Integrated Control Design for a Partially Turboelectric Aircraft Propulsion System

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Outline

- Electrified Aircraft Propulsion (EAP) – Benefits and Challenges
- Partially Turboelectric EAP Concept
  - Overview
  - System-Level Integrated Control Design
- NASA Electric Aircraft Testbed (NEAT) Test
  - Test Configuration
  - Test Results
- Conclusions

Electrified Aircraft Propulsion (EAP)

- EAP relies on the use of electrical power for aircraft propulsion
- Enables aircraft designs that apply advanced propulsion concepts such as distributed electric propulsion and boundary layer ingestion fans
- Benefits: a reduction in emissions and fuel burn
- Controls Challenge: Integrated nature of EAP system architectures requires system-level control solutions to ensure transient operability

NASA Aeronautics Strategic Implementation Plan

X-57 Maxwell
All Electric

N3-X
Distributed Turboelectric

STARC-ABL
Partial Turboelectric

Quadrotor
All Electric

Side-by-Side Helicopter
Hybrid Electric

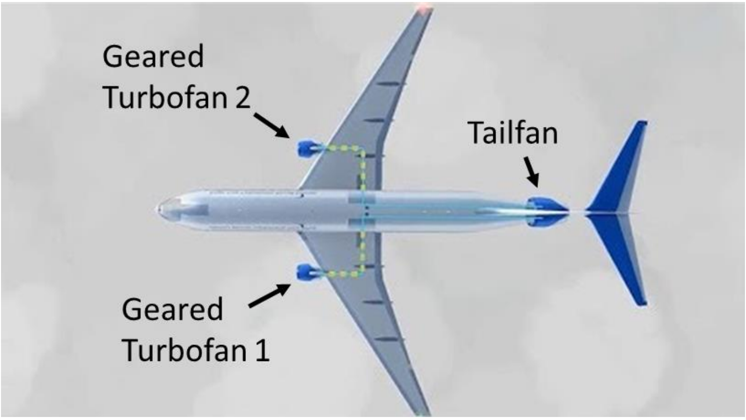
Tiltwing
Turboelectric

Example NASA EAP Concept Vehicles

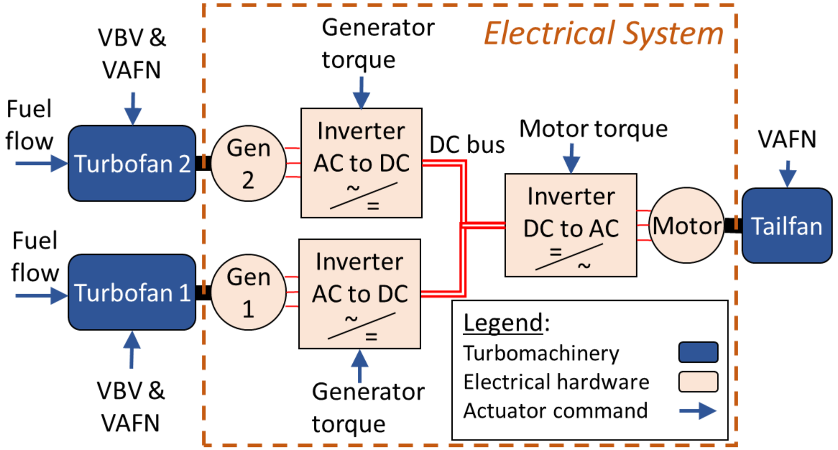
Partially Turboelectric Propulsion Concept Overview

- Single aisle Turboelectric AiRCraft with Aft Boundary Layer propulsor (STARC-ABL)
- Partially turboelectric propulsion aircraft concept proposed by NASA
  - Two wing-mounted geared turbofan engines
  - Electric motor-driven boundary layer ingestion tailfan propulsor
  - Generators attached to turbofan low-pressure shafts supply electric power to tailfan motor over a high-voltage DC power bus
- Under nominal state-state conditions the system operates in a state of "balanced" equilibrium

A system-level control strategy is required to enable transients and off-design operation!



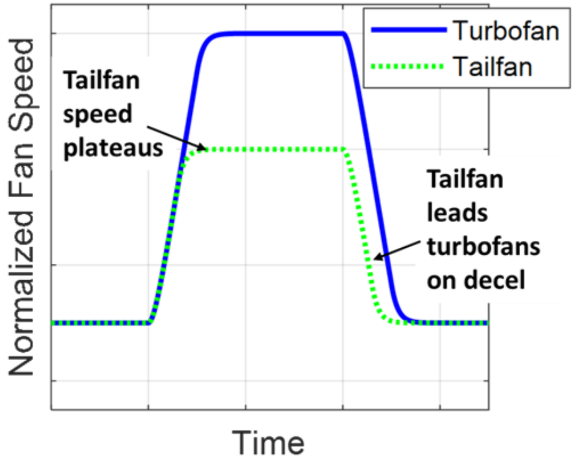
STARC-ABL EAP Concept



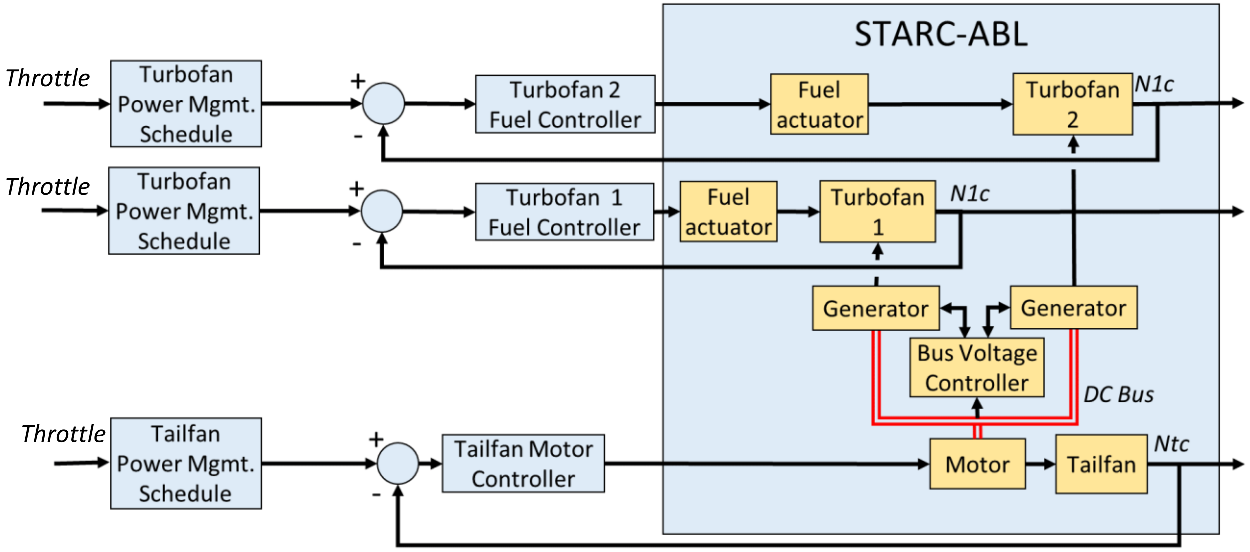
STARC-ABL Propulsion Architecture

STARC-ABL Integrated Control Design

- Control design setup:
  - Tailfan and turbofans operate under closed-loop speed control
  - Tailfan motor consumes power from DC bus
  - Turbofan generators operate to hold a target constant DC bus voltage
- Issue –uncoordinated turbofan and tailfan operation poses operability concerns



Notional illustration of tailfan leading turbofan on rapid deceleration, which can result in turbofan compressor stall



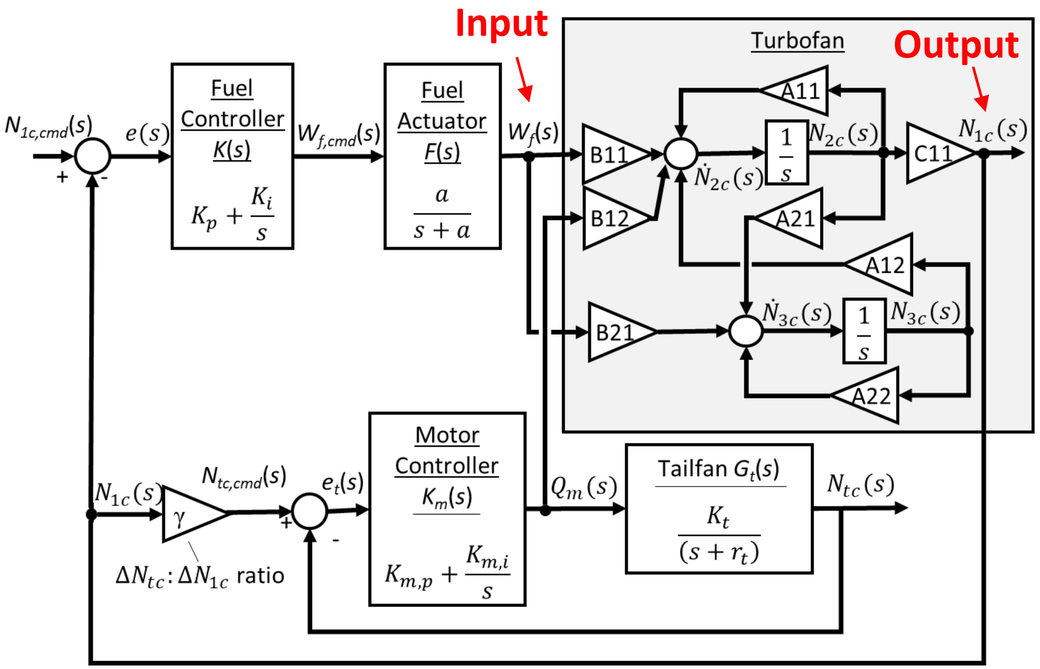
STARC-ABL Control Architecture

STARC-ABL Integrated Control Design

Implemented a single throttle input control strategy

- Both turbofans receive the same throttle command
- Tailfan receives a "synthesized" throttle input calculated as a function of average turbofan speed

- Simplifies turbofan control design to a single-input single-output (SISO) control problem



STARC-ABL Closed-Loop Control Architecture

$$\frac{\mathrm{N}_{1c}(s)}{W_f(s)} = \frac{K_e(s+z_1)}{[(s+r_1)(s+r_2) - C_{11}\gamma T(s) B_{12}(s-A_{22})]}$$

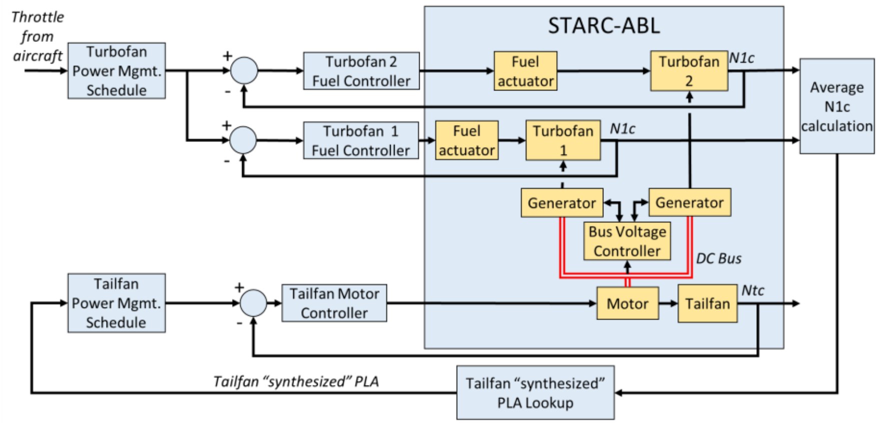
$$T(s) = \frac{K_{m,p}\left(s+\frac{K_{m,i}}{K_{m,p}}\right)(s+r_t)}{s(s+r_t) + K_{m,p}K_t\left(s+\frac{K_{m,i}}{K_{m,p}}\right)}$$

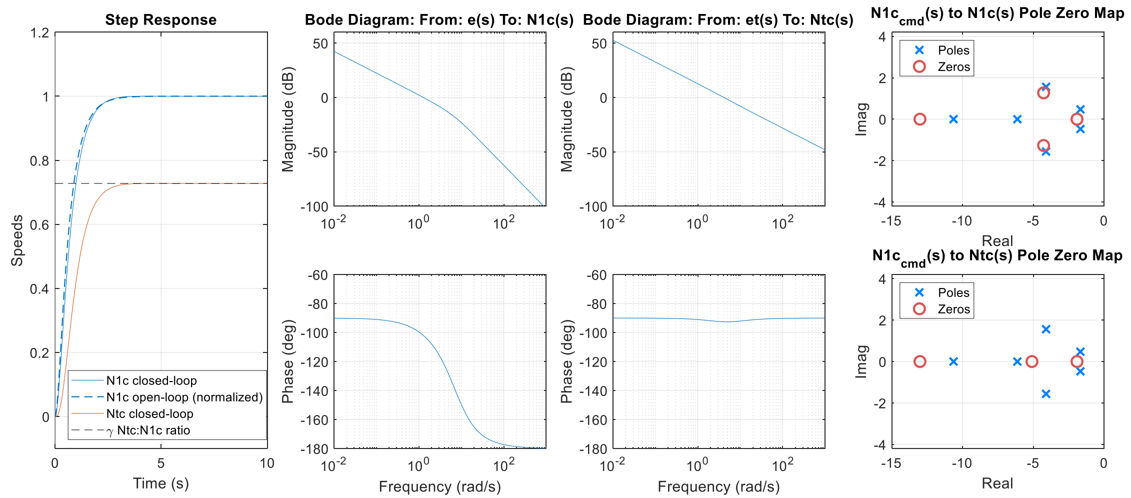
$$\gamma = \Delta N_{tc}:\Delta N_{1c}\ ratio$$

Derivation of STARC-ABL Open-Loop Linear Transfer Function

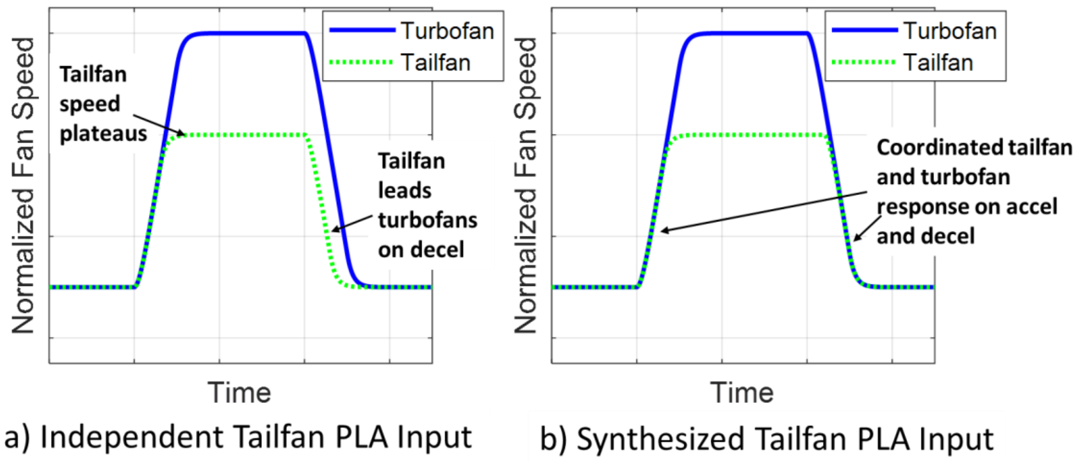
STARC-ABL Integrated Control Design Benefits

- Promotes coordinated turbofan and tailfan operation during transients
- Simplifies turbofan fuel control design to a single-input single-output (SISO) control problem enabling the application of classical linear control design techniques





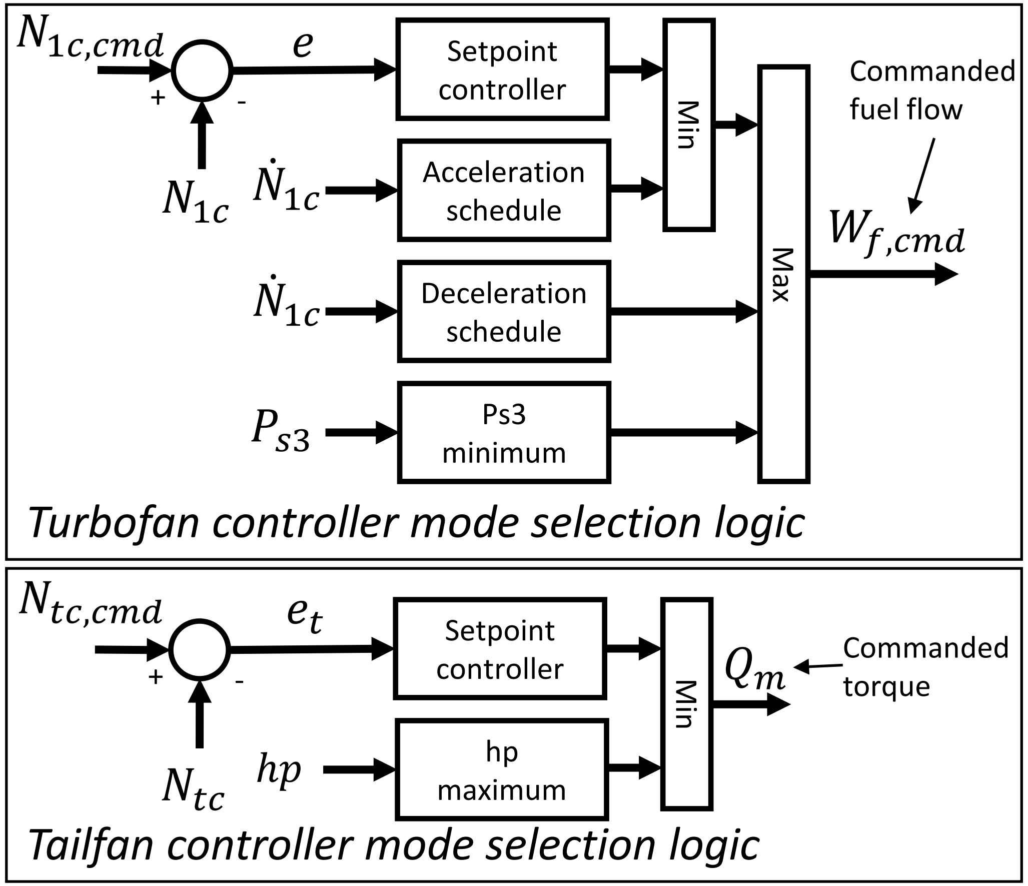
Integrated System Step Responses, Bode Diagrams, and Pole Zero Maps



Notional Illustration of Turbofan and Tailfan Transient Operation

STARC-ABL Integrated Control Design – Setpoint Control, Limit Logic, and Control Integration

- Control design features
  - Tailfan and turbofan proportional plus integral (PI) setpoint controllers
  - Turbofan PI corrected fan speed derivative, $\dot{N}_{1c}$, acceleration and deceleration schedules
  - Turbofan PI minimum high-pressure compressor exit pressure, P_{s3}, limiter
  - Tailfan maximum motor horsepower (hp) limit
- Control integration and mode selection logic
  - Conventional maximum-minimum mode selection logic with integrator windup protection applied to select active control regulator

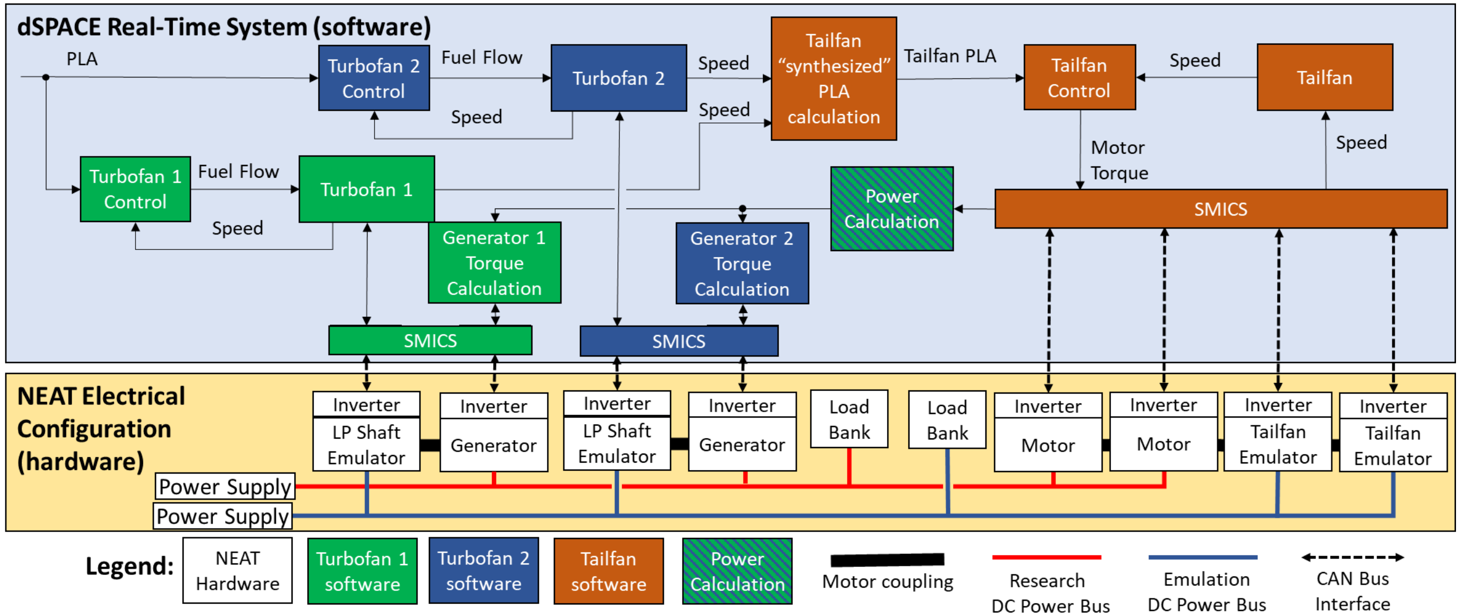


Max/Min Mode Selection Logic

NASA Electric Aircraft Testbed (NEAT) Facility Test Configuration

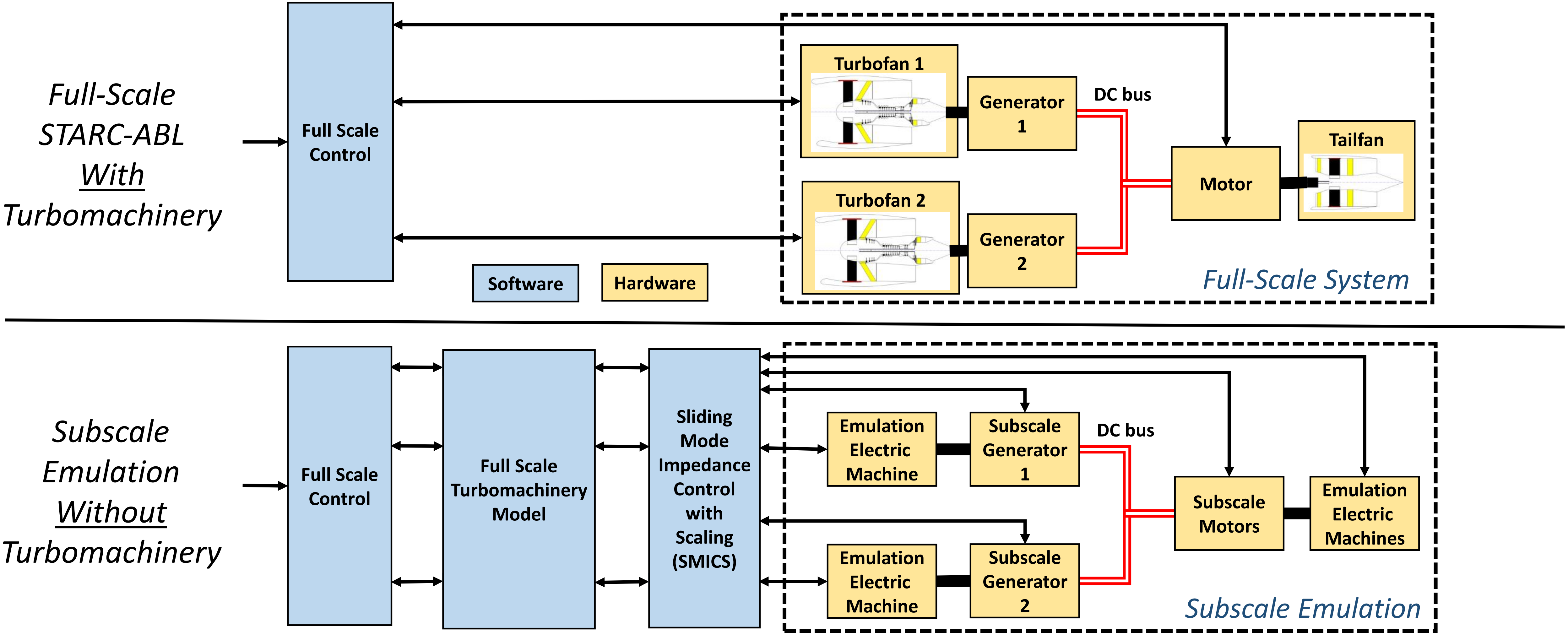
- NEAT enables the testing of megawatt-level electric aircraft power systems
- NEAT STARC-ABL Controls Test configured as a partially-simulated partially-hardware-in-the-loop experiment.
  - Turbomachinery simulation and control software implemented in real-time computer
  - Subscale version of electrical system and turbomachinery shaft dynamics implemented in hardware using eight 250kW electric machines
- Configuration details:
  - Efficiency mismatches between NEAT electrical hardware and the STARC-ABL accounted for by “power calculation” block implemented in software
  - Sliding Mode Impedance Controller with Scaling (SMICS) algorithm applied to emulate a subscale version of STARC-ABL electrical system and turbomachinery rotating shafts

NEAT Facility, Electrical Hardware, and Control Room



NEAT STARC-ABL Controls Test Configuration

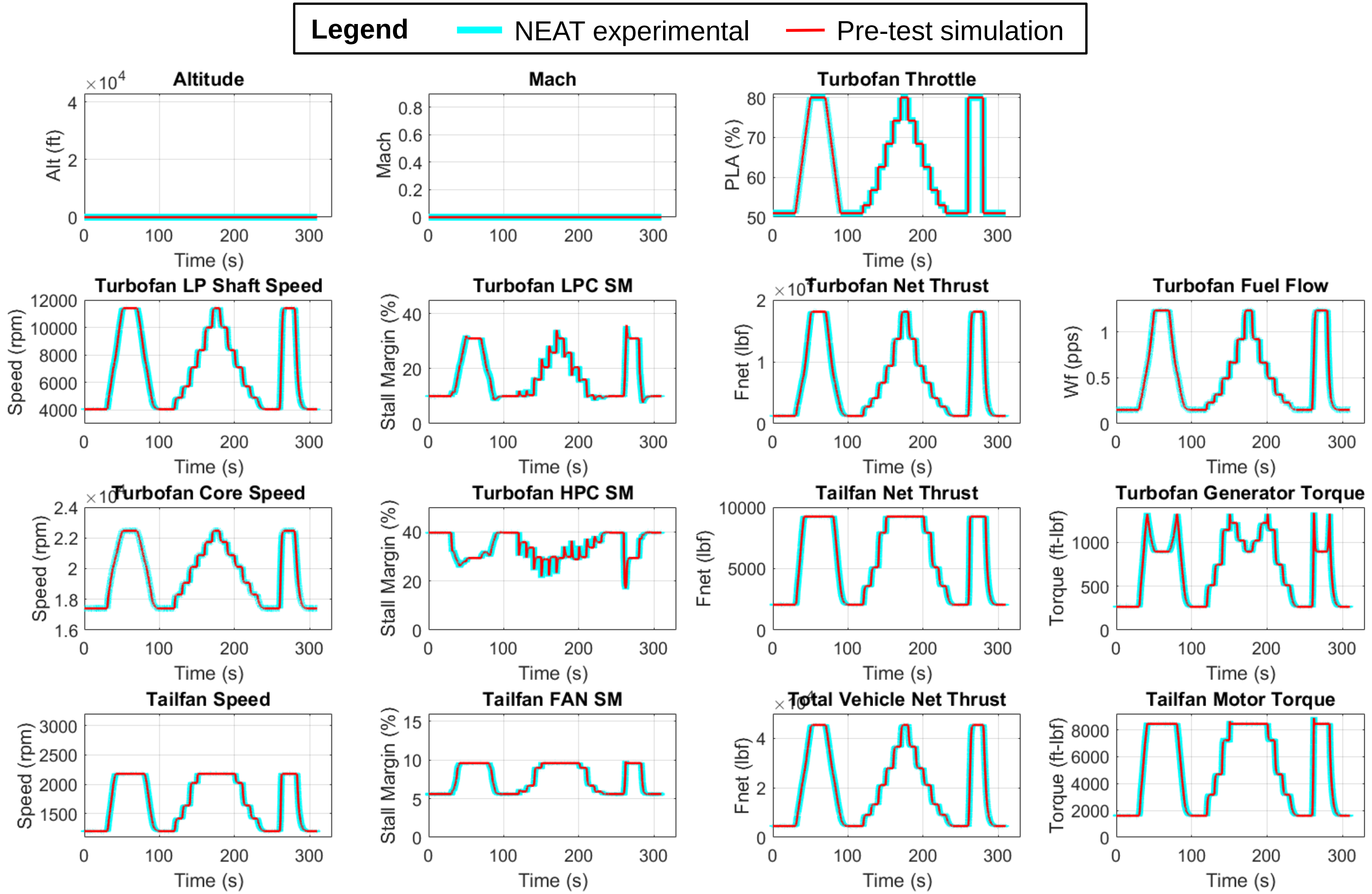
Sliding Mode Impedance Controller with Scaling (SMICS) Concept



For additional details on the SMICS algorithm see:
Bianco, S. J., Simon, D. L., (2023), "Control and Scaling Approach for the Emulation of Scaled Dynamic Torque Loads," AIAA Aviation/Electrified Aircraft Technology Symposium (EATS), San Diego, CA,

NEAT STARC-ABL Controls Test Results: Throttle Profile Test Cards

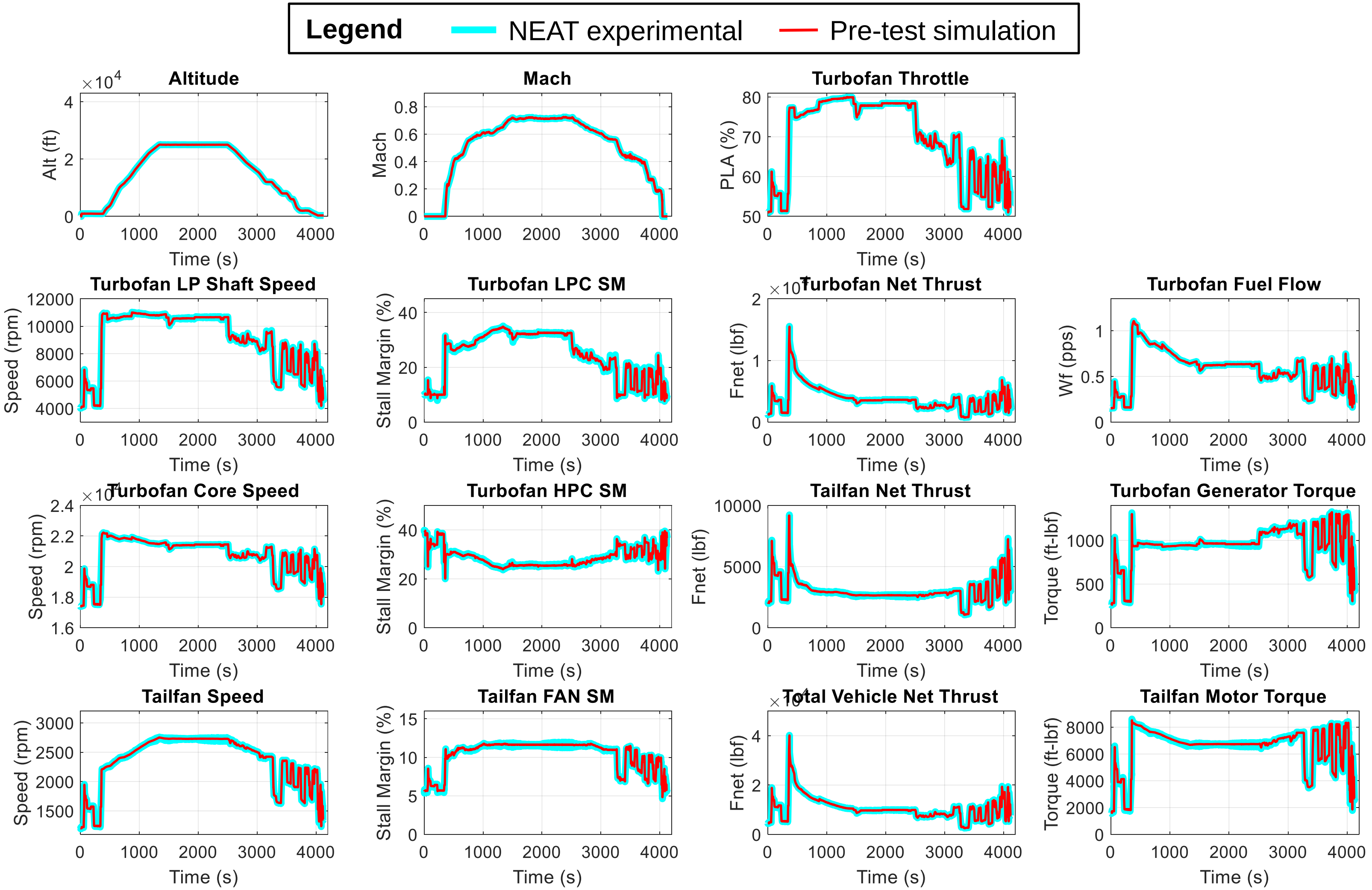
- Purpose: Subjects the integrated control design to a range of throttle input manipulations
- Completed at 57 different flight conditions spanning the STARC-ABL's operating envelope
  - Test cards ran under nominal turbomachinery health conditions and repeated under (simulated) degraded health conditions
- Findings:
  - No issues encountered
  - Control design, real-time simulation, and electrical system hardware operated as expected



Sea Level Static – Throttle Profile Test Card Results

NEAT STARC-ABL Controls Test Results: Mission Profile Test Cards

- Purpose: Subjects the integrated control design to realistic variations in flight conditions and throttle inputs
- Mission profiles
  - Test cards completed under nominal turbomachinery health conditions and repeated under (simulated) degraded health conditions
- Findings:
  - No issues encountered
  - Control design, real-time simulation, and electrical system hardware operated as expected



Actual Mission Profile Test Card Results

Conclusions

- Successfully demonstrated an integrated control design for a partially turboelectric propulsion system
  - Integrated control design exhibited robust performance when subjected to a range of flight conditions, throttle inputs, and simulated turbomachinery degradation
  - No operability issues encountered in turbomachinery simulation or facility electrical system hardware
- Integrated control design strategy
  - Holds promise for the development of integrated control solutions for other electrified gas turbine architectures that exhibit coupling between subsystems

Acknowledgements

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