Dynamic Analysis of the STARC-ABL Propulsion System

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Outline

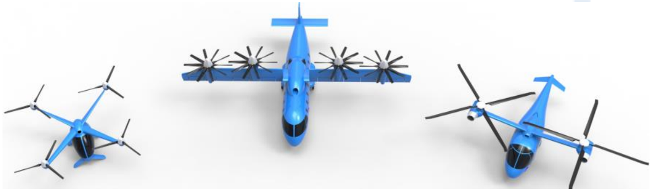
Organization

- Background on Electrified Aircraft Propulsion (EAP)
- Background on engine design
- Background on Dynamic System Analysis (DSA)
- Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsor (STARC-ABL)
- Control Development
- Dynamic System Studies
- Energy Storage Consideration
- Conclusion

Electrified Aircraft Propulsion (EAP)

- In recent years there has been an emergence of numerous electrified aircraft concepts, from small to large scale
- Leveraging electrification
  - Flexibility of where to place propulsors to get an aerodynamic benefit (boundary layer ingestion, wing tip propulsor)
  - Increasing the effective bypass ratio of the propulsion system
  - Potential to use propulsors for flight control
  - Adds additional degrees of freedom
  - Opens up design space
- Potential benefits
  - Improved system efficiency
  - Reduced noise
  - Reduced emissions
  - Enabling new capabilities for the aircraft

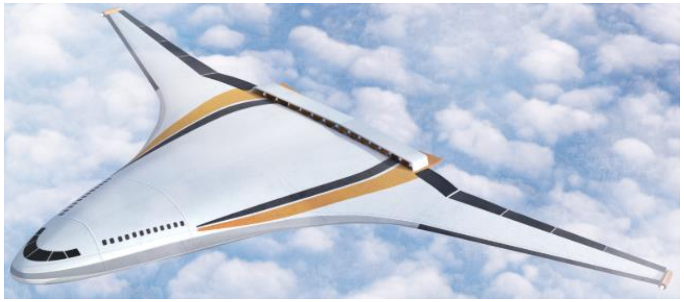
***The benefits are only realizable if the concepts are feasible**



Quadrotor Tilt-Wing Side by Side

PEGASUS

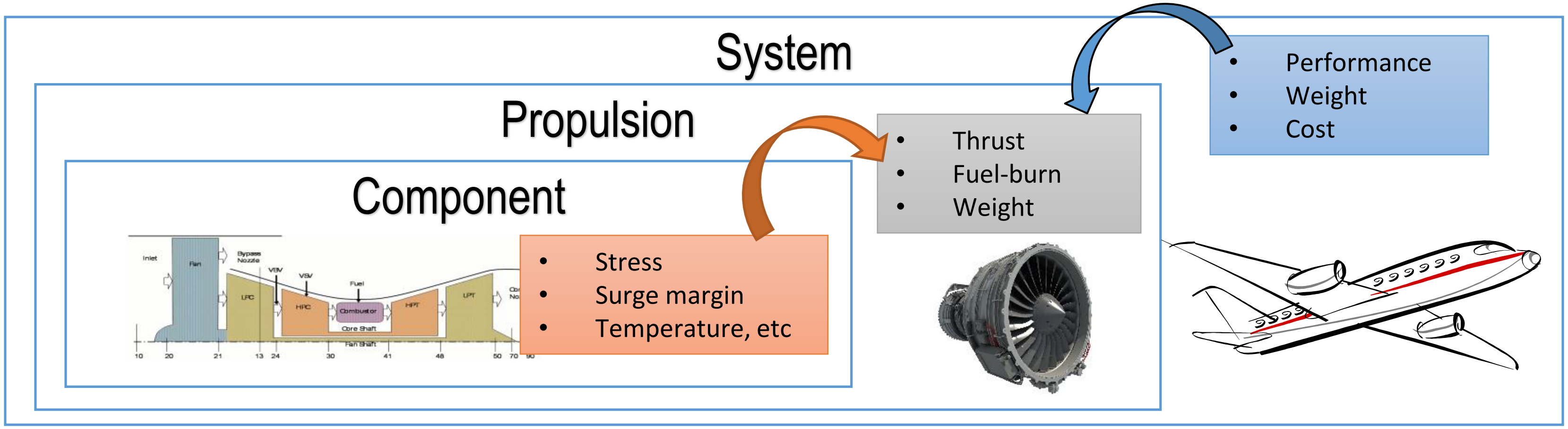
STARC-ABL



N3-X

Engine Design

- Engines are designed using system analysis with a focus toward steady-state performance
  - Steady-state system-level models
  - Evaluate tradeoffs to optimize the design
- Propulsion system design
  - Objectives: fuel burn, emissions, noise, cost, performance, thrust-to-weight ratio
  - Constraints: component min/max operating conditions (temperature, pressure, speed, stall margin)
  - Transients (dynamics) cause the engine to run closer to constraints and the typical solution is to add margin to the steady-state design



System

- Performance
- Weight
- Cost

Propulsion

- Thrust
- Fuel-burn
- Weight

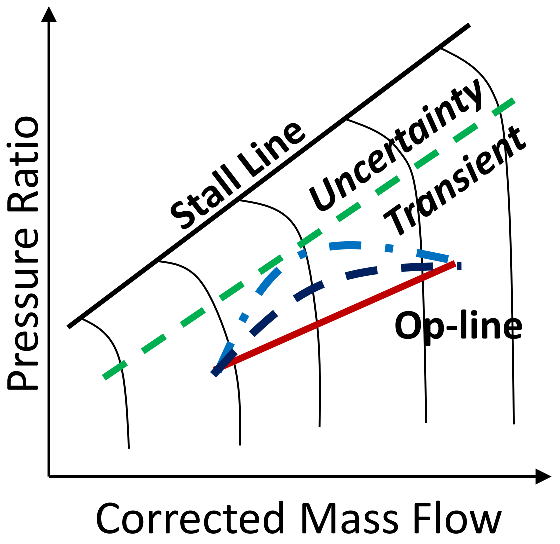
Component

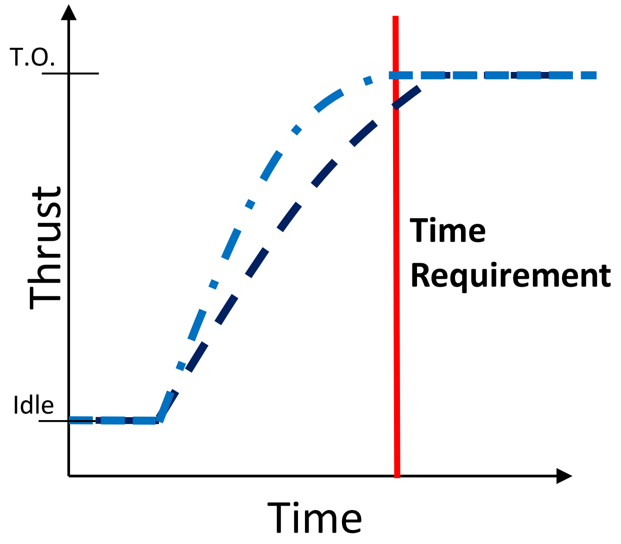
- Stress
- Surge margin
- Temperature, etc

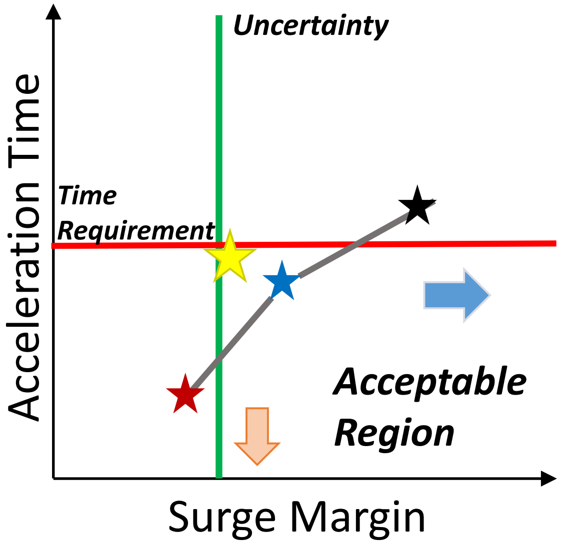
Dynamic Operation

- Less margin when transitioning between operating points
- Operability constraints
  - Uncertainty stack (off-nominal margin debits)
  - Transient stack (how much is needed for transients)
- FAA Requirement is to be able to accelerate from 15% to 95% thrust within 5 s.

- Ideal closed-loop design… (★)
  - Meets 5 second acceleration requirement (takeoff/go-around)
  - Has minimal excess margin
- Controls cannot improve efficiency for a given engine, but can reduce need for design margin
  - Engine designs with extra margin tend to be less efficient







Dynamic System Analysis (DSA)

Benefits are only realizable if the concept is feasible

Goals:

- Evaluate the feasibility of conceptual propulsion systems
- Bring the consideration of controls into the propulsion system design process

This entails:

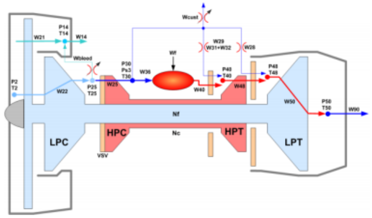
- Development of propulsion system controllers
- Assessment of dynamic operability
- Adjusting of the controller design to assess the trades between responsiveness and operability
- Identification of excess operability margin
- Inform the propulsion system designers

Previous Work:

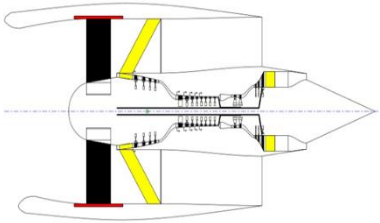
- Commercial-Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k)
- Advanced Geared Turbofan 30,000 lb_f (AGTF30)
- hFan - propulsion system for the Subsonic Ultra Green Aircraft Research (SUGAR) Volt parallel hybrid electric concept

Here we consider:

- Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsor (STARC-ABL)



C-MAPSS40k



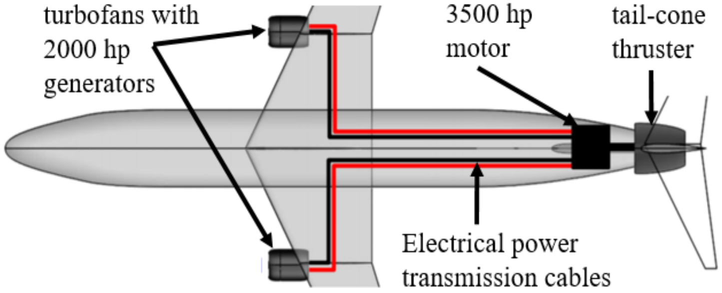
AGTF30

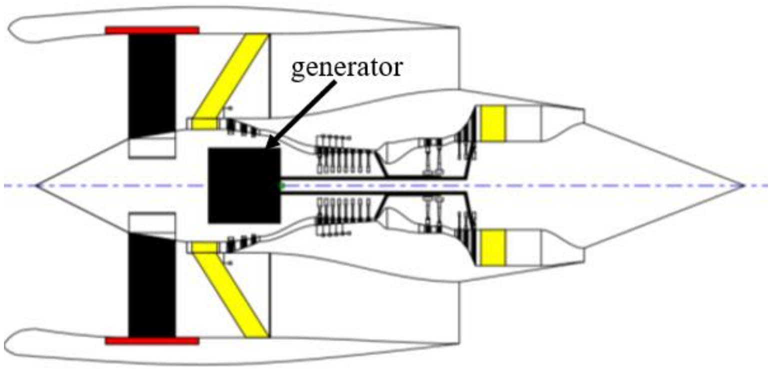
SUGAR Volt (hFan)

STARC-ABL

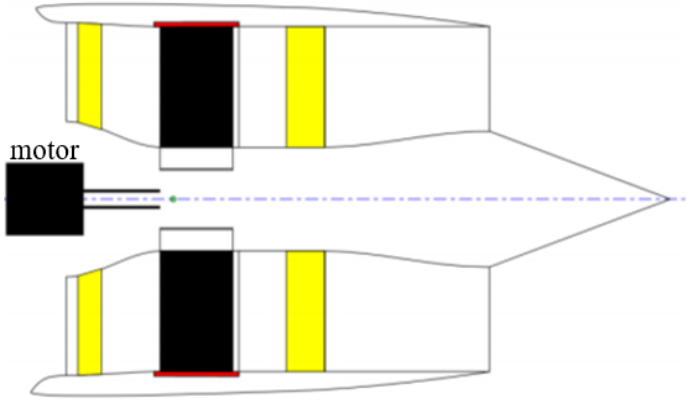
STARC-ABL – The Concept

- Single-aisle tube and wing commercial transport
- Capable of producing ~40,000 lb_f of thrust at sea level static conditions (SLS)
- Ducted, electrically driven, boundary layer ingesting tail-cone thruster
- 2 underwing engines, each has a 2000 hp generator
- A 3500 hp motor to drive the tail fan
- Turboelectric (no energy storage)
- Power is transmitted via a 1000V direct current bus
- At cruise ~1/3 of the thrust is provided by the tail fan





engines



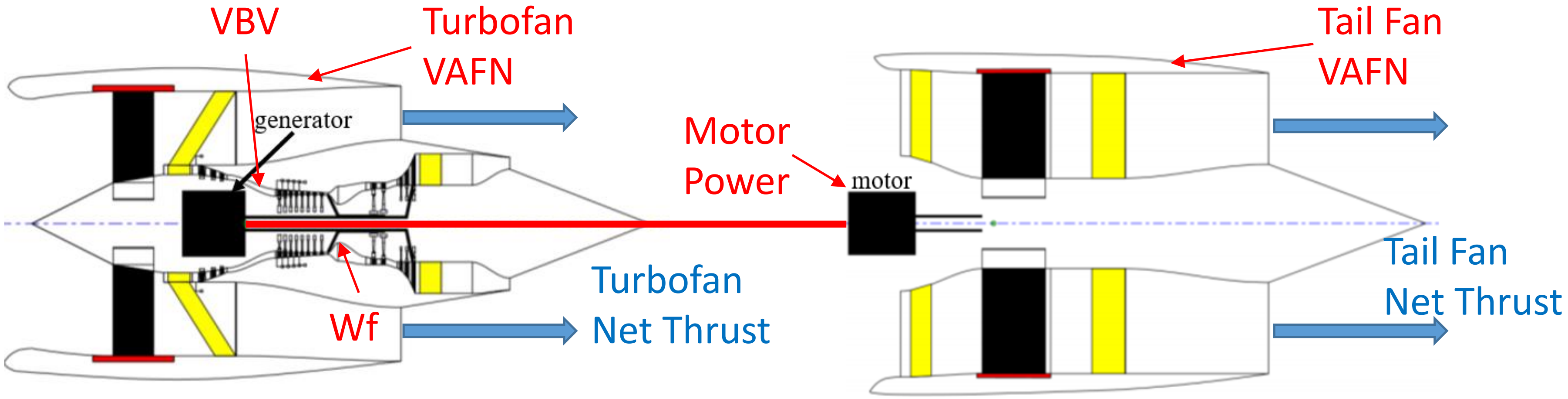
tail-cone thruster

STARC-ABL – The Model

- Modeled with Numerical Propulsion System Simulation (NPSS) code
- Modified to enable dynamic operation and include health parameters for capturing component deterioration
- Migrated to MATLAB/Simulink using the NPSS S-function interface
- Electrical system was modeled simplistically
  - Electric machines – 96% efficiency
  - Inverters – 98% efficiency
  - Cables – 99.6% efficiency
  - Each generator supplies half the power to the tail fan motor

STARC-ABL – The Controller

- Controller Inputs: fuel flow (Wf), variable bleed valve (VBV), turbofan variable area fan nozzle (VAFN), tail fan VAFN, tail cone thruster motor power
- Scheduled based on Mach number (MN), altitude (Alt), and corrected fan speed (turbofan - N1R, or tail fan - NTailR)
  - VBV
  - Turbofan VAFN
  - Tail fan VAFN
- Scheduled based on MN, Alt, and corrected thrust (FnR)
  - Tail cone thruster motor power
- Fuel flow is actively controlled w/ net thrust (Fn) as the control variable (simplification)



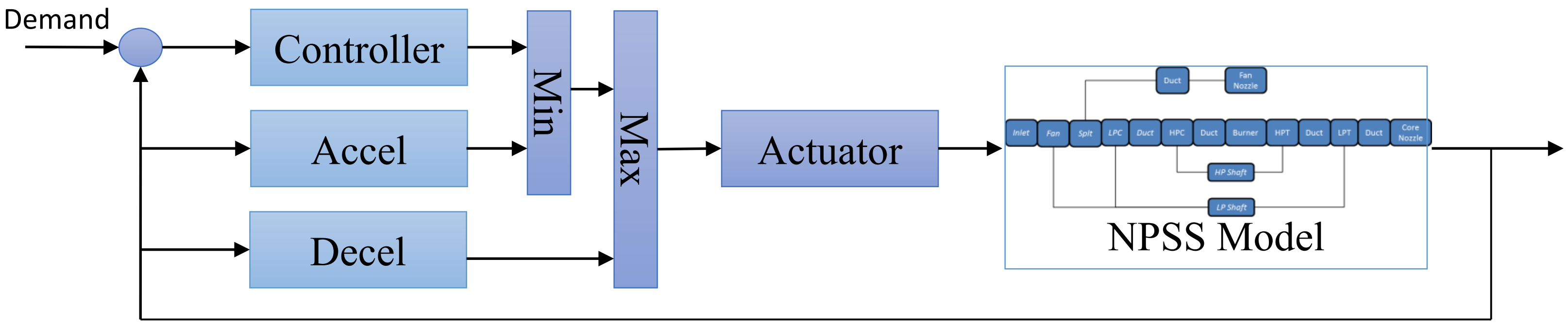
Fn = 2 × Turbofan Thrust + Tail Fan Thrust

Control Development – Overall Strategy

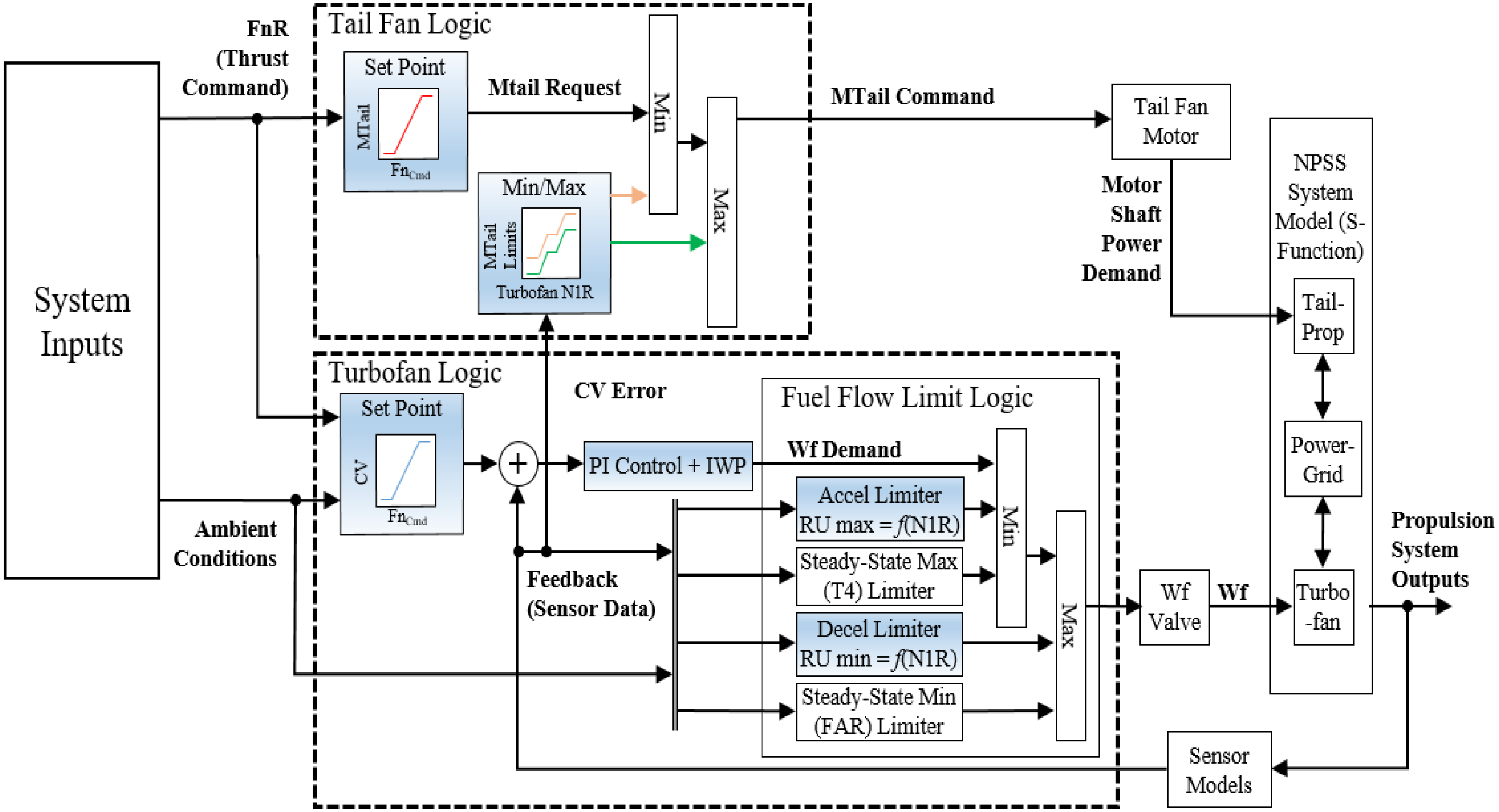
- VAFN control:
  - The original model: varied ~78% and ~70% of max area
  - The new schedule: varied ~45% of max area
- Tail Fan Motor Limit Logic:
  - The commanded FnR can change instantaneously → abrupt changes in motor power → operability issues
  - Constructed a limit schedule relating the tail fan motor power to N1R
  - Enforce that the motor power command must be within 5% of the new schedule

- Fuel control:
  - Used the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA) controller architecture and design tools (https://github.com/nasa/TTECTrA/releases)
  - Proportional Integral (PI) controller with Integral Wind-up Protection (IWP)
  - Limit Controllers:
    - acceleration & deceleration limiters
    - maximum high pressure turbine (HPT) inlet temperature (T4)
    - minimum fuel to air ratio (FAR)

*ps3 = high pressure compressor (HPC) static discharge pressure



Control Development



High Level Thrust/Power Control Logic

Controller Development – Accel/Decel Schedules

FAA Requirement (Title 14, Chapter I, Subchapter C, Part 33, Subpart E, §33.73)

- the engine must not surge, stall, exceed the maximum operating temperature, or experience any other detrimental factors while the engine is accelerated from minimum rated takeoff thrust to maximum thrust when the power control is moved from its minimum to maximum position in no more than 1 s
- the engine must be able to accelerate from its minimum flight idle power level, or from no more than 15% of the rated takeoff thrust, to 95% of the rated takeoff thrust within 5 s

- Max RU limiter – limits acceleration
  - Mainly guards against HPC stall and over-temperature
- Min RU limiter – limits deceleration
  - Mainly guards against LPC and fan stall and combustor blow-out due to reduced FAR
- TTECTrA has design functions that design the max and min RU schedules
  - Function of MN, Alt, and N1R
  - Runs through numerous points in the flight envelope and iteratively runs open-loop simulations which fuel is ramped at varying rates
  - Searches for a solutions for which the constraints are just met

Baseline Design Variable:

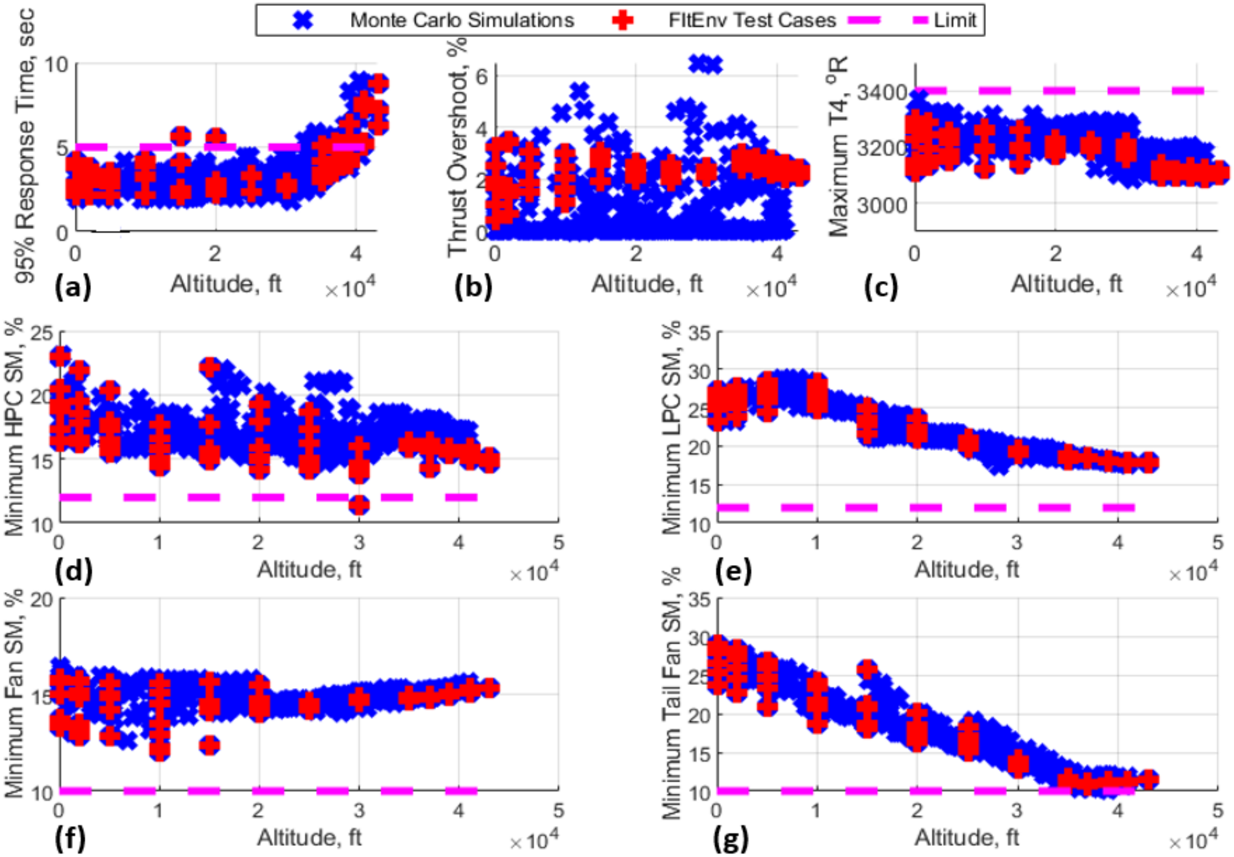
- Max T4: 3400 °R
- Min FAR: 0.01
- Min HPC SM: 12%
- Min LPC SM: 12%
- Min Fan SM: 10%
- Min Tail Fan SM: 10%

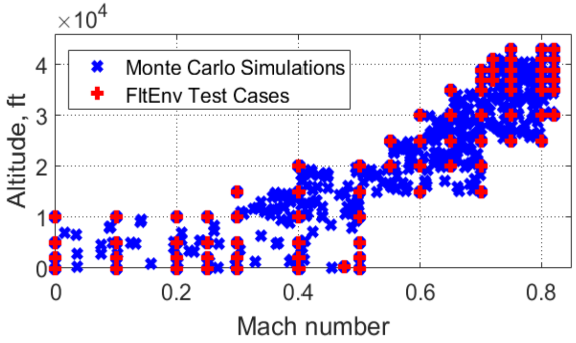
HPC = High Pressure Compressor, LPC = Low Pressure Compressor

Controller Development - Baseline Controller Results

- Model was simulated with aggressive burst & chop transients from idle to max power back to idle

SM = Stall Margin



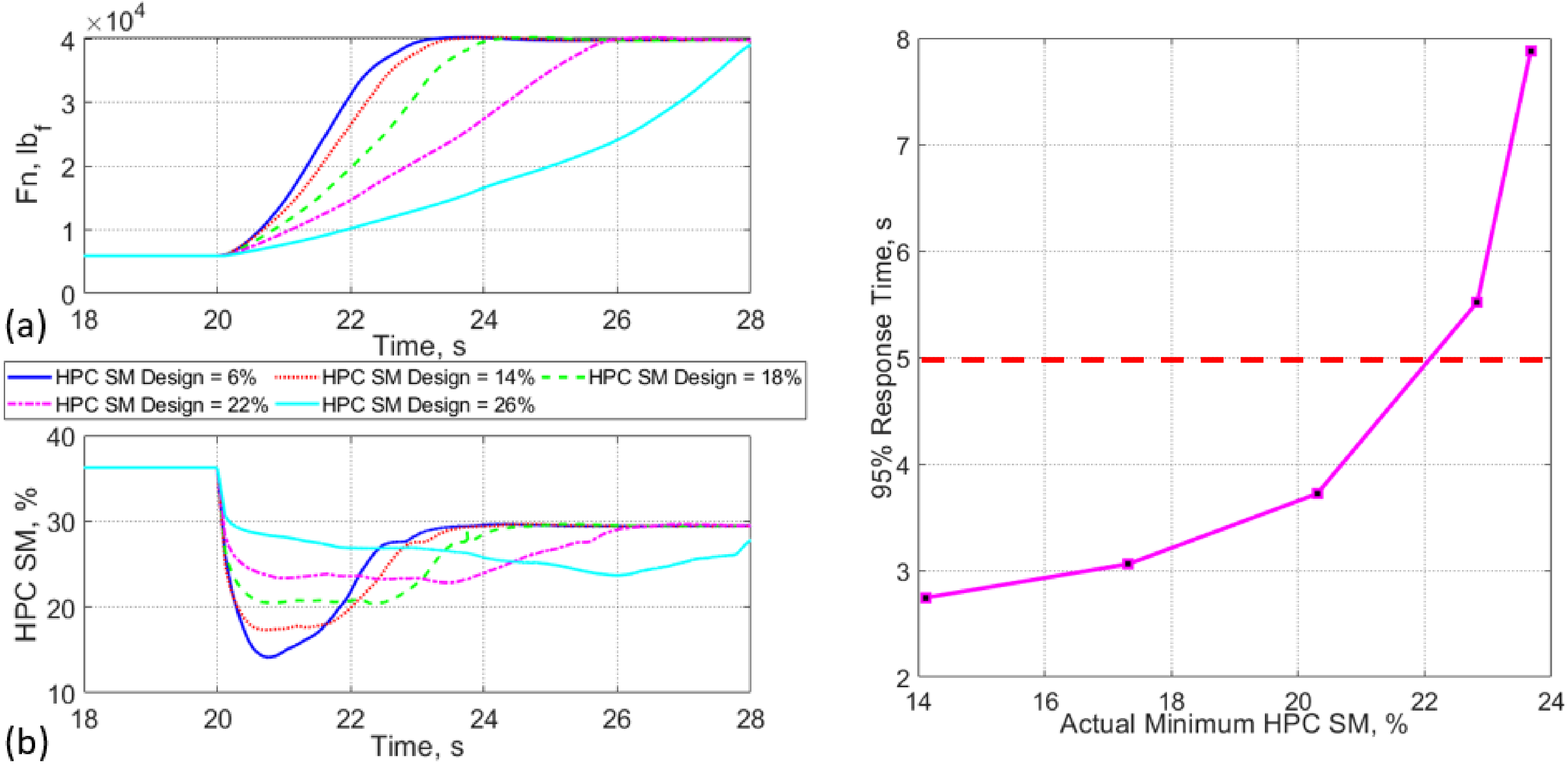


Monte Carlo Test Points

- Constraints are satisfied
    - Good response time
    - Acceptable overshoot
    - Respects all stall margin and other operating limits
- The concept is feasible from a dynamic operation perspective

Dynamic Systems Analysis

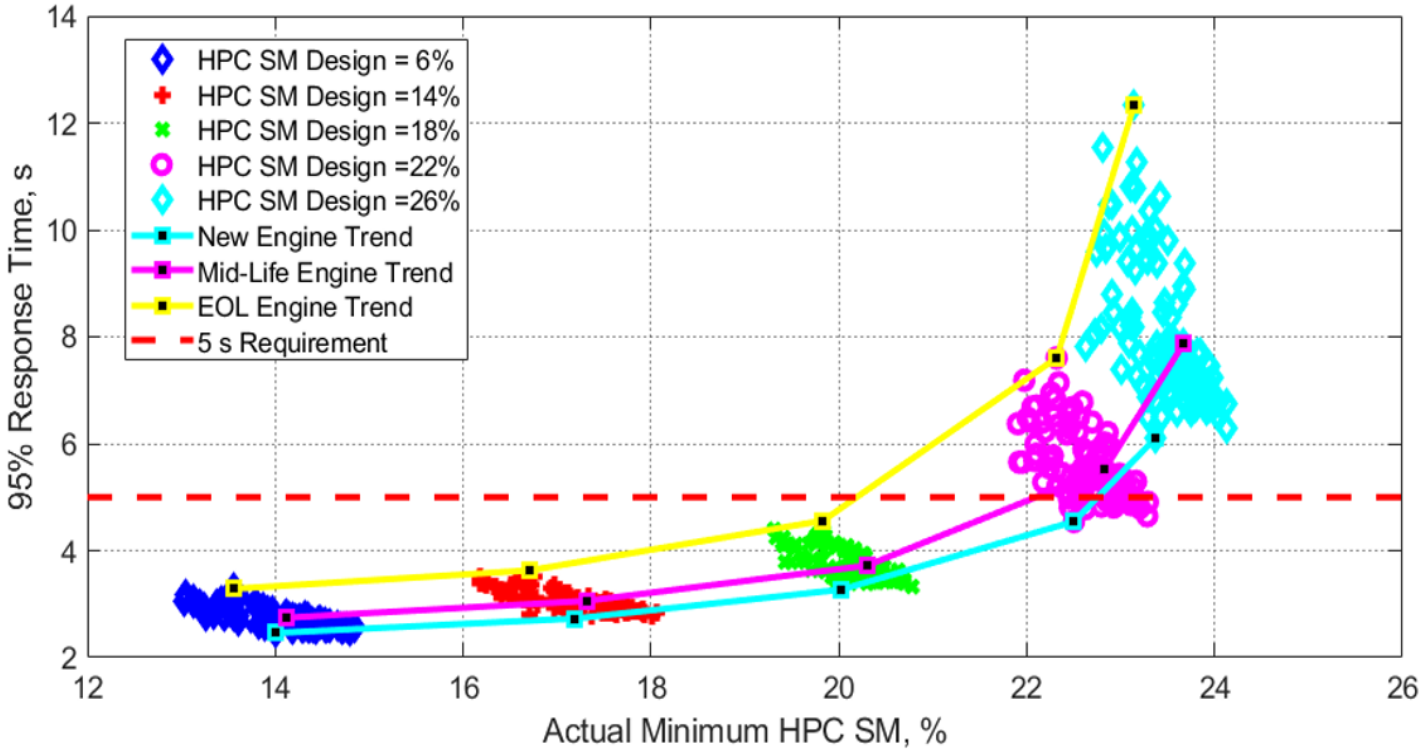
- Acceleration limit logic was designed for 5 different minimum HPC SM design values
- The design for 18% SM appears to do the best



Results for a burst transient at sea level static conditions and 27 °F above the standard atmosphere

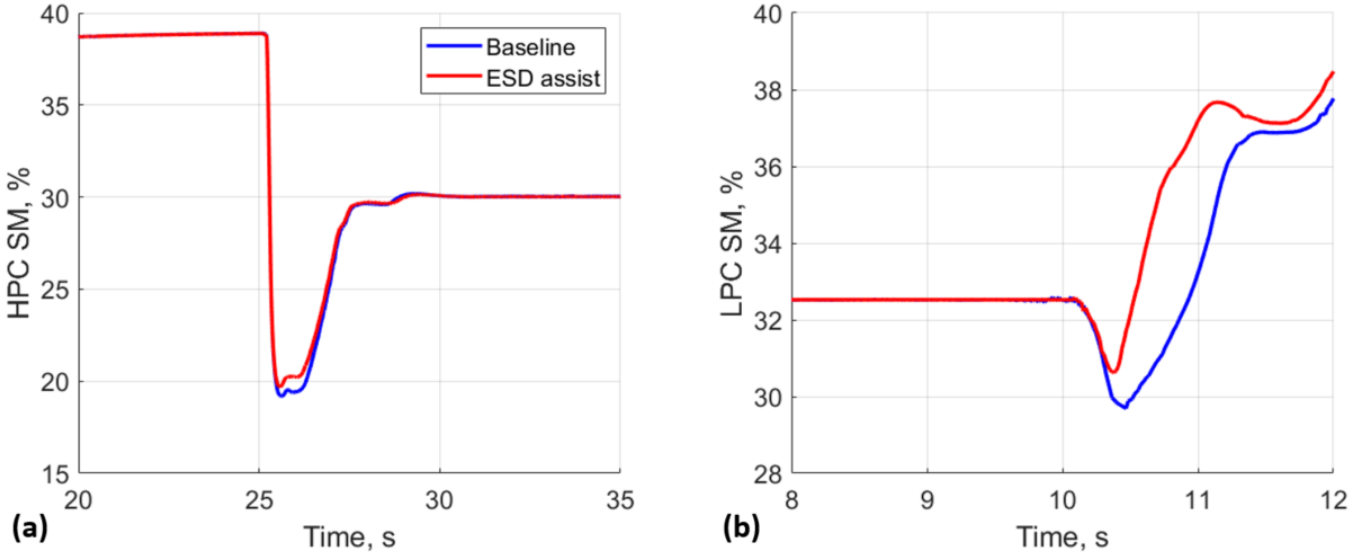
Dynamic Systems Analysis

- Engine health parameters were varied to build confidence that operability and responsiveness goals could be achieved throughout the life of the system
- The design to protect 18% SM remains the best option, meeting the FAA responsiveness requirements and maintaining an HPC SM > ~19%
- Allows for as much as a 7% HPC SM reduction at SLS conditions.
- Without a more comprehensive investigation a 3% HPC SM reduction is recommended



Energy Storage Consideration

- Consider if STARC-ABL had energy storage
- Energy storage could be used to decouple the turbofan engine and tail cone during transient (to some degree)
  - Tail cone operates the same but a portion of the power supplied to the motor could come from energy storage
  - Energy storage assists during accelerations → power extraction from turbofans decreases → naturally faster responding engine → acceleration schedule can be relaxed → improved HPC operability
  - During decelerations, more power extraction is allowed from the turbofans → improves LPC operability and excess energy can be absorbed by the energy storage devices



acceleration transient (burst)

deceleration transient (chop)

Results for sea level static burst and chop

Conclusion

- Demonstrated a Closed-loop STARC-ABL propulsion system
  - NPSS model integrated with Simulink-based TTECTrA controller using the NPSS S-function
  - Operational throughout the flight envelope
- Dynamic Systems Studies
  - Steady-state HPC SM can be reduced by ~3%
  - Use of energy storage to “somewhat” decouple the turbofans and tail cone thruster during transients could provide some modest operability benefits

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Questions

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TTECTrA download:

https://github.com/nasa/TTECTrA/releases

Extra Slides

Controller Development - Baseline Controller Results

- Constraints are respected
- Trends are mostly as expected with the exception of the LPC SM
- Effects of power extraction are evident LPC behavior