Adaptive Control and Scaling Approach for the Emulation of Dynamic Subscale Torque Loads

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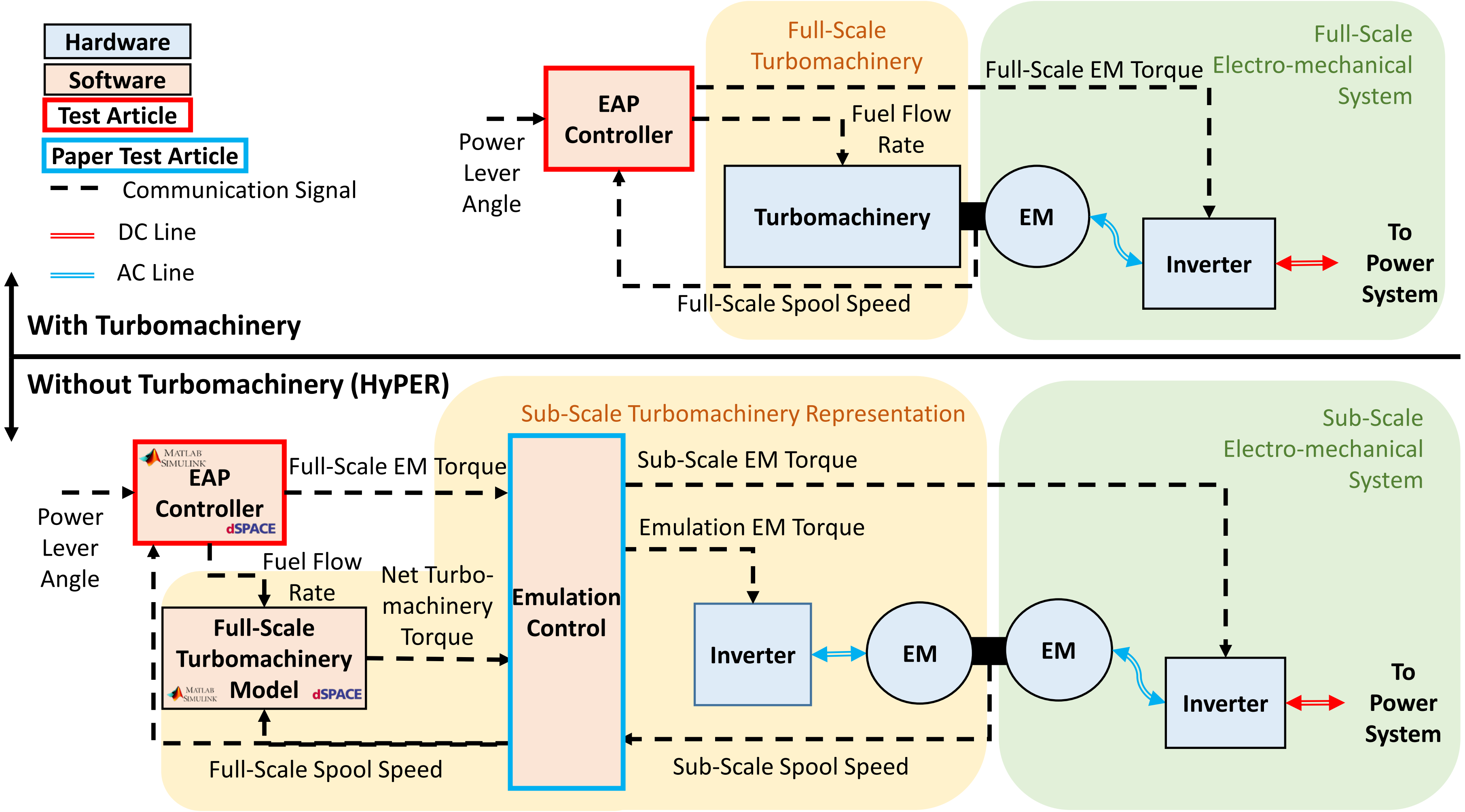
Introduction

- Motivation
  - The aviation industry is pursuing electrified aircraft propulsion (EAP) due to its ability to increase engine/aircraft performance, efficiency, and operability.
  - Need to replace turbomachinery during initial EAP control algorithm verification on hardware due to cost and safety risks.
  - Previously published approach for replacing turbomachinery has limitations.
- Purpose
  - Present a modification to published emulation control approach that reduces or eliminates its limitations.

Scope

1. Introduce original approach and discuss limitations.
2. Explain adaptive approach and prove stability.
3. Explain hardware-in-the-loop test setup to verify controller operation.
4. Show and discuss performance results.

Concept



Turbomachinery is replaced and the dynamical characteristics of the system are preserved.

Original Approach

- Sliding Mode Impedance Controller with Scaling (SMICS) [1]

Emulation EM Torque

$$T_M = J_P J_{E_s}^{-1}\left(T_{E_s} + T_{G_s} + \eta sat(s,\phi) + K_P s + K_I \int [s]dt + K_D \dot{s}\right) + B_P \omega_P - T_{G_s}$$

Plant Inertia

Plant Damping Coefficient

- Lyapunov Stability Analysis

$$\dot{V} = -s\left(\eta sat(s,\phi) + K_P s + K_I \int [s]dt + K_D \dot{s}\right)$$

- Because of red, asymptotic controller stability unable to be proven.
- Because of uncertainty in green, sliding mode control effort is increased. Thus, chatter is increased.

Unable to prove asymptotic stability or correct for plant parameter uncertainty using original approach.

Adaptive Approach

- Adaptive Sliding Mode Impedance Controller with Scaling (ASMICS)

$$T_M = \underbrace{\hat{J}_P J_{E_s}^{-1}\left(T_{E_s} + T_{G_s} - B_{E_s}\,\omega_P\right) - T_{G_s} + \hat{B}_P\omega_P}_{u_{eq}\text{: impedance portion}} - \underbrace{\eta\,\mathrm{sat}(s,\phi) - K_P s}_{\dot{s}\text{: sliding mode portion}}$$

- Adaptation Laws

$$\dot{\hat{J}}_P = -\gamma_{J_P} s J_{E_s}^{-1}\left(T_{E_s} + T_{G_s} - B_{E_s}\omega_P\right)$$

$$\dot{\hat{B}}_P = -\gamma_{B_P} s\omega_P$$

- Lyapunov Stability Analysis

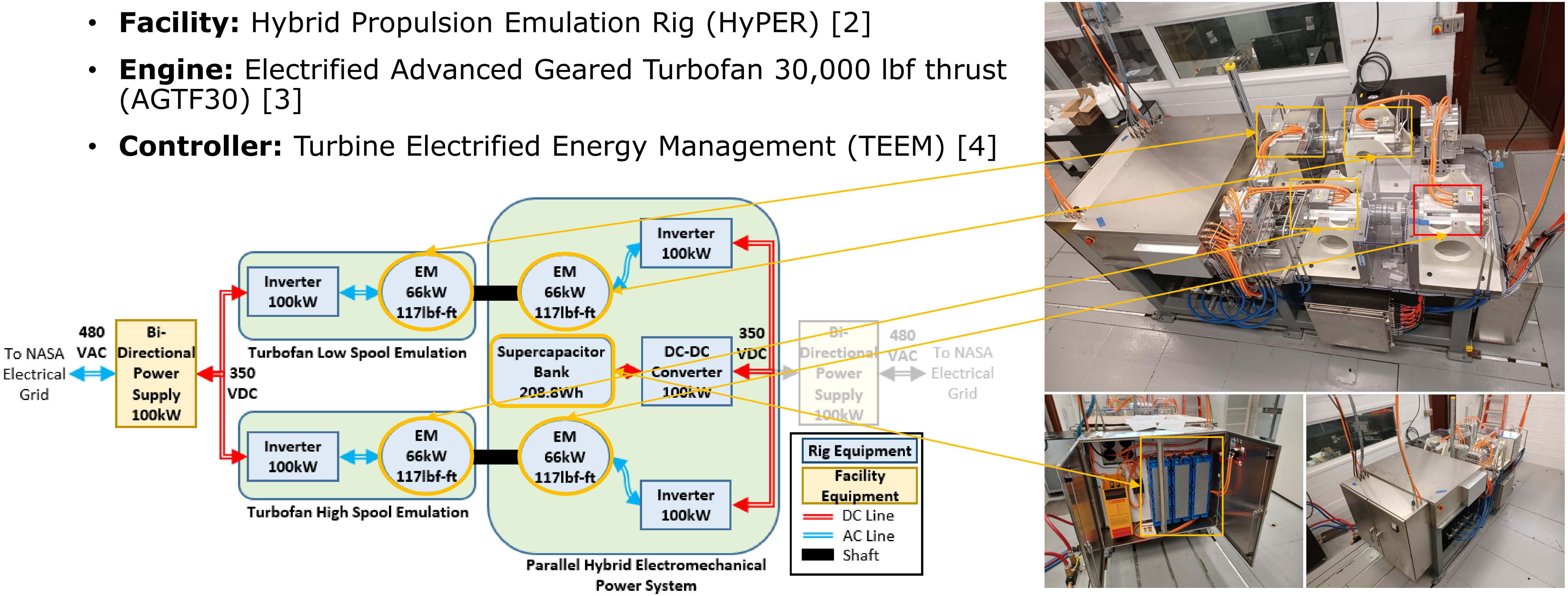
$$\dot{V} = -s(\eta sat(s,\phi) + K_P s)$$

- Controller stability proven due to removal of red and addition of adaptive parameters.

Adaptive approach is asymptotically stable and corrects for plant parameter uncertainty.

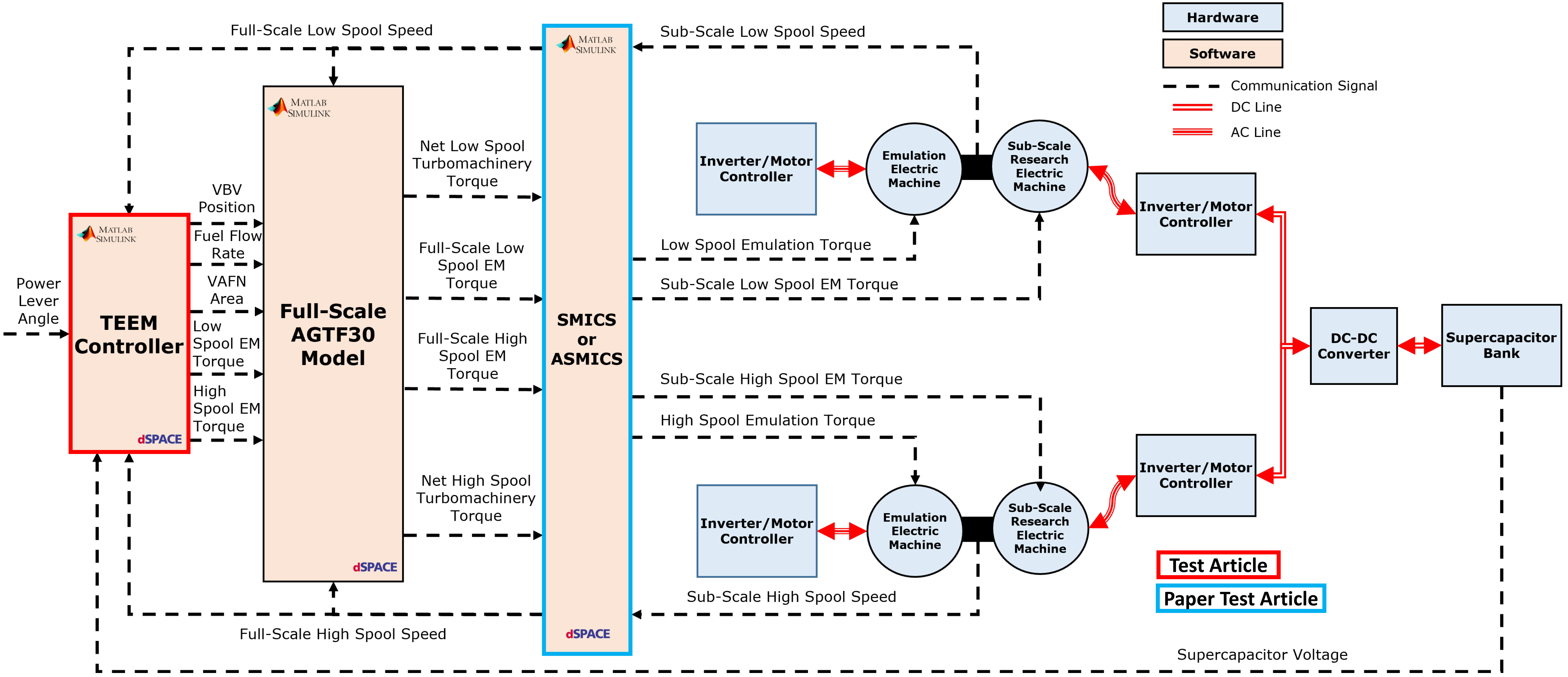
Implementation - 1

- **Facility:** Hybrid Propulsion Emulation Rig (HyPER) [2]
- **Engine:** Electrified Advanced Geared Turbofan 30,000 lbf thrust (AGTF30) [3]
- **Controller:** Turbine Electrified Energy Management (TEEM) [4]



Tested in a sub-scale facility configured to represent a parallel hybrid-electric turbofan propulsion system.

Implementation - 2



Hardware

Software

Communication Signal

DC Line

AC Line

Full-Scale Low Spool Speed

Sub-Scale Low Spool Speed

Power Lever Angle

TEEM Controller

VBV Position

Fuel Flow Rate

VAFN Area

Low Spool EM Torque

High Spool EM Torque

Full-Scale AGTF30 Model

Net Low Spool Turbomachinery Torque

Full-Scale Low Spool EM Torque

Full-Scale High Spool EM Torque

Net High Spool Turbomachinery Torque

SMICS or ASMICS

Inverter/Motor Controller

Emulation Electric Machine

Sub-Scale Research Electric Machine

Inverter/Motor Controller

Low Spool Emulation Torque

Sub-Scale Low Spool EM Torque

DC-DC Converter

Supercapacitor Bank

Sub-Scale High Spool EM Torque

High Spool Emulation Torque

Inverter/Motor Controller

Inverter/Motor Controller

Emulation Electric Machine

Sub-Scale Research Electric Machine

Sub-Scale High Spool Speed

Full-Scale High Spool Speed

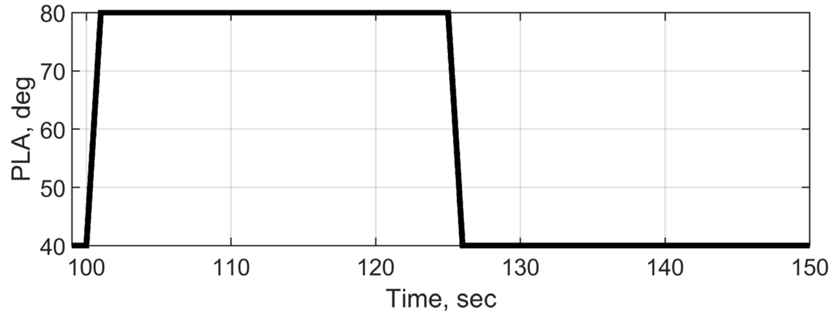
Supercapacitor Voltage

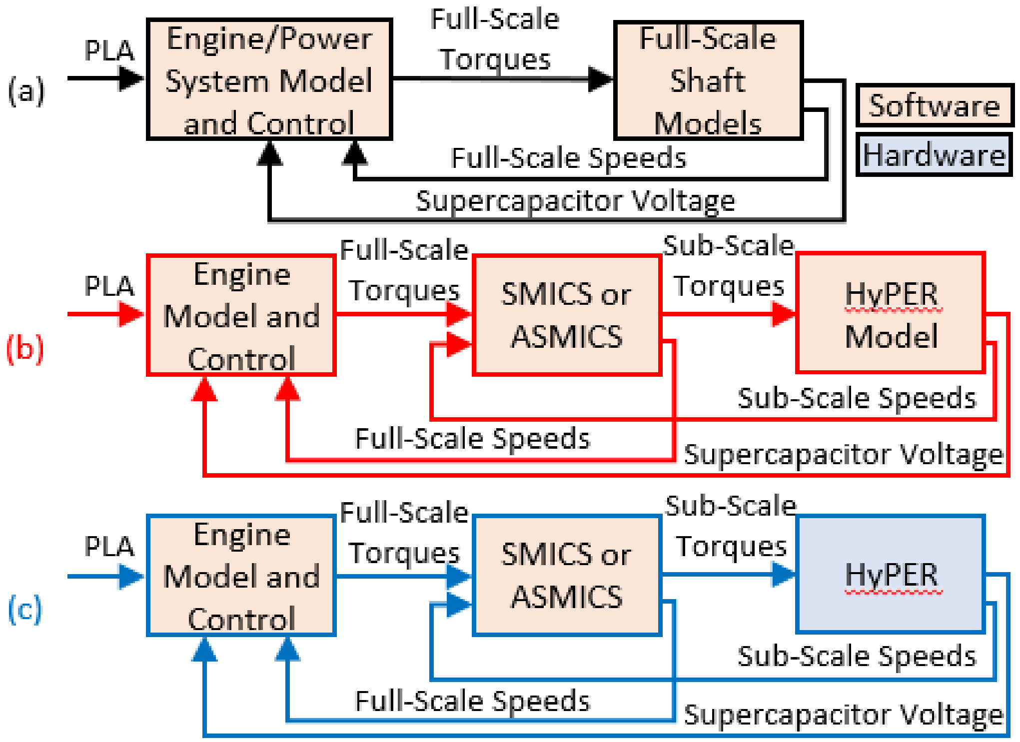
Test Article

Paper Test Article

Test Plan

- Sea-level static conditions.
- Nominal Tests
    1. SIL – Theoretical Simulation – (a)
    2. HIL – SMICS – (b)
    3. HIL – ASMICS – (c)
- Robustness tests with both controllers.
    1. Nominal plant parameters.
    2. Artificially doubled plant inertia and damping coefficient values.




(a)
PLA
Engine/Power System Model and Control
Full-Scale Torques
Full-Scale Shaft Models
Full-Scale Speeds
Supercapacitor Voltage
Software
Hardware

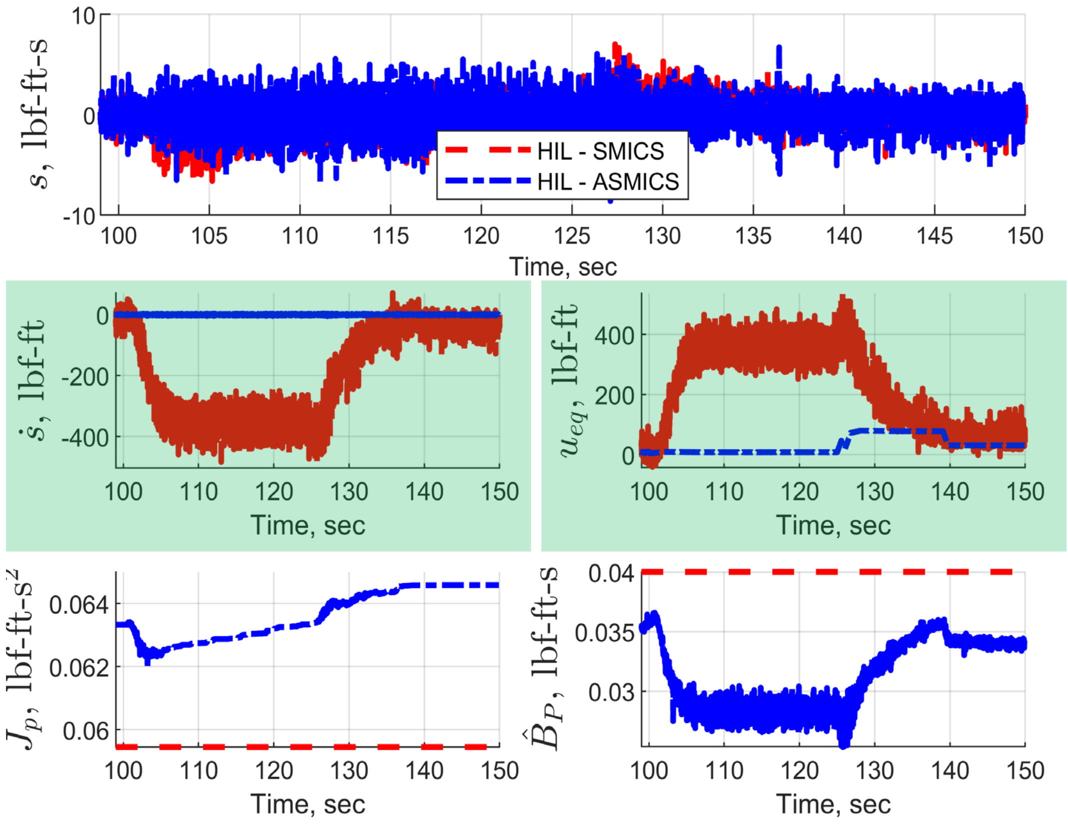
(b)
PLA
Engine Model and Control
Full-Scale Torques
SMICS or ASMICS
Sub-Scale Torques
HyPER Model
Sub-Scale Speeds
Full-Scale Speeds
Supercapacitor Voltage

(c)
PLA
Engine Model and Control
Full-Scale Torques
SMICS or ASMICS
Sub-Scale Torques
HyPER
Sub-Scale Speeds
Full-Scale Speeds
Supercapacitor Voltage

Turbofan model commanded burst/chop throttle maneuver at sea-level static conditions for seven different tests.

Results/Discussion

$$RE = 100\left(\frac{RMSRE_{ASMICS} - RMSRE_{SMICS}}{RMSRE_{SMICS}}\right)$$



Legend

VBV	- variable bleed valve
VAFN	- variable area fan nozzle
LS	- low spool
HS	- high spool
LPC	- low pressure compressor
HPC	high pressure compressor
HPT	- high pressure turbine
x	- generic variable
RMSRE	- root-mean-squared relative error
RE	- relative error

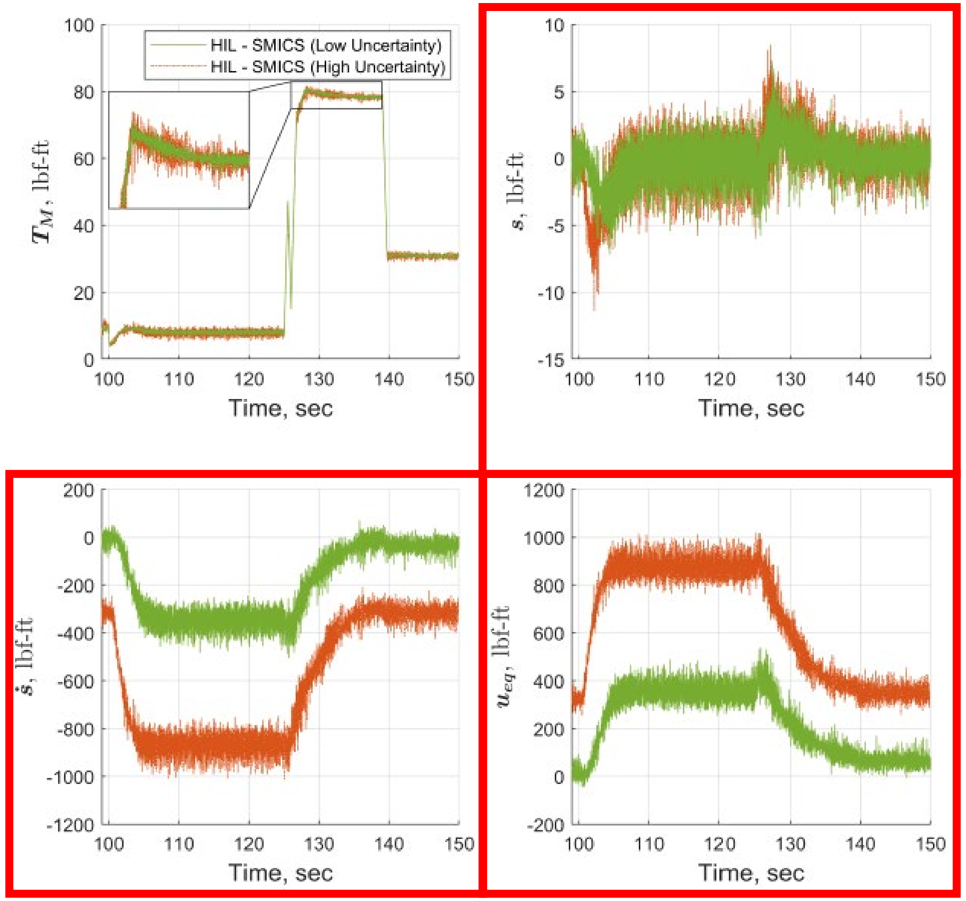
$$RMSRE = 100\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{x_{HIL} - x_{SIL}}{\max(|x_{SIL}|)}\right)^2}$$

Variable	RMSRE, % SIL vs. HIL		RE, %
	SMICS	ASMICS	
Fuel Flow Rate	0.055%	0.044%	-20.0%
VBV Position	0.333%	0.372%	+11.7%
VAFN Area	0.055%	0.048%	-12.7%
LS EM Torque	0.871%	0.813%	-6.6%
HS EM Torque	2.001%	0.975%	-51.2%
LS Speed	0.139%	0.142%	+2.1%
HS Speed	0.098%	0.116%	+18.3%
LPC Stall Margin	1.175%	1.464%	+24.5%
HPC Stall Margin	0.397%	0.422%	+6.2%
LPC Output Static Pressure	0.104%	0.074%	-28.8%
HPT Inlet Total Temperature	0.048%	0.023%	-52.1%
Thrust	0.180%	0.202%	+12.2%
Iteration Count	40.025%	27.413%	-31.5%

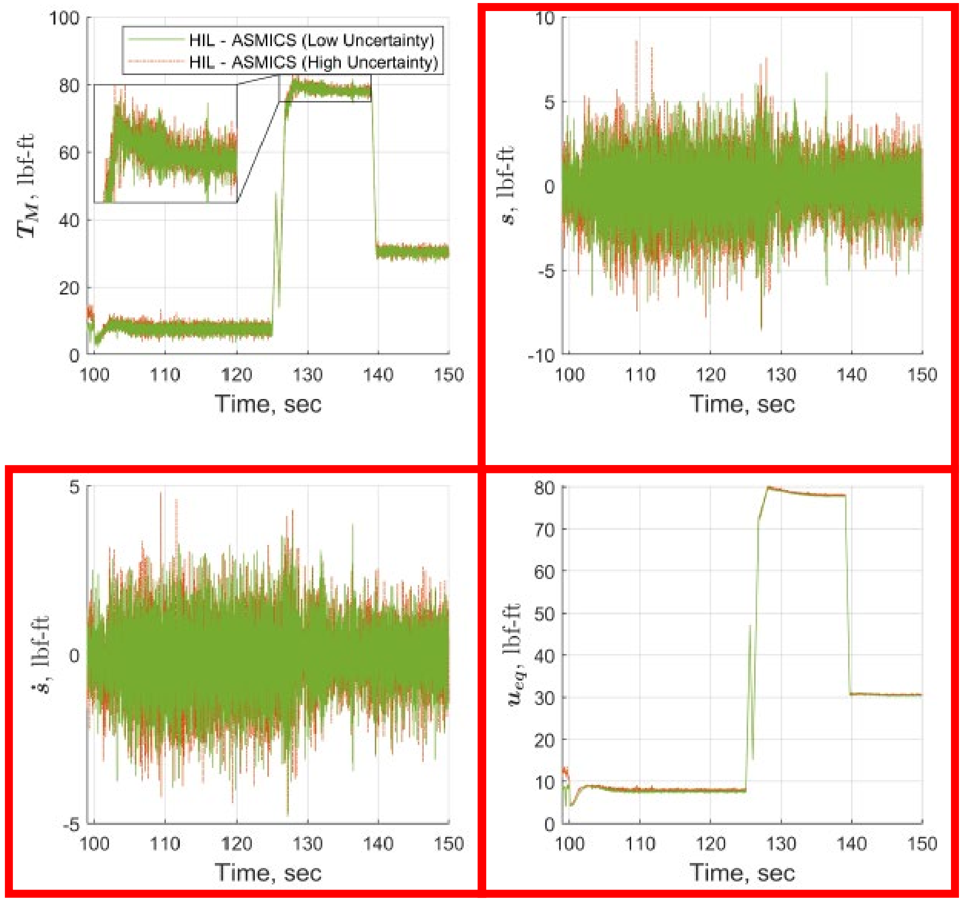
Accuracy of turbofan model behavior increased. Significantly reduced controller efforts.

Robustness Analysis

SMICS



ASMICS



100% change in initial plant parameter guess has little effect on ASMICS operation.

Summary/Conclusions

- An adaptive emulation controller was tested and verified in a hardware-in-the-loop environment.
  - Emulated mechanical loads of turbofan on a parallel hybrid electrical architecture.
- Compared against original, non-adaptive approach.
- Adaptive approach:
  - Asymptotically stable in the sense of Lyapunov.
  - Increases turbofan model operation accuracy.
  - Decreases control effort.
  - Robust to significant plant parameter uncertainty.

Acknowledgements

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  - Marcus A. Horning
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References

[1] Bianco, S. J., and Simon, D. L., “Control and Scaling Approach for the Emulation of Dynamic Subscale Torque Loads,” AIAA Aviation Forum/Electric Aircraft Technologies Symposium (EATS), San Diego, CA, 2023.

[2] Buescher, H. E., Culley, D. E., Bianco, S. J., Connolly, J. W., Dimston, A. E., Saus, J. R., Theman, C. J., Hunker, K. R., Garrett, M. J., Haglage, J. M., Horning, M. A., Cha, Y. C., and Purpera, N. C., “Hybrid- Electric Aero-Propulsion Controls Laboratory: Overview and Capability,” AIAA Science and Technology (SciTech) Forum, National Harbor, MD, 2022.

[3] Chapman, J. W., and Litt, J. S., “Control Design for an Advanced Geared Turbofan Engine,” AIAA Propulsion and Energy Forum, Atlanta, GA, 2017.

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