SUbsonic Single Aft eNgine (SUSAN) Power/Propulsion System Hardware-in-the-Loop Test Results

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Presentation Outline

- Background and Motivation
- SUbsonic Single Aft eNgine (SUSAN) Electrofan Concept Aircraft
- SUSAN Power/Propulsion System (PPS) Model and Control Architecture
- Hybrid Propulsion Emulation Rig Facility and SUSAN Model Integration
- Hardware-in-the-Loop (HIL) Test Results and Analysis
- Conclusions

SUSAN Electrofan Concept Renderings (NASA)

Motivation

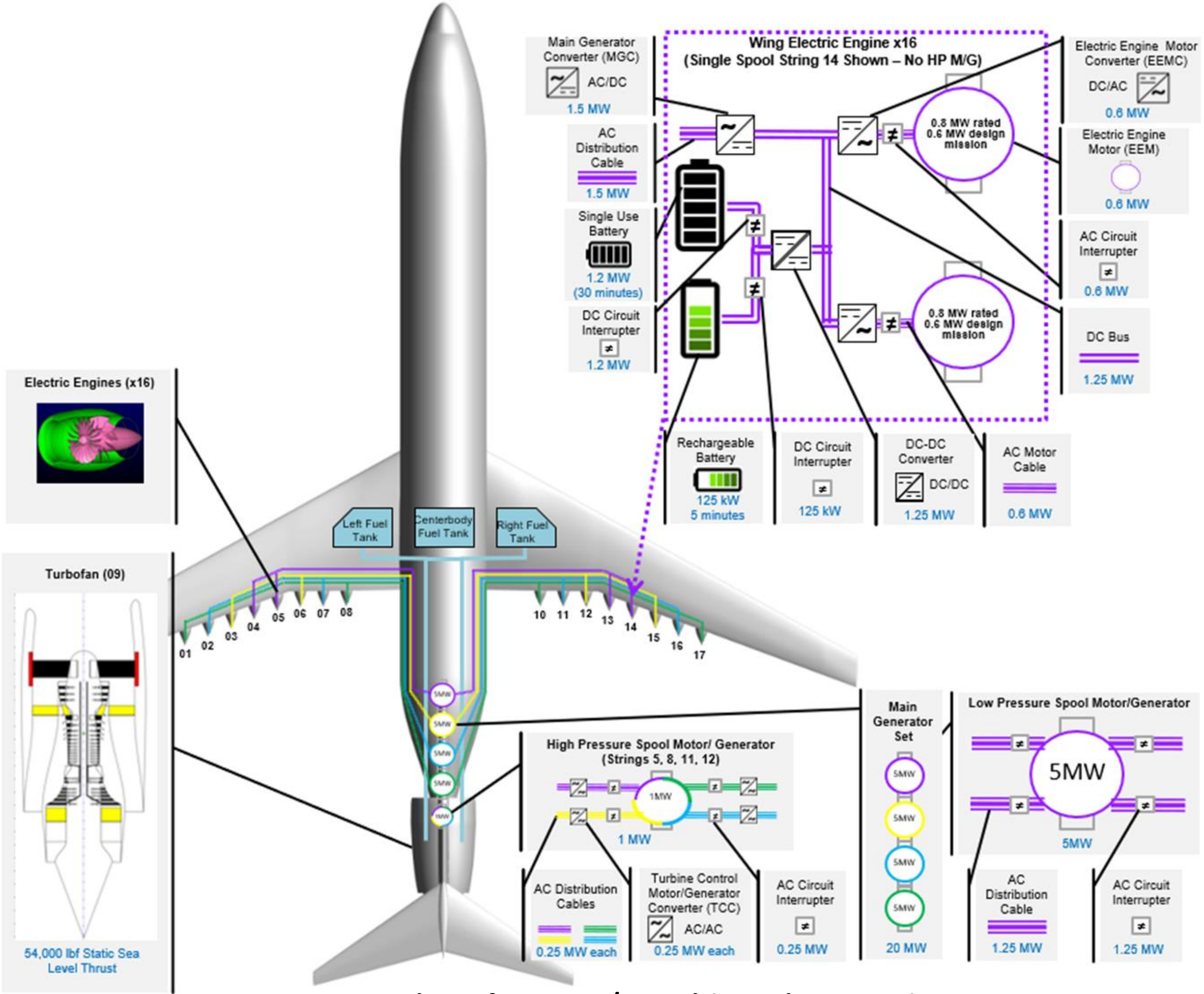
- Electrified Aircraft Propulsion (EAP) technology offers a potential leap forward for transport aircraft performance and efficiency, filling a gap between modern technology and true zero-emission aviation.
- EAP systems are frequently complex and with tightly coupled subsystems, requiring robust control algorithms to deliver basic functionality.
- Real-time models and Hardware-in-the-Loop (HIL) testing are important tools for bridging the gap between high-level systems analysis and detailed design and implementation.
    - Allow for validation of EAP system models and control algorithms in realistic environments at low cost.

SUbsonic Single Aft eNgine (SUSAN) Concept

- 20 MW Series/Parallel Partial Hybrid EAP system
- Leverages Boundary Layer Ingestion (BLI), Propulsion-Airframe Integration (PAI), and Distributed Electric Propulsion (DEP) technologies to reduce block fuel burn
- Aft-mounted geared turbofan engine with BLI and up to 20 MW power extraction
  - 16 motor/generators (M/Gs) on low-pressure shaft (LPS)
  - 4 M/Gs on high-pressure shaft (HPS)
- 16 electric engines (EEs), 8 mounted under each wing in a mail-slot configuration
  - Each EE has an independent, fully redundant electrical power system (EPS)
  - 4 EPSs include both HPS and LPS M/Gs
- Secondary (rechargeable) batteries (SBs) used to decouple EE and GTF operation
  - Enables independent throttle control of EEs and GTF
- Primary (non-rechargeable) batteries (PBs) used in case of engine failure

R. H. Jansen, C. C. Kiris, T. Chau, G. K. W. Kenway, L. G. Machado and J. C. Duensing, "Subsonic Single Aft Engine (SUSAN) Transport Aircraft Concept and Trade Space Exploration," in AIAA SciTech Forum, San Diego, CA, 2022.

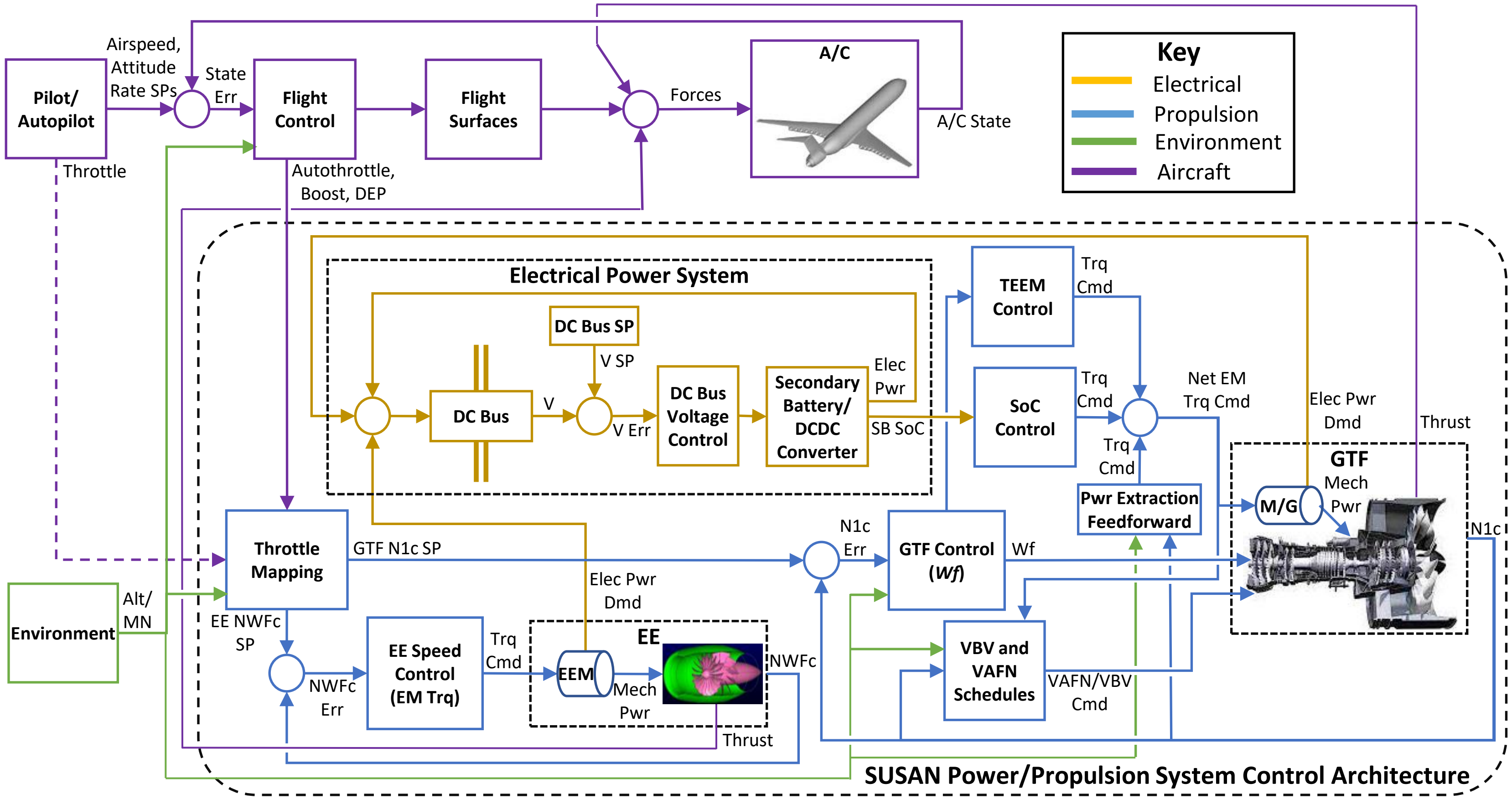
T. Chau and J. C. Duensing, "Conceptual Design of the Hybrid-Electric Subsonic Single Aft Engine (SUSAN) Electrofan Transport Aircraft," in AIAA SciTech Forum, Orlando, FL, 2024.



SUSAN Electrofan Power/Propulsion Subsystem Diagram

Power/Propulsion System and Controller

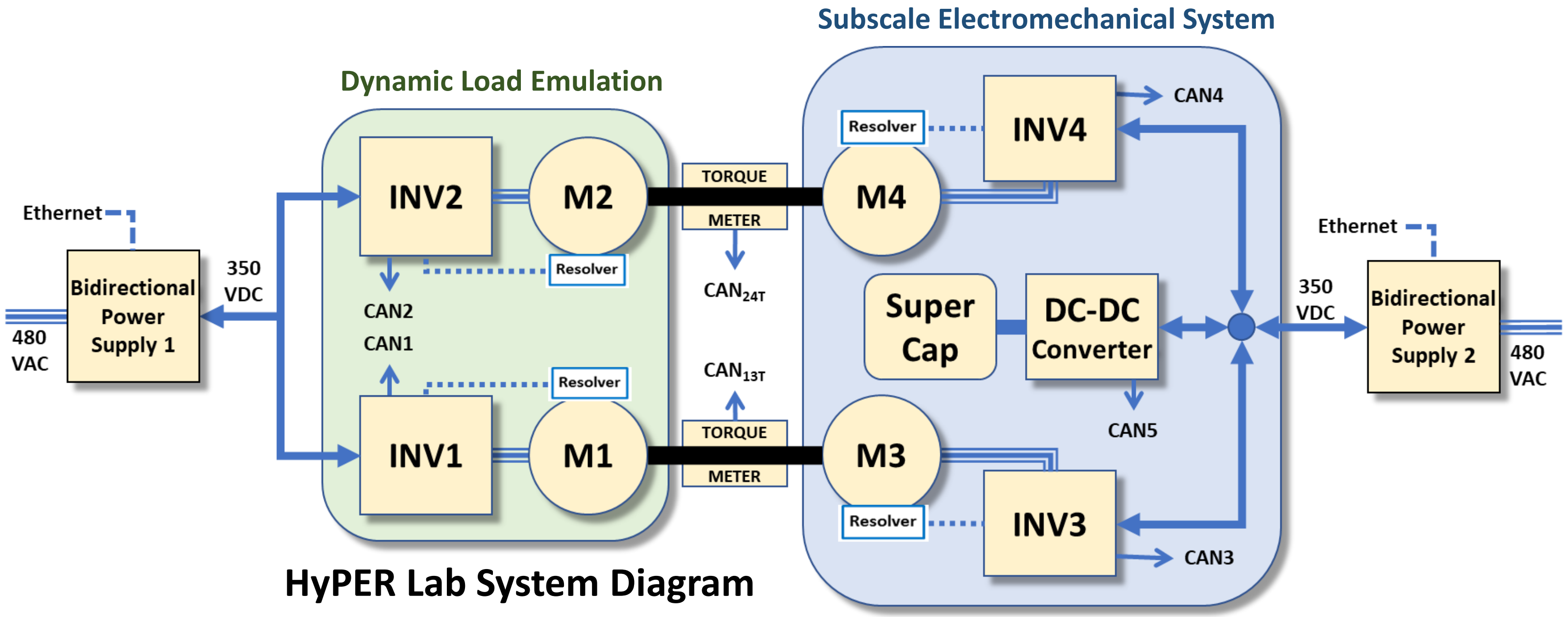
- SUSAN PPS Control Architecture diagram
- Utilizes multiple overlapping control loops with different time constants
  - GTF controlled through fuel flow
  - EEs controlled through motor torque
  - M/Gs used to regulate battery state-of-charge (SOC) and support GTF operability through Turbine Electrified Energy Management (TEEM)
  - DCDC Converter regulates DC Bus voltage



J. J. Sachs-Wetstone, J. S. Litt, J. L, Kratz, and H. E. Buescher, "SUbsonic Single Aft eNgine (SUSAN) Power/Propulsion System Control Architecture Updates," in AIAA SciTech Forum, Orlando, FL, 2024.

Hybrid Propulsion Emulation Rig (HyPER)

- Software reconfigurable sub-scale EAP controls testbed
  - 100 kW power level
  - 2 mechanical shafts
  - dSPACE SCALEXIO real-time (RT) computer
- Turbomachinery shaft dynamics (torque, speed) emulated with Adaptive Sliding Mode Impedance Controller with Scaling (ASMICS)
- Used to replace modeled components for one EE/EPS in a real-time implementation of the SUSAN PPS model



HyPER Lab System Diagram

Full-Scale SUSAN vs. Sub-Scale HyPER EPS Parameters

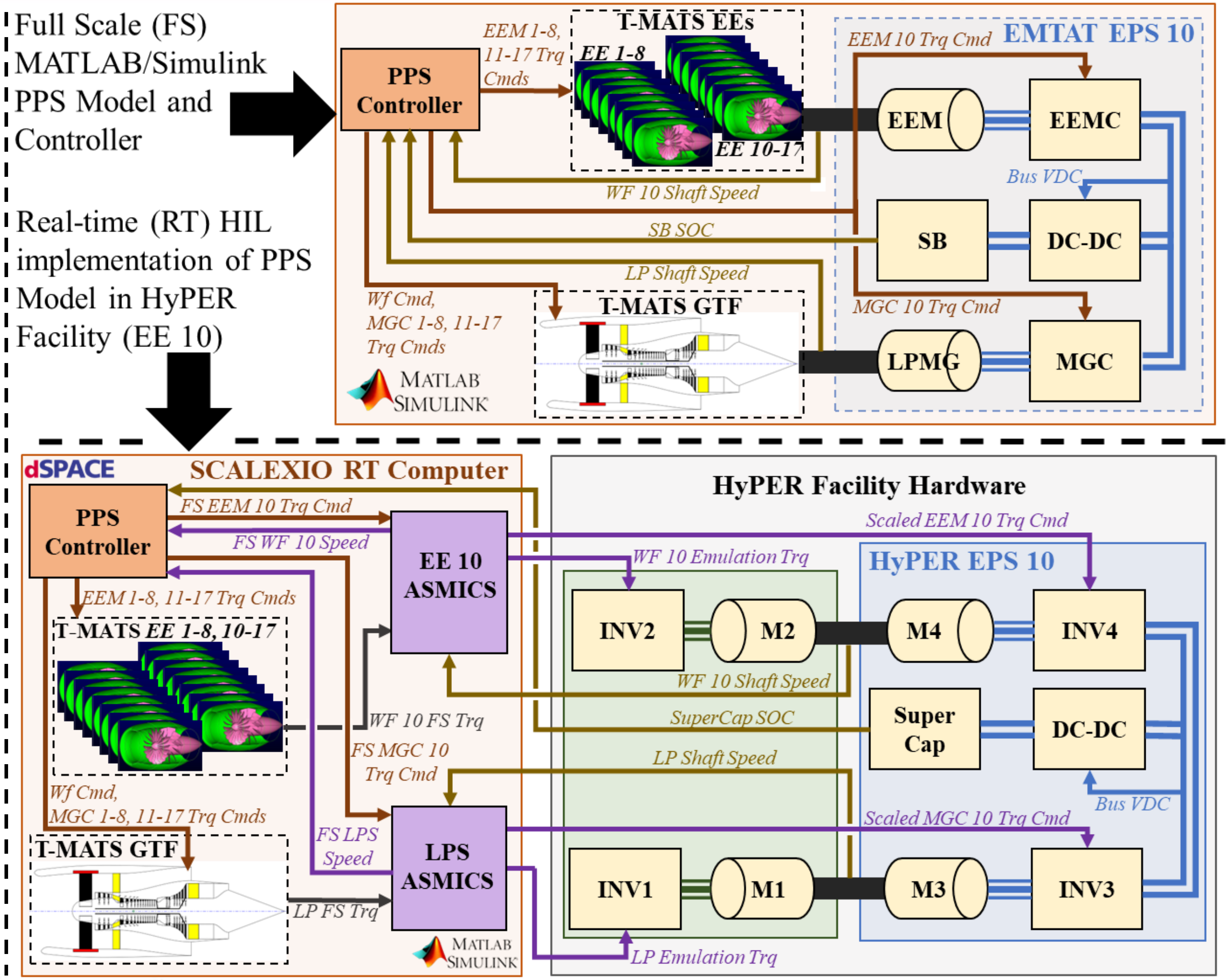
SUSAN EPS Parameter	Full-Scale Value	Sub-Scale Value
Max LP Shaft Speed	5504 RPM	3300 RPM
Max EE 10 EM Shaft Speed	3300 RPM	3300 RPM
MG 10 Peak Torque	1604 lbf*ft	168.6 lbf*ft
EEM 10 Peak Torque	2463 lbf*ft	168.6 lbf*ft
ESD Useful Energy Capacity	60 MJ	751 kJ
DC Bus Voltage	2000 V	350 V

Buescher, Halle E., et al.: Hybrid-Electric Aero-Propulsion Controls Testbed: Overview and Capability. AIAA 2023–0671, 2023.

S. J. Bianco, E. Hill and D. L. Simon, "Adaptive Control and Scaling Approach for the Emulation of Dynamic Subscale Torque Loads," in AIAA SciTech Forum, Orlando, FL, January 2024.

SUSAN PPS HyPER Implementation

- Full-Scale (FS) MATLAB/Simulink PPS Model and Controller (top).
  - Software-in-the-Loop (SIL) implementation, exists entirely in MATLAB/Simulink environment
    - Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)
    - Electrical Modeling and Thermal Analysis Toolbox (EMTAT)
- Real-time (RT) PPS model and controller with HyPER hardware replacing EPS 10 model
  - Hardware-in-the-Loop (HIL) implementation
  - RT MATLAB/Simulink model interfaces with sub-scale HyPER hardware
    - RT turbomachinery model drives shaft emulation through ASMICS
    - PPS Controller commands HyPER hardware in place of EPS 10 in model
  - EPS 10 selected for emulation as the inboard-most single-spool EPS
- Scaling driven by energy storage component (0.751 MJ supercapacitor vs 60 MJ SB)



J. Chapman, T. Lavelle, R. May, J. Litt and T.-H. Guo, "Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) User's Guide," NASA/TM-2014-216638, January 2014.

M. E. Bell and J. S. Litt, "Electrical Modeling and Thermal Analysis Toolbox (EMTAT) User's Guide," NASA/TM 20205008125, October 2020.

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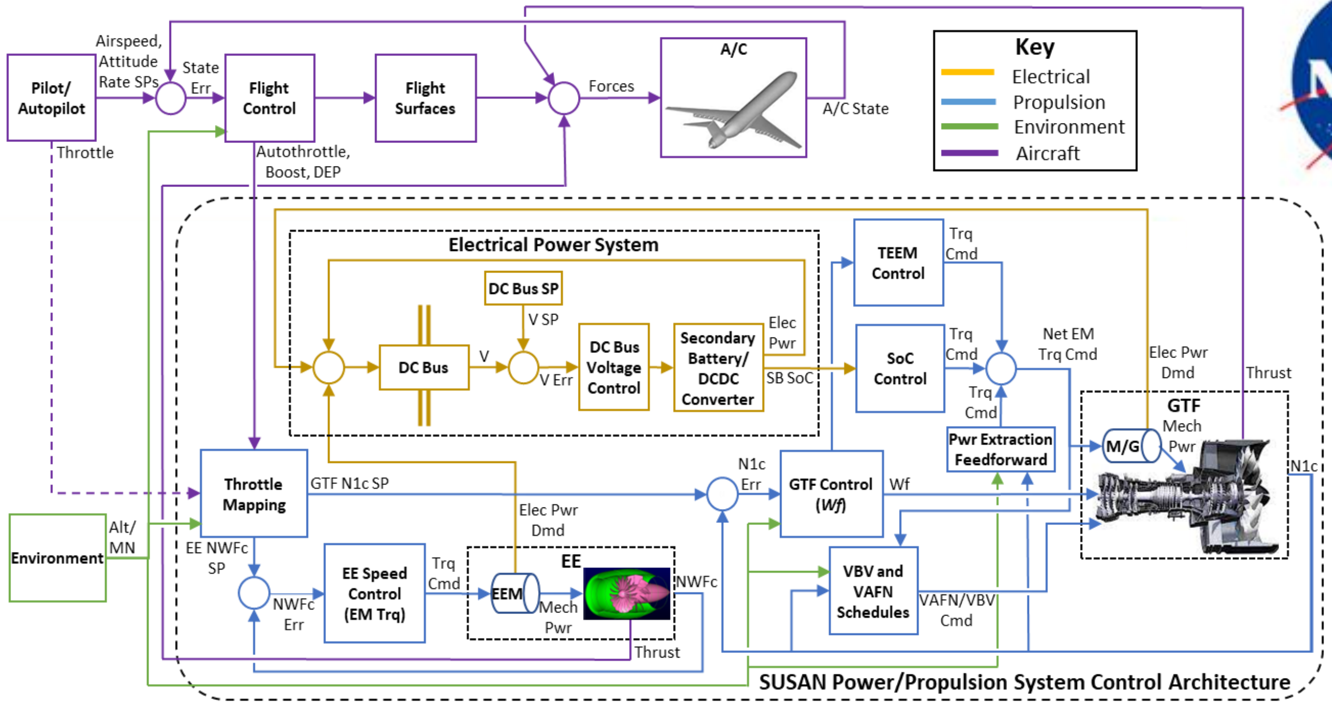
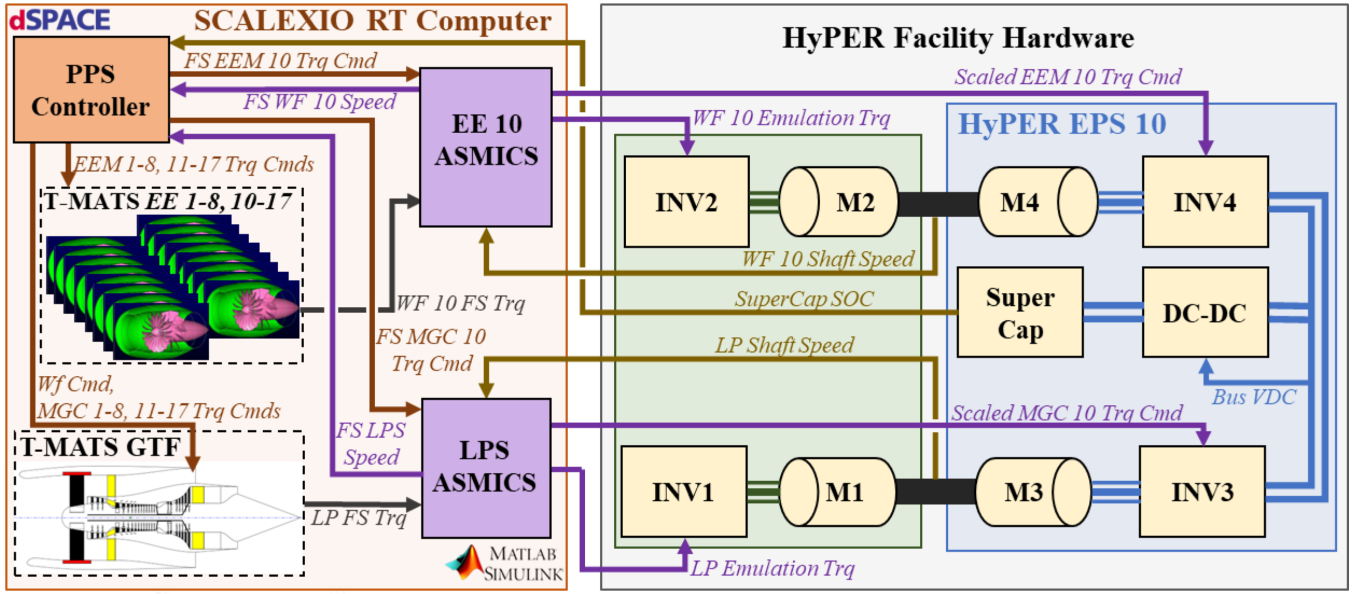
Control Architecture Implementation

Control Loop	Variable	Response Time
GTF Speed Control	W_f	5 – 20 sec
EE Speed Control	EEM Torque	2 sec
TEEM Control	HP and LP M/G Torque	< 5 sec
SB SoC Control	HP and LP M/G Torque	> 240 sec
DC Bus Voltage Control	SB charge/discharge current	< 0.5 sec

Comparing control loops in architecture diagram and HyPER HIL implementation





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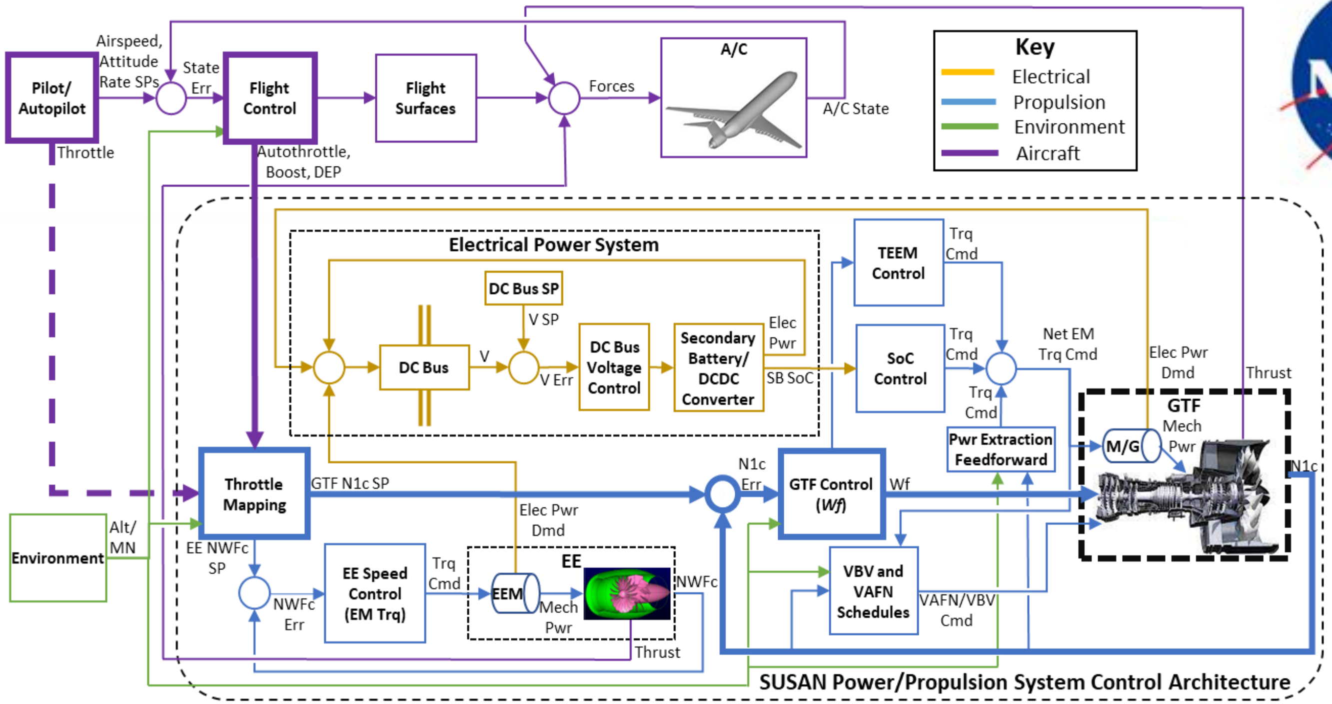

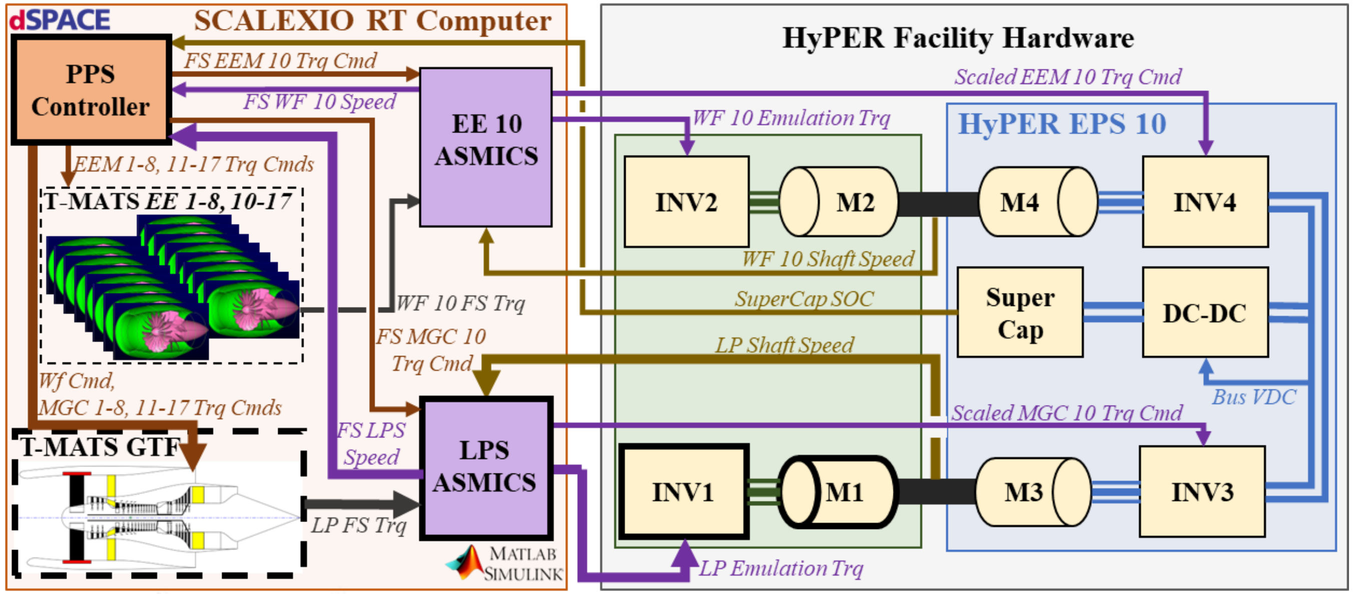

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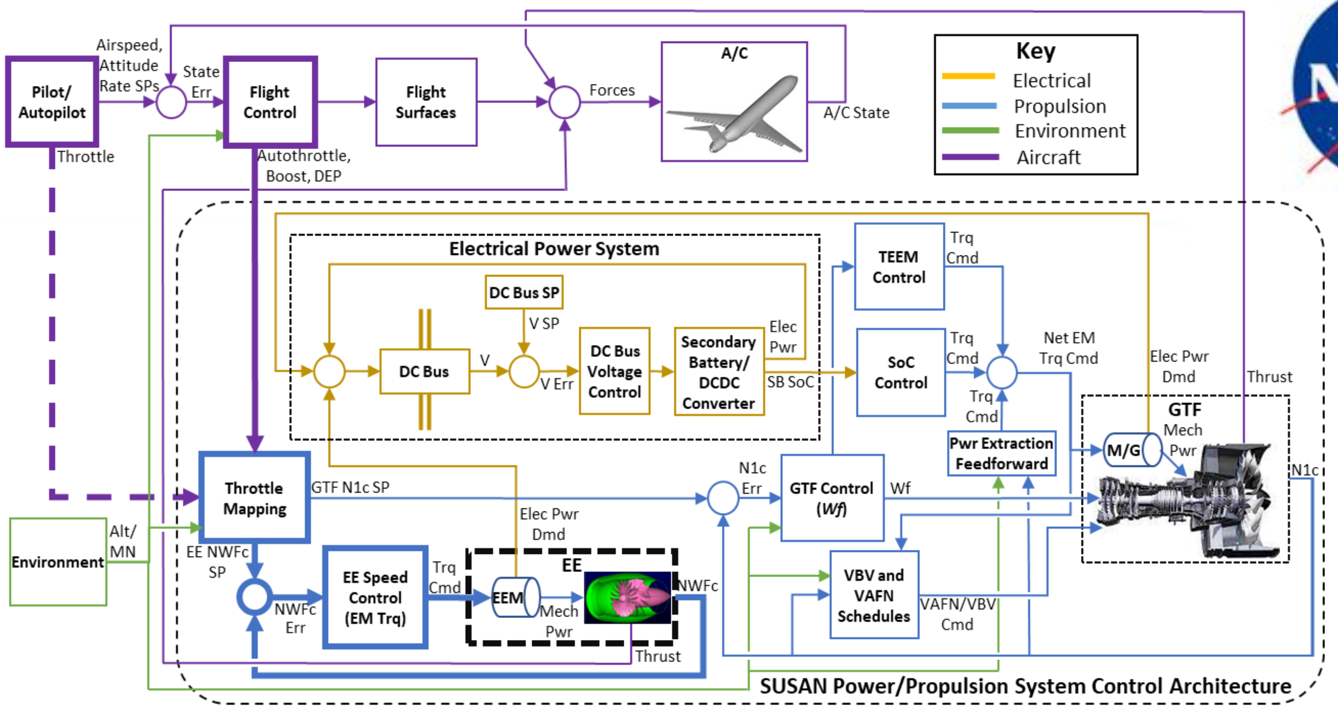

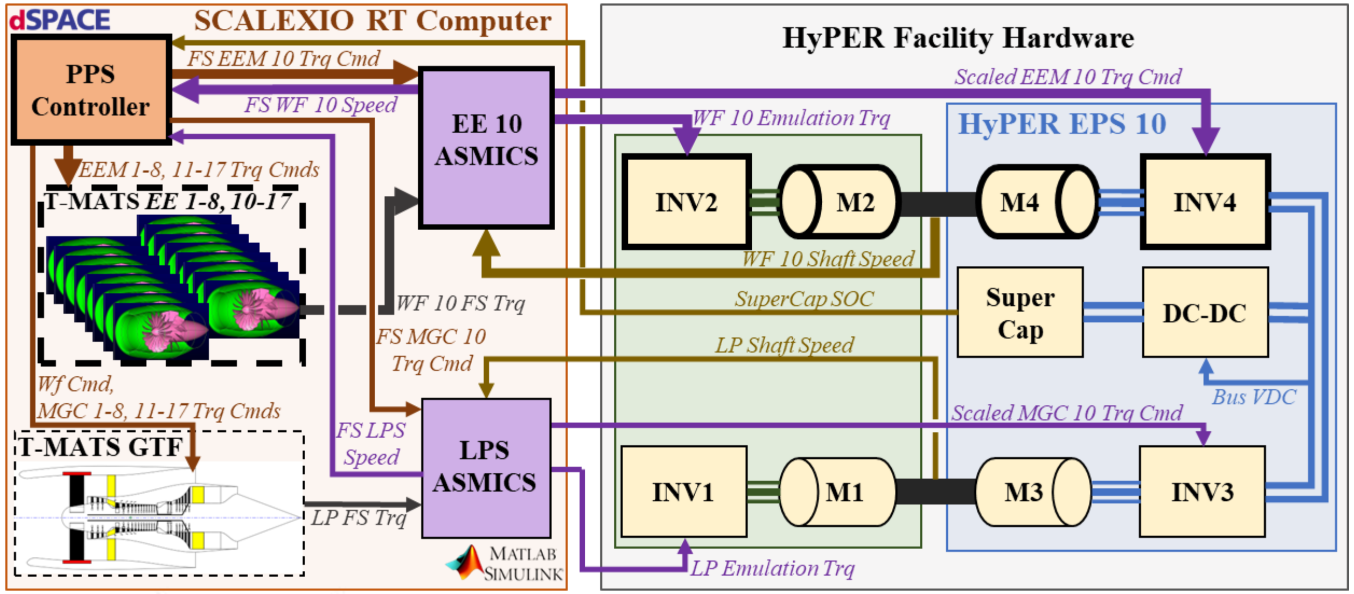

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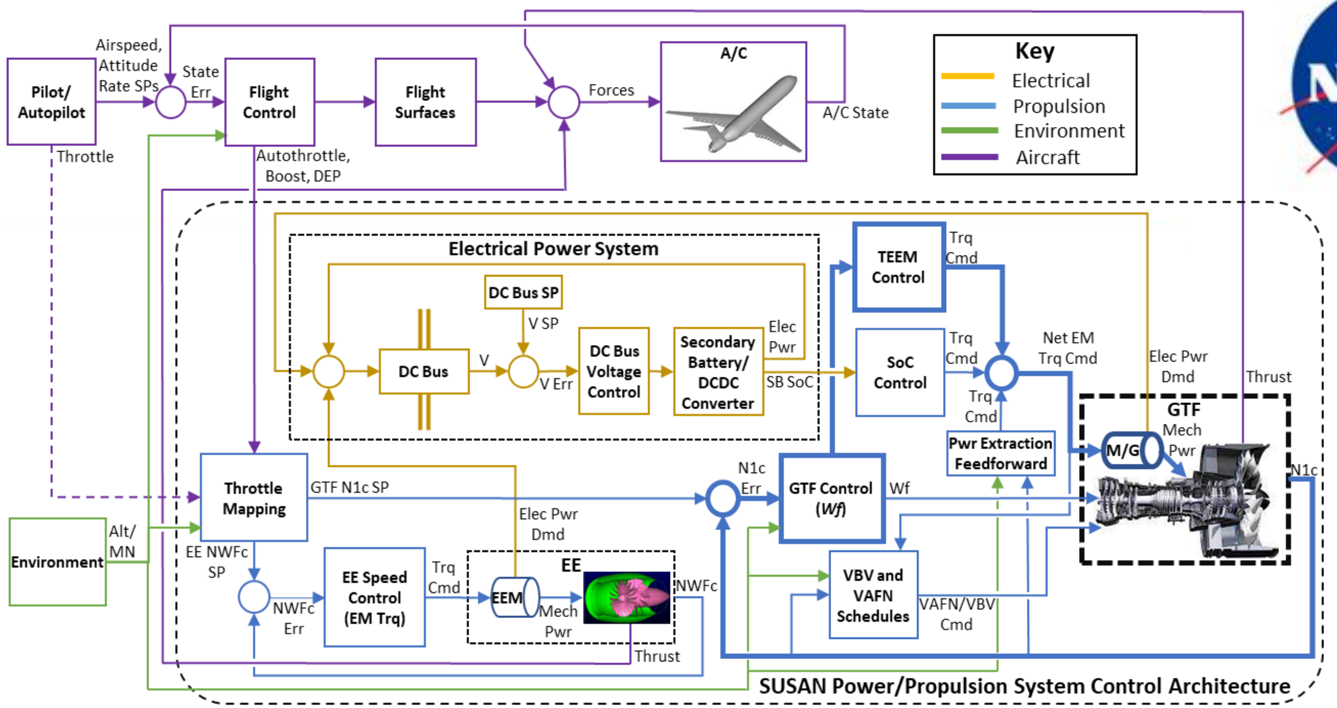

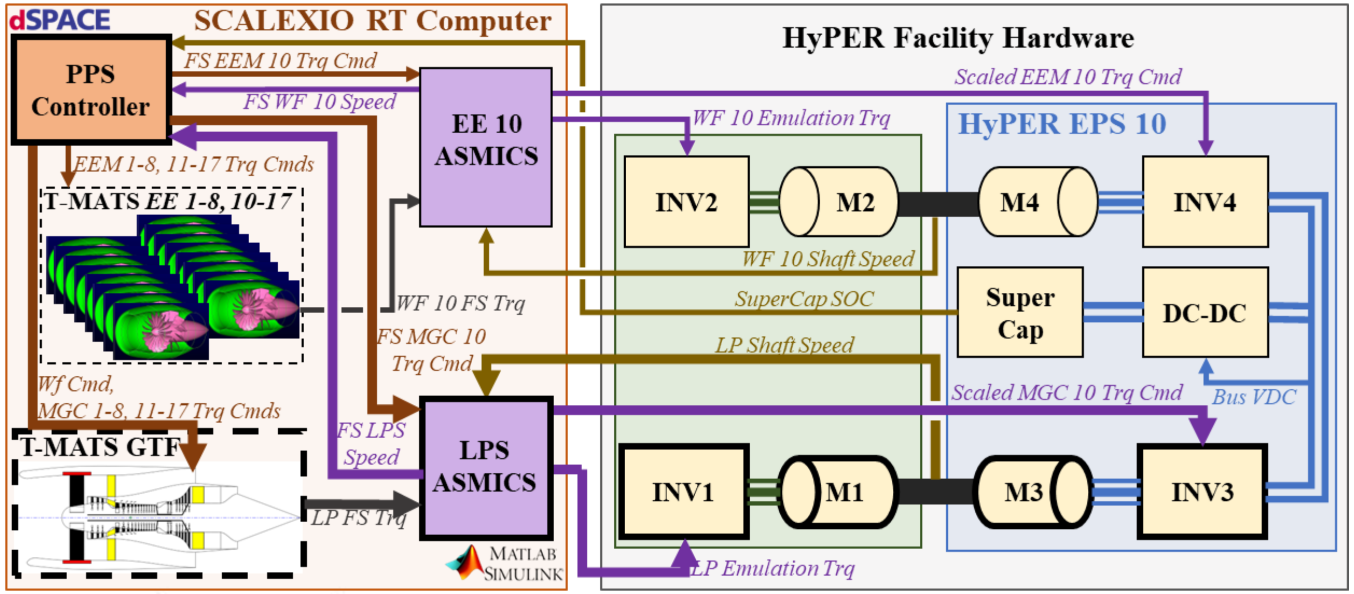

Comparing control loops in architecture diagram and HyPER HIL implementation

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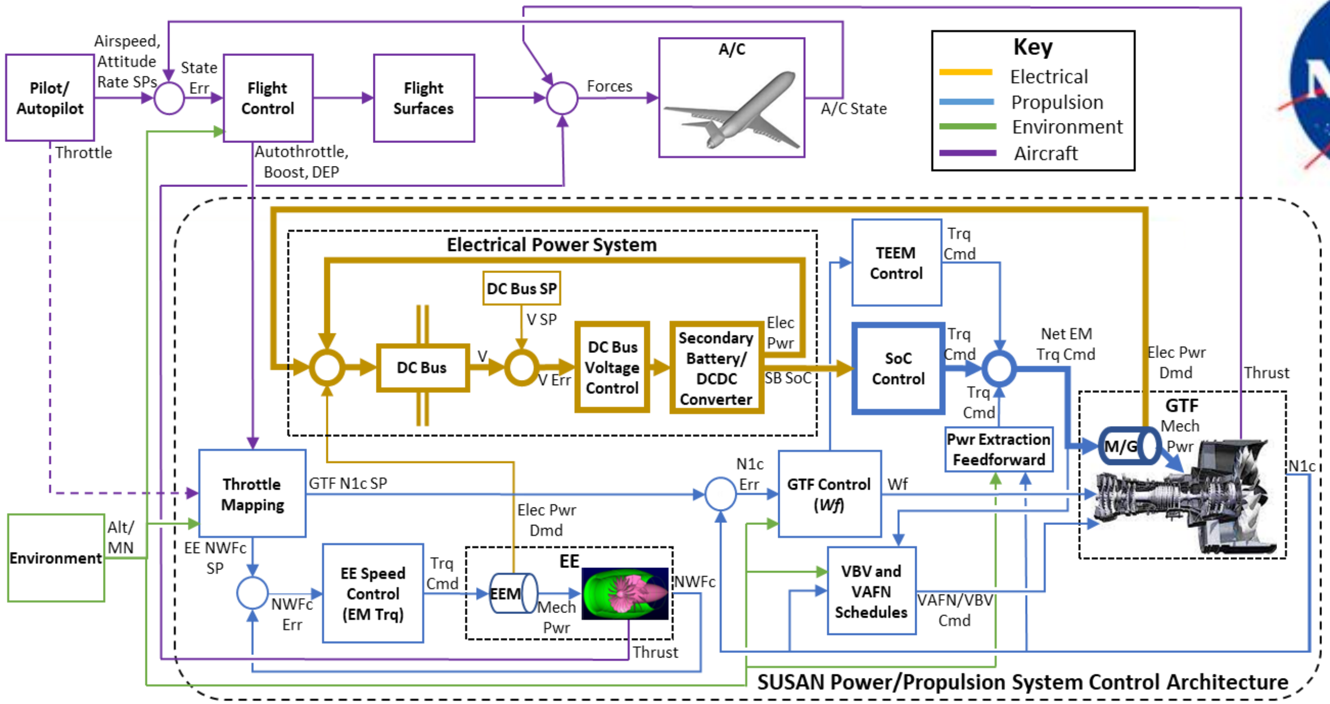

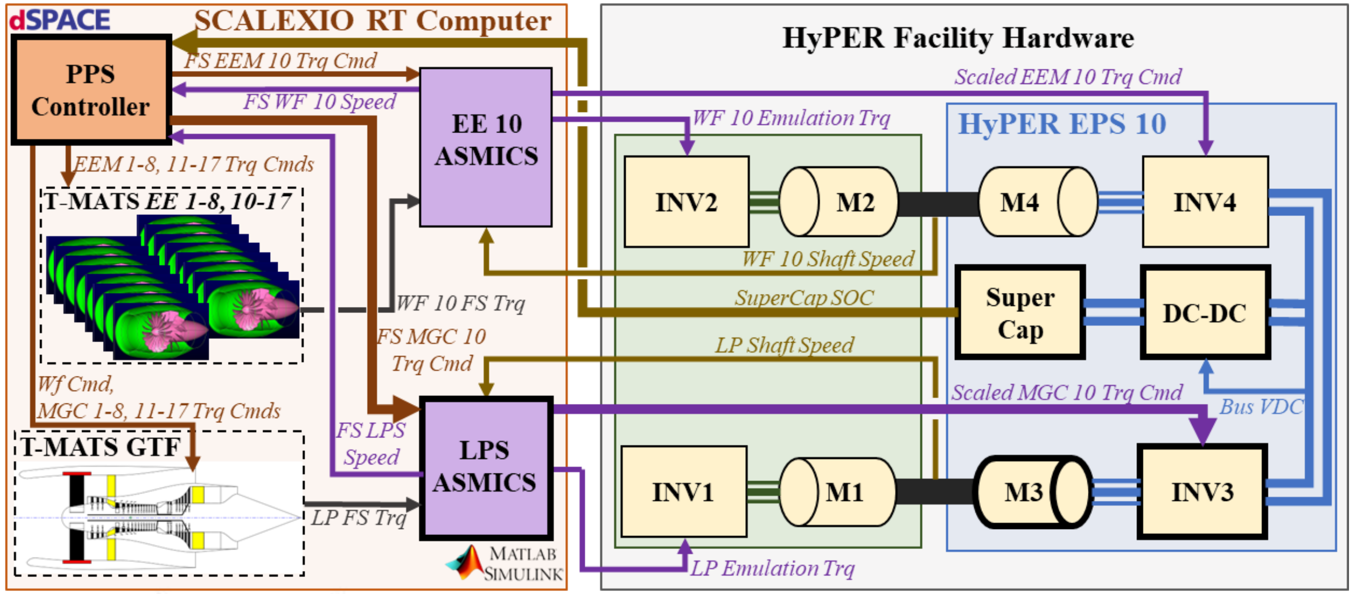

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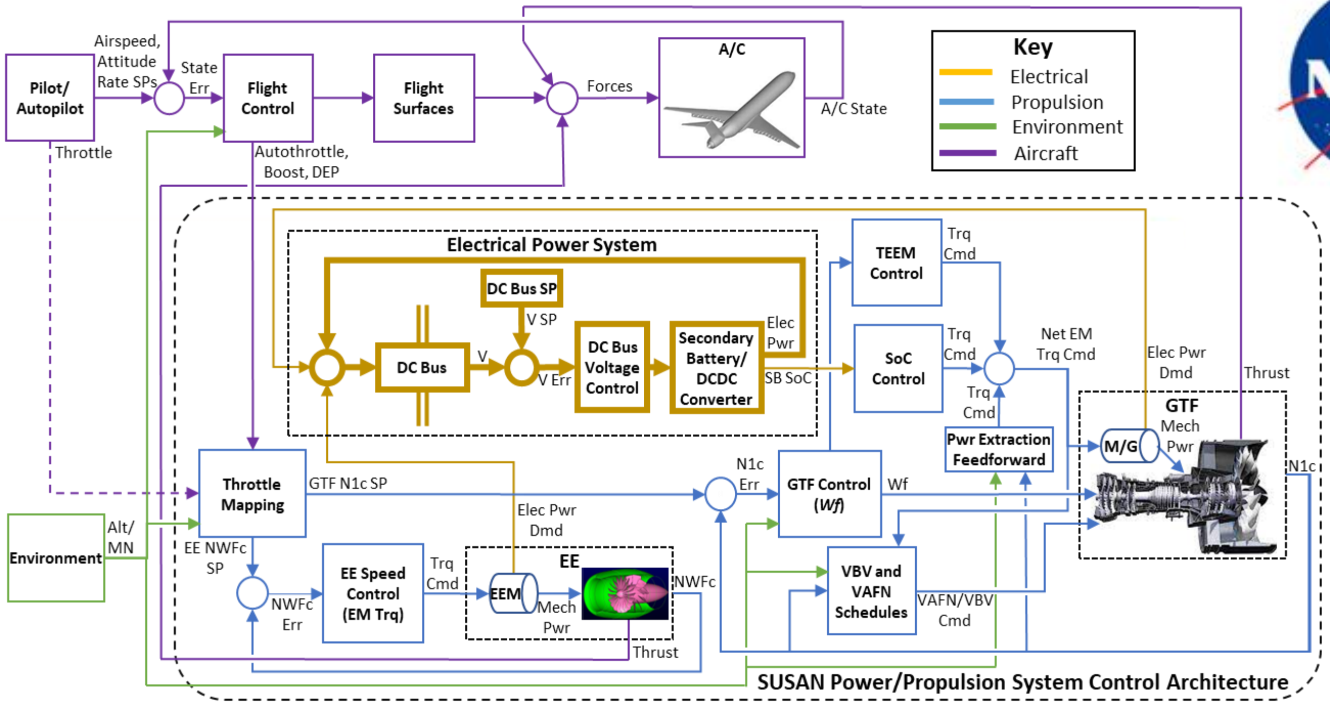
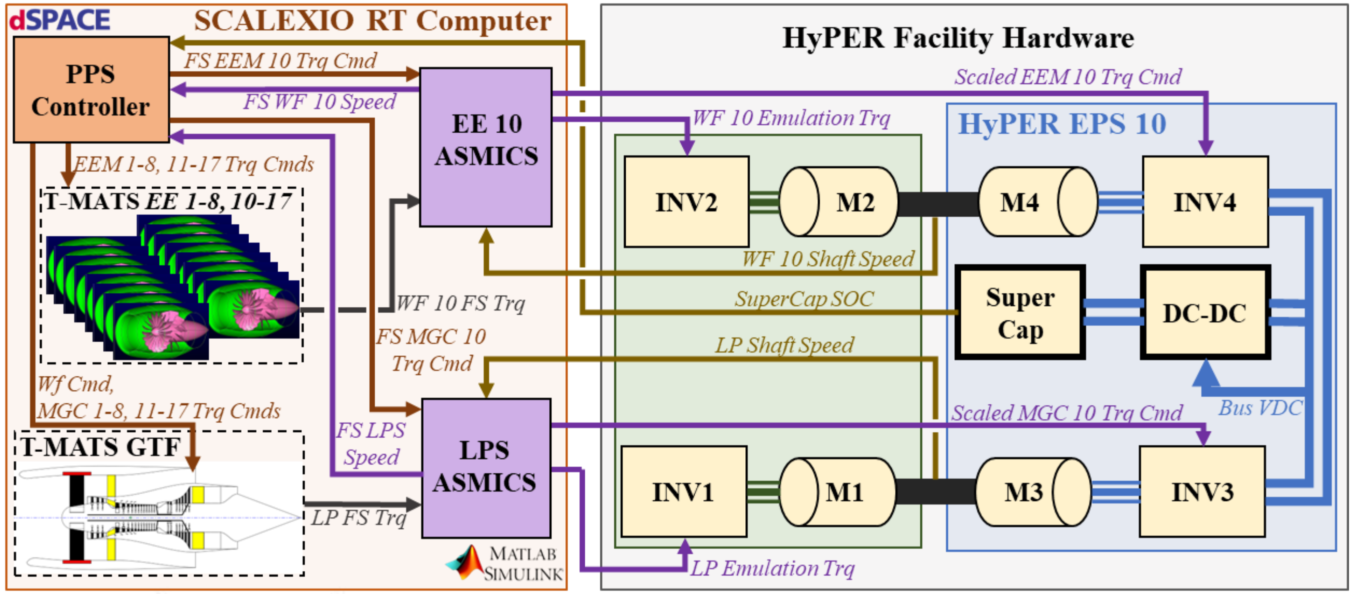
Control Architecture Implementation





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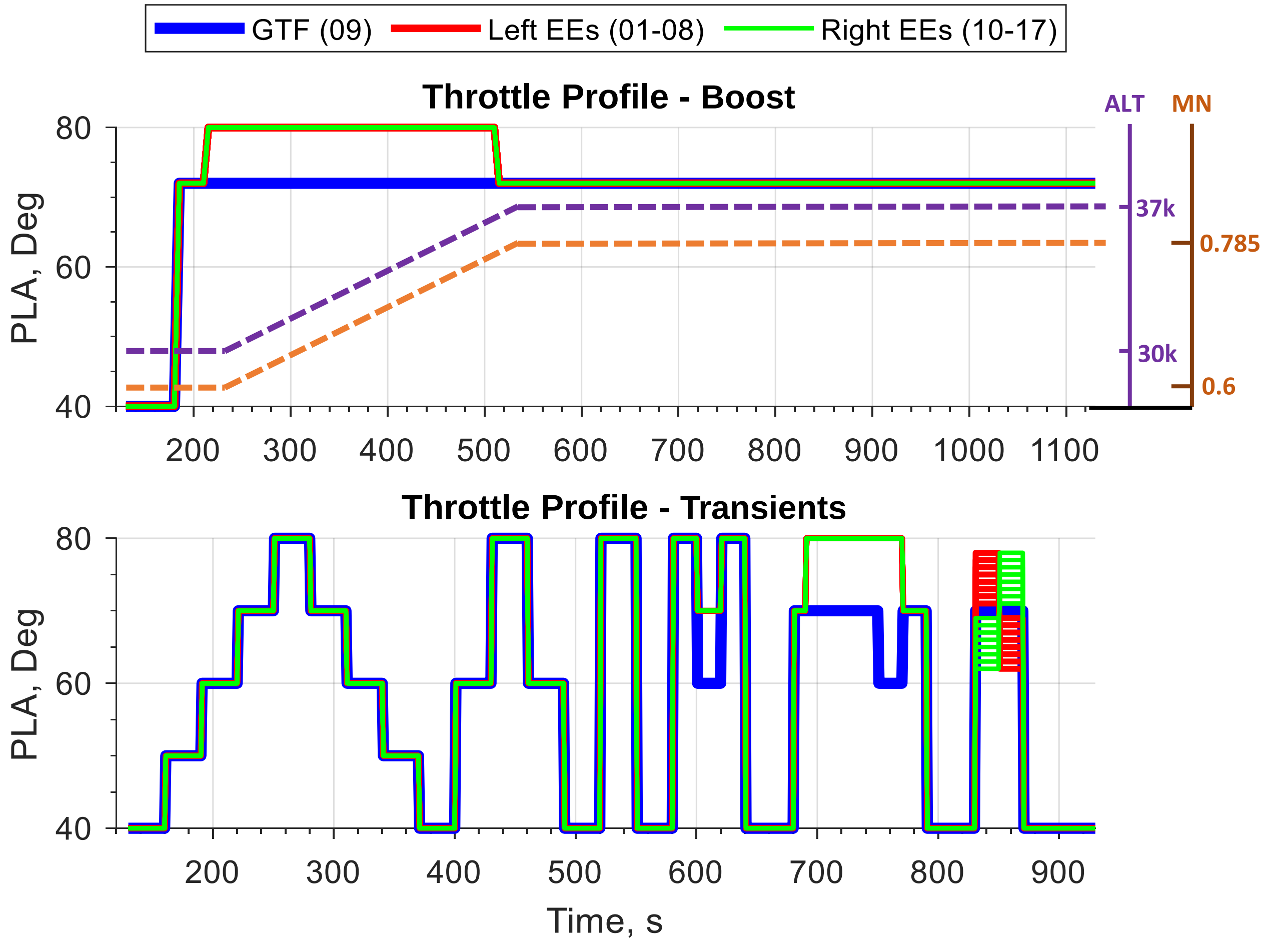
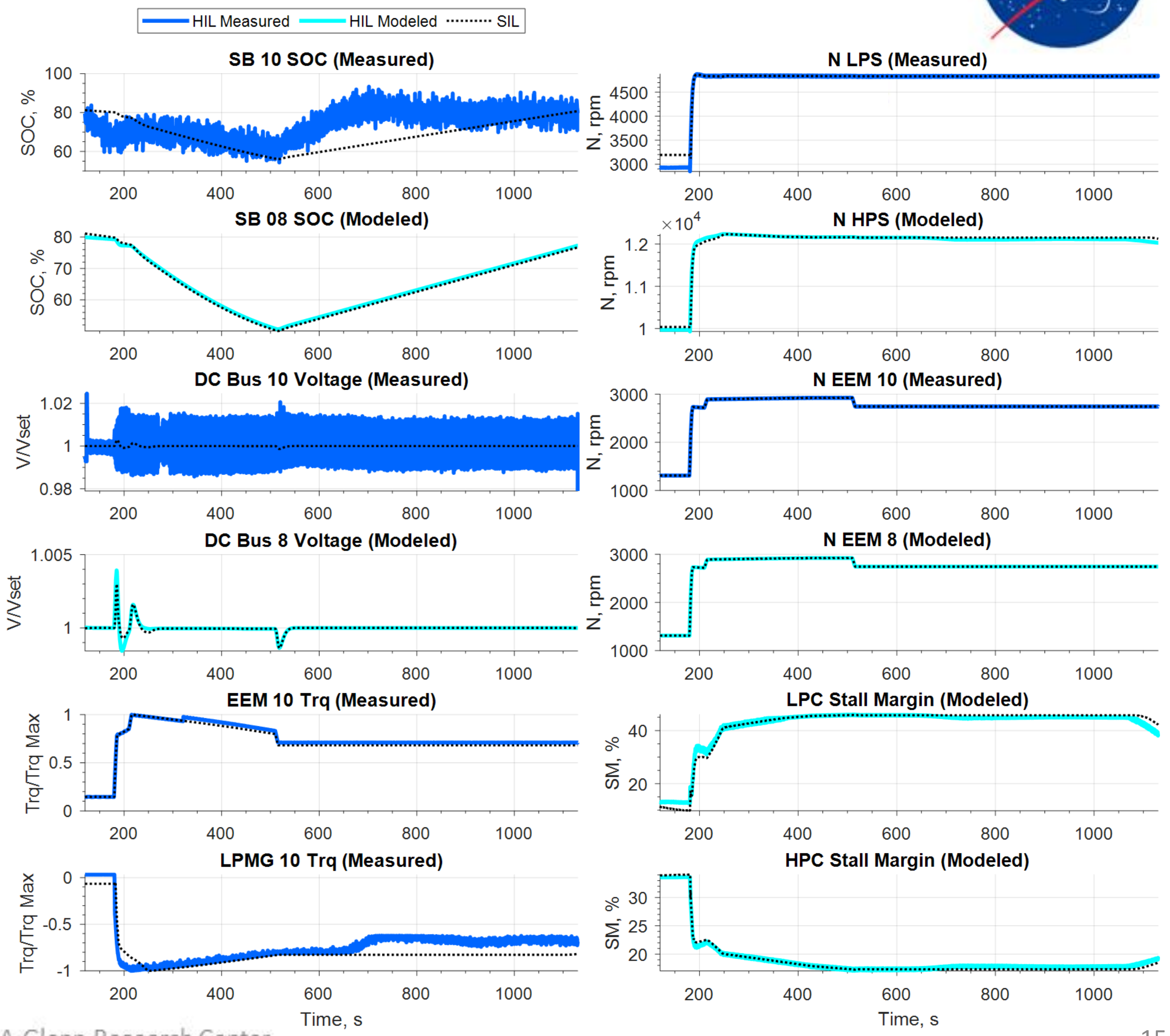
Test Results (1/3)

- Results for two test cases presented:
  - Boost/Simulated Top-of-Climb
    - Simulate 5 minute boost using EE's at end of climb.
    - Climb from 30kft, 0.6 MN to 37kft, 0.785 MN during boost (215 sec to 515 sec, shown in orange and purple).
  - Throttle Transient Profile.
    - Throttle steps of varying size, Boost, and DEP maneuvers.
    - Constant cruise conditions 37kft, 0.785 MN.



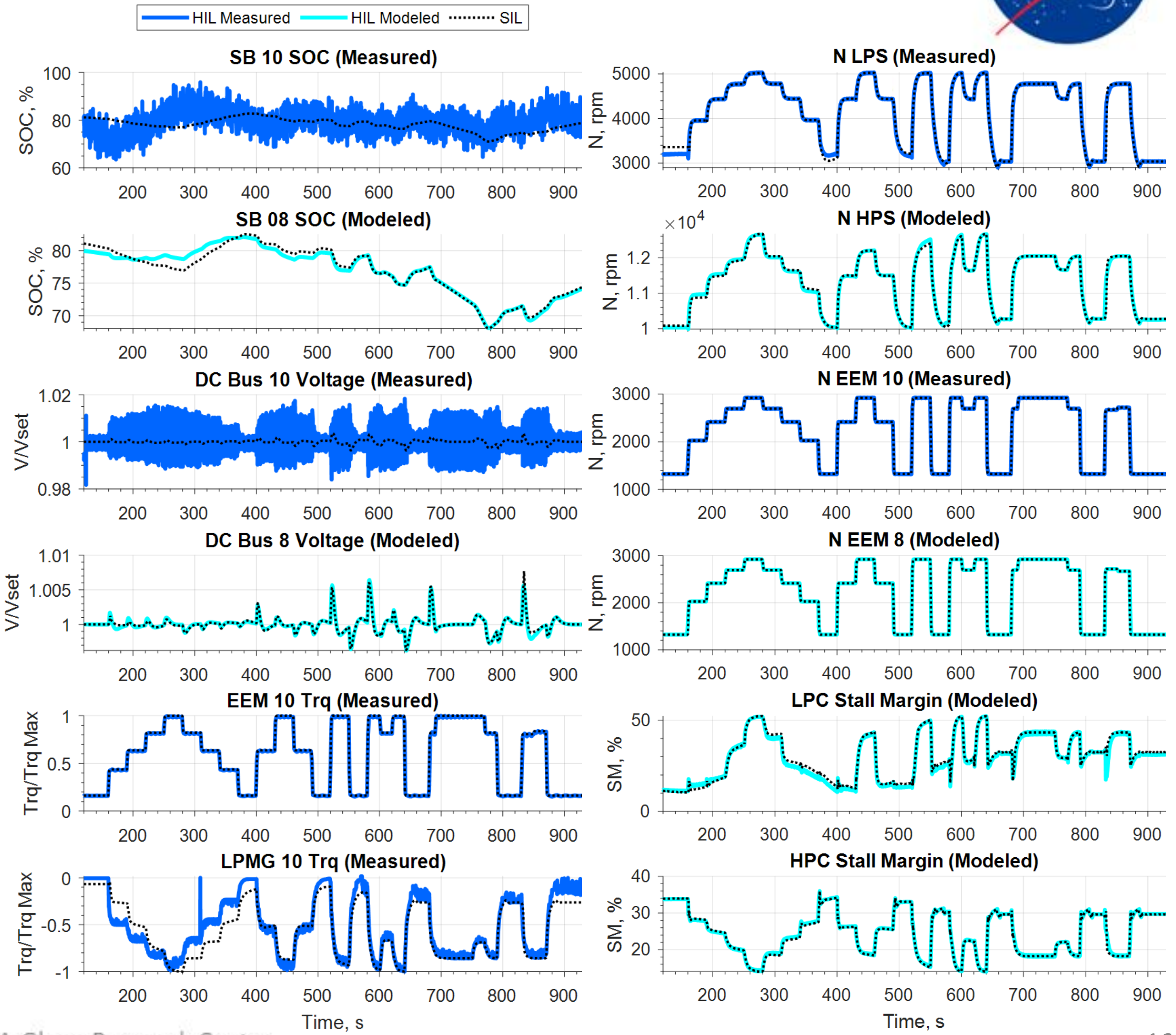
Test Results (2/3)

- Results from Boost test case.
  - Blue parameters are physical measurements.
  - Cyan parameters are from the HIL model implementation
  - Black line is the SIL model results.
- Shaft speeds align closely, indicating matching thrust response.
- Stall margins align closely, indicating similar turbomachinery component operabilities.
- Bus voltage and actuator commands align closely.
- SOC response is similar, but matching is not perfect.



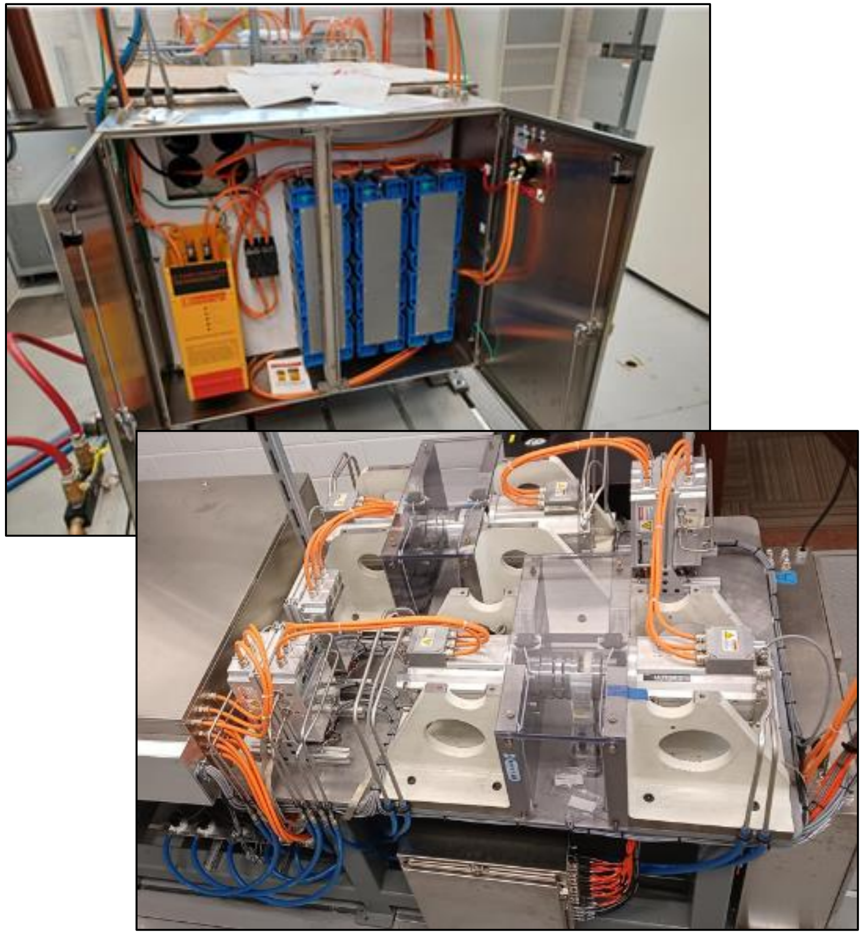
Test Results (3/3)

- Results from Throttle Transient test case.
- Good matching is shown between SIL and HIL signals in both RT model and Hardware.
- Primary causes of disagreement between SIL and HIL results.
  - Difference in power levels between HyPER and SUSAN EPS (100kW vs 1.4 MW).
  - Scaling driven by energy storage components, meaning HyPER EMs are operating below their nominal power range and can't be controlled as precisely.
  - Measurement noise is significantly greater in HIL implementation.
  - SUSAN EPS models are simplified, unmodeled effects such as nonlinear shaft damping, non-ideal component efficiencies, and transient electrical phenomena are not accounted for.



Conclusions

- Hybrid-electric aircraft propulsion technology potentially offers significant improvements to performance and efficiency.
  - These systems present significant control challenges
  - Hardware-in-the-loop (HIL) testing offers a path for maturing control technologies.
- The Power and Propulsion System (PPS) of the SUbsonic Single Aft eNgine (SUSAN) Electrofan hybrid-electric transport aircraft is tested in real-time with a HIL electromechanical subsystem.
  - The reconfigurability of the Hybrid Propulsion Emulation Rig (HyPER) lab allowed it to represent some of the electromechanical components of the SUSAN PPS.
  - The control architecture developed for the full-scale system model functioned well in the HIL environment, successfully delivering the required thrust response while maintaining energy storage device power levels and balancing energy between the turbomachinery and electrical subsystems.
- Future work could involve improving the realism of the HIL environment by including additional components or more flight-like hardware.



HyPER Laboratory (NASA)

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SUSAN Electrofan Concept Rendering (NASA)

Thank You!

Questions?

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