



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

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Audience and Description

Audience:

- Multidiscipline engineers supporting ***Sustainable 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

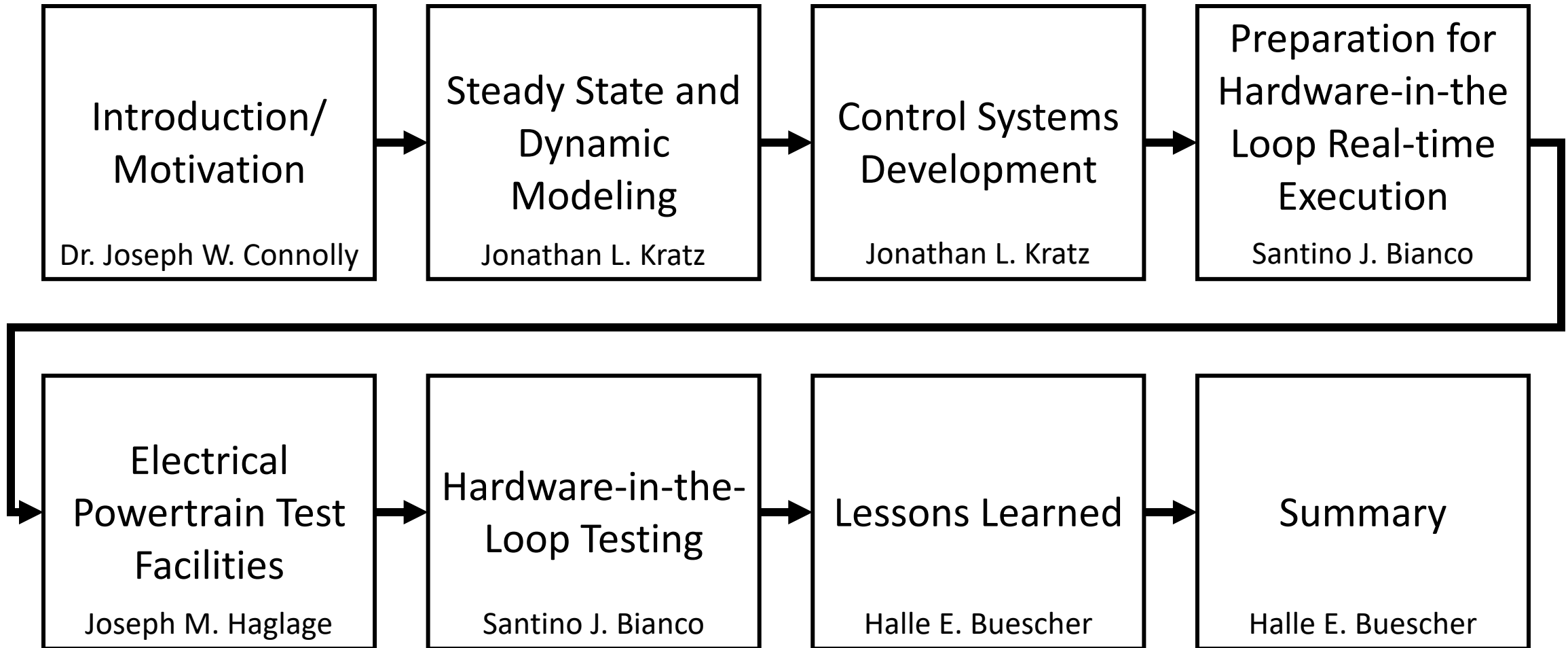


Learning Objectives

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

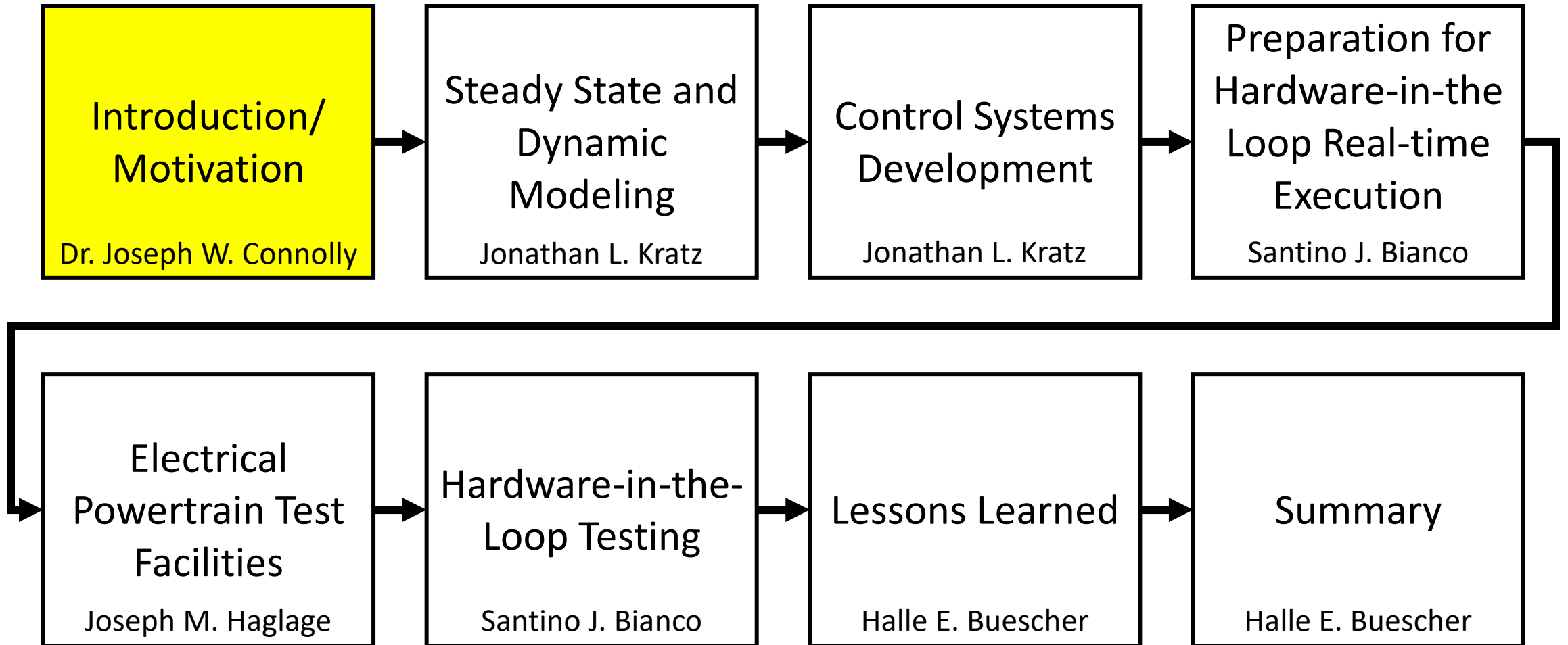


Scope





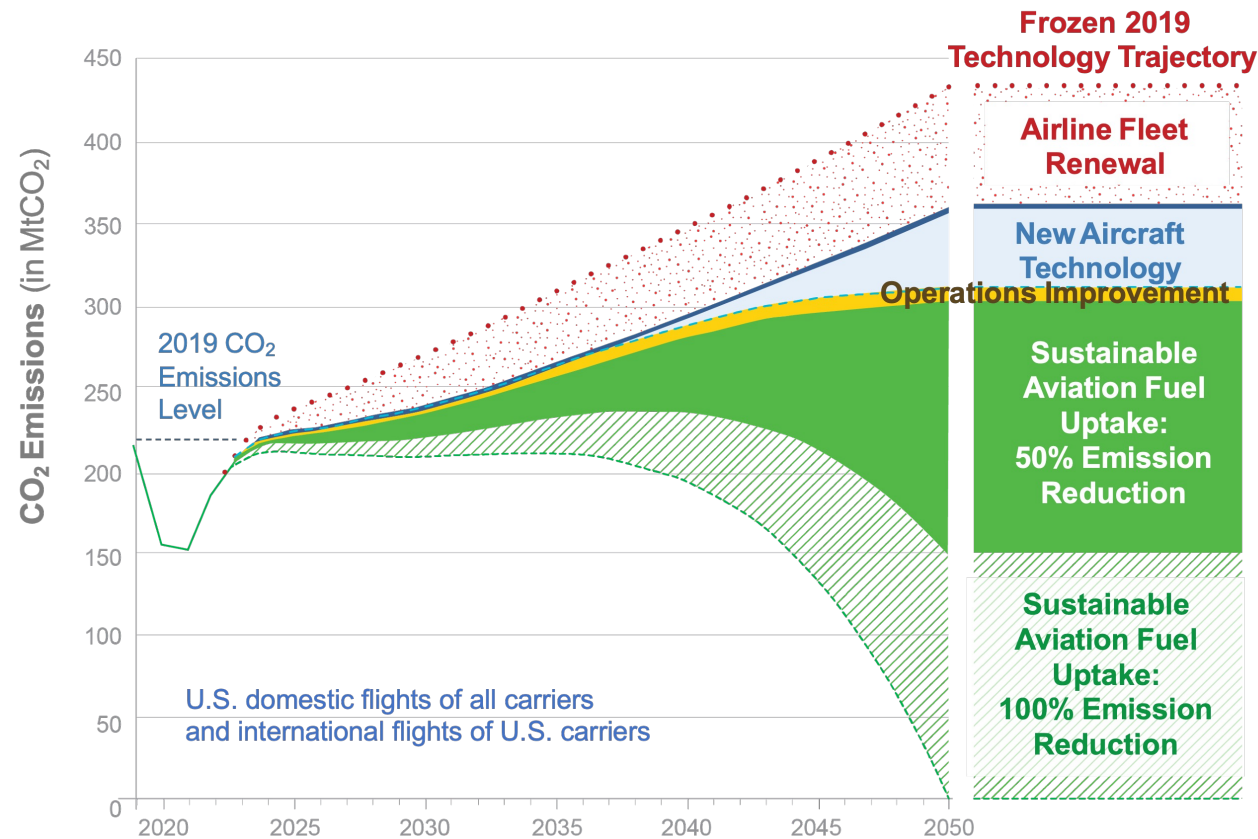
Scope



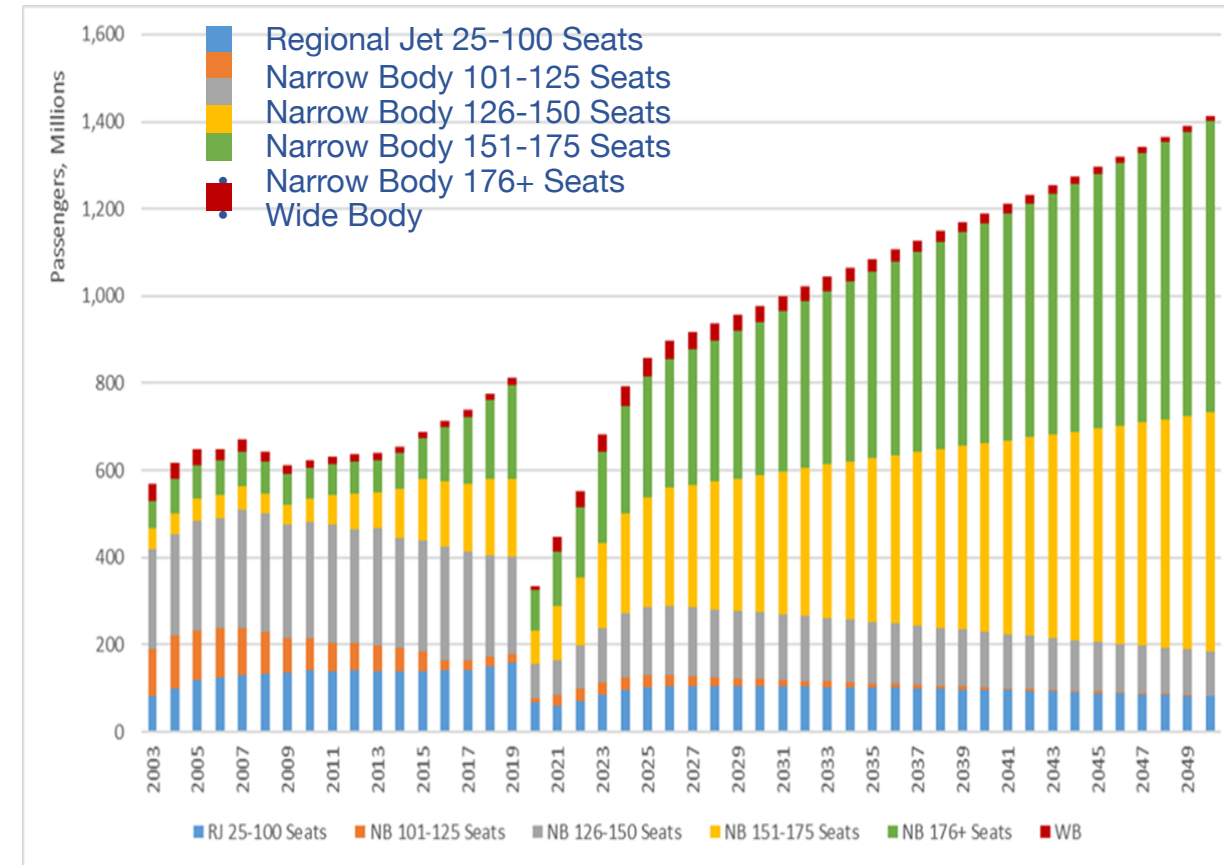
Introduction/Motivation - Climate

U.S. Aviation Climate Action Plan - 2021

Global Context for Sustainable Aviation



https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf



Fleet size category forecast to 2050

Introduction/Motivation - Hybrid

Evolution of Electrified Aircraft Propulsion with Advances in Battery Technology

- Pack specific energy
- Notional specific energy for each class of aircraft

Single-aisle, 737 class



1000 Wh/kg

Regional



500 Wh/kg



50 – 70 PAX

400 Wh/kg

20 PAX
commuter



200 -250 miles



eVTOL

100 miles

20 PAX
commuter



100 miles



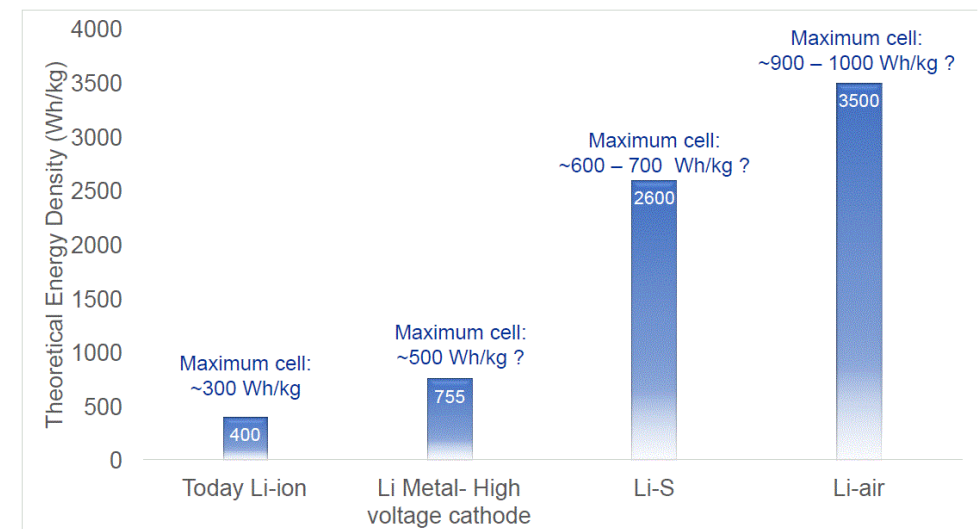
eVTOL

25-50 miles

300 – 350 Wh/kg

Current, 170-200 Wh/kg

Beyond Li - Ion



Near term

Far Term

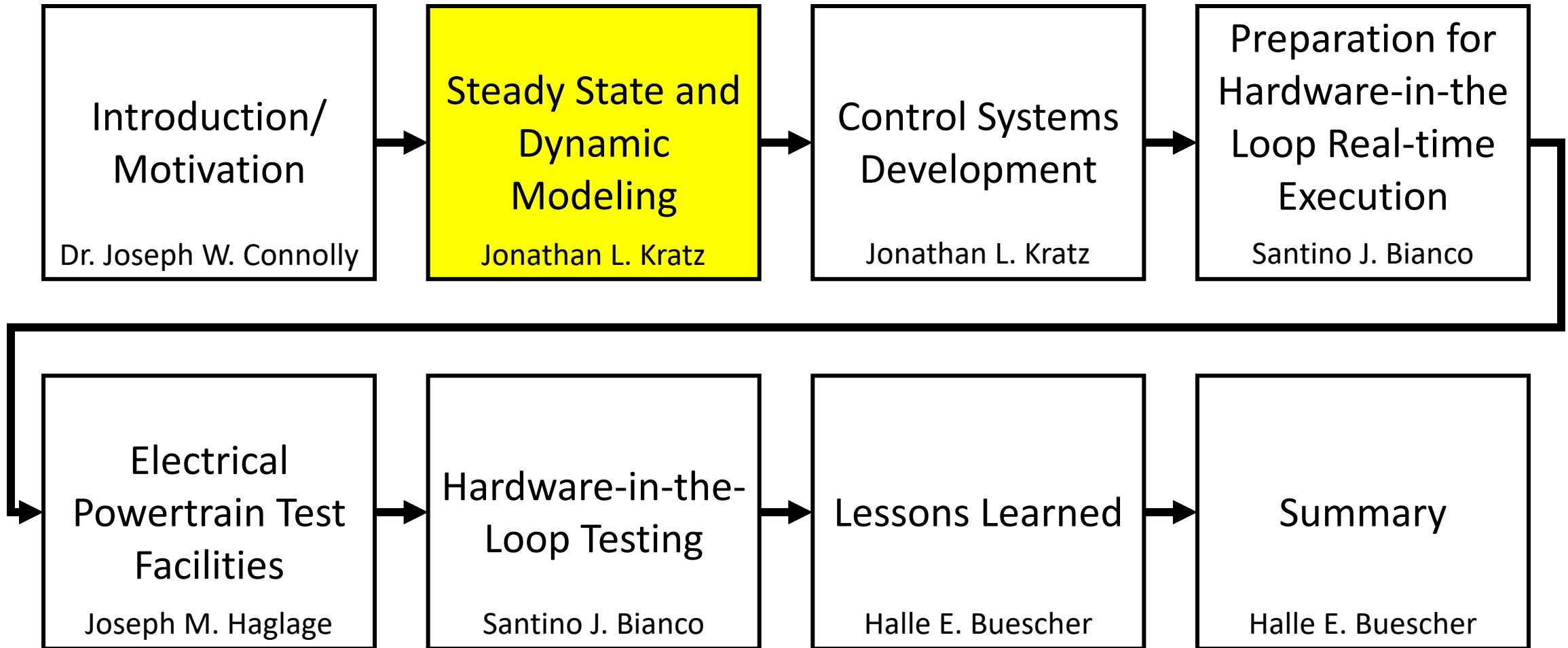


Introduction/Motivation - Tutorial

- 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



Gas Turbine Engine Modeling Tools

Numerical Propulsion Systems Simulation (NPSS)

- C++
- Non-linear thermodynamic modeling environment.
- Used for the development and assessment of engine designs and performance.

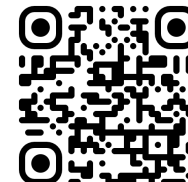


NPSS to T-MATS Conversion Tool

- MATLAB/Simulink
- Finds required information in NPSS model files to parameterize T-MATS Simulink model.

Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)

- MATLAB/Simulink
- Modular dynamical modeling tool for gas turbine engines.
- Used to develop propulsion control systems.
- <https://github.com/nasa/T-MATS>



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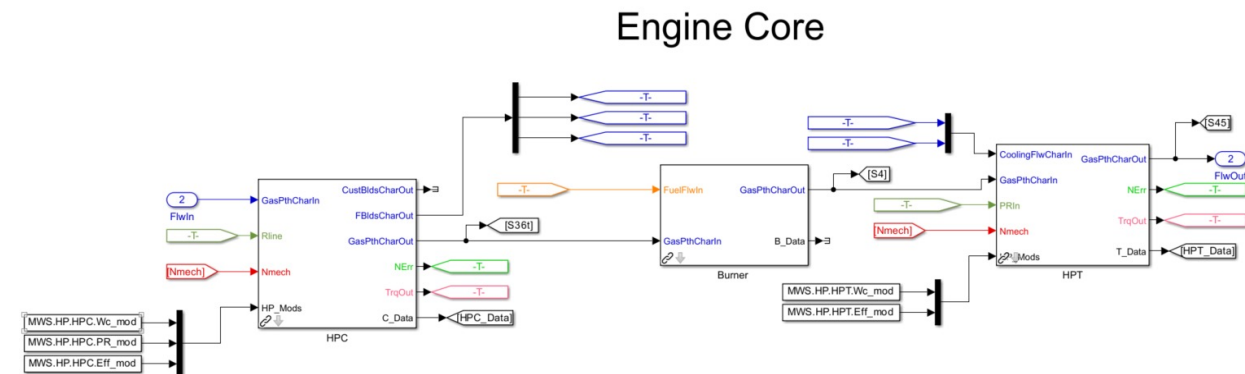
NPSS & T-MATS

NPSS

- Developed in 1995, largely through the role
- Became and remains a standard tool used in propulsion system modeling
- Currently curated by the Southwest Research Institute (SwRI)
- Modular extensible framework for the integration of multicomponent, multidisciplinary analysis tools
- Coded in C/C++
- Gas Turbine Engine (GTE) models: typically consists 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

T-MATS

- Developed in 2014
- 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



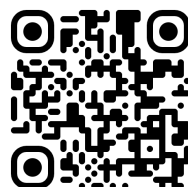
Dynamical Modeling Tools

- Important dynamical phenomenon to consider:

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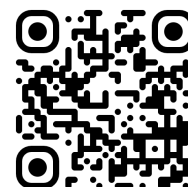
T-MATS

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



Thermal Systems Analysis Toolbox (TSAT)

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

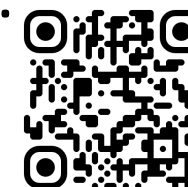


Tip Clearance Modeling Library (TCML)

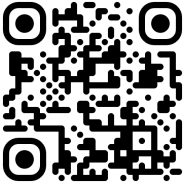
- MATLAB/Simulink
- **Tip clearance variations** as a result of centrifugal forces and thermal deformation
- **Effect on engine cycle**

Electrical Modeling and Thermal Analysis Toolbox (EMTAT)

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

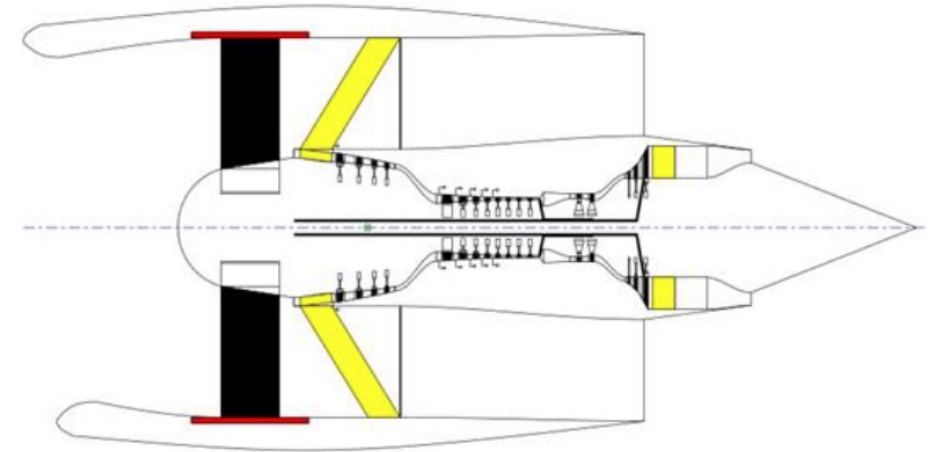
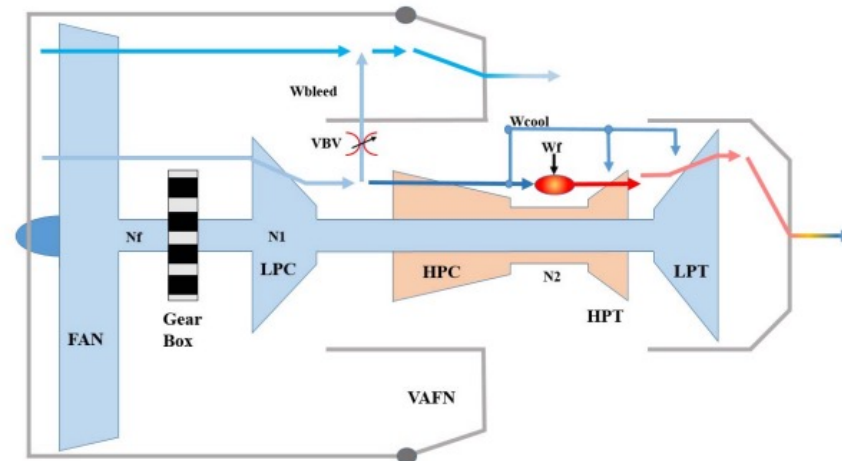


Conceptual Advanced Turbofan Model



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.)



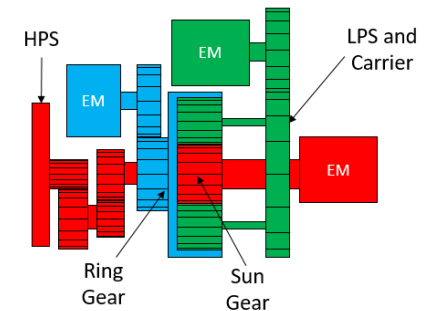
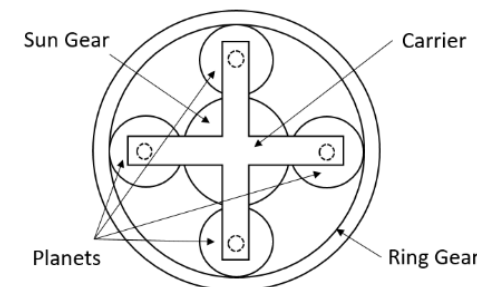
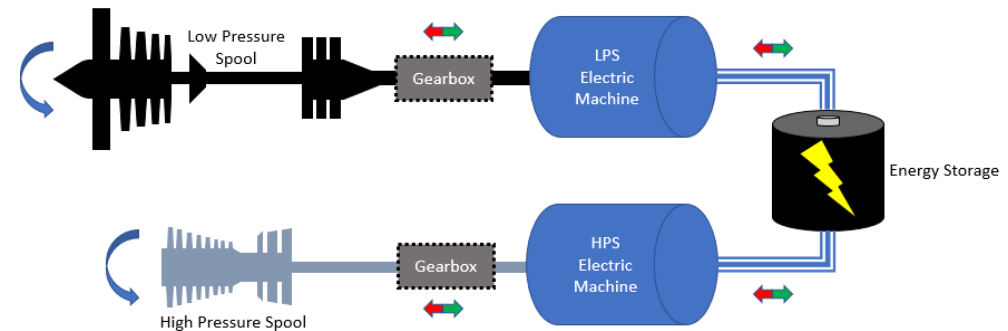
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Electrified Advanced Turbofan Model

Advanced Geared TurboFan 30,000 lbf – electrified (AGTF30-e)

- Builds on the AGTF30
- Primary mode of operation
 - Standard/conventional engine
 - Boost mode (parallel hybrid)
 - Power Extraction (PEX) mode (turboelectric)
- Secondary electrification options
 - Electric power transfer (EPT) – low engine power electric power transfer to reduce fuel burn
 - Turbine electrified energy management (TEEM) – electric power injection/extraction/transfer on the shafts to improve operability
 - Charging – charging or discharging of energy storage to achieve the desired state of charge (SOC) during the mission.
- Engine – EM integration options
 - Dedicated EM (DEM) approach – each shaft has a dedicated EM connected through a gearbox
 - Versatile Electrically Augmented Turbine Engine (VEATE) Planetary Gearbox (PGB) approach – one or more EMs are connected to the engine shafts through a PGB
- Simple electrical power system model framework
- Revamped, versatile control implementation

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***EM = electric machine**





Example of using the AGTF30-e

```
inputMethod = 2; % use excel spreadsheet
In = []; % empty array for now
filename = 'AGTF30e_Inputs.xlsx'; %file to derive inputs from
Mdl = 1; % dynamic model
SSsolverSP = 2; % doesn't matter, not using steady-state model
dem = []; % empty array - use default values
veate = []; % empty array - use default values
MWS = Setup_Simulation(inputMethod,In,filename,Mdl,SSsolverSP,dem,veate);
```

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	AGTF30-e INPUTS												
2													
3	NOTE: ENTRIES BEYOND 10000 TIME INSTANCES ARE INVALID												
4													
5	Definitions:	EM - Electric Machine											
6		TEEM - Turbine Electrified Energy Management											
7		EPT - Electric Power Transfer											
8		LP - Low Pressure (refers to low pressure shaft along with LPS)											
9		HP - High Pressure (refers to high pressure shaft along with HPS)											
10													
11	Simulation Options												
12	Hybridization Option:	1	1 - Standard Engine, 2 - Boost, 3 - Power Extraction										
13	Engine-EM Integration Option:	1	1 - Dedicated EM approach, 2 - VEATE Gearbox approach										
14	VEATE Gearbox Option:	2	1 - HP Sun/LP Ring, 2 - HP Sun/LP Carrier, 3 - HP Ring/LP Sun, 4 - HP Ring/LP Carrier, 5 - HP Carrier/LP Sun, 6 - HP Carrier/LP Ring (NOTE: c										
15	Transient Limit Logic Option:	2	1 - Generic limiter, 2 - Ratio Unit limiter (designed for nominal power schedules defined with the model)										
16	TEEM Option:	0	0 - TEEM disable, 1 - TEEM enabled										
17													
18	ENGINE INPUT VARIABLES												
19	Altitude		Ambient Temp. Diff		Mach Number		Aircraft Power Load						
20	t_Alt	Alt	t_dTamb	dTamb	t_MN	MN	t_PExAC	PExAC	<-- variable names -->				
21	Time, s	Value, ft	Time, s	Value, °R	Time, s	Value	Time, s	Value, hp					
22	0	0	0	0	0	0	0	175					
23	10	0	10	0	10	0	10	175					
24													
25													
26													
27													
28													

Power Lever Angle		Boost Toggle	
t_PLA	PLA	t_Boost	Boost
Time, s	Value, deg	Time, s	Value, 0 or 1
0	40	0	0
10	40	10	0
10.015	80		
40	80		
40.015	40		
90	40		

% Options

```
MWS.In.Options.HybridConfig = 2; %1-Standard, 2-Boost, 3-PEx
MWS.In.Options.EngineEMInt = 1; %1-DEM, 2-VEATE-PGB
MWS.In.Options.PGBConfig = 2; %1-HP Sun, LP Ring, 2-HP Sun, LP Carrier
                                %3-HP Ring, LP Sun, 4-HP Ring, LP Carrier
                                %5-HP Carrier, LP Sun, 6-HP Carrier, LP Ring
MWS.In.Options.WfTransientLogic = 2; % 1-General Limiter, 2-Ratio Unit Schedule
MWS.In.Options.TEEM = 1; %0-disable TEEM, 1-Enable TEEM
```

% Environment Inputs

```
MWS.In.t_Alt = [0 10];
MWS.In.Alt = [0 0];
MWS.In.t_MN = [0 10];
MWS.In.MN = [0 0];
MWS.In.t_dTamb = [0 10];
MWS.In.dTamb = [0 0];
```

% Control Inputs

```
MWS.In.t_PLA = [0 20 20.015 40 40.015 90];
MWS.In.PLA = [40 40 80 80 40 40];
MWS.In.t_Boost = [0 3 3.015 60 60.015 90];
MWS.In.Boost = [0 0 1 1 0 0];
MWS.In.t_Charge = [0 70 70.015 90];
MWS.In.Charge = [0 0 1 1];
MWS.In.t_EPT = [0 55 55.015 70 70.015 90];
MWS.In.EPT = [0 0 1 1 0 0];
```

% Engine-EM Integration Specification

```
dem = [];
veate = [];
```

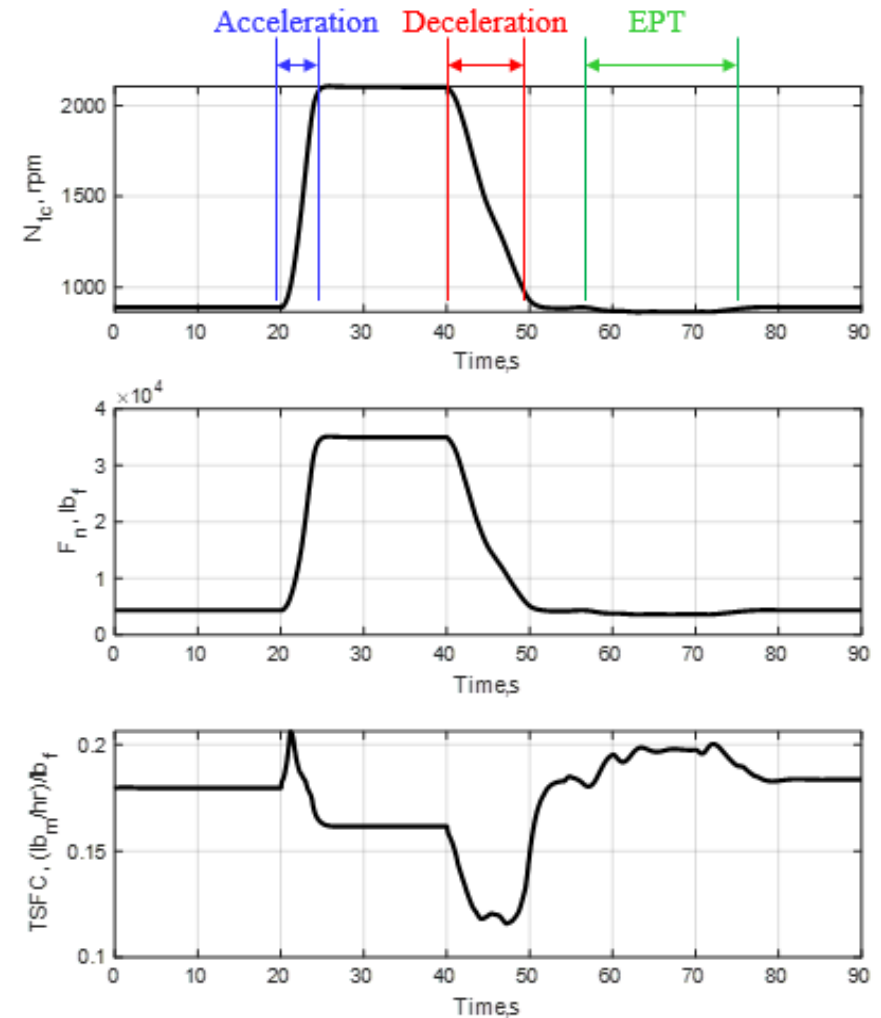
% Update MWS

```
inputMethod = 1;
MWS = Setup_Simulation(inputMethod,MWS.In,filename,Mdl,SSsolverSP,dem,veate);
```

Example of using the AGTF30-e

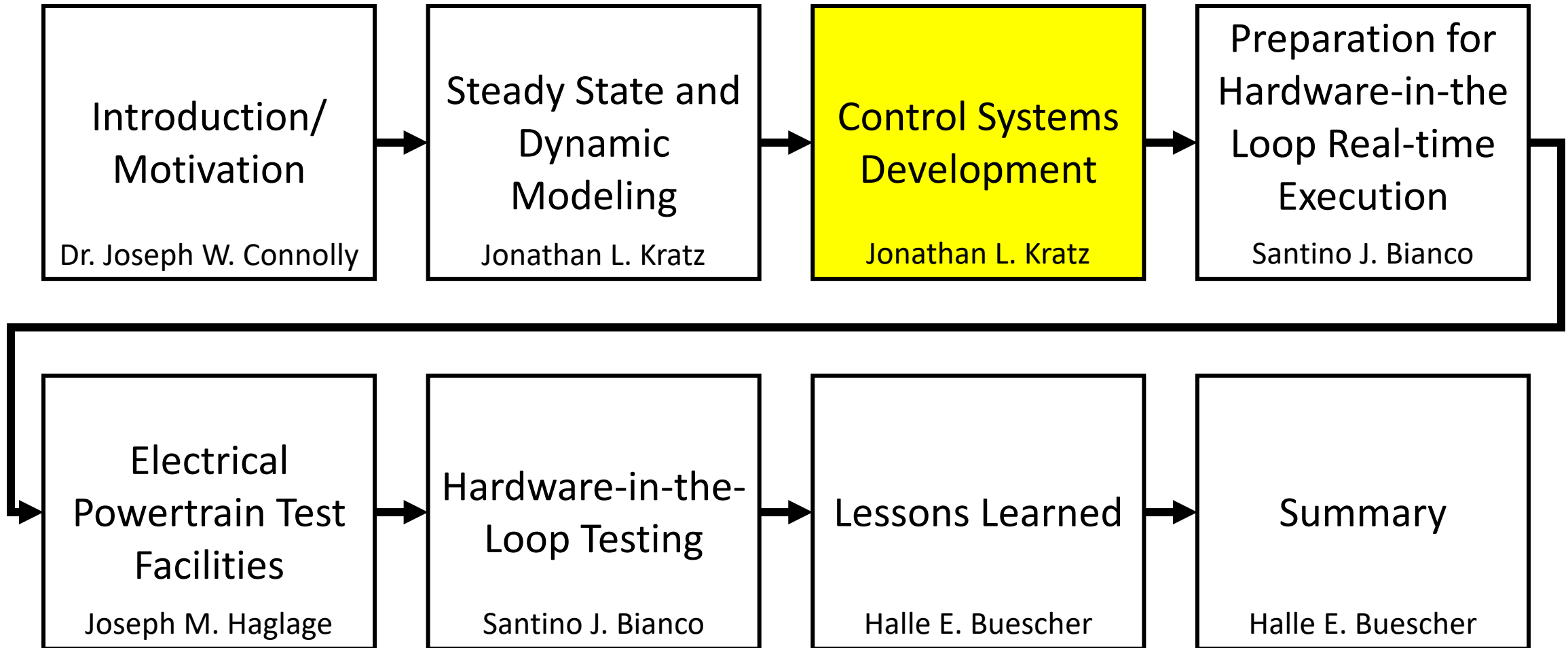
```
sim('AGTF30SysDyn_PExPIIn.slx');

% N1c, Thrust, TSFC
figure();
subplot(3,1,1);
plot(out_Dyn.eng.Data.FAN_Data.Nc.Time,out_Dyn.eng.Data.FAN_Data.Nc.Data,'-k','LineWidth',2)
xlabel('Time,s')
ylabel('N_{1c}, rpm')
grid on;
subplot(3,1,2);
plot(out_Dyn.eng.Perf.Fnet.Time,out_Dyn.eng.Perf.Fnet.Data,'-k','LineWidth',2)
xlabel('Time,s')
ylabel('F_n, lb_f')
grid on;
subplot(3,1,3);
plot(out_Dyn.eng.Perf.Fnet.Time,(out_Dyn.act.Wfact.Data*3600)./out_Dyn.eng.Perf.Fnet.Data,'-k','LineWidth',2)
xlabel('Time,s')
ylabel('TSFC, (lb_m/hr)/lb_f')
grid on;
```





Scope



Examples of Control Considerations

1. 0-95% 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.

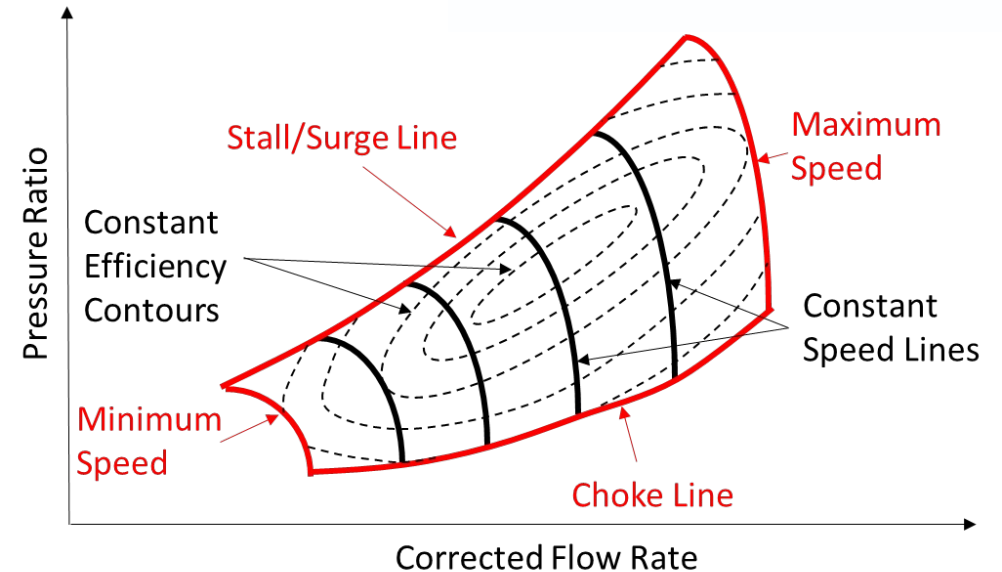
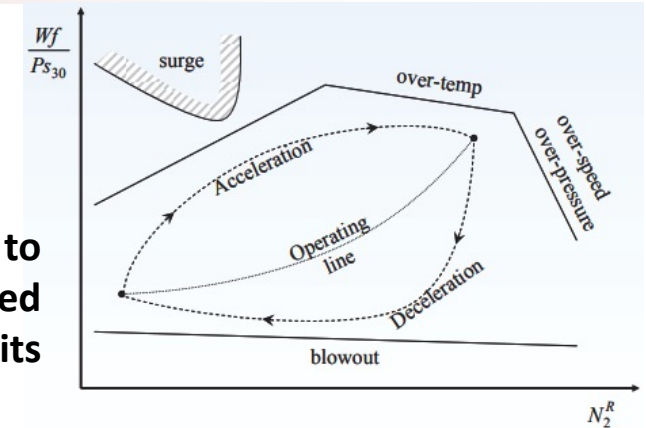
Performance

Operability

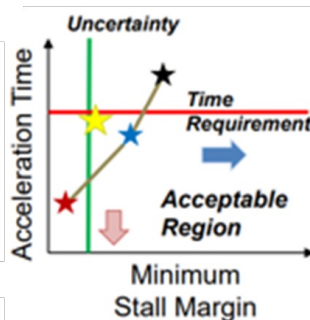
Limits

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

Traditional Control of Gas Turbine Engines

- Various actuation systems are common including:
 - Fuel metering value (FMV)
 - Variable stator vanes (VSVs) for HPC operability
 - A variable bleed valve (VBV) for LPC operability
 - Various bleeds such as for tip clearance management
 - Variable area nozzles (VANs) – common among military engines, a luxury concept for future low pressure ratio fans
 - An augmenter FMV – common among military engines
- Fuel flow rate is the primary means of controlling the engine power level. Closed loop control is utilized. In our practice ...
 - Typical control variables: corrected fan speed or engine pressure ratio (thrust is not measurable in-flight for feedback)
 - Classical proportional integral (PI) controllers are designed and employed for engine power management and limiters
 - Various limit controllers prevent their respective limits from being violated (over-speed, over-pressure, under-pressure, etc.)
 - A Min-Max controller selection logic is used to decide which controller command to use.
 - Integral windup protection is used to prevent the accumulation of excessive error while the controllers are not in use
- Other actuators tend to have open loop controllers with prescribed schedules
- Control law computation is accomplished through the Full Authority Digital Engine Controller (FADEC)

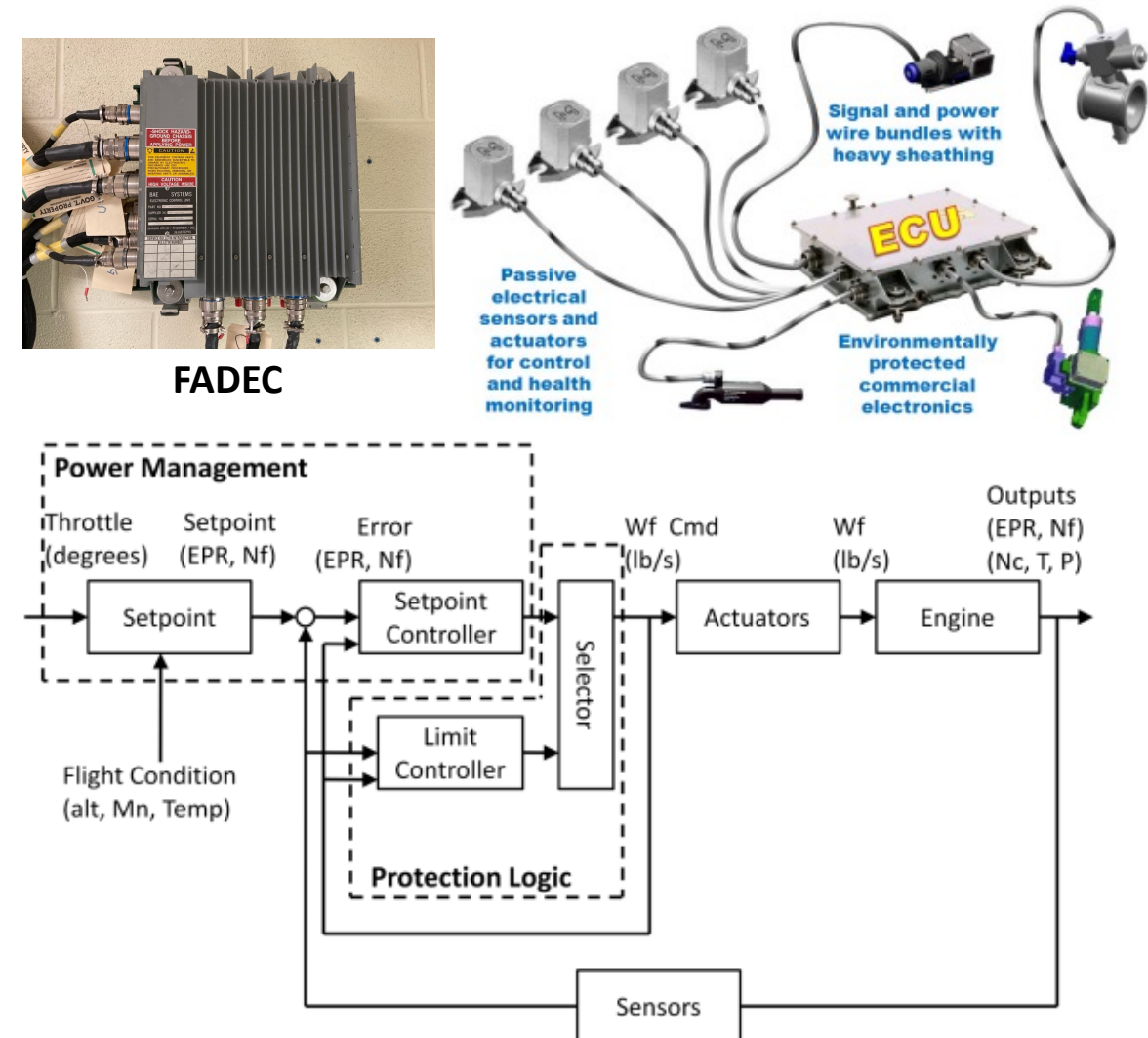


Figure 1.—Diagram of an Aircraft Engine Control System.

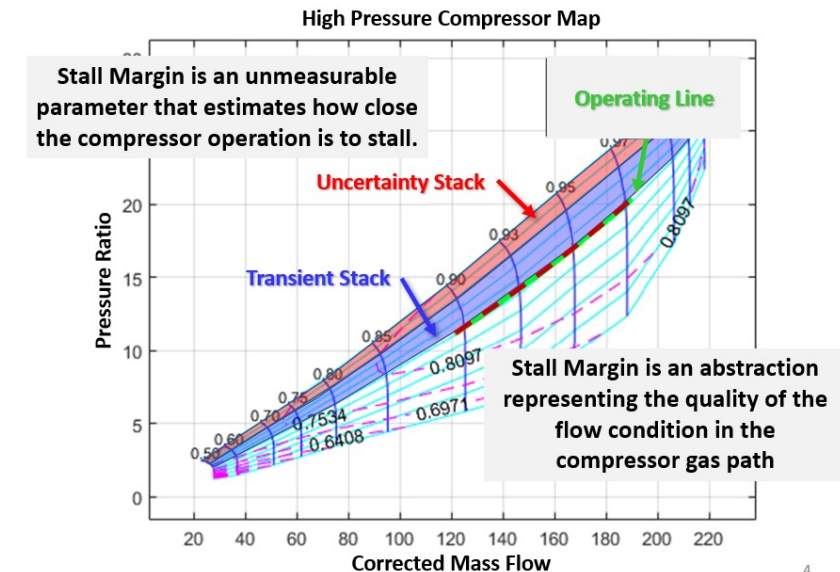
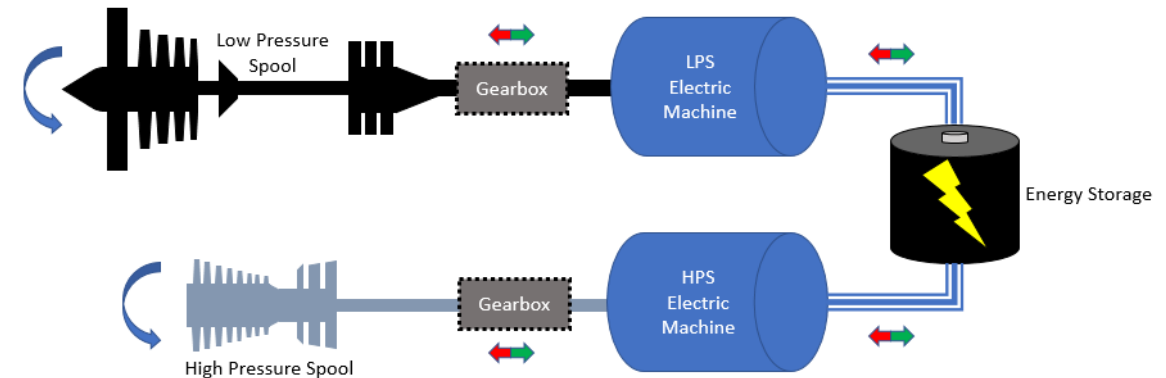
Hybrid Electric Control Considerations

- 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
 - Turboelectric or partial hybrid electric: power extraction for producing propulsion elsewhere on the airframe with aerodynamic benefit
- Considerations:
 - Managing propulsive, mechanical, and electrical energy
 - Coordinating an expanded propulsion system to maximize performance while maintaining operability
 - 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?



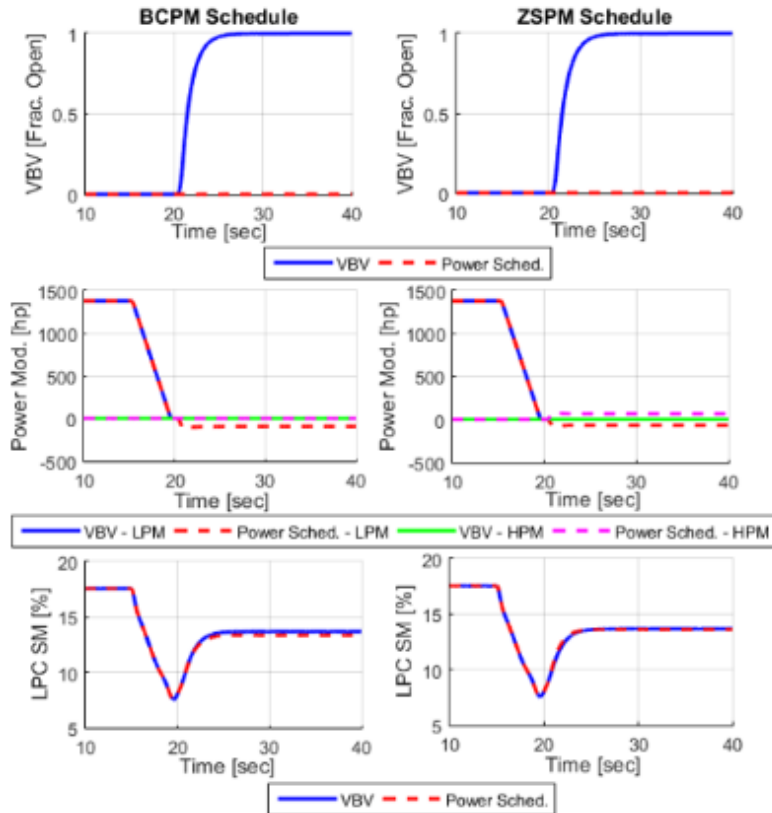
Turbine Electrified Energy Management (TEEM)

- Objective: Leverage an electrical power system to alter engine operation to the benefit of the turbomachinery.
- Focus: Improve transient compressor operability.
- 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



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Examples of TEEM



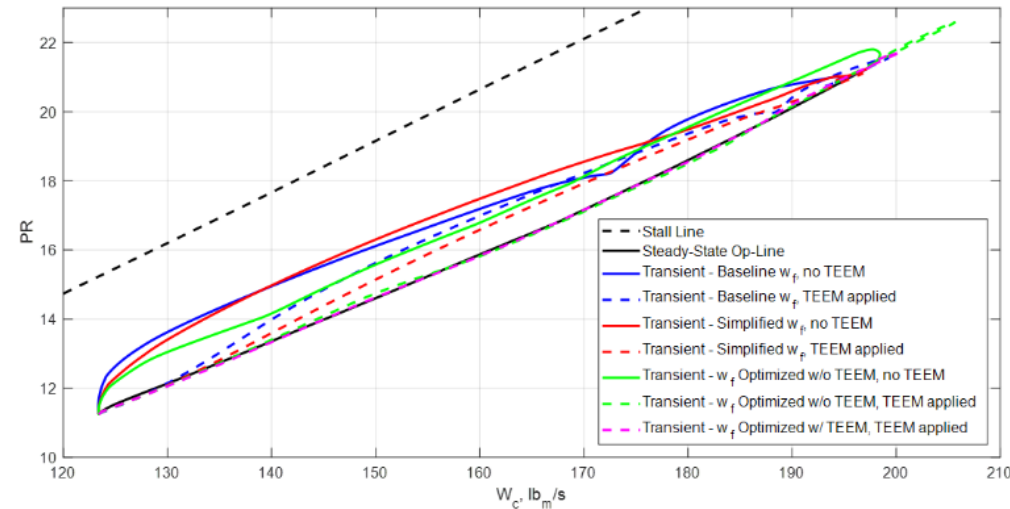
Sugar-Volt hFan

Elimination of the Variable Bleed Valve

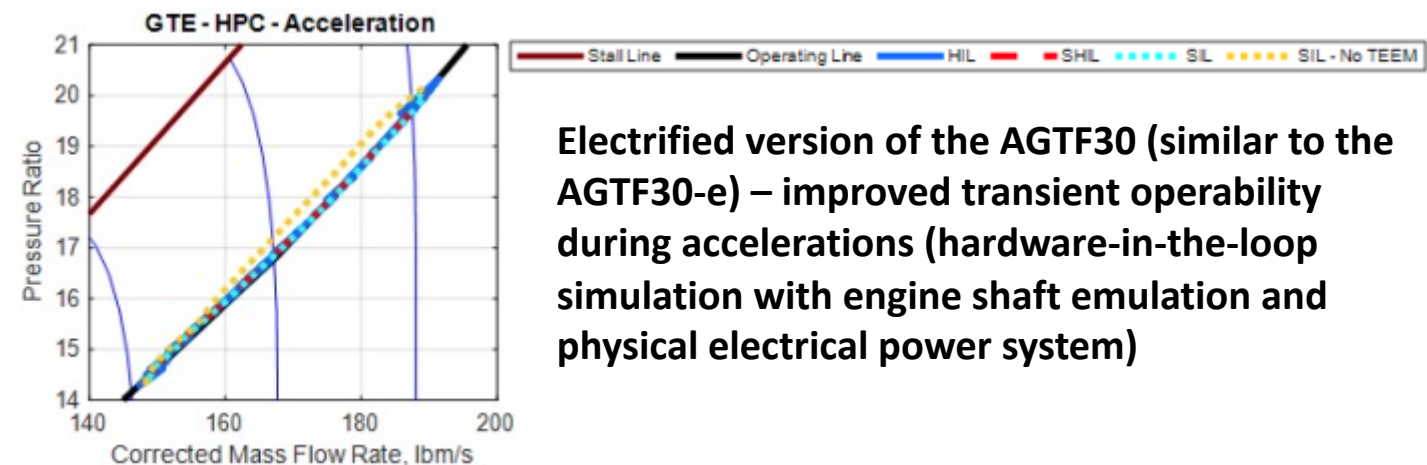
*** Power transfer to reduce idle thrust and fuel consumption**

ZSPM – zero sum power mode

BCPM – battery charge power mode



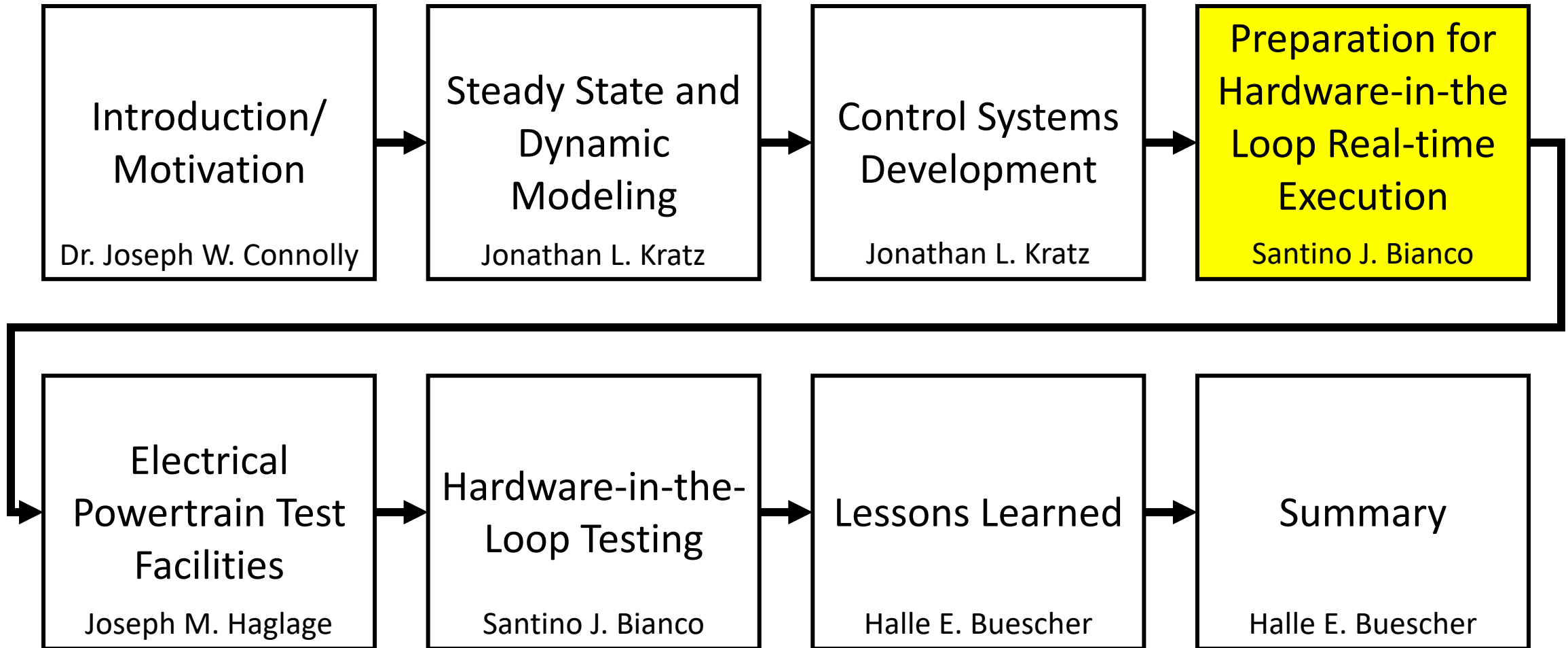
Electrified version of the AGTF30 (similar to the AGTF30-e) – improved transient operability during accelerations (pure simulation)



Electrified version of the AGTF30 (similar to the AGTF30-e) – improved transient operability during accelerations (hardware-in-the-loop simulation with engine shaft emulation and physical electrical power system)

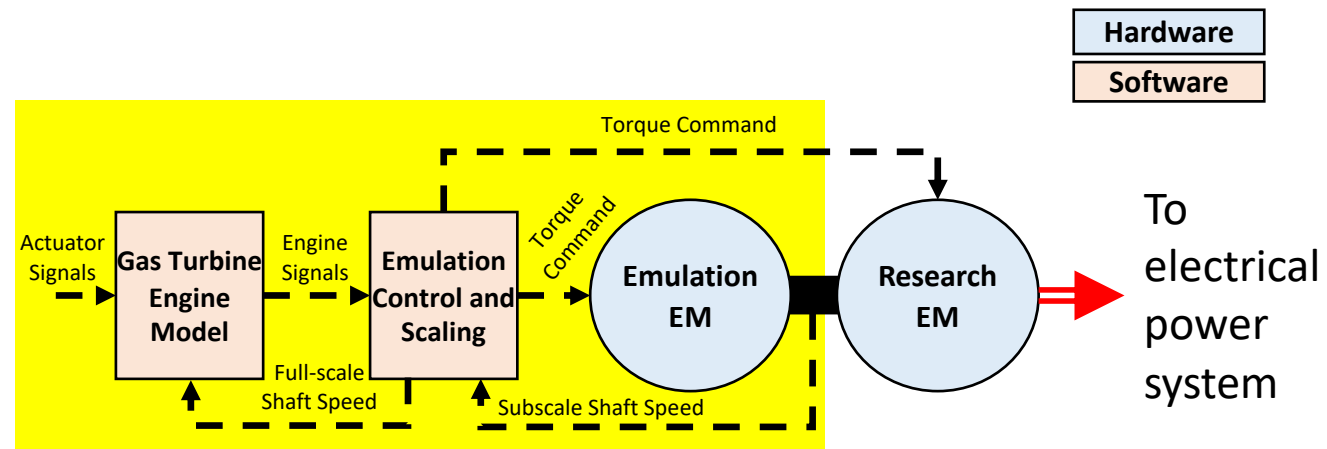
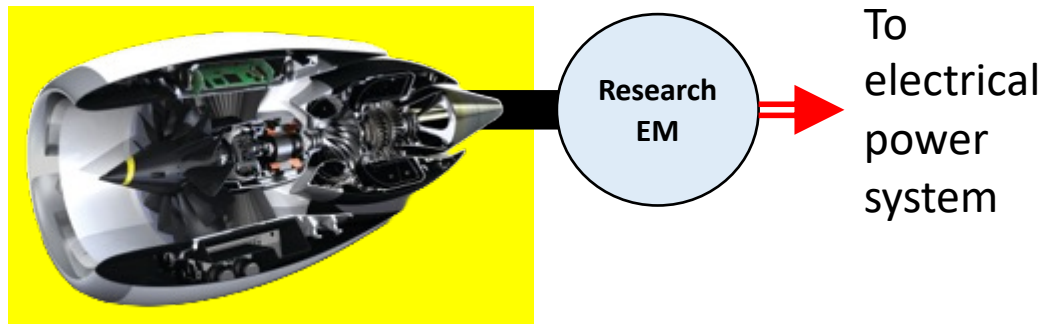


Scope



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



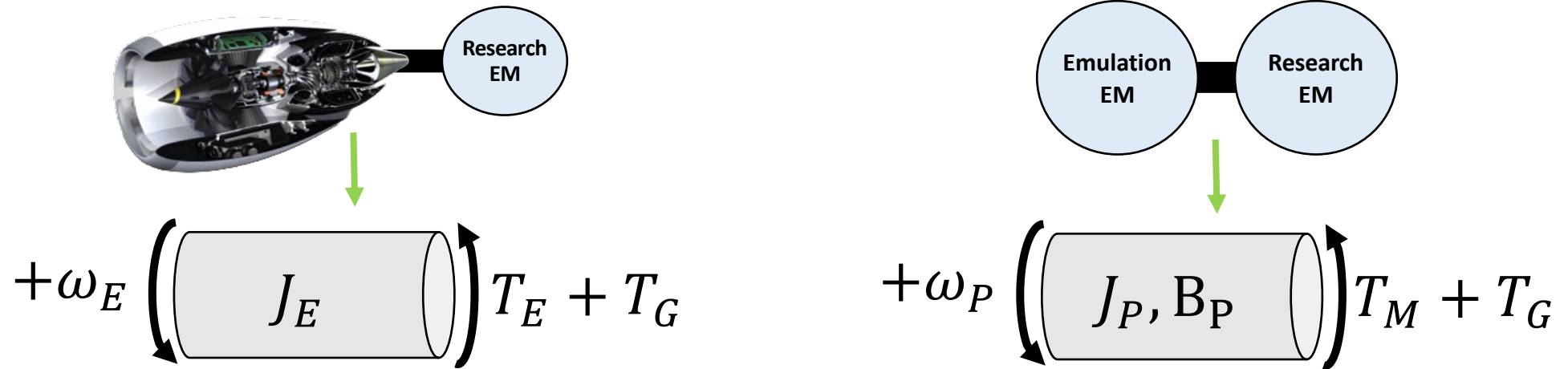
2. Adaptive Sliding Mode Impedance Controller with Scaling (ASMICS)

- 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

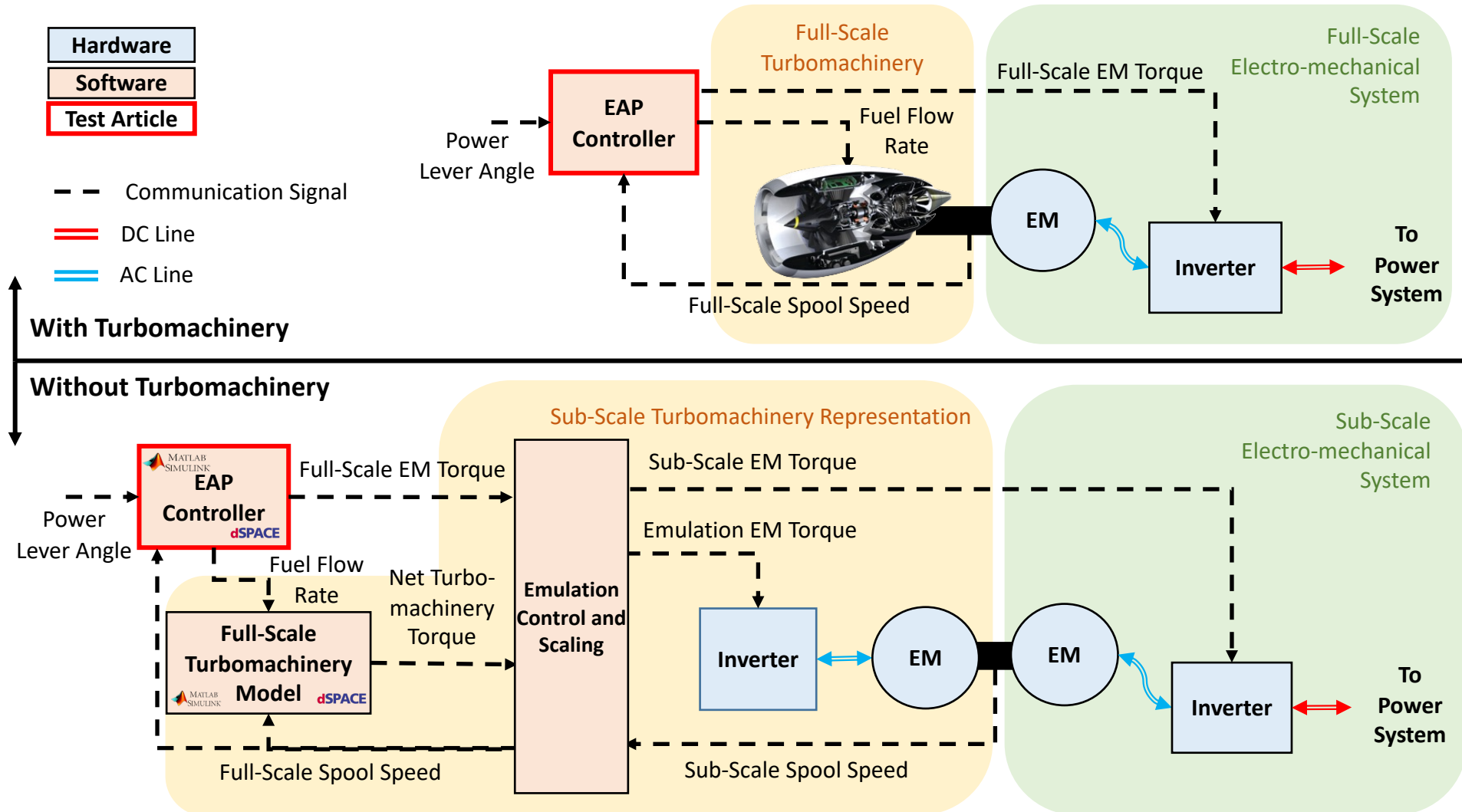
$$T_M = J_P \frac{T_E + T_G}{J_E} + B_P \omega_P - T_G$$

Substitute into engine equation.

Closed Loop System

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

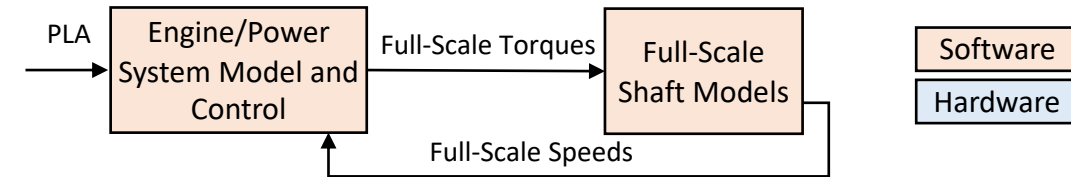
No physical gas turbine engine?



Steps to Hardware-in-the-loop Testing

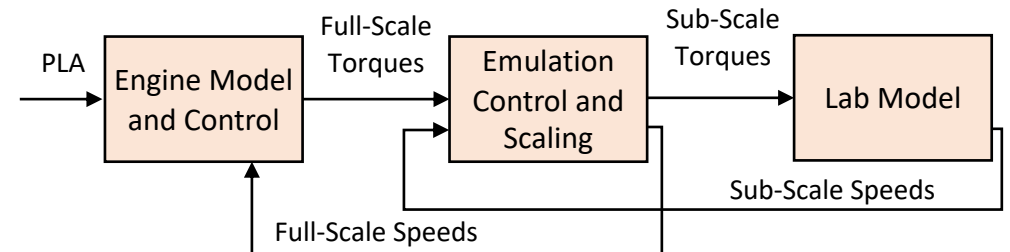
1. Software-in-the-loop (SIL) Testing

- Computer simulation of intended plant and controller.



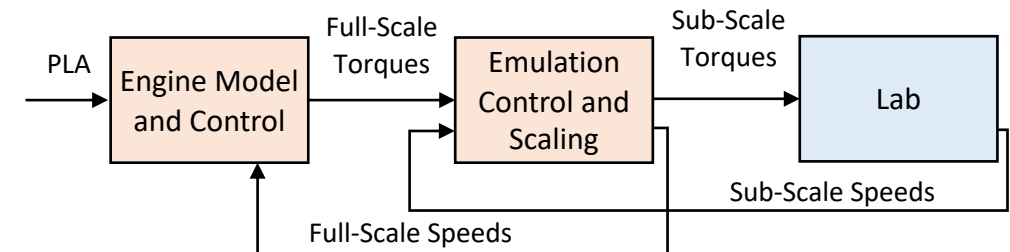
2. Simulated Hardware-in-the-Loop (SHIL) Testing

- Computer simulation of surrogate plant and controller.



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

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



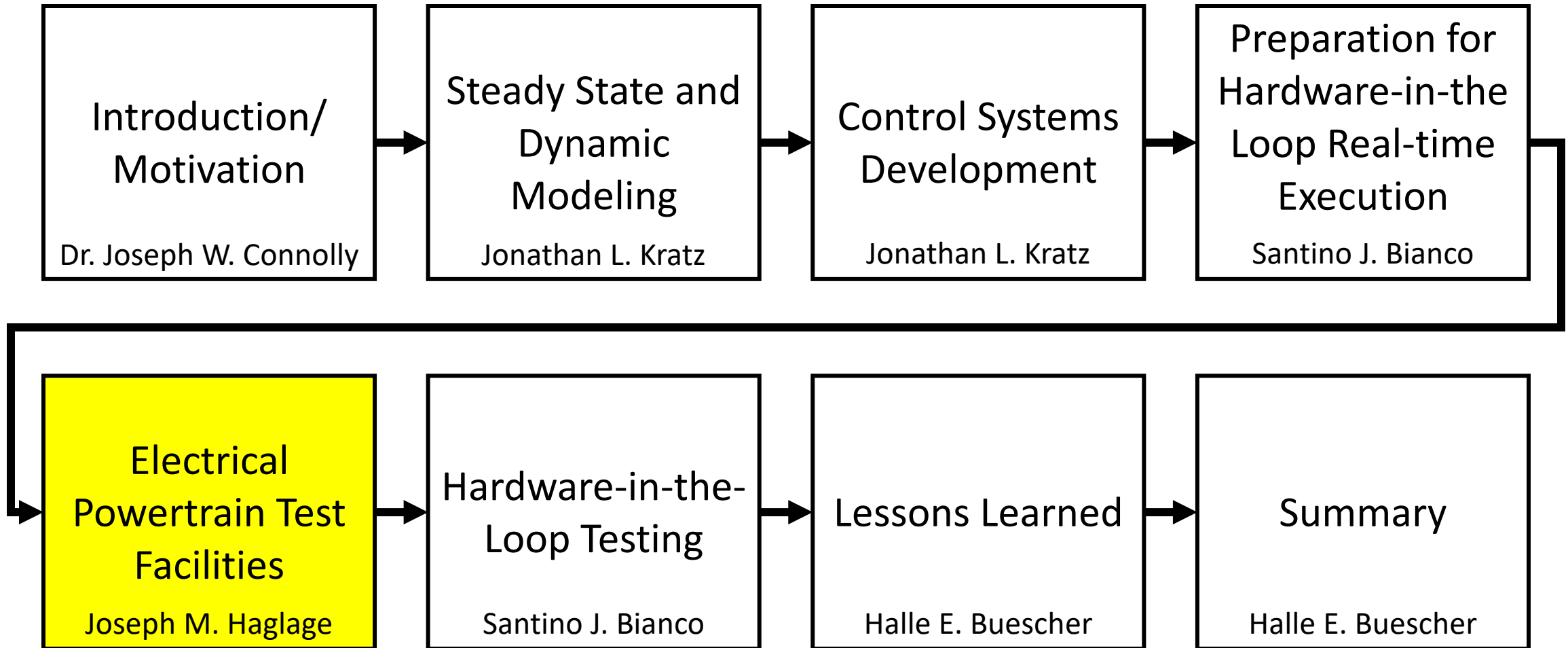


Real-time Implementation Considerations

- 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





Facilities

- 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
- Facilities
 - Hybrid Propulsion Emulation Rig (HyPER)
 - NASA Electric Aircraft Testbed (NEAT)

NASA Electric Aircraft Testbed (NEAT)



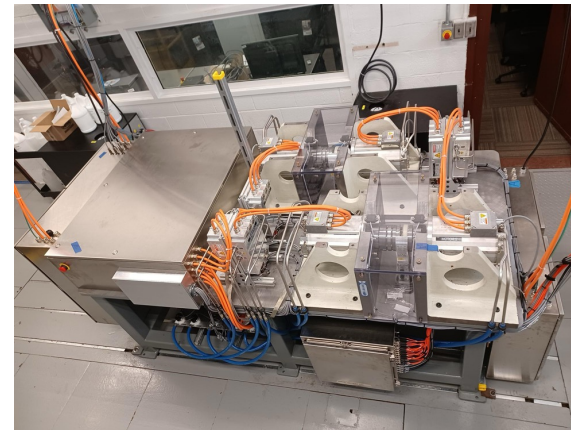
Additional Info

- NASA Armstrong Test Facility, Sandusky, Ohio
- Designed to be reconfigurable to accommodate multiple technologies
- High-power electrical component testing
- Single-aisle full-scale powertrain testing
- Attributes:
 - High bay area capable of 737-class electric powertrain
 - Electrical dynamometer
 - 1MW at 7000RPM
 - Mechanical dynamometer (water brake)
 - Electrical power up to 3.75MW
 - Bi-directional DC power up to 550kW
 - Altitude chamber capable of 60,000+ ft



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)

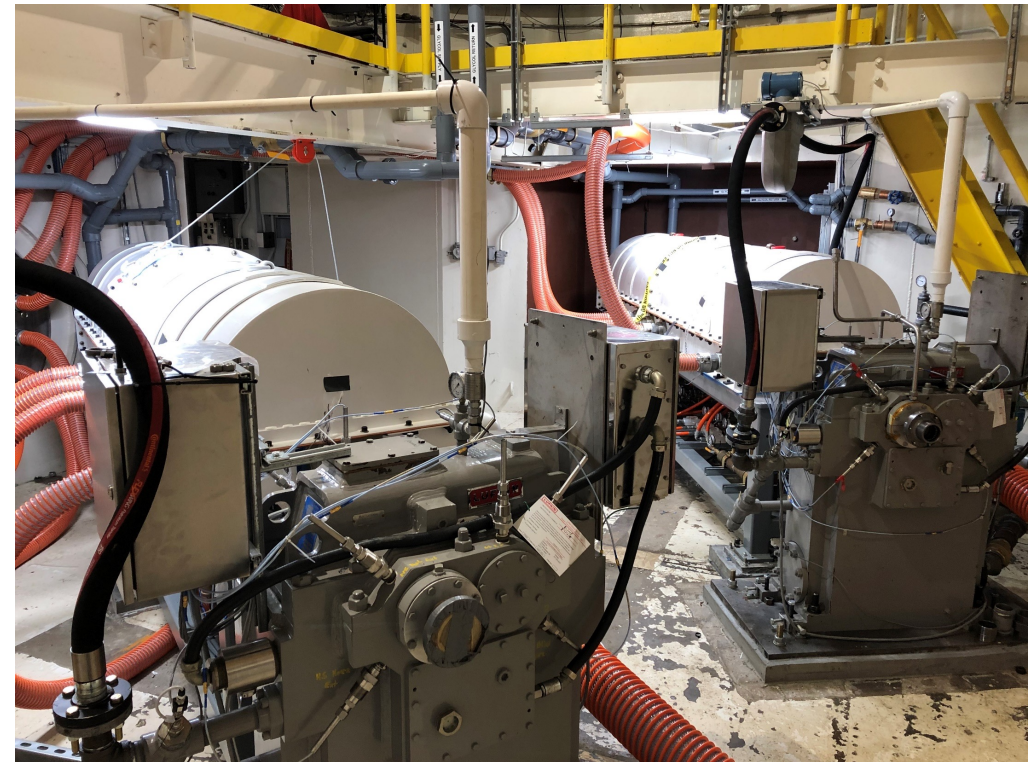


Example NEAT Test

- Powertrain test with GE Aviation in 2022
- First of a kind test
 - Multi-kilovolt, megawatt power
 - Power transfer
 - Altitudes over 45,000 ft
- Utilized dual electric dynamometers inside altitude chamber

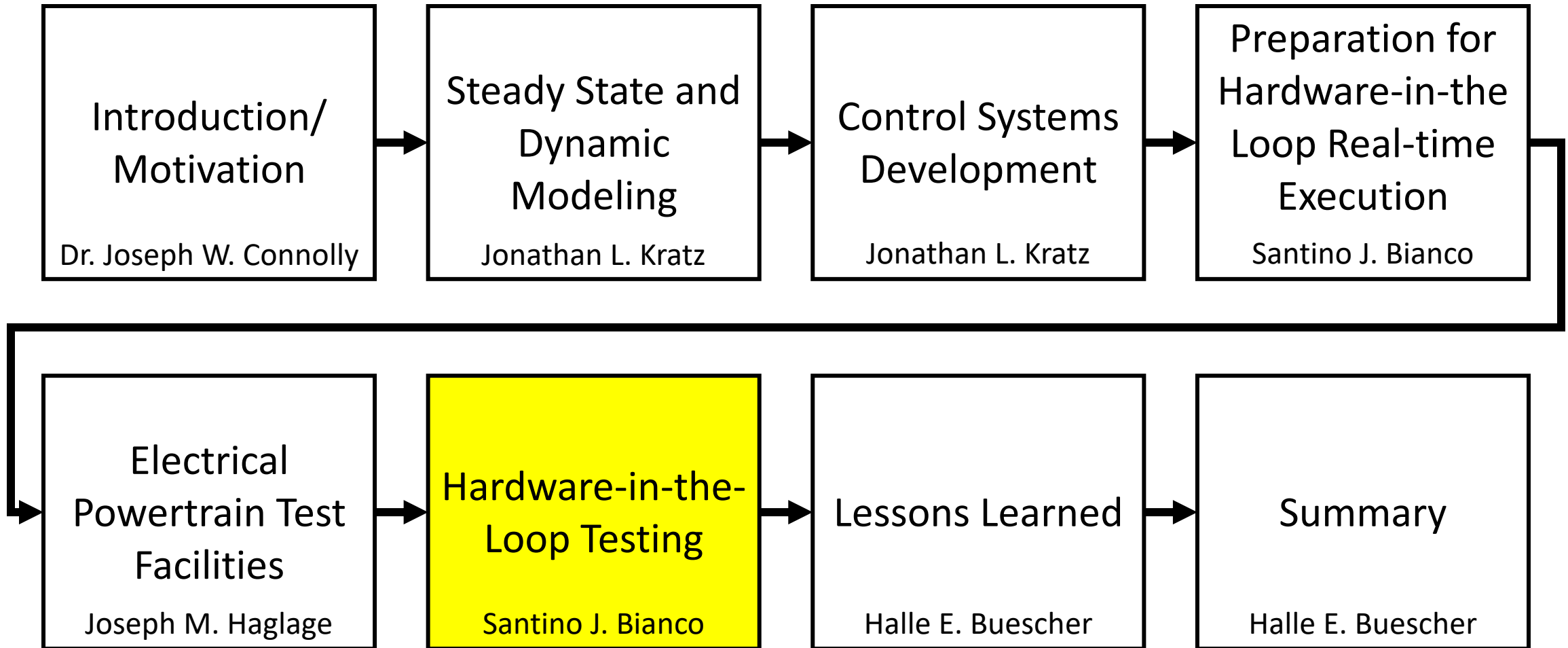


NASA Press Release



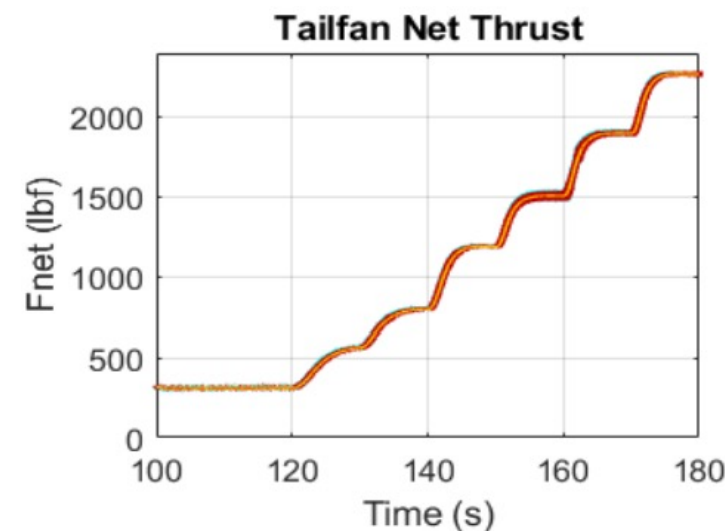
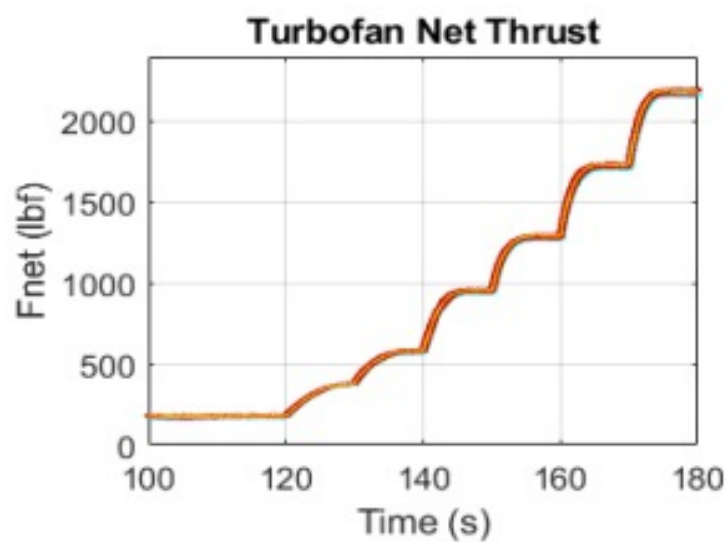
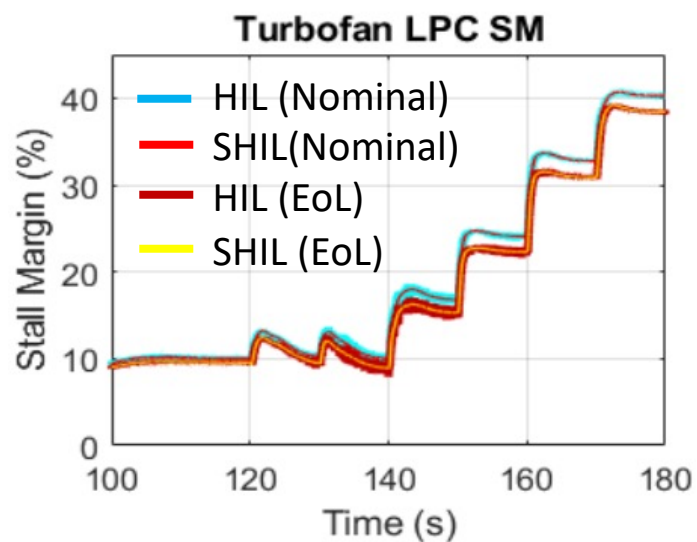
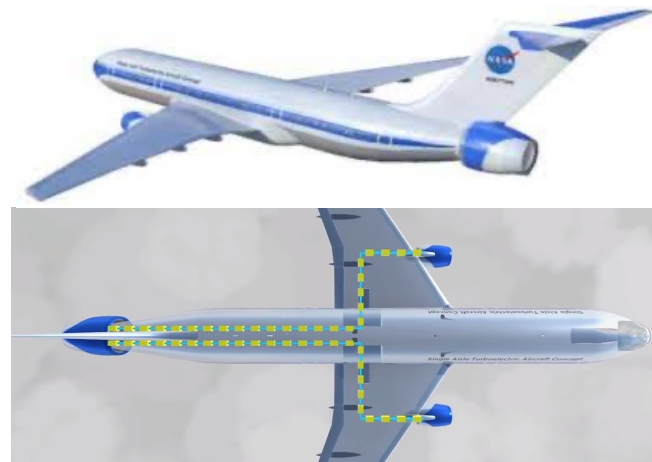


Scope



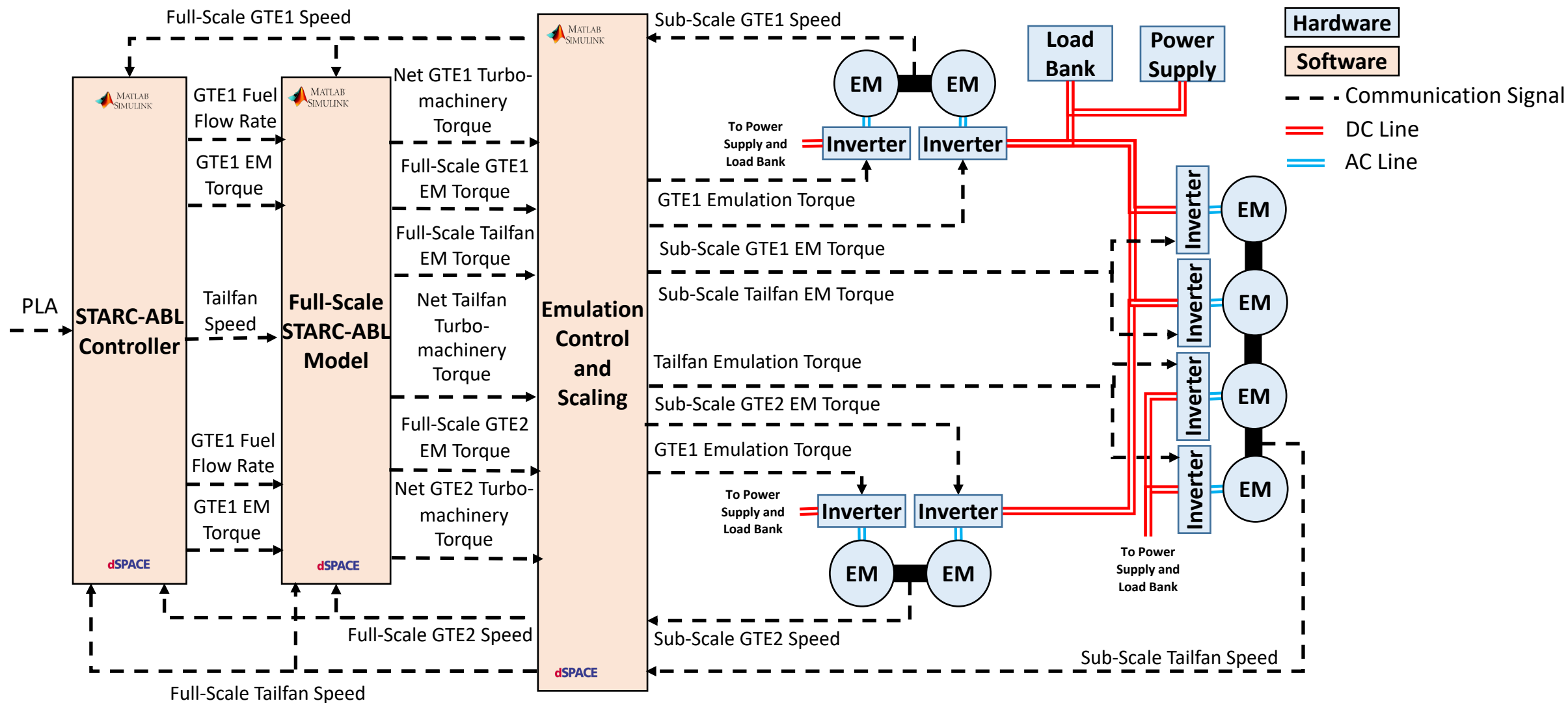
HIL Controller Testing at NEAT – STARC-ABL - 1

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



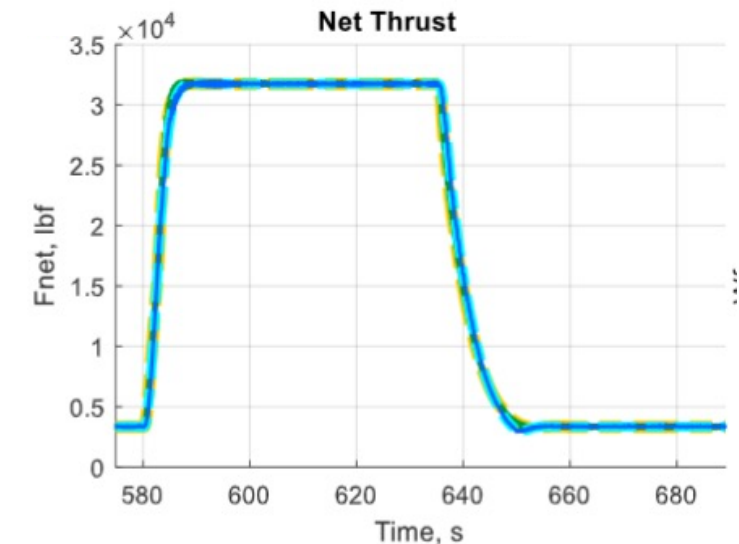
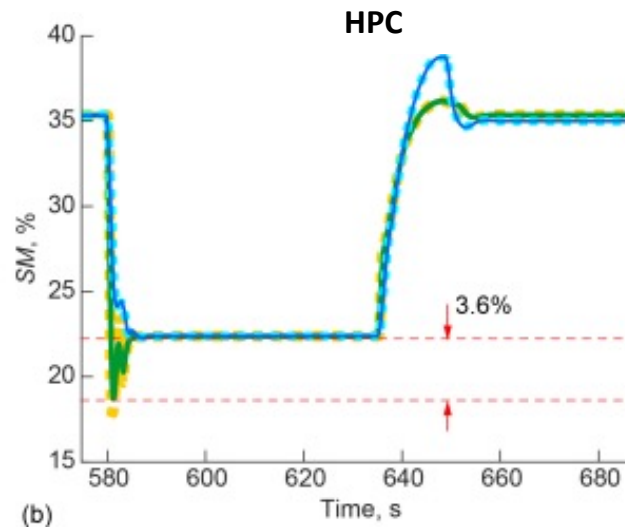
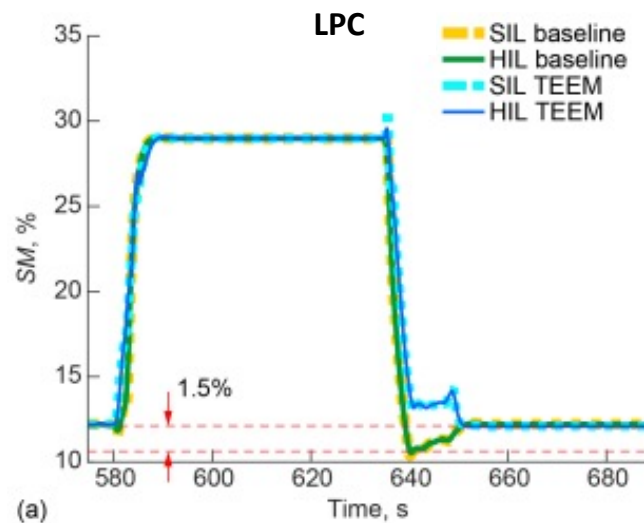
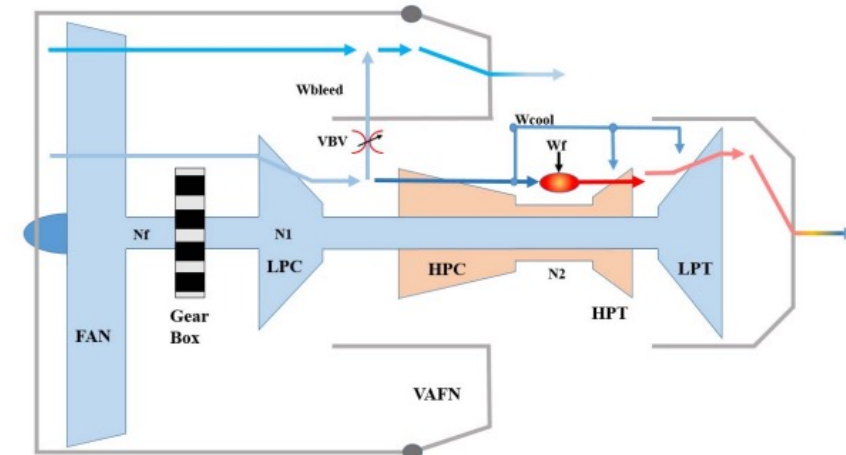


HIL Controller Testing at NEAT – STARC-ABL - 2

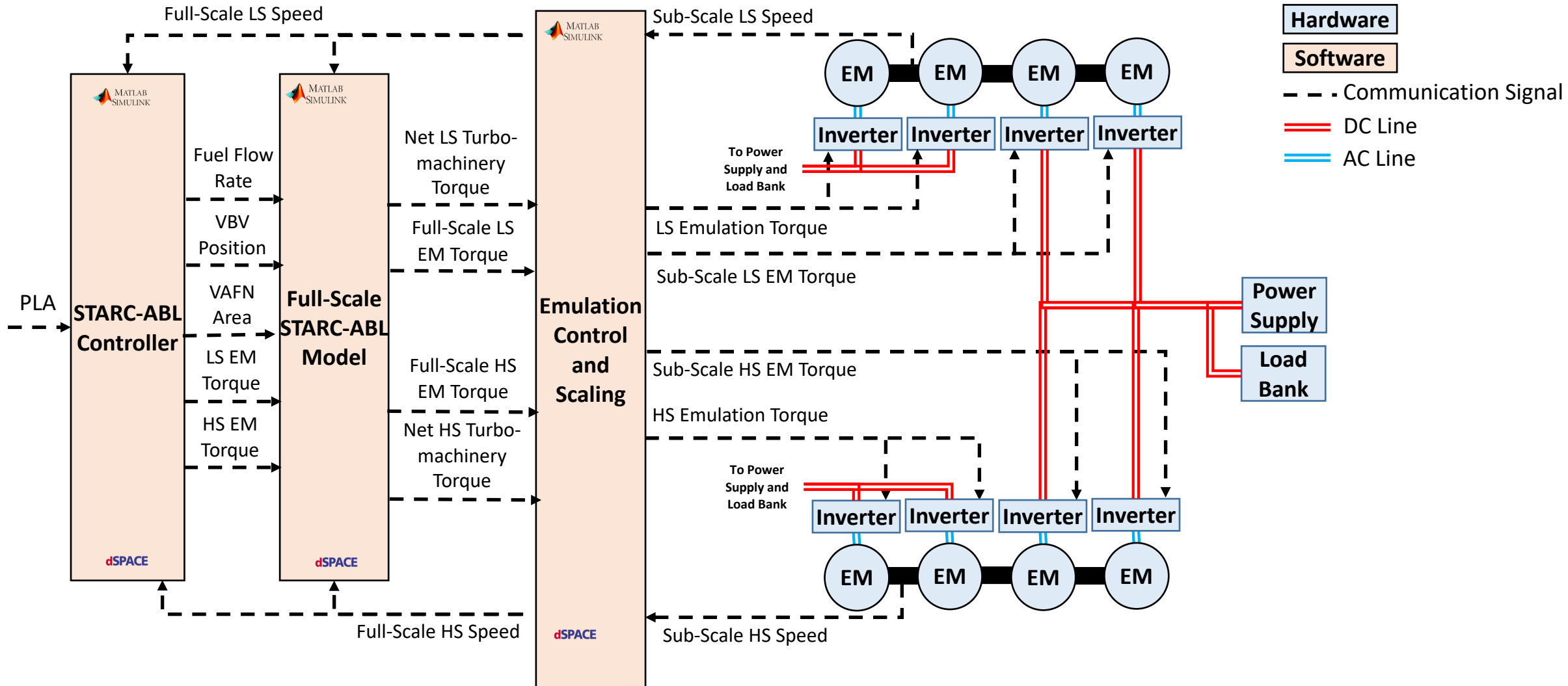


HIL Controller Testing at NEAT – AGTF30 - 1

- Tested conceptual parallel hybrid engine controller.
- Advanced Geared TurboFan 30000 (AGTF30)
- Turbine Electrified Energy Management (TEEM)
- Megawatt scale equipment.

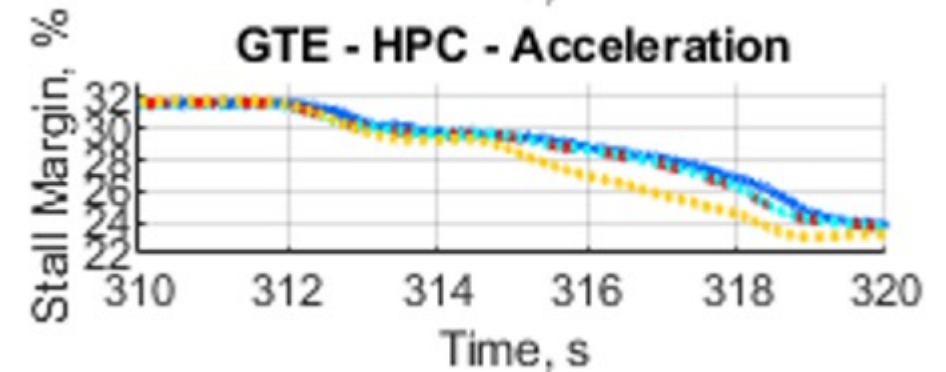
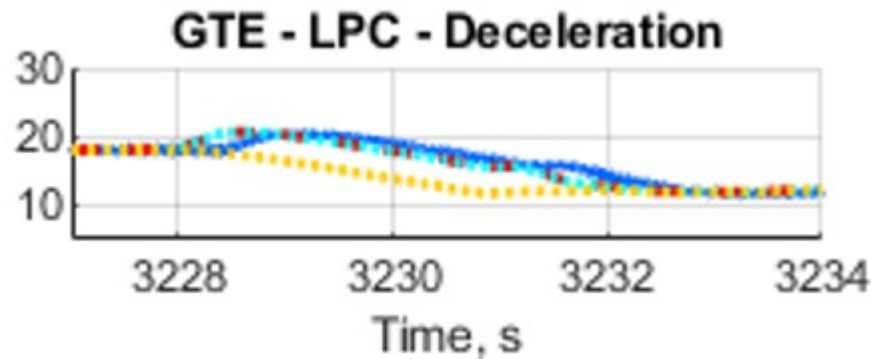
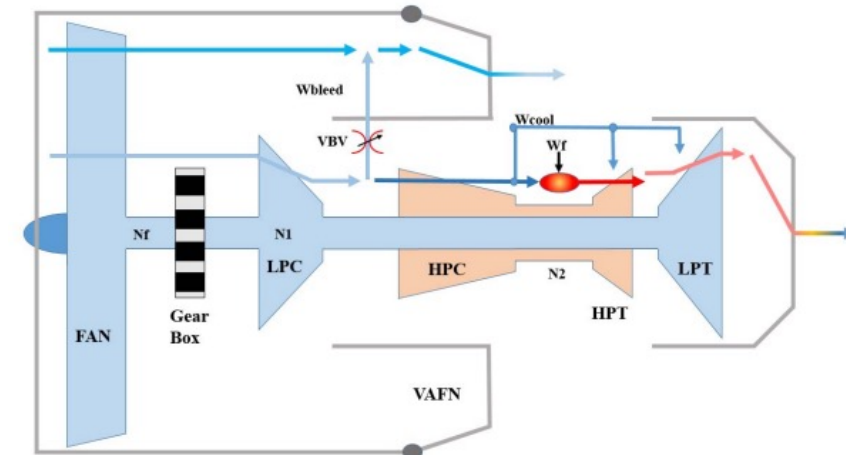


HIL Controller Testing at NEAT – AGTF30 - 2

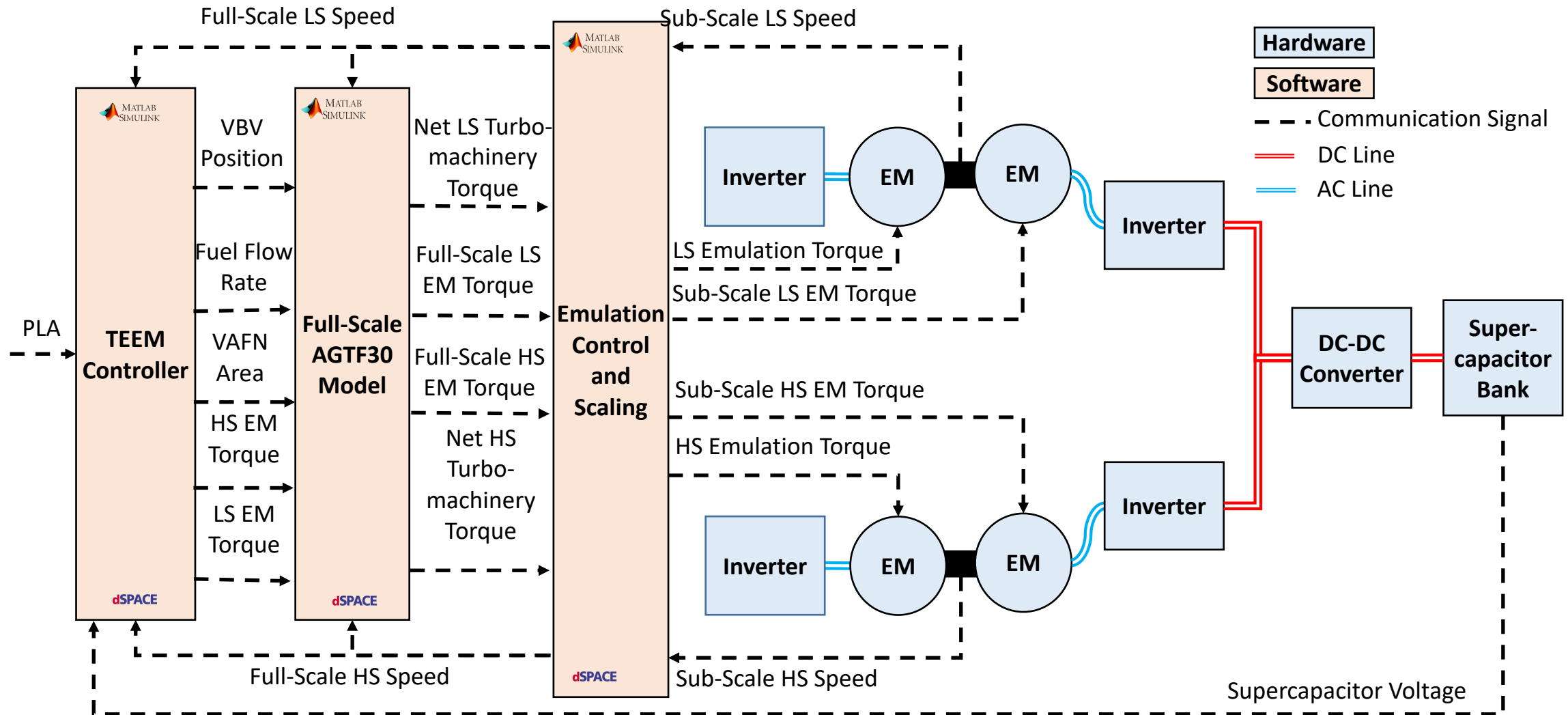


HIL Controller Testing at HyPER - 1

- Tested conceptual parallel hybrid engine controller.
- Advanced Geared TurboFan 30000 (AGTF30)
- Turbine Electrified Energy Management (TEEM)
- Kilowatt scale equipment.
- Energy storage present.

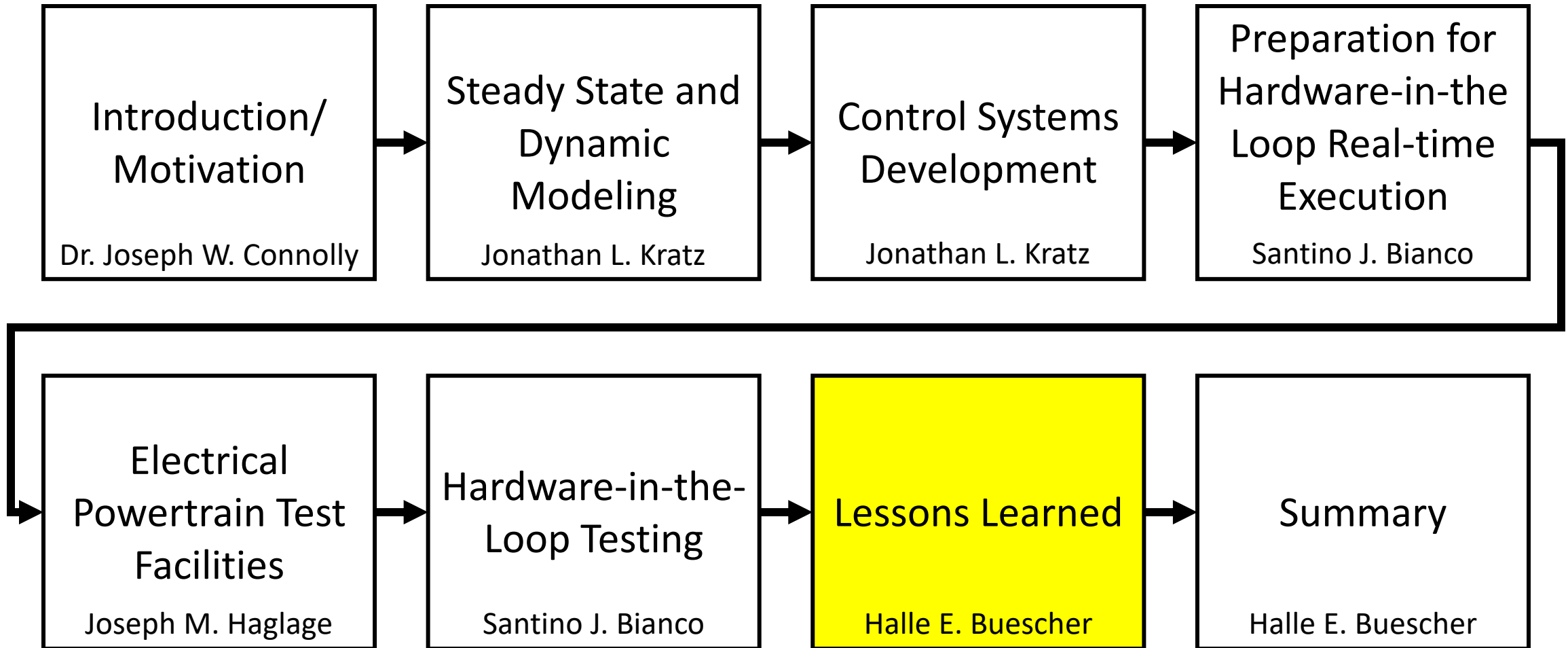


HIL Controller Testing at HyPER - 2





Scope



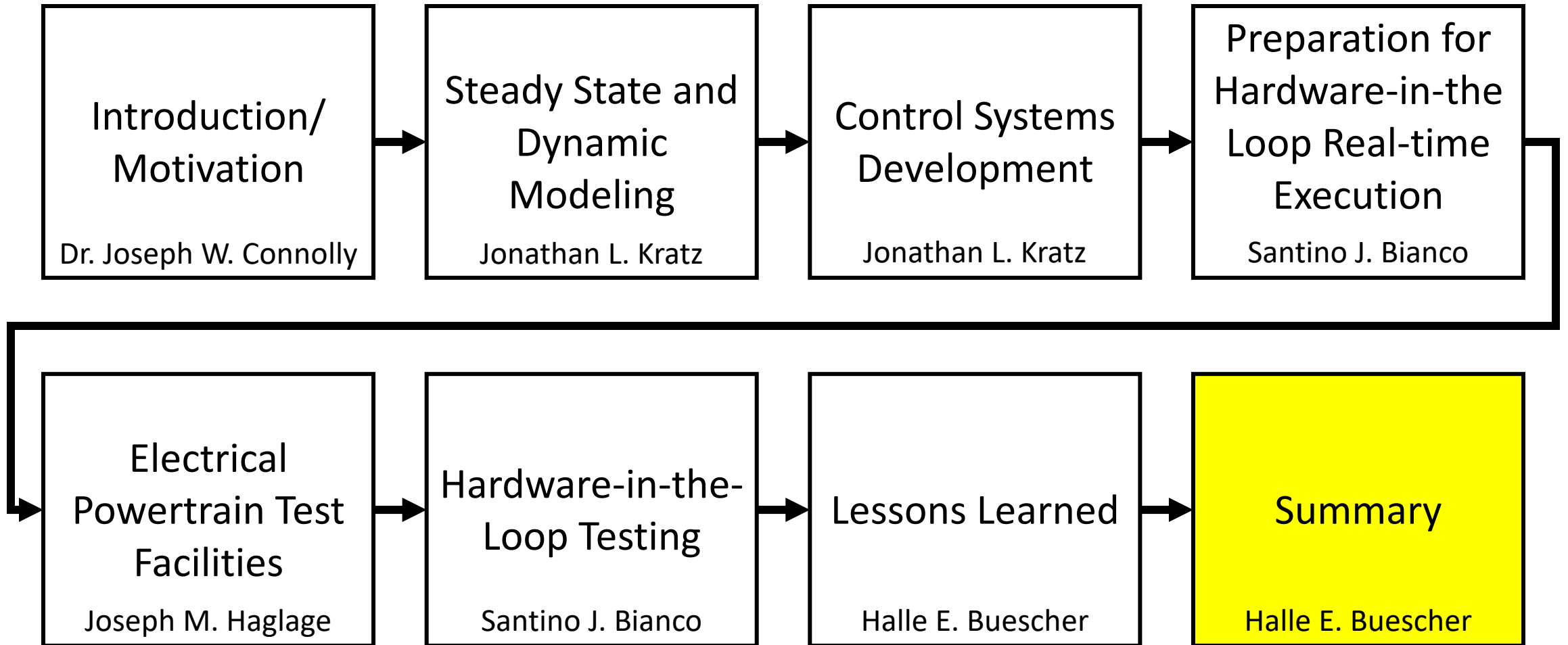


Lessons Learned [review]

1. When simulating dynamic models in real-time, noise, computational load, and non-ideal hardware operation can negatively impact simulations.
2. 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. 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. 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. 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.



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.

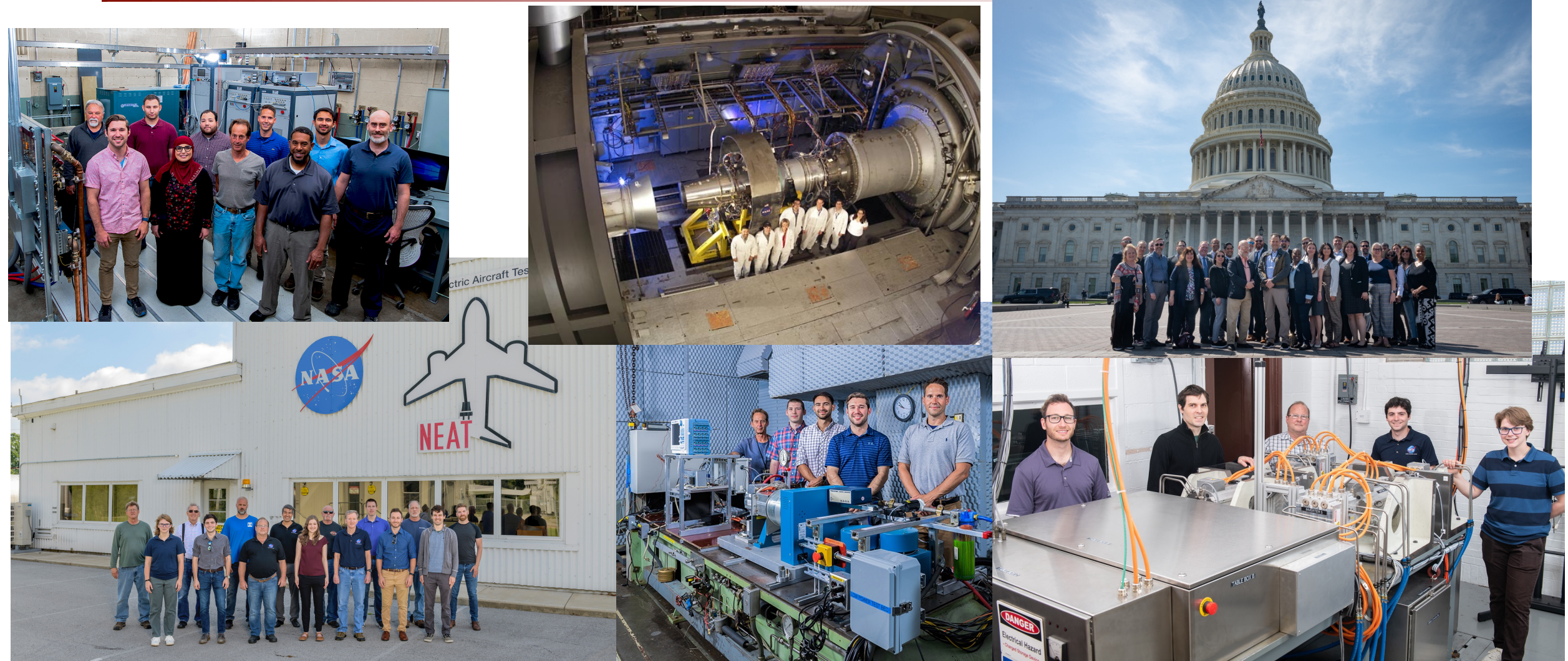


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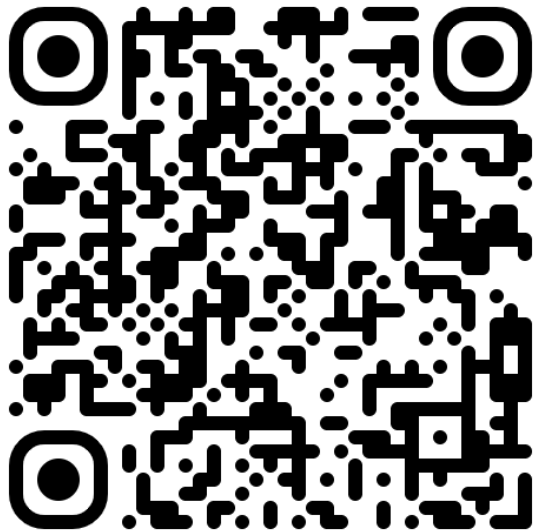
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HyTEC



EPFD



TTT



