SUbsonic Single Aft eNgine (SUSAN) Power/Propulsion System Control Architecture Updates

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Presentation Outline

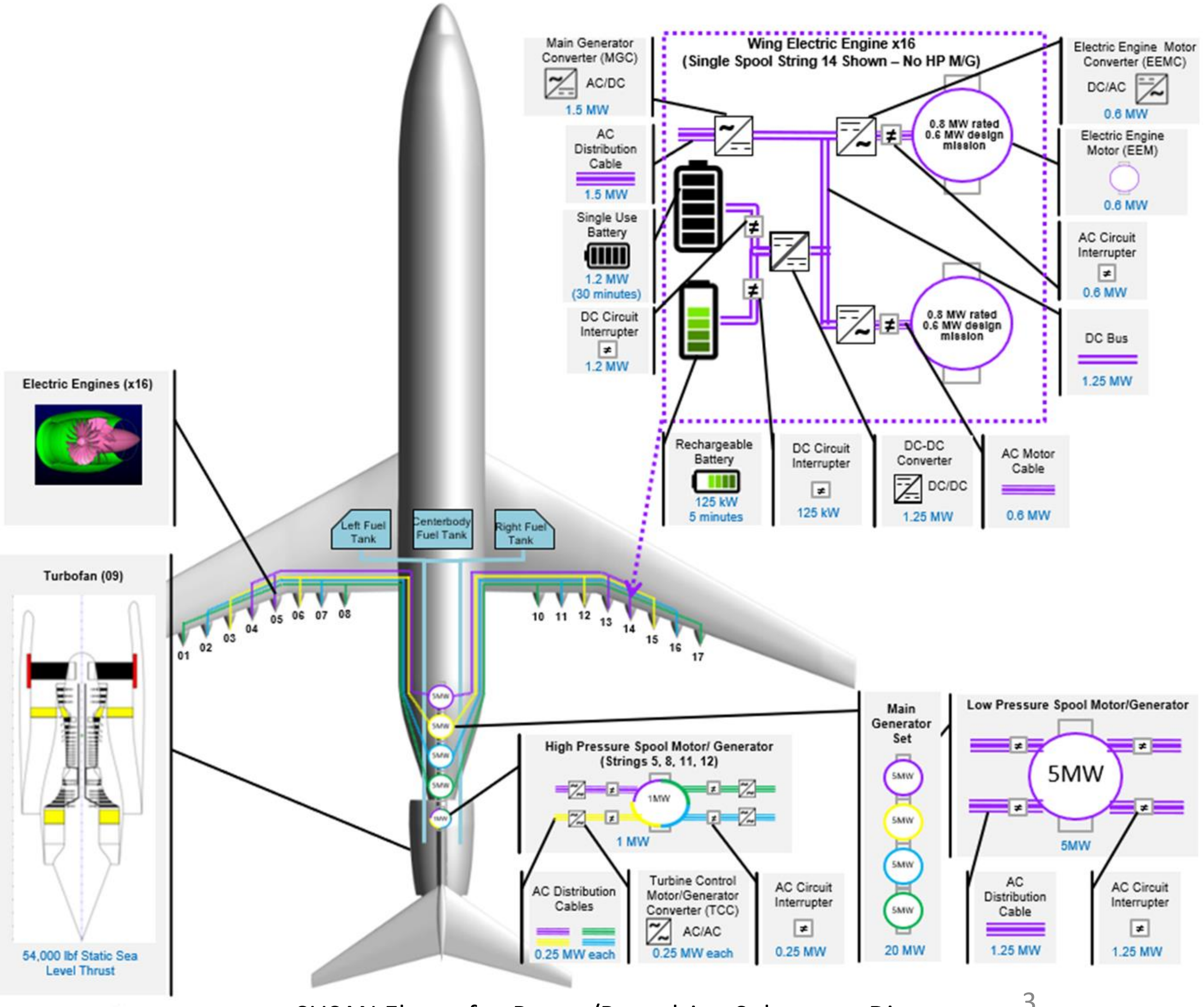
- SUbsonic Single Aft eNgine (SUSAN) Concept
- Power/Propulsion System (PPS) Model
- PPS Control Architecture
- Model Results and Validation
- Future Work and Applications
- Conclusions

SUSAN Electrofan Concept Renderings (NASA)

SUbsonic Single Aft eNgine (SUSAN) Concept

- 20 MW Series/Parallel Partial Hybrid Electrified Aircraft Propulsion (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 (GTF) 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
- 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.

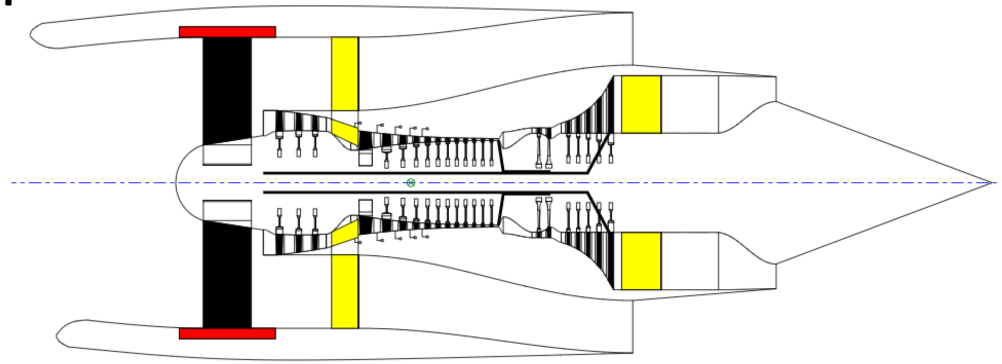


SUSAN Electrofan Power/Propulsion Subsystem Diagram

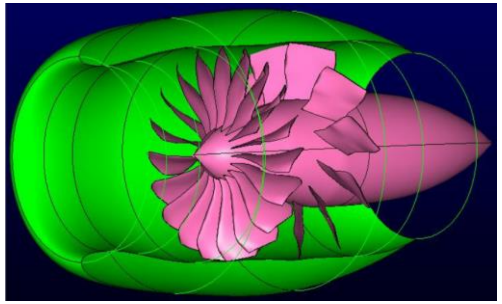
Propulsion System Model

- Turbomachinery model
  - Developed using Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)
  - Dynamic 0-dimensional non-linear aero-thermal turbomachinery model based on component performance maps
  - GTF is modeled as an advanced dual-spool engine with M/Gs on LPS and HPS
    - Also includes variable bleed valve (VBV) and variable area fan nozzle (VAFN)
  - EEs modeled as ducted fans with VAFNs
    - Concept includes contra-rotating fans driven by two motors
    - T-MATS model captures performance using one compressor map and one shaft

GTF



EE

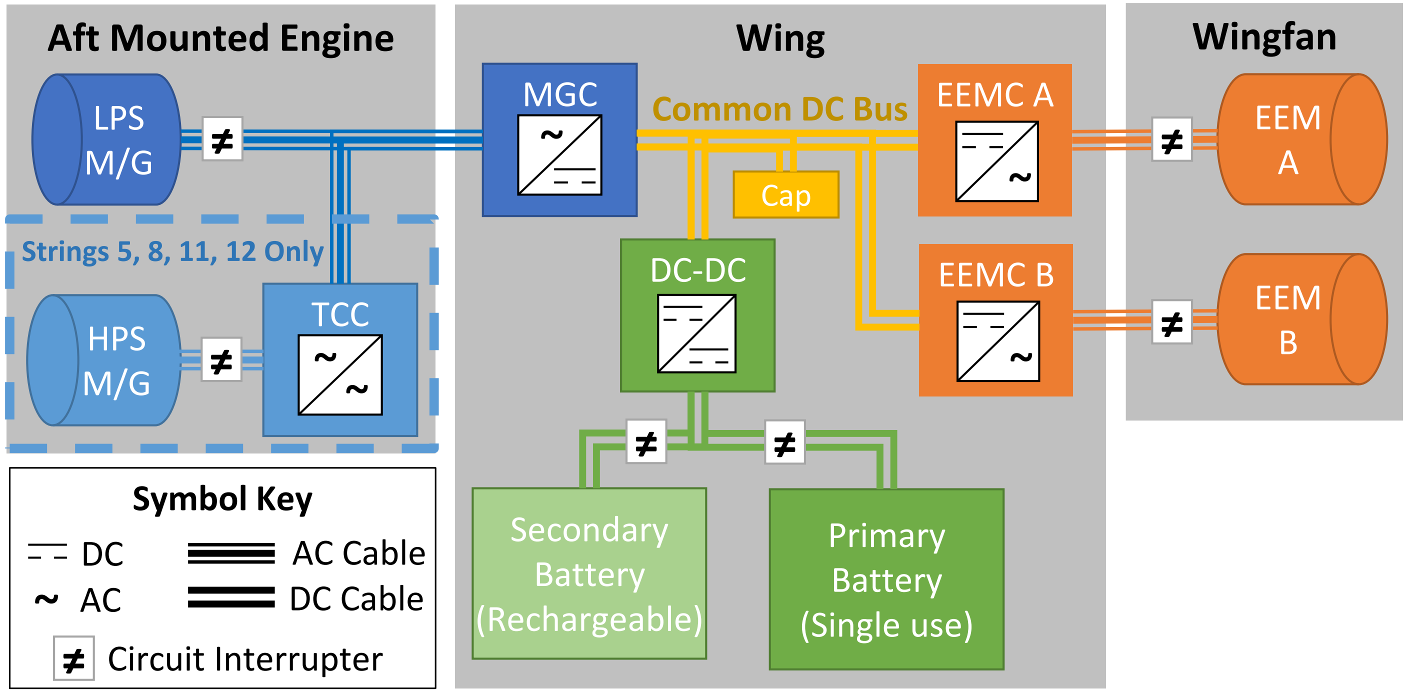


J. Chapman, T. Lavelle, R. May, J. Litt and T.-H. Guo, "Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) User's Guide," NASA/TM-2014-216638, January 2014.

EPS Model

- Built using Developed using Electrical Modeling and Thermal Analysis Toolbox (EMTAT) PowerFlow blockset
  - Models electrical components on turbomachinery timescales
  - Uses component efficiency maps to determine voltages and currents
- Updates from previous version
  - Updated component efficiencies
  - Updated battery models
  - Adjusted DC bus time constant to be consistent with turbomachinery model timestep
  - Modeled TCC component as back-to-back inverter and rectifier

SUSAN EPS String EMTAT Model Component Diagram



J. W. Chapman, et. al, "Update on SUSAN Concept Vehicle Power and Propulsion System," in AIAA SciTech Forum, National Harbor, MD, 2023.

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

SUSAN PPS Control System Architecture

- Utilizes multiple overlapping control loops with different time constants
  - Manage system energy levels
  - Maintain turbomachinery stability and operability
  - Provide required thrust responses
- GTF uses a gain-scheduled proportional-integral (PI) controller
  - Uses fuel flow, W_f, to control corrected fan speed N_{1c}
  - Limit controllers and min/max logic used to protect components and engine operability
  - Turbine Electrified Energy Management (TEEM) leverages HP and LP M/Gs to improve operability
  - VBV and VAFN are scheduled based on inlet conditions, N_{1c}, and power extraction (VBV only)
- EEs use similar PI controllers
  - Use EEM torque to control wingfan corrected shaft speed N_{WFc}
  - VAFN scheduled on inlet conditions and N_{WFc}

Gain-scheduled PI controller with integral windup protection:

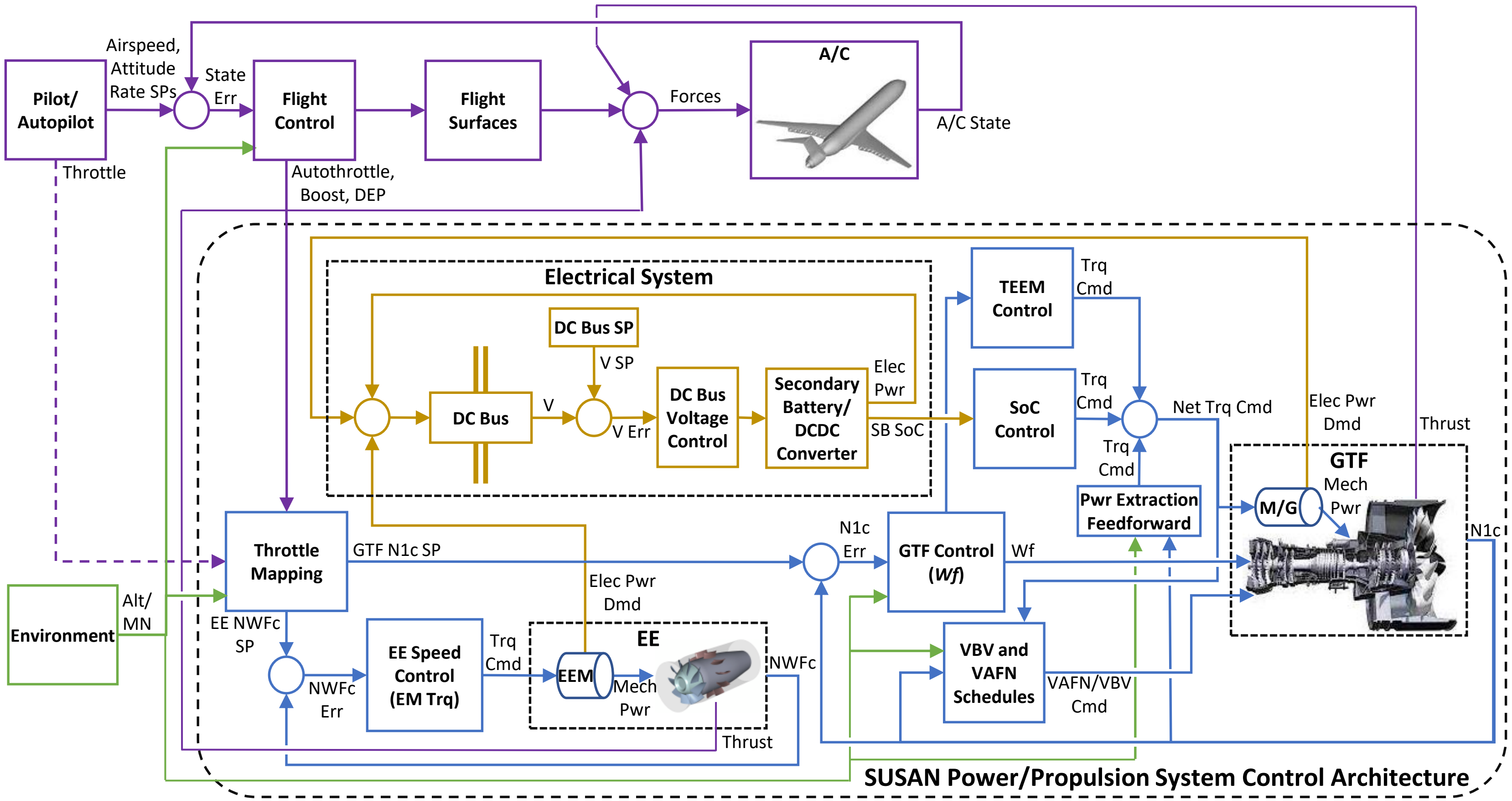
$$u(t) = \overbrace{K_p e(t)}^{\text{Proportional Term}} + \overbrace{\int \underbrace{K_i}_{\text{Integral Gain}} \big(e(t) - \underbrace{K_{iwp}(u(t-1) - u^*(t-1))}_{\text{Integral Windup Protection Term}}\big)\, dt}^{\text{Integral Term}}$$

$u(t-1) - u^*(t-1)$ is the difference between the ideal controller command, u, and the controller command accounting for limits and saturation, u^*

Gains K_p and K_i determined via lookup table

Control System Architecture

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



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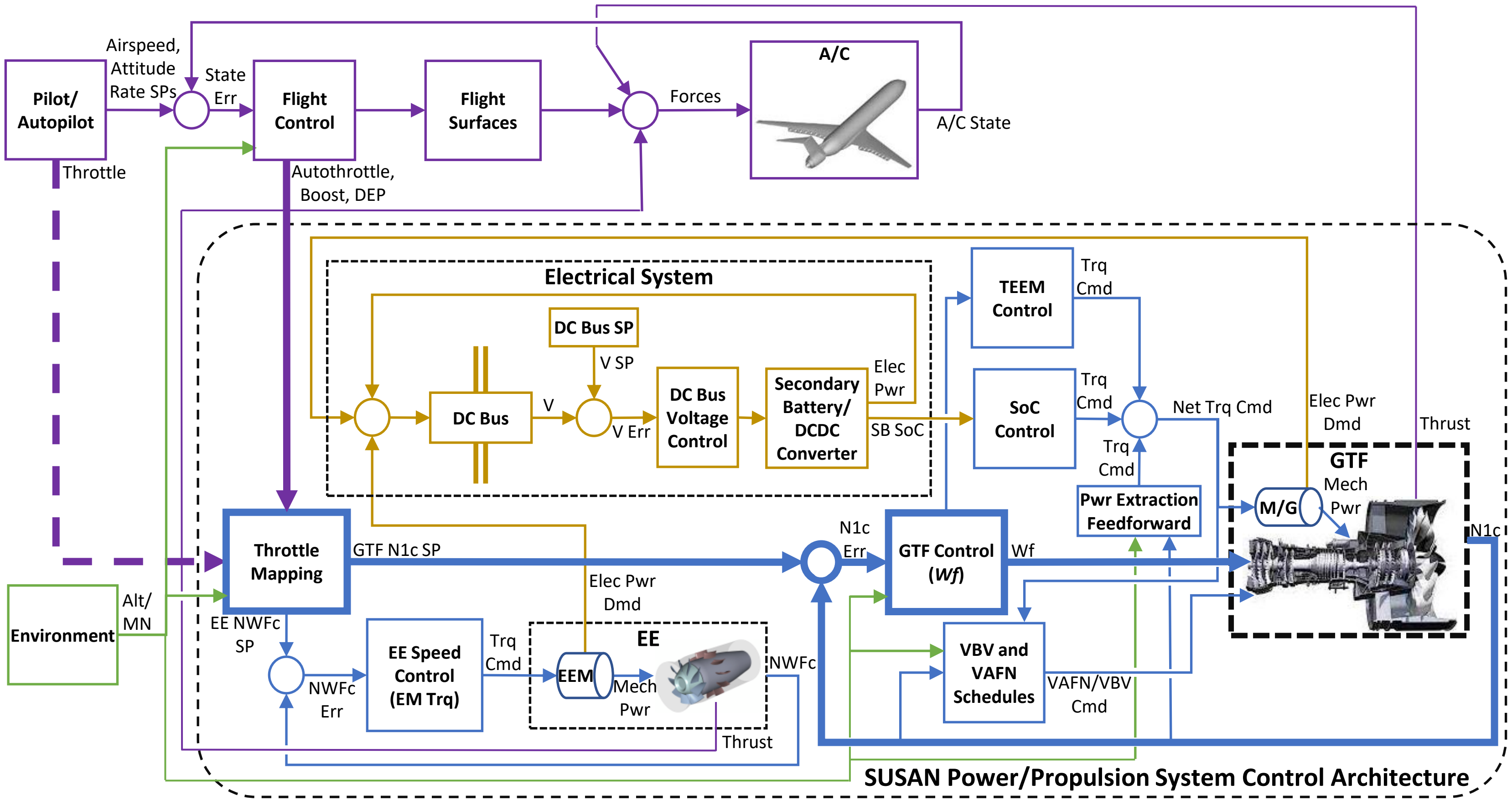

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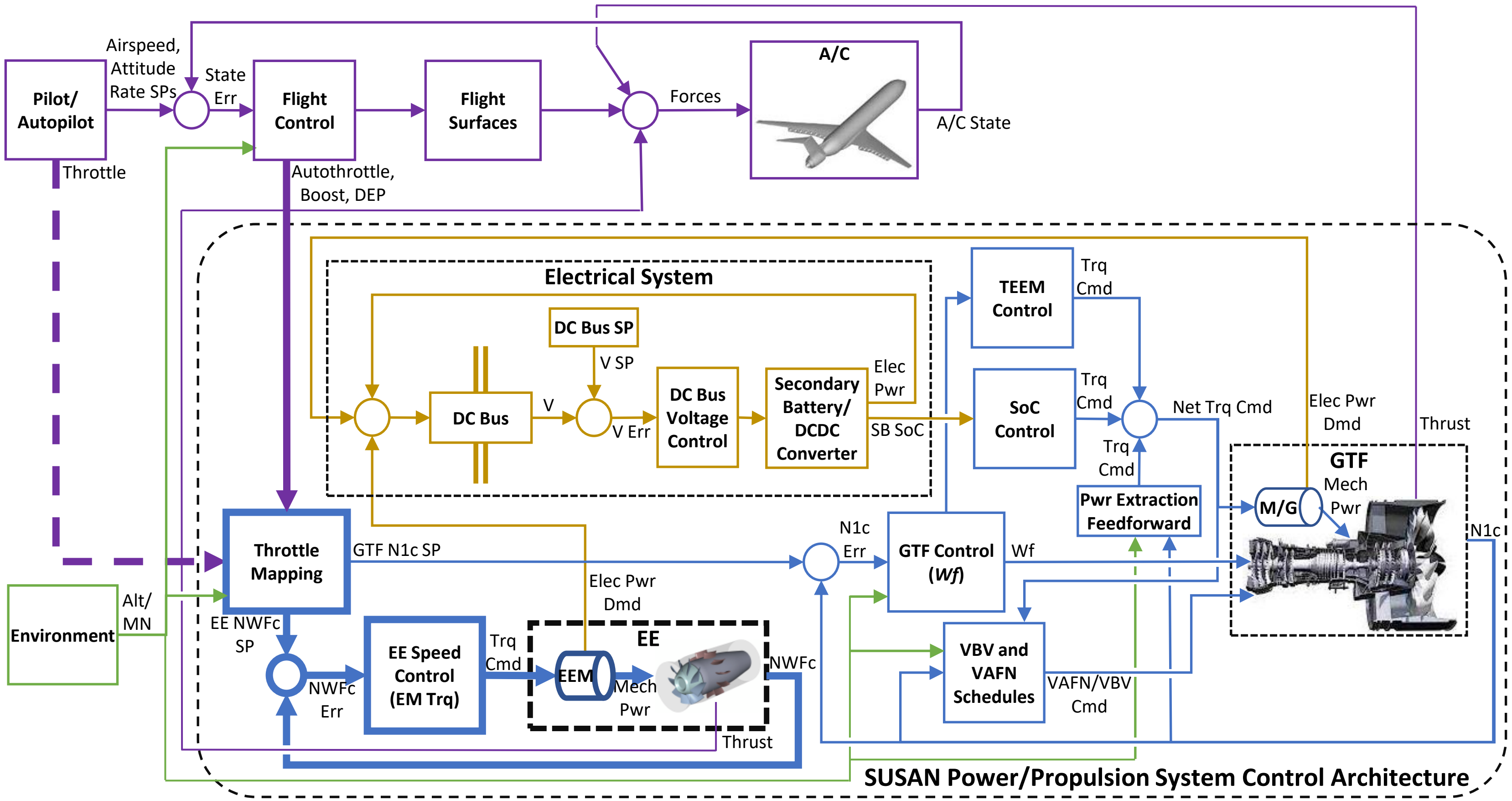

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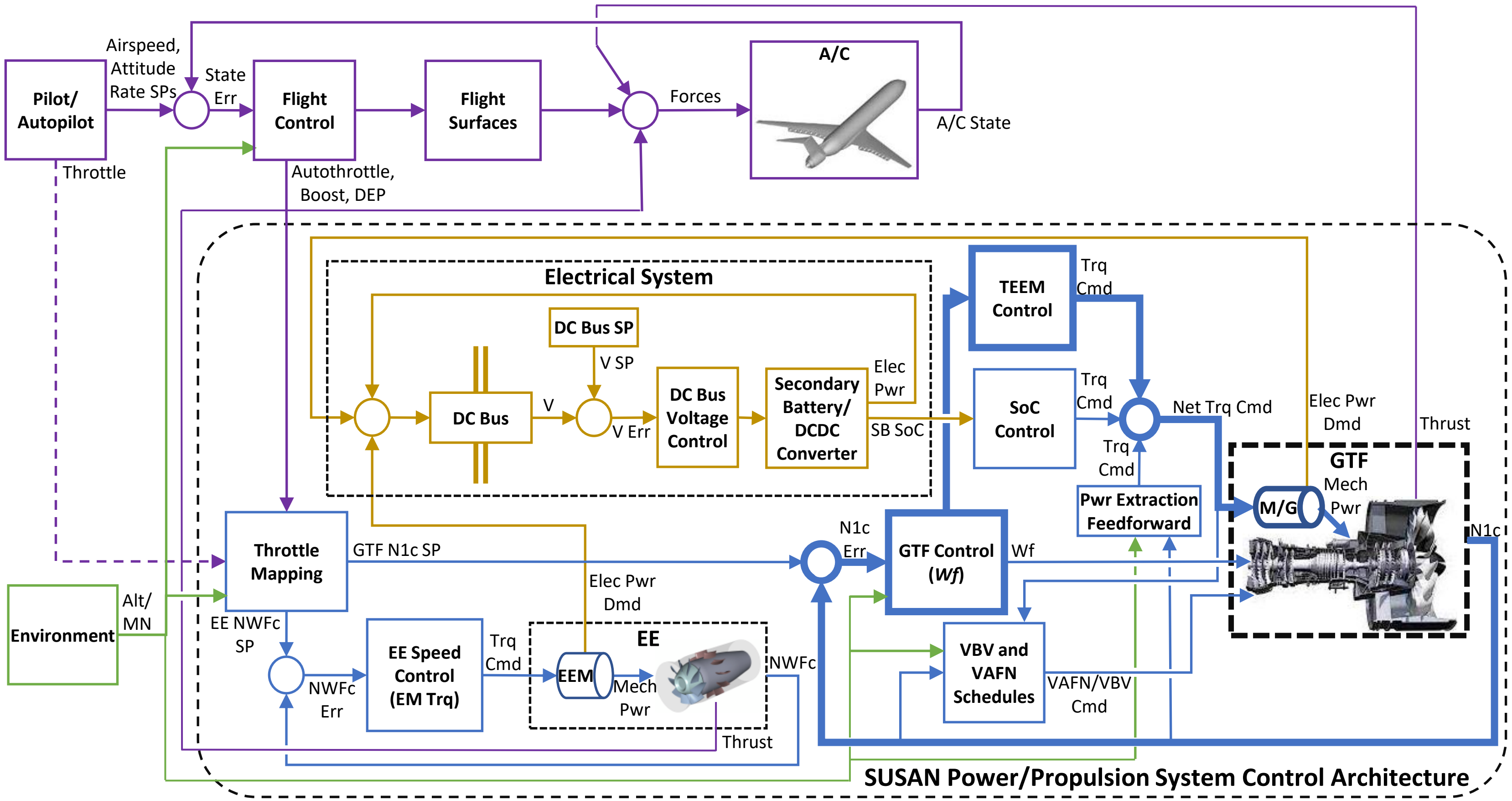

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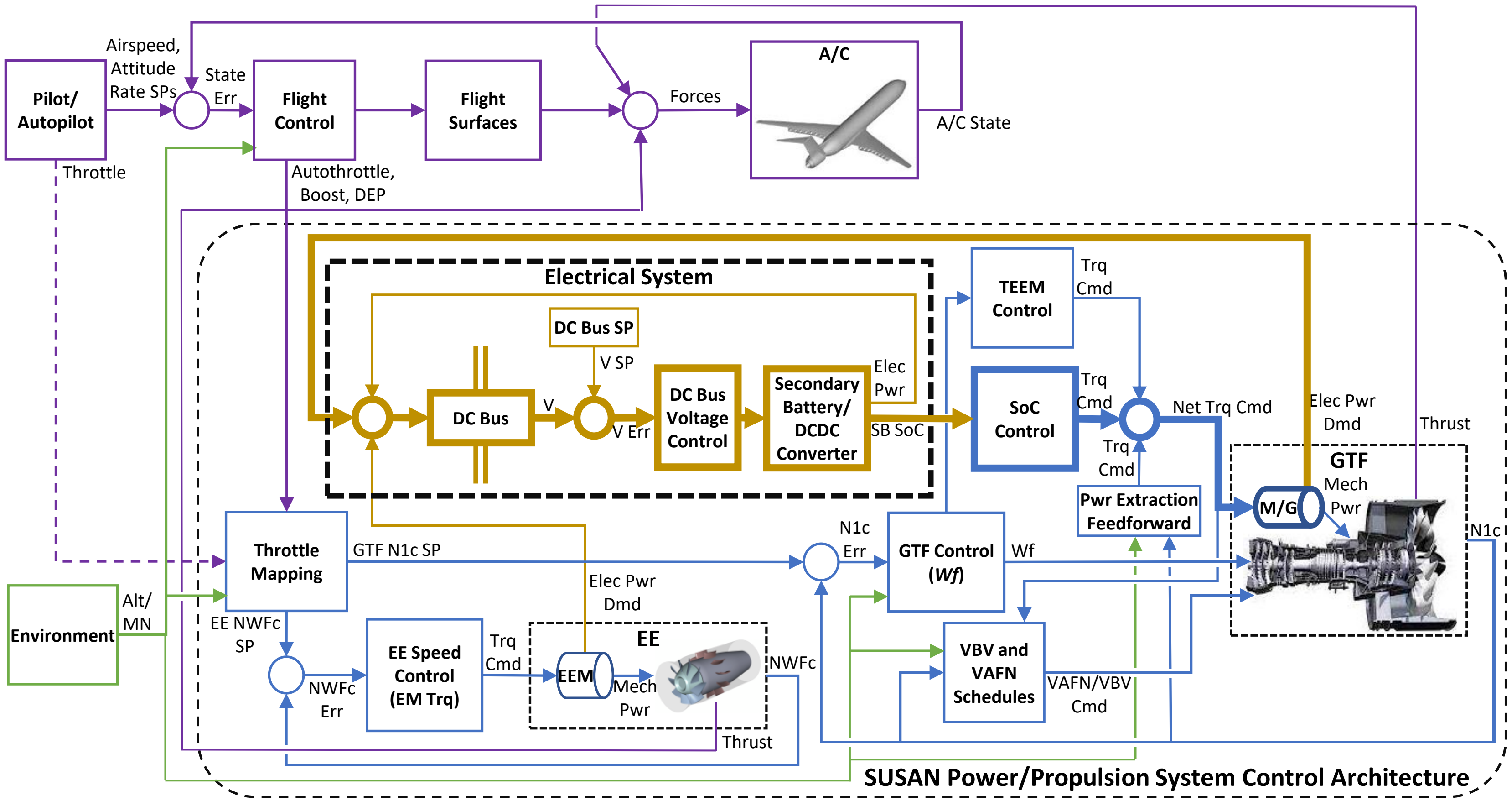

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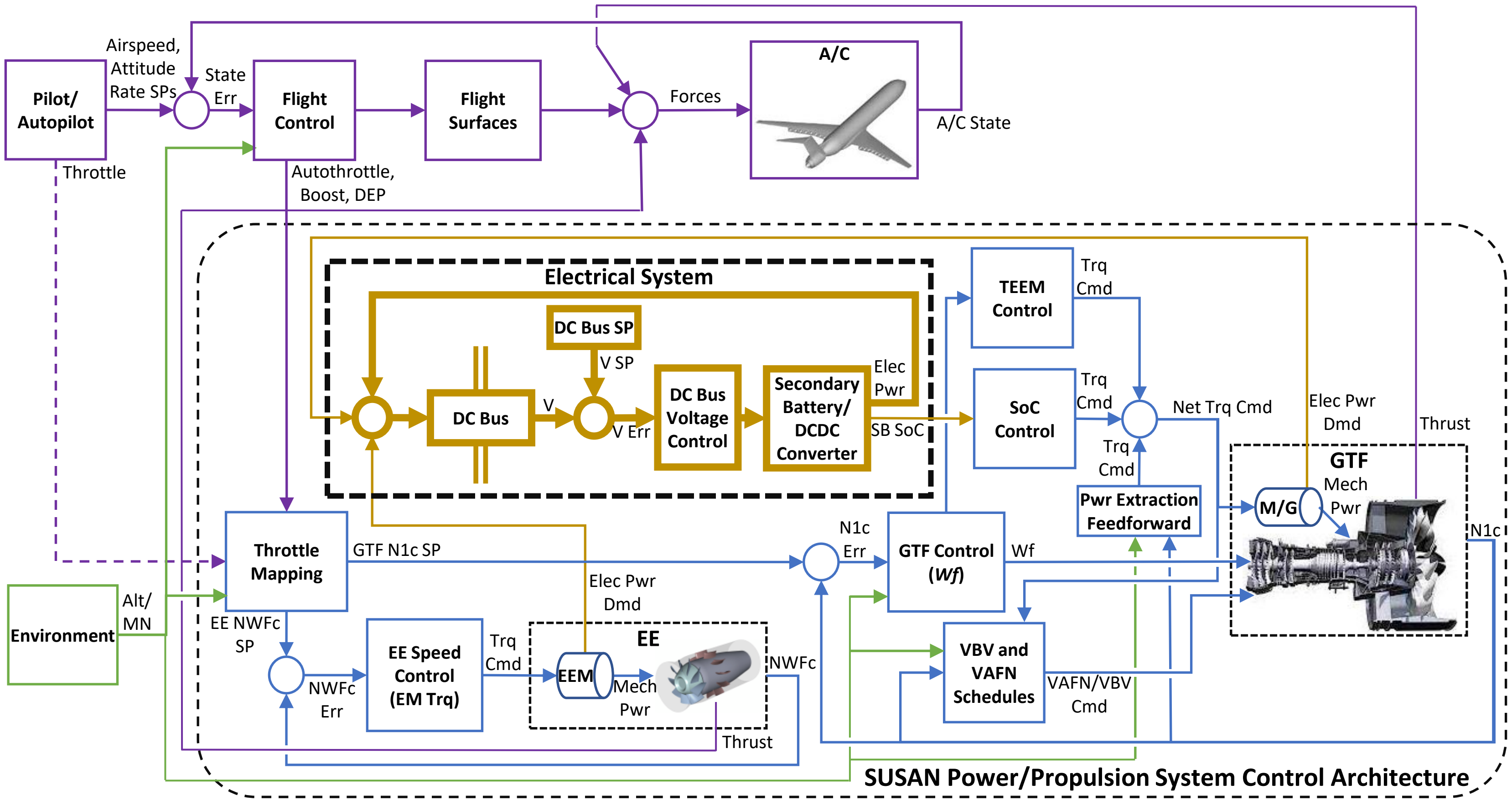
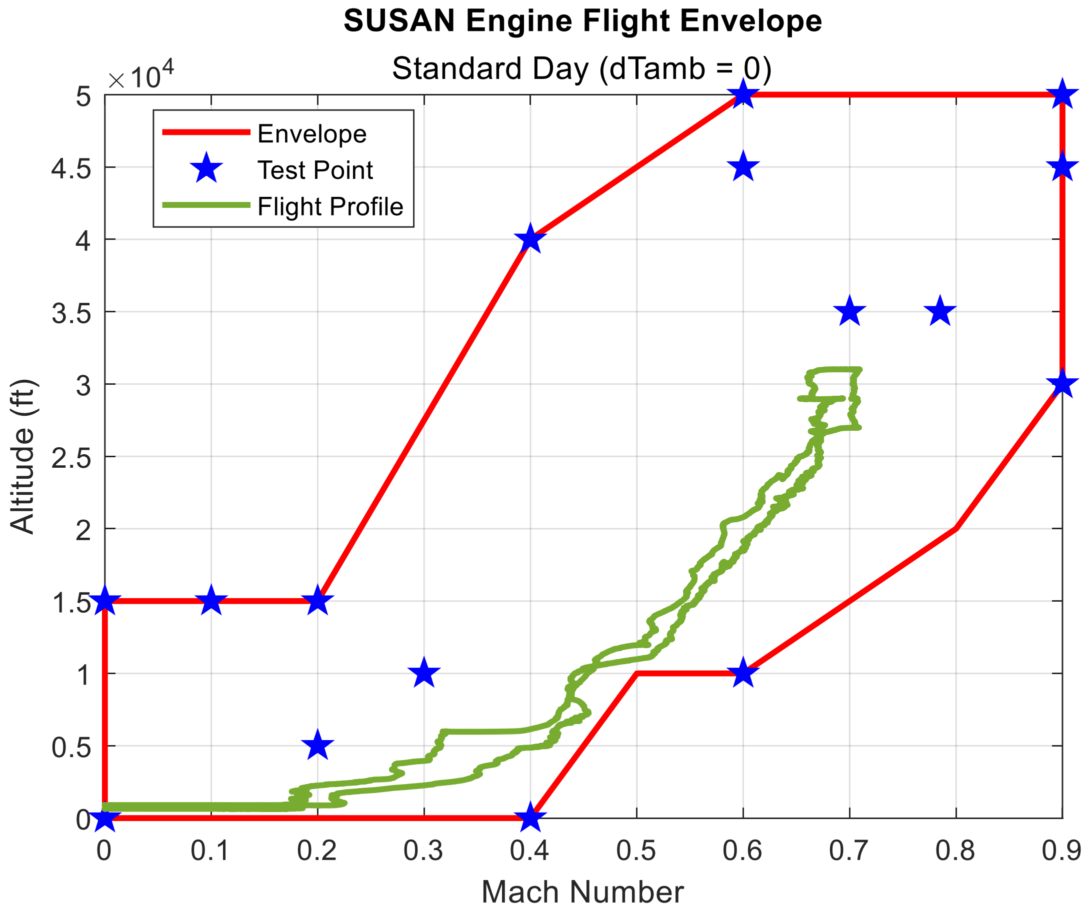


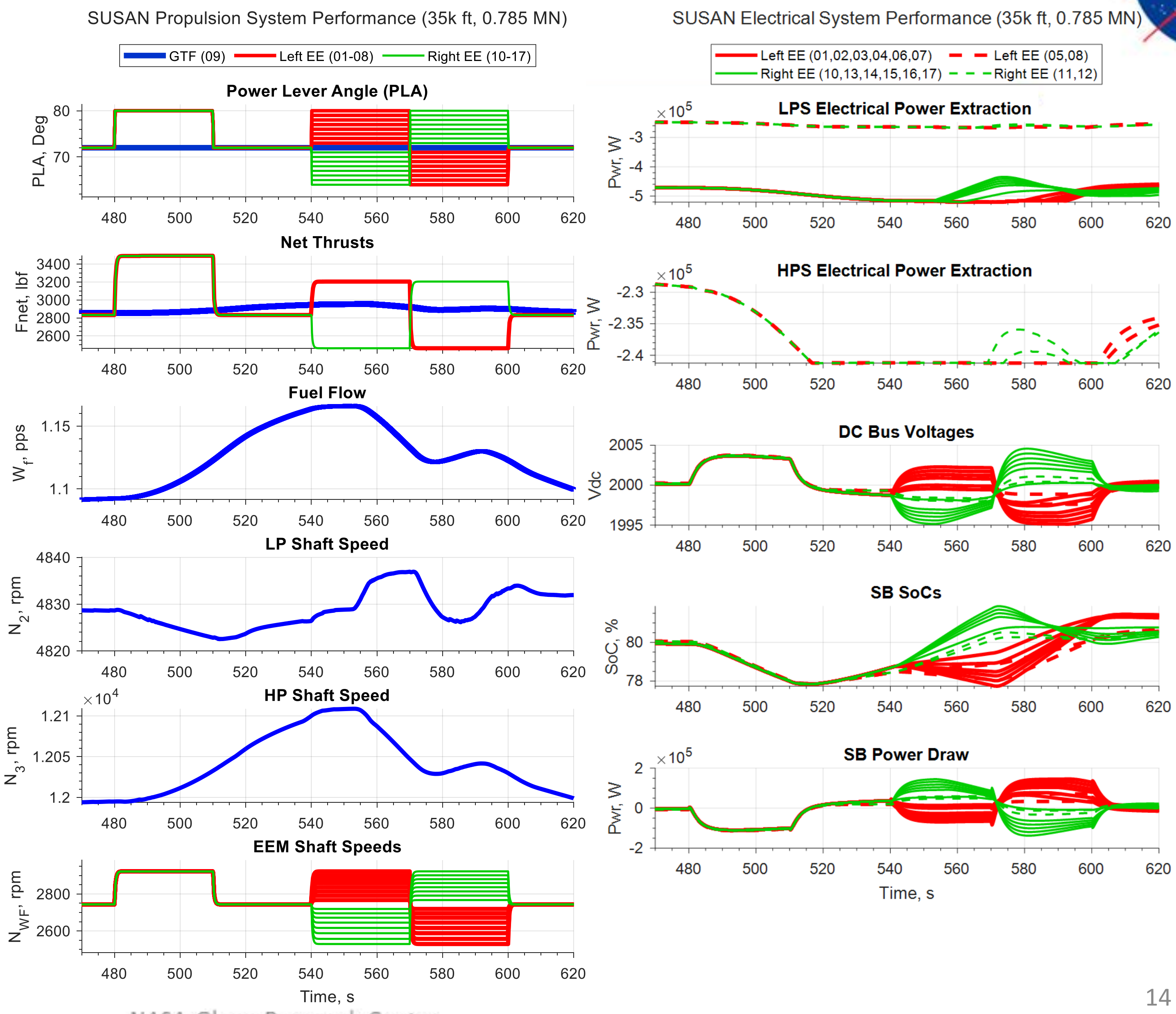
Testing the Model

- Model was tested at multiple fixed flight conditions throughout the flight envelope with a series of aggressive throttle maneuvers
  - Maintained thrust response across flight envelope
  - Maintained engine operability limits and battery charge levels



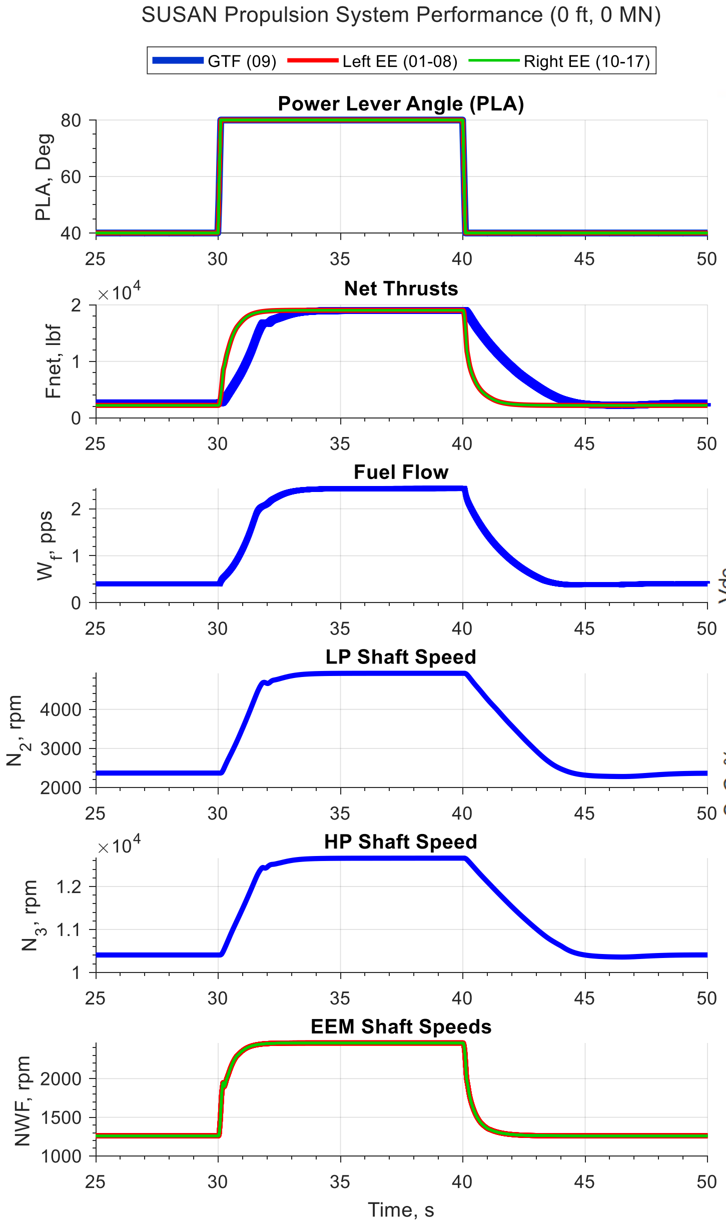
Model Results

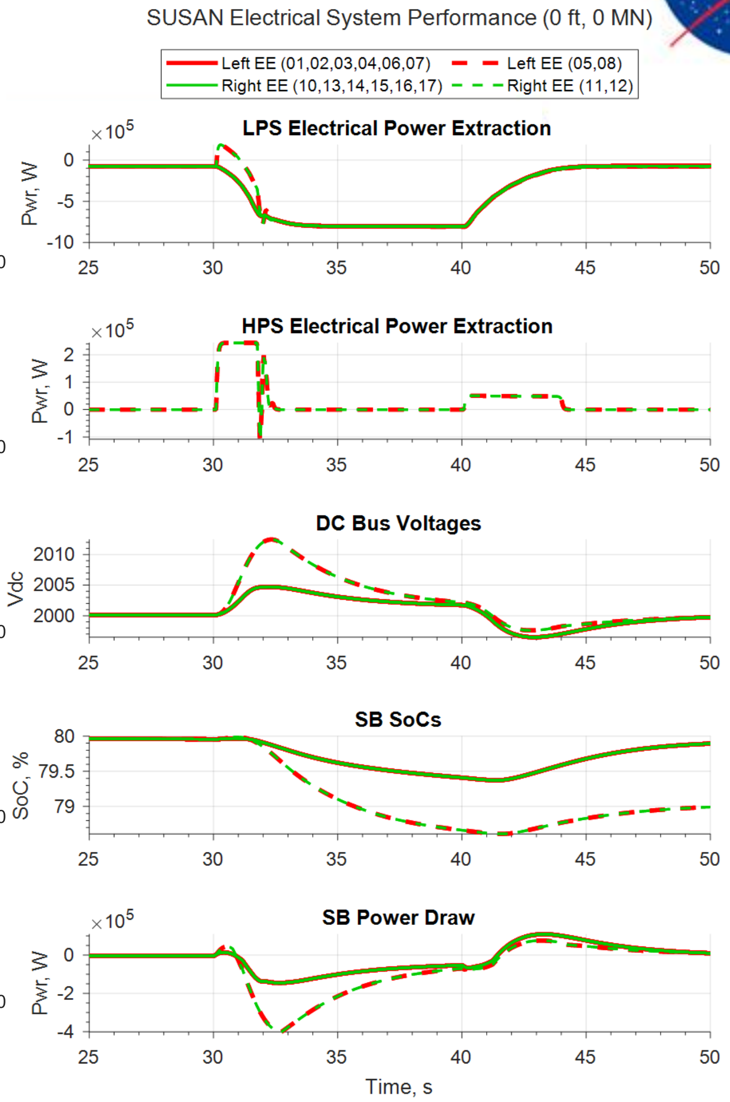
- Boost and DEP Maneuvers at cruise condition (35,000 ft, 0.785 MN)
- EEs respond rapidly (<2 seconds) to Boost and DEP commands
- SB SOCs are maintained



Model Results

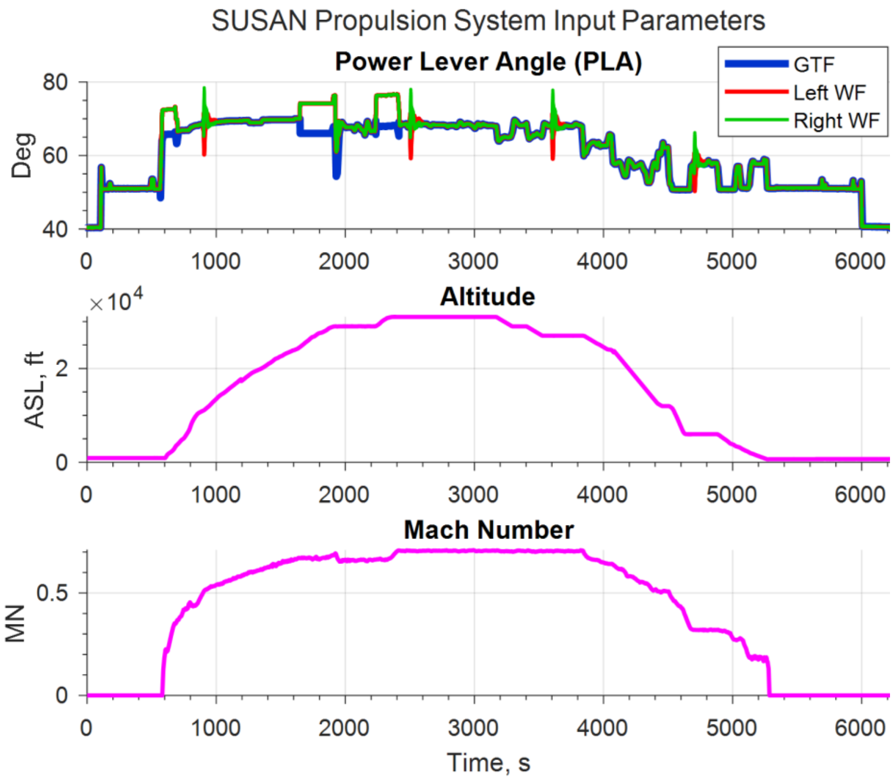
- Throttle Burst and Chop at sea-level-static (SLS) conditions
- EEs respond faster than GTF
  - 2 seconds vs 5 seconds at SLS
- TEEM maintains GTF operability
- SBs support TEEM and rapid EE response





Model Results: Simulated Flight Profile

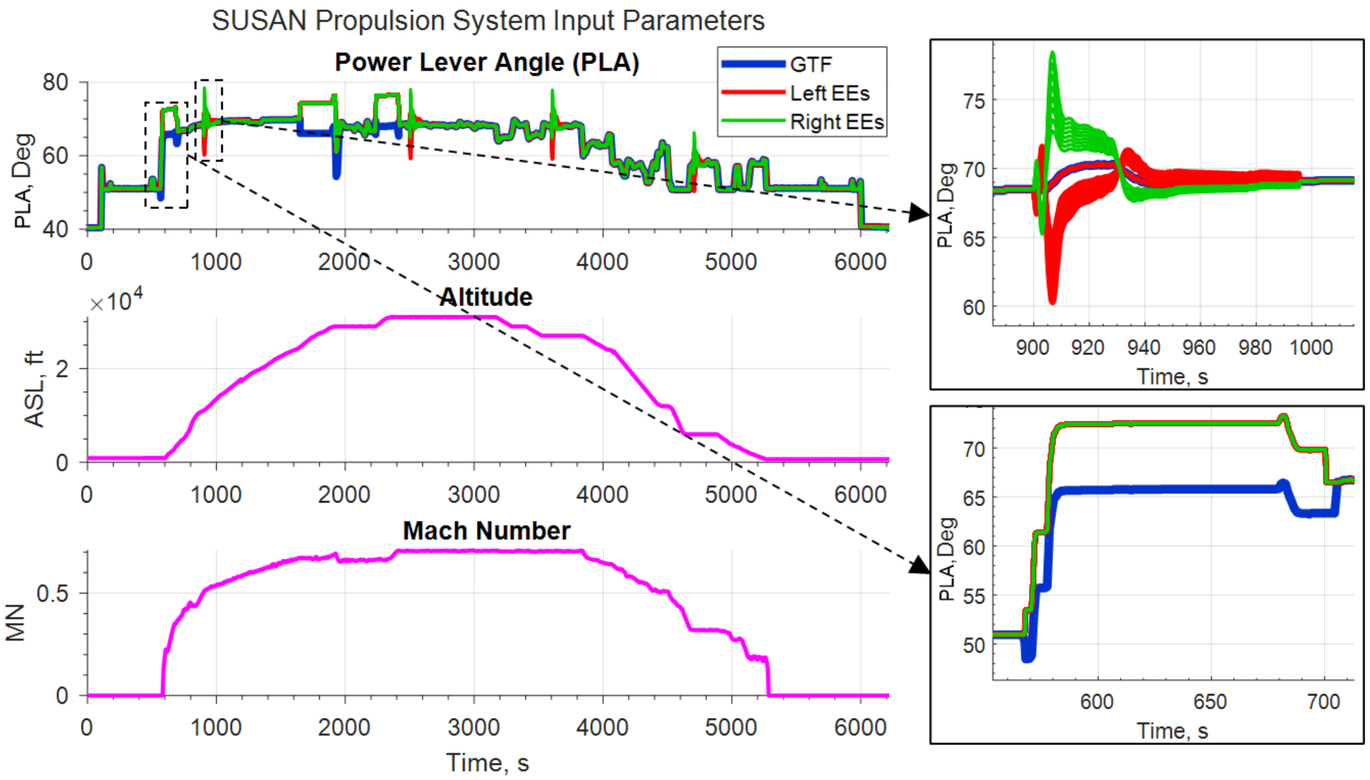
- Tested the PPS model with a simulated 90-minute flight profile
  - Not including pre- and post-flight taxi
  - Flight profile taken from real, de-identified flight data from NASA DASHlink



B. Matthews, "DASHlink Sample Flight Data," *NASA DASHlink*, 29 November 2012. [Online]. Available: https://c3.ndc.nasa.gov/dashlink/projects/85/. [Accessed 2022].

Model Results: Simulated Flight Profile

- Tested the PPS model with a simulated 90-minute flight profile
  - Not including pre- and post-flight taxi
  - Flight profile taken from real, de-identified flight data from NASA DASHlink
- Modified profile to demonstrate SUSAN PPS
  - Implemented EE boost at takeoff and top-of-climb
  - Included 4 nominal DEP maneuvers



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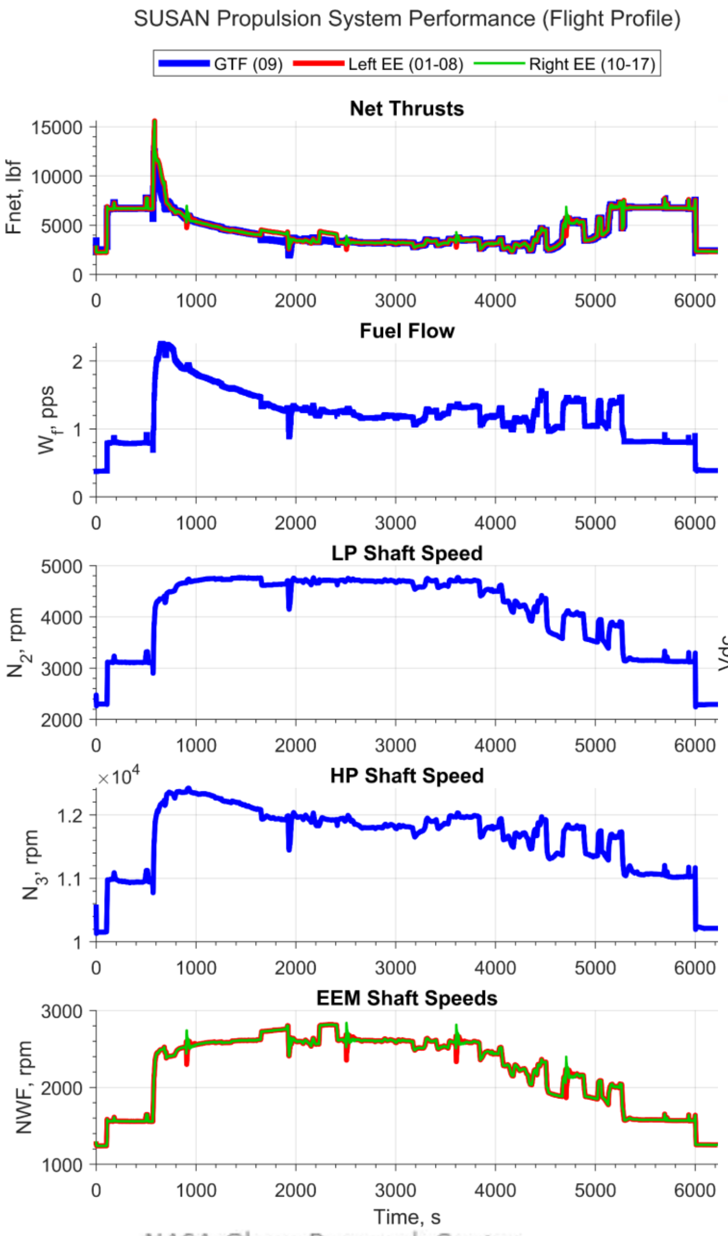
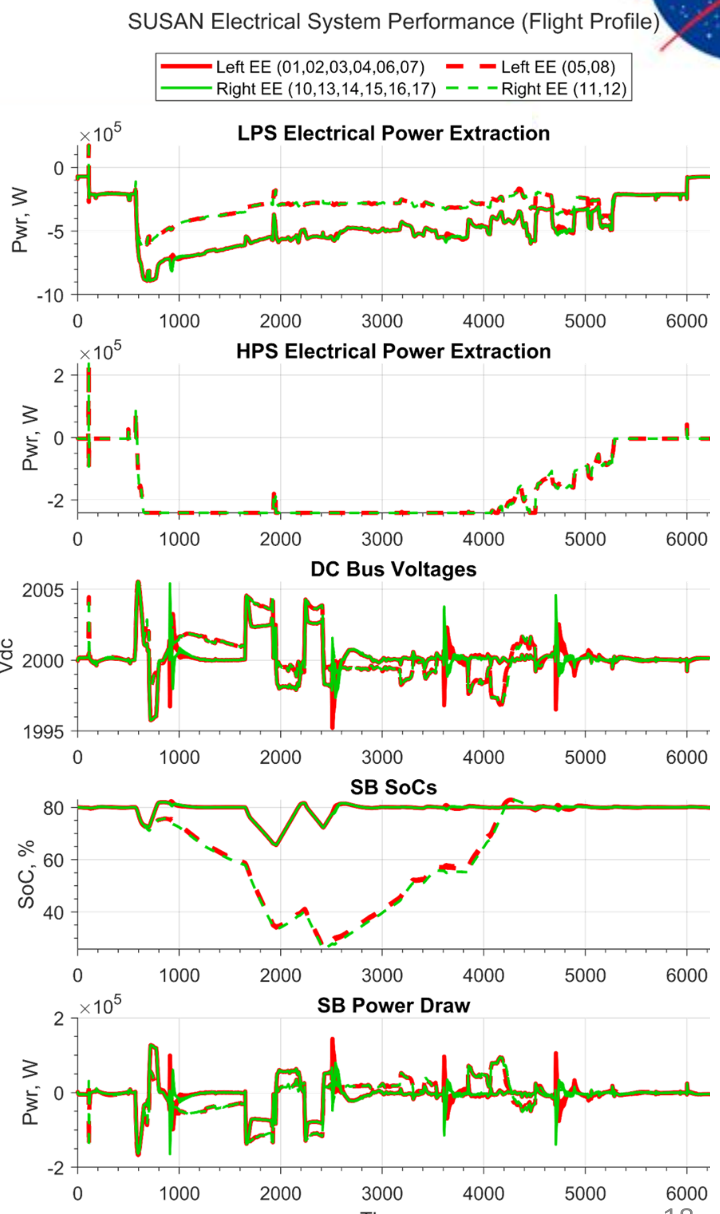
Model Results

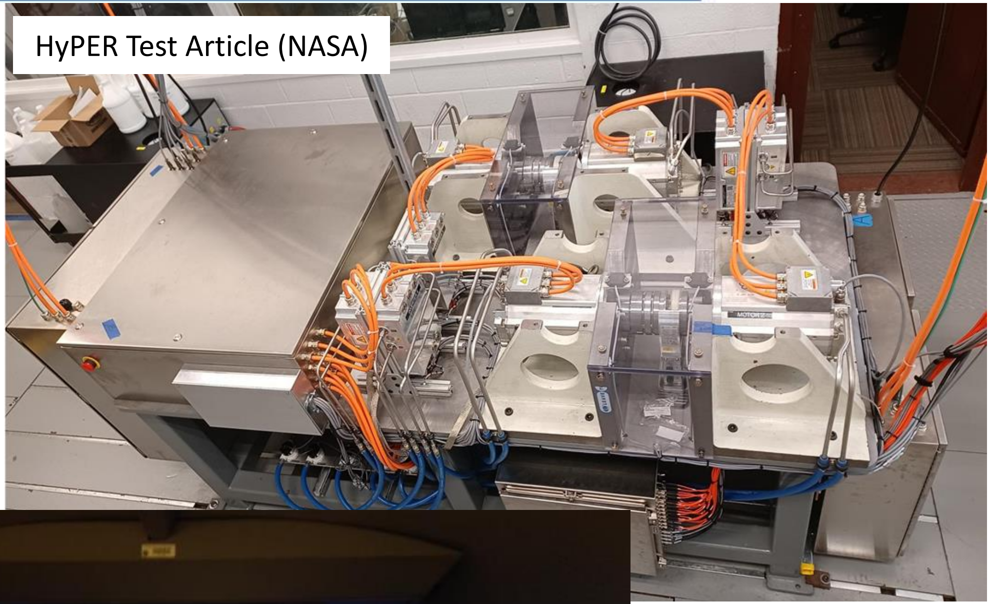
- Full flight profile results
  - System maintains thrust response and SB SOCs across flight
  - Dual-spool SBs lose more SOC due to TEEM





Future Work and Applications

- Integration with SUSAN airframe, flight control, and thermal models
  - Iterate on trade studies and further refine system requirements
- GRC Hybrid Propulsion Emulation Rig (HyPER) Laboratory
  - Electromechanical hardware-in-the-loop testing
- GRC Modular Flight Deck (MFD)
  - Piloted simulation studies
  - Flight displays



HyPER Test Article (NASA)

GRC MFD (NASA)

Conclusions

- SUSAN PPS model updated to account for ongoing trade-space exploration
- SUSAN PPS control architecture updated to improve responsiveness and flexibility
  - Enabled Boost and DEP capabilities
- Model and control architecture tested and validated across SUSAN flight envelope

Acknowledgments

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SUSAN Electrofan Concept Rendering (NASA)

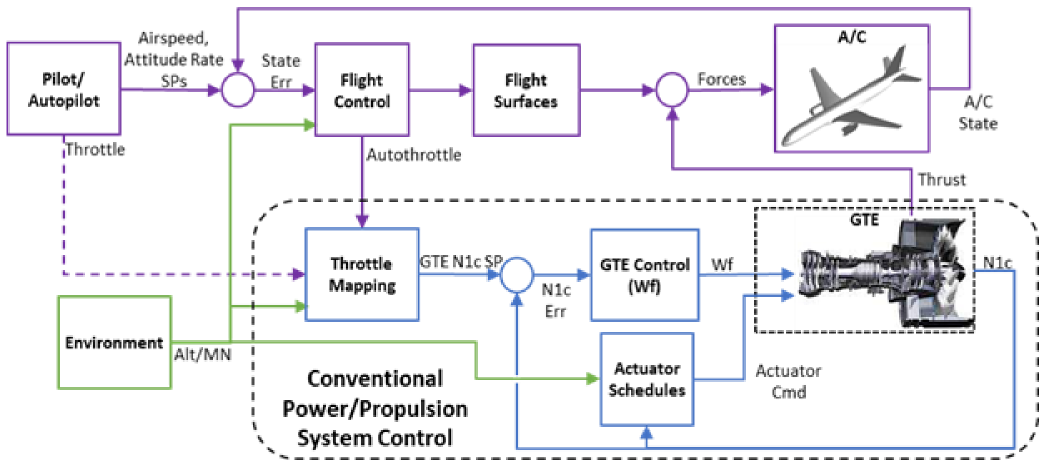
Thank You!

Questions?

Contact: jonah.j.sachs-wetstone@nasa.gov

Control Architectures: Modern vs. SUSAN

Modern Propulsion Control Architecture



SUSAN PPS Control Architecture