Intelligent Control & Autonomy Branch Research Overview

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University of Cincinnati (Virtual)
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Agenda

- Introduction
  - Organizational Overview
- Overview of Current Research Activities
  - Electrified Aircraft Propulsion
    - Introduction
    - Turbine Electrified Energy Management Research
    - Systems Health Management
    - Free Software Tools
    - Relevant Facilities
  - Space Launch System Mission & Fault Management
    - Introduction
    - Function Fault Modeling
    - Mission & Fault Management Algorithm Development
  - Closing
    - Web Site
    - Internship Opportunities
    - References

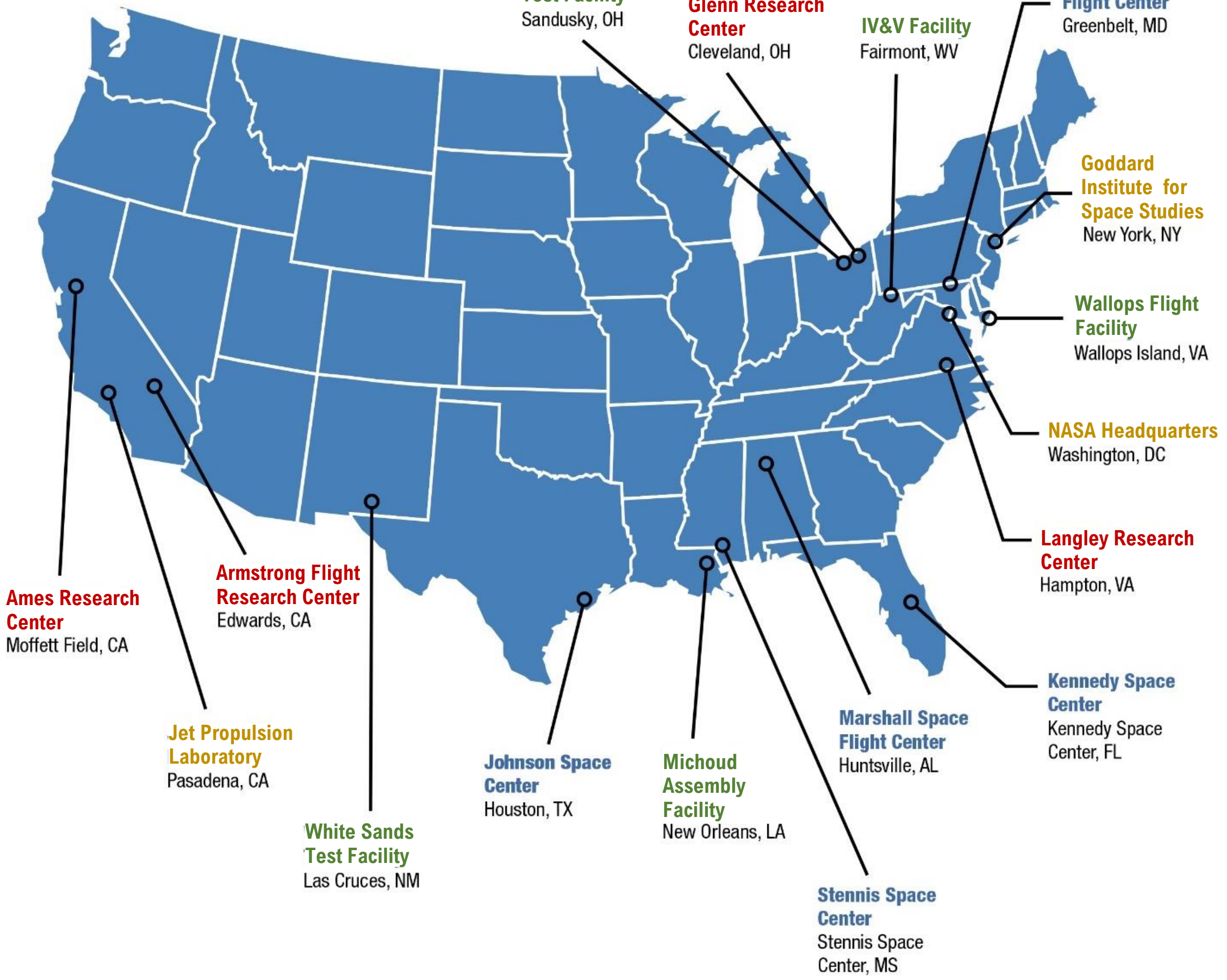
NASA Organization

Mission Directorates, $19.8B

- Aeronautics Research, $0.8B
- Human Exploration & Operations, $10.5B
- Science, $7.3B
- Space Technology, $1.1B

Other, $3.5B

Centers & Facilities



NASA John H. Glenn Research Center

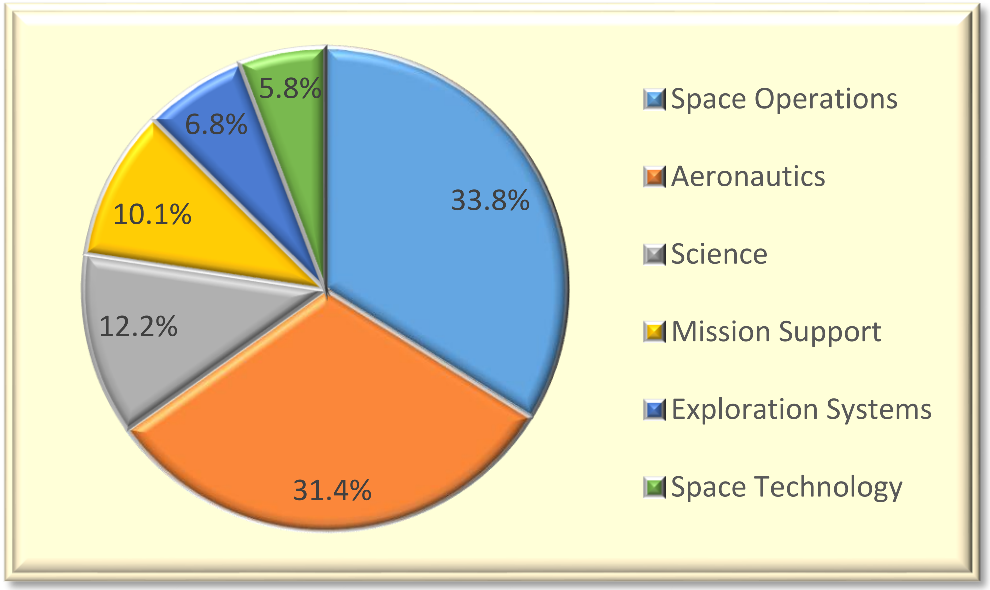
Lewis Field (Cleveland)
- 350 acres
- ~1500 civil servants and ~1,500 contractors
- plus 84 Pathways Interns

Neil A. Armstrong Test Facility (Sandusky)
- 6,500 acres
- 21 civil servants and 105 contractors

Communications & Intelligent Systems Division

- MISSION: Perform and direct research and engineering in the competency fields of Advanced Communications and Intelligent Systems with emphasis on **advanced technologies, architecture definition and system development** for application in current and future aeronautics and space systems.
- Research and discipline engineering covers a broad range of technology readiness levels (TRL).

Support to NASA Mission Directorates



Competency Elements

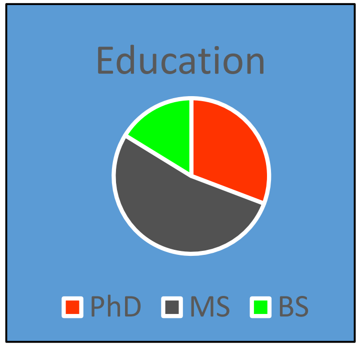
Space and Aeronautical Communications Expertise

- Architecture Definition & Analysis
- Network Research
- Communication System Integration & Test
- Signal Processing & Cognition
- Advanced High Frequency Components & Systems
- Optical Communications

Intelligent Systems Expertise (Cross-Cutting Competencies)

- Optics and Photonics
- Smart Sensor Systems
- Electronic Instrumentation
- Controls Systems – Propulsion Control

Communications and Intelligent Systems Division



107 FTE, 42 WYE

+ 27 Summer Students
+ 2 Summer Faculty

Extensive Laboratories (~60)

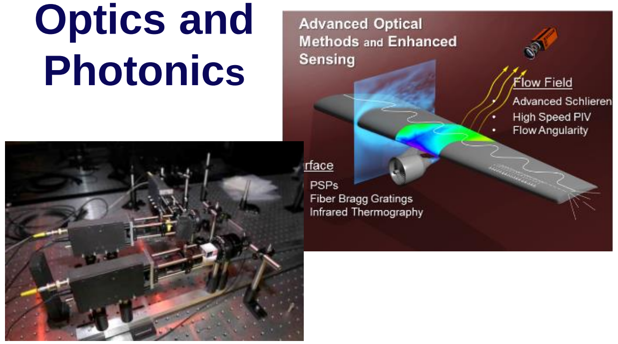
NEW Aerospace Communication Facility

Communications and Intelligent Systems Division
Chief: Dawn Emerson
Deputy Chief: Dr. Félix Miranda
Senior Technologist: Dr. Robert Romanofsky

- **System Architectures and Analytical Studies Branch** — Chief, Richard Reinhart
- **Intelligent Control and Autonomy Branch** — Chief, Kevin Melcher
- **Secure Networks, Systems Integration and Test Branch** — Chief, Robert Jones
- **Smart Sensing and Electronics Systems Branch** — Chief, Diana Centeno-Gomez
- **Advanced High Frequency Branch** — Chief, Dr. James Nessel
- **Optics and Photonics Branch** — Chief, Dr. Margret Nazario
- **Cognitive Signal Processing Branch** — Chief, Gene Fujikawa

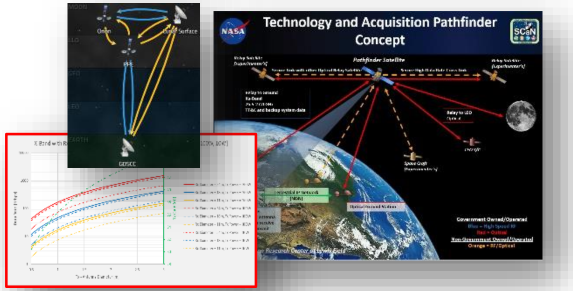
Communications & Intelligent Systems Division

Optics and Photonics



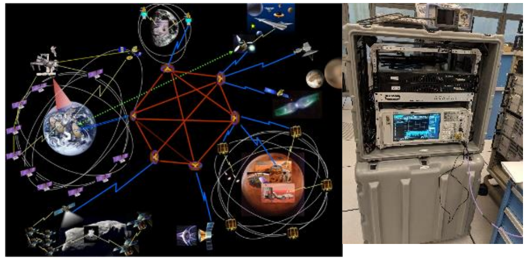
Optical Communications/Quantum Comm
Hyperspectral Imaging
Optical Instrumentation- Flow Diagnostics
Health Monitoring

Systems Architectures & Analytical Studies



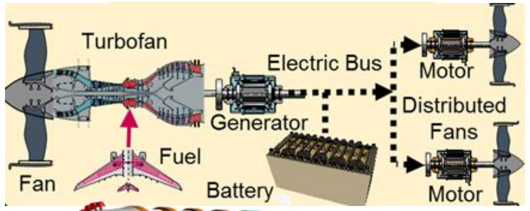
Communications System Architectures
Analytical System Studies, Mod & Sim
Spectrum Analysis

Secure Networks, System Integration and Test Branch



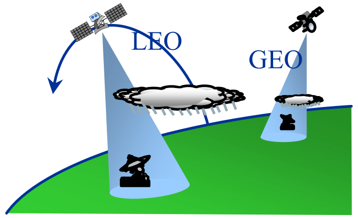
Network Research/Security
System Integration/Test/Demo

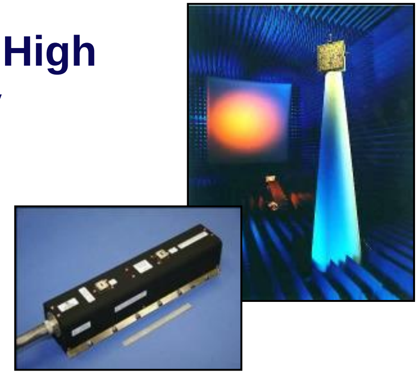
Intelligent Control and Autonomy



Intelligent Controls,
Dynamic Modeling,
Systems Health Mgmt

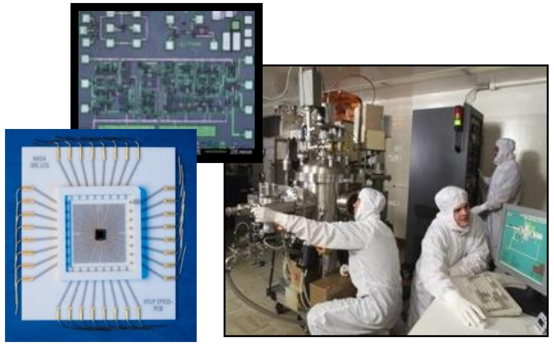
Advanced High Frequency





Antenna Design and Metrology, Propagation,
RF Systems and Components, 3-D Electromagnetic Modeling

Smart Sensing and Electronics Systems



Extreme Environment Sensors & Electronics,
Electro-Optical Sensing, Thin Film Physical Sensors

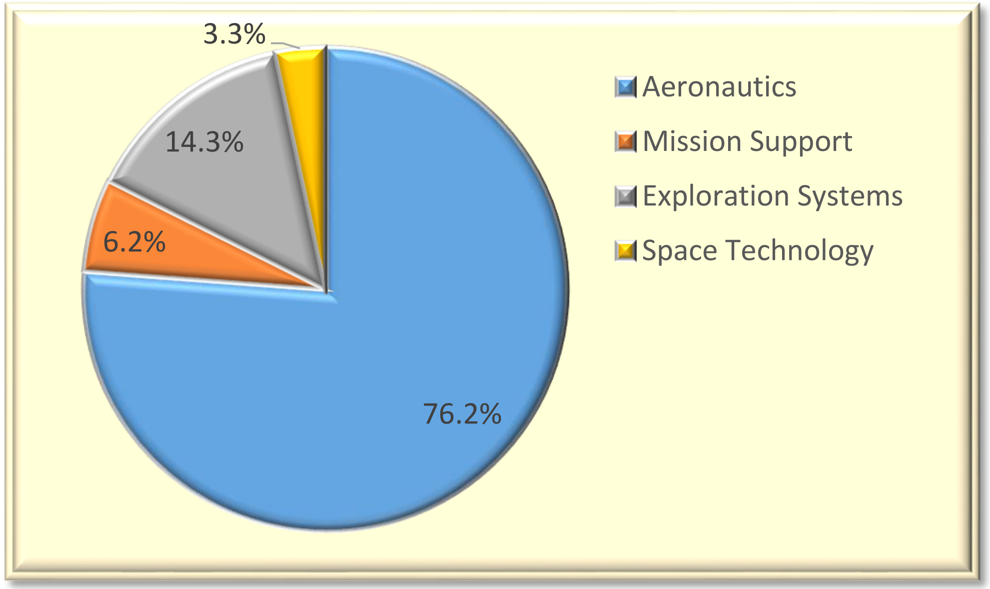
Cognitive Signal Processing

Radio Systems – SDRs, Signal Processing and Cognition Position, Navigation & Timing

Intelligent Control and Autonomy Branch

- MISSION: Conduct research & engineering to develop, demonstrate, and mature technologies for advanced control concepts, systems health management, and modeling of dynamics systems – with a strong focus on aerospace propulsion systems
  - To increase the level of intelligence and autonomy in complex aerospace systems
  - Improve the performance, safety, environmental compatibility, & durability of aerospace systems.

Support to NASA Mission Directorates



Available Personnel

- Mix of Aeronautical/Astronautical, Electrical, and Mechanical Engineers – most with advanced degrees
  - 15 Civil Servants
  - 6 Contractor Employees
  - 2-4 Interns/semester

Current Research and Engineering Activities

- Electrified Aircraft Propulsion (EAP)
- Space Launch System (SLS)
- Hypersonic Propulsion Technologies
- Pressure Gain Combustion
- Integrated Radio Optical Communications

EAP / Introduction

- Strategic Thrusts
  1. Safe, Efficient Growth in Global Operations
  2. Innovation in Commercial Supersonic Aircraft
  3. Ultra-Efficient Subsonic Transports
     - Ultra-efficient Airframes
     - Ultra-efficient Propulsion
     - Ultra-efficient Vehicle System Integration
     - Modeling, Simulation, and Test Capability
  4. Safe, Quiet, and Affordable Vertical Lift Air Vehicles
     - Clean and Efficient Propulsion
     - Efficient and Quiet Vehicles
     - Safety, Comfort, and Accessibility
     - Modeling, Simulation, and Test Capability
  5. In-Time System-Wide Safety Assurance
  6. Assured Autonomy for Aviation Transformation

NASA Aeronautics Strategic Implementation Plan

EAP / Introduction

Alternative Power, Propulsion, and Vehicle Architectures

- NASA is conducting research on the development of transformative propulsion systems that offer efficiency and emission reduction benefits
- Innovative tools and methods are being developed to enable the design and evaluation of these systems

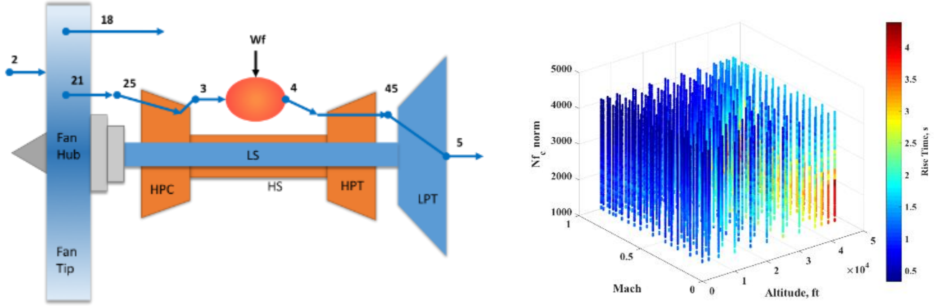
Hybrid Electric-Turbine Engine System Modeling and Controls

- Dynamic model of Single-aisle Turboelectric AiRCraft with Aft Boundary Layer (STARC-ABL) partial turboelectric propulsion concept developed
- STARC-ABL baseline control system developed and shown to provide acceptable performance throughout flight envelope

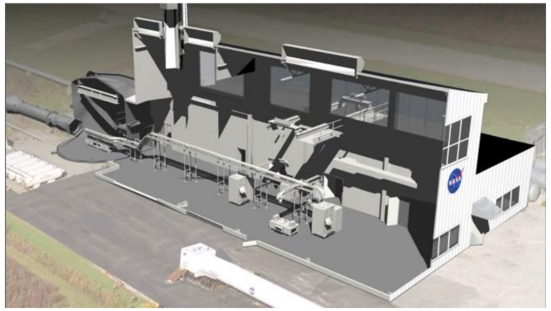
Facility Demonstrations

- Hardware-in-the-loop testing of STARC-ABL propulsion system conducted at the NASA Electric Aircraft Tested (NEAT) facility
  - Simulated turbomachinery components integrated with actual motor, generator, and power distribution hardware

STARC-ABL Turboelectric Aircraft Concept



HGEP System Modeling and Controls



NASA Electrified Aircraft Testbed (NEAT)

EAP / Introduction

- EAP relies on the generation, storage, and transmission of electrical power for aircraft propulsion
- Enables aircraft designs that apply advanced propulsion concepts such as distributed electric propulsion and boundary layer ingestion fans
- Benefits include a potential reduction in emissions, fuel burn, noise, and cost

Example NASA EAP Concept Vehicles

PEGASUS

X-57 Maxwell
All Electric

N3-X
Distributed Turboelectric

STARC-ABL
Partial Turboelectric

Quadrotor
All Electric

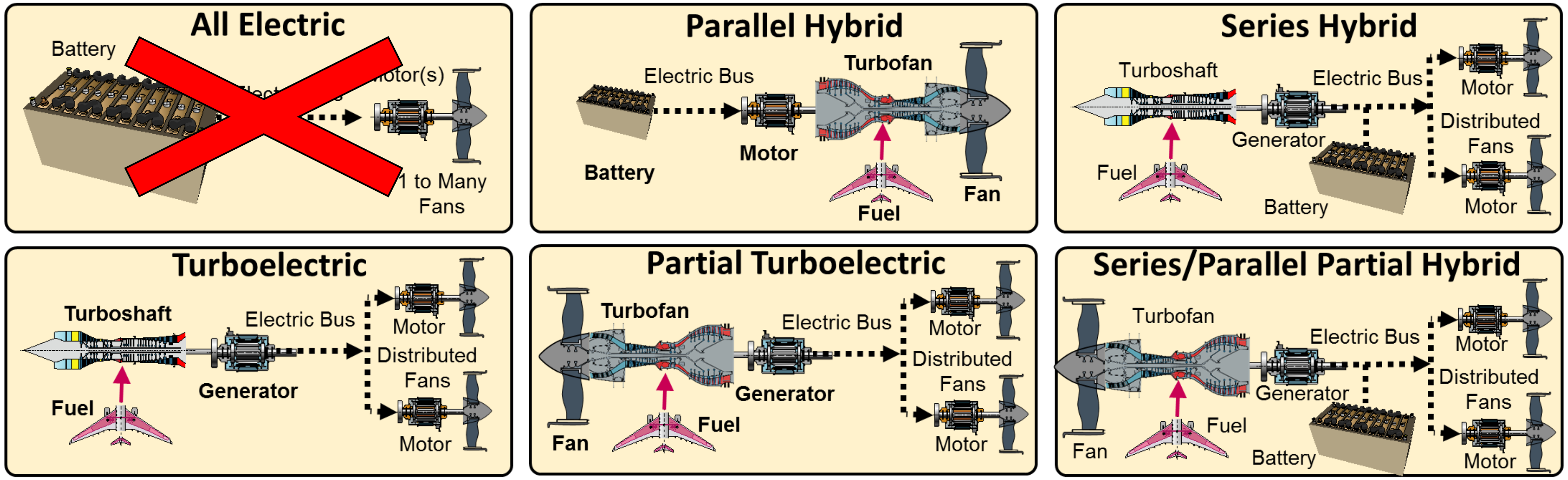
Side-by-Side Helicopter
Hybrid Electric

Tiltwing
Turboelectric

EAP / Propulsion System Architectures

Classes of EAP Propulsion & Power Architectures

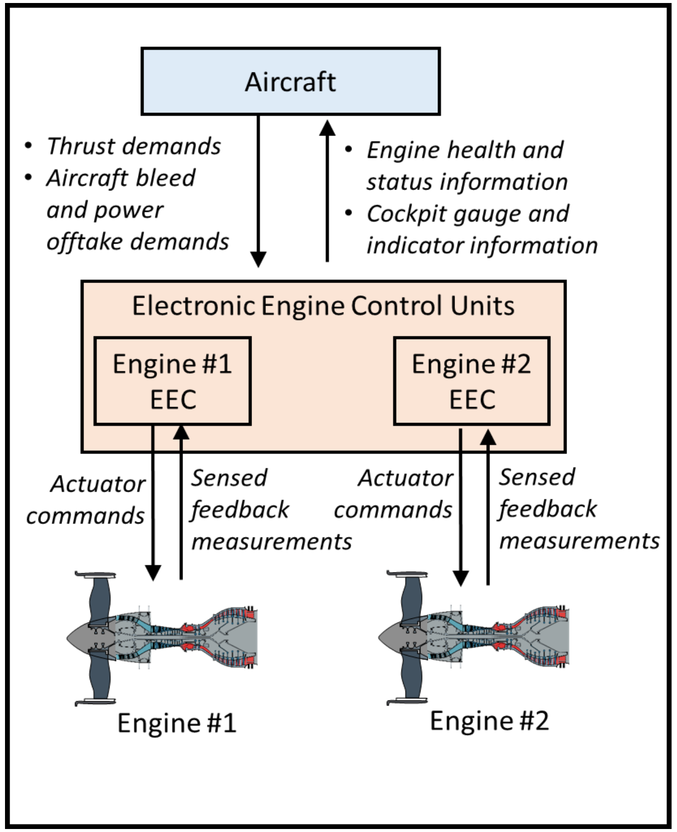
The Intelligent Control and Autonomy Branch focuses on architectures that include gas turbine engine technology



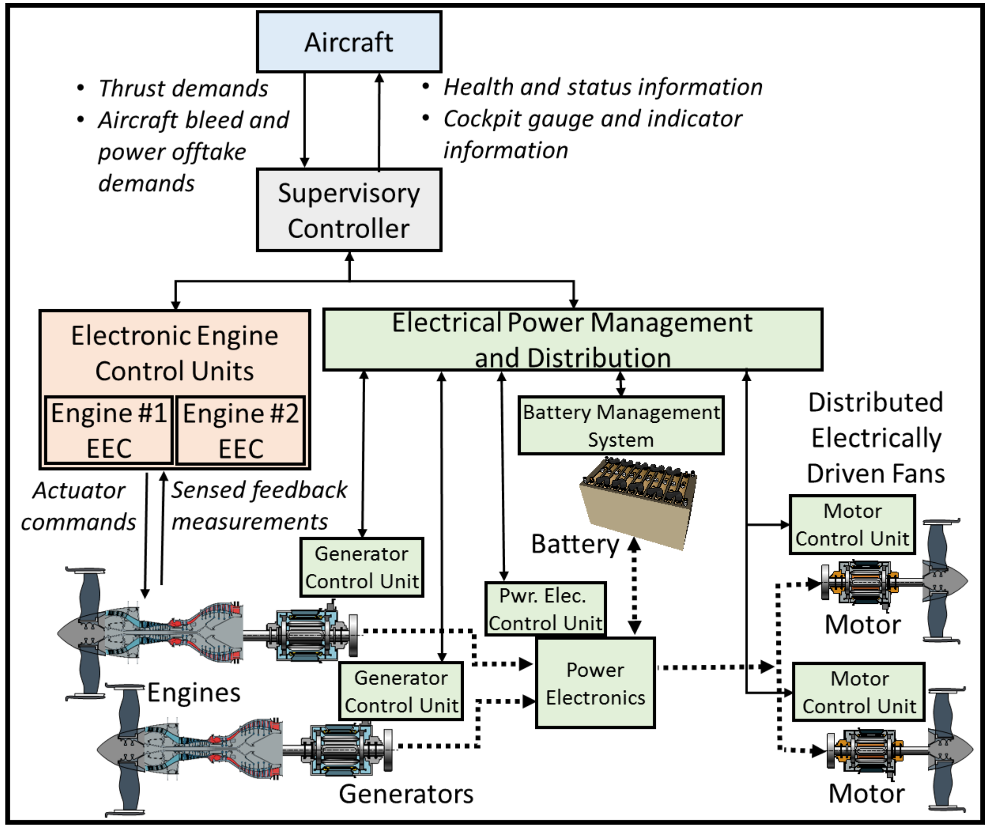
- EAP presents multiple technology challenges
  - Batteries with increased specific energy and fault mitigation
  - Flight quality electric machines with high efficiency and specific power
  - Power electronics & distribution technologies that enable high-voltage operation at altitude
  - Turbomachinery advances to enable high levels of power extraction with high efficiency

EAP / Conventional vs. EAP Propulsion Control Architectures

Conventional Aircraft Propulsion Control Architecture



Electrified Aircraft Propulsion Control Architecture (notional)

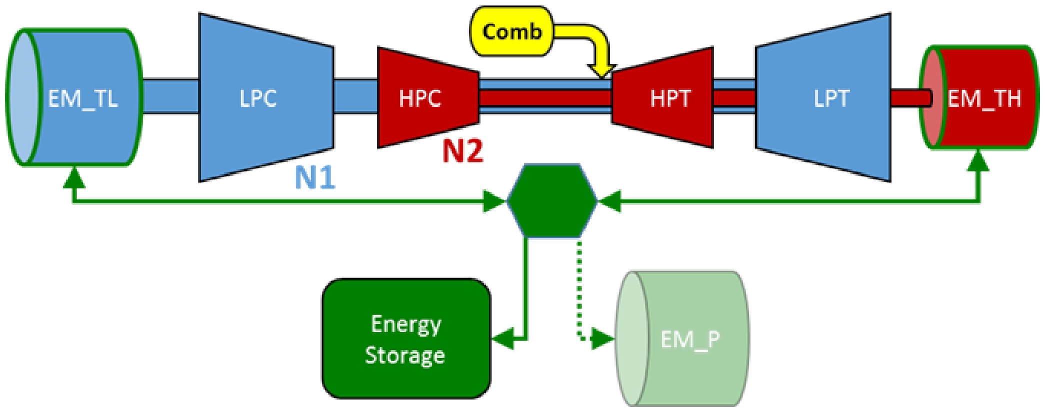


- ❑ EAP control architectures are more distributed, more complex, and more coupled.
- ❑ This presents control design challenges and control design opportunities!

EAP / Turbine Electrified Energy Management (TEEM)

- ❑ At its broadest level, TEEM is about managing energy in a hybrid electric-gas turbine engine propulsion system
  - ❍ Goal: Improve operability of the turbomachinery → enable better performing engine designs and/or enhance aircraft capabilities
  - ❍ The Means: electric machines (EMs) coupled to the engine shaft(s)
    - ■ EMs are new actuators that can alter engine operation
- ❑ Transient operability (main focus of TEEM)
  - ❍ Supplement fuel flow to operate closer to desired design conditions
  - ❍ Tailoring of the transient response

steady-



- Steady-state operability
  - Can also alter steady-state operability to provide some benefit or function

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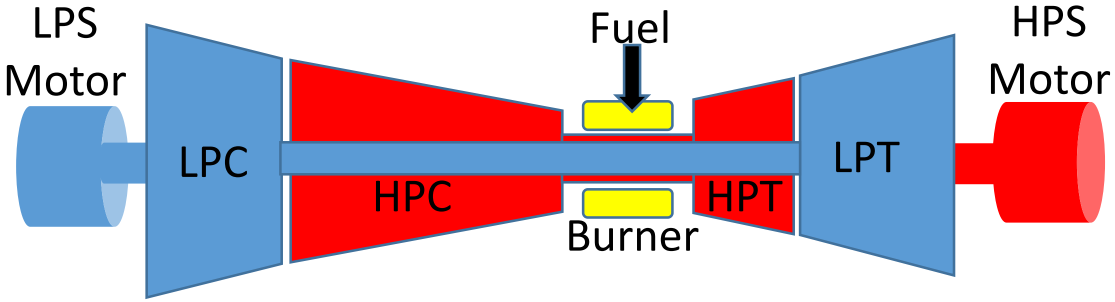
- Steady-state operability
  - Can also alter steady-state operability to provide some benefit or function

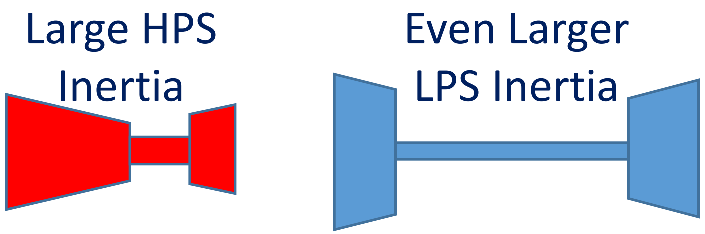
Potential Benefits:

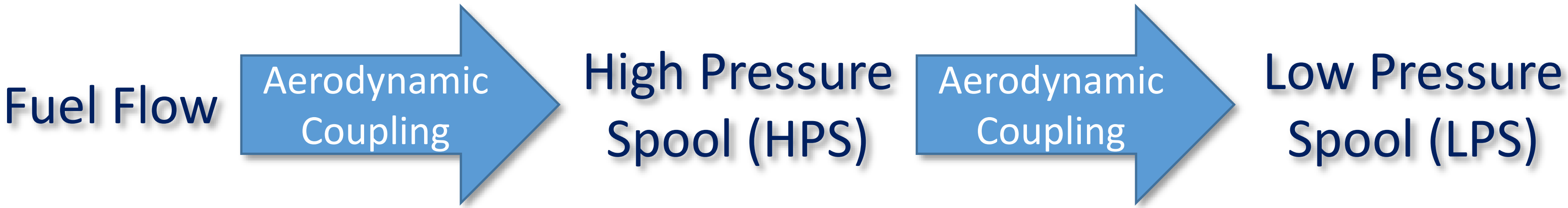
- Reduction or elimination of stability bleeds & variable geometries
- Variable cycle capability
- Expand operating range → enable new concepts of operation
- Some flexibility to reconfigure the system (reversionary control)
- Etc.

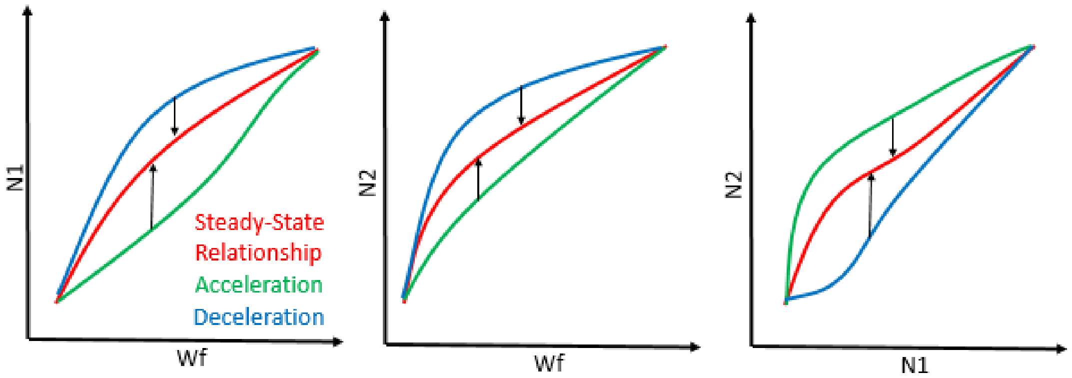
EAP / TEEM / Transient Operability



HPS lags fuel flow and LPS lags HPS



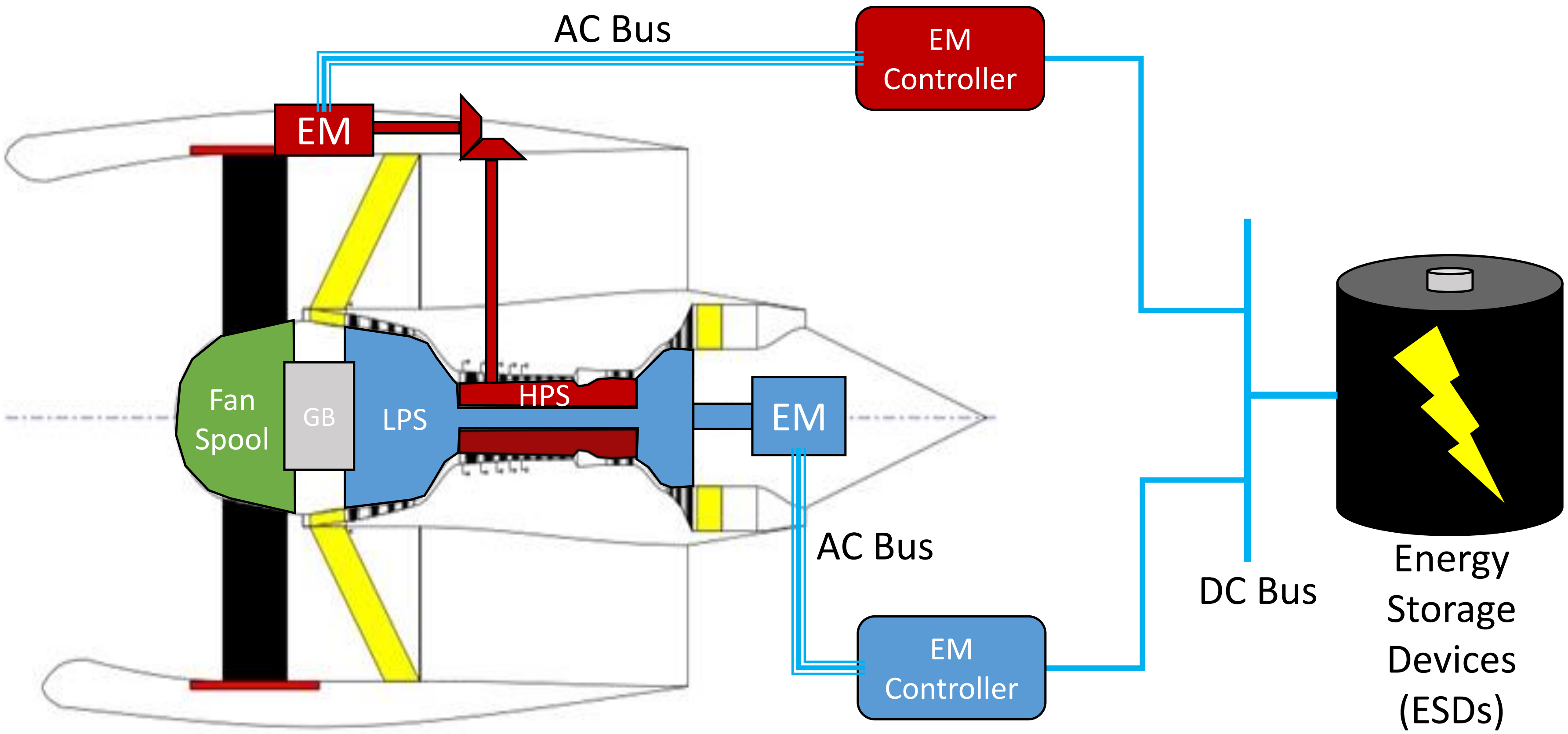




Wf – Fuel Flow [lb_m/s], N1 – LPS Speed [rpm], N2 – HPS Speed [rpm]

- Electric Machines (EMs) provide a means to modify the operation of traditional turbine engines
- EMs can add/subtract torque from one or both shafts to alter shaft dynamics and allow for more consistent on-design operation
- An electrical storage device can be used to impulsively supply or absorb energy added or subtracted by the EMs

EAP / TEEM / Propulsion System Configurations

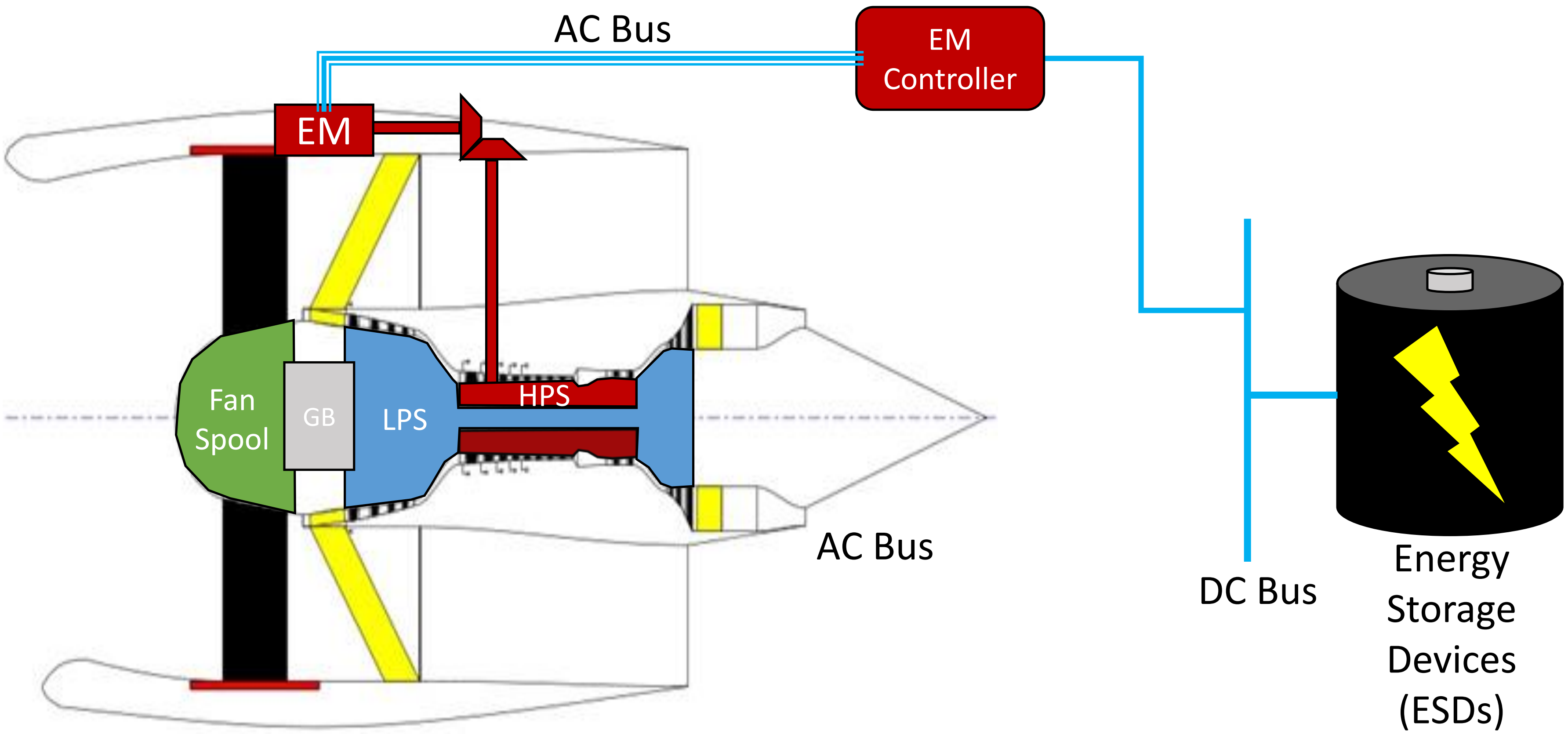


EM – Electric Machine
GB – Gearbox
HPS – High Pressure Spool
LPS – Low Pressure Spool

DC – Direct Current
AC – Alternating Current

Dual-Spool Configuration

EAP / TEEM / Propulsion System Configurations



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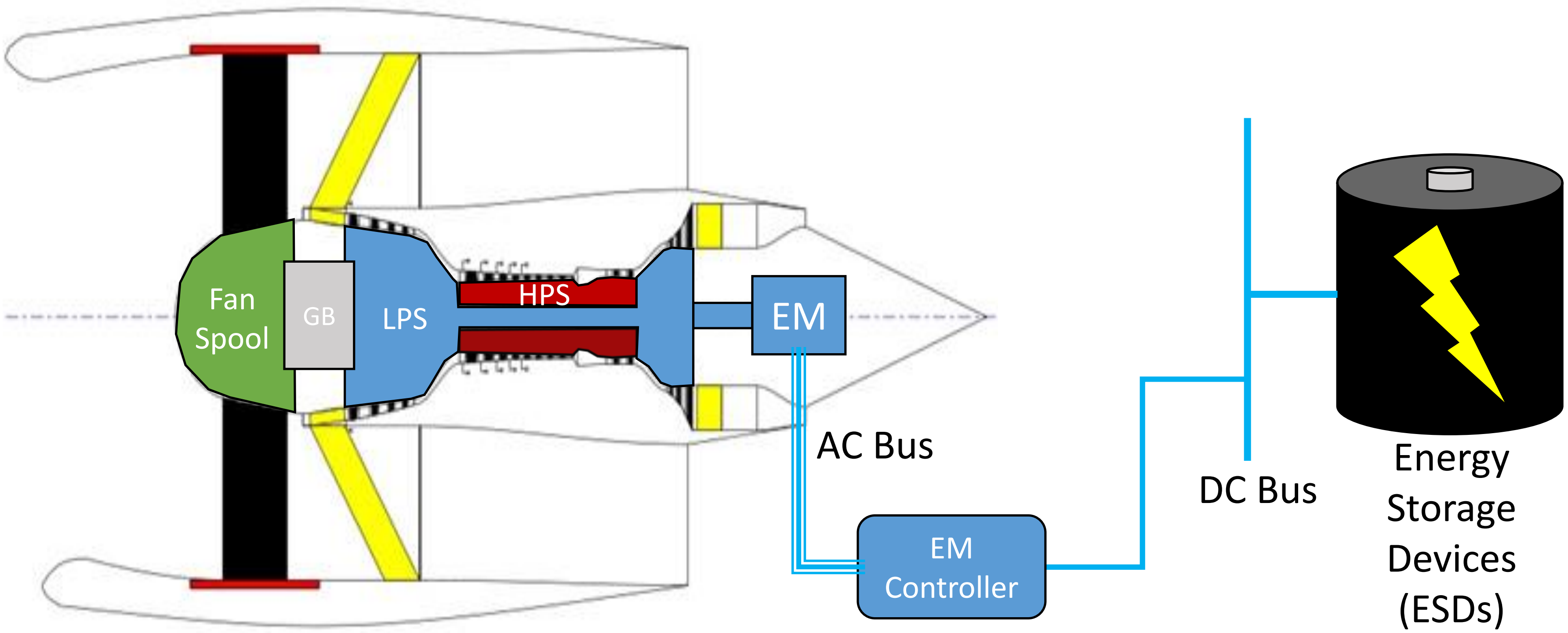
HPS Configuration

EAP / TEEM / Propulsion System Configurations



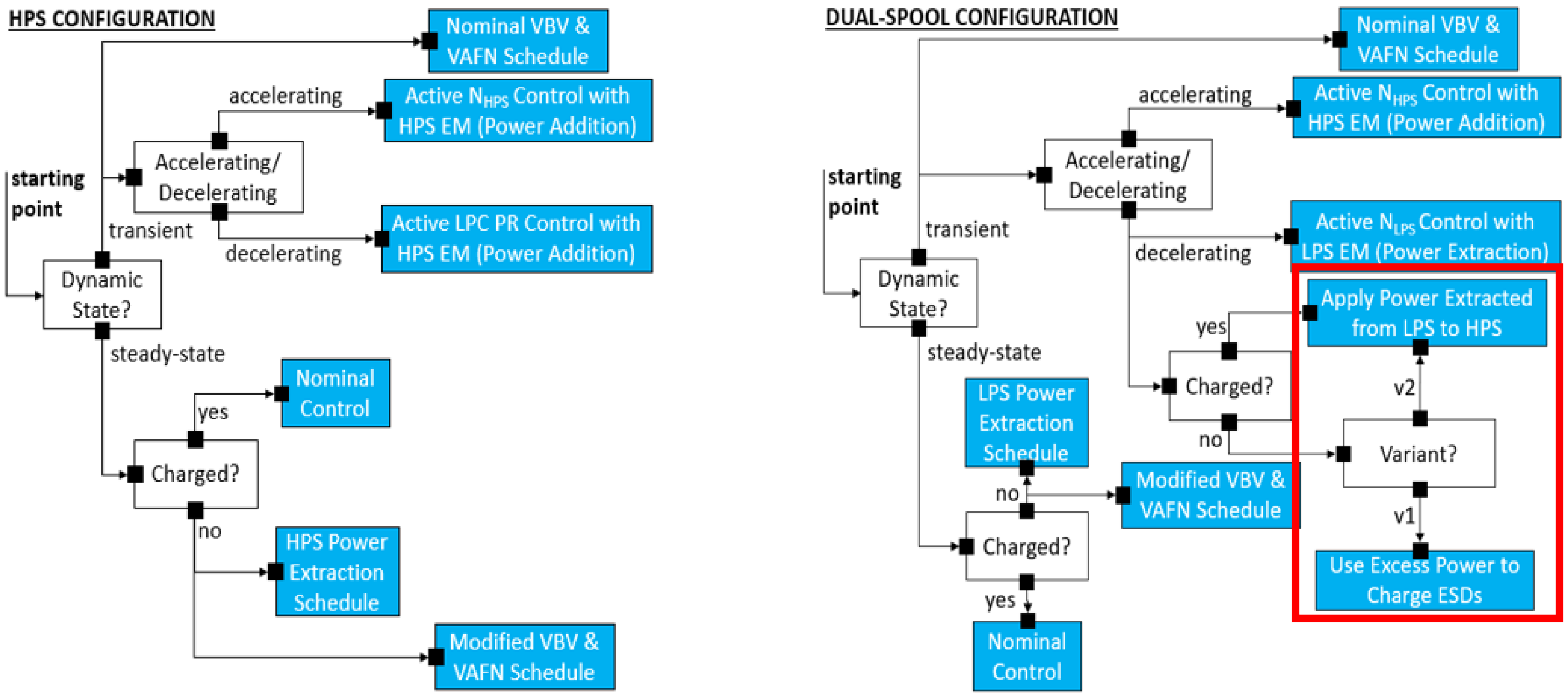
EM – Electric Machine
GB – Gearbox
HPS – High Pressure Spool
LPS – Low Pressure Spool

DC – Direct Current
AC – Alternating Current

LPS Configuration

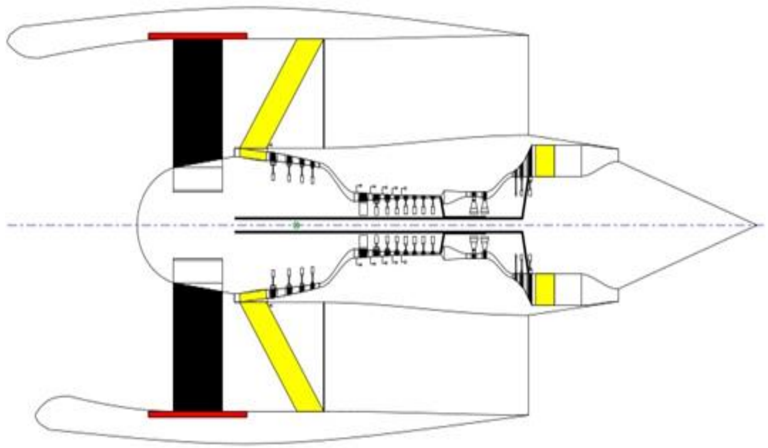
EAP / TEEM / Control Strategy

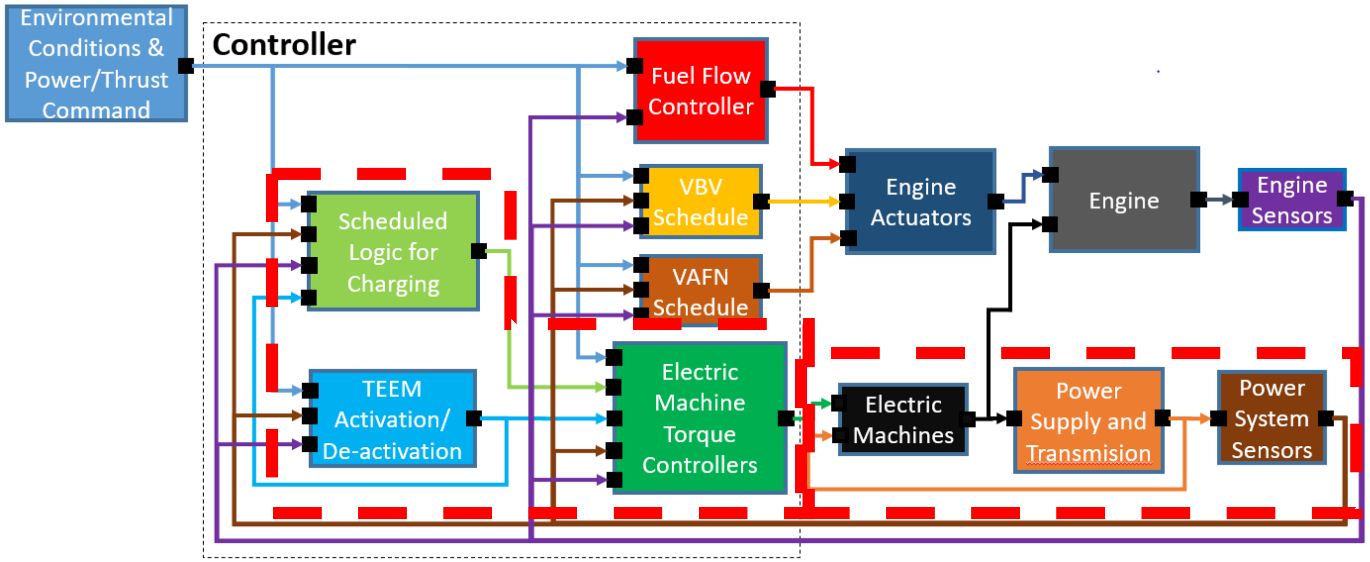
- Dual-spool variants differ in strategy to deal with excess power during engine decelerations
  - Variant 1 (v1) – ESDs absorb excess power until they are fully charged, then apply any additional excess power to the HPS via the HPS EM
  - Variant 1 (v2) – Excess power is applied to the HPS via the HPS EM regardless of the state of charge of the ESDs



EAP / TEEM / Propulsion System Model

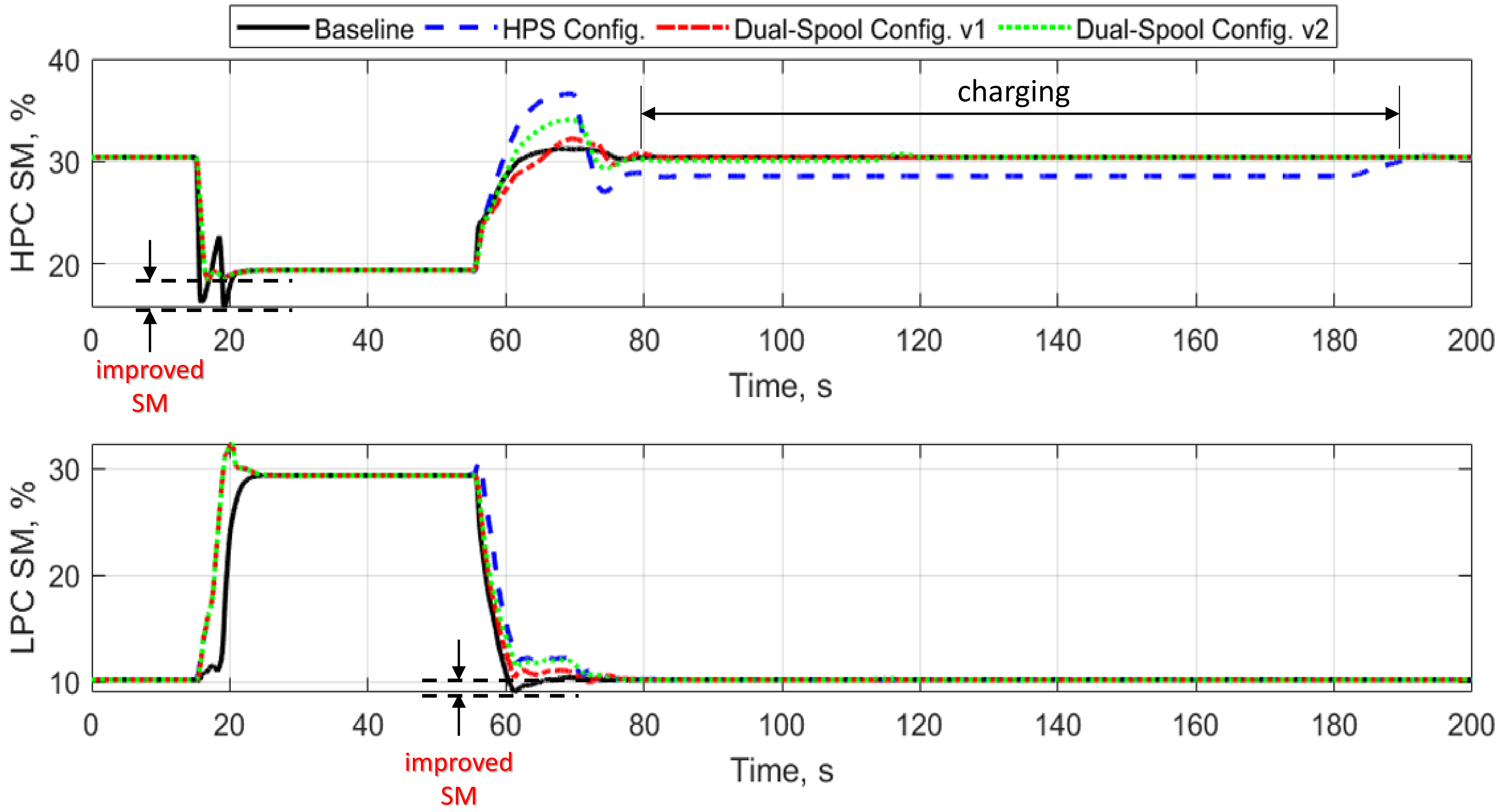
- Application to the Advanced Geared Turbofan 30,000 lbf (AGTF30) engine model
  - Conventional turbofan with advanced technologies
- Adjustable engine component health parameters
  - Analysis assumes a worst-case end-of-life engine
- Added electrical system components for applying the TEEM concept
- The control strategy presented previously has been leveraged in this effort
  - Transient operability
  - Charging
  - Simplified transient limit logic





EAP / TEEM / Simulation-based Study Results

- Burst and chop transient performed at go-around conditions for a high-altitude airport (Mach number = 0.2, altitude = 5,000 ft)
- Reduced or eliminated SM undershoot
- HPC SM is reduced temporarily while charging (only with the HPS configuration)



EAP / TEEM / Simulation-based Study Results

General takeaways
- Requirements seem to be in the realm of possibility
- Requirements are substantially less for a new engine
- There is a desire for advances in energy and power density of energy storage devices

Worst-case energy used during transients, kW-hr		
Worst-case search range	Dual-spool configuration	HPS configuration
Entire Flight Envelope	1.3	3
MN < 0.3, Alt < 10,000 ft	0.8	2.5

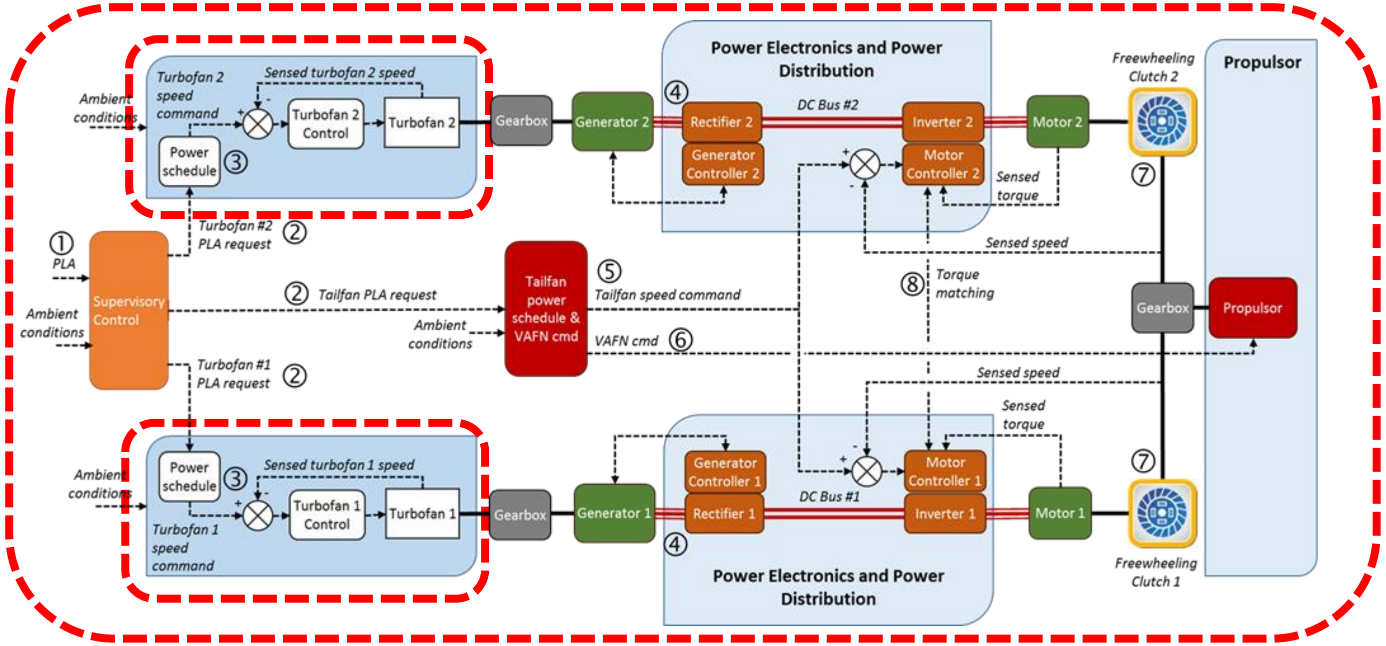
Configuration Tradeoffs
- Dual-spool config. v2 vs. v1
  - v2 reduces the LPS EM power requirement by 33%
  - v1 makes better use of energy storage by charging the ESDs + shortens time to charge
- HPS config. vs. dual-spool config.
  - HPS config. eliminates the need for a LPS EM
  - HPS config. will likely require more energy storage
- At first glance the trade-offs are in the favor of the dual-spool configuration but advances in the energy density of super-capacitors could change that

Electric Machine	Maximum Torque, ft-lb_f	Maximum Power , hp	Maximum Torque Rate, ft-lb_f/s	Time to achieve Maximum Torque, s
HPS EM	200	750	250	0.8
LPS EM (dual-spool v1)	550	610	150	3.7
LPS EM (dual-spool v2)	350	410	95	3.7

EAP / SHM / Fault Management

- Fault Management capabilities are necessary to enable certification of aircraft systems
  - Any potential failure modes and hazards must be identified and properly mitigated
- Electrified Aircraft Propulsion (EAP) systems are complex and tightly coupled, requiring integrated control and fault management functionality
  - Presents new design challenges that must be addressed

NASA Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsor (STARC-ABL) Concept Aircraft



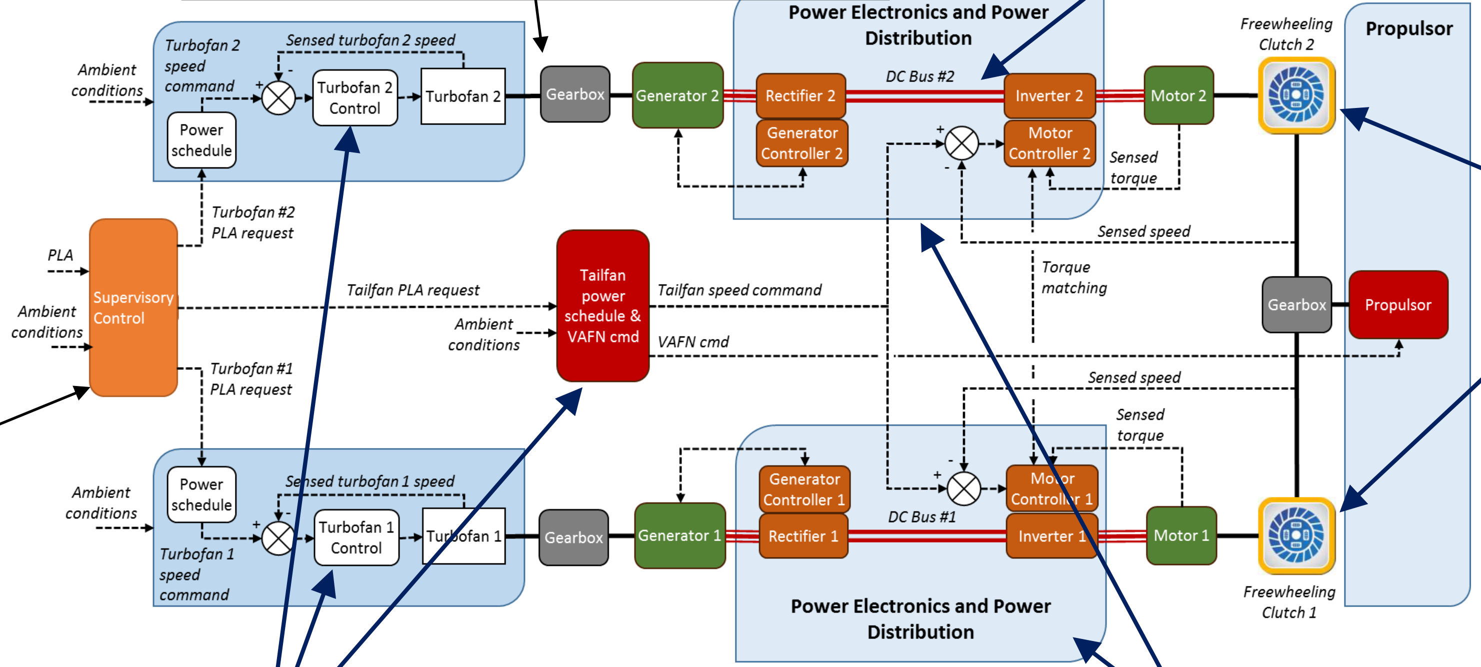
STARC-ABL Architecture

EAP / SHM / Fault Management

- Break away spline coupling for catastrophic failures
- Actuated disconnects that allow generators to decouple from engine if failure detected

Circuit breakers to guard against over-current conditions

Supervisory control
- Communicates with vehicle
- Receives health and status information from propulsion subsystems
- Sends reconfiguration commands to subsystems in the event of a failure



Freewheeling clutches allow tailfan propulsor to continue to operate in the event of a failure in one string

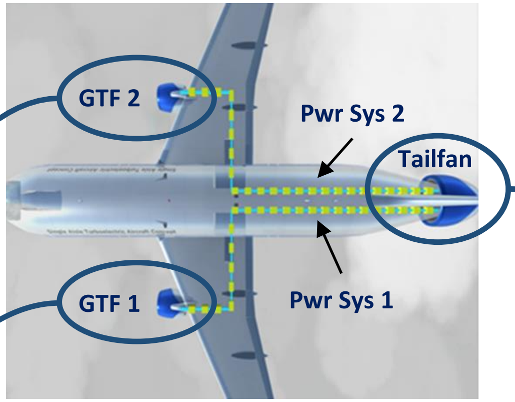
- Control limit logic for over-speed protection and operability
- Reversionary control modes in the presence of failures

- Parallel turbofan and power strings for added redundancy
- System sized to provide ≥ 50% max thrust in the event of any single point failure

EAP / SHM / Reversionary Control Logic

Geared Turbofan (GTF) Reversionary Control Modes:

- VBV schedule updates to maintain LPC operability
- Fuel controller updates to maintain HPC operability and symmetric acceleration response



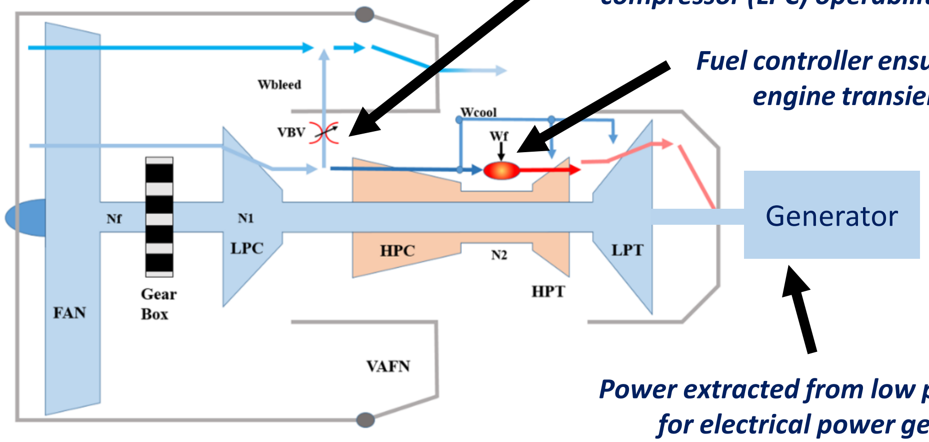
STARC-ABL Architecture

Tailfan Reversionary Control Mode:

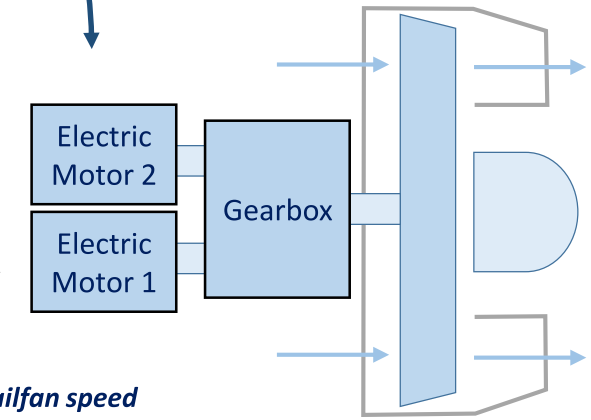
- PLA schedule and acceleration schedule updates to maintain GTF compressor operability and symmetric acceleration response

Variable Bleed Valve (VBV) maintains low pressure compressor (LPC) operability

Fuel controller ensures safe, reliable engine transient operation



Power extracted from low pressure shaft for electrical power generation



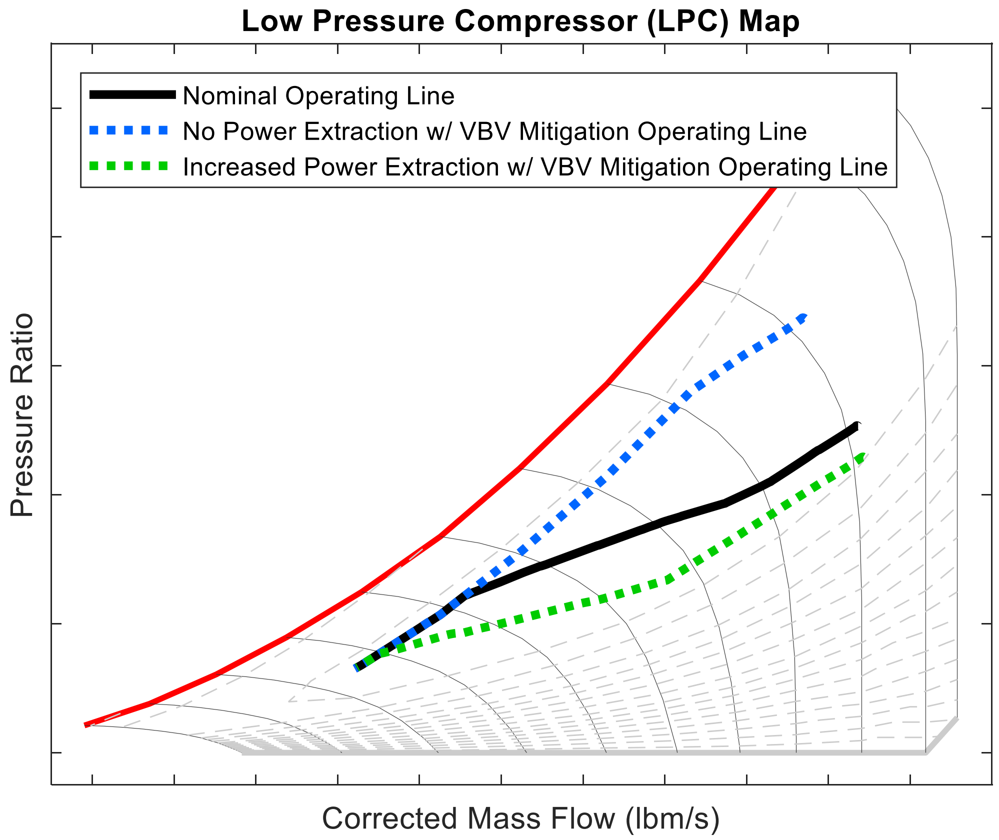
Motor controllers control tailfan speed and transient operation

EAP / SHM / Fault Mitigation

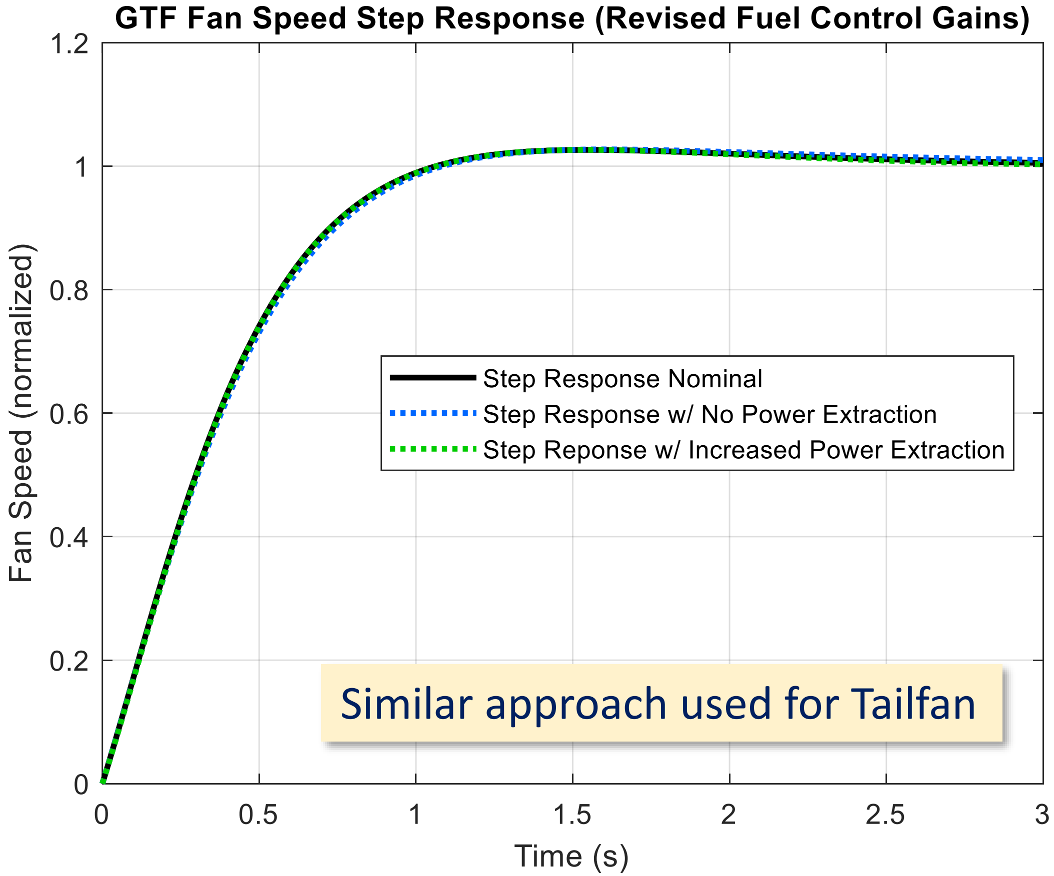
STARC-ABL Revised GTF and Tailfan Control Logic

(results shown at Alt = 25k feet, MN = 0.6, PLA = 61 operating condition)

Revised GTF Variable Bleed Valve (VBV) Schedule



Revised GTF Fuel Control Setpoint Control Gains



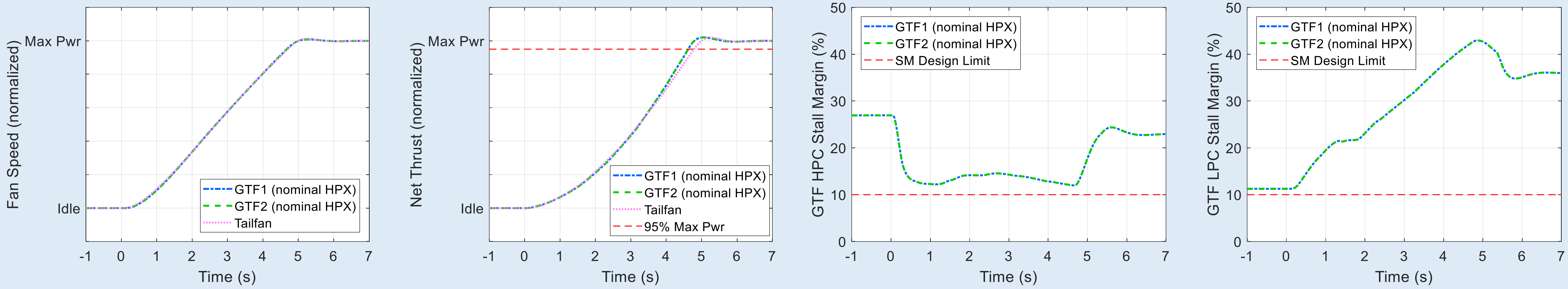
Similar approach used for Tailfan

EAP / SHM / Fault Mitigation

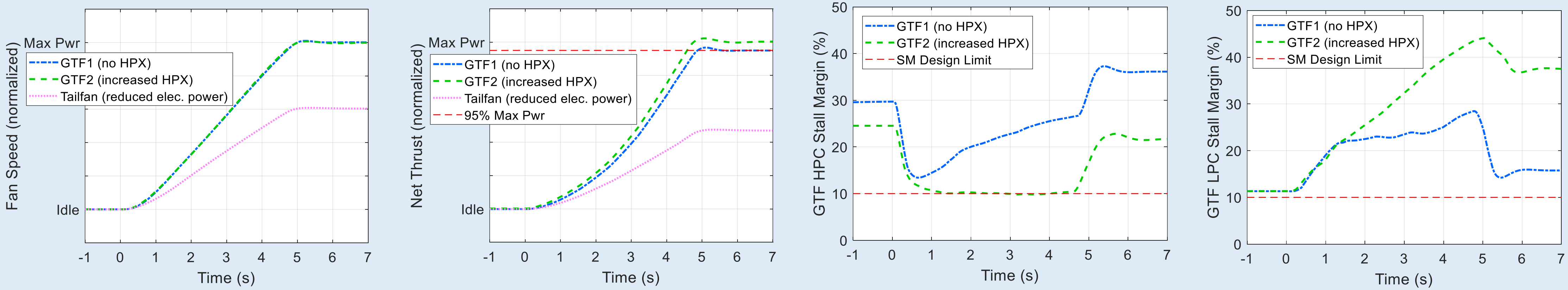
Revised GTF and Tailfan Control Logic

(results shown at Alt = 25k feet, MN = 0.6, PLA = 61 operating condition)

Nominal Response

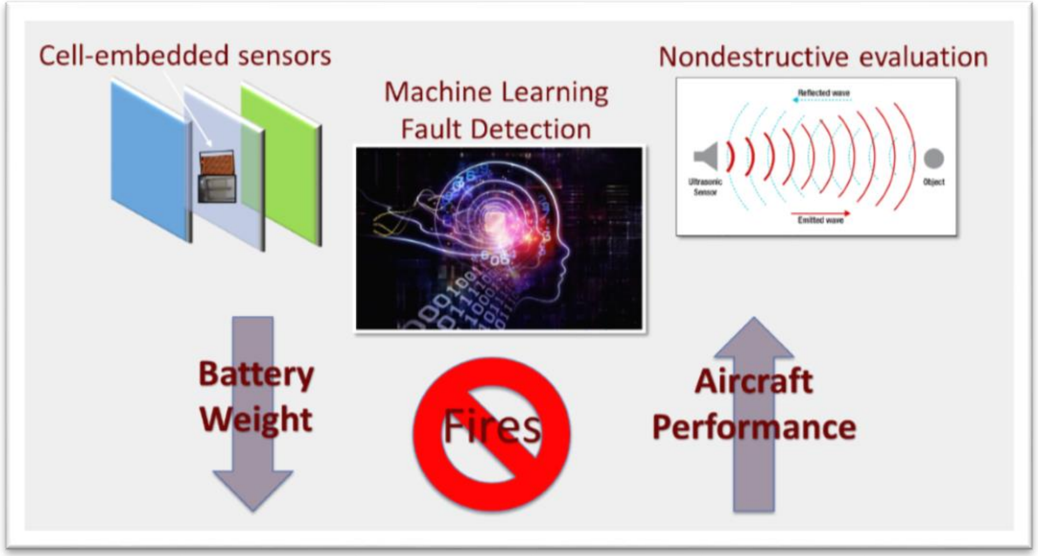


Mitigated Power System 1 Failure Response



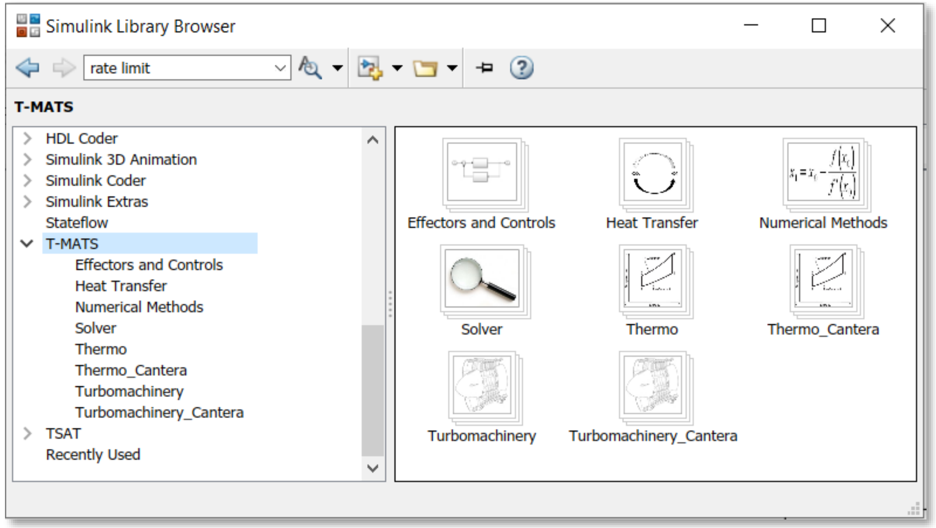
EAP / SHM / Battery Diagnostics & Prognostics

- The Sensor-based Prognostics to Avoid Runaway Reactions and Catastrophic Ignition (SPARRCI) Project is a GRC-led partnership between GRC, LaRC, ARC
- Challenge: To develop technologies that avoid catastrophic battery failure and, thus, enable safe next-generation ultra-high energy batteries for propulsive aircraft power
- State-of-the-Art: Bulky containment systems designed to prevent thermal runaway adds significant weight to overall design
- SPARRCI Solution: Use cell-embedded sensors, Non-Destructive Evaluation (NDE), and physics-based + *machine learning* diagnostics to *avoid* catastrophic failures, rather than engineer around them.
- Performance goal >400 Wh/kg

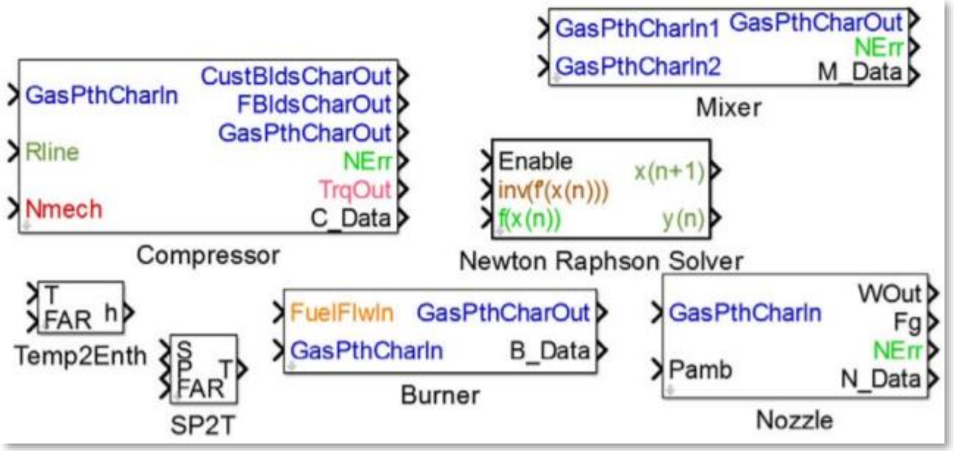


EAP / Free Software Tools / T-MATS

- The Toolbox for Modeling and Analysis of Thermodynamics Systems (T-MATS) is a modular thermodynamic modeling framework for building dynamic simulations
- Mimics NPSS in many ways, but natively exists in the MATLAB/Simulink coding environment
  - Component level (0-D) cycle model utilizing turbomachinery performance maps
  - Iterative Newton-Raphson solver
  - Incorporates shaft dynamics
- Additional tools for …
  - Actuator and sensor modeling
  - Controller implementation
  - Heat transfer
- Applications beyond turbomachinery include fuel cells and rocket engines
- Available at https://github.com/nasa/T-MATS



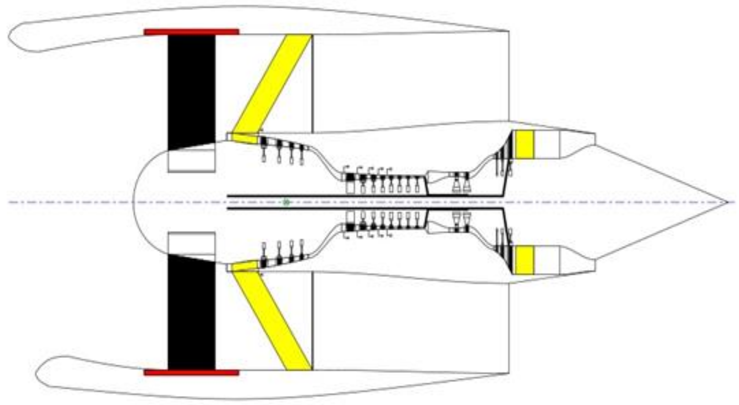
T-MATS Library within the Simulink Library Browser



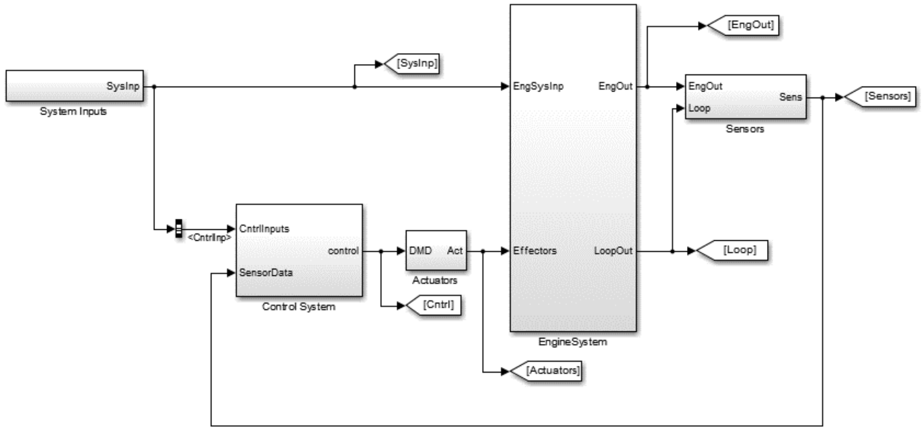
Subset of T-MATS Simulink blocks

EAP / Free Software Tools / AGTF30

- The Advanced Geared Turbofan 30,000lb$_f$ is a T-MATS model of the NASA N+3 (2030-2035 technology) reference engine (originally coded in NPSS)
  - High bypass
  - Compact core
  - Geared fan
  - Variable area fan nozzle
- Good virtual testbed for dynamic system studies and control
- Available at https://github.com/nasa/AGTF30



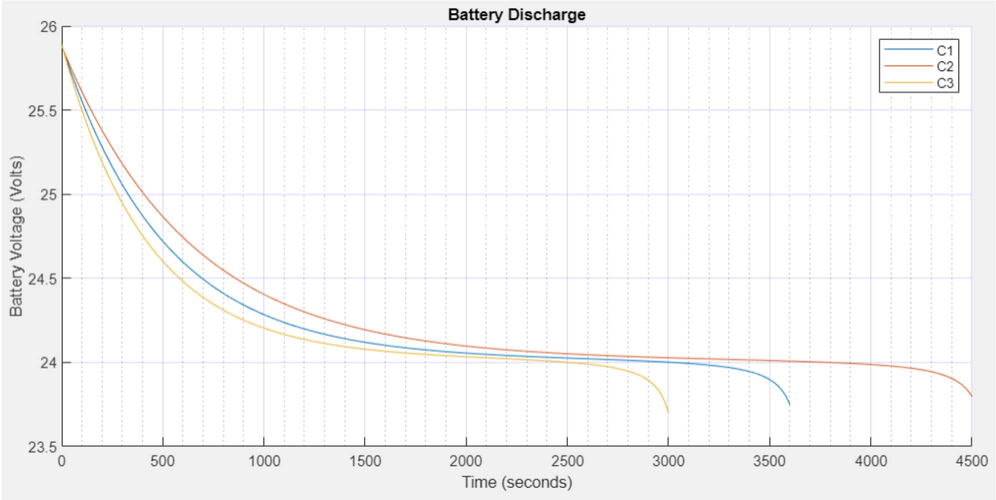
AGTF30 engine schematic



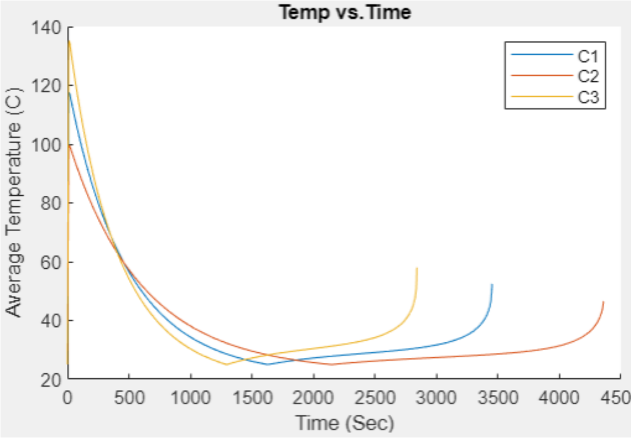
AGTF30 engine model top level with added control system

EAP / Free Software Tools / EMTAT

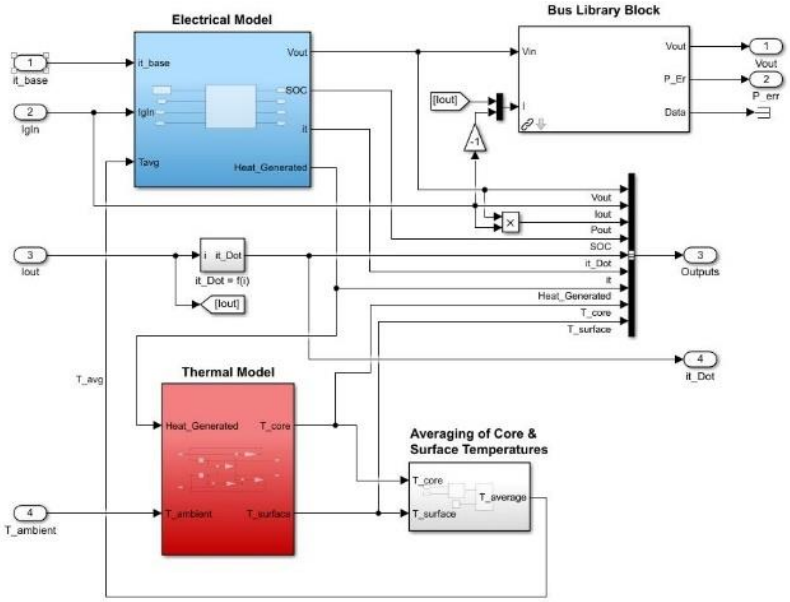
- The Electric Modeling and Thermal Analysis Toolbox (EMTAT) is a MATLAB/Simulink library similar to T-MATS for modeling electrical systems
  - Utilizes an iterative solver (like T-MATS and NPSS)
  - Component models include (motors/generators, converters, inverters, batteries, capacitors, etc.)
  - Provides power flow and physics-based modeling approaches
  - Includes thermal effects
  - Designed to model dynamic interaction with turbomachinery at the appropriate time scale
  - Available at https://github.com/nasa/EMTAT



Battery discharge curves



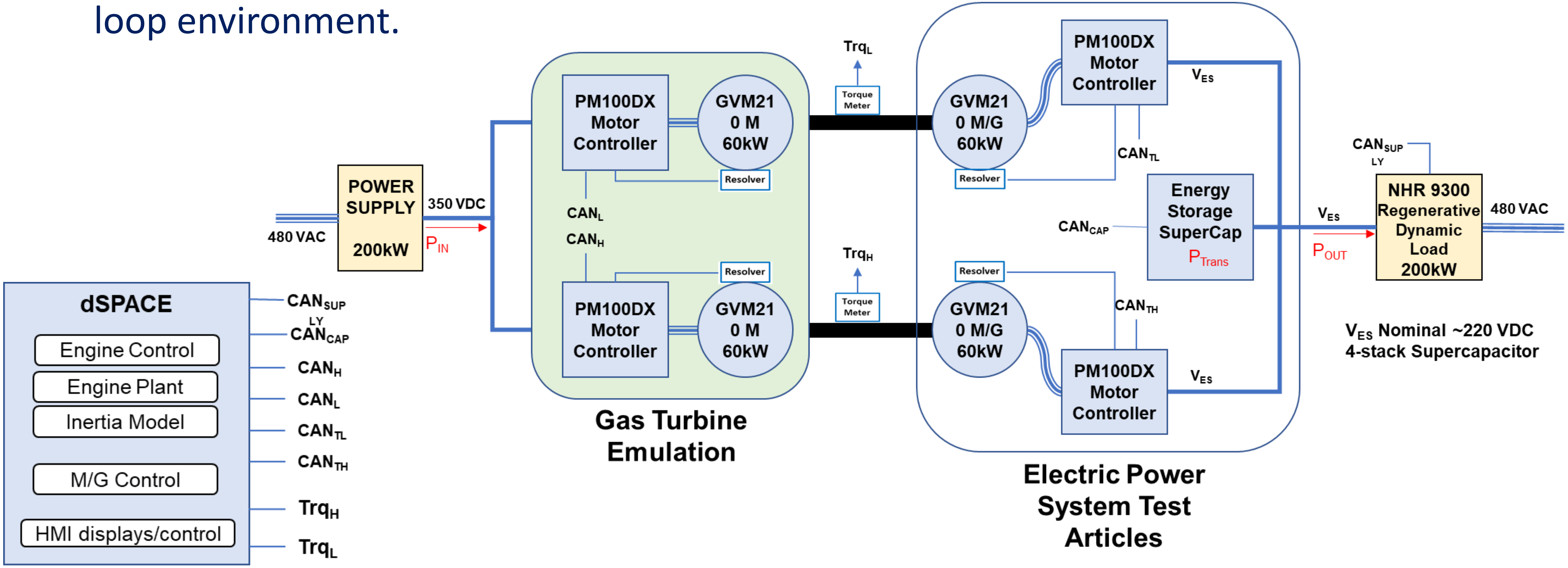
Battery pack temperature



Visual inside the EMTAT battery block

EAP / Relevant Facilities / HiPER

The High-Performance Electromagnetic Rig (HiPER) is being developed to perform testing of hybrid electric-turbine engine concepts in a small-scale hardware-in-the-loop environment.

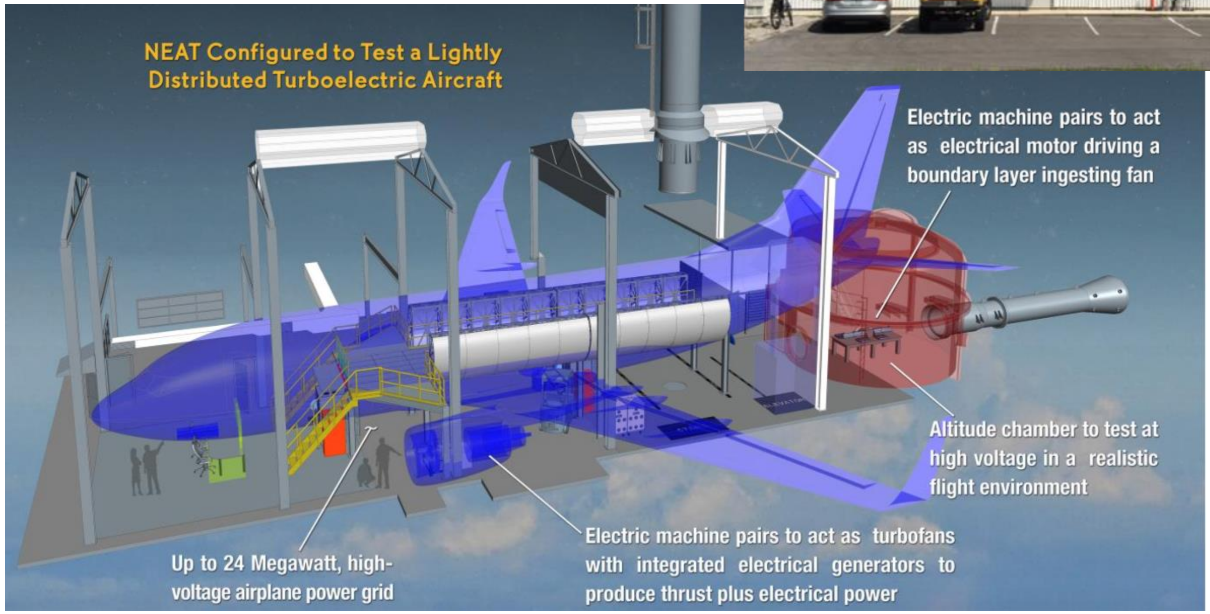


EAP / Relevant Facilities / NEAT

- NASA Electric Aircraft Testbed (NEAT) enables
  - Large-scale flight-like powertrain testing at ambient and flight conditions (e.g., altitude)
  - Enables hardware-in-the-loop testing of EAP supervisory and fault mitigation controls

Facility includes:

- Bus Architecture
- MW Inverters & Rectifiers
- MW Motors & Generators
- System Communication
- EMI Mitigation
- System Fault Protection

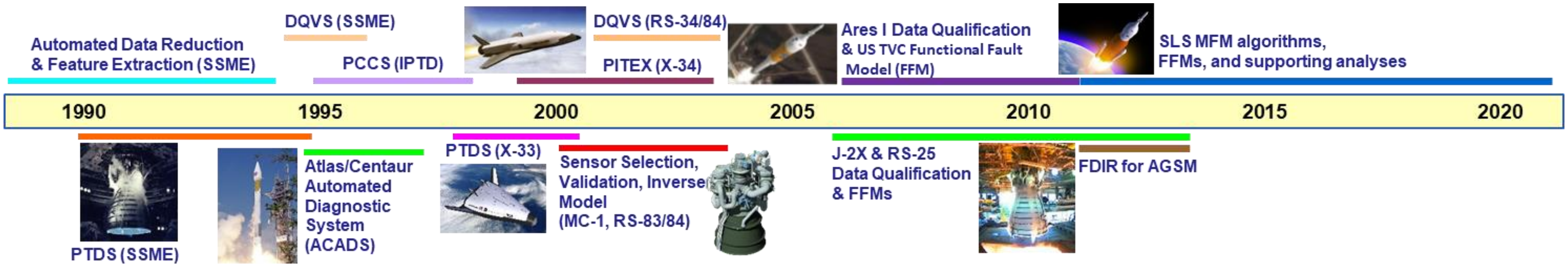


EAP / Summary

- Electrified Aircraft Propulsion offers a paradigm shift in the design and control of aircraft propulsion systems
- EAP systems are more complex than standard turbofan engines and require coordinated operation between the turbomachinery and electrical components
- Hazards associated with new failure modes must be identified and properly mitigated to enable certification
- Dynamic coupling between EAP turbomachinery and electrical components offers new control design challenges and opportunities
- ICAB is developing technologies to meet this challenges and opportunities

Including control considerations early in the EAP design process can improve overall efficiency and performance!

SLS / Introduction / Space SHM Heritage



Fault Management (FM) Design & Optimization

- Systematic Sensor Selection Strategy for MC-1, RS-83 and RS-84 Engine Systems
- Testability Analysis for X-34 Main Prop. System & Non-Toxic Reaction Ctrl System
- Optimization of the J-2X Redline system

Diagnostic Modeling and Analysis

- Post Test Diagnostic System (PTDS) for SSME & X-33 Aerospike Engine Ground Tests
- ACADS Monitoring & Analysis of Centaur Pneumatic System
- IPTD Propulsion Checkout & Control System (PCCS)
- Inverse Model for MC-1, RS-83 and RS-84 Engines
- Propulsion IVHM (Integrated Vehicle Health Management) Technology Experiment (PITEX) for X-34 Main Propulsion System
- Pre-test Predictions and Post-test Diagnostic Analysis for J-2X & RS-25 Engines
- Functional Fault Model (FFM) for Ares I US Thrust Vector Control (TVC) System
- Fault Detection Isolation & Response (FDIR) for Advanced Ground Systems Maintenance (AGSM)

Sensor Data Qualification/Validation

- DQ for X-33 Aerospike Engine and Integrated Propulsion Technology Demo (IPTD)
- Data Qualification (DQ) for the SSME, RS-83 and RS-84 Engine Systems.
- Post-test Sensor Data Qualification & Consolidation (SDQC) for the Ares I US, J-2X test series, and RS-25 test series

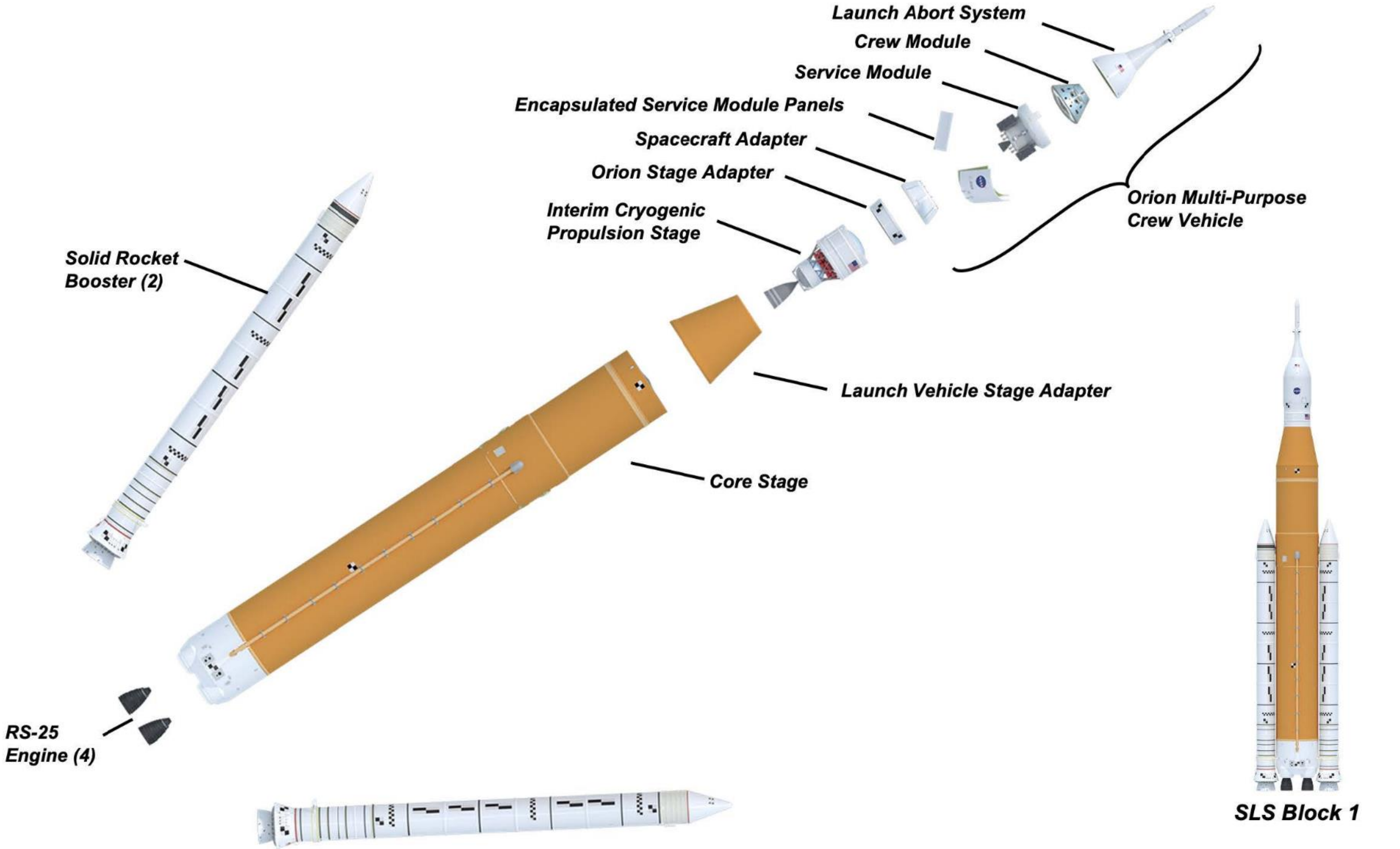
Space Launch System

- Space Launch System (SLS) Mission & Fault Management (MFM) Flight Computer Algorithms for TVC Systems and the Electrical Power System
- SDQC Algorithms for SLS Block 1 & 1b
- FFMs for TVC systems and EPS, plus integrate sub-system FFMS into Vehicle-level FFM with 40,000+ failure modes.
- False Positive/False Negative Analysis for SLS Block 1 & 1b
- Tier 2 TVC & SDQC support for the SLS Hotfire & Artemis I Day of Launch activities

IC&AB has more than 30 years of experience building and deploying fault management solutions for launch vehicle flight and ground systems.

SLS / Introduction / Block 1

- The Vehicle
  - Development supported by 1,000+ companies and every NASA center.
  - Height: 322 ft.
  - Weight: 5.75 million lb.
  - Max. Thrust: 8.8 million lbf.
- Artemis I Flight
  - Uncrewed test flight
  - Approx. 3 week mission
  - Multiple passes around the moon
  - Will travel farther into space than any human-rated spacecraft to-date



SLS / Introduction / IC&AB Responsibilities

Space Launch System

Systems Engineering & Integration

Vehicle Management

Mission & Fault Management

LCC Support

- NASA is responsible for performing all SE&I activities including Vehicle Management (VM) which includes Mission and Fault Management (M&FM)
- The Intelligent Controls and Autonomy Branch is directly:
  - Supporting the M&FM activities under the SLS Program.
  - Coordinating with M&FM Leads and is integrated with the M&FM team at MSFC.

Algorithm Development & Verification

- Core Stage & Booster Thrust Vector Control
- Sensor Data Qualification and Consolidation
- Core Stage Electrical Power System

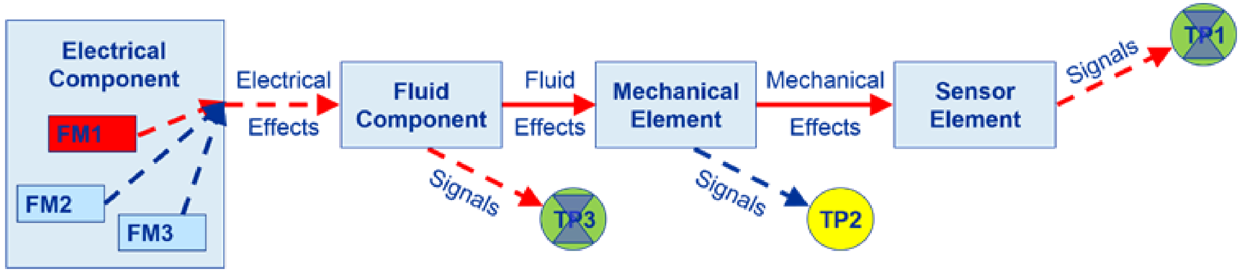
Analysis Support

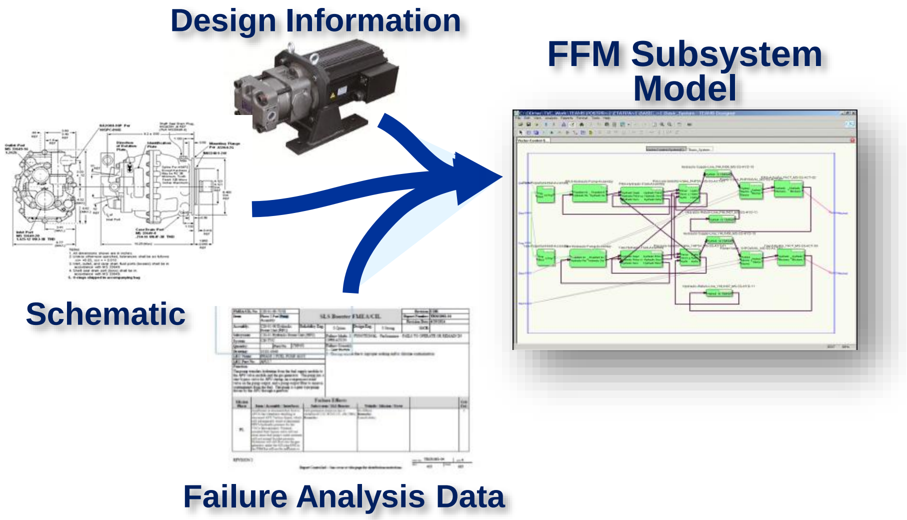
- Integrated Vehicle Failure Model
- False Positive/False Negative Analysis
- Goal Tree/Success Tree

SLS / Functional Fault Modeling

Functional Fault Models (FFM) are directed graphs designed to provide qualitative representation of failure effect propagation within a system architecture

- Failures can be propagated from their source to the sensors available to detect the failure effects
- FFMs are developed using:
  - Design documents (schematics and design descriptions)
  - Failure Modes and Effects Analysis (FMEA)
- Application
  - System Design Analysis Tool:
    - Qualitative models used early in the design process to identify un-met SHM requirements when changes to the design are less costly
  - SLS Integrated Vehicle Failure Model (IVFM):
    - Developed an integrated set of FFMs of the SLS subsystems, which contains *40,000+* failure modes





SLS / Flight Computer Algorithm Development

Develop flight computer algorithms to provide mission and fault management (M&FM) capabilities for space vehicles:

- Perform onboard nominal vehicle operations during pre-launch ($T < 0$) and inflight ($0 \geq T$)
- Perform fault management to detect, identify, and isolate off-nominal conditions (vehicle faults) and provide predetermined operational responses:
  - Redundancy Management (RM) to maintain flight critical functions
  - Caution and Warning (C&W) to provide crew and ground with situational awareness of vehicle conditions related to key failures
  - Safing Actions:
    - During pre-launch - prevent launching the vehicle with failures that could propagate to a loss of mission and a need to abort
    - During inflight - prevent failures from propagating to an uncontained failure and loss of vehicle
  - Enacting aborts to prevent loss of crew when eminent loss of vehicle is determined

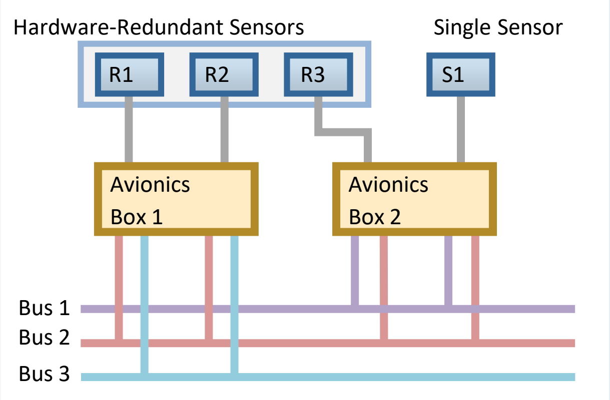
SLS / Sensor Data Qualification

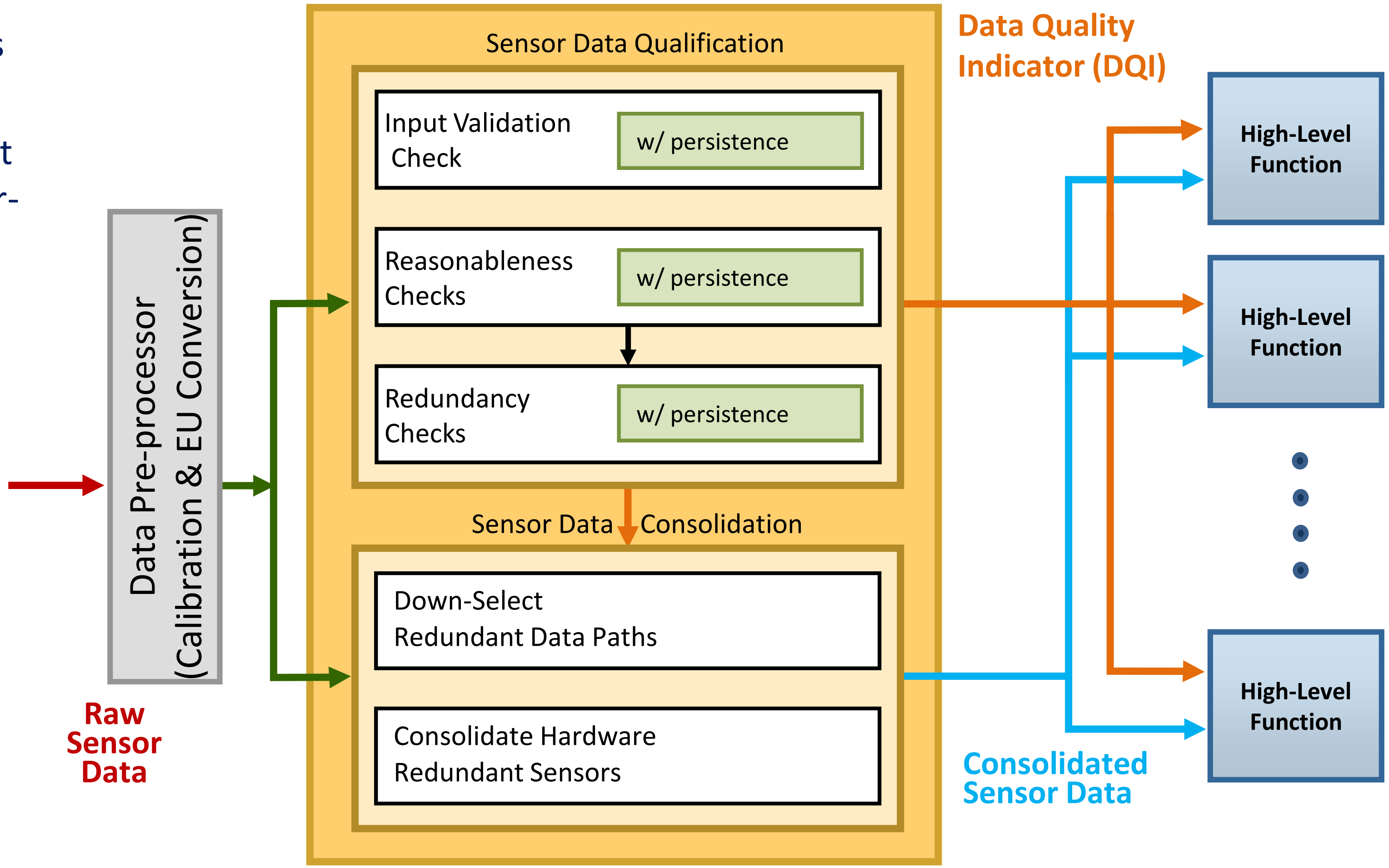
Sensor Data Qualification: analyzes sensor data to detect faults and anomalies anywhere along entire sensor data path. Data Quality Indicators (DQI) that capture analysis results.

Sensor Data Consolidation: reduces the amount of redundant sensor data prior to use by higher-level decision-making functions

Rationale

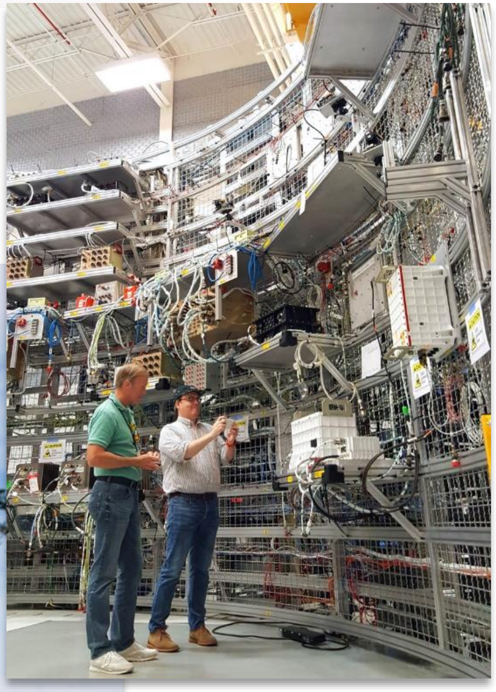
- Avionics hardware redundancies provide fault tolerant flight-critical sensor measurements

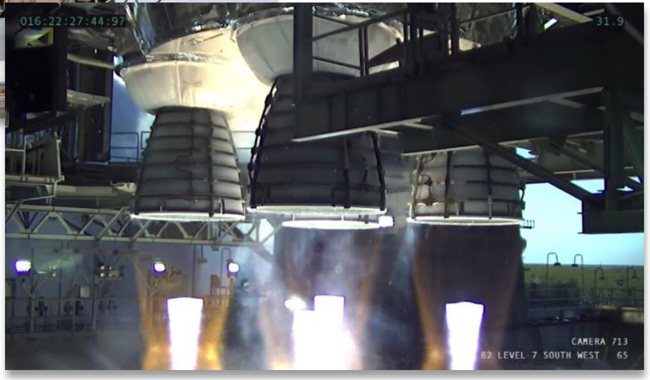




SLS / Algorithm Verification & Validation

Provide capability to analyze and evaluate algorithm performance during several stages of testing to ensure that the flight software (FSW) code behaves as intended, and to feed assessments back into the design process.
** Able to support testing at other facilities.*





<u>Unit Testing of Algorithms</u>

- Develop prototype code and test function of individual algorithms

<u>Integrated Software Verification Testing</u>

- Support FSW testing in a computer simulated test-bed

<u>Verification, Validation & Accreditation Testing</u>

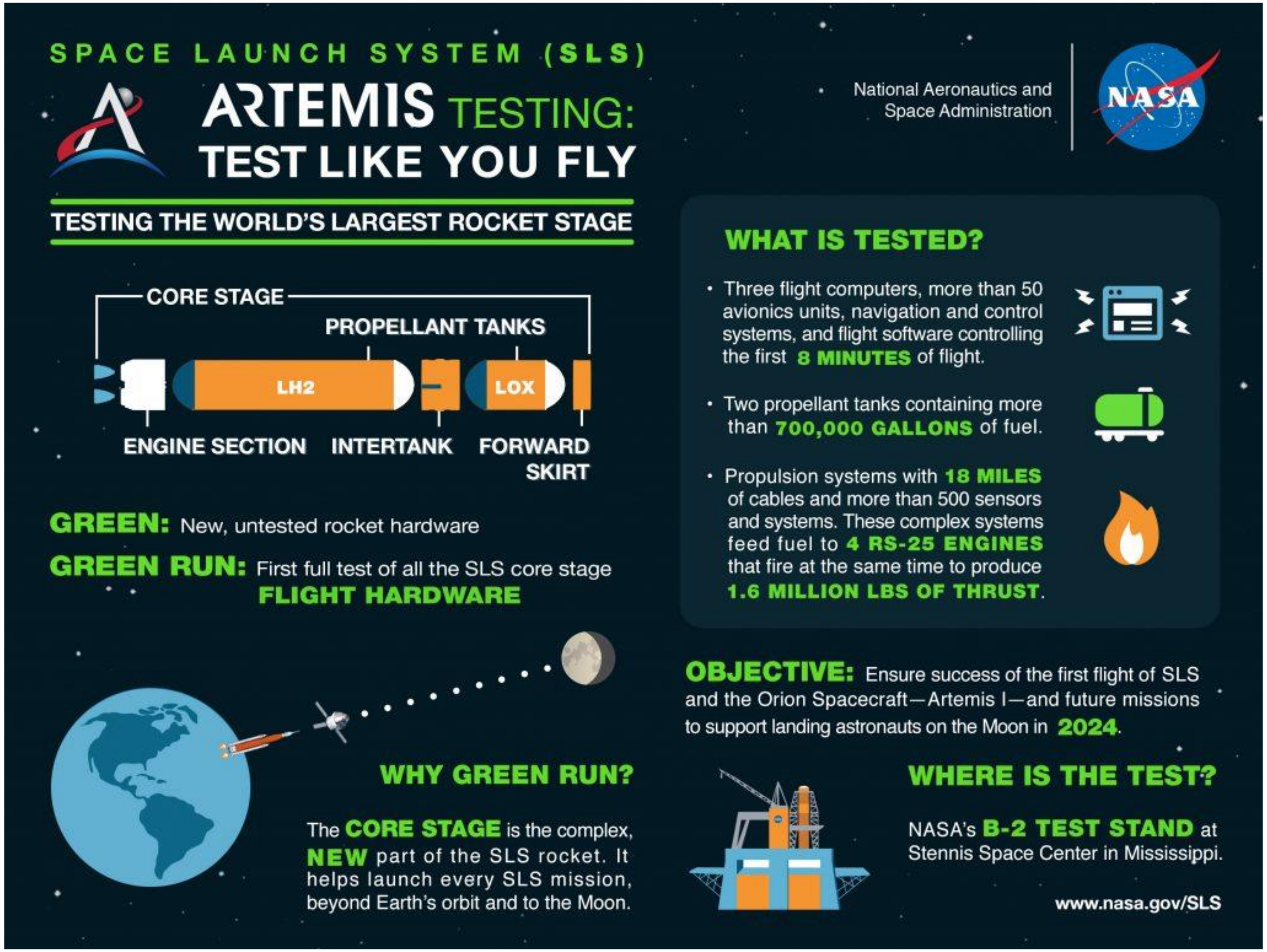
- Support FSW testing on flight computers in a hardware-in-the-loop facility to assure performance meets requirements

<u>Acceptance Testing (e.g. SLS Artemis I Green Run Testing)</u>

- Support live monitoring and analysis of FSW operation on the actual flight vehicle, configured on a test-stand during firing of engines

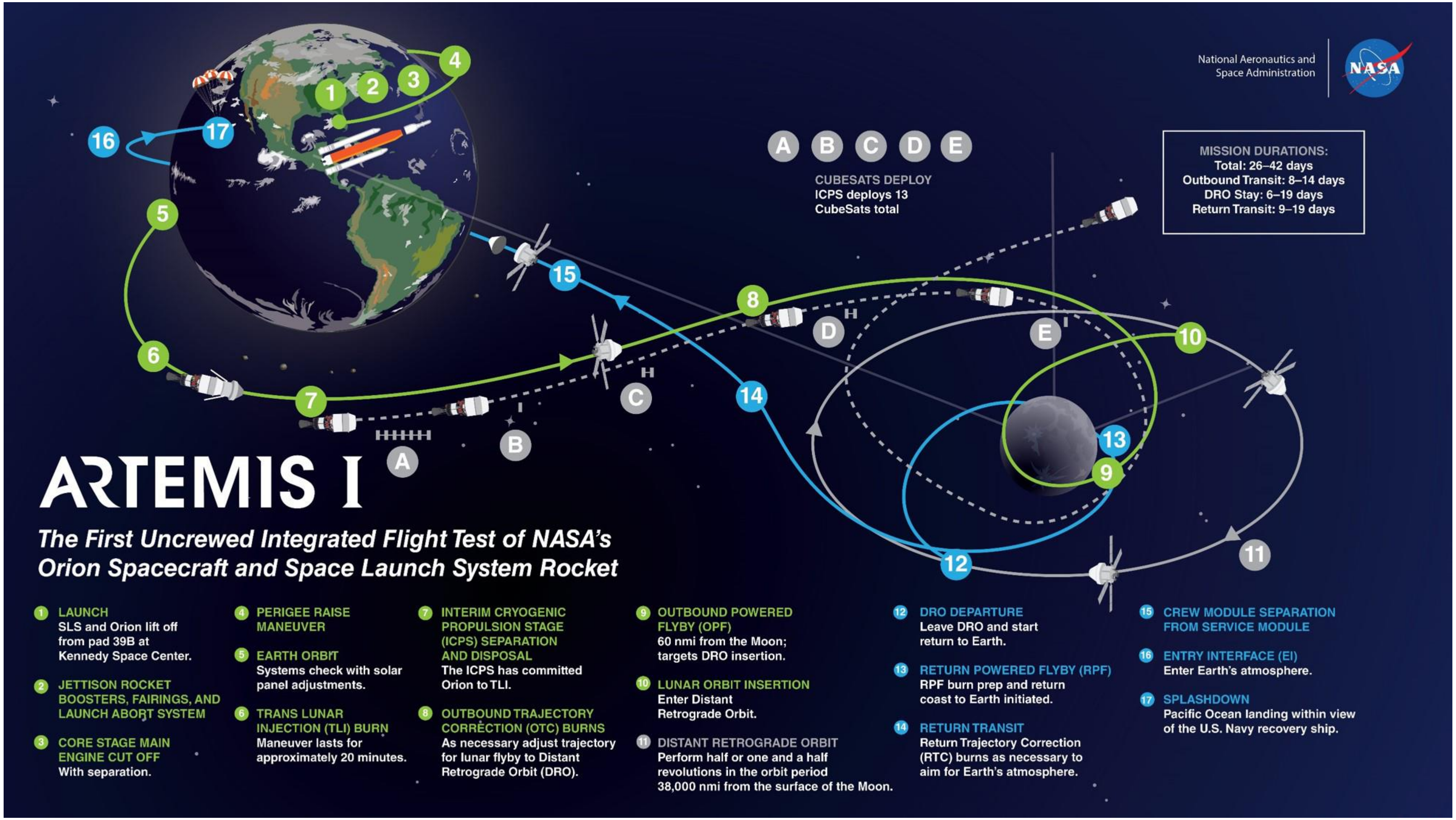
SLS / Green Run Hot Fire Test

https://blogs.nasa.gov/artemis/2021/03/10/green-run-update-nasa-targets-march-18-for-sls-hot-fire-test/

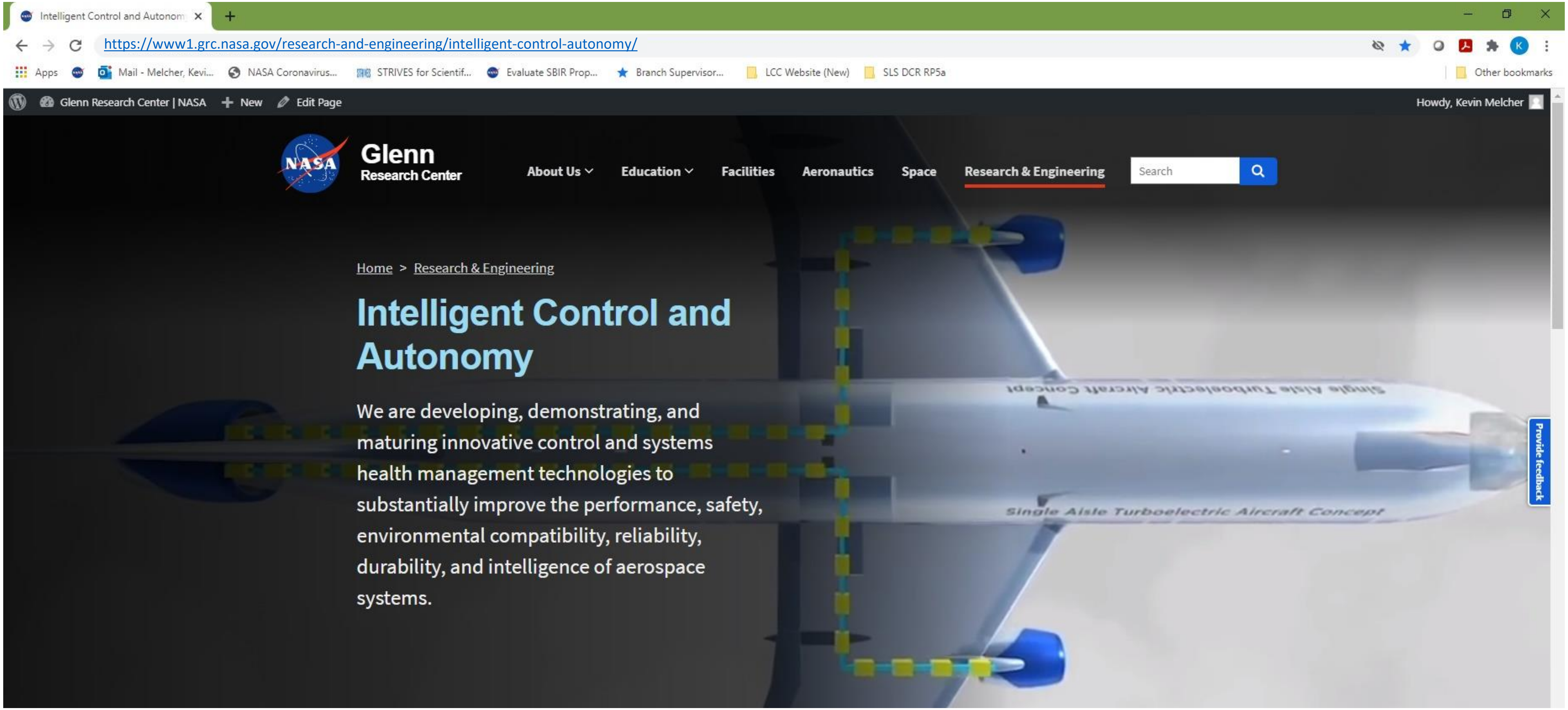


- Jan 16 – Hot Fire Test #1
  - Test terminated early due to conservative failure detection limits for TVC hydraulic system being exceeded
  - Software correctly shutdown the engines ~ 1 minute after ignition
- Mar 18 – Hot Fire Test #2
  - 8+ minute test completed successfully about 4:45p EDT

SLS / What's Next?

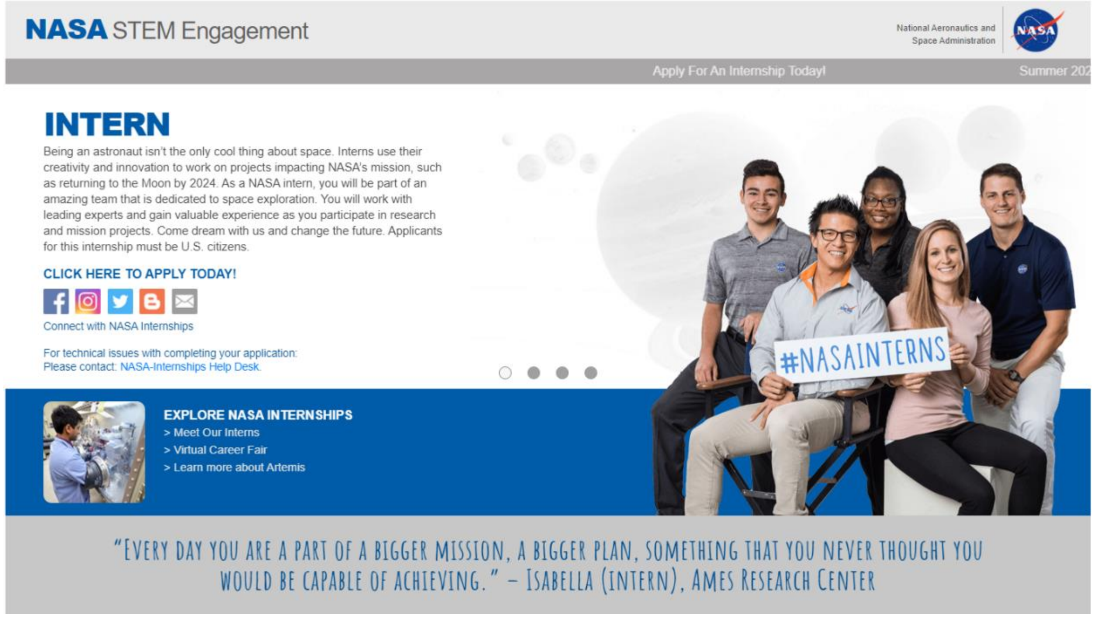


Conclusion / Intelligent Control & Autonomy Web Site



Conculsion / Internships with NASA and the IC&A Branch

- The ICAB provides paid 10-week internship opportunities most semesters
  - Undergraduate
  - Graduate (M.S., Ph.D.)
- U.S. Citizenship Required
- Contact kevin.j.melcher@nasa.gov for information regarding specific opportunities with the ICAB – include resume!



To register, go to intern.nasa.gov

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Many of these papers are available free at ntrs.nasa.gov

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