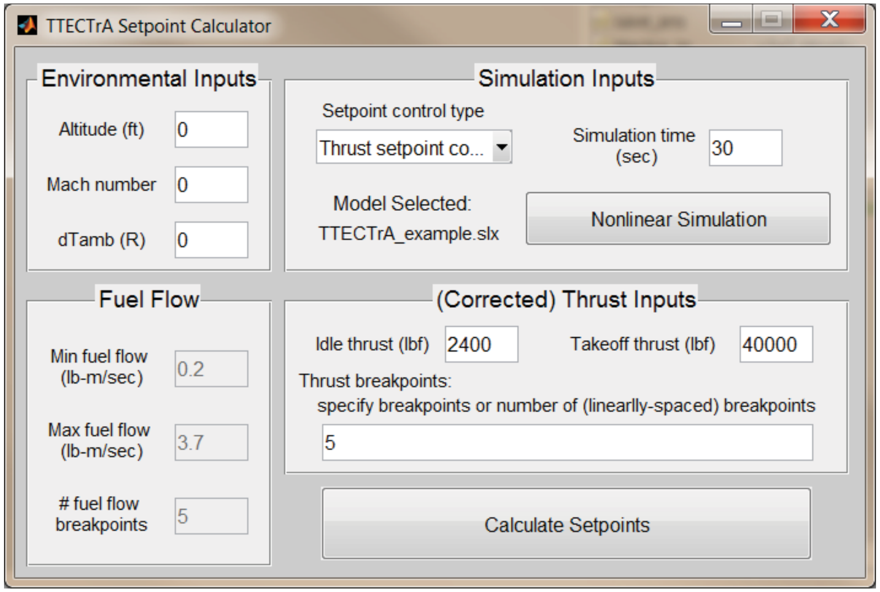
TTECTrA Architecture



- TTECTrA software automatically designs:
  - Set Point
  - Set Point Controller
  - Limit Controller
- Simulates different thrust profiles

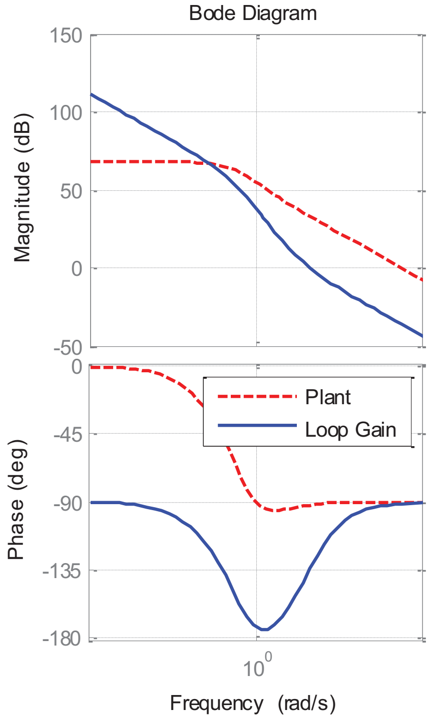
TTECTrA - Set Point Function

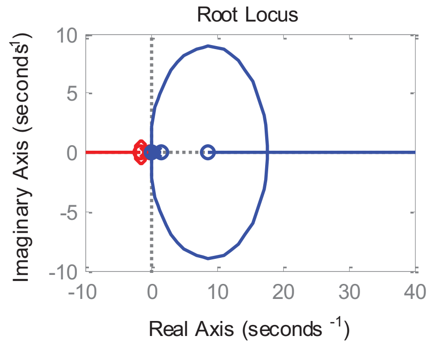


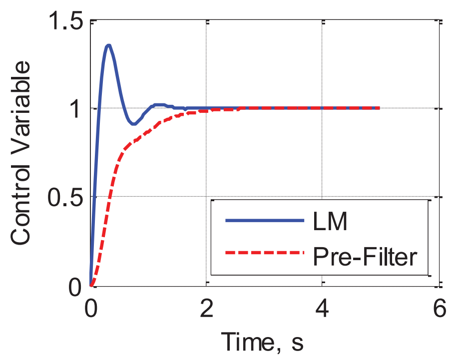


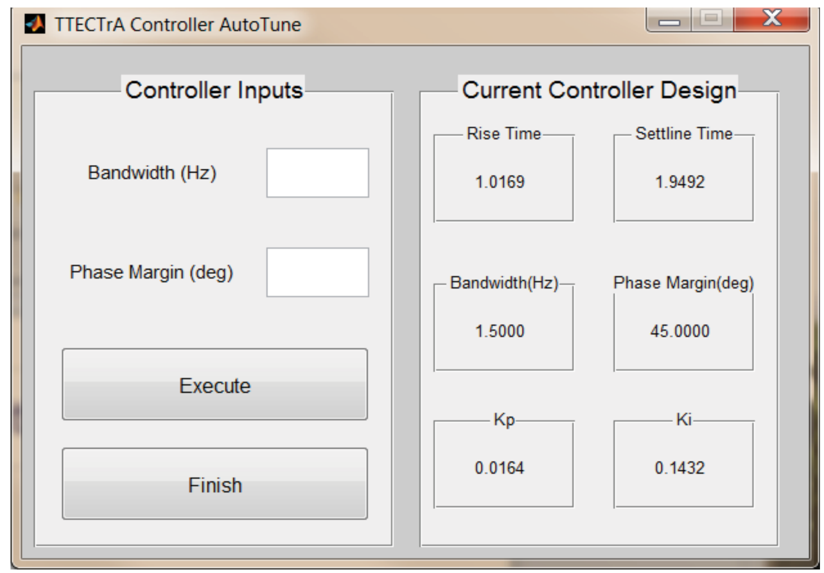
- Flight condition (altitude, Mach, temperature)
- Define set point bounds and number of breakpoints
  - Fuel flow
  - Thrust

TTECTrA – Set Point Controller



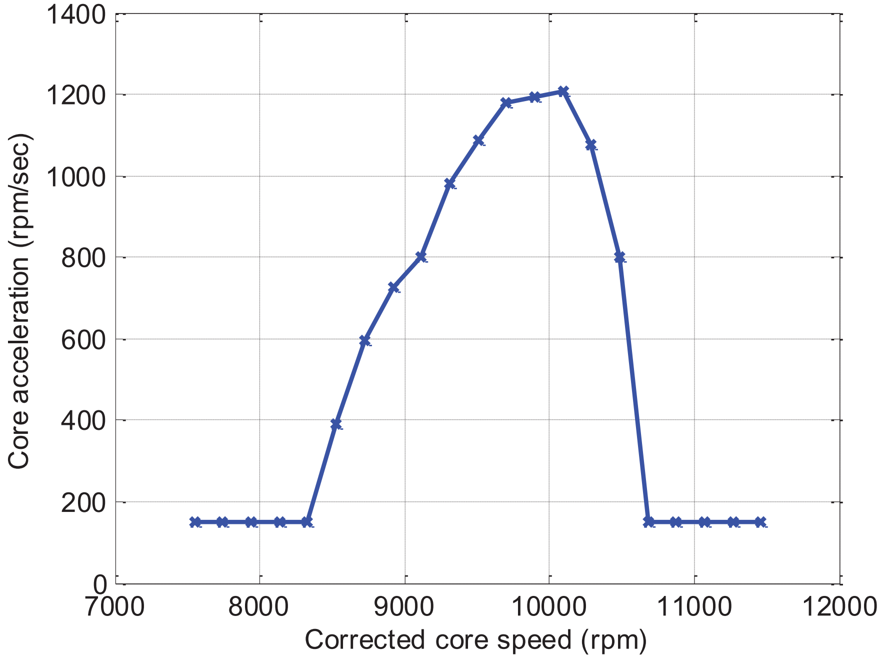


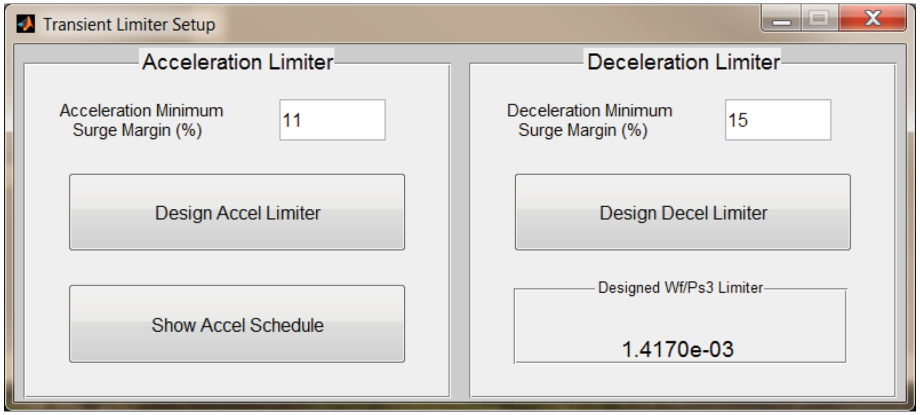




- Bandwidth (Hz)
- Phase Margin
- *Feedback filter (Hz)*
- *Throttle Filter (Hz)*

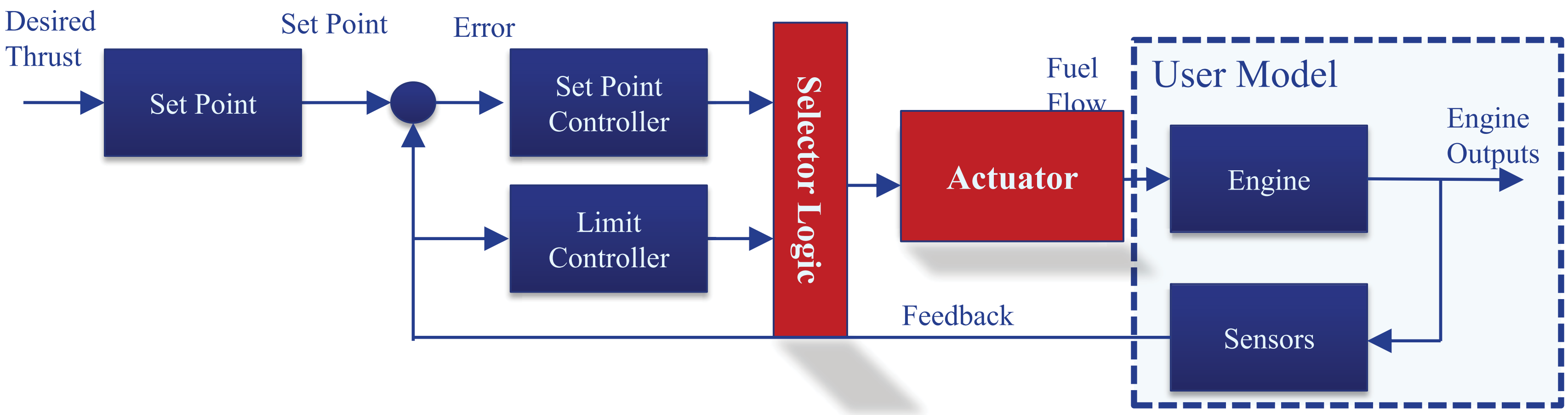
TTECTrA – Limit Controller





- Acceleration Minimum Surge Margin (HPC)
  - Ncdot vs NcR25
- Deceleration Minimum Surge Margin (LPC)
  - Wf/Ps3

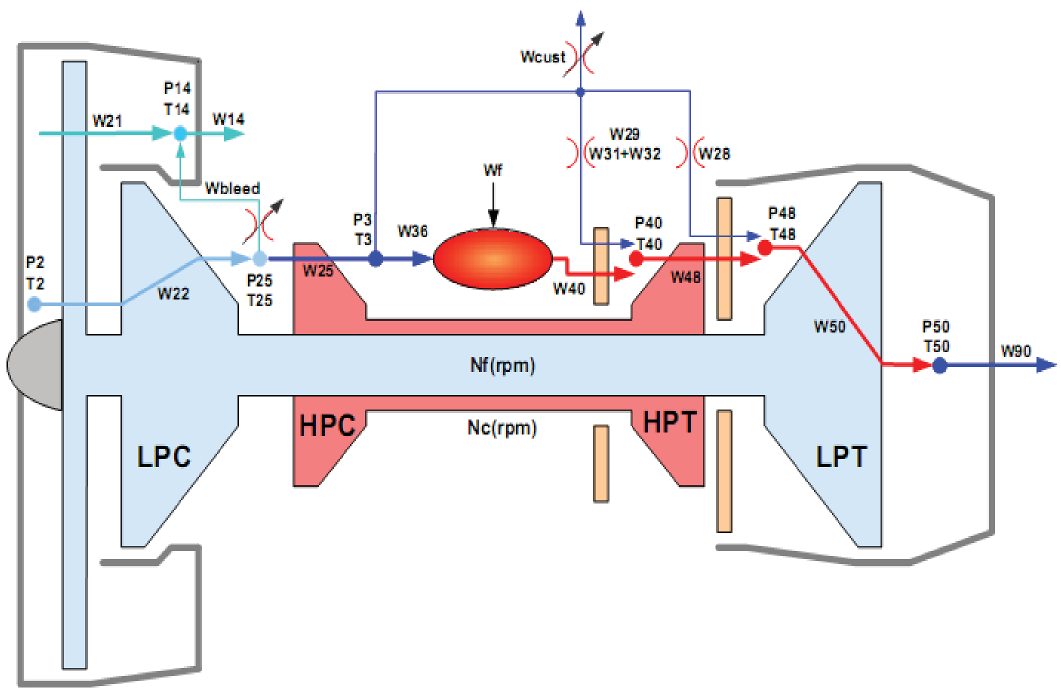
TTECTrA - Selector Logic / Actuator



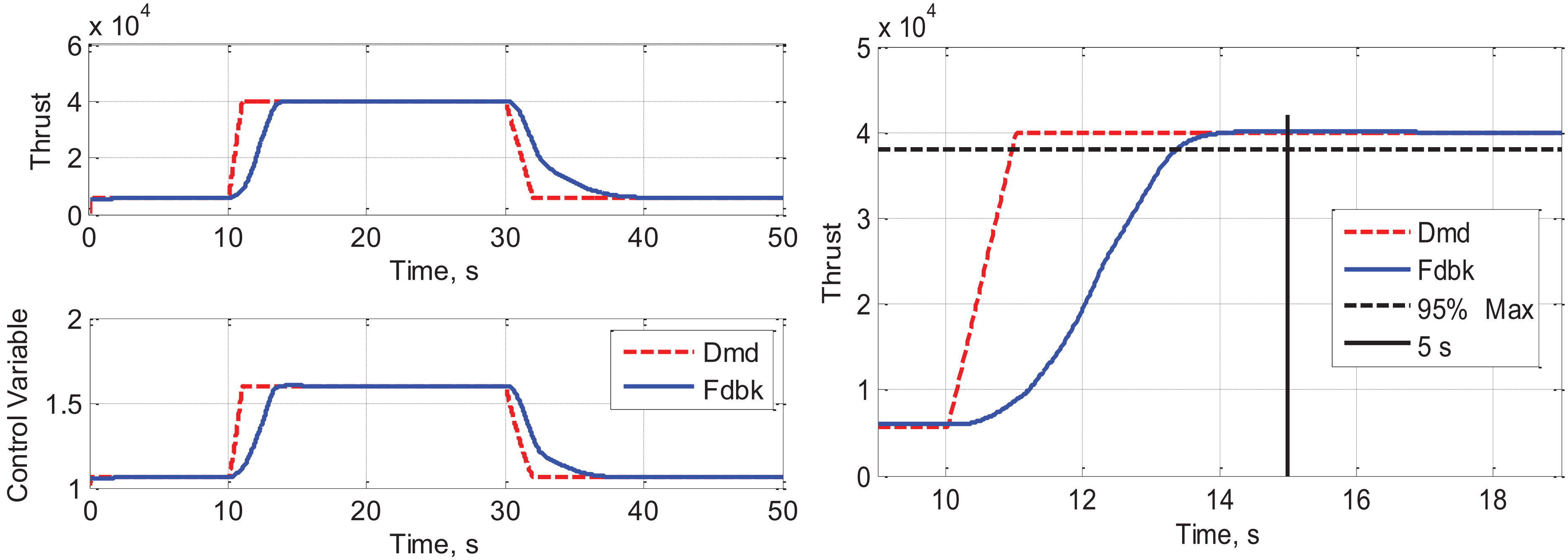
- Selector Logic (Min/Max scheme)
  - Min (Set Point, Acceleration)
  - Max (Min, Deceleration)
- Actuators
  - Currently only models fuel flow
  - First order filter

Commercial Modular Aero Propulsion System Simulator 40,000 (C-MAPSS40k)

- 40,000 Lb Thrust Class High Bypass Turbofan Engine Simulation
- Matlab/Simulink Environment
- Publically available
- Realistic controller
- Realistic surge margin calculations

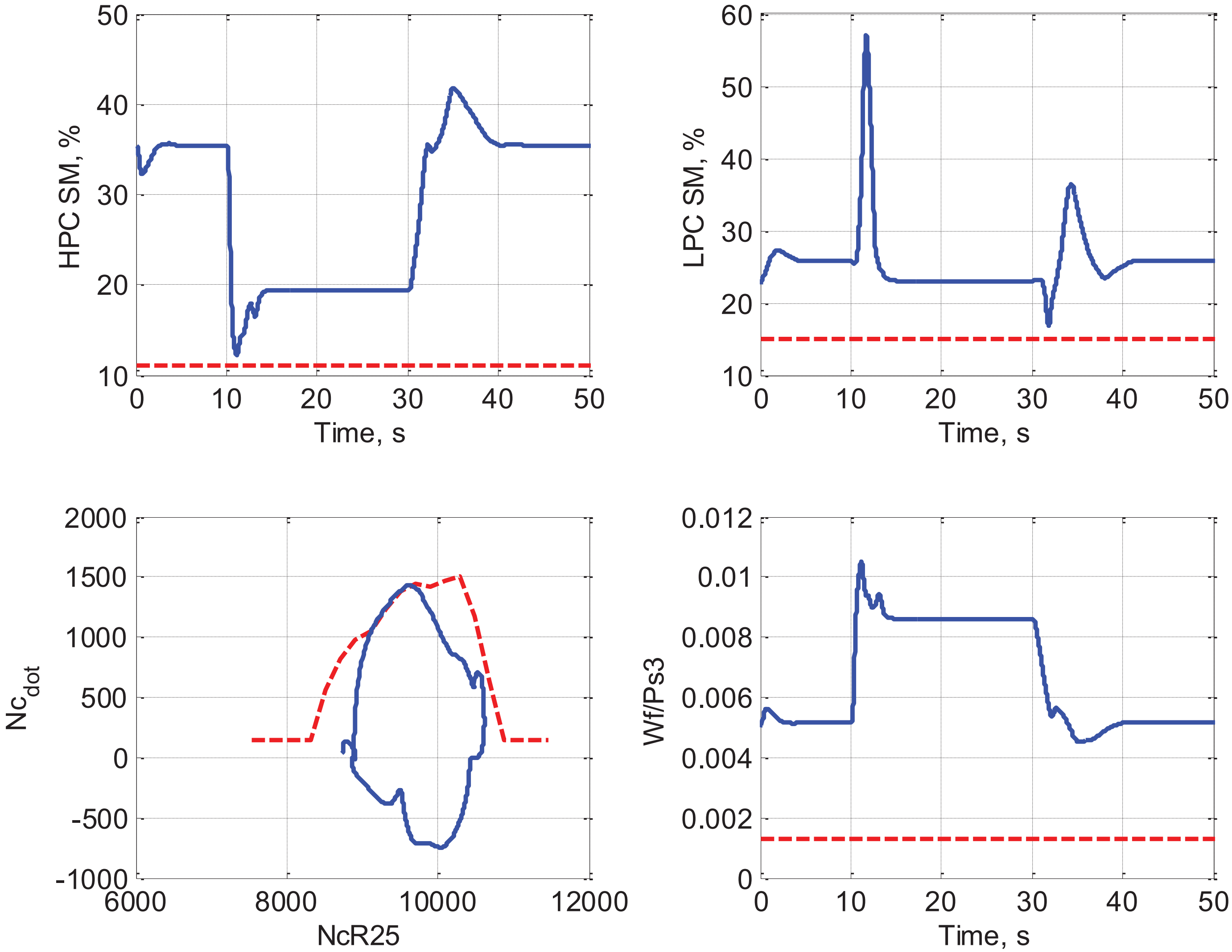


Burst and Chop Thrust Profile

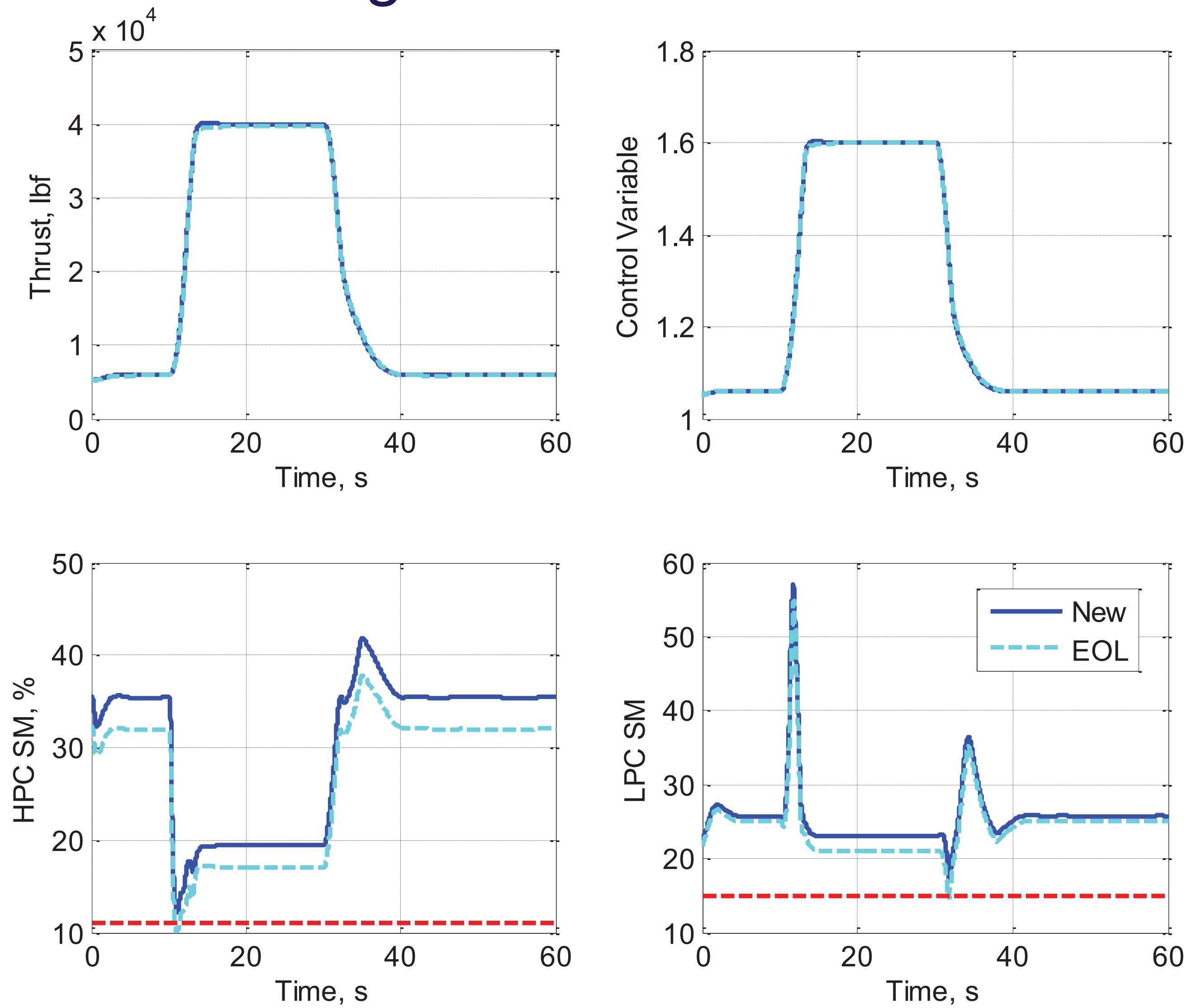


- Idle (14% of max thrust) to Take-off thrust profile to test the TTECTrA controller
- Compare the thrust response to the Federal Aviation Administrations (FAA) Federal Aviation Regulation (FAR) Part 33, Section 33.73(b)

Burst and Chop Thrust Profile



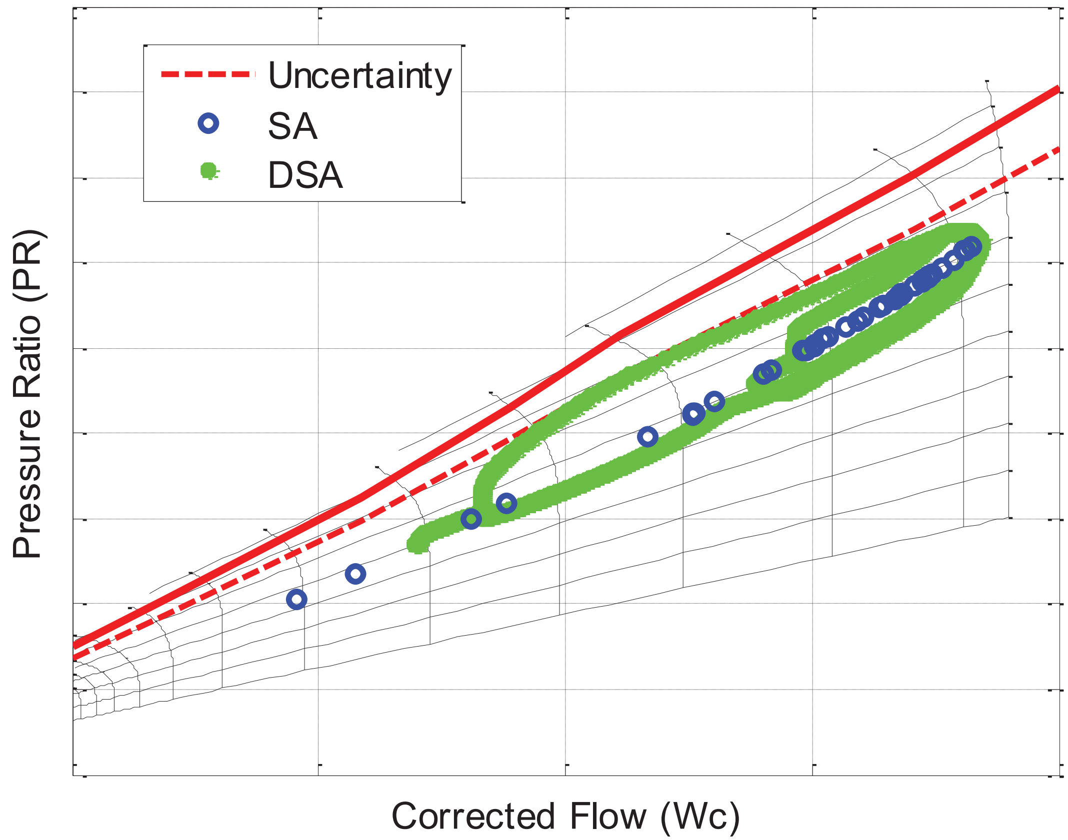
Engine Deterioration



The Benefit of TTECTrA

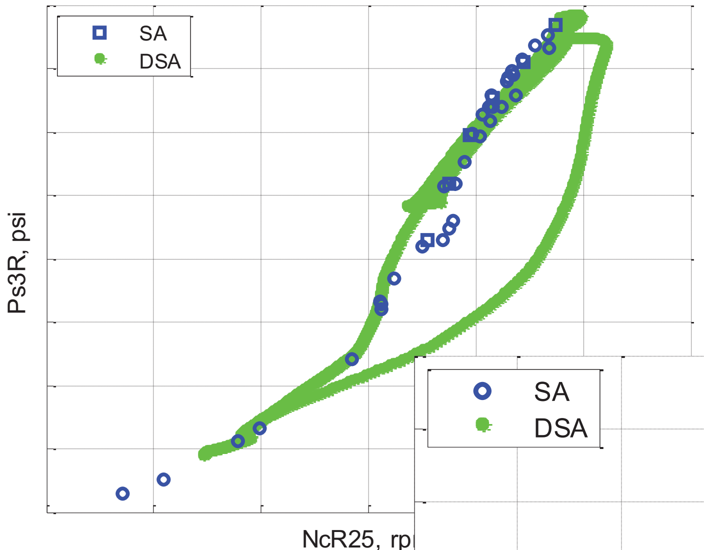
Do we have enough margin? Too much margin?

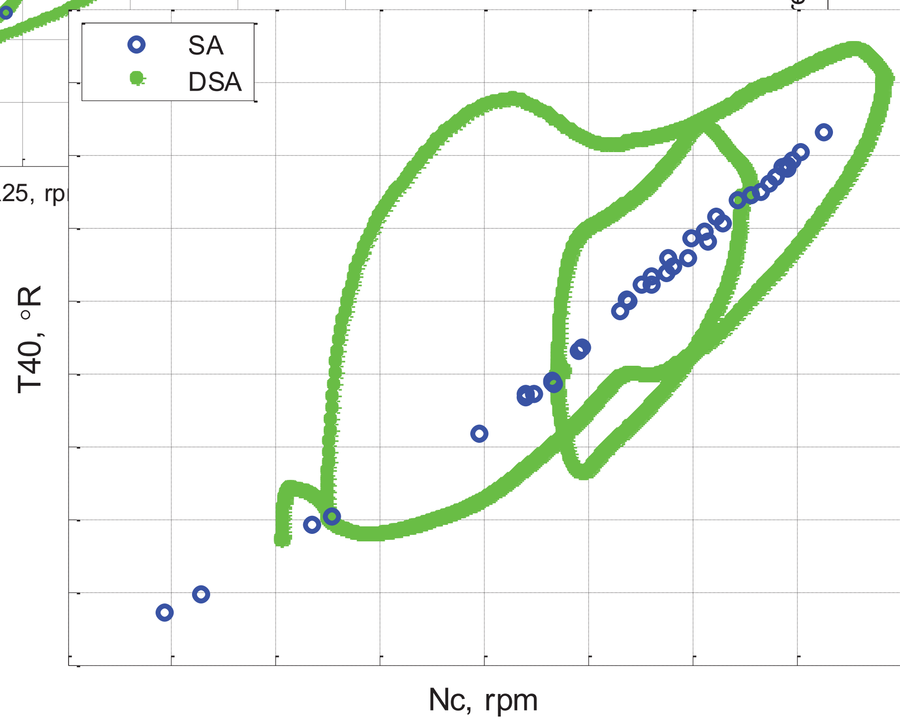
Stack	%
Uncertainty	11
Reynolds Number	*2*
Distortion	*4*
Tip Clearances	*1.5*
Deterioration	*1.5*
Random	*2*
Transient Allowance	12
Total	**23**

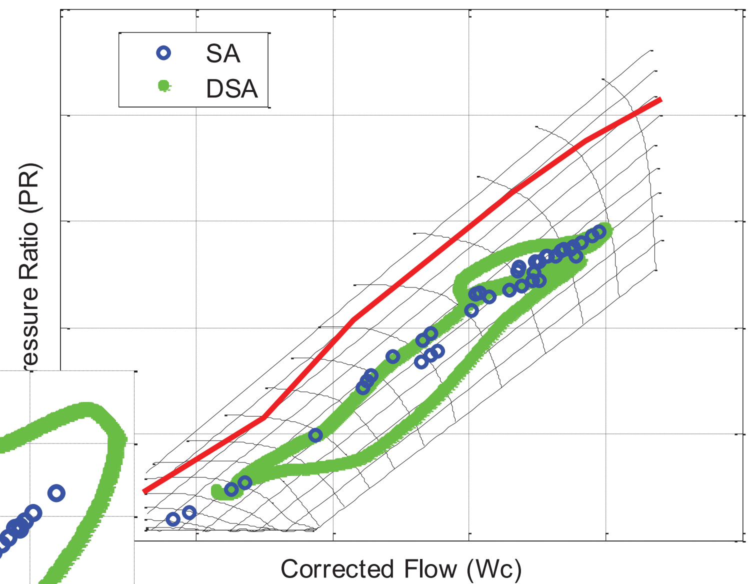


The Benefit of TTECTrA

- Combustor Stability







- Low Pressure Compressor

- Turbine life

Future Work

- NPSS Model in Simulink
  - Georgia Institute of Technology
- Integrate TTECTrA with the NPSS Simulink model
  - NASA/RHC
- Integrate TTECTrA/NPSS Simulink with a larger systems analysis optimization algorithm
  - NASA/RHC and NASA/RTM

Conclusion

- Dynamic systems analysis:
  - Enables engine transient performance to be accounted for in the optimization of the engine design and early in the preliminary design of turbine engines.
  - Allows trading of overly conservative surge margin for better performance through system redesign (or opline).

- Developed the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)
  - Capable of automatically designing a controller at a single flight condition.
  - Easily integrates with users engine model in MATLAB/Simulink environment.
  - Open source

Thank you

Questions?

Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)

Jeffryes W. Chapman
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4th Propulsion Control and Diagnostics Workshop
Ohio Aerospace Institute (OAI)
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Outline

- T-MATS Description
- Background
- Framework
- Block Sets
- Examples
- Conclusion
- Future work

T-MATS Description

- Toolbox for the Modeling and Analysis of Thermodynamic systems, T-MATS
  - Modular thermodynamic modeling framework
  - Designed for easy creation of custom Component Level Models (CLM)
  - Built in MATLAB®/Simulink®
- Package highlights
  - General thermodynamic simulation design framework
  - Variable input system solvers
  - Advanced turbo-machinery block sets
  - Control system block sets
- Development being led by NASA Glenn Research Center
  - Non-proprietary, free of export restrictions, and open source
    - Open collaboration environment

Background

- Thermodynamic simulation examples

Model Type	**Examples**
Steady-State (system convergence may be required)	Gas turbine cycle model • e.g., performance models
Dynamic with Quasi-steady-state variables (multi-iteration simulation; time and system convergence)	Gas turbine model with spool dynamics only. (real time running capability) • e.g., control models
Fully Defined Dynamic Simulation (iteration over time)	Dynamic gas turbine model with spool and volume dynamics (typically runs more slowly) • e.g., near stall performance models

Background: Industry Study

Package	User Friendly*	Flexibility*	Export Restricted	Source code available	Dynamic	Control System	Cost
C-MAPSS40k, NASA	High	Low	Yes	Yes	Yes	Yes	MATLAB
Matlab: Thermlib toolbox, Eutech	High	Medium	No	No	Yes	No	MATLAB + $4900
Cantera, Open source	Low	High	No	Yes	No	No	None
Gas Turbine Simulation Program (GSP), NRL	Medium	Medium	No	No	Yes	Yes	$4,000
GasTurb, Nrec	Medium	Low	No	No	Yes	Yes	$1340
T-MATS, NASA	High	High	No	Yes	Yes	Yes	MATLAB

Definitions:

1* User Friendly, Controls Perspective

Low : Code based

Med: Model based

High: Model based with package implemented in a platform that is an industry standard

2* Flexibility

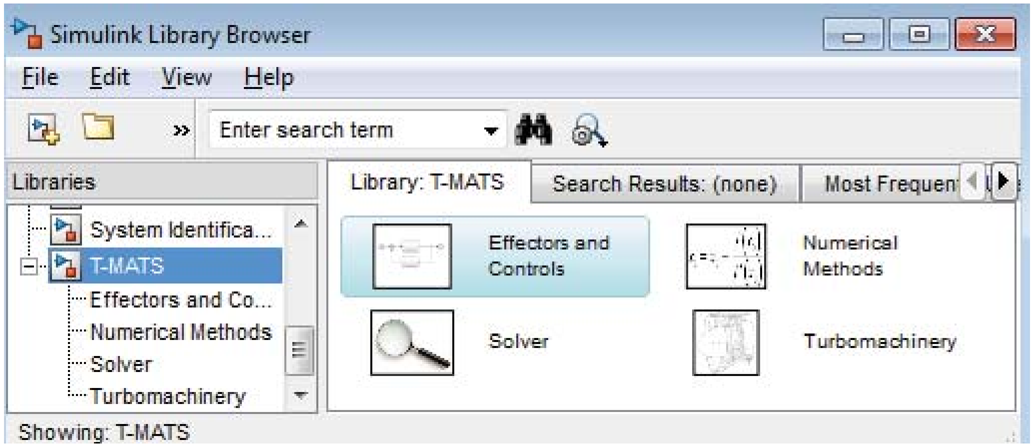
Low : Plant configuration set

Med: Object oriented, objects difficult to update

High: Object oriented, objects easily adaptable by user

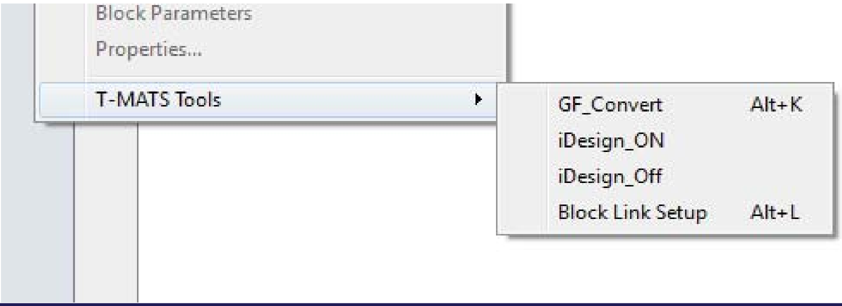
T-MATS Framework

- T-MATS is a plug-in for a MATLAB/Simulink platform
  - additional blocks in the Simulink Library Browser:



Added Simulink Thermodynamic modeling and numerical solving functionality

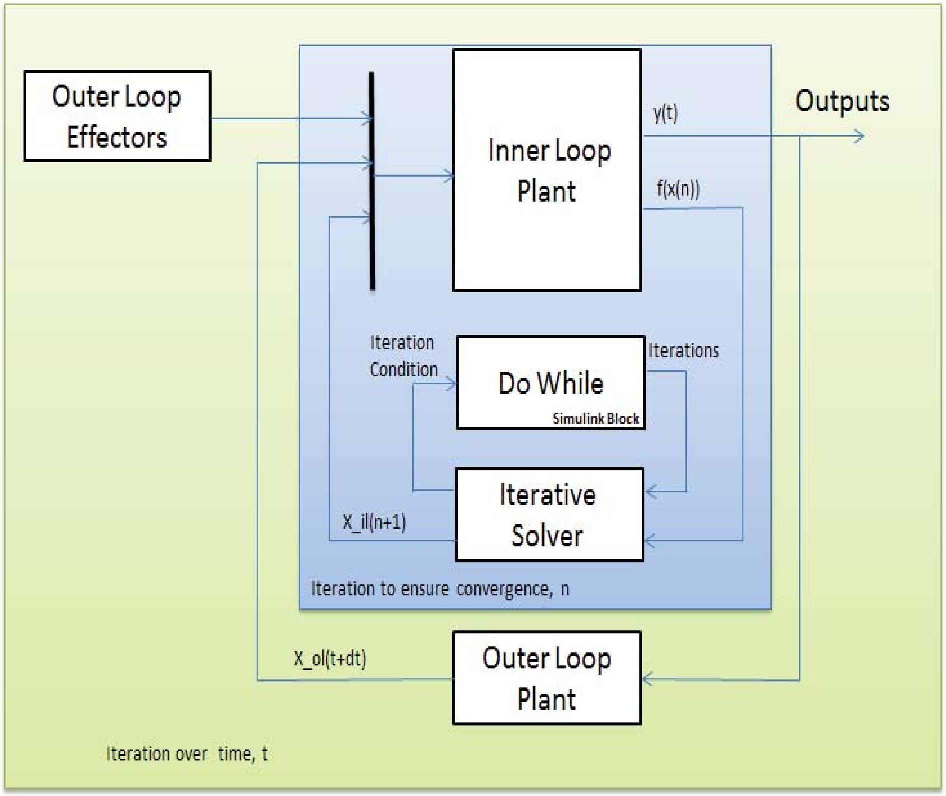
  - additional diagram tools for model development in Simulink:



Faster and easier model creation

T-MATS Framework

- Dynamic Simulation Example:
  - Multi-loop structure
    - The “outer” loop (green) iterates in the time domain
      - Not required for steady-state models
    - The “inner” loop (blue) solves for plant convergence during each time step



Blocks: Numerical Solver

- Many Thermodynamic models are partially defined and require a solver to ensure model conservation (e.g., mass, energy, etc.).
  - In many gas turbine simulations, component flow will typically be solved by an independent solver.

- T-MATS contains solvers that perform in two main steps:
  - Automated Jacobian (system gradient) Calculation

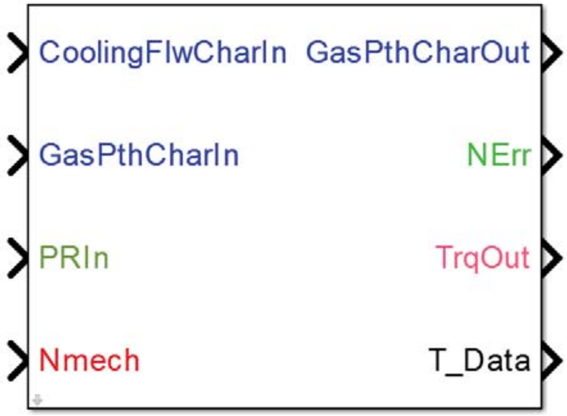
$$J = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_m}{\partial x_1} & \cdots & \frac{\partial f_m}{\partial x_n} \end{bmatrix}$$

    - Each plant input is perturbed to find the effect on each plant output.
  - Newton-Raphson method is used to “converge” the system.

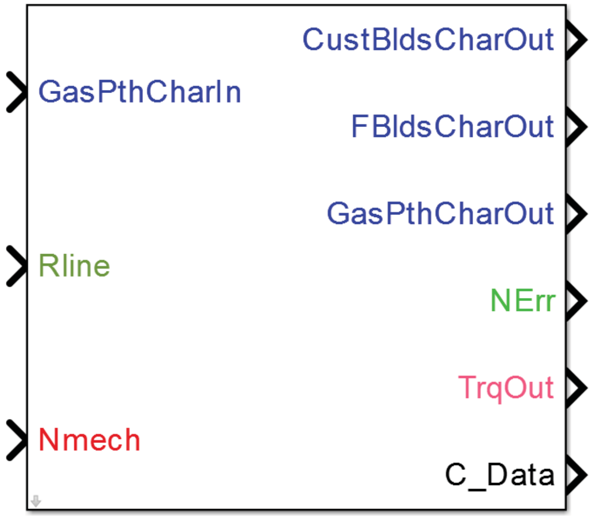
$$x(n+1) = x(n) - \frac{f(x(n))}{f'(x(n))} \qquad \text{where,} \qquad f'x(n) = J$$

Blocks: Turbo-machinery

- T-MATS contains component blocks necessary for creation of turbo-machinery systems
  - Models based on common industry practices
    - Energy balance modeling approach
    - R-line compressor maps in Compressor model
    - Pressure Ratio maps in Turbine model
    - Single fuel assumption
    - Flow errors generated by comparing component calculated flow with component input flow
  - Includes blocks such as; compressor, turbine, nozzle, flow splitter, and valves among others.
  - Built with S-functions, utilizing compiled MEX functions



Turbine



Compressor

Blocks: Controls

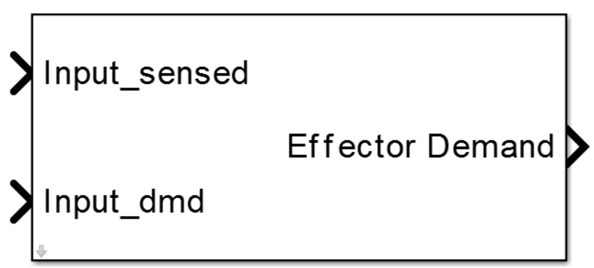
- T-MATS contains component blocks designed for fast control systems creation
  - Sensors:

1st order Sensor

  - Actuators:

1st order Actuator

  - PI controllers:

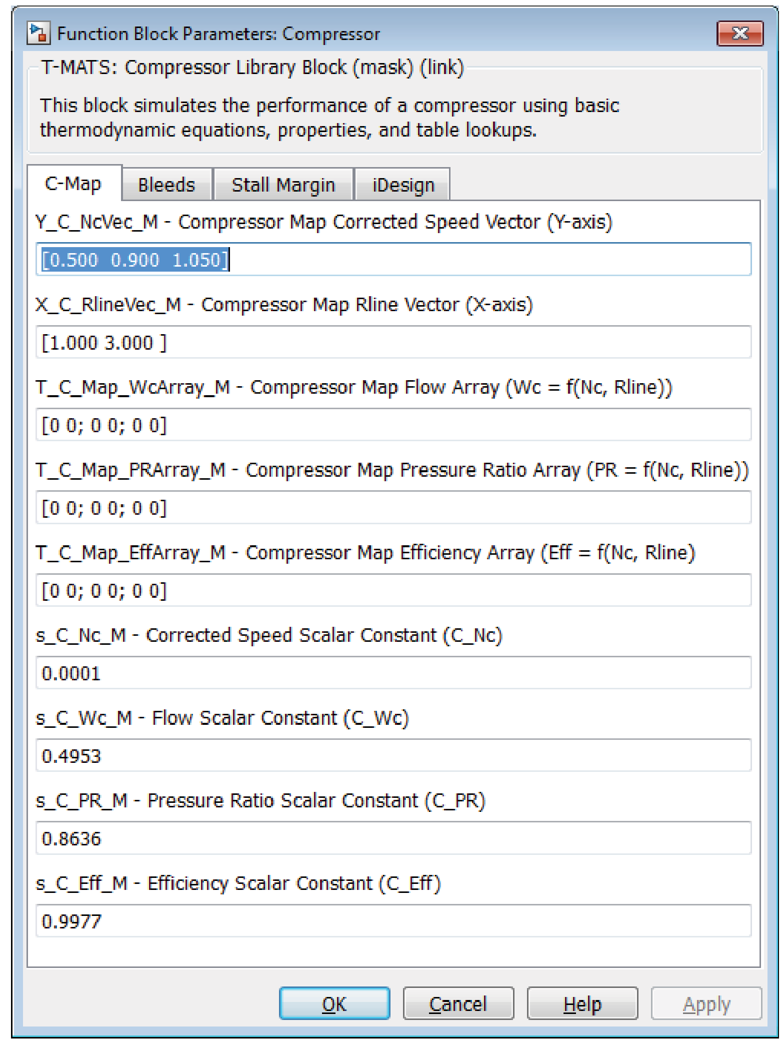


Simple PI controller

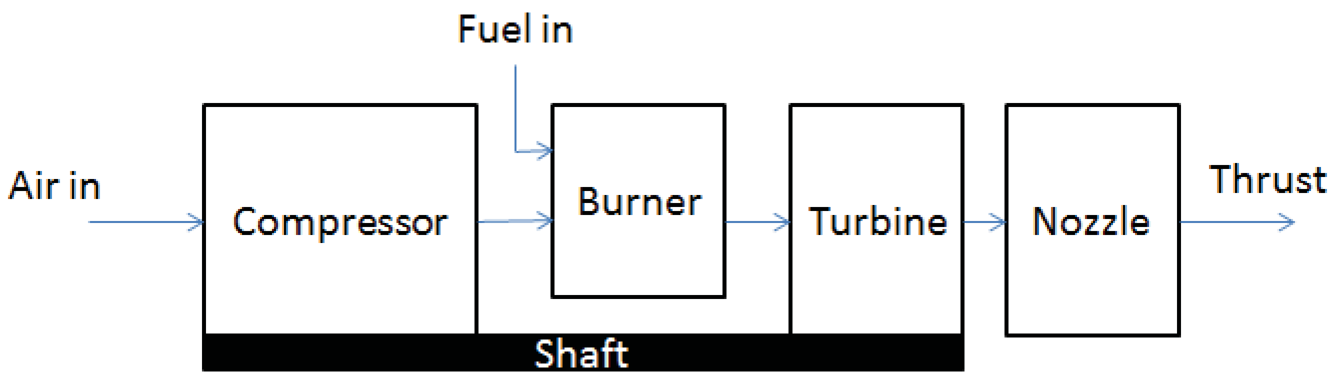
Blocks: Settings

- The T-MATS Simulation System is a highly tunable and flexible framework for Thermodynamic modeling.

  - T-MATS block Function Block Parameters
    - fast table and variable updates
  - Open source code
    - flexibility in component composition, as equations can be updated to meet system design
  - MATLAB/Simulink development environment
    - user-friendly, powerful, and versatile operation platform for model design

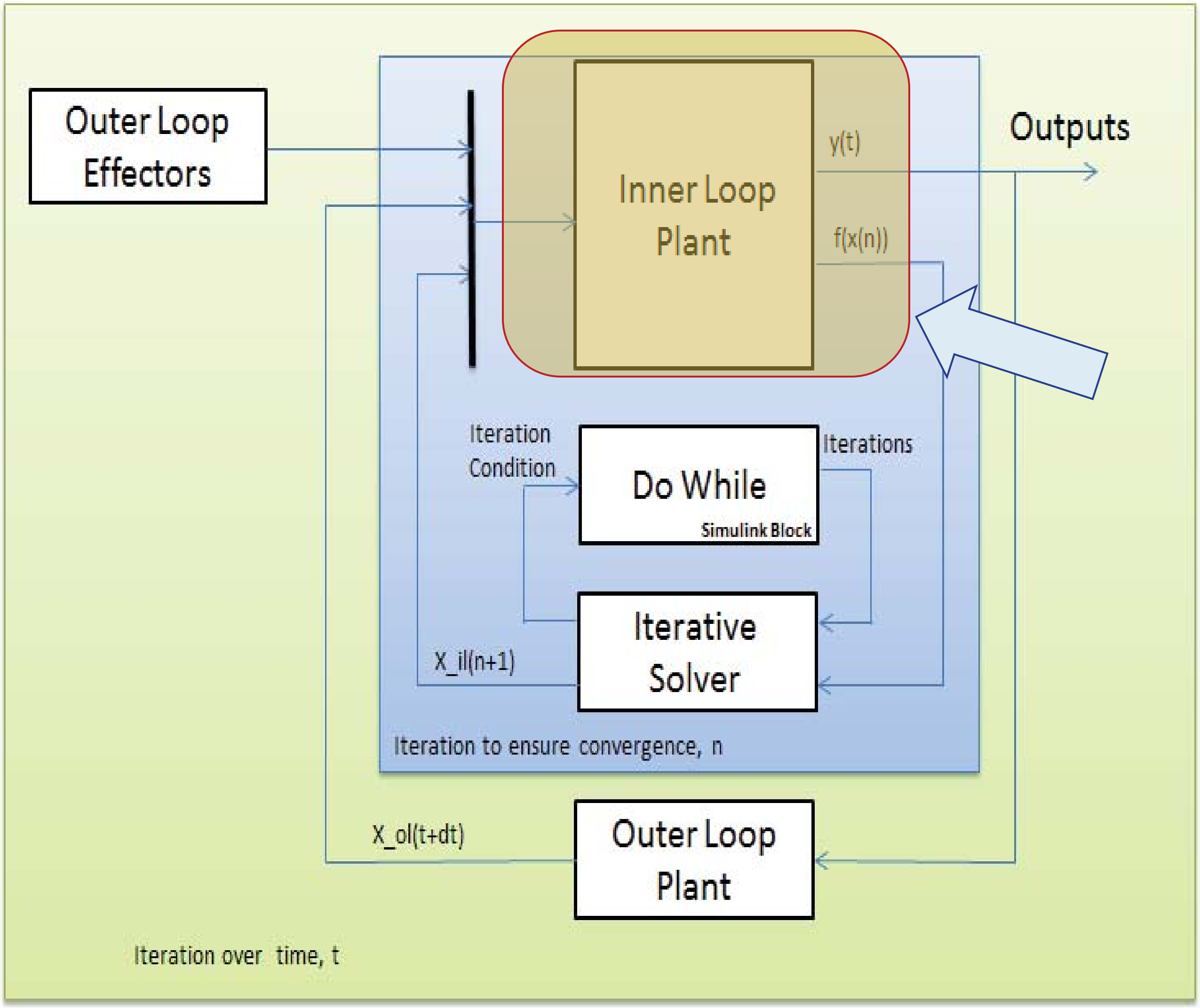


Dynamic Gas Turbine Example: Objective System

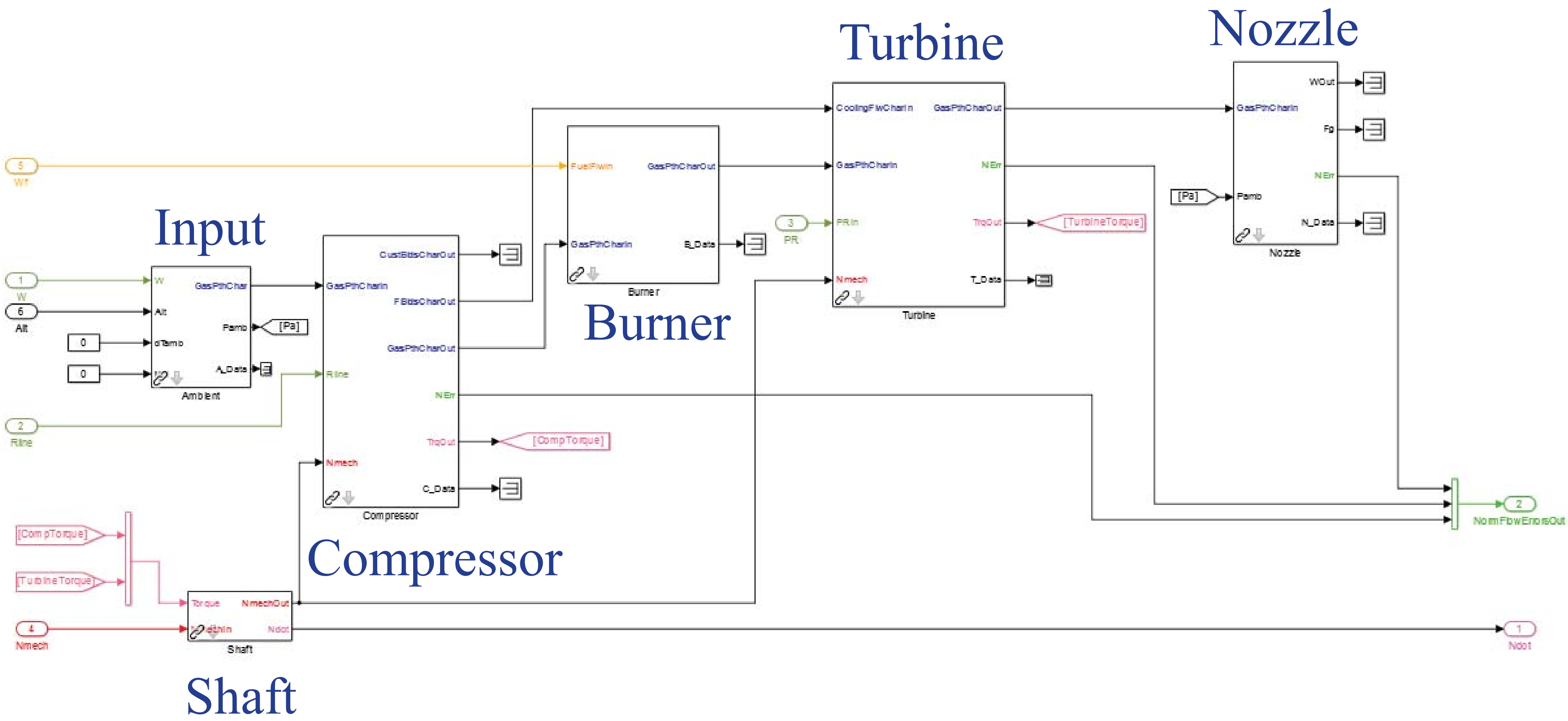


Simple Turbojet

Dynamic Gas Turbine Example: Creating the Inner Loop

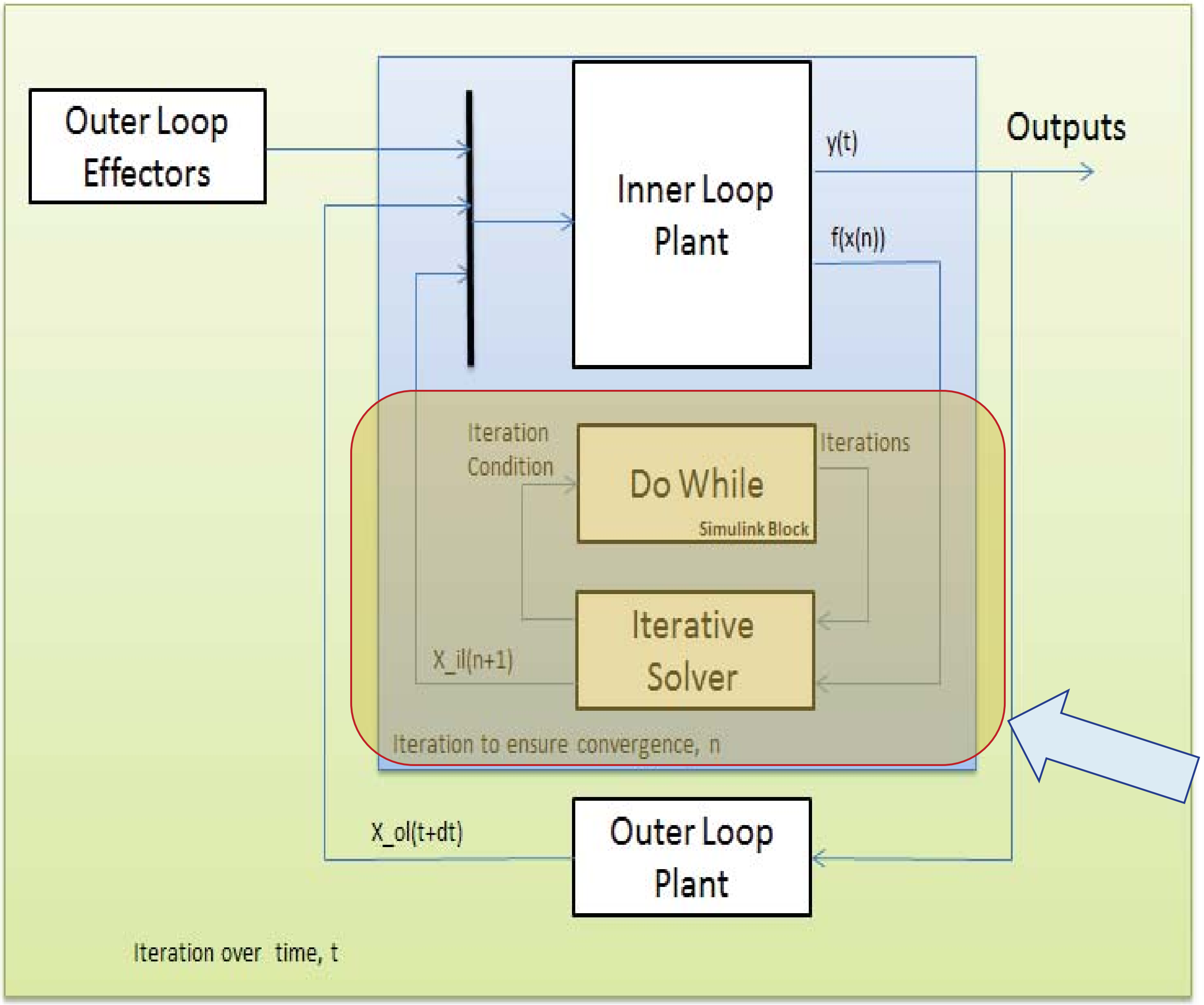


Dynamic Gas Turbine Example: Inner Loop Plant

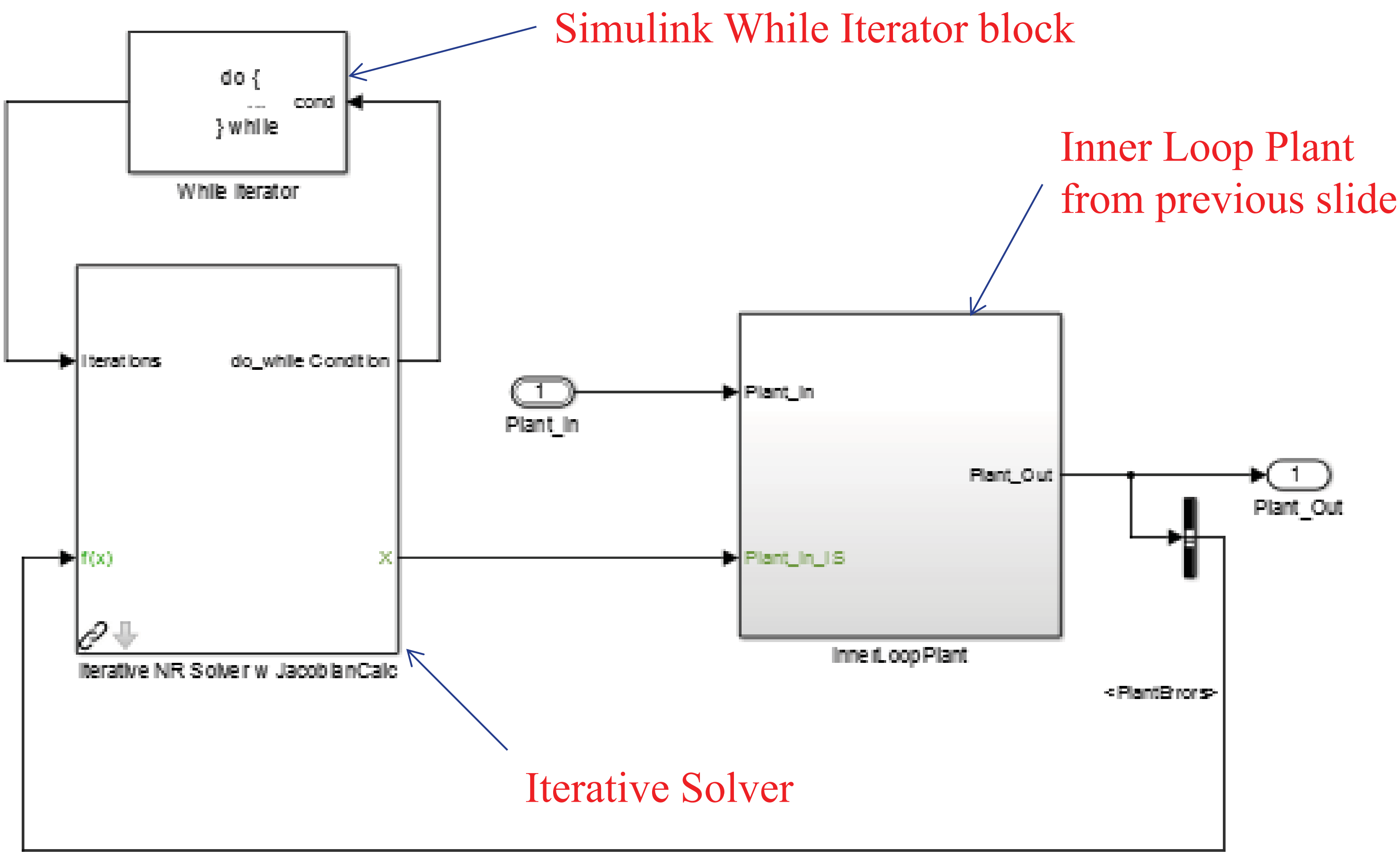


Turbojet plant model architecture made simple by T-MATS vectored I/O and block labeling

Dynamic Gas Turbine Example: Creating the Solver

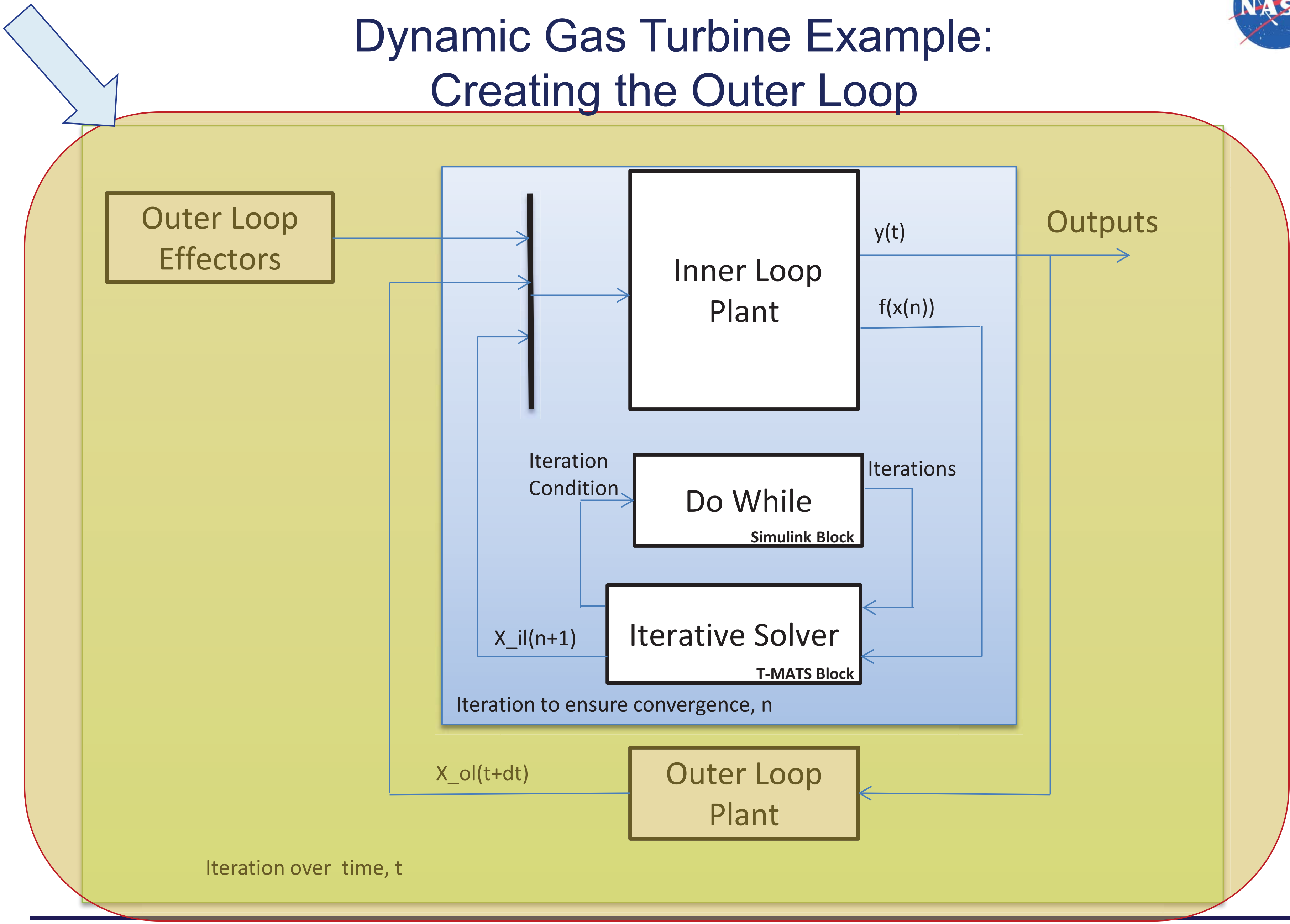


Dynamic Gas Turbine Example: Solver

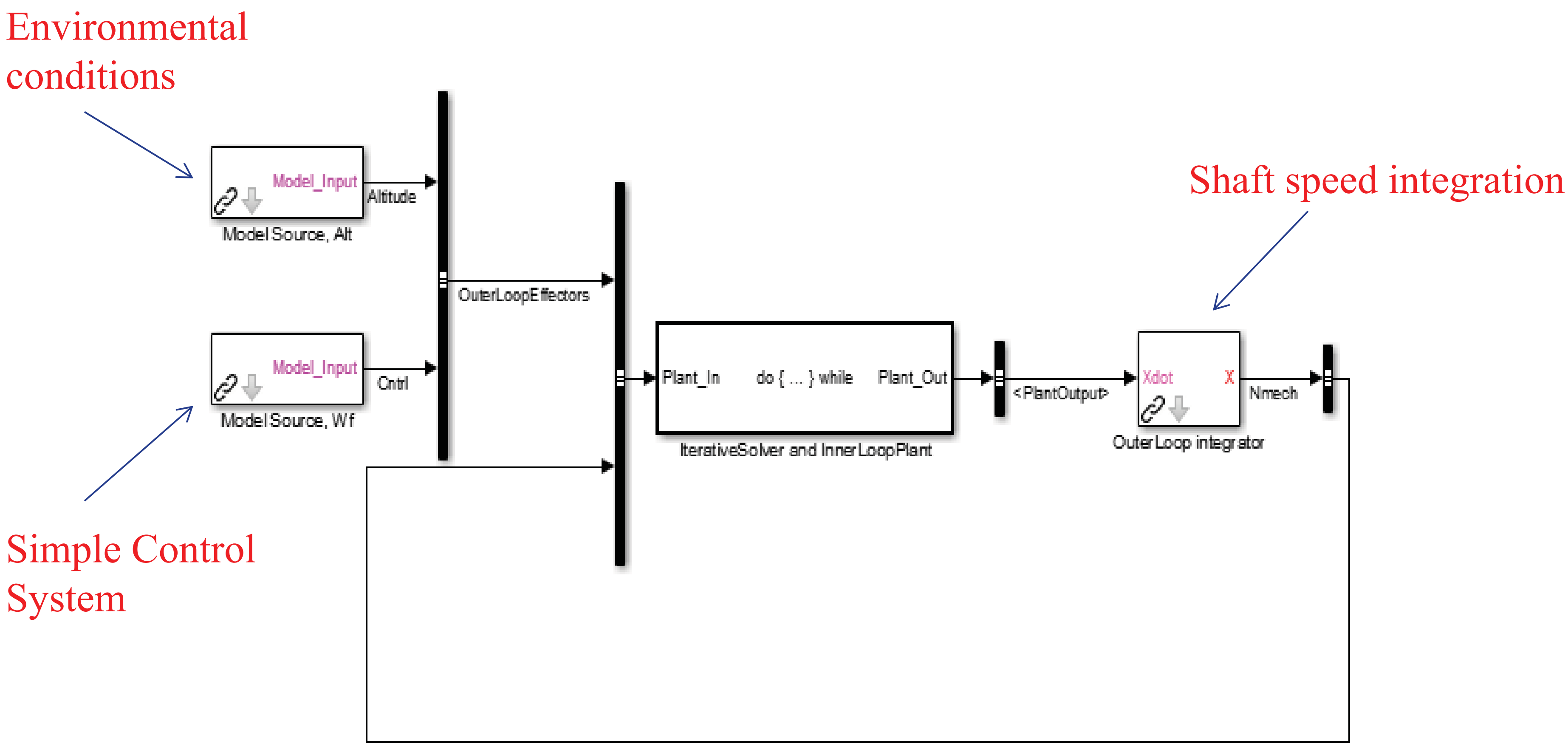


Plant flow errors driven to zero by iterative solver block in parallel with While Iterator

Dynamic Gas Turbine Example: Creating the Outer Loop



Dynamic Gas Turbine Example: Outer Loop Plant



Shaft integrator and other Outer Loop effectors added to create full system simulation

Verification and Release

- Verification was performed by matching T-MATS simulation data with other established simulations.
  - Models chosen for verification
    - NPSS steady-state turbojet model
    - C-MAPSS – High bypass turbofan engine model
  - In all cases differences in simulation performance were within acceptable limits.

- Expected Release: Q4,2013 or Q1,2014.
  - Pre-built examples will include:
    - Newton-Raphson equation solver
    - Steady state turbojet simulation
    - Dynamic turbojet simulation

Conclusions

- T-MATS offers a comprehensive thermodynamic simulation system
  - Thermodynamic system modeling framework
  - Automated system “convergence”
  - Advanced turbo-machinery modeling capability
  - Fast controller creation block set

Future Work

- Increase thermodynamic modeling capability
  - Introduce Cantera to T-MATS
    - "Cantera is a suite of object-oriented software tools for problems involving chemical kinetics, thermodynamics, and/or transport processes"
    - Open source
    - Increases thermodynamic modeling capability to include:
      - **Non-fuel specific gas turbine modeling**
      - **Fuel cells**
      - **Combustion**
      - **Chemical Equilibriums**

$$O + CH \Leftrightarrow H + CO$$

National Aeronautics and Space Administration

Reducing Conservatism in Aircraft Engine Response Using Conditionally Active Min-Max Limit Regulators

Ryan D. May

Vantage Partners, LLC

Sanjay Garg

NASA Glenn Research Center

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www.nasa.gov

Overview

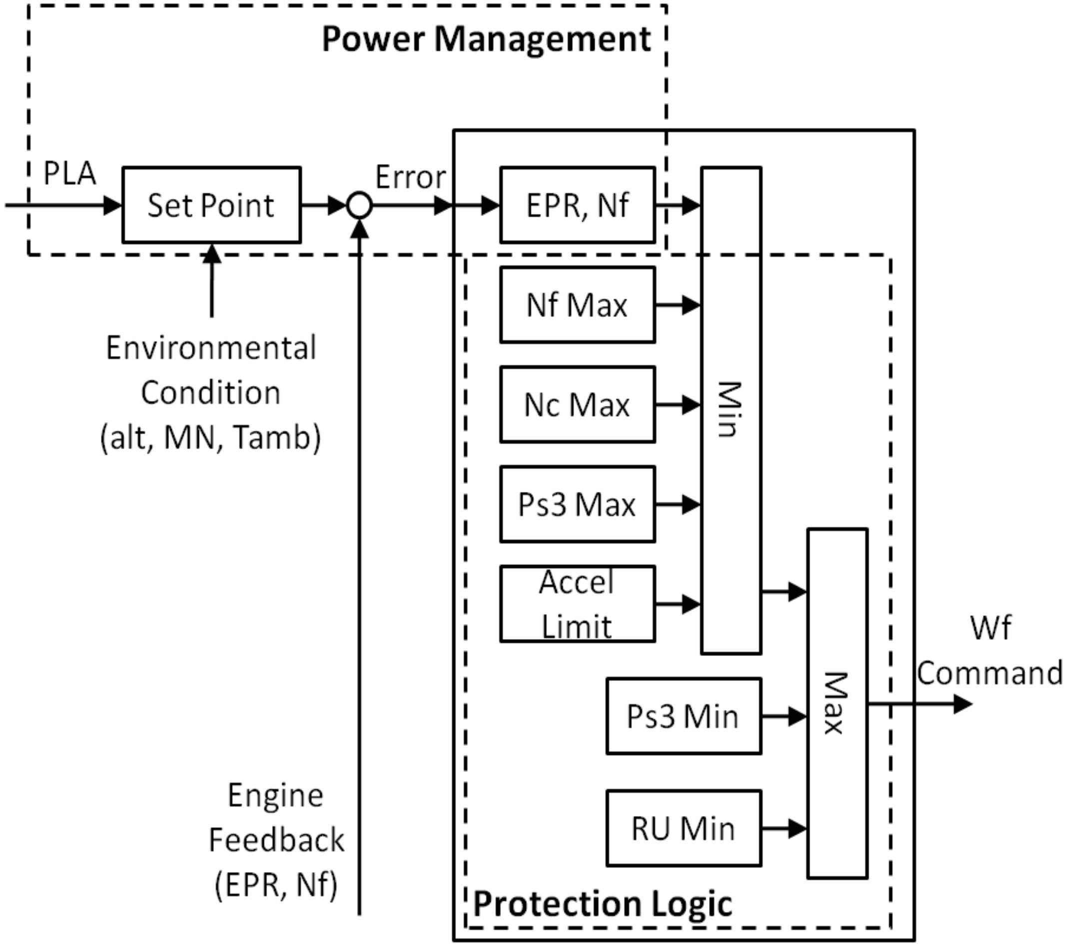
- Introduction
- Baseline Control Architecture
- Conditionally Active Limit Regulator Approach
- Simulation Examples
- Conclusions & Future Work

Introduction

- The primary task of an engine control system is to deliver the guaranteed performance while ensuring safe operation throughout operating envelope over the life of the engine
- Guaranteed performance is defined as meeting the FAA certification requirements for engine responsiveness – maximum allowed 95% rise time for idle to max thrust command

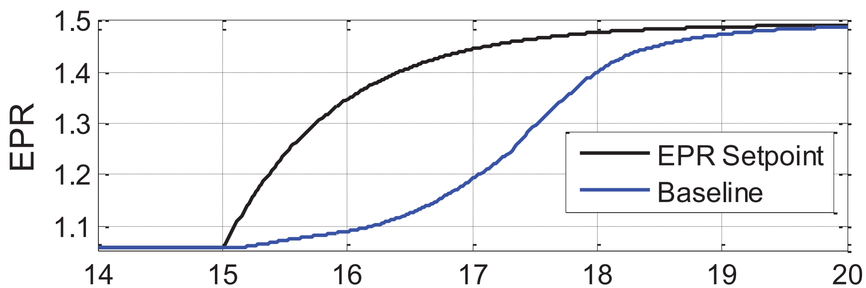
Baseline Control Architecture

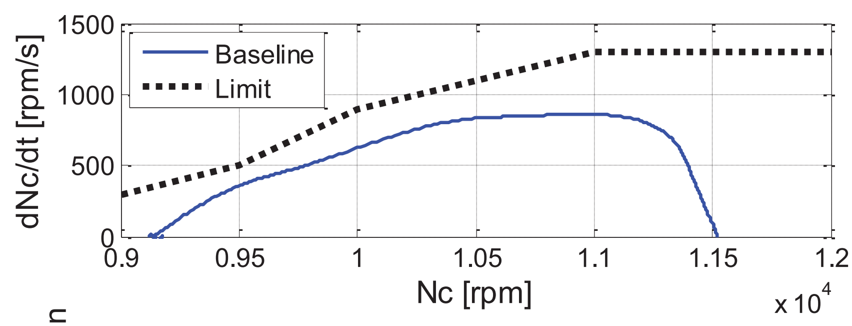
- Typical aircraft engine control is based on a Min-Max scheme
- Designed to keep the engine operating within prescribed mechanical and operational safety limits

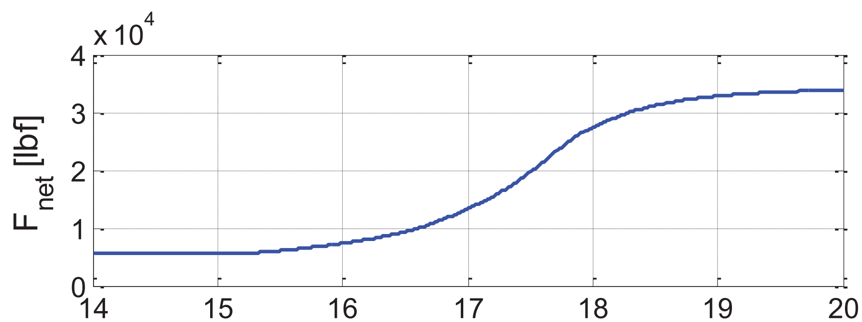


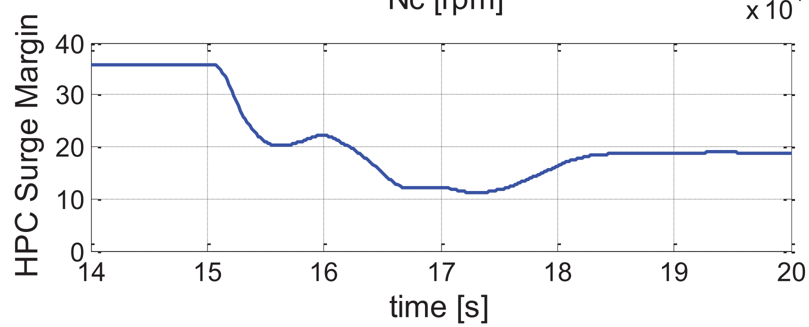
Engine Response with Baseline Control

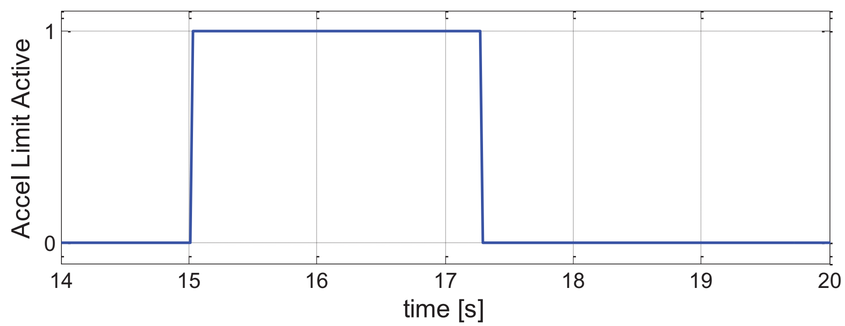
- C-MAPSS40k Full throttle burst at sea-level static conditions with an end-of-life engine











- Acceleration limit regulator is active immediately even though it is far from the limit - **Conservative Response**

Is the Conservative Response an issue?

- No:
  - Not during normal flight as long as it meets the FAA response requirements
- Yes:
  - On aircraft where primary flight control surfaces are damaged (e.g. UAL 232, Bagdad DHL, AA 587)
  - On aircraft with integrated flight/propulsion control
- Can we improve the engine response while maintaining the current architecture?

The Case for Conditionally Active Limit Regulators

- The baseline Min-Max selection control approach is inherently conservative
- Every limit regulator is capable of limiting fuel flow to engine – regardless of proximity to current limit
- Depending on how the individual PI regulators are tuned, the regulator may intervene when there is no danger of a limit being violated
- **To reduce conservatism, limit regulators should become active only when a limit is in “danger” of being violated.**

Conditionally Active Limit Regulators

- For operation with reduced conservatism while still ensuring safety, following two criteria must both be satisfied to enable a limit regulator:
  1) The regulated variable must be “close” to the specified limit
  2) The rate of change of the regulated variable is such that the regulated variable will reach the limit within a specified number of control update time steps

Conditionally Active Limit Regulators

- The conditions for the limit regulator to be active can be stated as:

For a maximum limit variable y_1 with limit y_{1max}:

$$y_1 \geq (1-\alpha_1) * y_{1\max}$$

$$y_1 + \frac{d}{dt} y_1 * \beta_1 * \Delta T \geq y_{1\max}$$

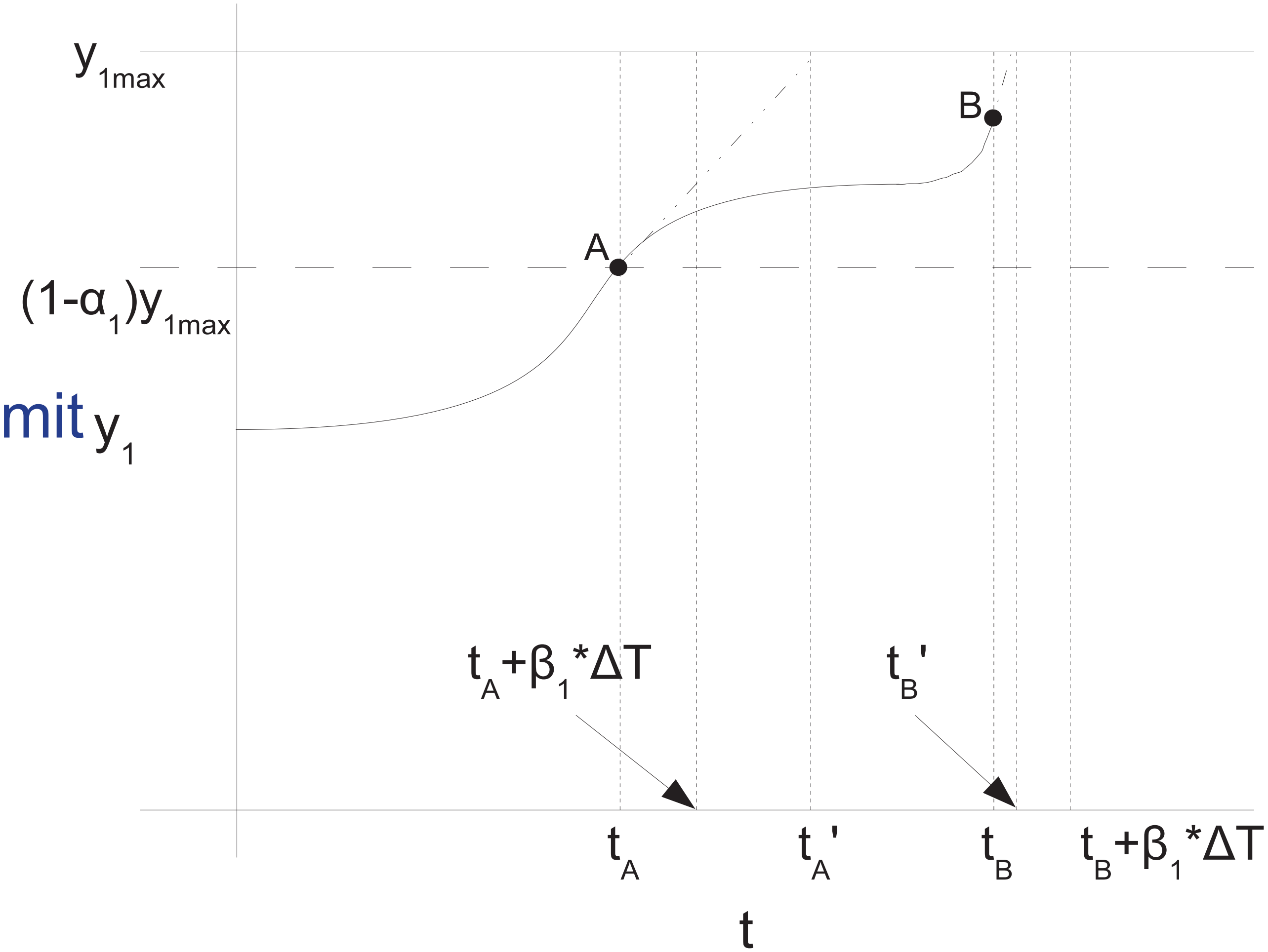
–where α_1 and β_1 are positive design parameters

- Similar equations can be developed for minimum limit variables

Conditionally Active Limit Regulators

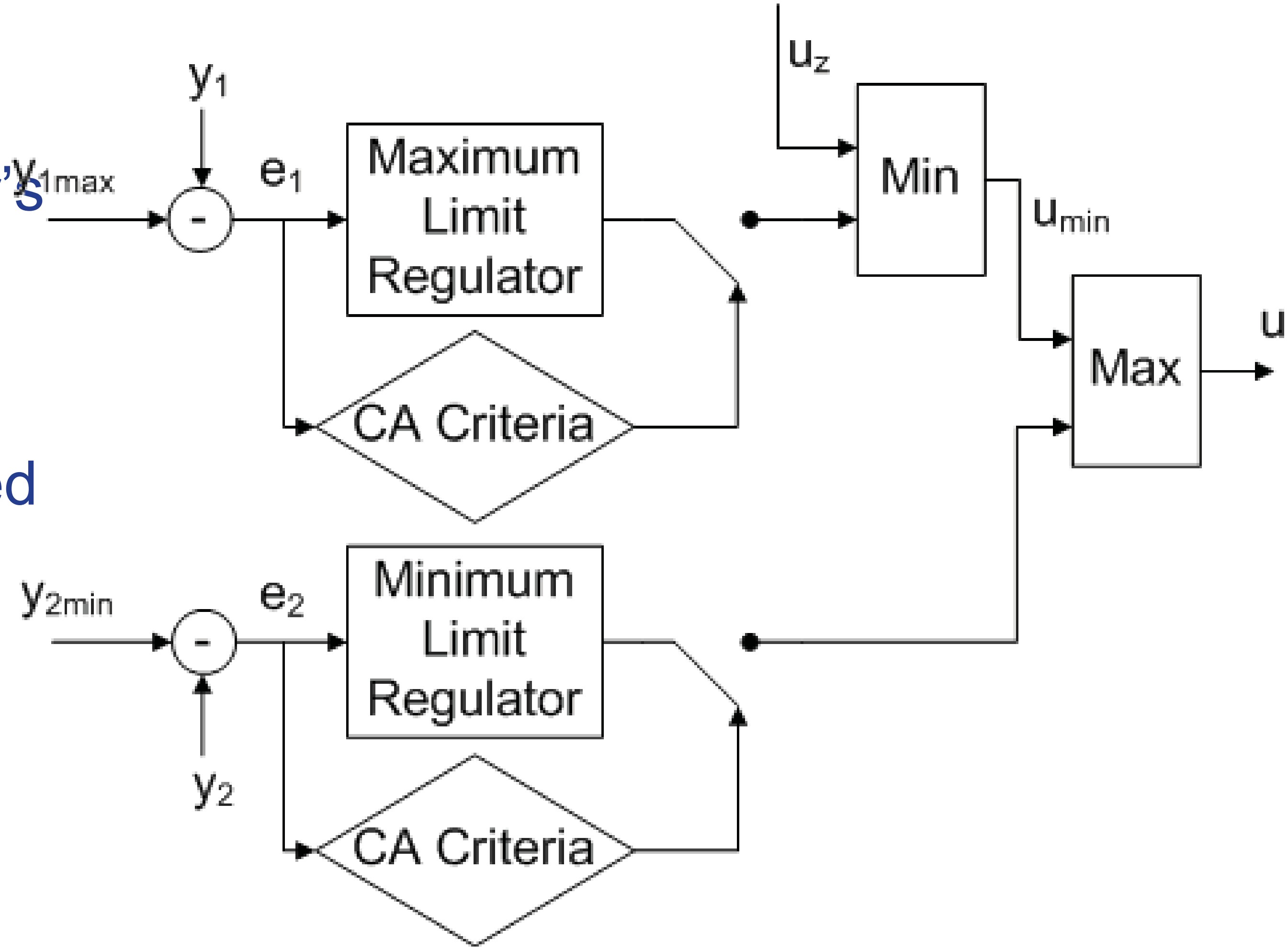
Graphical interpretation:

- Criteria 1 is satisfied at t_A
- Criteria 2 is satisfied at t_B
- Therefore the limit regulator is enabled at t_B



CA Architecture Modifica

Uses the existing Min-Max architecture, but each regulator's output is only considered if the associated criteria are satisfied

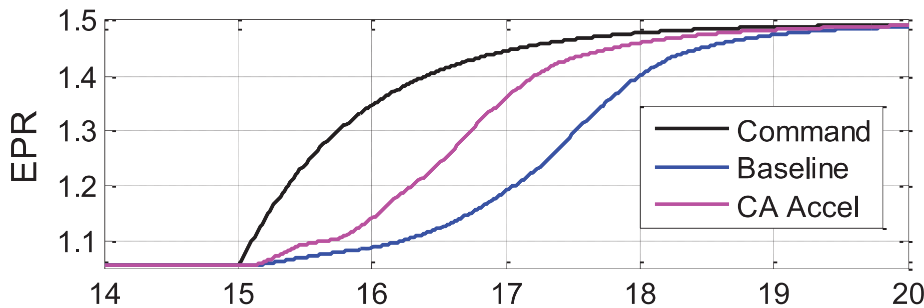


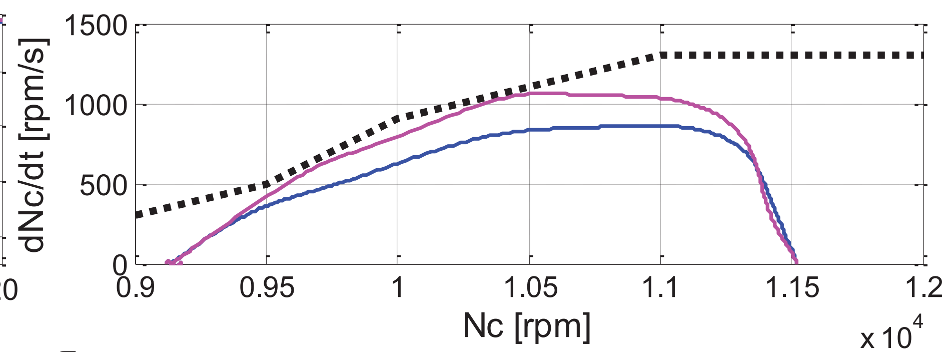
Choice of CA Design Parameters

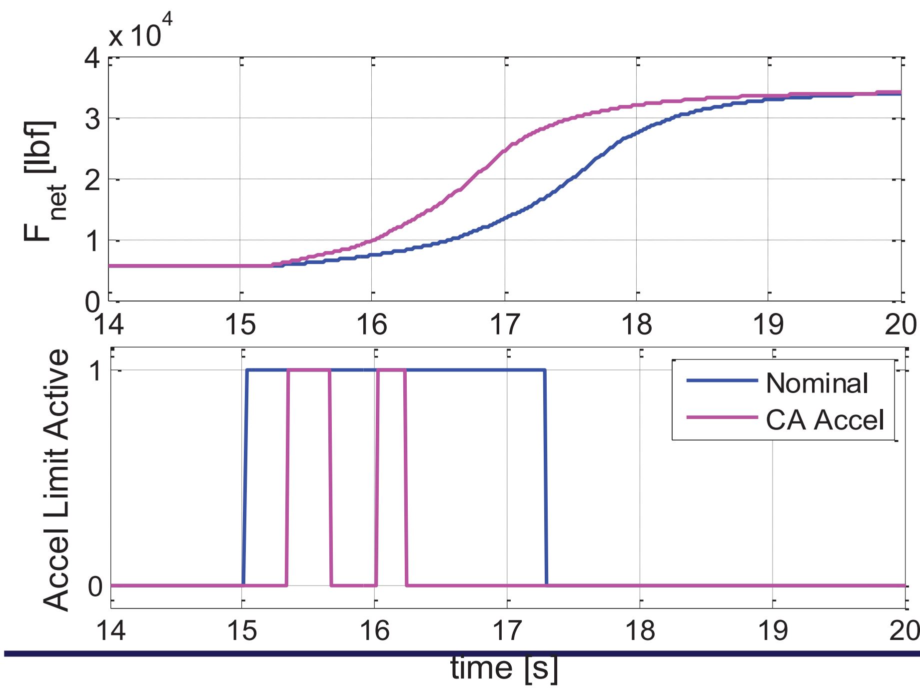
- We currently do not have an analytical approach to selecting the CA limit regulator design parameters α and β
- The CA parameters are tuned empirically
  - \- α value selected first to ensure limit is not violated for operation under worst case conditions
  - With a fixed α, the β value is selected to provide fastest possible response without violating limit
- Numerical optimization algorithm has been developed

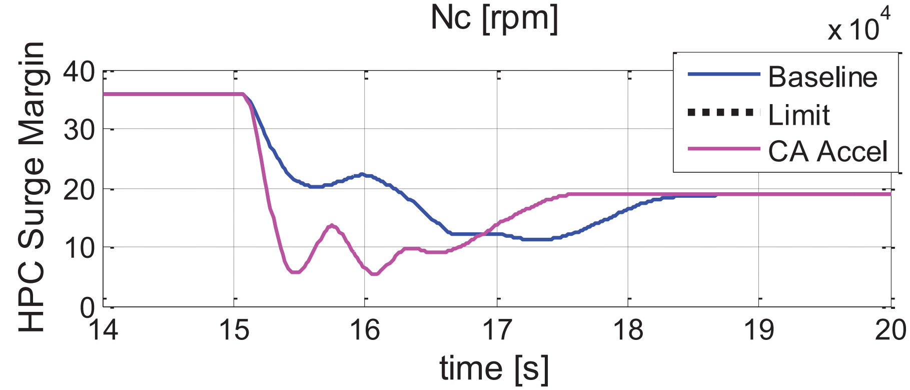
Simulation Results

- Full throttle burst at sea-level static conditions with an end-of-life engine





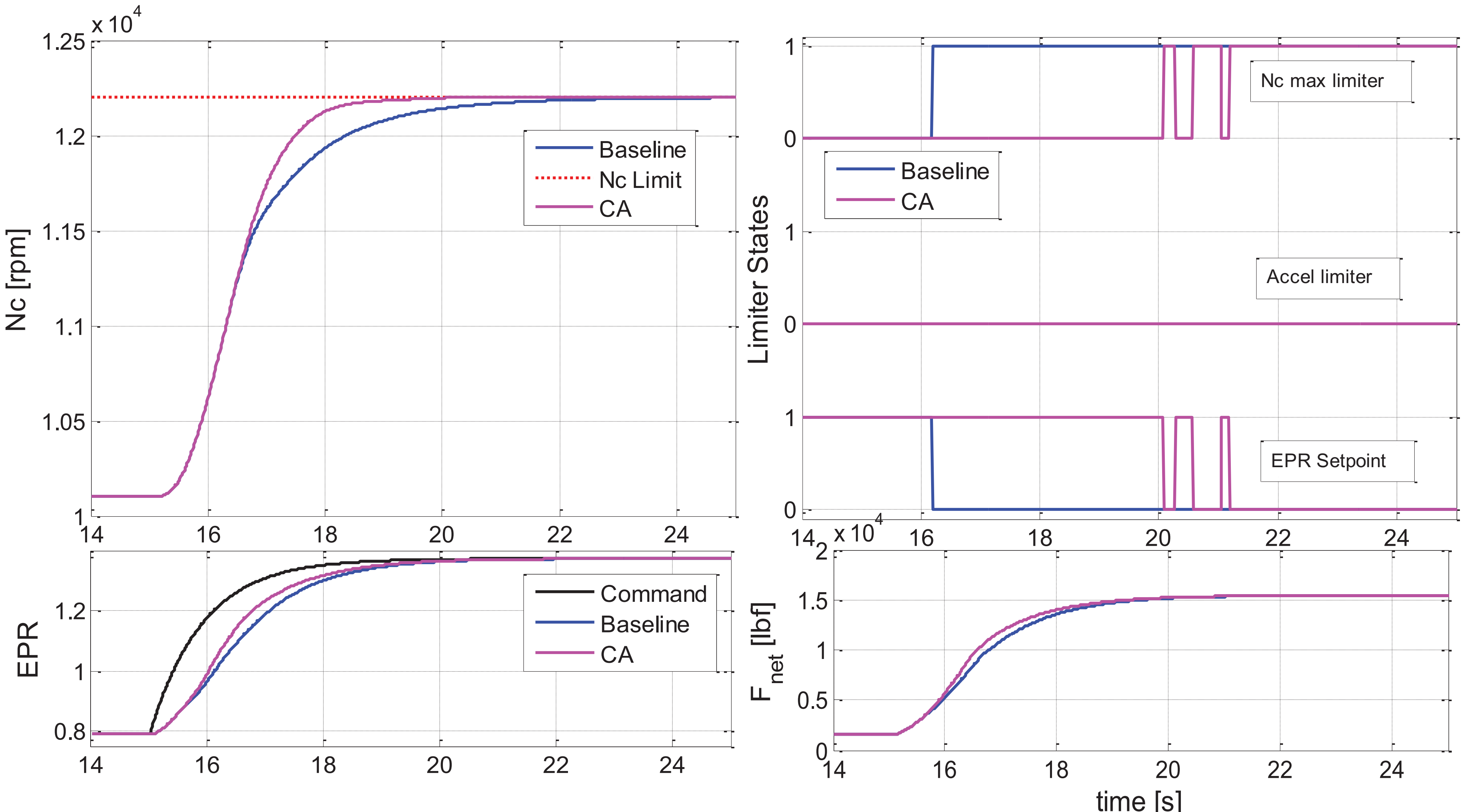




- Reduced conservatism resulting in much faster response

Simulation Results

- Case when a limit (Nc) is reached



Conclusions

- The use of properly tuned Conditionally Active limit regulators can improve the engine response without compromising safety
- This approach should simplify the tuning and validation of the limit regulator gains as the regulators are only active in a small number of possible cases
- The CA limit regulator does not require modifications to any other aspect of the well established control architecture

Future Work

- Formulate the CA limit regulator approach in a proper mathematical framework
- Investigate development of analytical approach to determining the CA design parameters so as to satisfy performance and safety requirements

References

- May, R.D., Garg, S., "Reducing Conservatism in Aircraft Engine Response Using Conditionally Active Min-Max Limit Regulators," ASME-GT2012-70017, ASME Turbo Expo 2012, Copenhagen, Denmark, June, 2012.
- Nassirharand, A., "Optimization of conditionally active MIN-MAX limit regulators for reducing conservatism in aircraft engines," Part of 2013 NASA Glenn Faculty Fellowship Program Final Report.