Controls for Electrified Aircraft Propulsion

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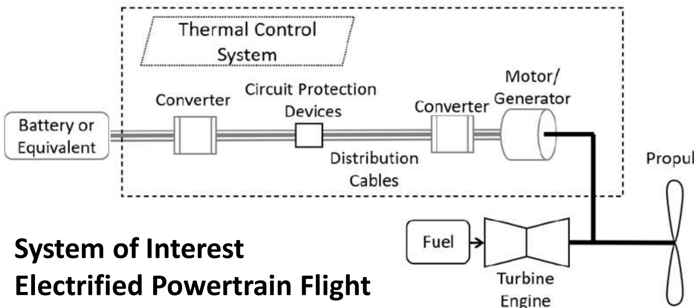
Subsonic Vehicle Technologies and Tools (SVTT) Project

SVTT research focuses on the long-term technology timeframe.

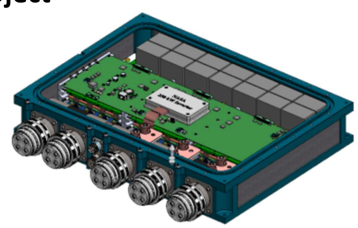
- Electrified aircraft propulsion (EAP)
- Complimentary gas turbine engine research needed to develop new engines to provide onboard power
- High power and high efficiency

N3-X, an advanced vehicle concept. *Credit: NASA*

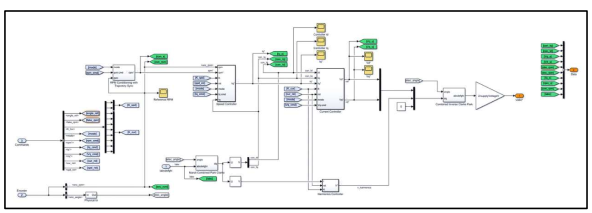
NASA EAP Technology



System of Interest
Electrified Powertrain Flight Demonstration (EPFD) Project
Credit: NASA.

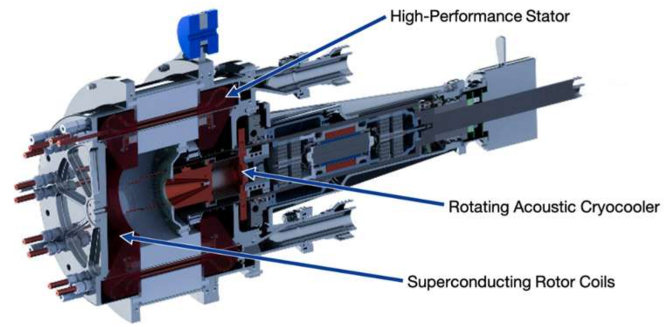


Motor and Generator Intelligent Converter (MAGIC)
Credit: NASA.

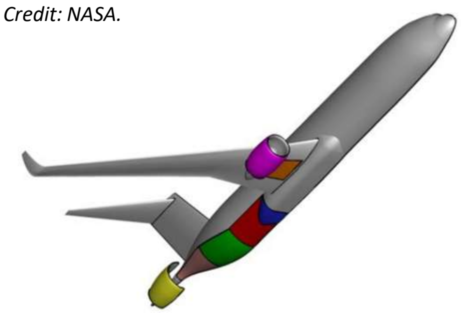


Motor Controller Code Generation
Credit: NASA.

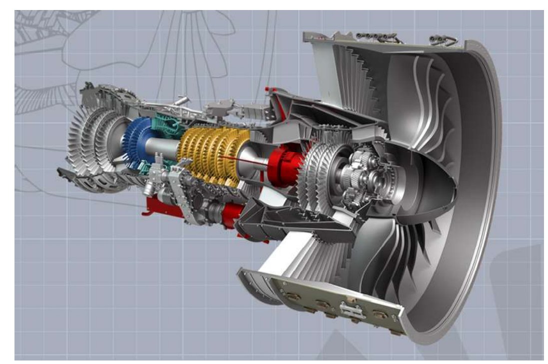
X-57 Battery Pack
Credit: NASA.



High-Efficiency Electric Megawatt Motor (HEMM)
Credit: NASA.



Outer Mold Line Heat Exchangers
Credit: NASA.



Hybrid Thermally Efficient Core (HyTEC)
Credit: NASA.

Controls for Electrified Aircraft Propulsion (EAP)

Supervisory, System-Level

Electrified Aircraft Propulsion

- Highly coupled propulsion, power, and thermal systems
- Need for multi-disciplinary modeling (average fidelity)
- Controls robust to uncertainty

Optimal energy management

- Turbine Electrified Energy Management (TEEM)

System Health Management

- Digital Twin and state estimation

Fault detection and response

- Reversionary and adaptive control

Modular, Component-Level

High power at altitude

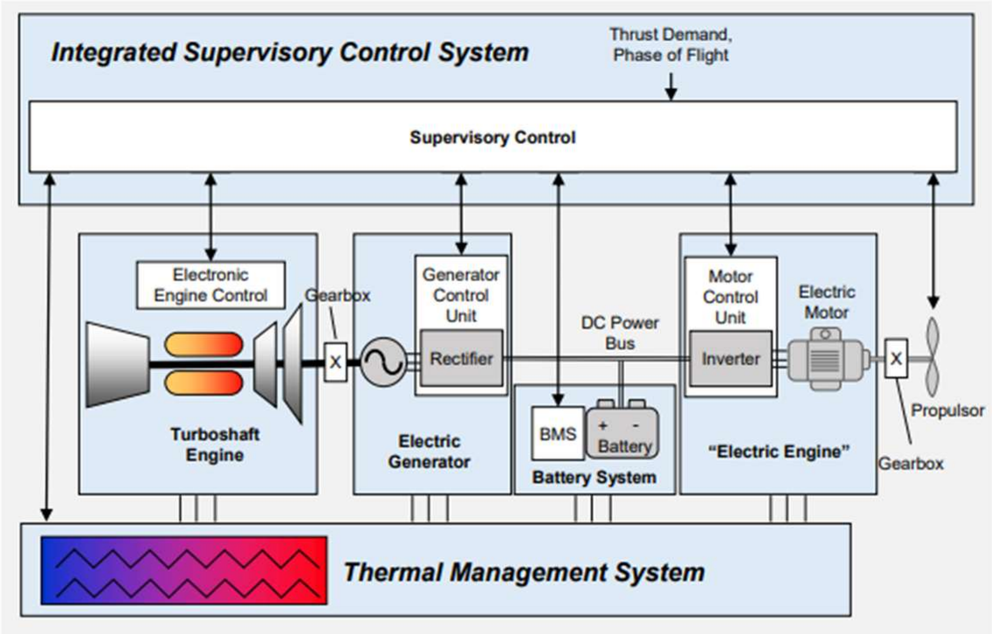
- Electrical bus stability
- Battery cell balancing

Engine Advancements

- Adaptive Cycles
- Variable geometries

Thermal Management Systems

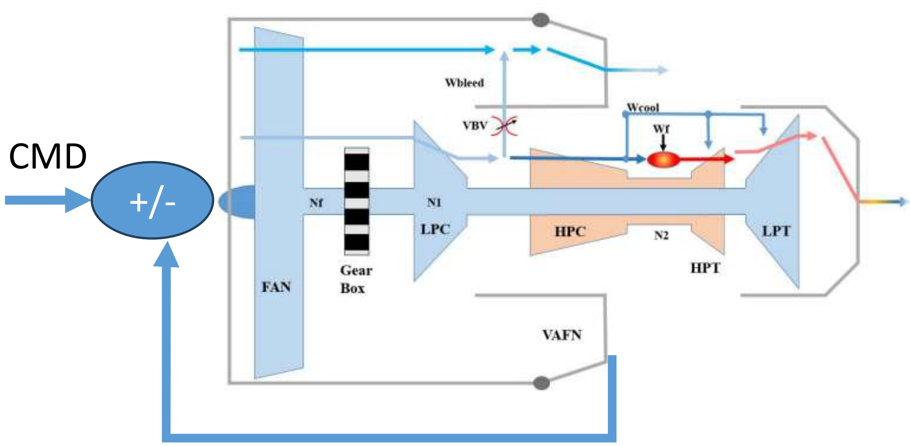
- Coordinating between multiple sources and sinks
- Multi-domain: cryogenic + ambient



Generic Hybrid Electric Power, Propulsion, and Thermal System.
Credit: NASA.

Existing Engine Control

Turbofan Engine



Shaft Speed, Limits, Schedules

Traditionally fuel flow rate (Wf) has a closed loop control

- Consists of a power lever set-point (set by the throttle) and various limit controllers
- Logic decides which controller is active

Additional engine actuators are often scheduled

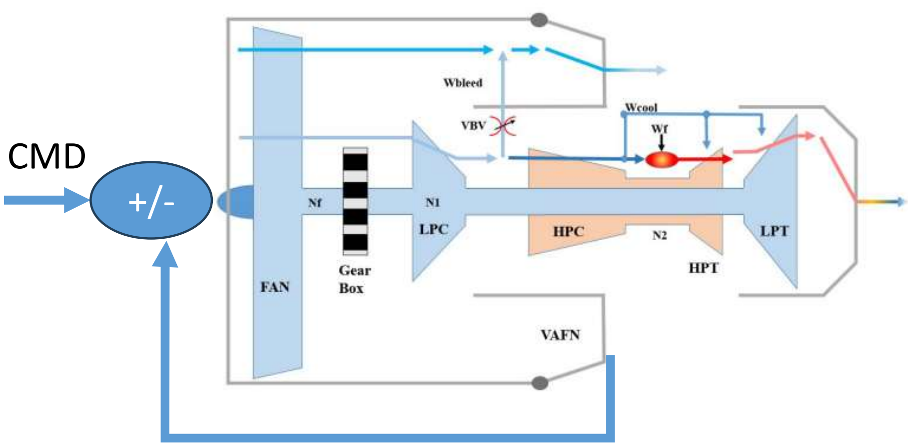
- Variable area fan nozzle
- Bleed valves

The electric power system must be coordinated with the engine control

- Nominal power can be schedule with engine power level (fan speed)
- Off-nominal inputs for various use cases like in-flight charging, TEEM, EPT, etc.

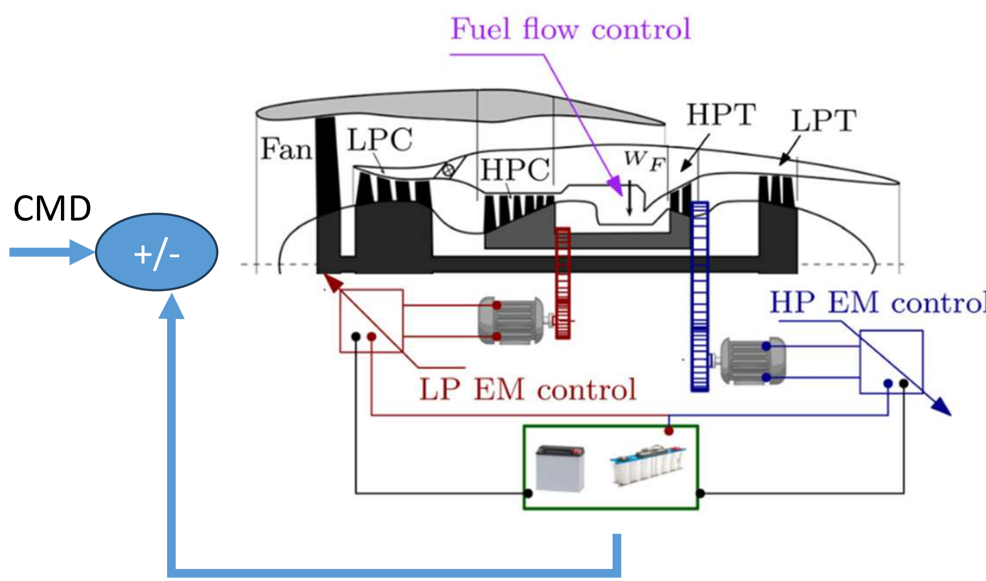
Simple Controls Fuel Only to Hybrid Electric

Turbofan Engine



Shaft Speed, Limits, Schedules

Hybrid Turbofan Engine



Shaft Speed, Torques, States of Charge, Limits, Schedules

Hybrid-Electric Engine Control

Use cases:
- Mild hybrid: e-Taxi, Turbine Electrified Energy Management (TEEM), low engine power electric power transfer (EPT), relatively small electric boost, etc.
- Parallel hybrid: thrust augmentation to reduce engine size and weight

Considerations:
- Managing propulsive, mechanical, and electrical energy
- Limited by available power and thermal constraints
- Leveraging the added electrical and mechanical integration components to benefit the operation of the turbomachinery that is still at the heart of the propulsion system

Example questions:
- When to use electric machine augmentation to boost thrust?
- How to coordinate the engine control with extraneous electrically driven propulsors that it supplies?
- How can the power balance of the shafts be manipulated to gain benefits in performance and/or operability?

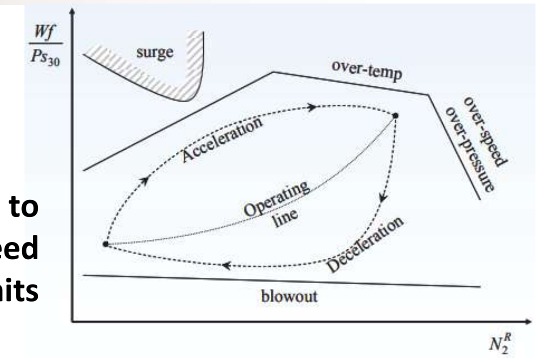
Turbofan Engine Power Extraction Demonstration Project. *Credit: GE Aerospace.*

STARC-ABL, turboelectric. *Credit: NASA.*

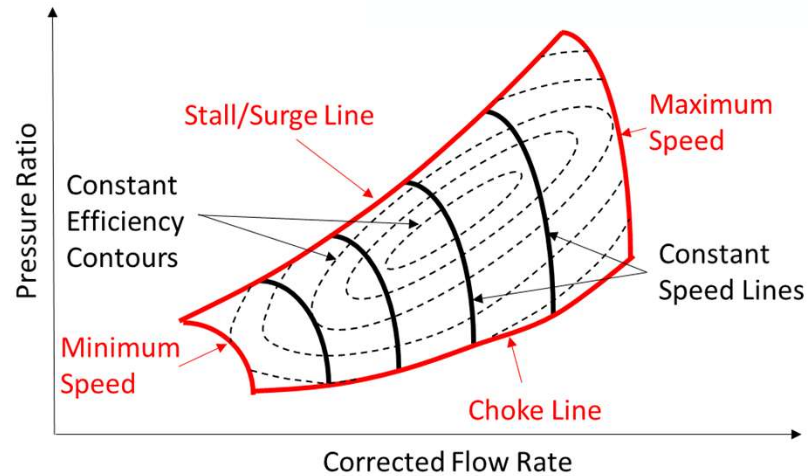
Examples of Engine Control Considerations

1. 15-95% thrust in 5 seconds.
2. Minimize thrust specific fuel consumption (TSFC).
3. Compressor stall/surge.
4. Combustor blowout.
5. Spool overspeed.
6. Compressor overpressure
7. Minimum pressures
8. Turbine blade temperature limit.
9. Electrical energy storage capacity.

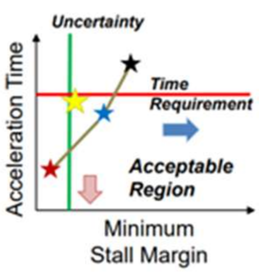
Items 1–2: Performance
Items 3–4: Operability
Items 5–8: Limits
Item 9: Hybrid-electric



Ratio unit related to corrected core speed relative to operating limits



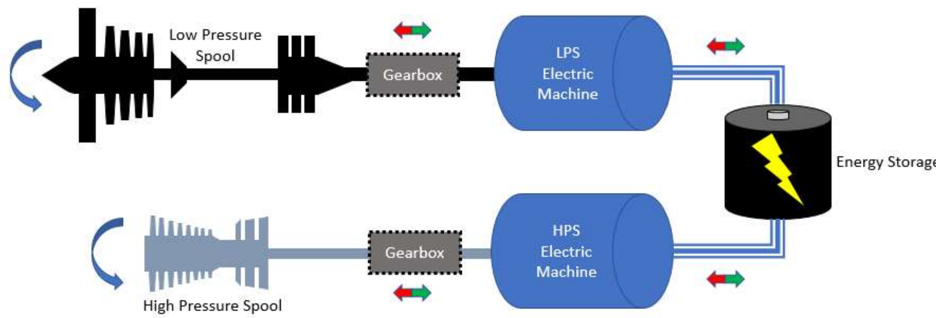
Example of a compressor map with marked operating limits

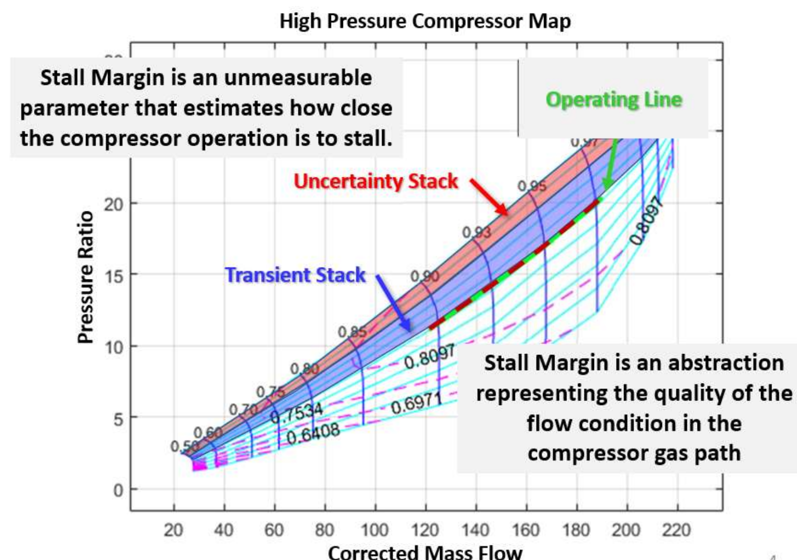


Trade between thrust response time and compressor operability

Turbine Electrified Energy Management (TEEM)

- **Objective:** Leverage an electrical power system to alter engine operation to the benefit of the turbomachinery.
- **Purpose:** Alleviate design constraints on engine design that will lead to a more efficient engine, lighter engine, and/or more capable engine.
- **Approach:** Use electric machines and electrical energy storage to modify the shaft speeds to improve flow incidence angle during transients that will help improve stall/surge margin.
- Investigated Implementation Strategies:
  - PID controllers with activation logic
  - Schedules guided with optimization methods
  - Model Predictive Control



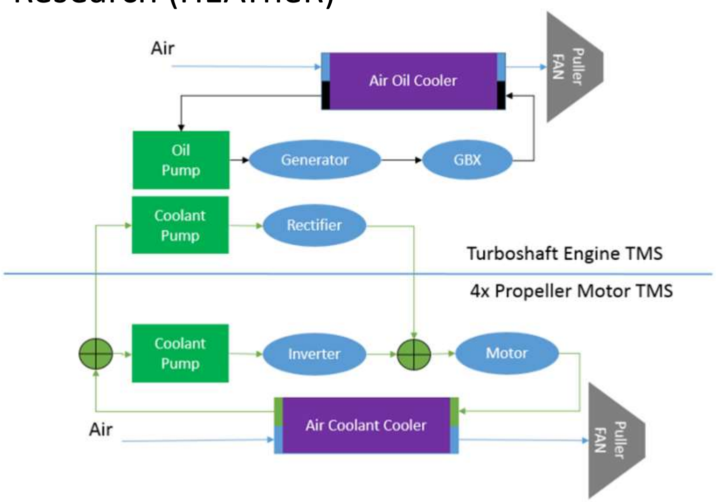


*Developed under the NASA Transformational Tools & Technologies Project

Thermal Control

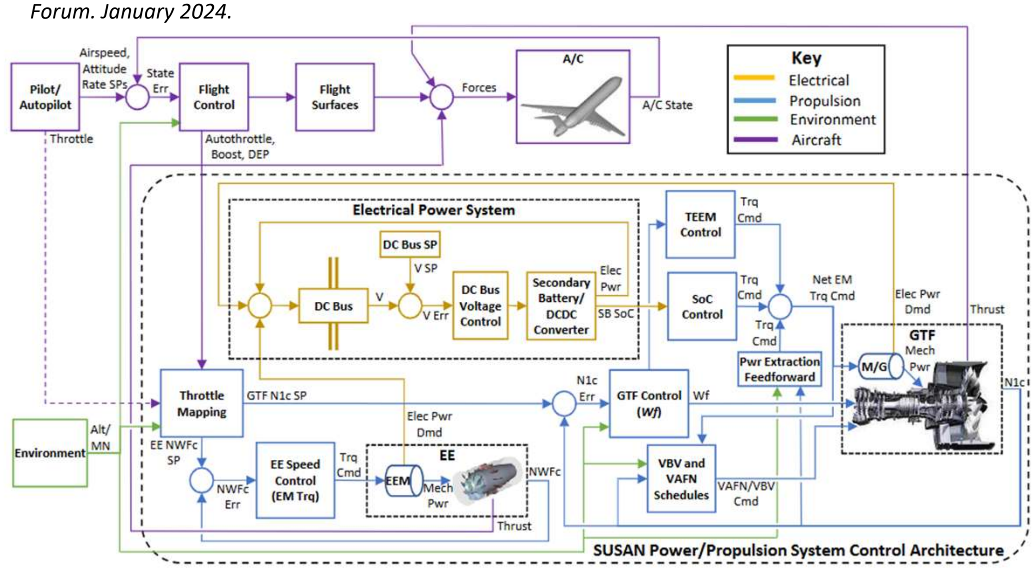
There is a gap in thermal management system control.

- Subsonic Single Aft Engine (SUSAN) Electrofan
- High-Efficiency Electrified Aircraft Thermal Research (HEATheR)



Thermal Management System for a 15 passenger tiltwing vehicle.
Jeffryes W. Chapman, Sydney L. Schnulo and Michael P. Nitzsche. "Development of a Thermal Management System for Electrified Aircraft," AIAA 2020-0545. AIAA Scitech 2020 Forum. January 2020.

SUSAN Power and Propulsion System Control Block Diagram.
Jonah Sachs-Wetstone, Jonathan S. Litt, Jonathan L. Kratz and Halle Buescher. "SUbsonic Single Aft eNgine (SUSAN) Power/Propulsion System Control Architecture Updates," AIAA 2024-1330. AIAA SCITECH 2024 Forum. January 2024.



System Health Management and Fault Detection

EAP systems present new system health management and fault accommodation challenges:

- Architectures are more coupled and integrated in nature
- Boundary between propulsion system and vehicle not as clearly defined
- Data compression and feature extraction techniques for high-frequency electrical system measurements will be necessary
- Electrical systems may not exhibit graceful degradation / failure making timely diagnostics and prognostics more challenging
- See publication:

  Simon, D.L., Thomas, R., Dunlap, K.M., "Considerations for the Extension of Gas Path Analysis to Electrified Aircraft Propulsion Systems," ASME GT2021-58578, 2021 ASME Turbo Expo, June 7-11, Virtual, Online https://doi.org/10.1115/GT2021-58578.

Motivation of Modeling

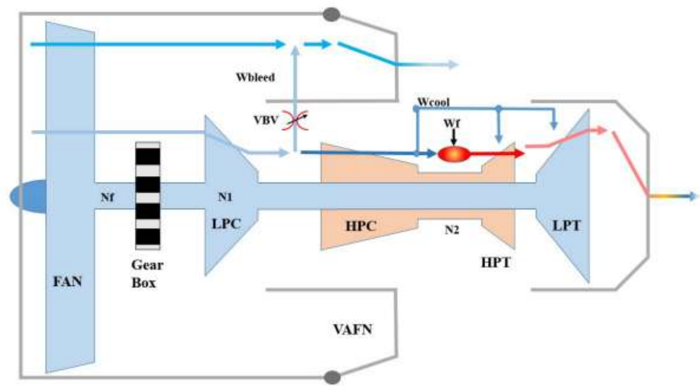
- Key to fundamental research, technology evaluation, and preliminary concept development
  - Establish understanding of trends
  - Establish understanding of physical phenomena with first principles
  - Parametric studies for trade space exploration
  - Optimization studies
  - Varying ranges of fidelity to perform efficient investigations
  - Etc.
- Typically time- and cost-efficient
- Low risk
- Enables emulation of what is not practical to implement in hardware

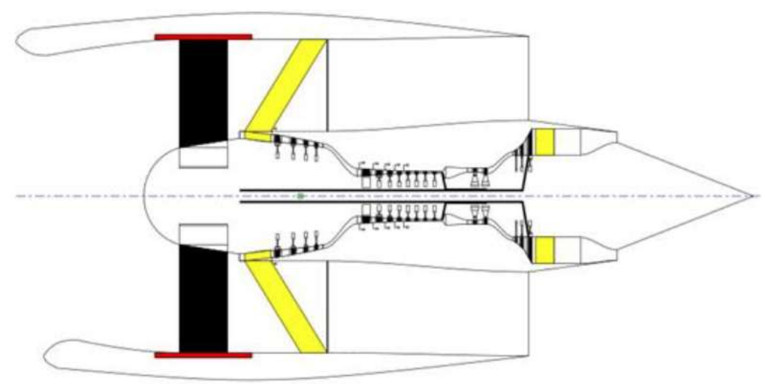
Conceptual Advanced Turbofan Model

Why release system models?
Provides a relevant, generic basis for comparisons and collaboration among the community

Advanced Geared TurboFan 30,000 lbf (AGTF30)

- N+3 (Technologies with mid-2030's entry to service)
- 30,000 lbf thrust at sea level static conditions
- Small core
- Geared fan
- Actuators
  - Fuel Metering Valve
  - Variable Bleed Valve
  - Variable Area Fan Nozzle
- Utilizes T-MATS
- Controller with representative performance
- Used in numerous studies since 2016 (distributed engine control, tip clearance control, secondary flows, fault analysis, engine electrification, hardware-in-the-loop, etc.)





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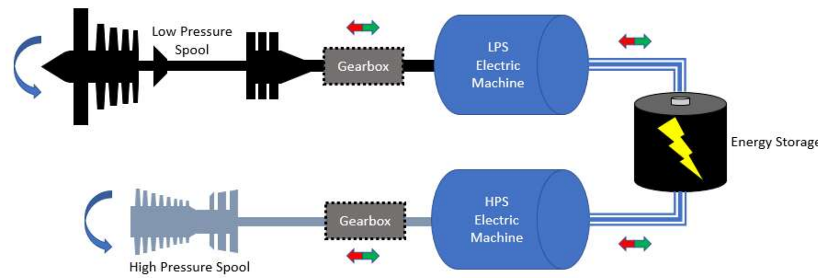
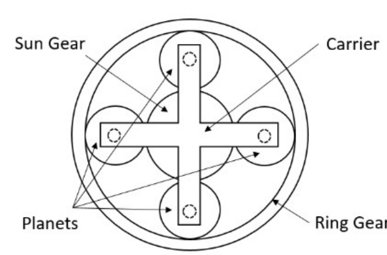
Electrified Advanced Turbofan Model

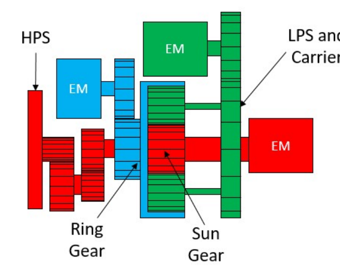
<u>A</u>dvanced <u>G</u>eared <u>T</u>urbo<u>F</u>an <u>30</u>,000 lbf – <u>e</u>lectrified (AGTF30-e)

- Builds on the AGTF30
- Primary modes of operation
  - Standard mode
  - Boost mode
  - Power Extraction (PEx) mode
- Secondary electrification options
  - Electric power transfer (EPT)
  - Turbine electrified energy management (TEEM)
  - Charging an energy storage device
- Engine – Electric Machine (EM) integration approaches
  - Dedicated EM (DEM)
  - Versatile Electrically Augmented Turbine Engine (VEATE) Planetary Gearbox (PGB)
- Simple electrical power system model framework
- Updated, versatile control implementation

User's Guide Included!!







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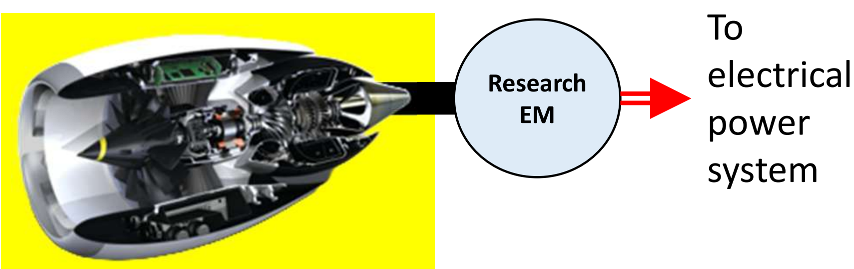
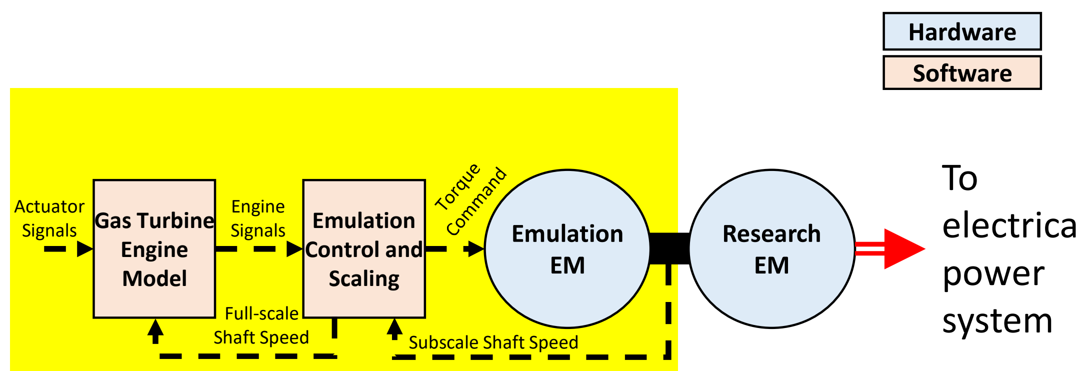
Hardware-in-the-Loop Implementation

- Problem
  - Gas turbine engine not available for testing.
  - Sub-scale electrical hardware.
- Solution
  - Emulate the sub-scale mechanical characteristics of the gas turbine engine shafts using electric machines.





Emulation Solution

- Impedance Control
  - Typically used to regulate interaction between robotic manipulator and environment.

Impedance Control

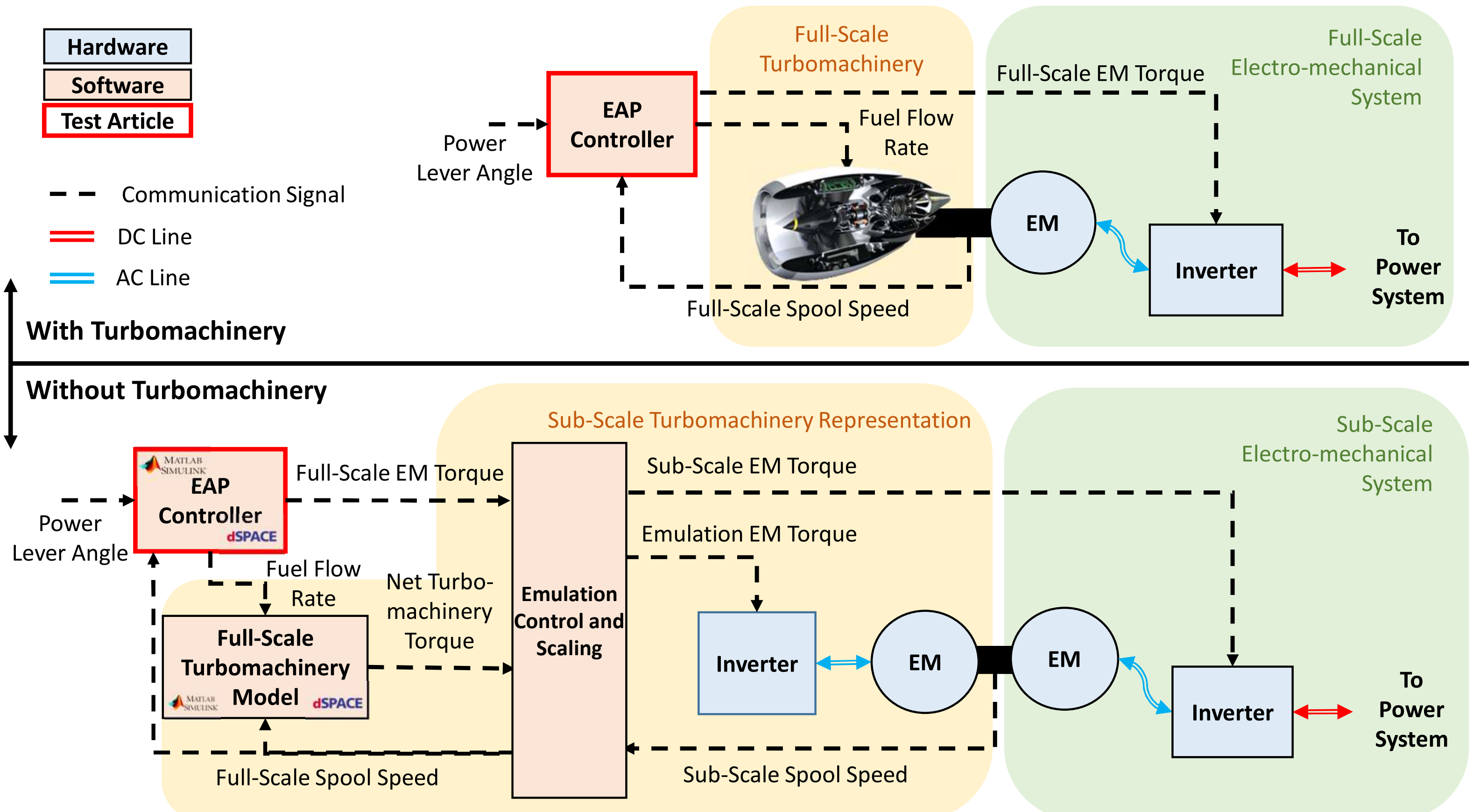
1. Sliding Mode Impedance Controller with Scaling (SMICS)
   - Robust
   - Model-based.
   - Not proven to be stable.

SMICS

2. Adaptive Sliding Mode Impedance Controller with Scaling (ASMICS)
   - Robust
   - Adapts model-based parameters.
   - Proven to be stable.

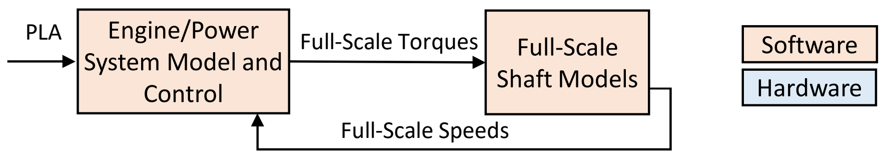
ASMICS

No physical gas turbine engine?

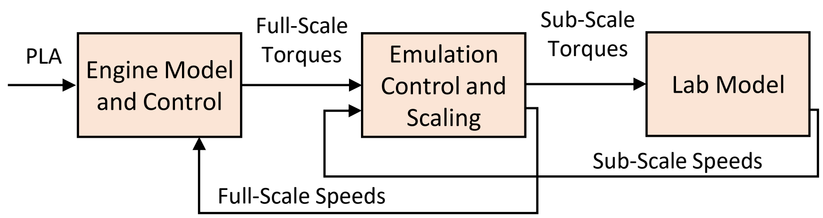


Steps to Hardware-in-the-loop Testing

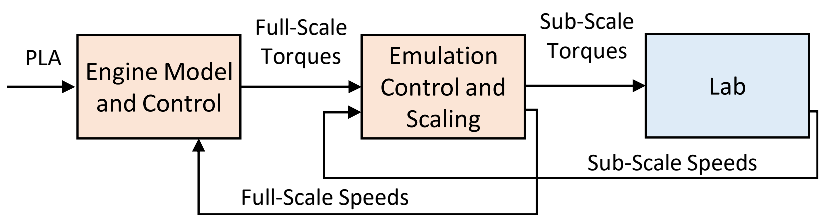
1. Software-in-the-loop (SIL) Testing
   - Computer simulation of intended plant and controller.



2. Simulated Hardware-in-the-Loop (SHIL) Testing
   - Computer simulation of surrogate plant and controller.



3. Hardware-in-the-Loop (HIL) Testing
   - Real-time simulation of controller driving surrogate plant hardware.



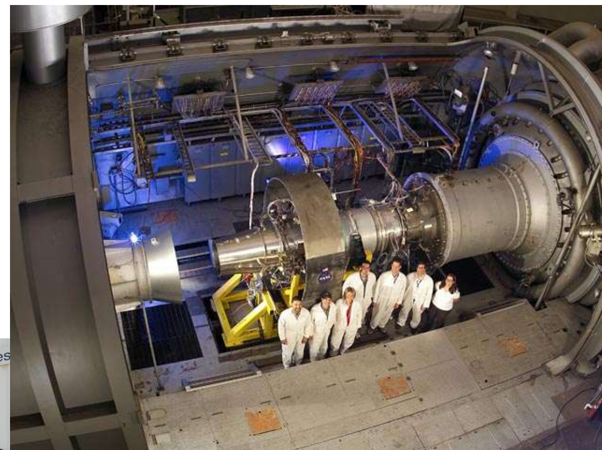
Control Research Areas

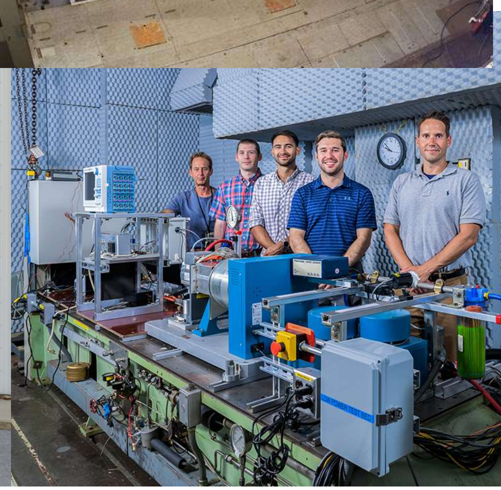
- Thermal management system control
- Electrical bus stability
- Energy storage system (batteries) management
- Optimal (thermal, mechanical, electrical) energy management
- Fault detection & accommodation and systems health management

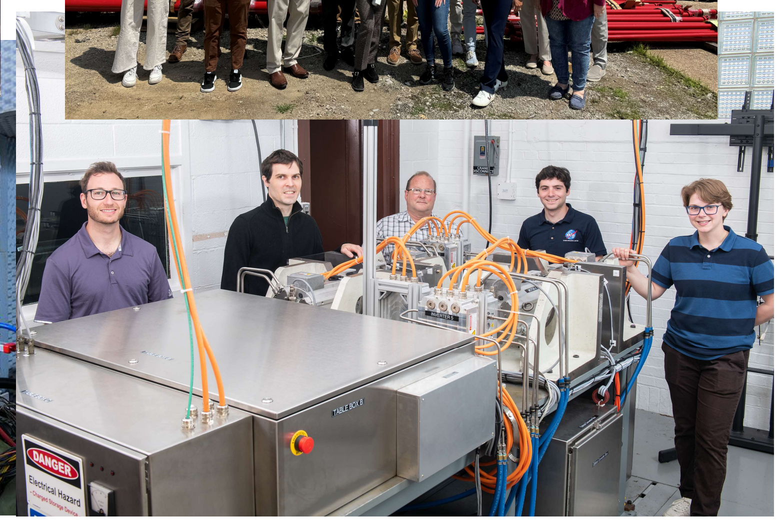
Summary

- Complex, integrated systems require advanced control. These controllers can be developed earlier on in the design process. Hybrid-electric engine control considers performance, operability, system limits, and energy management.
- Modeling hybrid-electric architectures can be done with various tools such as T-MATS and EMTAT.
- It is possible to test an advanced controller on emulated turbomachinery using sub-scale hardware using ASMICS.
- Software-in-the-loop, simulated hardware-in-the-loop, and hardware-in-the-loop.

The NASA EAP Team







Thank you!

Advanced Air Vehicles Program (AAVP)

Subsonic Vehicle Technologies and Tools (SVTT) Project

https://www.nasa.gov/directorates/armd/aavp/svtt/