



Tutorial: Electrified Aircraft Propulsion Approaches for Modeling and Electrical Hardware-in-the-Loop Testing

Dr. Joseph W. Connolly · Santino J. Bianco · Halle E. Buescher · Terry J. Lantz
NASA Glenn Research Center, Cleveland, Ohio, USA

Dr. Elyse D. Hill

NASA Langley Research Center, Hampton, Virginia, USA

Tutorial
IEEE Transportation Electrification Conference/Electric Aircraft Technologies Symposium
June 18-20, 2025



Audience and Description

Audience:

- Multidiscipline engineers supporting ***Ultra Efficient Aviation – Hybrid Electric Systems.***

Description:

- Outline advances in modeling and testing of electrified aircraft propulsion (EAP) hardware and software prior to integration with turbomachinery.
- Discussion of test facilities that support: MW-scale electrical and electromechanical systems at altitude and EAP control systems on sub-scale representative electromechanical architectures.
 - Examples of past testing showcase modeling approaches and test capability

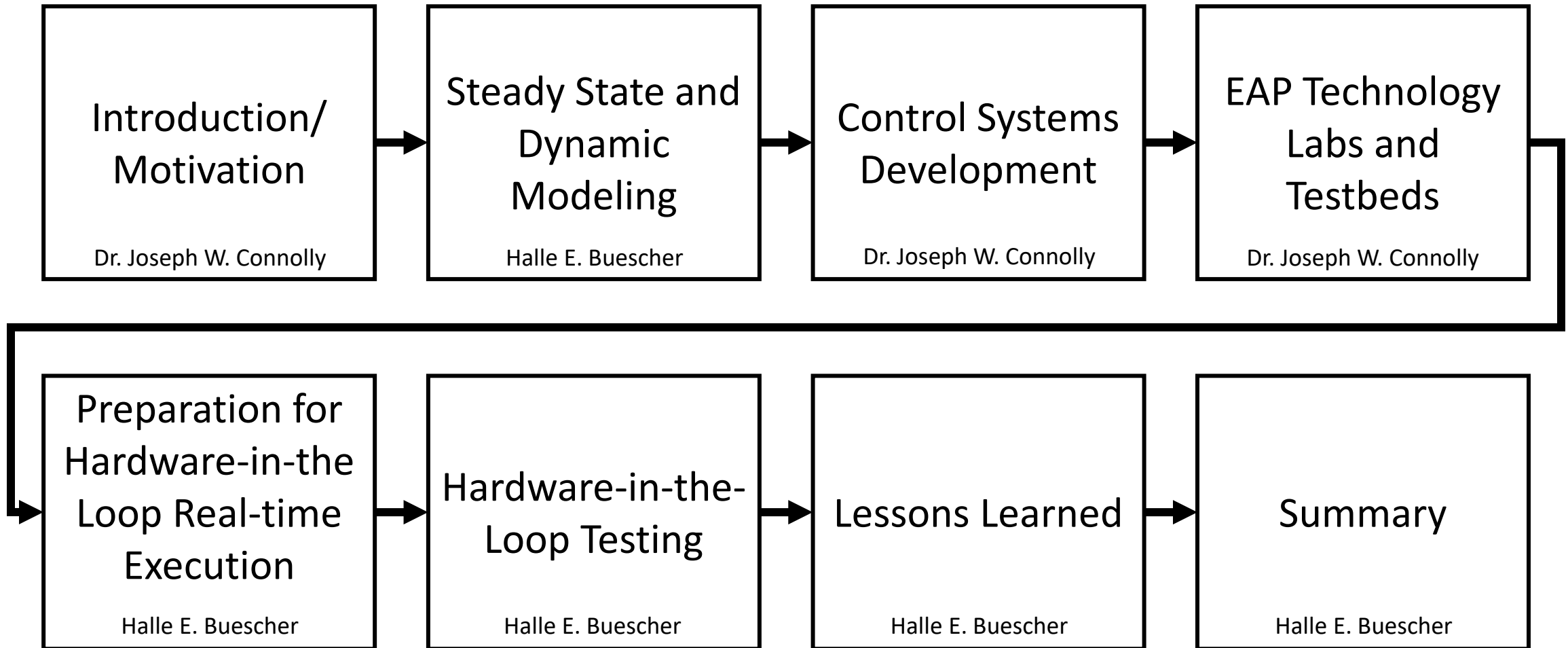


Learning Objectives

- Understanding of modeling hybrid electric turbofan engines
- Hardware in the Loop implementation of supporting control models
- Advantages of testing early and lessons learned

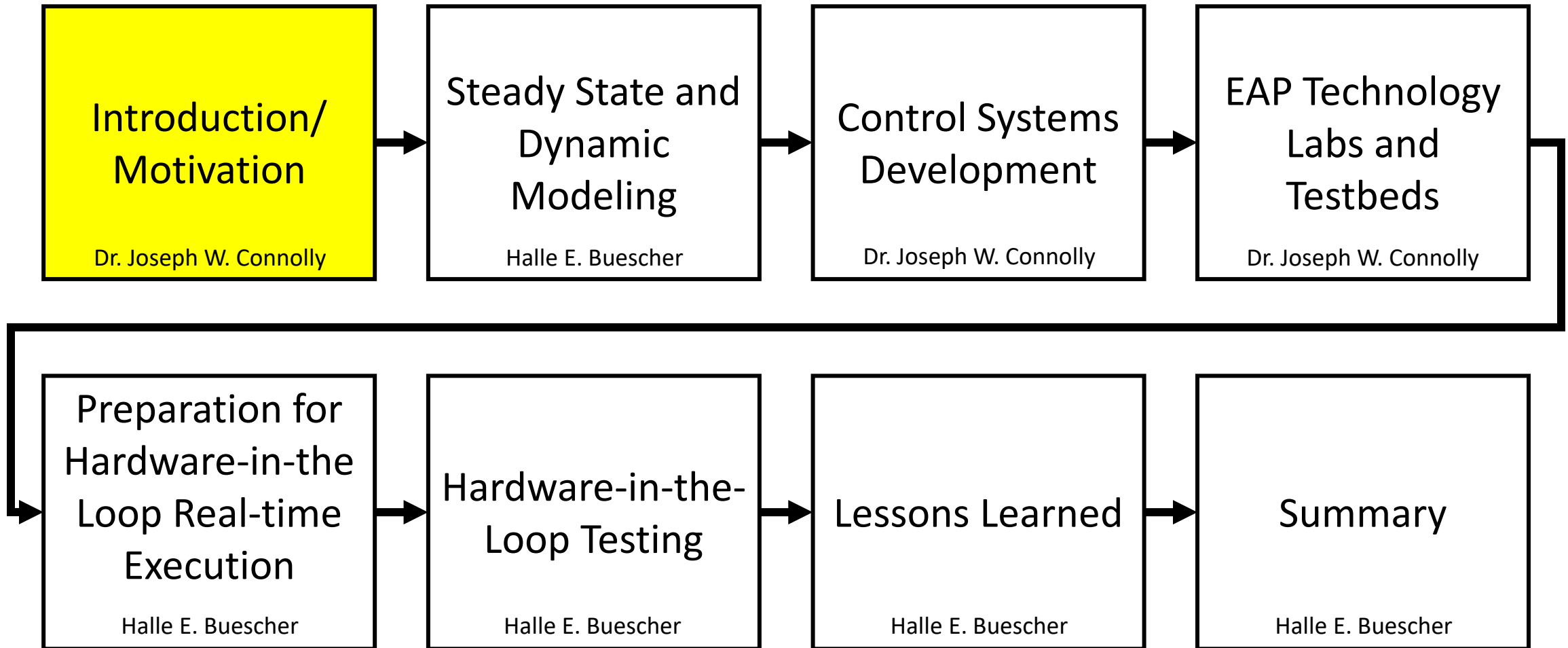


Scope





Scope



Introduction/Motivation

Enable a 30% fuel burn reduction in next generation ultra-efficient airliners by retiring technical risks for key 2030s entry-into-service vehicle technologies

**Ultra-Efficient
Airliners**

1.2030

Practical vehicle-level integration of MW-class electrified aircraft propulsion systems, to enable future single-aisle systems and potential adoption in developing regional and smaller aircraft markets.



Practical
Vehicle-Level
Integration of
EAP Technology



Cost-Shared
Industry Flight
Demonstration
Partnerships



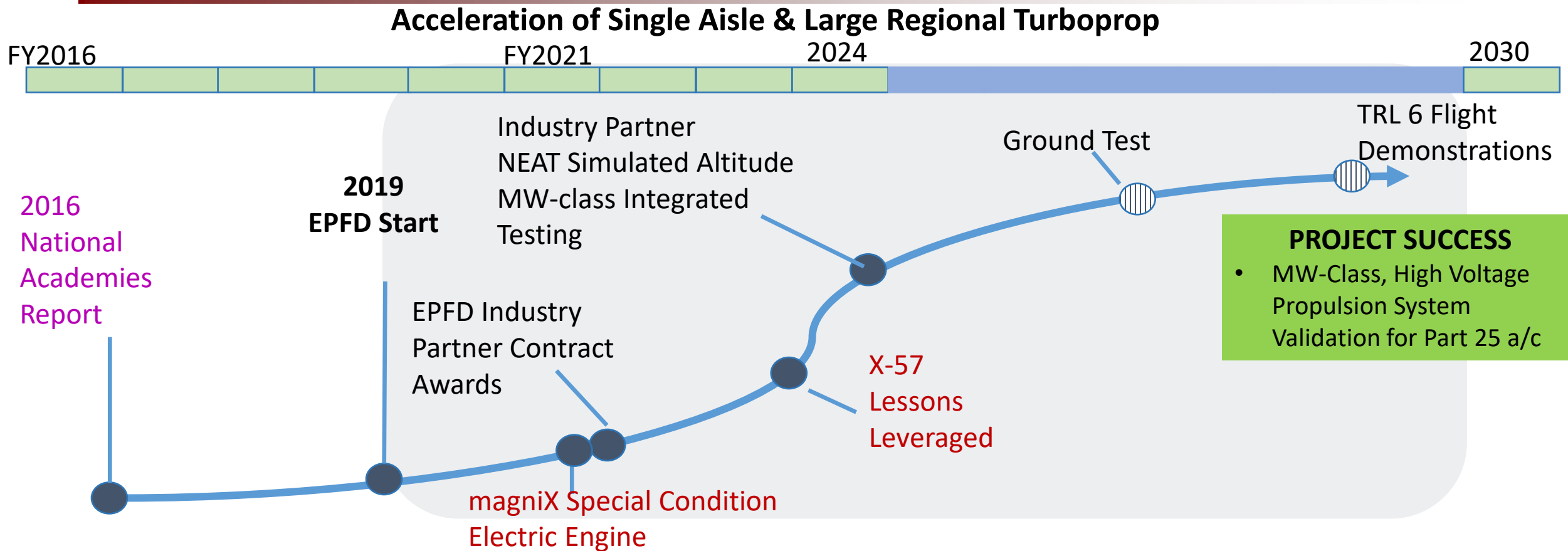
EAP Regs &
Standards
Gaps &
Closures



Regional,
Emerging,
and Single –
Aisle Markets



Introduction/Motivation - Timeline



EPFD and its Industry Partners are addressing the challenges of a/c, propulsion, 1MW/high voltage power and energy storage integration to enable large regional turboprop hybrid electric operations.

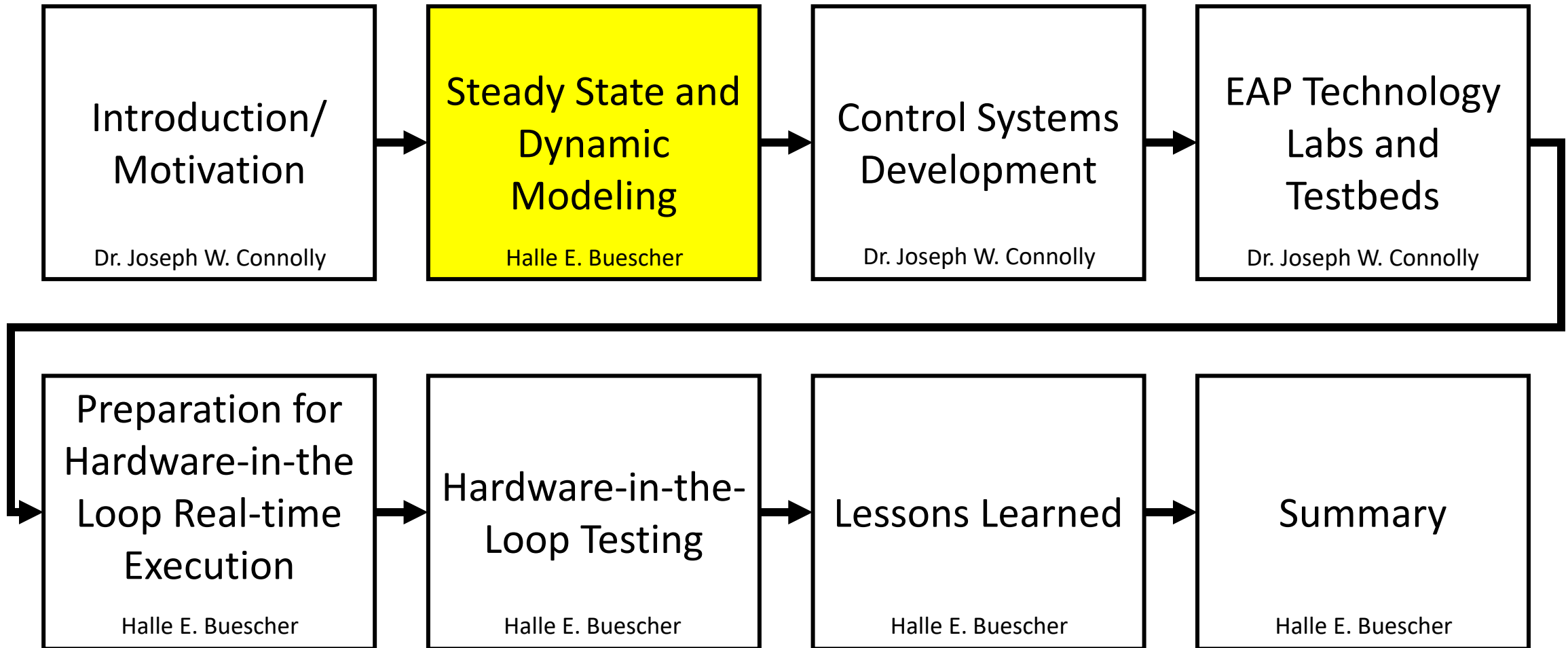


Introduction/Motivation - Tutorial

- Conceptual Trade Studies using Aviary
- Need to develop system level models of promising concepts in more detail
- Test early while electrical hardware is still being developed
- Develop expertise in hybrid modeling and test execution



Scope





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

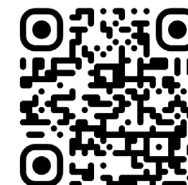
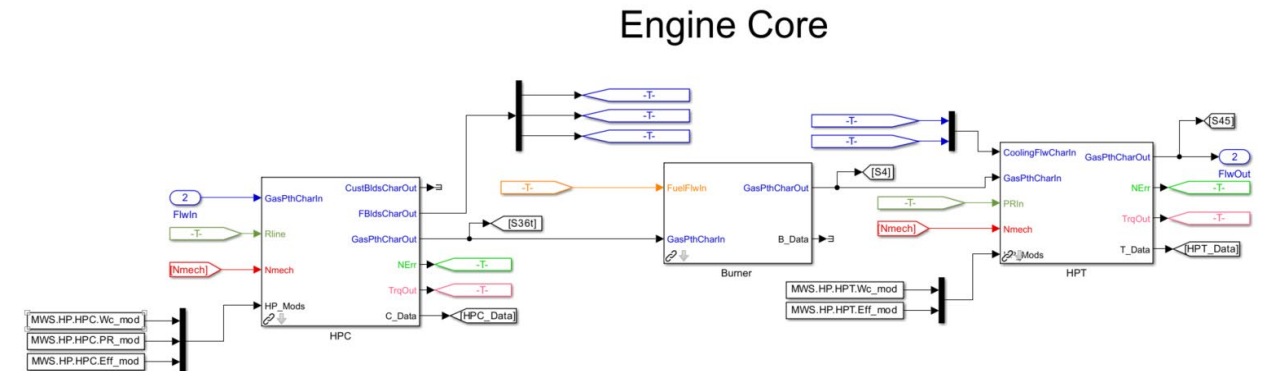
NPSS & T-MATS

NPSS

- Gas Turbine Engine (GTE) models typically consist of the instantiation of various engine components that are parameterized and tied together through code
 - Models are often 0-D (component level)
 - Great for cycle design and system level analysis and benefit studies
- Capable of transients but the environment is not the best for control development and implementation
- Modular extensible framework for the integration of multicomponent, multidisciplinary analysis tools
- Written in C/C++

T-MATS

- Brings much of the same modeling methods and capabilities to the visual coding environment of Simulink with access to the control design tools of MATLAB
- Models often begin with an existing NPSS model that is easily translated to T-MATS
- Well suited for dynamic system studies and control design and implementation



***Developed under the NASA Transformational Tools & Technologies Project**



Dynamical System Modeling Tools in MATLAB/Simulink

*All Tools developed under the NASA
Transformational Tools & Technologies Project

T-MATS

- Mechanical **shaft inertia effects** on dynamics
- Includes thermodynamic effects
- Models turbomachinery, propulsors, valves, etc.

Thermal Systems Analysis Toolbox (TSAT)

- **Heat soak effects**
- 1-D, 2-D cartesian and axisymmetric heat transfer
- Boundary condition approximations



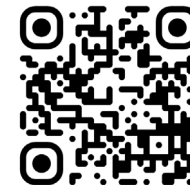
Electrical Modeling and Thermal Analysis Toolbox (EMTAT)

- Modular electrical system modeling tool.
- Power Flow or Physics Based.
- **Only includes electrical system dynamics at turbomachinery time step.**



Tip Clearance Modeling Library (TCML)

- **Tip clearance variations** as a result of centrifugal forces and thermal deformation
- **Effect on engine cycle**



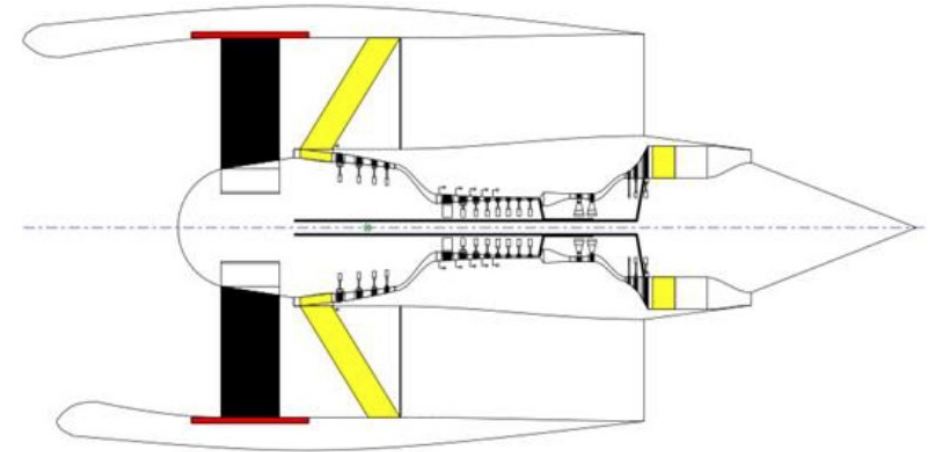
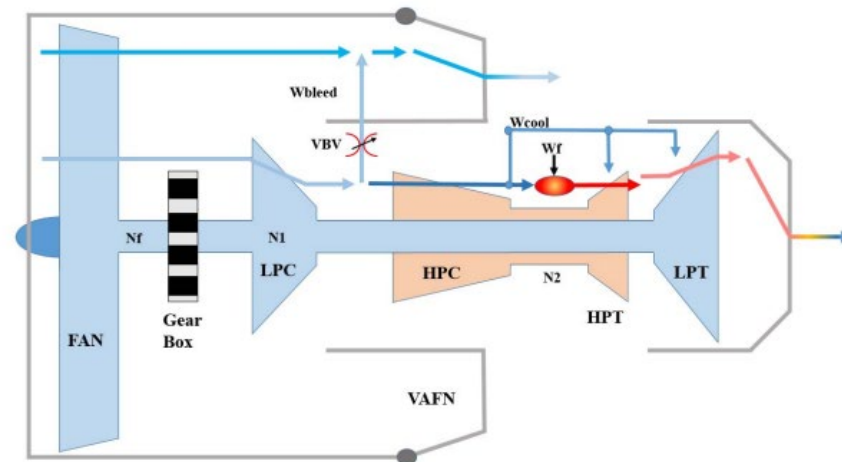
Conceptual Advanced Turbofan Model

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.)



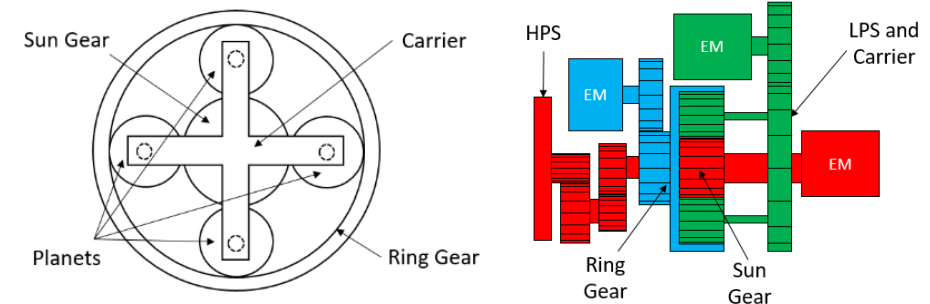
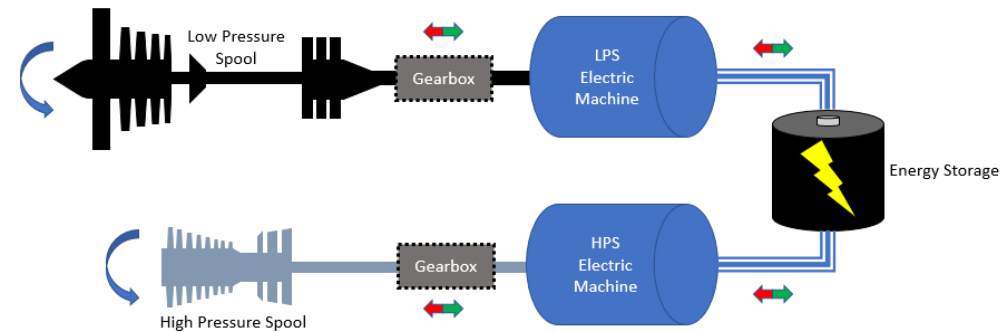
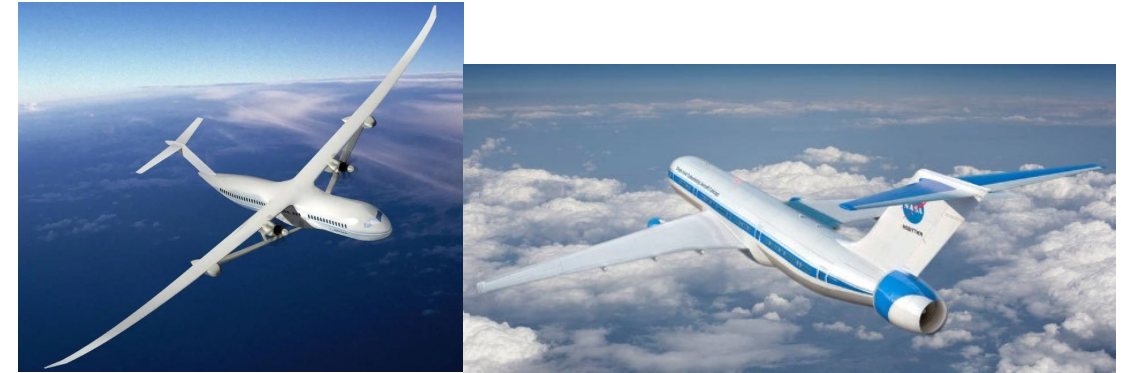
***Developed under the NASA Transformational Tools & Technologies Project**

Electrified Advanced Turbofan Model

Advanced Geared TurboFan 30,000 lbf – electrified (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)
- Simple electrical power system model framework
- Updated, versatile control implementation

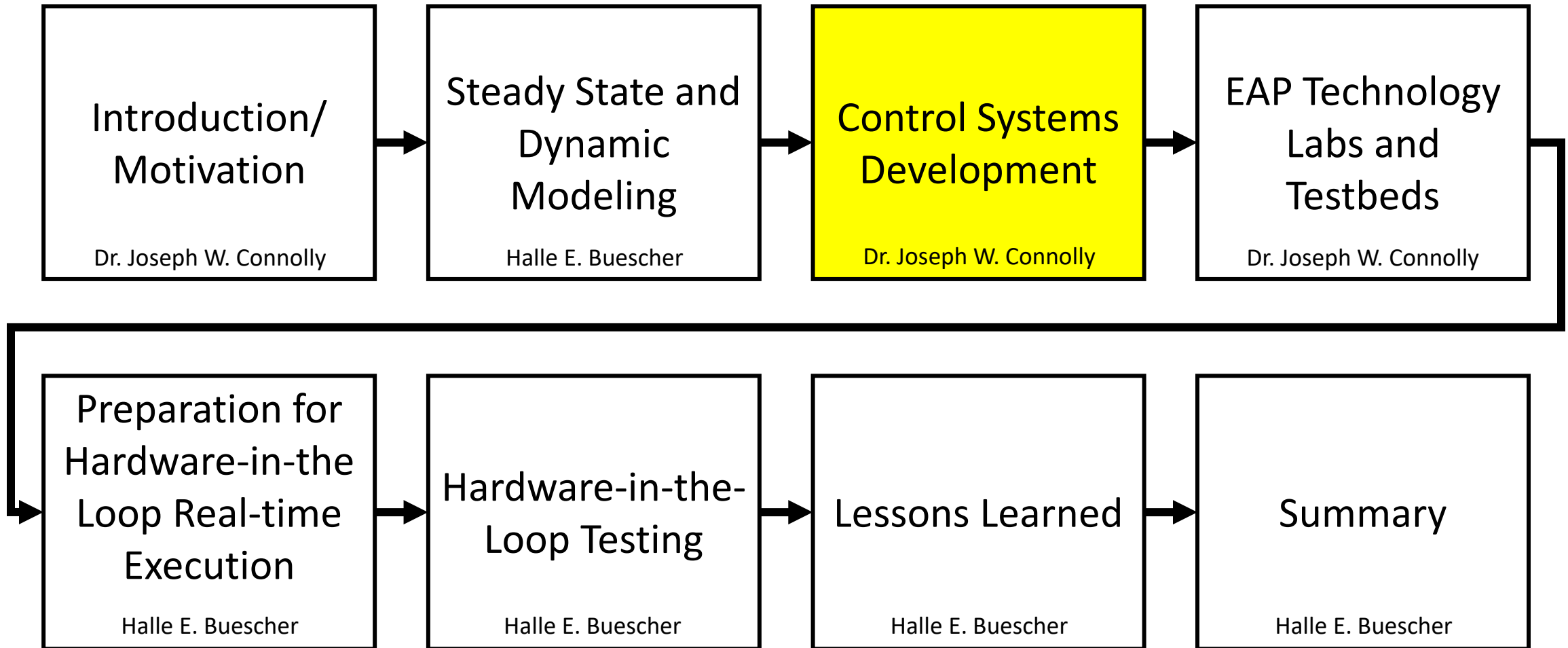
User's Guide
Included!!



***Developed under the
NASA Transformational Tools & Technologies Project**



Scope



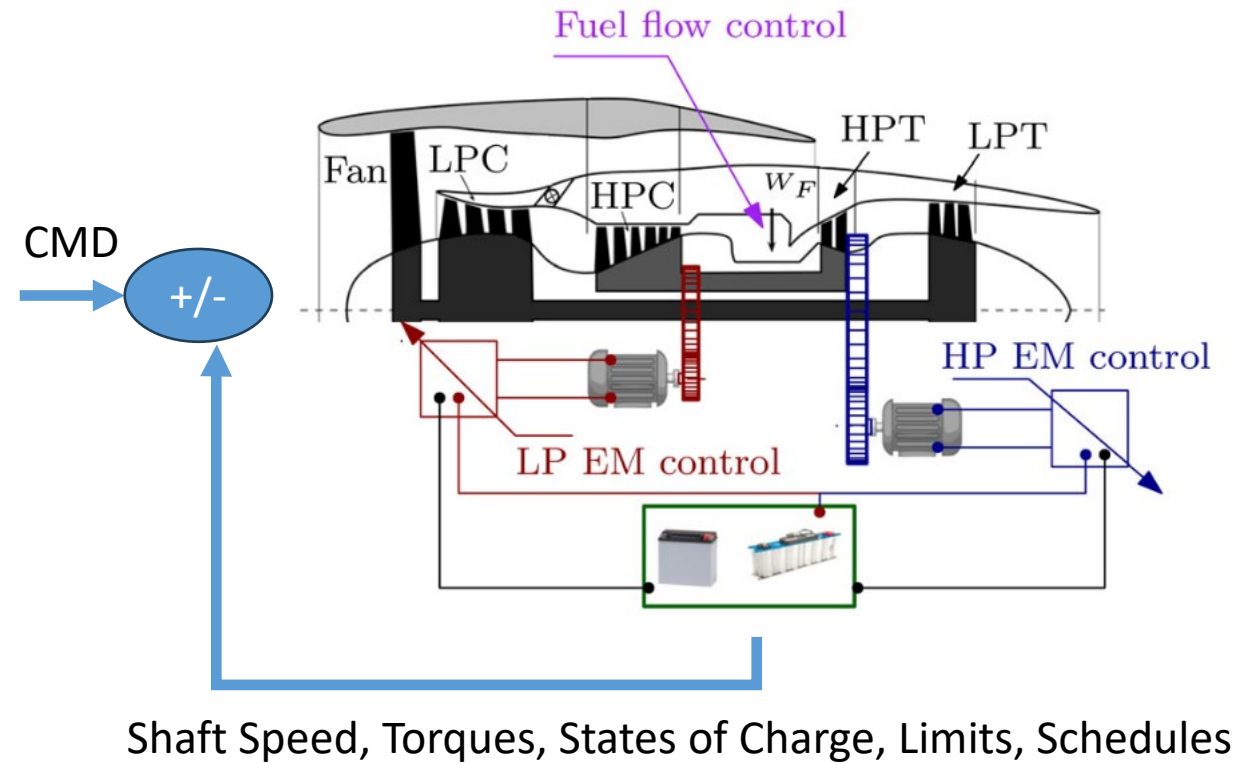
Hybrid Electric Control Considerations

- 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
 - 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?



- 17

Hybrid Turbofan Engine



Examples of 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.

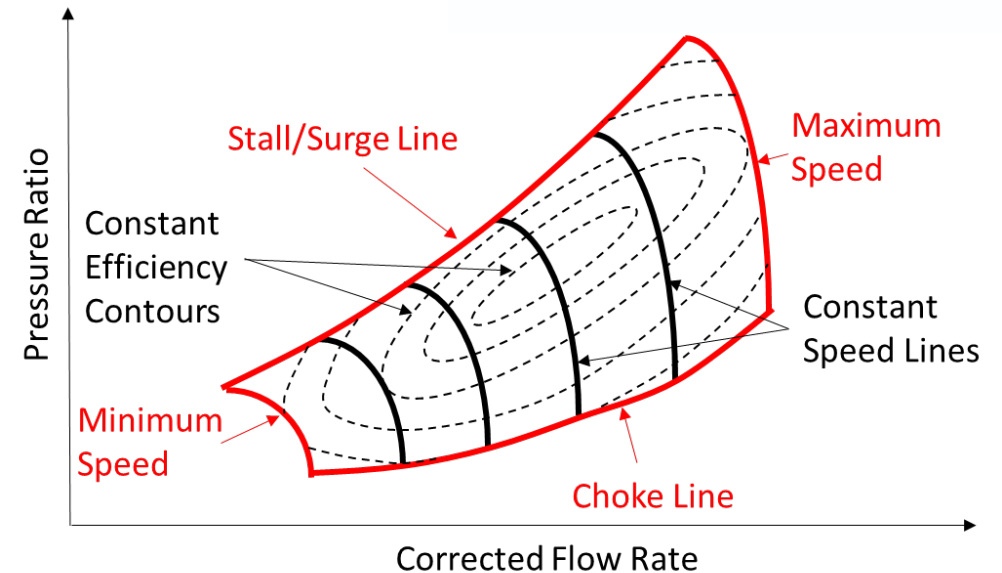
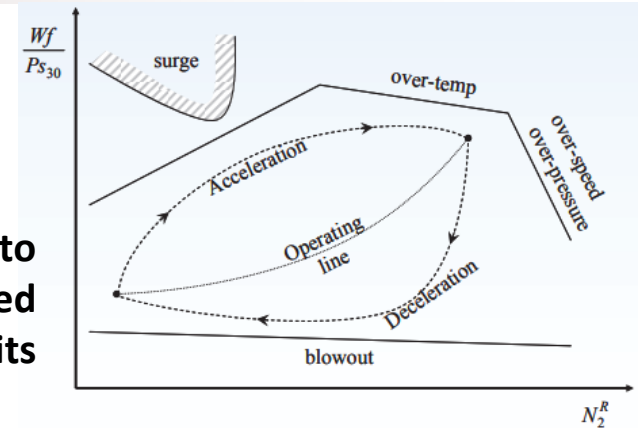
Performance

Operability

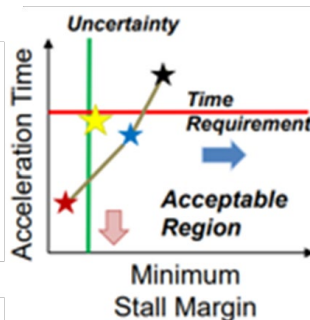
Limits

Hybrid-electric

Ratio unit related to corrected core speed relative to operating limits



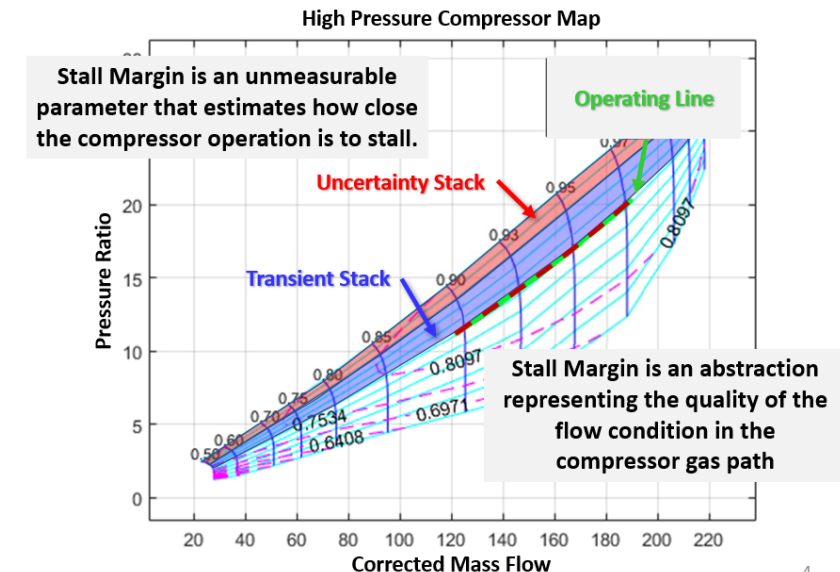
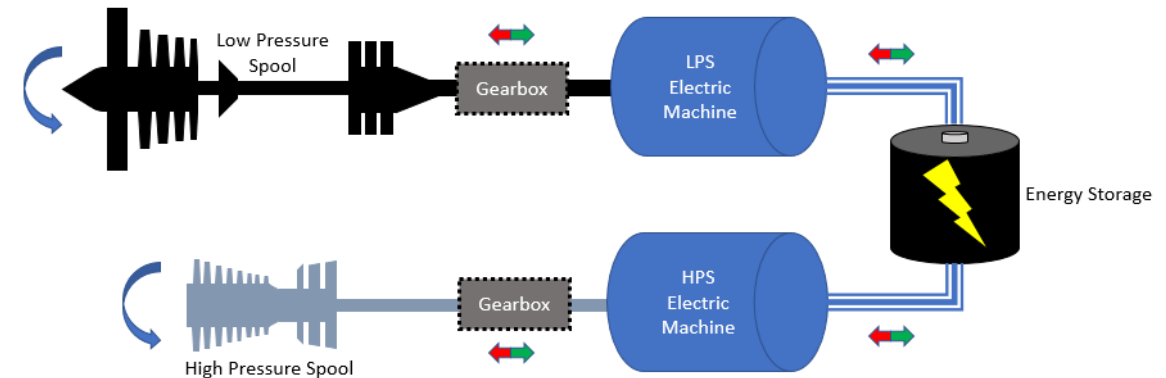
Example of a compressor map with marked operating limits



Trade between thrust response time and compressor operability

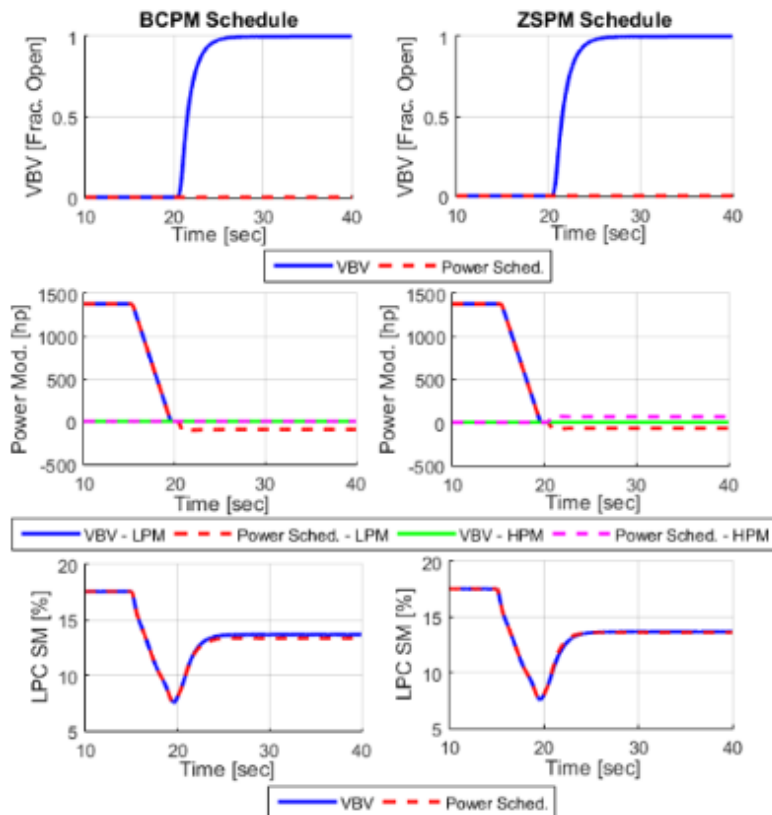
Turbine Electrified Energy Management (TEEM)

- **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 prevent stall/surge.
- Investigated Implementation Strategies:
 - PID controllers with activation logic
 - Schedules guided with optimization methods
 - Model Predictive Control



*Developed under the NASA Transformational Tools & Technologies Project

Examples of TEEM



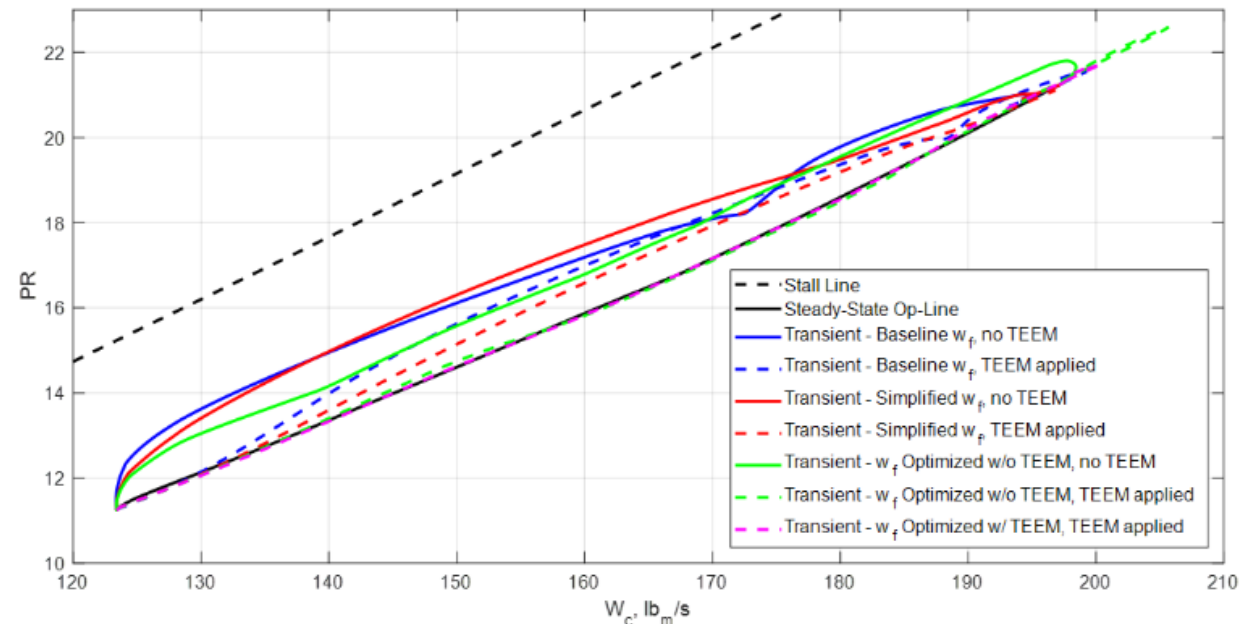
Sugar-Volt hFan

Elimination of the Variable Bleed Valve

* Power transfer to reduce idle thrust and fuel consumption

ZSPM – zero sum power mode

BCPM – battery charge power mode



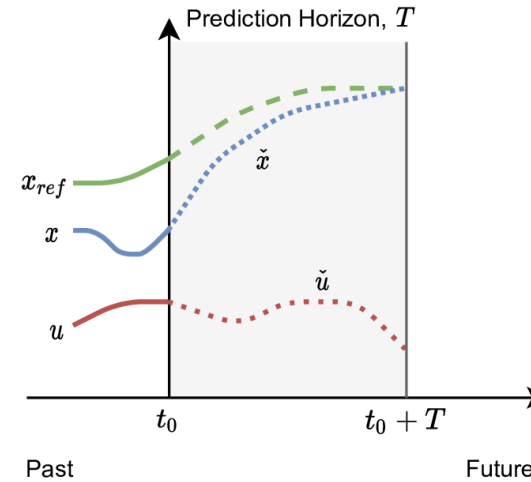
**AGTF30-e –
improved
transient
operability during
accelerations
(pure simulation)**

Benefits:

- Reduced bleed
- Reduced need for variable geometries
- Ability to tailor the transient response
- Transient operability improvement --> alleviates design constraints --> more efficient and/or lighter weight engine

Model Predictive Control

- Model-based, optimal control scheme.
- Generates optimal control trajectories subject to state, input, or output constraints.
- Computational complexity scales with horizon length, sampling time, and number of decision variables.
- Historically applied to slow dynamic systems (e.g. process control) due to hardware limitations.



Continuous

$$\min_{u(\cdot)} J(x, u) = \int_{t_0}^{t_0+T} l(x(\tau), u(\tau)) d\tau$$

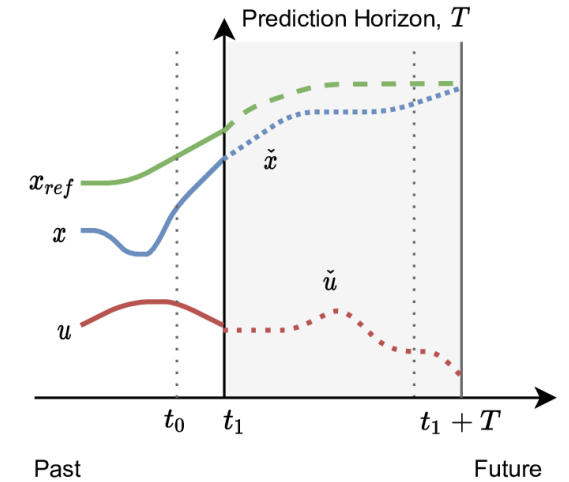
subject to $x(t_0) = x_0$

$$\dot{x}(\tau) = f(x(\tau), u(\tau)),$$

$$x(\tau) \in \mathcal{X},$$

$$u(\tau) \in \mathcal{U},$$

$$\tau \in [t, t + T]$$



Discrete

$$\min_{u(\cdot)} J(x, u) = \sum_{k=0}^{N-1} l(x_k, u_k)$$

subject to $x_0 = x_k$

$$x_{k+1} = f(x_k, u_k),$$

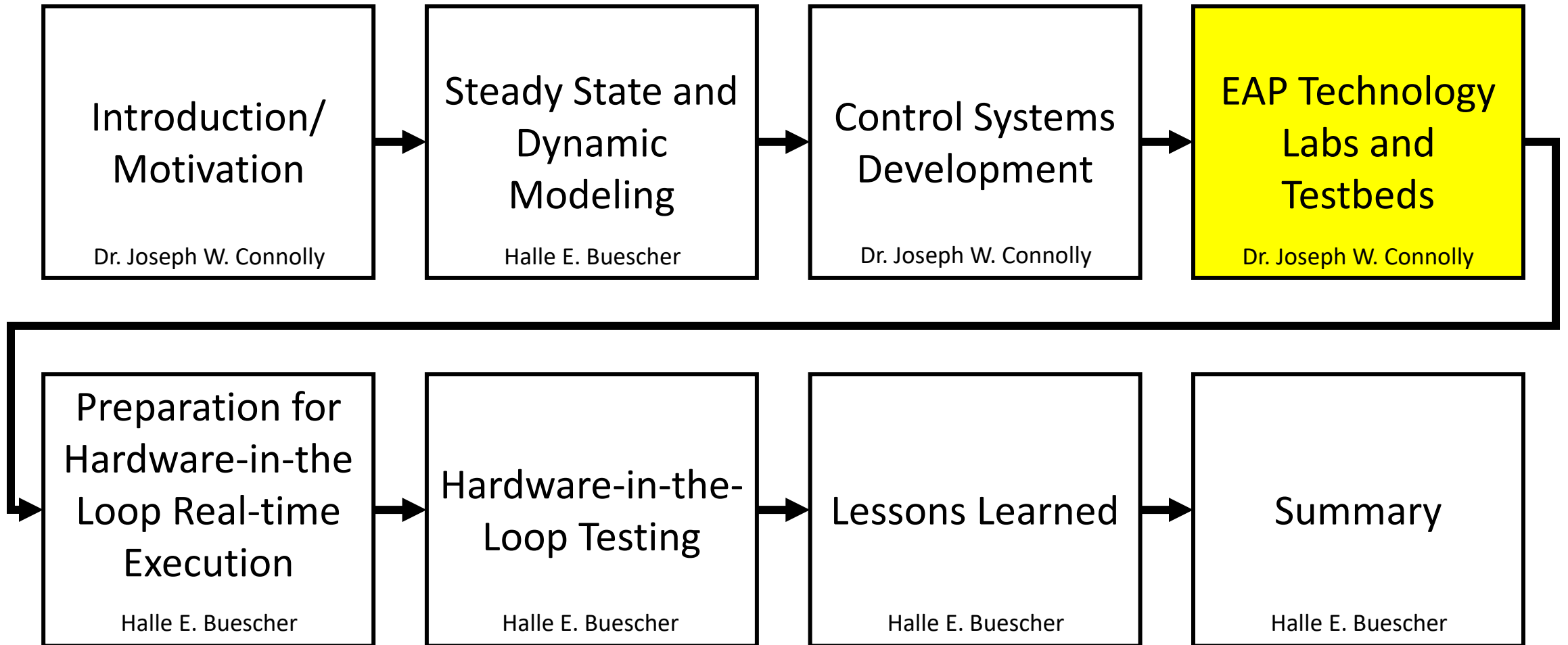
$$x \in \mathcal{X},$$

$$u \in \mathcal{U},$$

$$k \in \mathbb{Z}_{0:N}$$



Scope



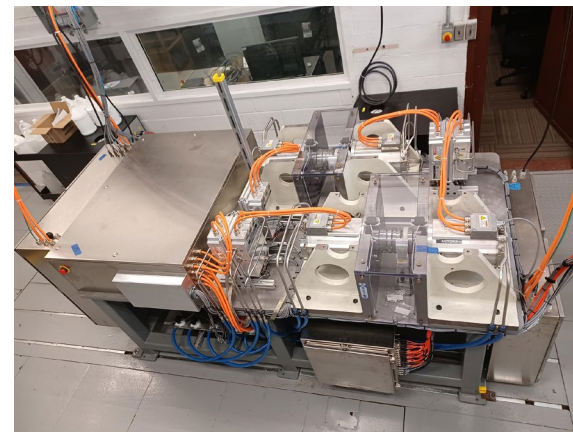


EAP Technology Labs and Testbeds

- Focus
 - Enable end-to-end development and testing of the electric portion of MW-scale electric aircraft powertrain systems
 - High power, high voltage component testing
 - Motors, controllers, cables, circuit protection, etc.
 - Full-scale and sub-scale powertrain system
 - Control systems with hardware-in-the-loop
 - Electrical component testing at altitude
- Labs
 - Hybrid Propulsion Emulation Rig (HyPER)
 - NASA Electric Aircraft Testbed (NEAT)

Hybrid Propulsion Emulation Rig (HyPER)

- NASA Glenn Research Center, Cleveland, Ohio
- Designed for real-time control testing/simulation
- Aeronautic propulsion controls testing with hardware-in-the-loop
- Max Power: 100kW
- Attributes:
 - 400 volts
 - Bi-directional power flow
 - Emulates turbomachinery or general load interface
 - Energy storage (supercapacitor)



NASA Electric Aircraft Testbed (NEAT)

- NASA Armstrong Test Facility, Sandusky, Ohio
- Designed to enable end-to-end development and testing of the electric portion of MW-scale electrified aircraft powertrain systems
- Designed with a reconfigurable architecture that industry, academia, and Government can utilize to further mature electrified aircraft technologies

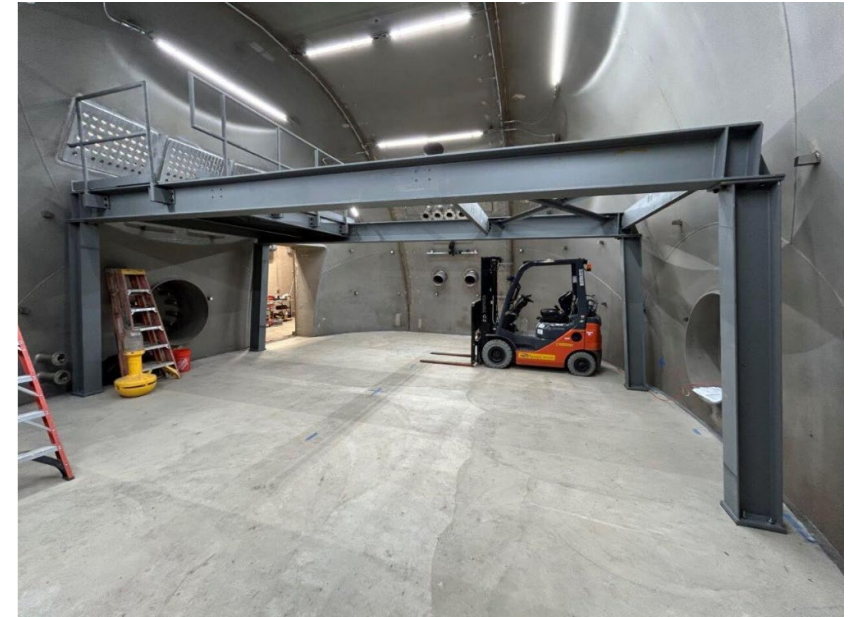


NEAT Additional Info



NASA Electric Aircraft Testbed (NEAT)

- Relocation to new facility
 - Commissioning Begins in Fall 2025 – Integrated System Test
- Capability:
 - Electrical dynamometer
 - 1MW at 7000RPM
 - Mechanical dynamometer 3.3
 - 3.3 MW - Water Brake
 - Electrical power up to 3.75MW
 - 3 kVA available as 480V AC-3 ϕ power to date on our sub-station E
 - Potential to power up to 12 MW (more if regenerating)
 - Altitude (up to 60,000 feet pressure)

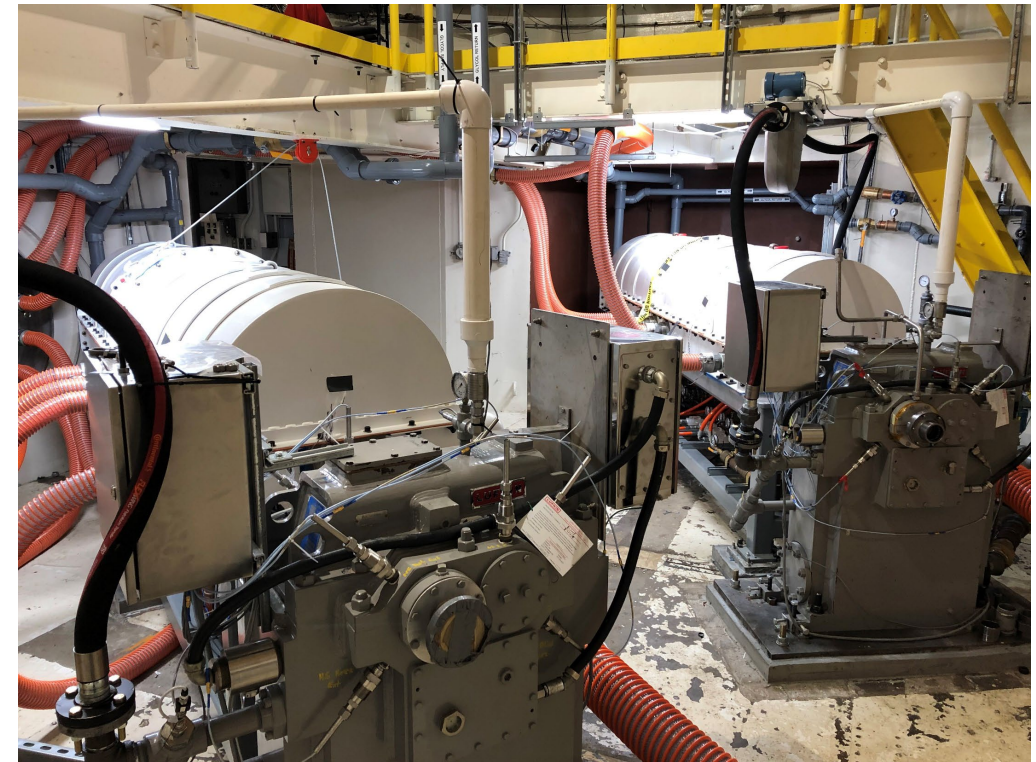


NEAT Test GE Aerospace

- Powertrain test with GE Aerospace in 2022
- First of a kind test
 - Multi-kilovolt, megawatt power
- Utilized dual electric dynamometers inside altitude chamber



NASA Press Release

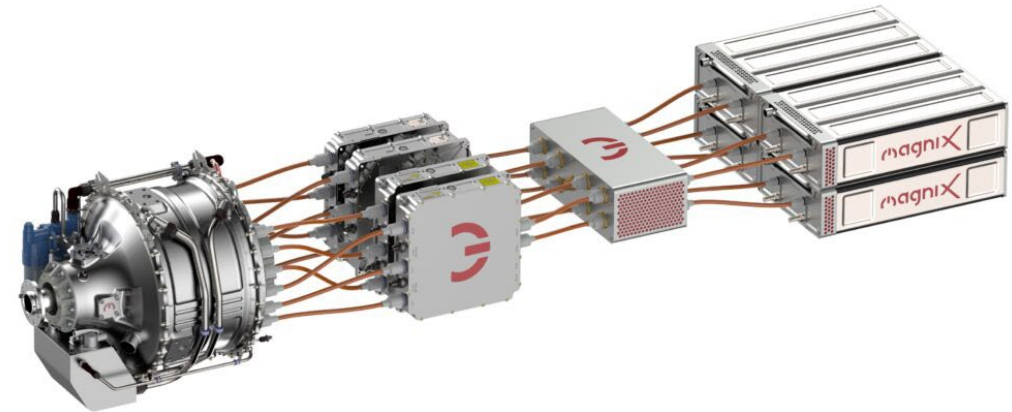


NEAT Test magniX

- Powertrain test with magniX in 2024
- Performance test of Electric Propulsion Unit (EPU)
- Work supported by NASA's Electrified Powertrain Flight Demonstration (EPFD) project



Skies Magazine Article

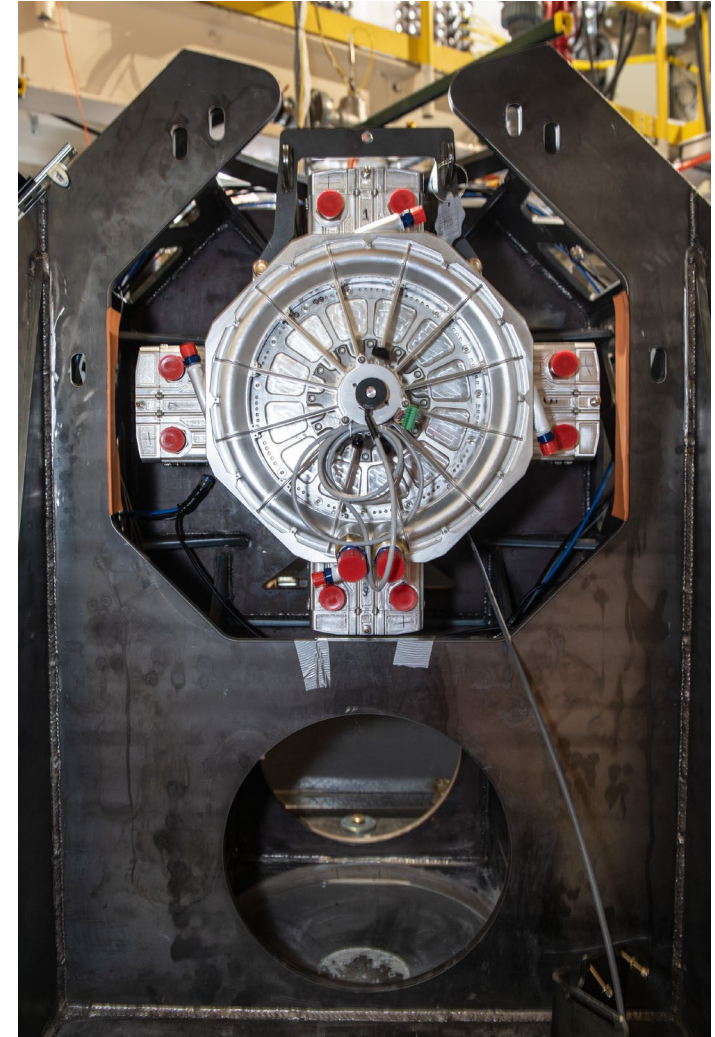


NEAT Test Wright Electric

- Powertrain test with Wright Electric in 2025
- Testing of WM2500 2.5-megawatt electric propulsion system
- Work supported by U.S. Dept of Energy – Advanced Research Projects Agency – Energy’s (ARPA-e) Ascend Program



Aviation Week Article

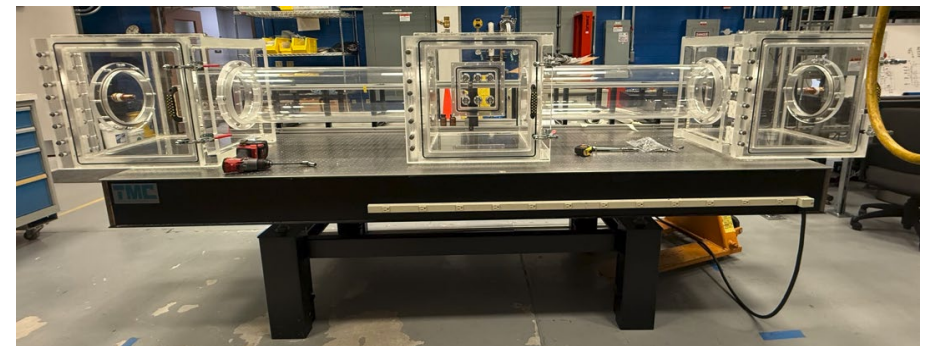
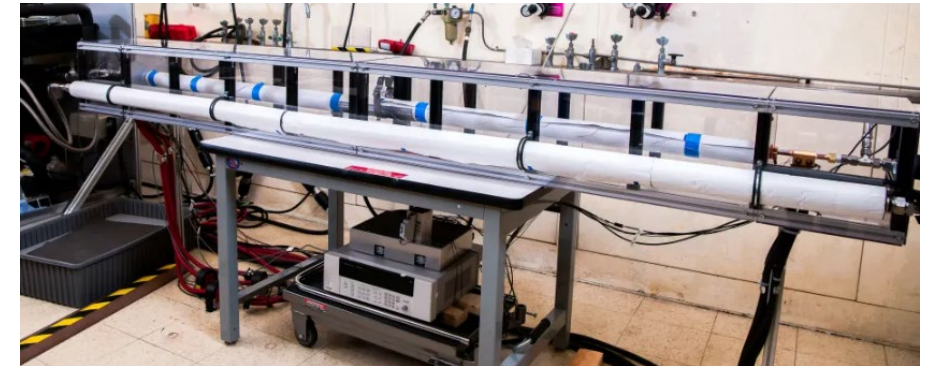


High-Power Advanced Cable Technology (HiACT)

- Thermal and altitude performance testing of advanced cable and connector technologies for EAP
- Close gaps in current aircraft ampacity standards for high-powered cables
- 10' - Ampacity Test Stand:
 - Thermally insulated cables
 - Up to 1500 amps (constant current)
- 10' - Acrylic Altitude Chamber
 - Non-conductive
 - High-Voltage Partial Discharge testing up to 6000V at 60000 feet



HiACT



EAP Technology Labs and Testbeds

Point-of-Contact:

- NASA Electric Aircraft Testbed (NEAT):
 - Amy Jankovsky - amy.l.jankovsky@nasa.gov
- Hybrid Propulsion Emulation Rig (HyPER)
 - Santino J. Bianco - santino.bianco@nasa.gov
- High-Power Advanced Cable Technology (HiACT)
 - Terry J. Lantz – terry.j.lantz@nasa.gov



EAP Labs and Testbeds



NASA Electric Aircraft Testbed (NEAT)



Advanced Reconfigurable Electrified Aircraft Lab (AREAL)



High-Power Advanced Cable Technology (HiACT)



Scaled Power Electrified Drivetrain (SPEED)



Dynamic Spin Rig



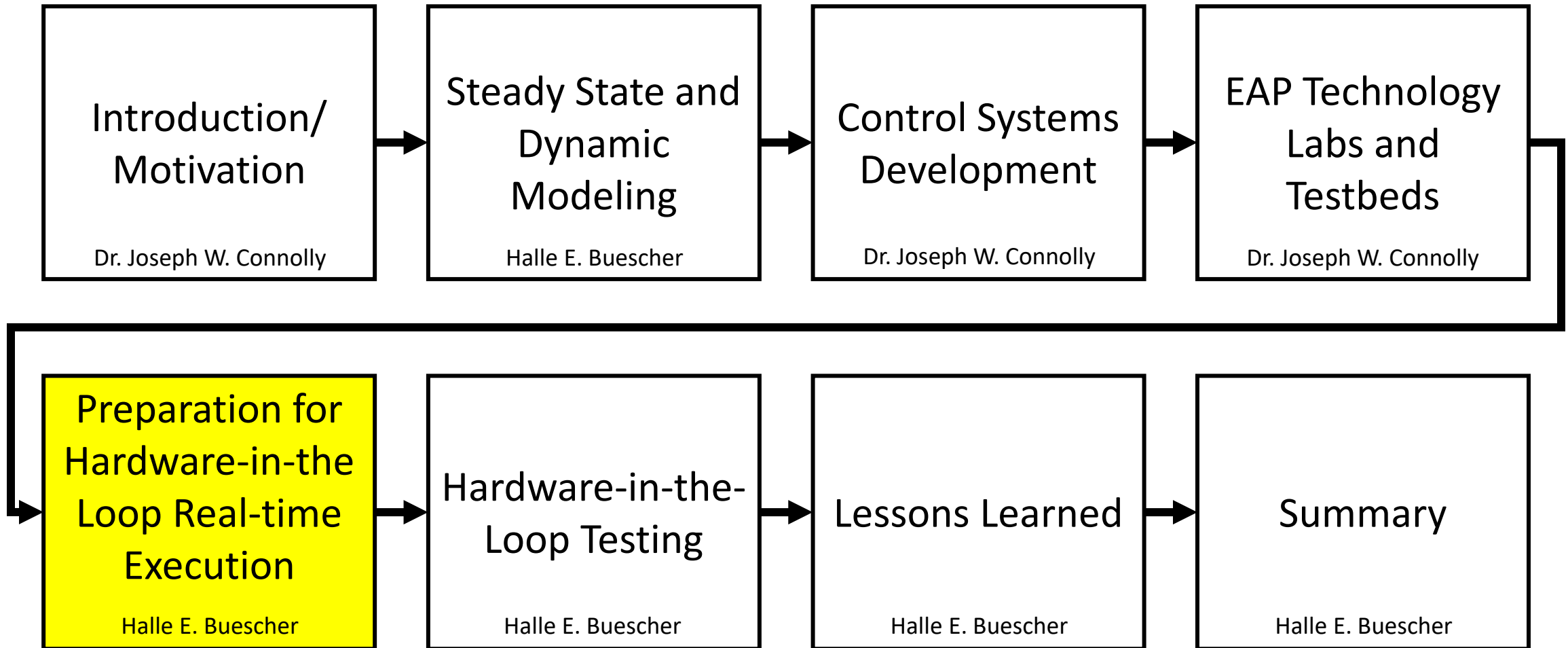
Integrated Cryogenically-Cooled Experiment Box (ICE-Box)



Hybrid Propulsion Emulation Rig (HyPER)

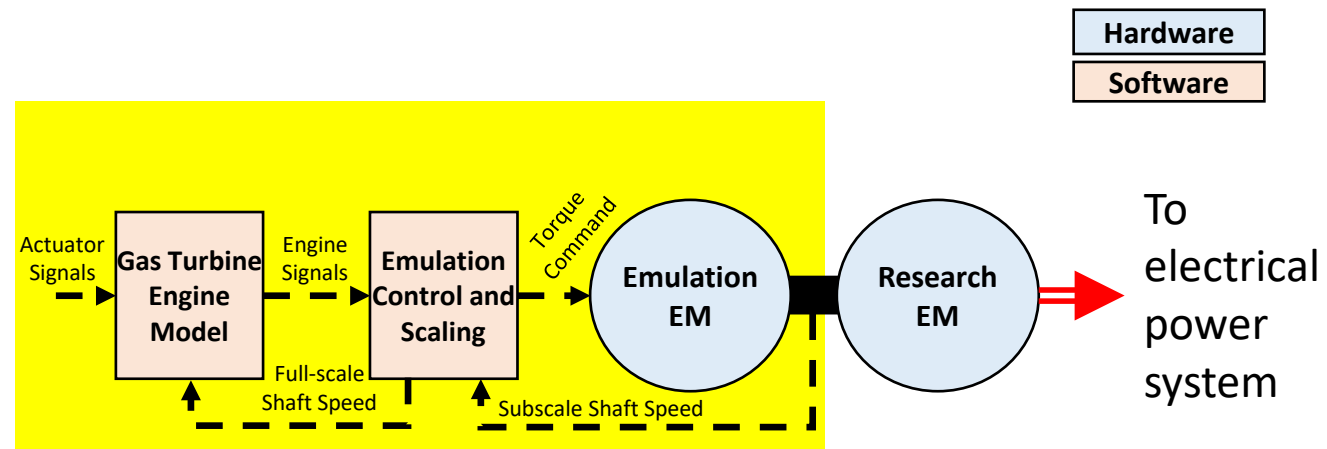
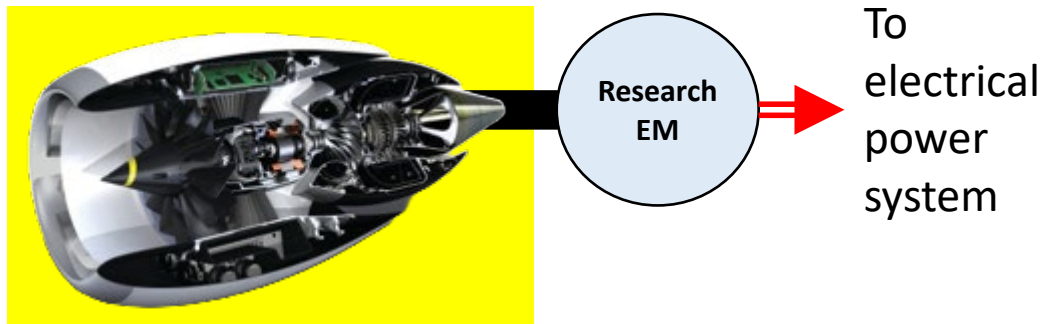


Scope



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



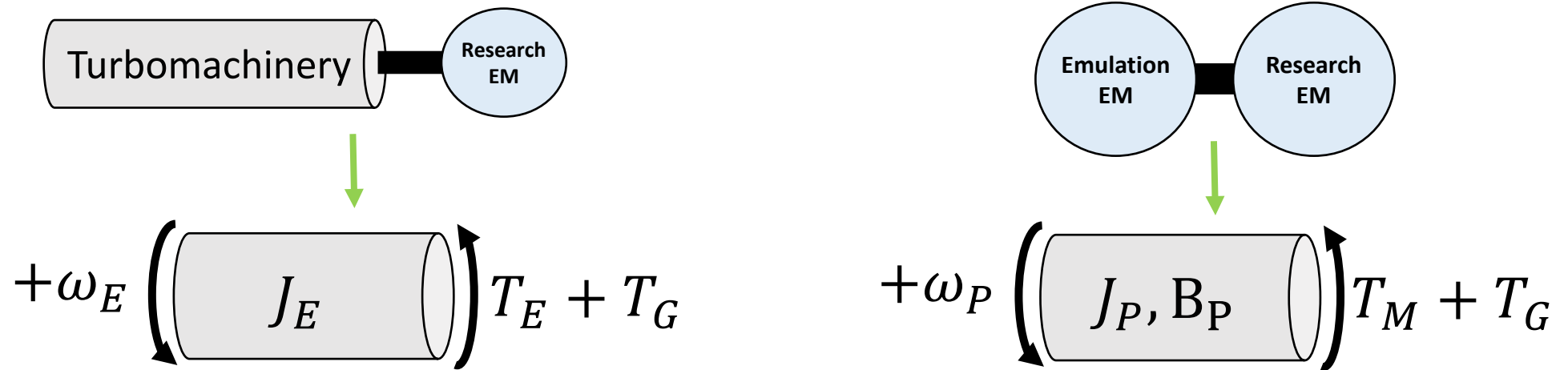
2. Adaptive Sliding Mode Impedance Controller with Scaling (ASMICS)

- Robust
- Adapts model-based parameters.
- Proven to be stable.

ASMICS



Simple Impedance Control Example



$$T_E + T_G - J_E \dot{\omega}_E = 0$$

$$T_M + T_G - J_P \dot{\omega}_P - B_P \omega_P = 0$$

Legend

- T = Torque
- J = Moment of Inertia
- B = viscous damping coefficient
- ω = Rotational Speed
- $\dot{\omega}$ = Rotational Acceleration
- $*_E$ = Engine
- $*_G$ = Research Electric Machine
- $*_P$ = Lab Shaft
- $*_M$ = Emulation Electric Machine

Solve for $\dot{\omega}_E$.

$$\dot{\omega}_E = \dot{\omega}_P$$

Solve for $\dot{\omega}_P$.

Controller

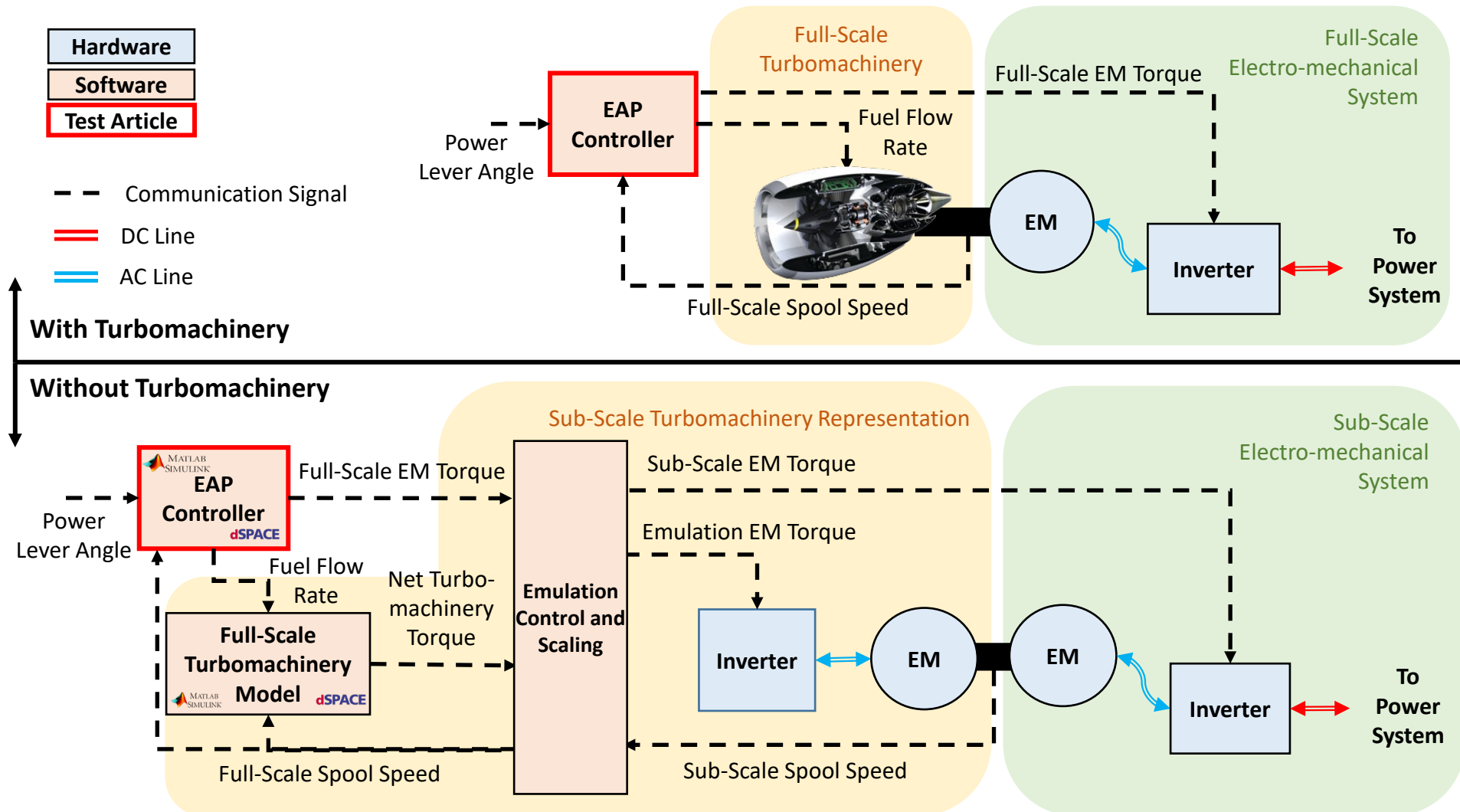
$$T_M = J_P \frac{T_E + T_G}{J_E} + B_P \omega_P - T_G$$

Substitute into
engine equation.

Closed Loop System

$$T_E + T_G - J_E \dot{\omega}_P = 0$$

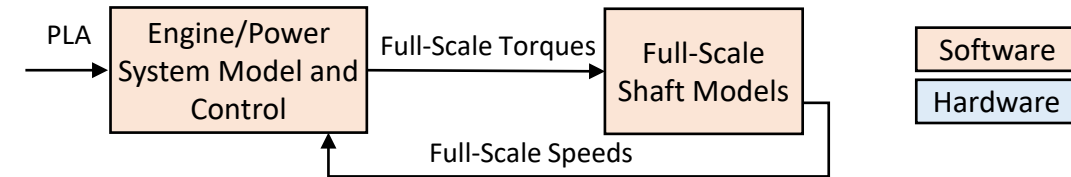
No physical gas turbine engine?



Steps to Hardware-in-the-loop Testing

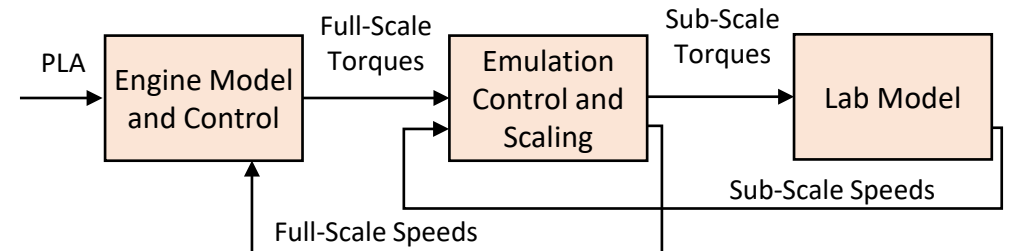
1. Software-in-the-loop (SIL) Testing

- Computer simulation of intended plant and controller.



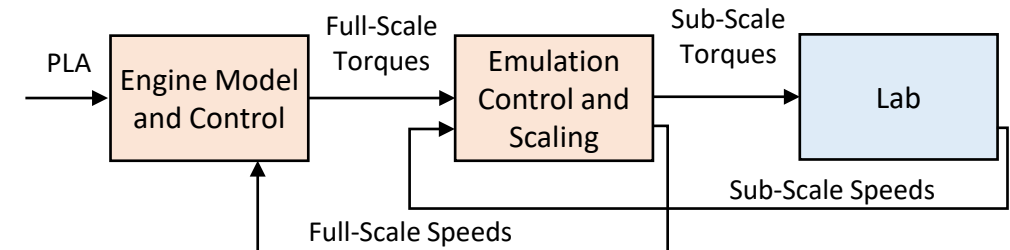
2. Simulated Hardware-in-the-Loop (SHIL) Testing

- Computer simulation of surrogate plant and controller.



3. Hardware-in-the-Loop (HIL) Testing

- Real-time simulation of controller driving surrogate plant hardware.



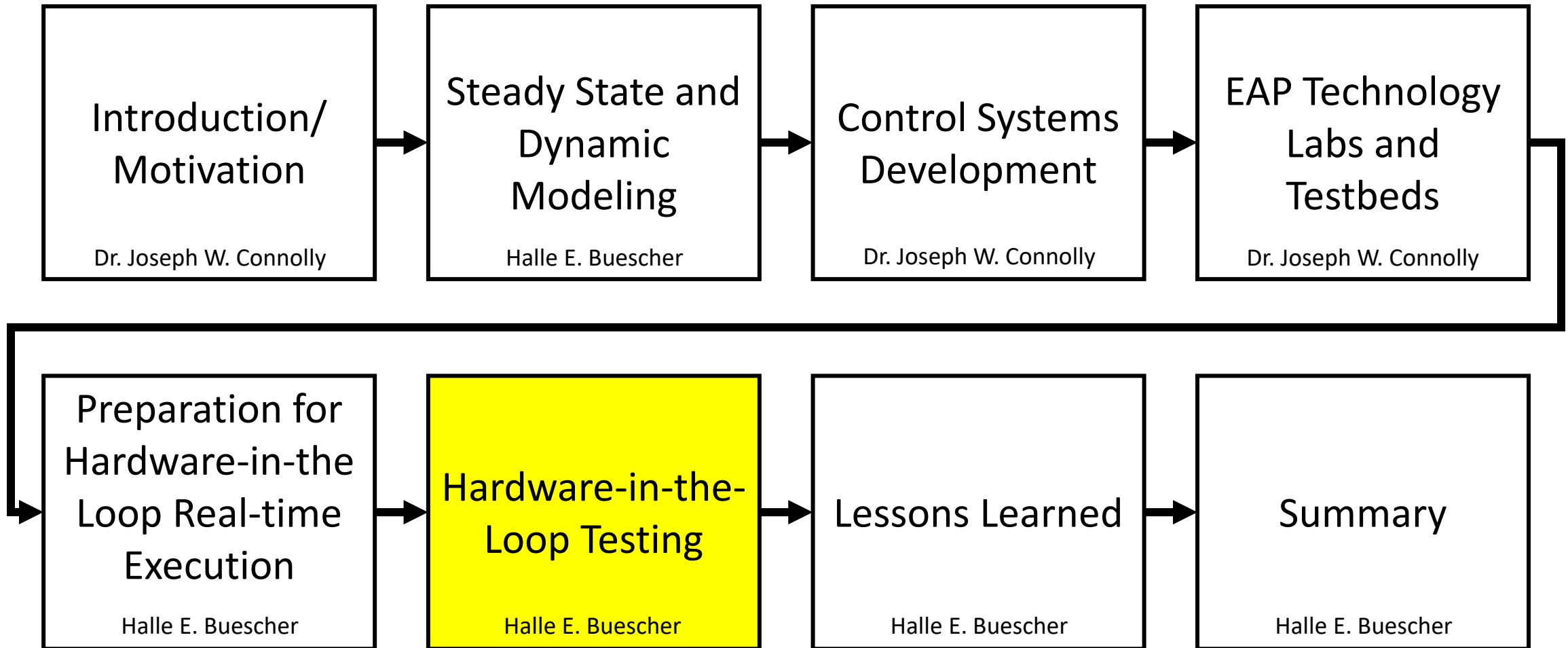


Real-time Implementation Considerations

- Noise
 - Non-convergence of numerical solver within engine model.
 - Amplification of noise by controller.
 - Controller stability margin reduction.
- Computational Load
 - Over-runs (not computing simulation in real-time).
- Non-Ideal Hardware Operation
 - Variations/degradations in emulation and engine controller performance.

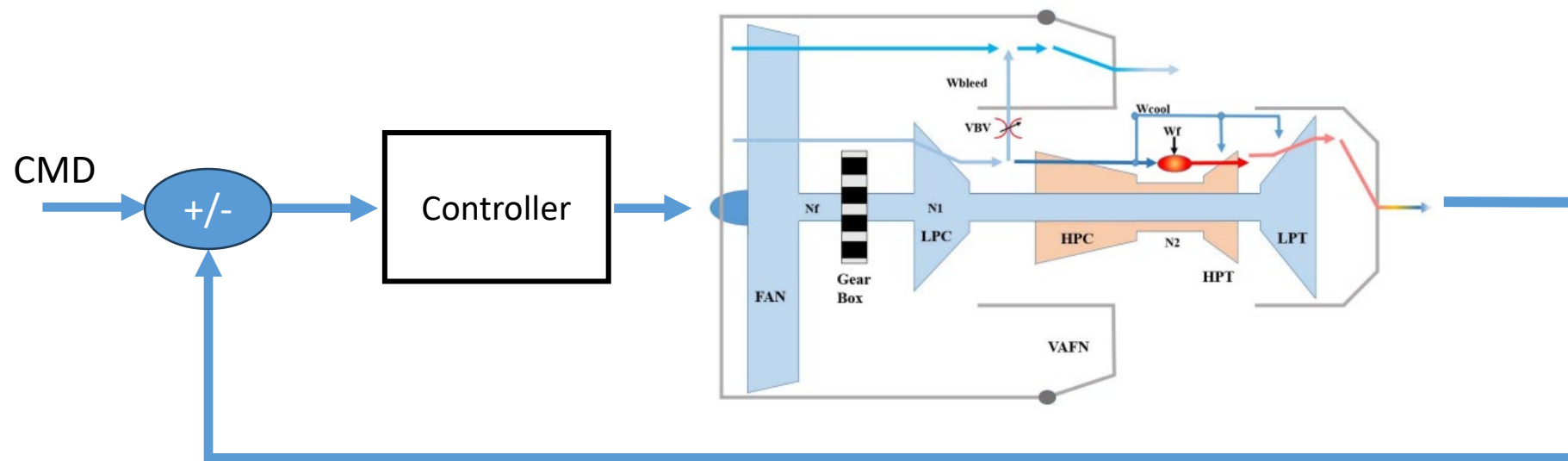


Scope



Hybrid Electric Turbofan Control System

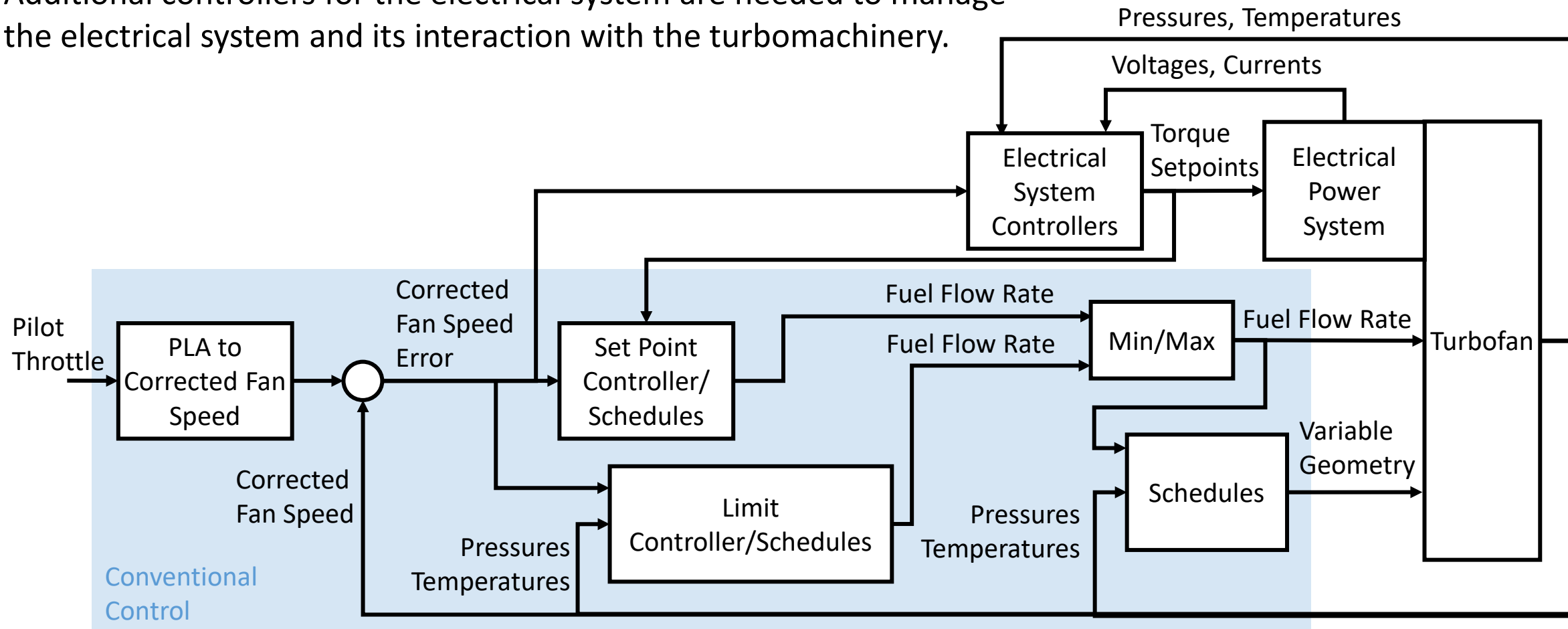
- Conventional control are typically scheduled proportional-integral controllers.
- Additional controllers for the electrical system are needed to manage the electrical system and its interaction with the turbomachinery.



Shaft Speed, Limits, Schedules

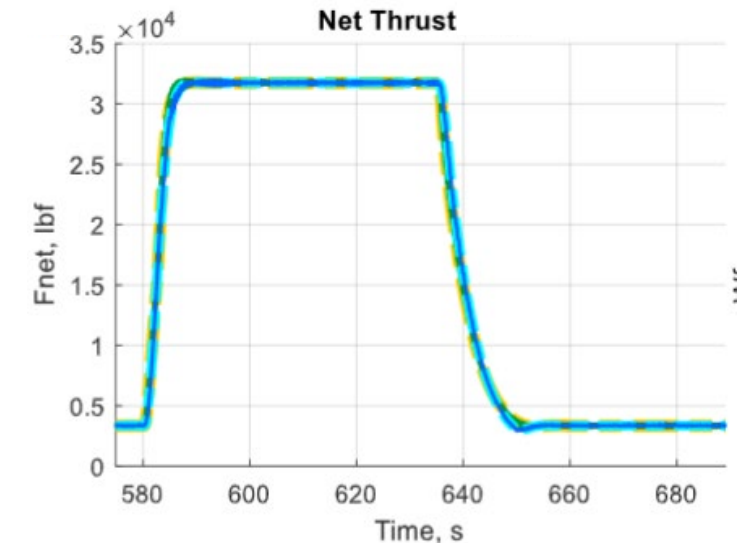
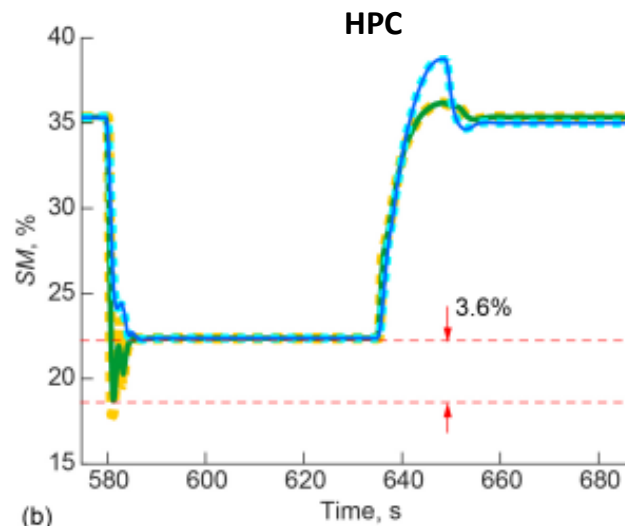
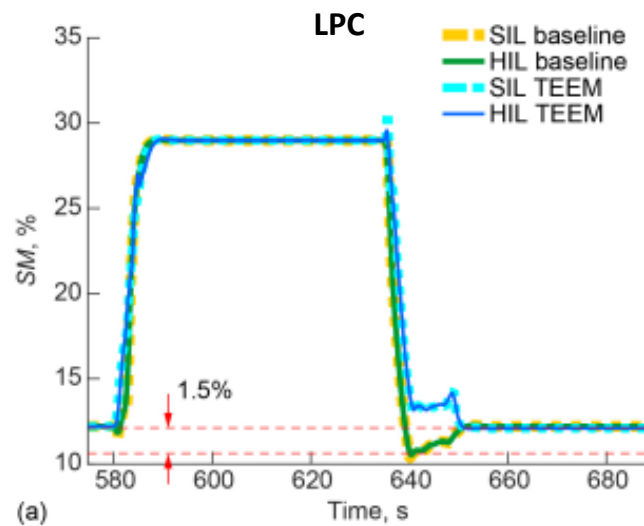
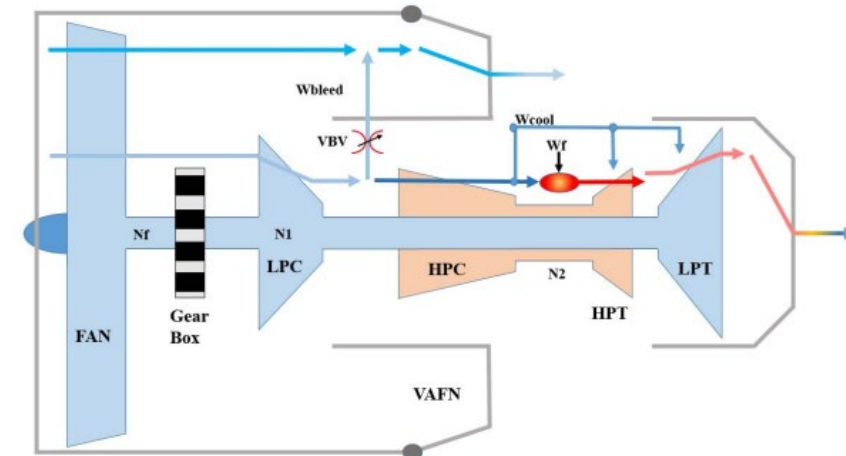
Hybrid Electric Turbofan Control System

- Conventional control are typically scheduled proportional-integral controllers.
- Additional controllers for the electrical system are needed to manage the electrical system and its interaction with the turbomachinery.

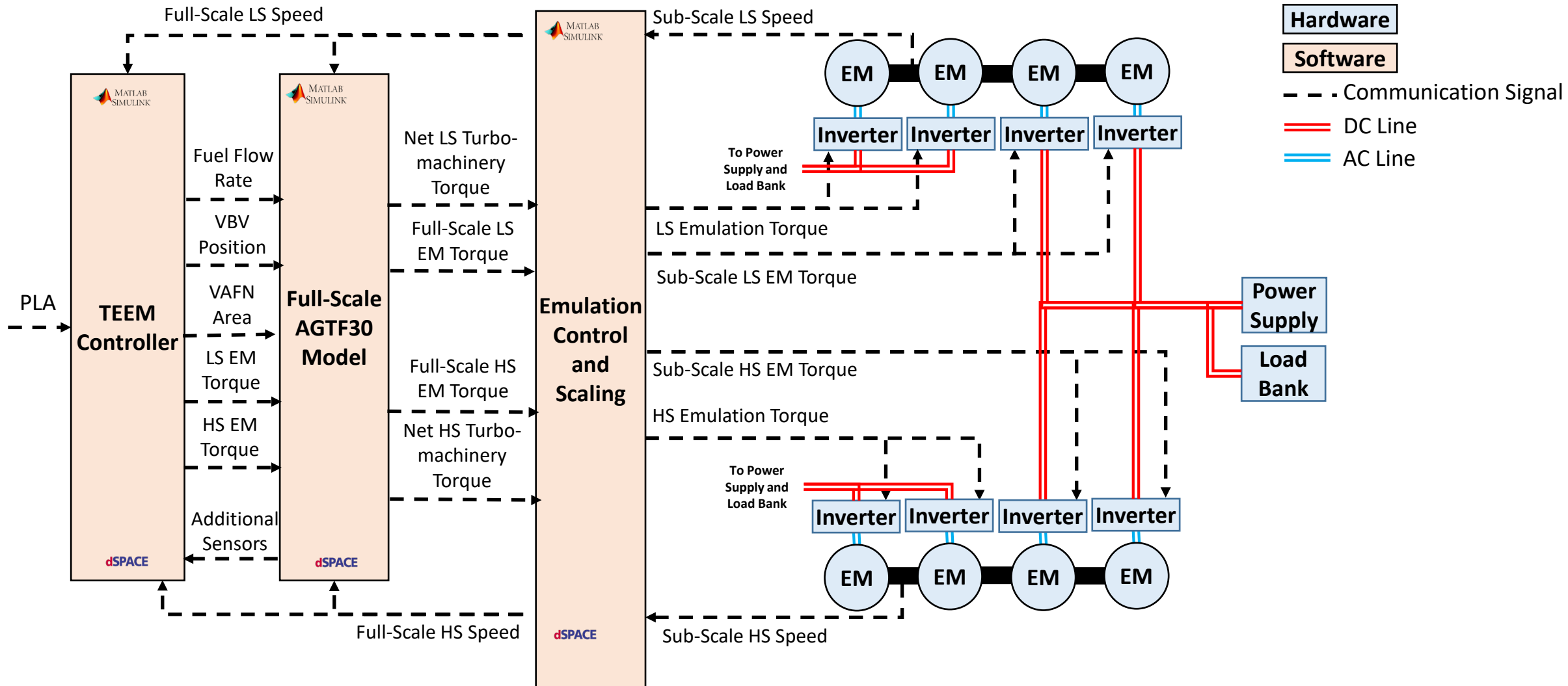


HIL Controller Testing at NEAT – AGTF30e - 1

- Tested conceptual parallel hybrid engine controller.
- Electrified Advanced Geared TurboFan 30000 (AGTF30e)
- Turbine Electrified Energy Management (TEEM)
- Megawatt scale equipment.

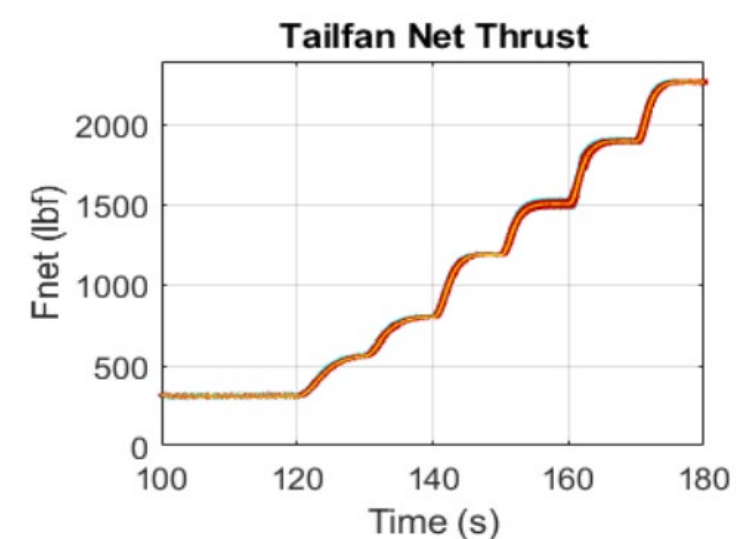
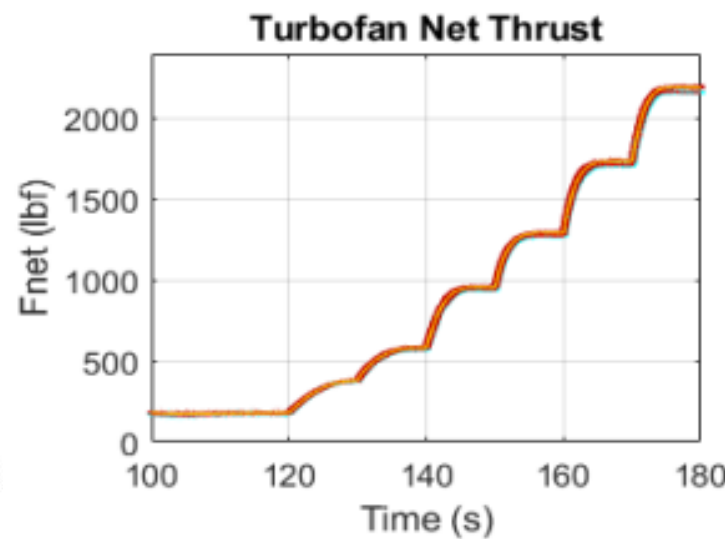
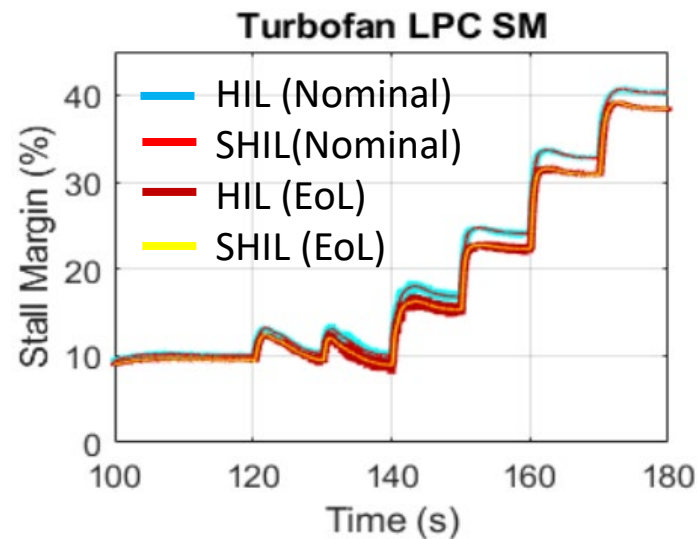
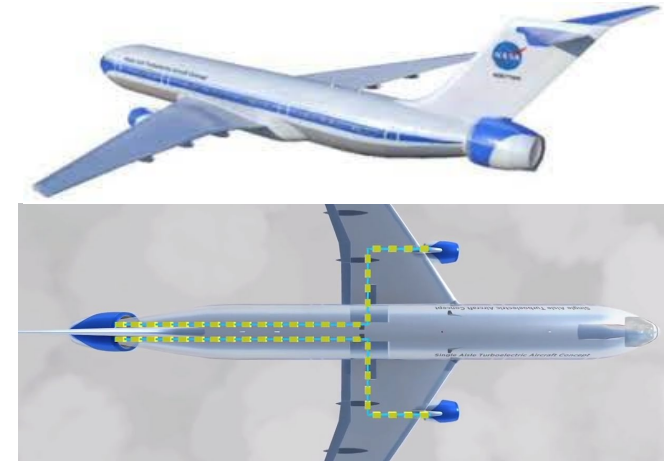


HIL Controller Testing at NEAT – AGTF30e - 2



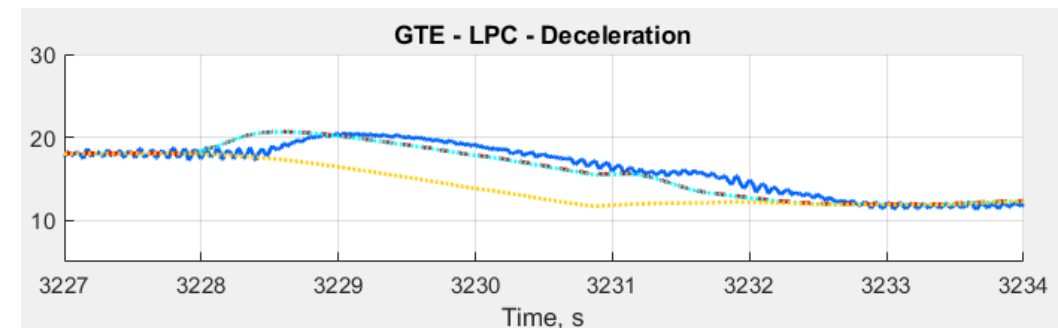
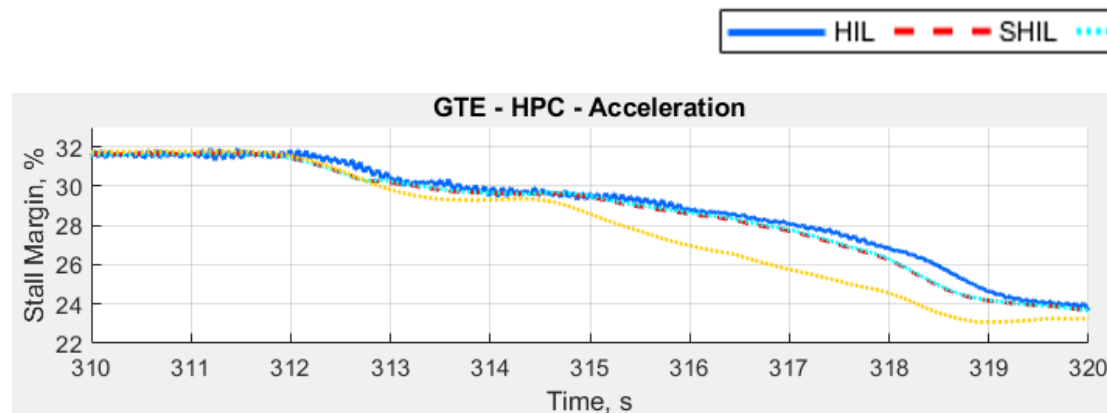
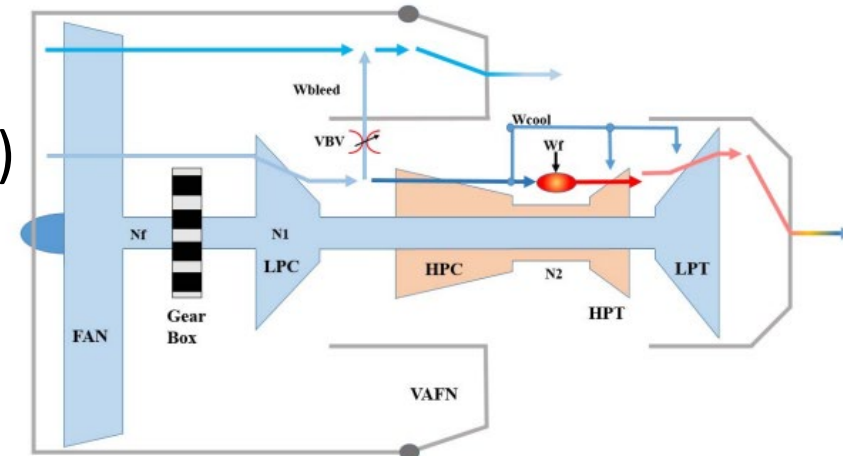
HIL Controller Testing at NEAT – STARC-ABL

- Tested conceptual turboelectric aircraft propulsion system controller.
- Single aisle Turboelectric AiRCraft with Aft Boundary Layer propulsion (STARC-ABL)
- Megawatt scale equipment.

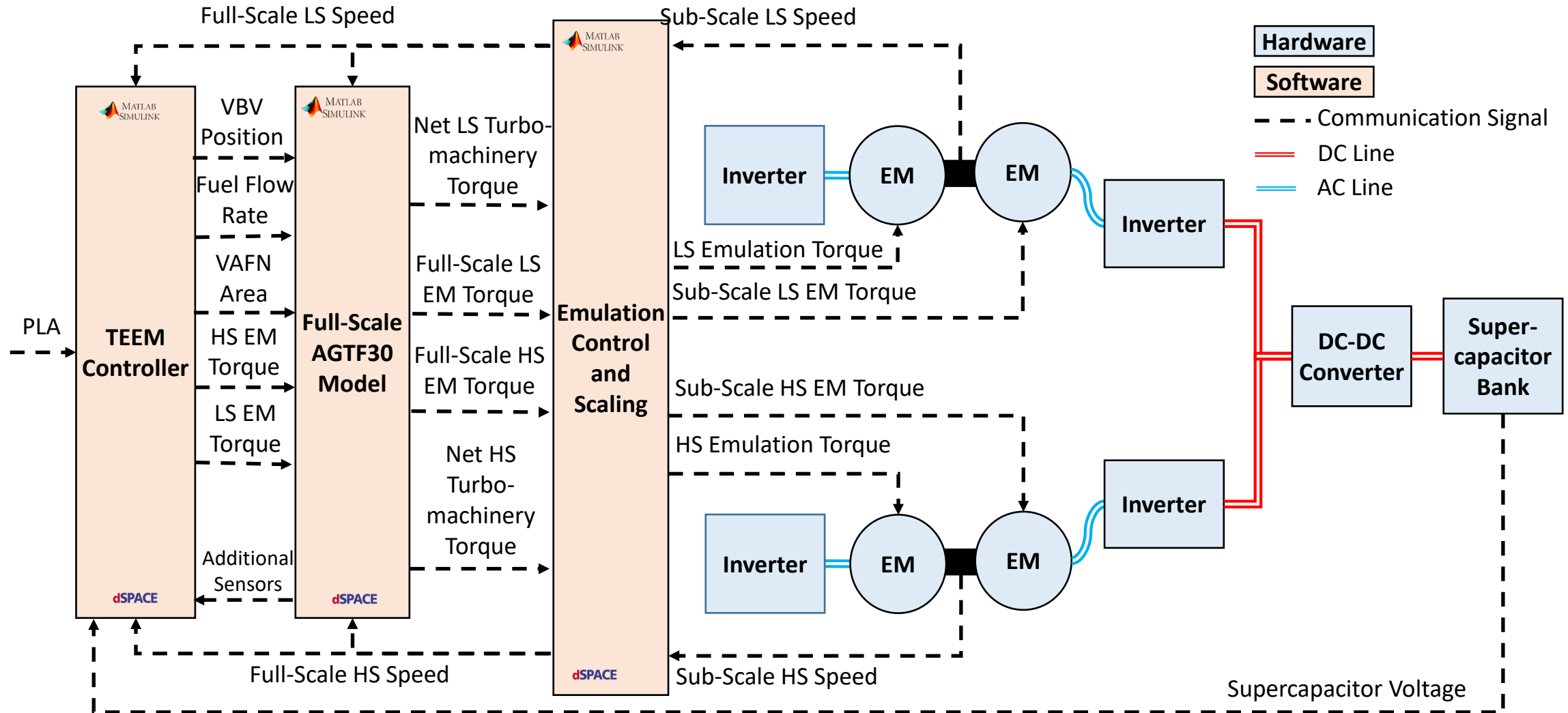


HIL Controller Testing at HyPER - 1

- Tested conceptual parallel hybrid engine controller.
- Electrified Advanced Geared TurboFan 30000 (AGTF30e)
- Turbine Electrified Energy Management (TEEM)
- Kilowatt scale equipment.
- Energy storage present.

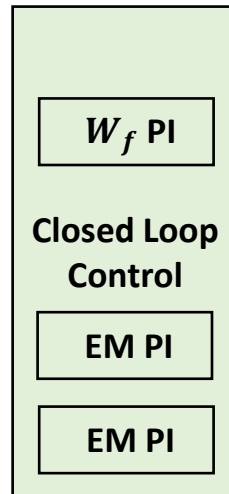
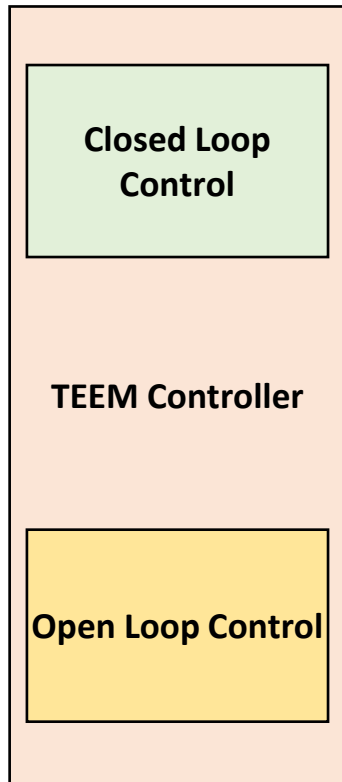


HIL Controller Testing at HyPER - 2

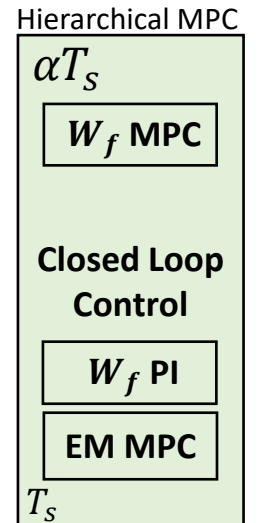
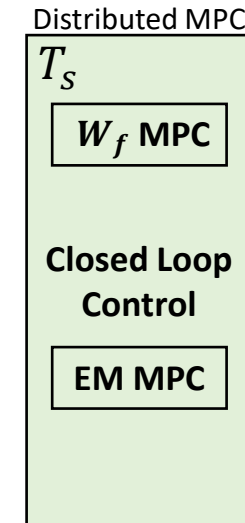
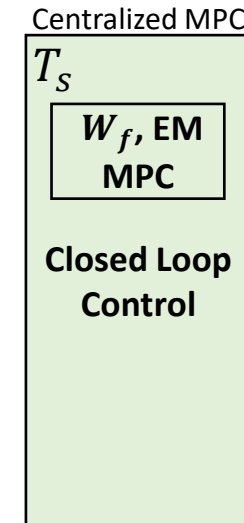
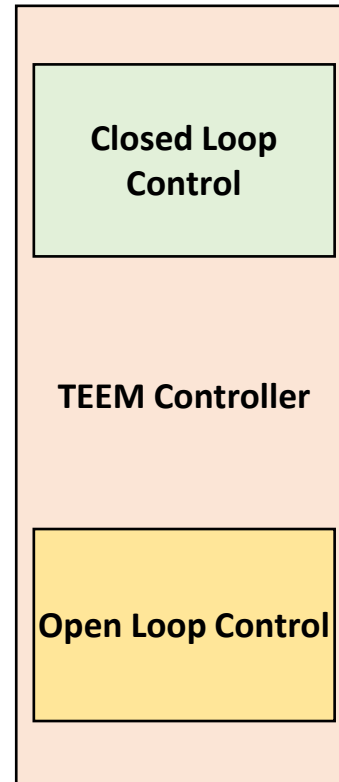


HIL Controller Testing at HyPER - 3

Standard Control Approach using proportional-integral (PI) controllers.



Model-based Control Approach using model predictive controllers (MPC).



Designed with:

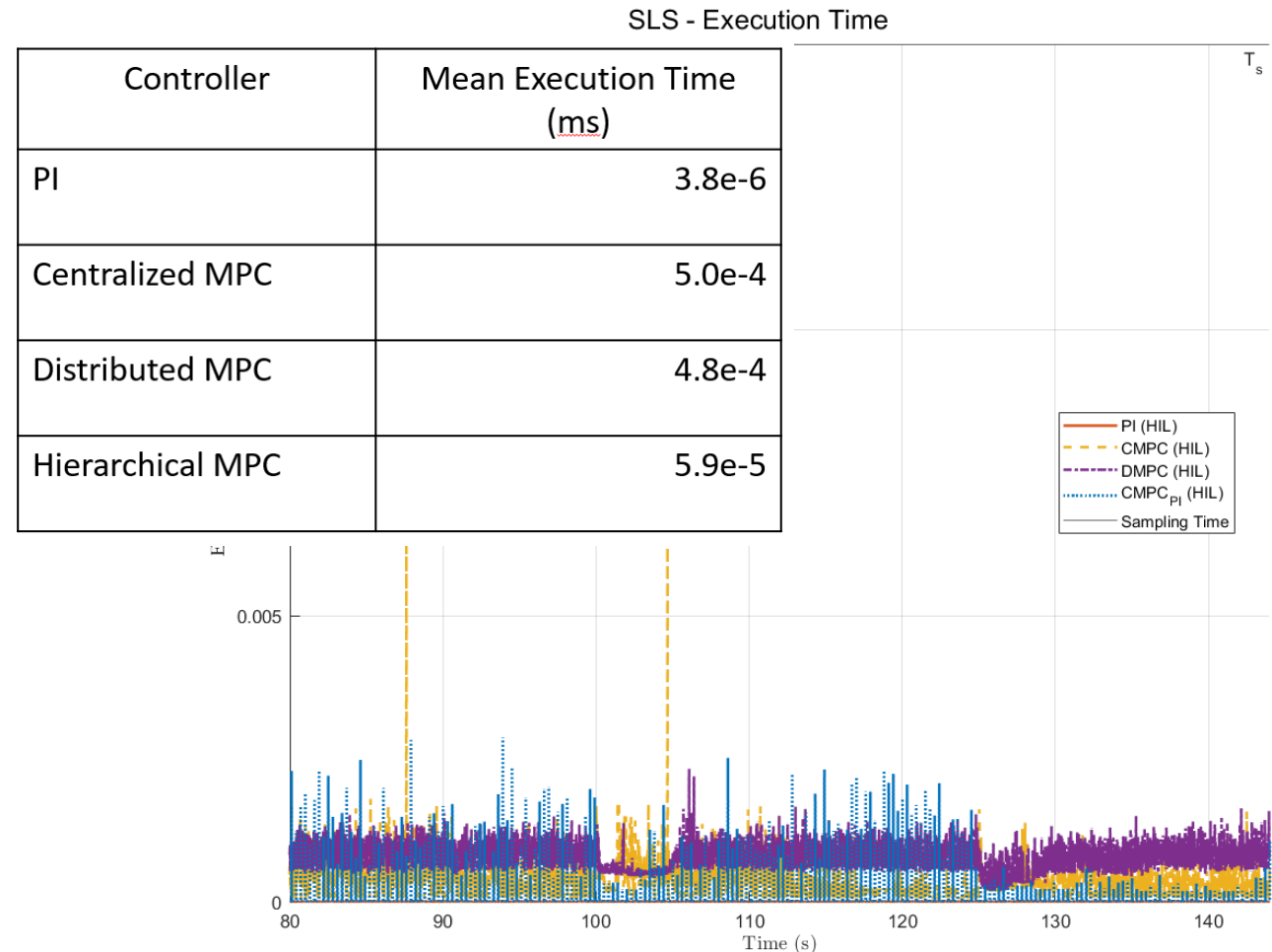
- Piecewise linear state-space model.
- Tracking and energy management goals.
- *fmincon* with 'sqp' solver.

HIL Advanced Controller Considerations

- Code Generation limits Matlab functions.
 - MPCs implemented with *fmincon* via MATLAB Function block.
 - Code generation limits solver selection to '*sqp*' or '*sqp-legacy*'. Refer to documentation.
- Horizon length could cause overruns. MPC architecture can mitigate computational issues.

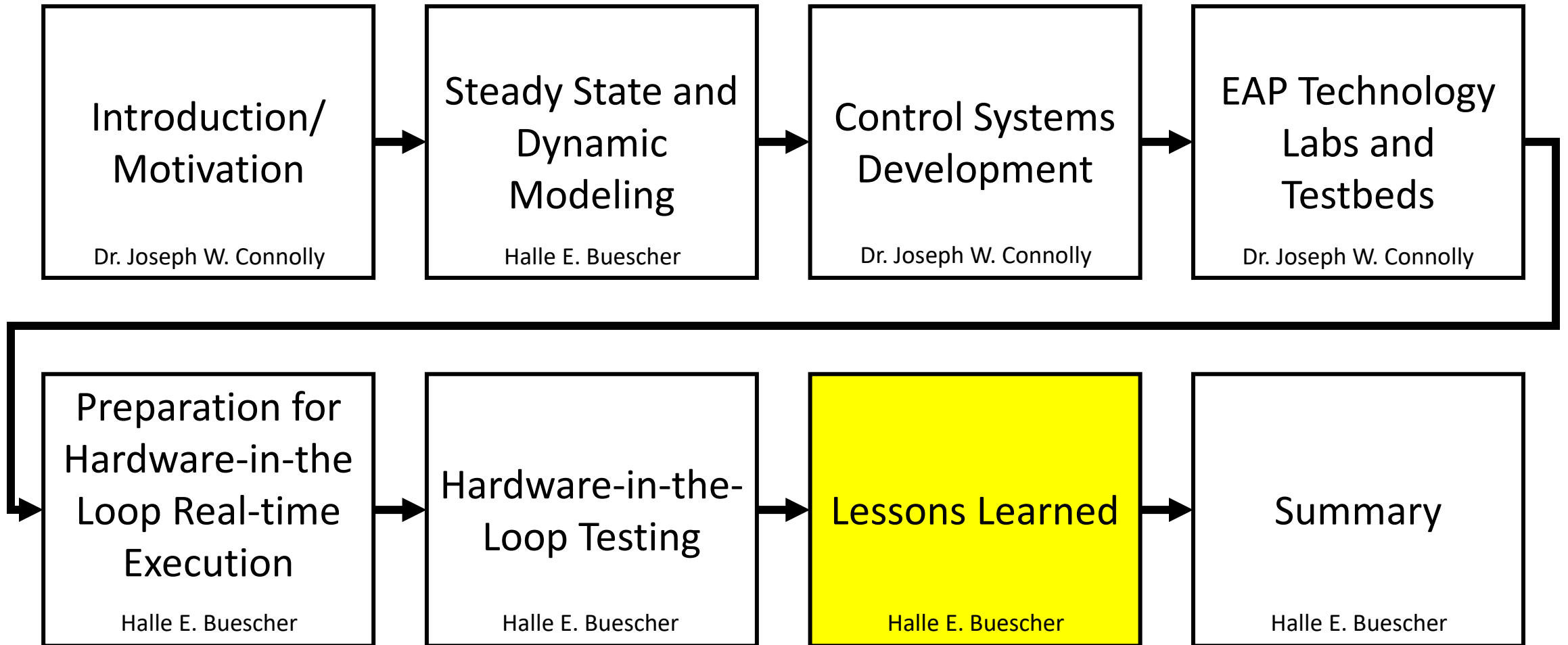


Hill, E., et. al., "A Comparison of Model Predictive Control Architectures for Application to Electrified Aircraft Propulsion Systems," ASME Turbo Expo 2024.





Scope





Lessons Learned

1. **Modeling:** When simulating dynamic models in real-time, noise, computational load, and non-ideal hardware operation can negatively impact simulations.
2. **Interface documentation:** As a result of modular facilities, the integration of facility equipment with a test article can be a difficult process without clear interface and procedural documentation.
3. **Step-wise approach:** Developing control algorithms earlier on in the system design process may lead to improvements in performance and operability. This is best done through simulation-in-the-Loop, then simulated hardware-in-the-loop, and finally hardware-in-the-loop.
4. **Hardware choices:** When using unidirectional power supplies in a test facility, unused power must be dissipated through resistive banks after testing. The benefit of using bidirectional power supplies is the unused power can be returned to the grid after use.
5. **Electrical integration:** The impedances from high power components such as electric machines, drives, energy storage devices, and power converters alter the power quality and stability of a common electrical bus.

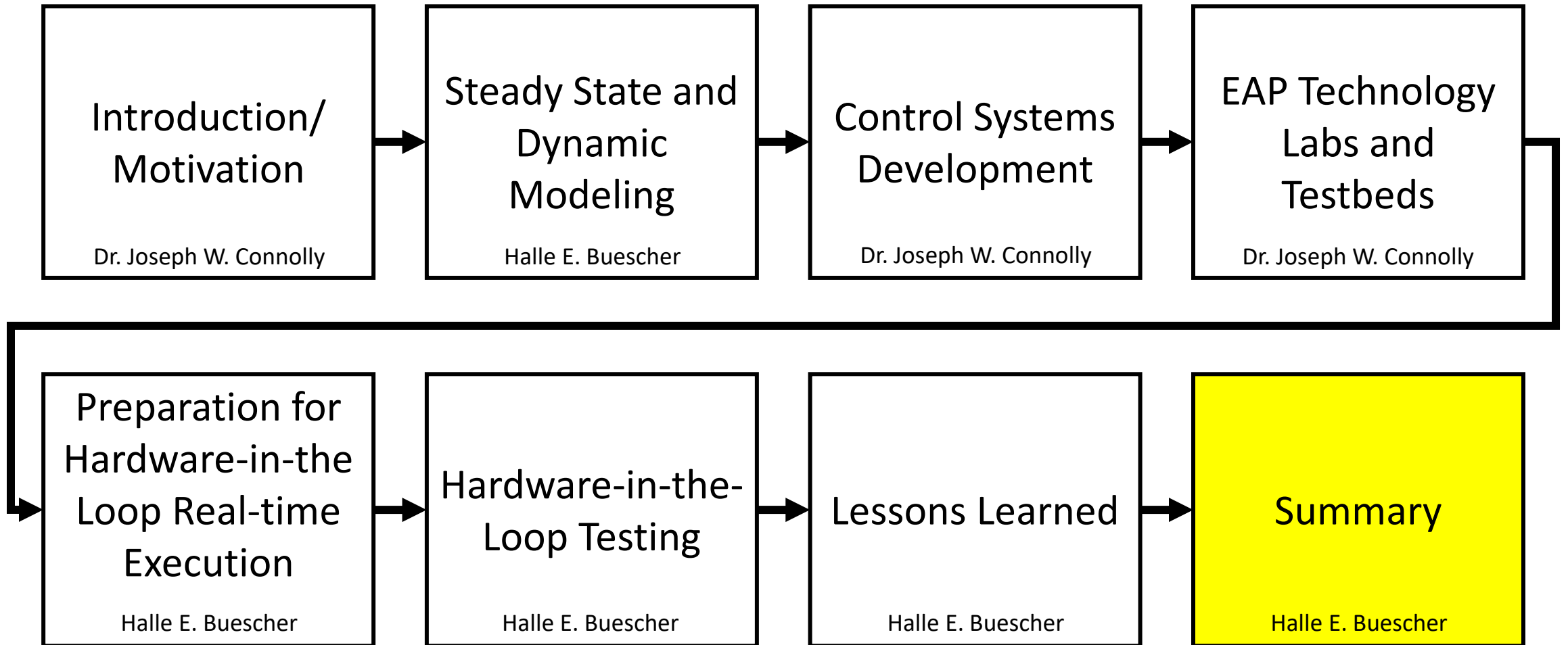
Next steps

Once a technology has been demonstrated in HIL environment...

- Government investments are more informed
- Focus areas for risk reduction
- Industry partners and internal work



Scope





Summary

- Hybrid-electric aircraft systems require multi-discipline engineering solutions.
- Modeling hybrid-electric architectures can be done with various tools such as NPSS, T-MATS, TSAT, TCML, and EMTAT.
- Complex, integrated systems require advanced control. These controllers can be developed earlier on in the design process. Hybrid-electric control considers performance, operability, system limits, and energy management.
- 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.
- NASA's NEAT facility can test full-scale HIL at altitude.
- NASA's HyPER facility can test sub-scale HIL using energy storage.

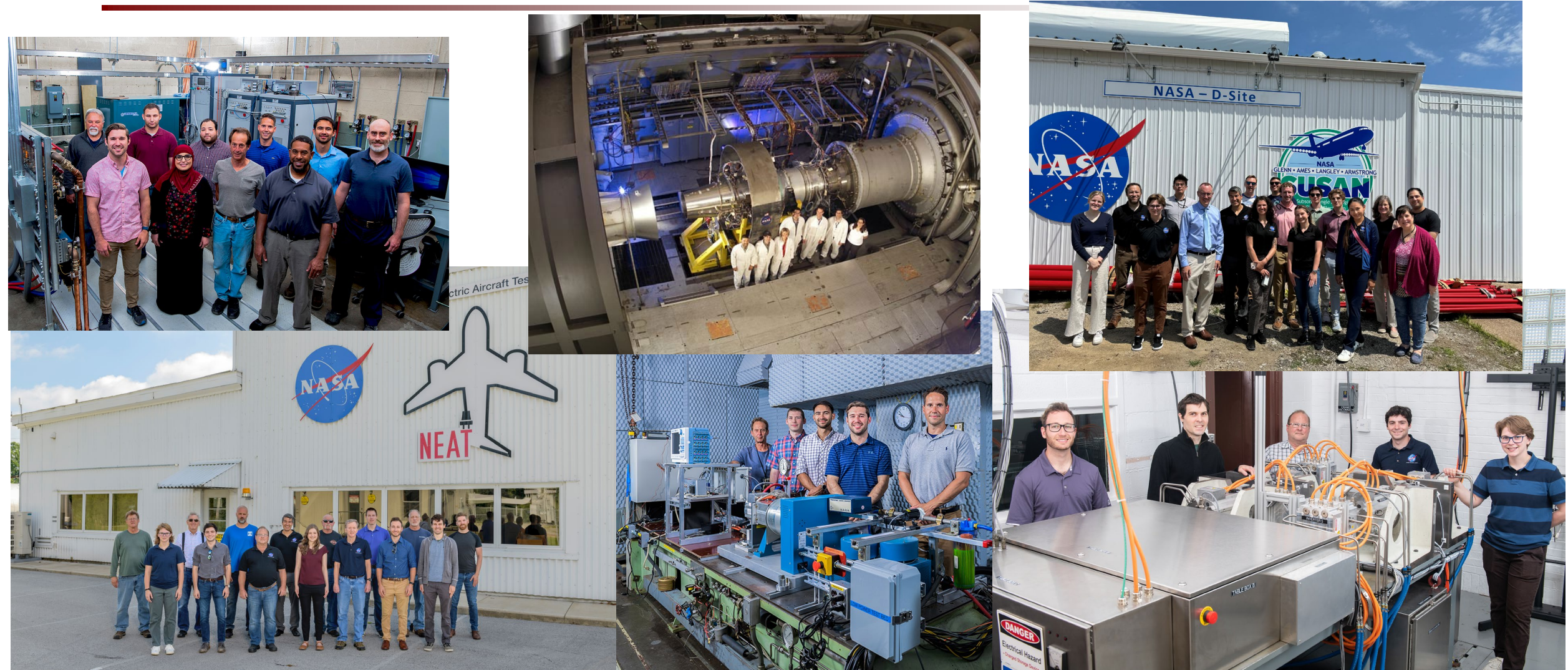


References

- [1] Lytle, J., "The Numerical Propulsion System Simulation: An Overview," NASA/TM-2000-209915, 2000.
- [2] Chapman, J., Lavelle, T., May, R., Litt, J., and Guo, T.-H., "Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) User's Guide," NASA TM-2014-216638, 2014.
- [3] Jones, S., Haller, W., Tong, M., "An N+3 Technology Level Reference Propulsion System," NASA/TM-2017219501, 2017.
- [4] Chapman, J., Litt, J., "Control Design for an Advanced Geared Turbofan Engine," AIAA Joint AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Atlanta, GA, 2017.
- [5] Jaw, L., and Mattingly, J., Aircraft Engine Controls: Design, System Analysis, and Health Monitoring, AIAA Educational Series, AIAA, Virginia, 2009.
- [6] May, R., Csank, J., Litt, J., and Guo, T.-H., "Commercial Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k) User's Guide, NASA TM-2010-216831, 2010.
- [7] Kratz, J., "The Advanced Geared Turbofan 30,000 lbf – electrified (AGTF30-e): A Virtual Testbed for Electrified Aircraft Propulsion Research", AIAA Aviation Forum, 2024. (accepted pending publication)
- [8] Culley, D., Kratz, J., and Thomas, G., "Turbine Electrified Energy Management (TEEM) for Enabling More Efficient Engine Designs," AIAA 2018-4798, Joint Propulsion Conference, Cincinnati, OH, July, 2018.
- [9] Kratz, J. L., Culley, D. E., and Thomas, G. L., "A Control Strategy for Turbine Electrified Energy Management," AIAA Propulsion and Energy Forum, Indianapolis, IN August 19-22, 2019.



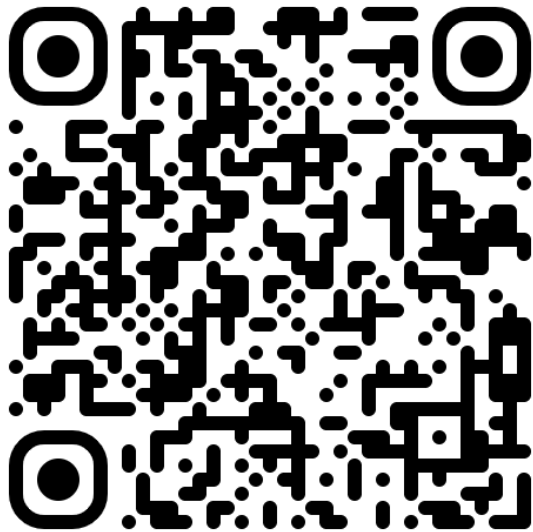
Thanks to the NASA EAP Team



Acknowledgements

- All of the engineers presenting are and much of the work presented in this tutorial was funded by the **NASA Hybrid Thermally Efficient Core (HyTEC)** project and **Transformational Tools and Technologies (TTT)** project and **Electrified Powertrain Flight Demonstration (EPFD)** project.

HyTEC



EPFD



TTT







Backup

HIL Controller Testing at NEAT – STARC-ABL - 2

