Dynamic Modeling, Controls, and Testing for Electrified Aircraft

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Outline

- Introduction and Motivation
- STARC-ABL Concept
- NEAT Facility
- Modeling and Simulation Approaches
- Single String Test and Upcoming Scaled System Level Test
- Conclusions

Advanced Propulsion Systems: Motivating Controls Research

NASA Aeronautics Research Mission Directorate

Mega Drivers

Strategic Thrusts

6 Strategic Thrusts

Safe, Efficient Growth in Global Operations
Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

Transition to Low-Carbon Propulsion
Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Innovation in Commercial Supersonic Aircraft
Achieve a low-boom standard

Real-Time System-Wide Safety Assurance
Develop an integrated prototype of a real-time safety monitoring and assurance system

Ultra-Efficient Commercial Vehicles
Pioneer technologies for big leaps in efficiency and environmental performance

Assured Autonomy for Aviation Transformation
Develop high impact aviation autonomy applications

STRATEGIC THRUST 4: TRANSITION TO ALTERNATIVE PROPULSION AND ENERGY

	2015	2025	2035
Outcomes	Introduction of Low-carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems	Initial Introduction of Alternative Propulsion Systems	Introduction of Alternative Propulsion Systems to Aircraft of All Sizes

Research Themes

Alternative Power, Propulsion, and Vehicle Architectures **Advanced Air Vehicles**

Research and development of clean, quiet, and efficient transformative alternative integrated energy, power, and propulsive systems with synergistic vehicle-level integration

Alternative Fuel Combustors and Environmental Impact

Research and development of engine/fuel system integration, optimization, and performance including characterization of emissions and environmental impact

Electrified Aircraft Propulsion Components and Technology

Research and development of electrical components (e.g., electric machines, converters) and enabling technologies (e.g., materials, controls) that address weight, efficiency, and altitude challenges unique to flight

Modeling, Simulation, and Test Capability **Transformative Aeronautics Concepts**

Research and development of innovative tools and methods (computational, experimental, analytical) to transform power and propulsion system capability in less time with reduced uncertainty and cost

Major System Level Challenge

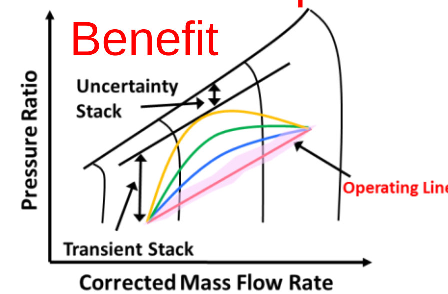
Electrified Aircraft have the potential to provide significant benefits for efficiency and emissions reductions, to assess these potential benefits modeling tools are needed to provide rapid evaluation of diverse concepts and ensure safe operability and peak performance over the mission

- For large scale vehicles (>90 PAX) it is expected that initial vehicles introduced to the market will require turbomachinery

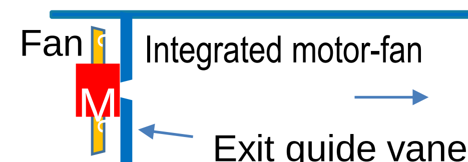
***The Modeling challenge for these vehicles is the ability to show significant benefits over the current highly refined aircraft systems**. To illustrate benefits:*

- Modeling and controls tools need to be more detailed early in the design phase.
- Integration of the subsystems are required to take advantage of potential performance enhancements of the coupled system.
- Need to enable subsystem experts the ability to work simultaneously

Power-Propulsion Benefit

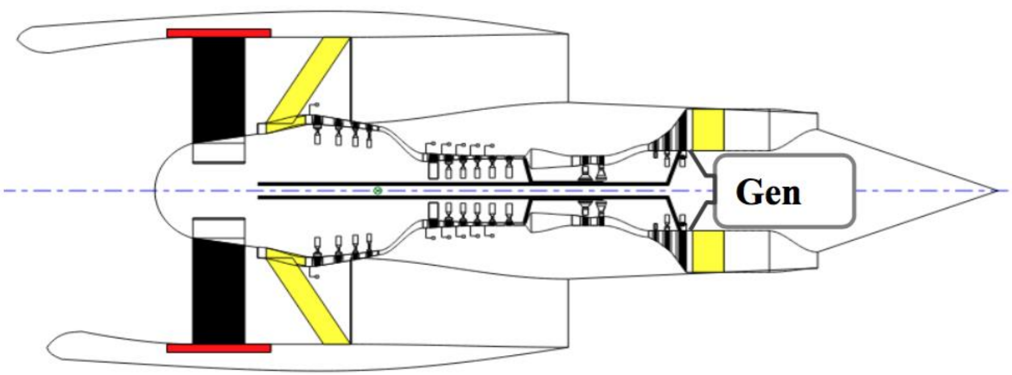


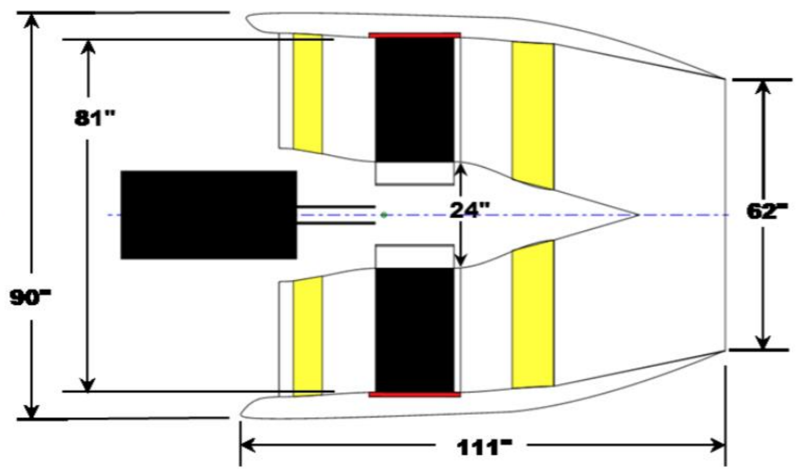
Thermal System Benefit



STARC-ABL*
(Partial Turboelectric/Fuselage BLI Fan)

Passengers	**150**
Range	3500 nm
Cruise Speed	Mach 0.7
Tailcone Thruster Motor	2.6 MW (3500 hp)
Turbofan Generator	1.44 MW (1940 hp)
Turbofan Fan	1.95 MW (2615 hp)
Fuel Burn Reduction (vs same tech turbofan)	~10%



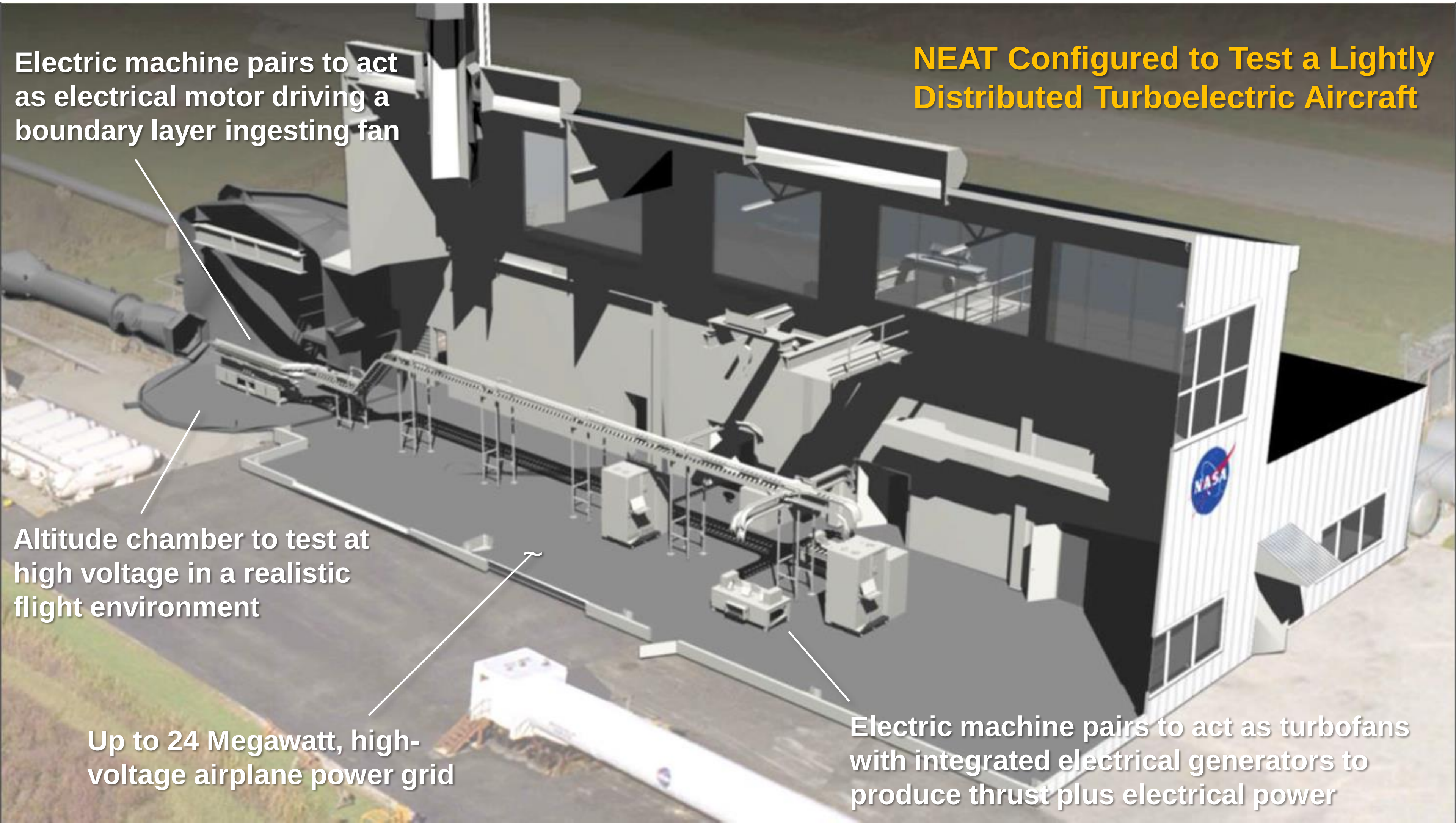


*STARC-ABL: Single-aisle Turboelectric AirCRaft – Aft Boundary Layer

NASA Electric Aircraft Testbed (NEAT)

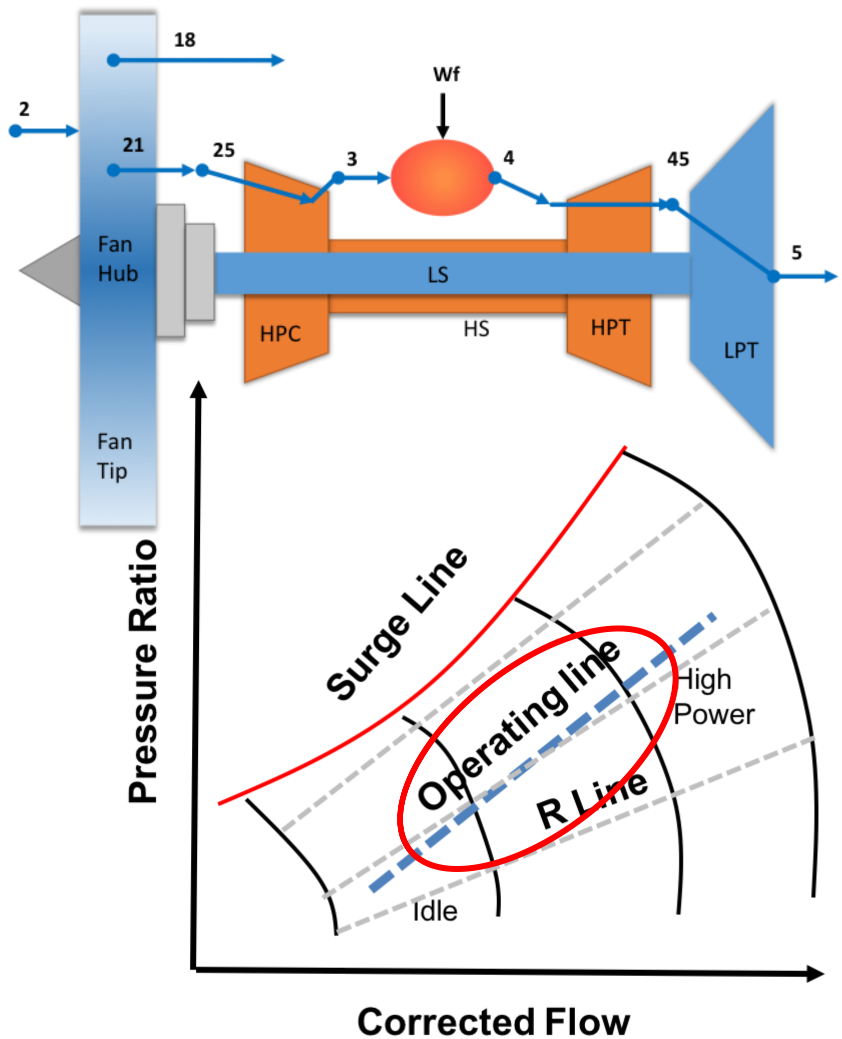
- Primary purpose of the testbed is to enable the high power ambient and cryogenic flight-weight power system testing that is required for the development of the following components to Technology Readiness Level 6
  - **Bus Architecture**
  - **MW Inverters & Rectifiers**
  - **MW Motors & Generators**
  - **System Communication**
  - **EMI Mitigation**
  - **System Fault Protection**

NASA Electric Aircraft Testbed (NEAT)



Turbofan Simulation NEAT Integration

- **Objective:**
  - Enable a more realistic dynamic response for the NEAT facility that accounts for the turbofan shaft inertias impact on power generation.
- **Approach:**
  - Numeric Propulsion System Simulation
    - Industry standard engine cycle modeling tool, able to model shaft dynamics.
    - Integrating NPSS into the Matlab/Simulink environment via the S-function for a common platform with other NEAT simulation tools
  - Engine Model Integration for NEAT
    - A Simulink UDP library block in the NPSS Simulink Simulation is used to send and receive data from the NEAT GUI that includes



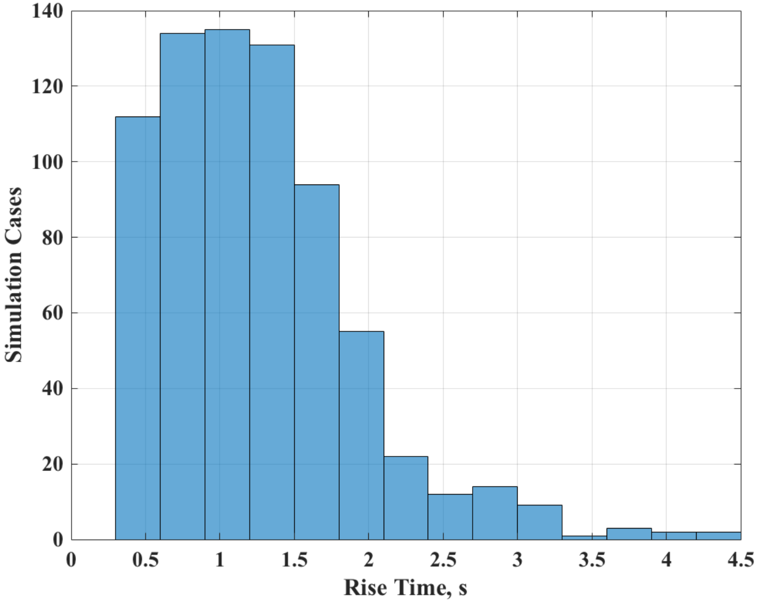
Risks:

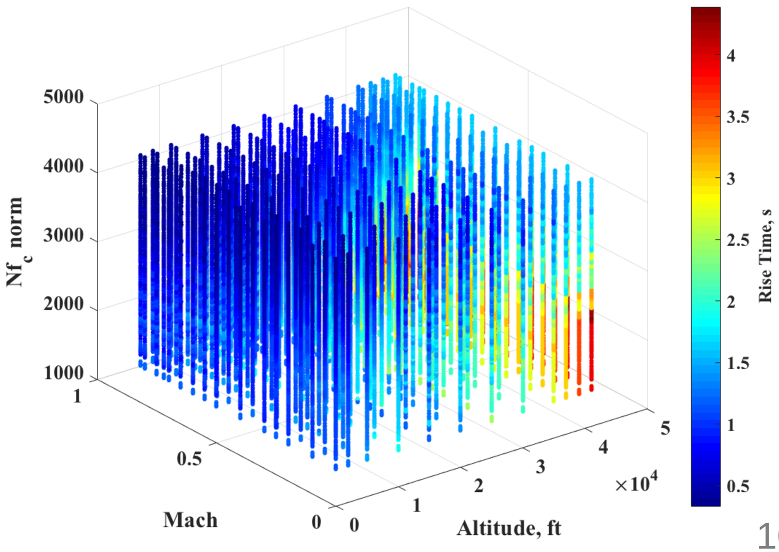
Torsional vibrations on motor shafts

Communications safe guards for erroneous NPSS values or loss of signal

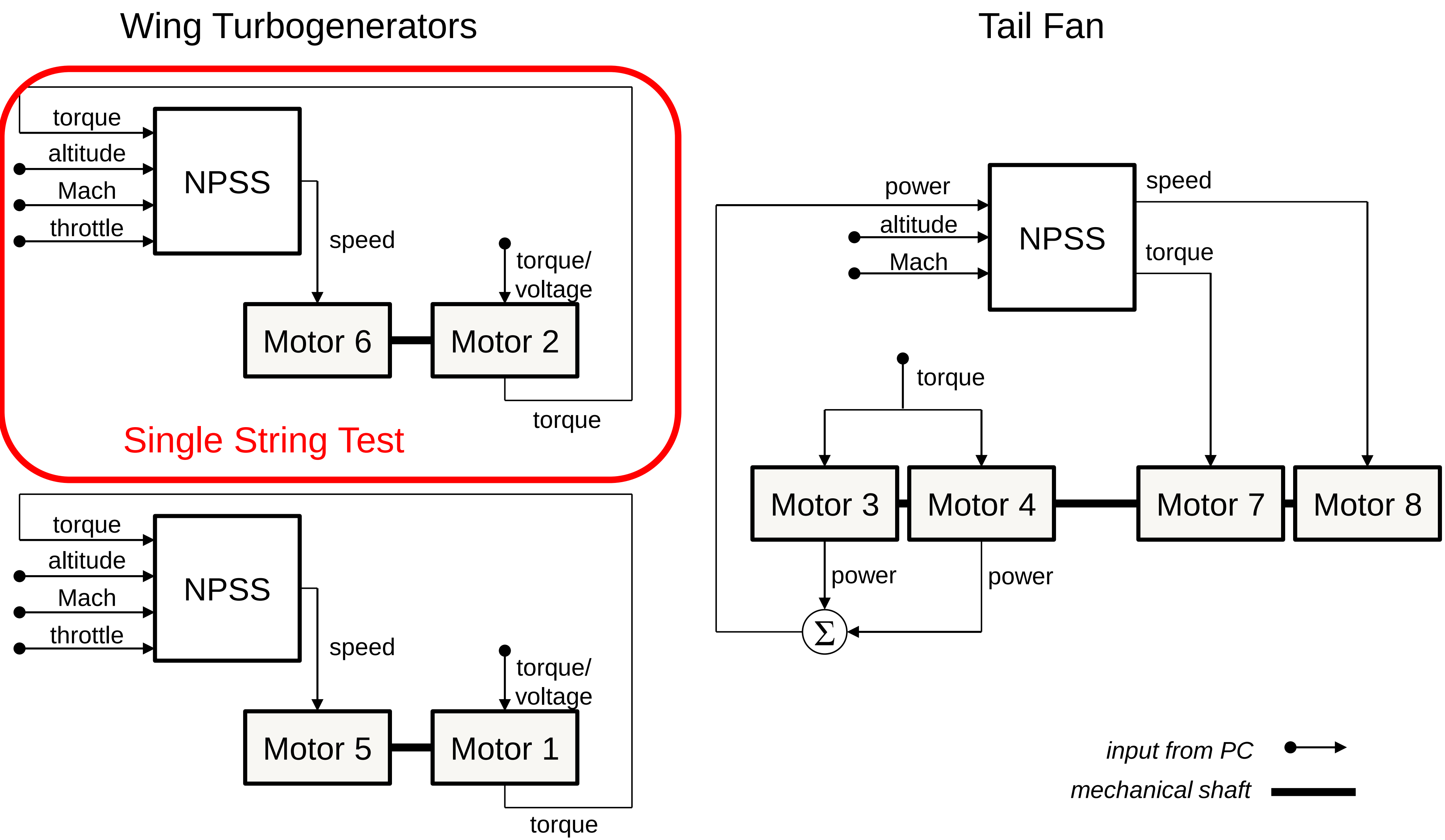
Turbofan Engine Controls Development

- The turbomachinery controller is required to provide two critical operations
  - It must be able to go from an idle condition to 95% of power within 5 seconds to simulate an emergency takeoff
  - It must be able to operate through out the operational envelope without encountering a stall event that results in a rapid loss of thrust.
- The STARC-ABL dynamic turbofan simulation was executed at 720 operating points encompassing the full flight envelope.
  - The controller was able to provide the a rise time of less than five seconds meeting the FAA requirement
  - Further analysis is being conducted for operability changes with newly available electrical machines





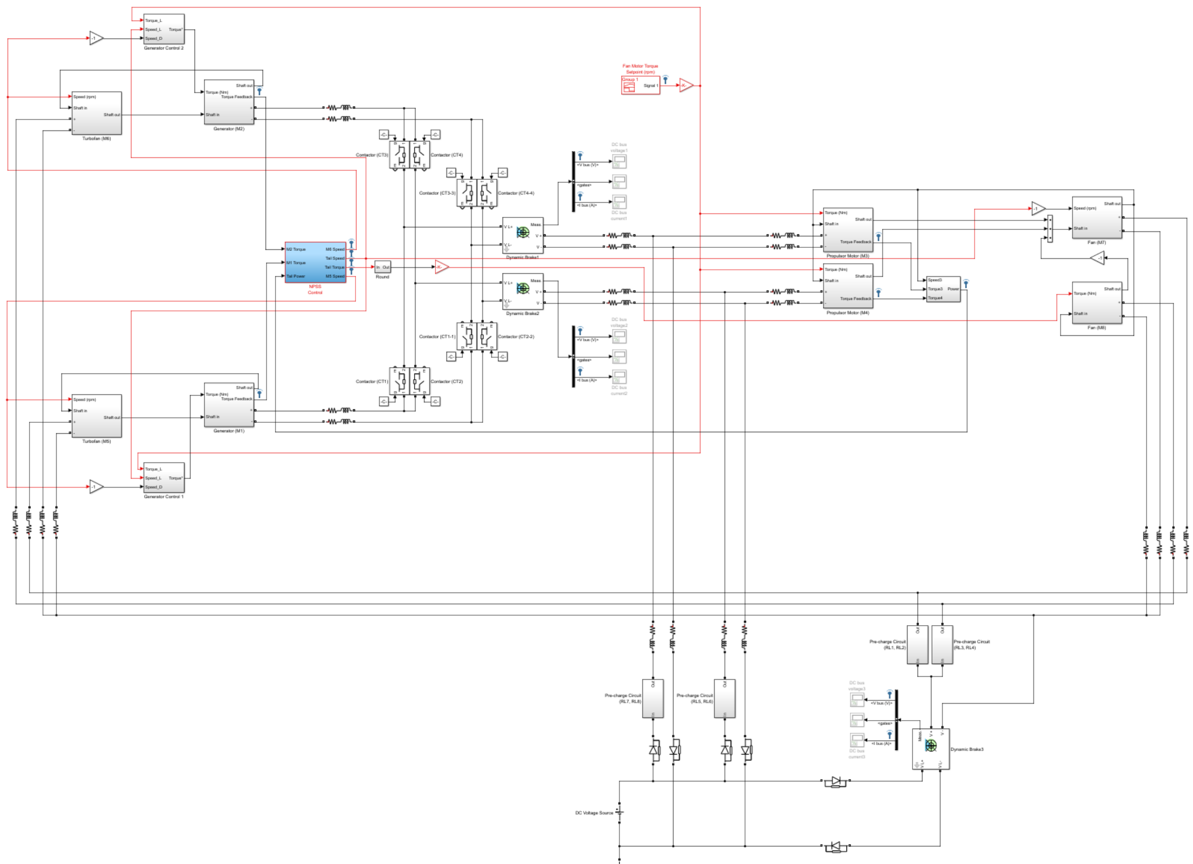
NEAT STARC-ABL Control Diagram



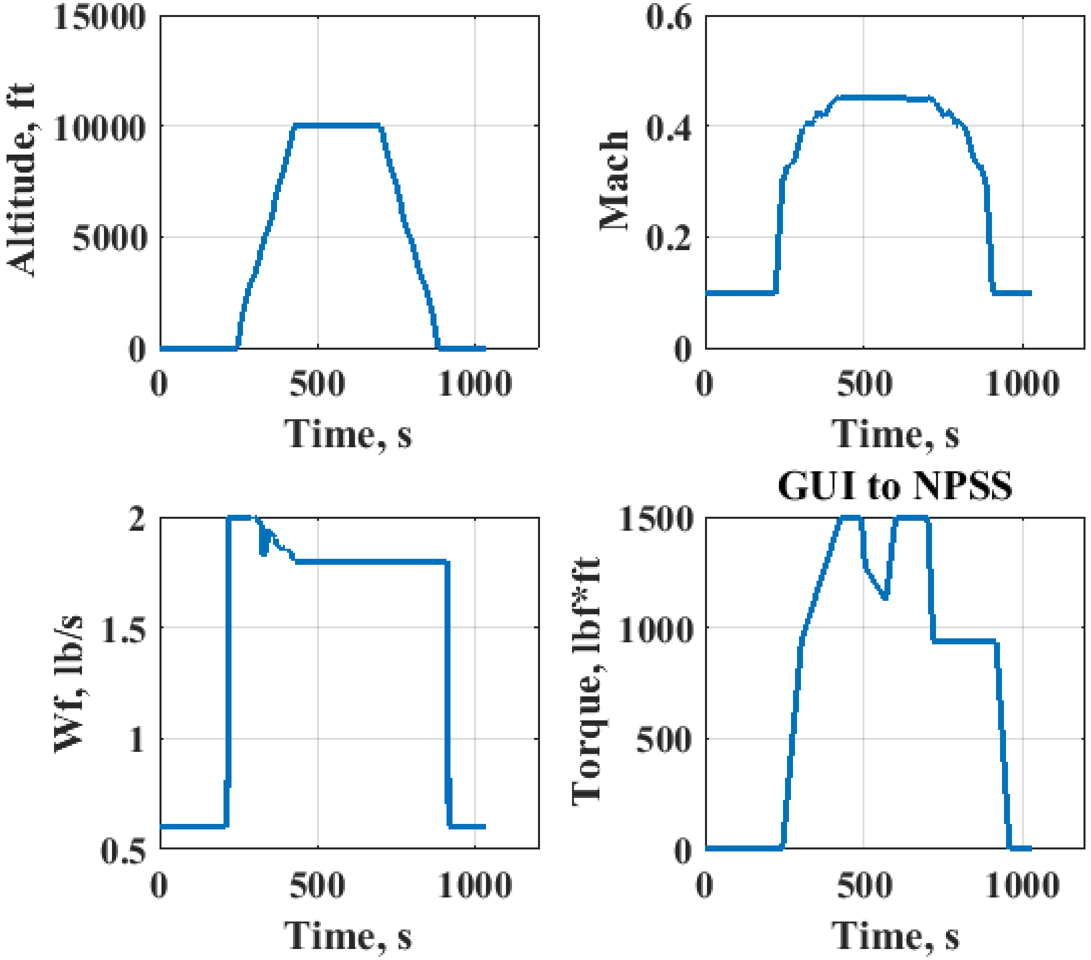
NEAT Power Systems and Control Modeling

Modeling done in MATLAB/Simulink with the SimPowerSystems toolbox

- AC/DC power supplies (SCR controlled or ideal DC source)
- Space vector PWM inverters (switch-level or average-value models)
- Permanent magnet motors
- Diodes, brake resistors, cables, pre-charge circuits
- NPSS integration

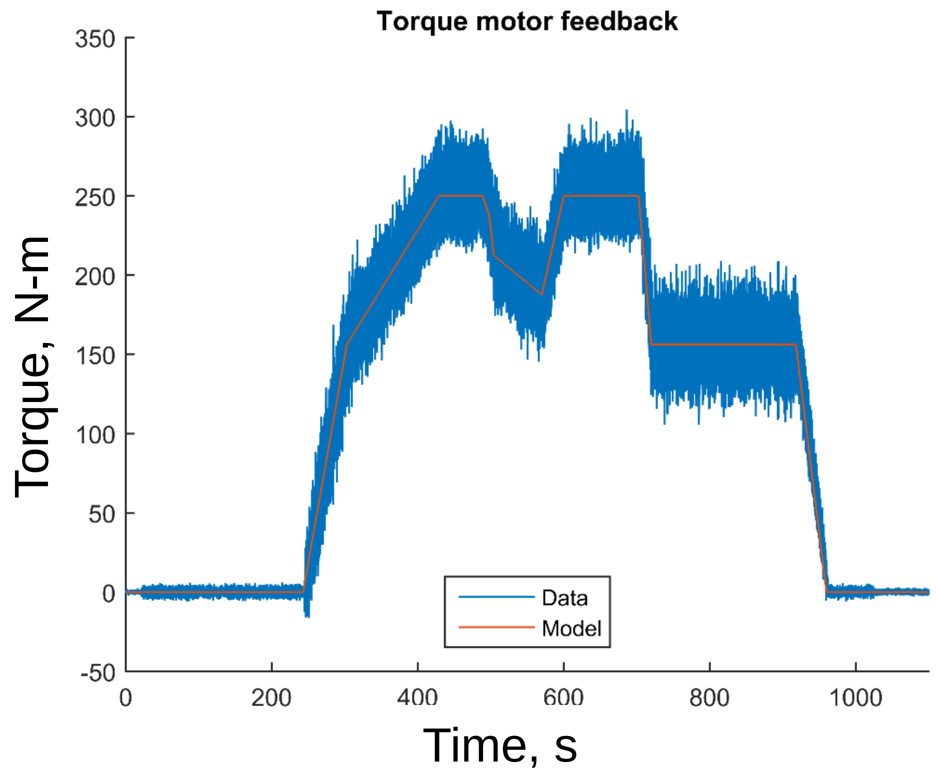


Flight Profile for Single String Test

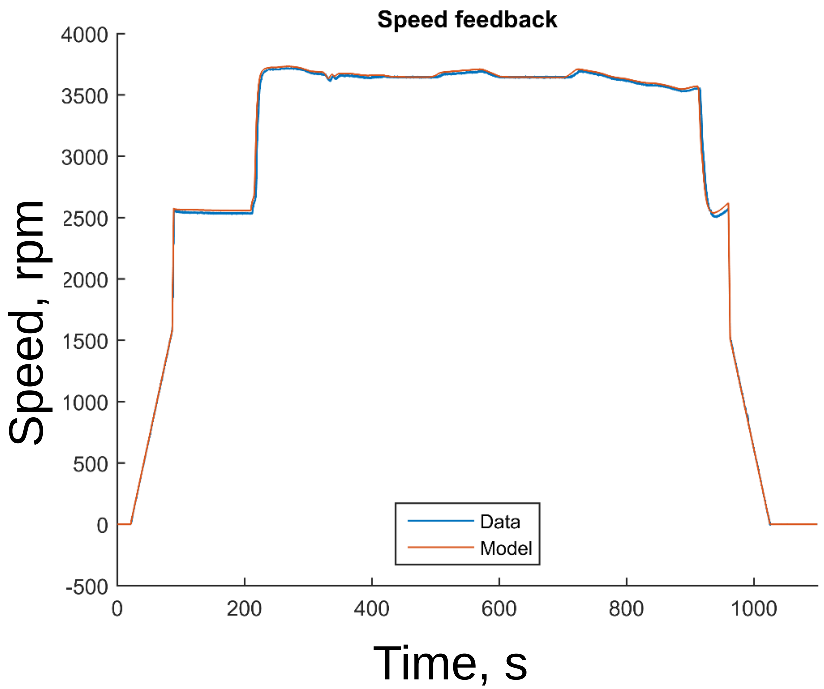


Single String: Speed/Torque Response

- Model over predicts speed command since the model used load torque feedback while the test used drive torque feedback
- Test data shows more noise than model

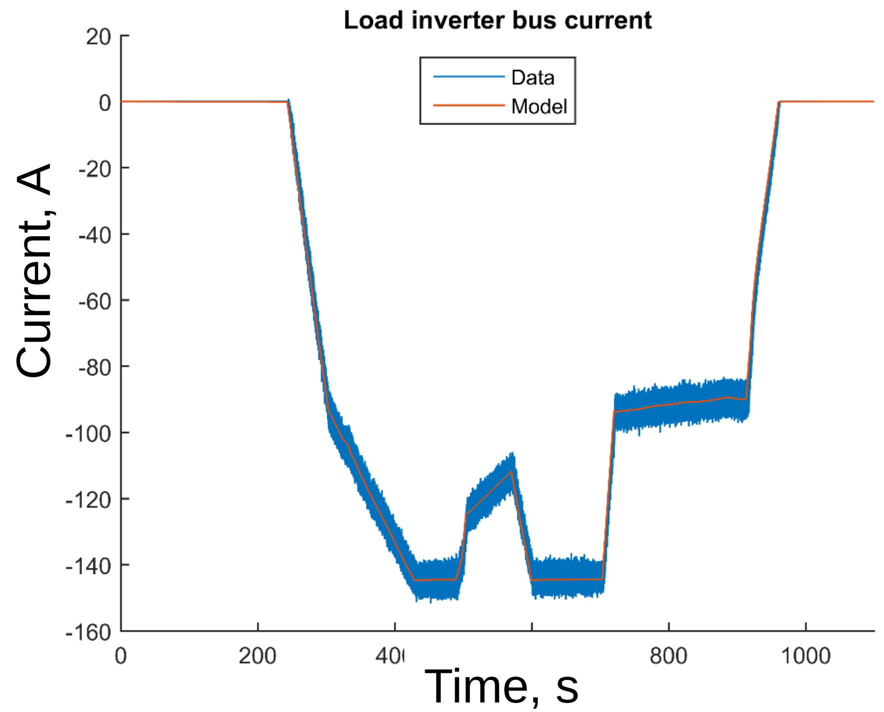


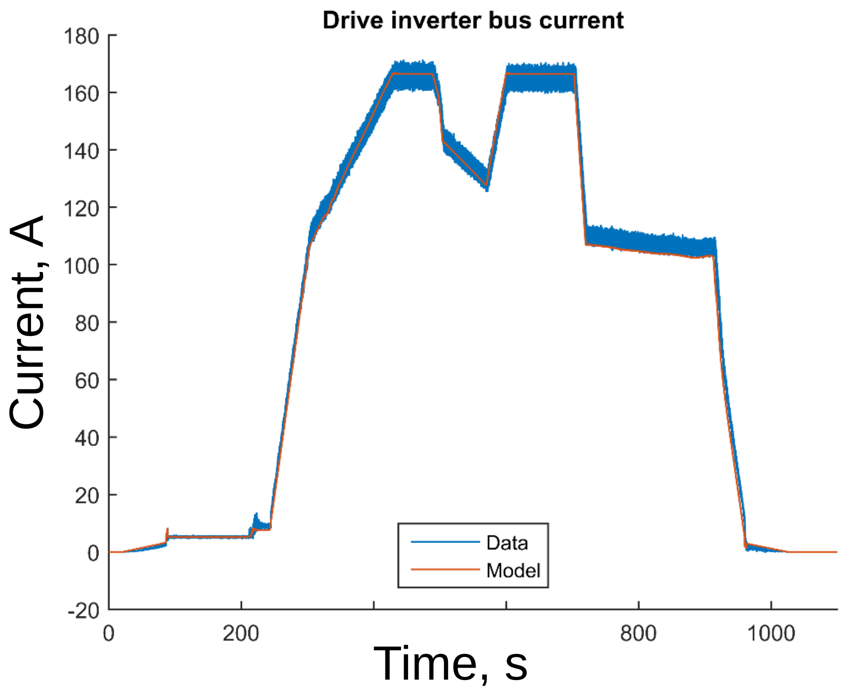
- Both the model and test hardware follow the command closely



Single String: Current Response

- Test data shows more noise than model since switching harmonics are not modeled
- Data shows higher current draw due to lack of inverter losses in model

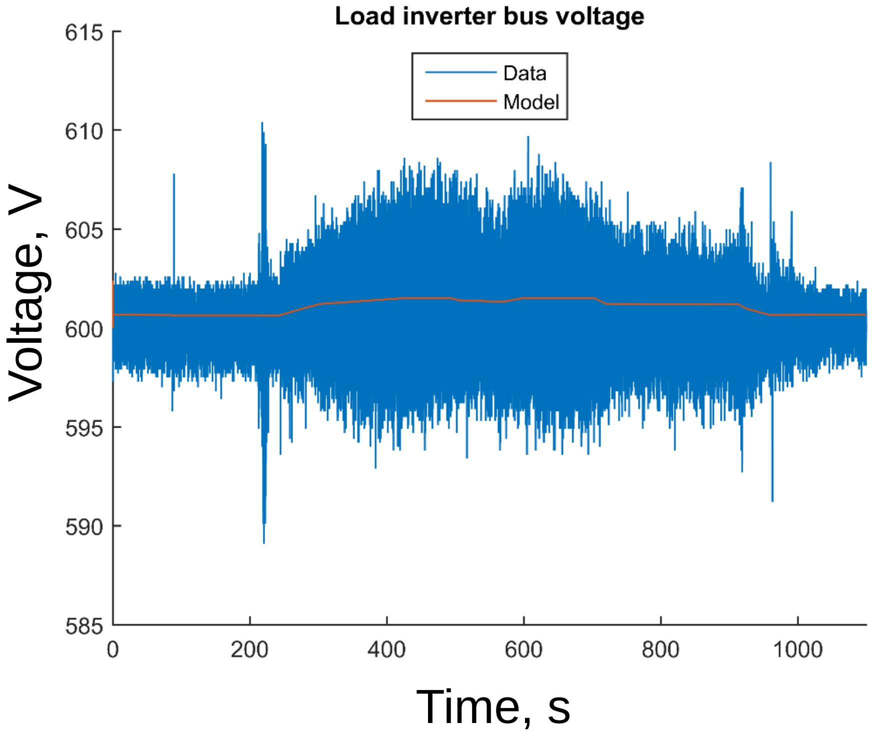


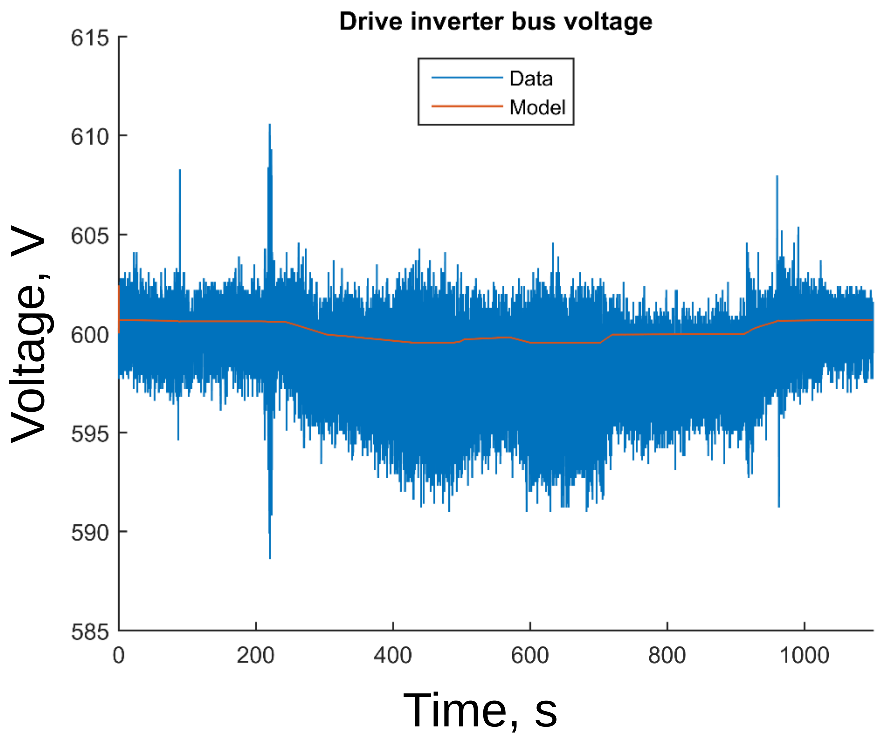


Simplified shaft model may over predict losses, offsetting under prediction of inverter losses

Single String: Voltage Response

- Test data shows more noise than model since switching harmonics and DC supplies are modeled as ideal
- Model prediction follows same trend as data but does not capture spikes





- Model prediction follows same trend as data but does not capture spikes

Conclusions

- Analysis conducted on N+3 STARC-ABL concept
  - Verified transient operability of NASA concept engine with baseline control designs
  - Electric component modeling using MATLAB Simscape provides a good comparison to test data with/without including the higher fidelity electrical switching
    - The ability to neglect the switching provides a tool for more rapid control system development, whereas the electrical switching model provides a high fidelity test environment
- NASA is exploring various ways to reduce the emissions of commercial aircraft. A key technology is moving toward more electric aircraft
  - Conducting studies of aircraft powered by turboelectric systems to better understand the benefits, component performance sensitivities, certification issues, and trade-offs related to key aircraft systems.
  - Developing research facilities and simulation tools for megawatt-class electric power suitable for turboelectric aircraft propulsion systems.
- A near term goal is to develop and demonstrate critical technologies for hybrid gas-turbine electric propulsion by 2025 to impact the next generation of single aisle aircraft

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Acknowledgments

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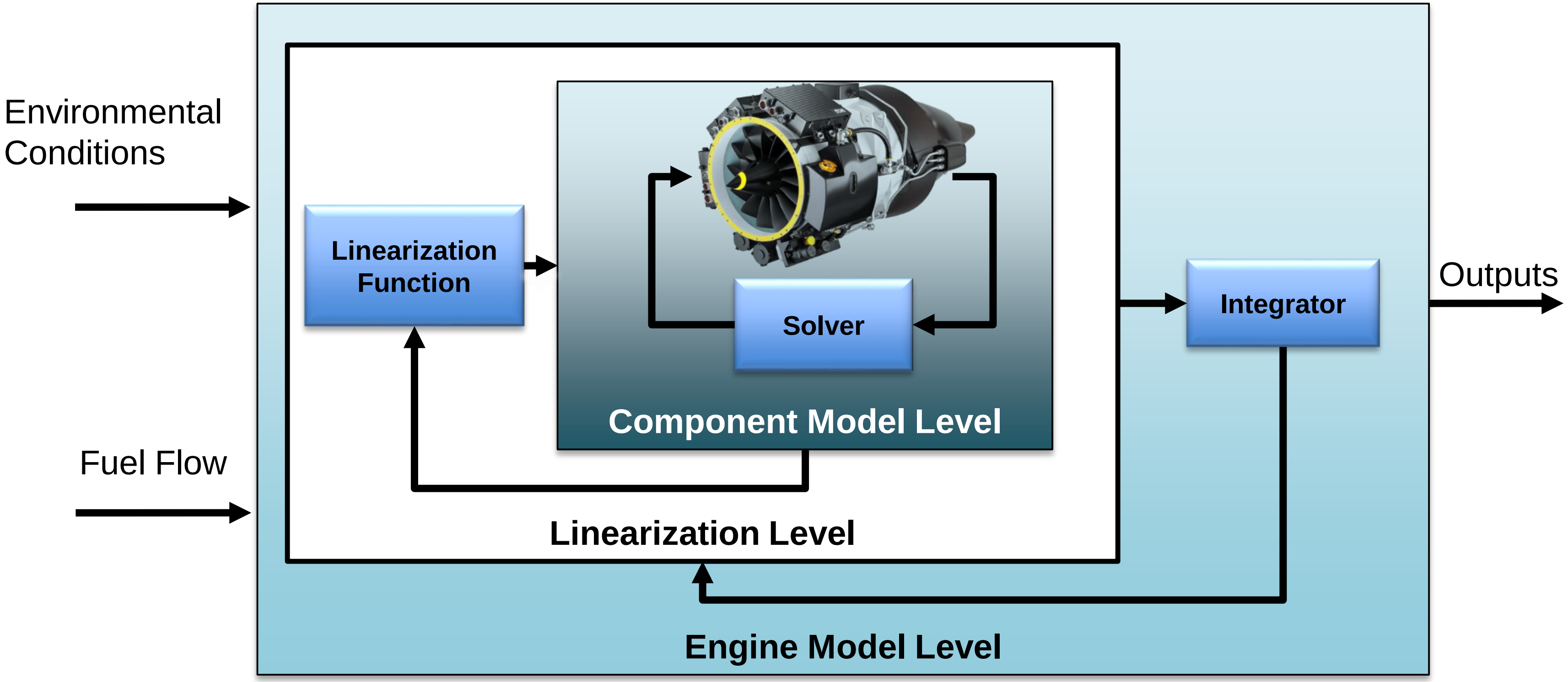
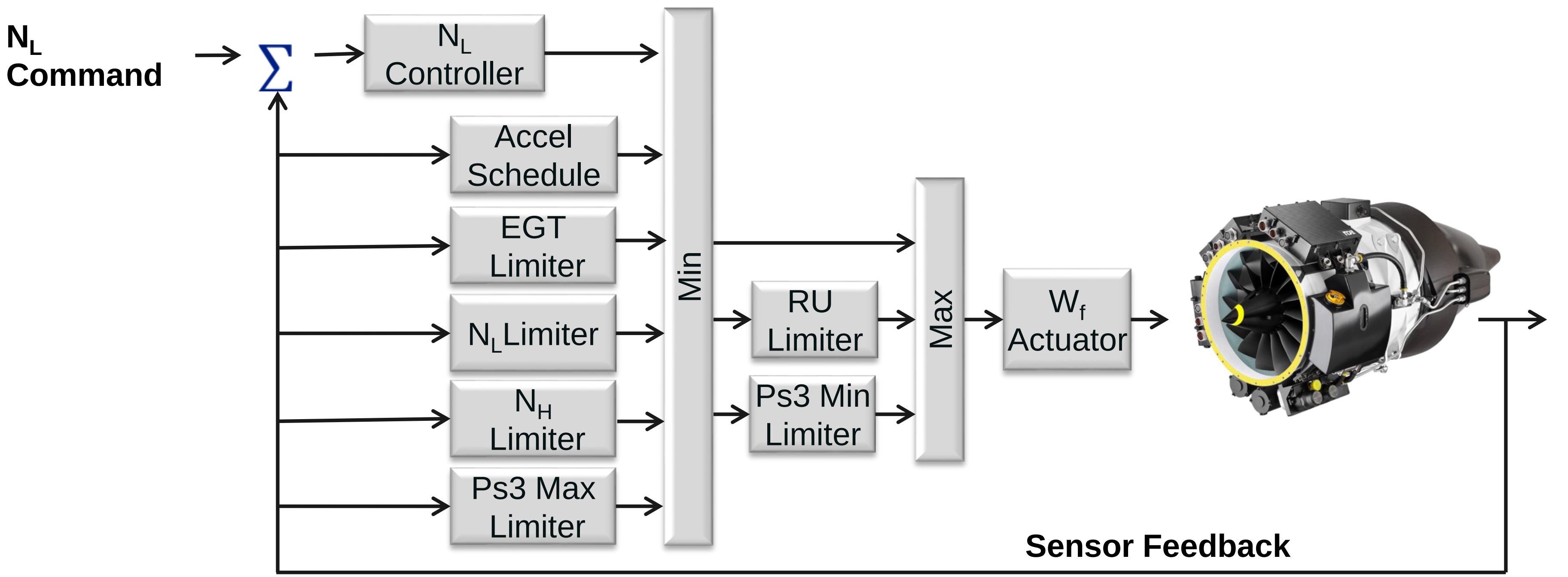
BACKUP

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

- T-MATS abilities:
  - Iterative solving capability
  - Generic thermodynamic component models
  - Control system modeling (controller, actuator, sensor, etc.)



Baseline Control Architecture



- Thrust cannot be measured and hence is indirectly controlled through regulating a measured variable which correlates with thrust e.g. Low Speed Spool (N_L).
- For DART facility safety the key limiter to enable operation has been the N_L max limiter