NASA's Open Source Electrified Aircraft Propulsion Modeling and Simulation Tools

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Overview

This presentation describes a suite of interoperable tools for the development and testing of control systems for electrified aircraft powertrains with examples, including:

- Dynamic modeling and analysis
- Modeling physical components from data
- Real time testing
- Hardware-in-the-Loop testing
- Design evaluation
- Characterization of hardware components from data

TOOLBOXES

Open Source, MATLAB™/Simulink™-based, no cost

- Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)
  - https://github.com/nasa/T-MATS/releases
- Electrical Modeling and Thermal Analysis Toolbox (EMTAT)
  - https://github.com/nasa/EMTAT/releases
- Thermal Systems Analysis Toolbox (TSAT)
  - https://github.com/nasa/TSAT/releases
- The Tip Clearance Modeling Library (TCML)
  - https://github.com/nasa/TCM
- Advanced Geared Turbofan 30,000 (AGTF30)
  - https://github.com/nasa/AGTF30/releases
- AGTF30 Fast Steady-State Solver
  - https://github.com/nasa/-AGTF30-mex-solver-
- Advanced Geared Turbofan 30,000 electrified (AGTF30-e)
  - https://github.com/nasa/AGTF30-e/releases

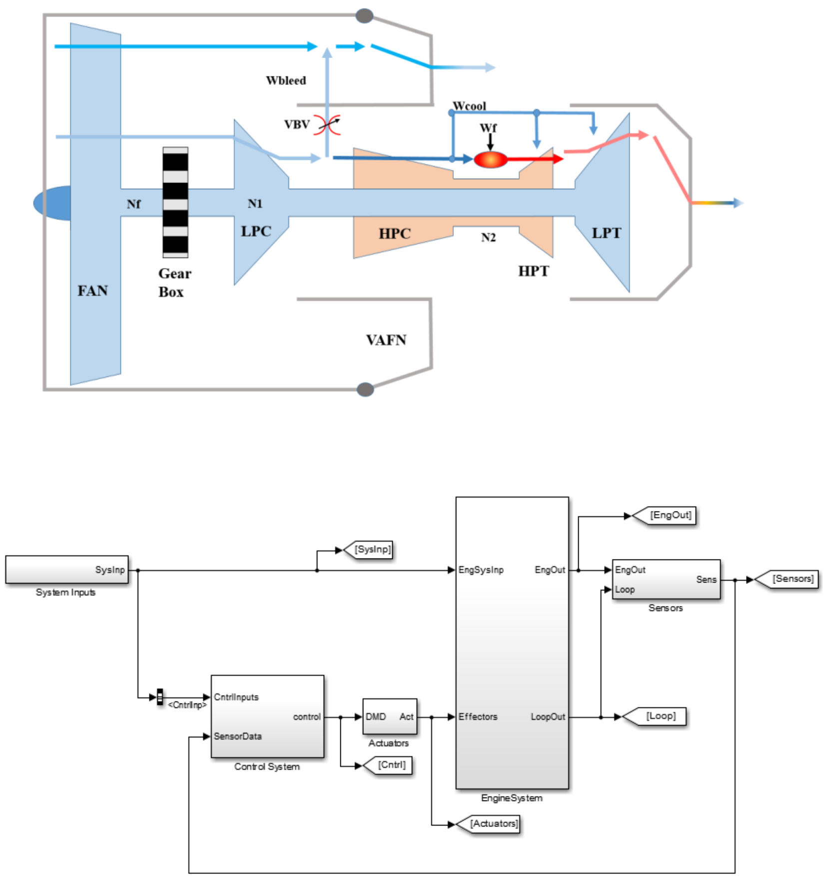
OVERVIEW OF MODELING APPROACHES

- Can create dynamic models of powertrain and related components with simple graphical drag-and-drop tools
- Can model the dynamic interaction of the power system and the turbomachinery—including thermal effects—at a time scale appropriate for control design (time scale of the shaft dynamics)
- Flexible complementary compatible toolboxes for various types of multi-physics simulations
- Models can generate electrical, mechanical, and thermal variables
- Tools designed to execute efficiently so most models (depending on complexity) run faster than real time, enabling their use in control systems

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

- Modular thermodynamic modeling framework for building dynamic simulations
- Designed for easy creation of custom Component Level Models (CLM) of jet engines
- Includes convenient tool to convert Numerical Propulsion System Simulation (NPSS) cycle design code steady state models to T-MATS dynamic models
- Although originally intended to simulate turbomachinery, it has been used for other applications, such as fuel cell modeling using Cantera*

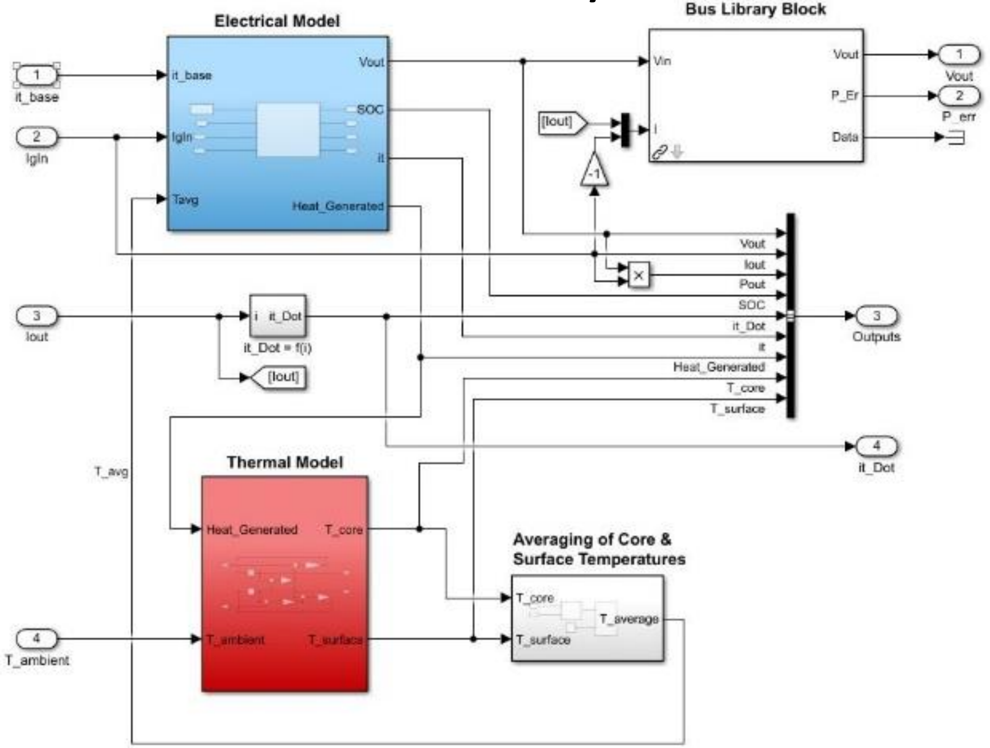
  *an open-source suite of tools for problems involving chemical kinetics, thermodynamics, and transport processes

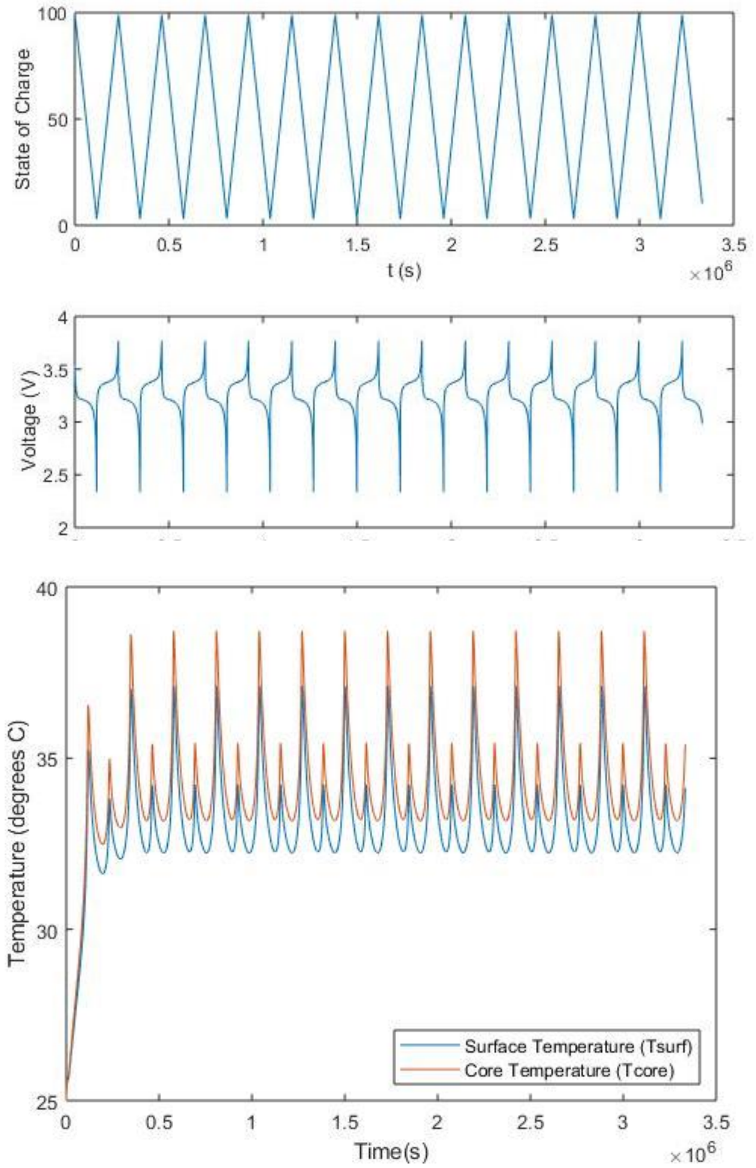


Advanced Geared TurboFan 30k (AGTF30)

Electrical Modeling and Thermal Analysis Toolbox (EMTAT)

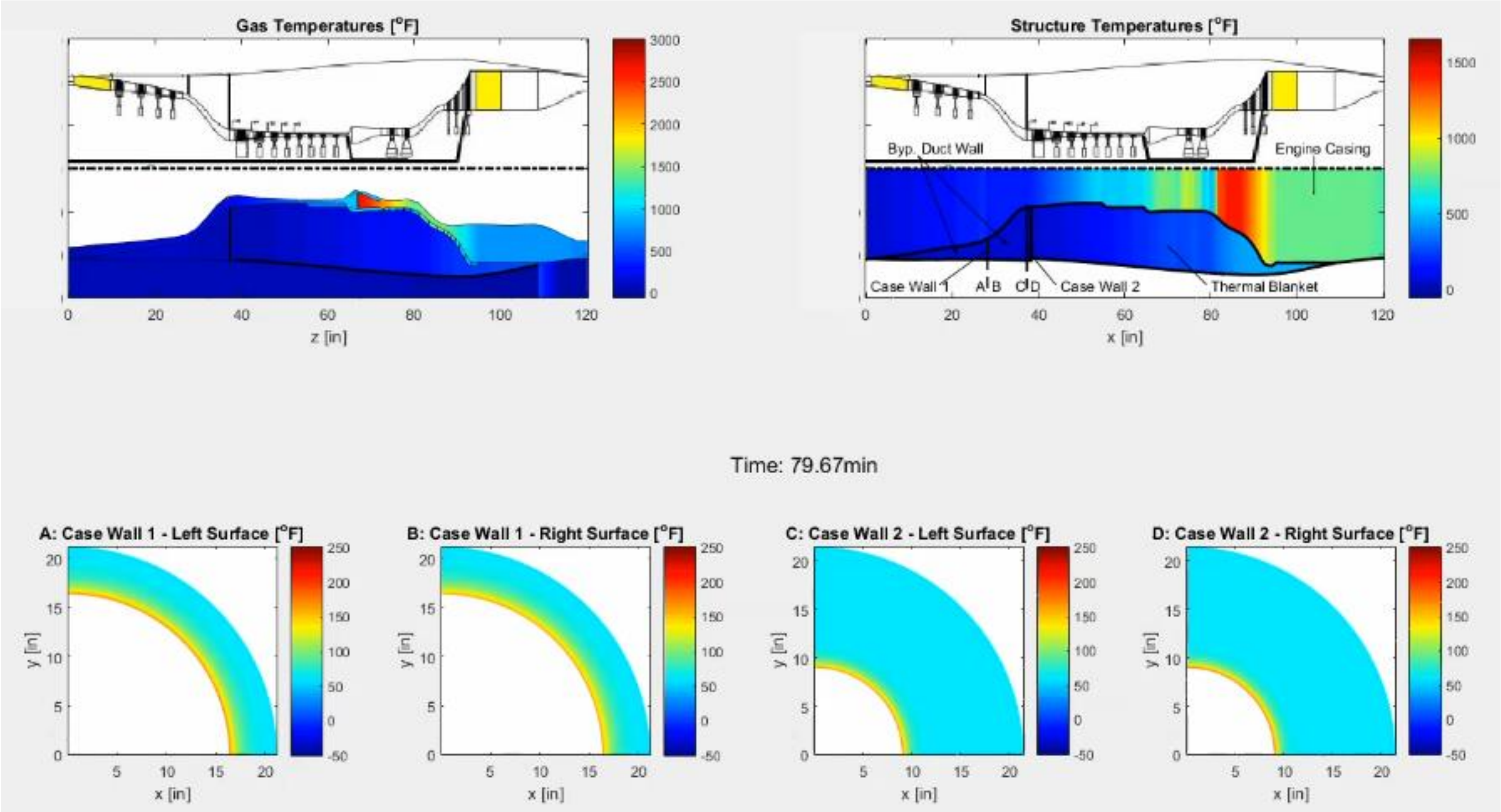
- Power Flow based Electrical/Thermal modeling package
- Vectorized for simplified implementation of multiple similar electrical strings
- Runs at the turbomachinery timescale





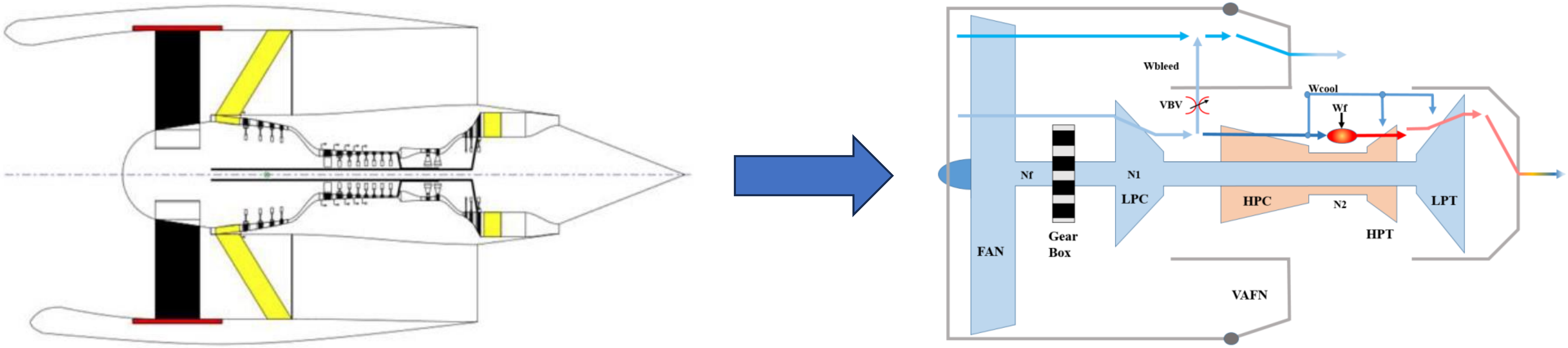
Thermal Systems Analysis Toolbox (TSAT)

- Used for the modeling and analysis of dynamic heat transfer
- Related code: The Tip Clearance Modeling Library (TCML) leverages TSAT for thermal expansion calculations



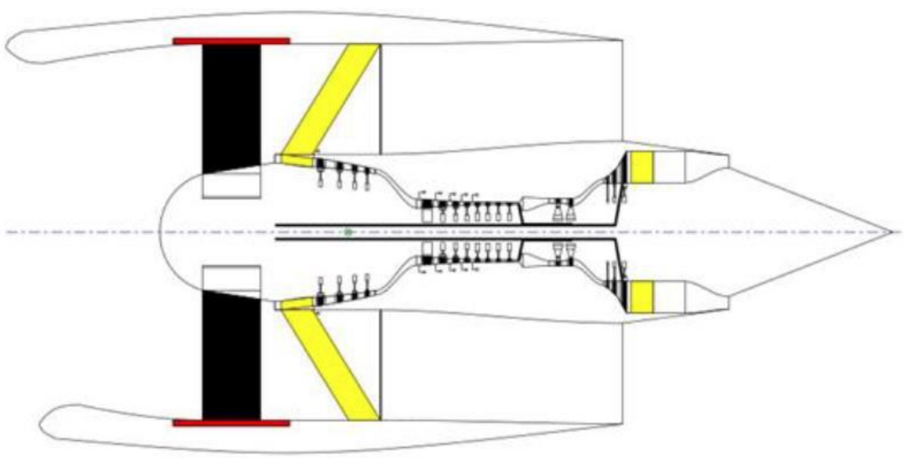
Advanced Geared Turbofan 30,000 (AGTF30)

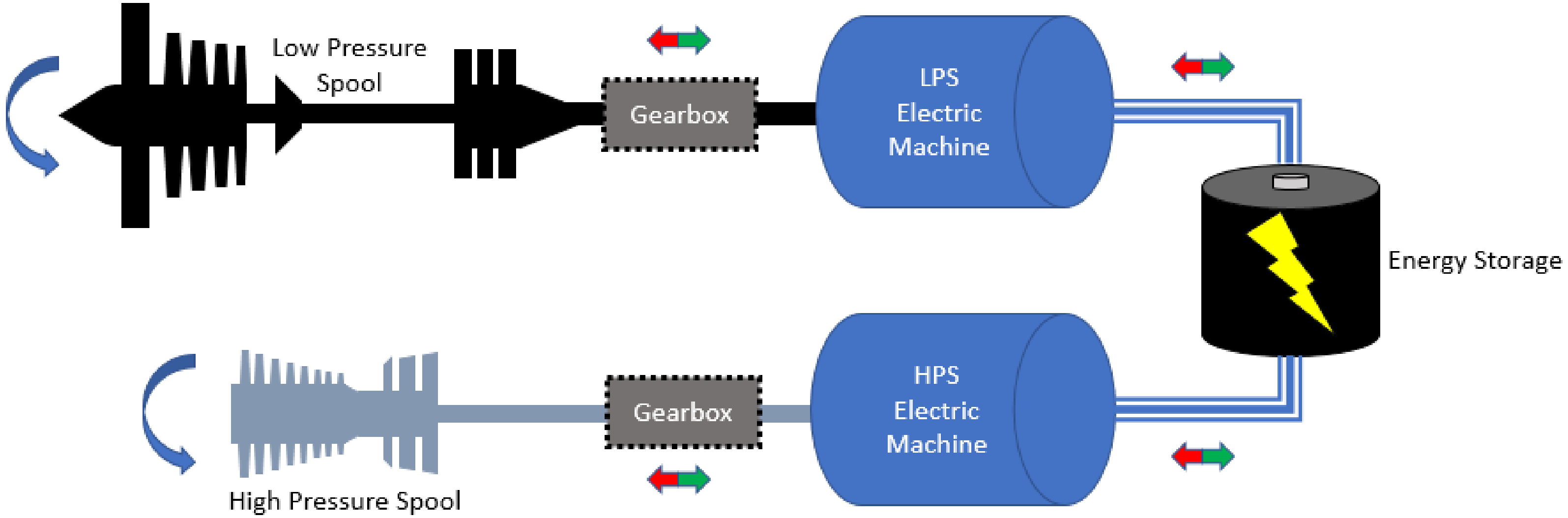
- Based on NASA N+3 Concept Engine
- Features include: geared fan, variable bleed valve (VBV), variable area fan nozzle (VAFN), a small engine core, and an ultra-high bypass ratio
- NPSS 30,000 lbf geared turbofan design converted to T-MATS and matched at the design points
- Actuators include a variable area fan nozzle and variable bleed valve
- Related code: MATLAB™ Executable Steady-State Solver and Linearization Tool for the AGTF30 Engine Simulation



Advanced Geared Turbofan 30,000 electrified (AGTF30-e)

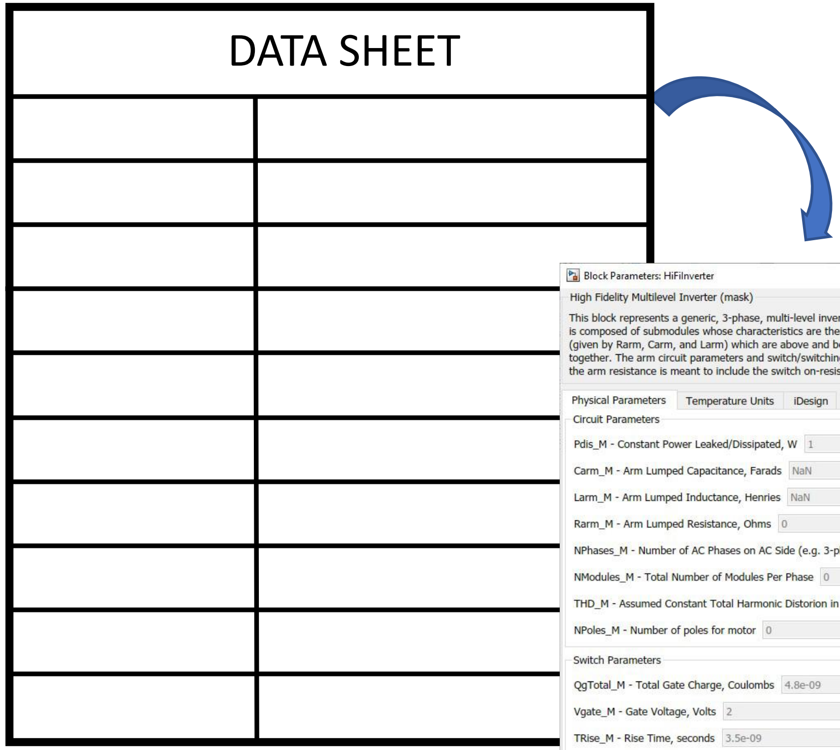
- Electrified version of the AGTF30
- Includes multiple implementations of Turbine Electrified Energy Management (TEEM) for transferring power between engine shafts
- Includes multiple variations of electric machine integration including
  - Directly to the engine shafts
  - Through the Versatile Electrically Augmented Turbine Engine (VEATE) gearbox

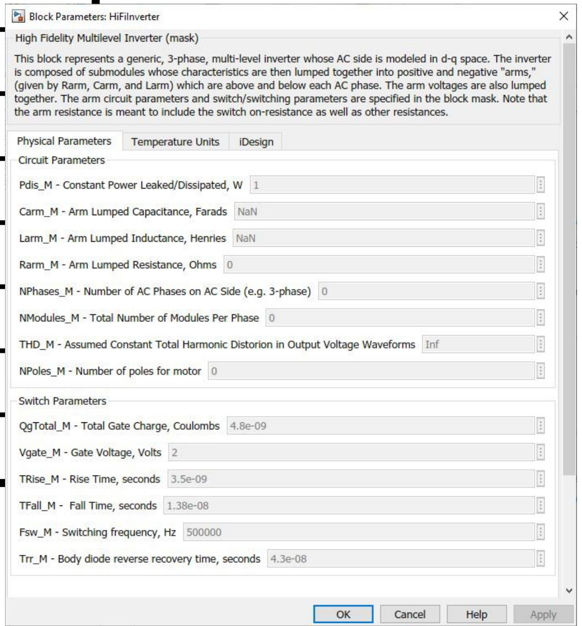




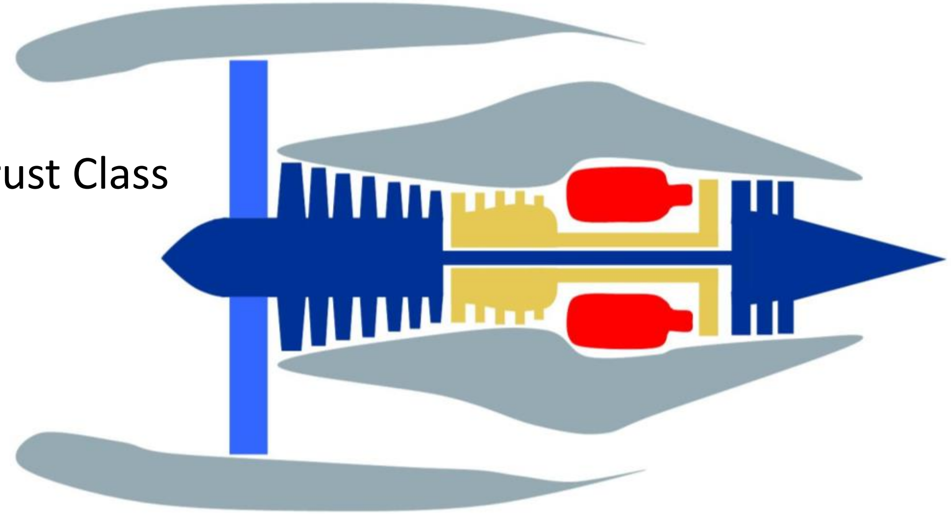
EXAMPLE: SIMULATION OF HARDWARE COMPONENTS

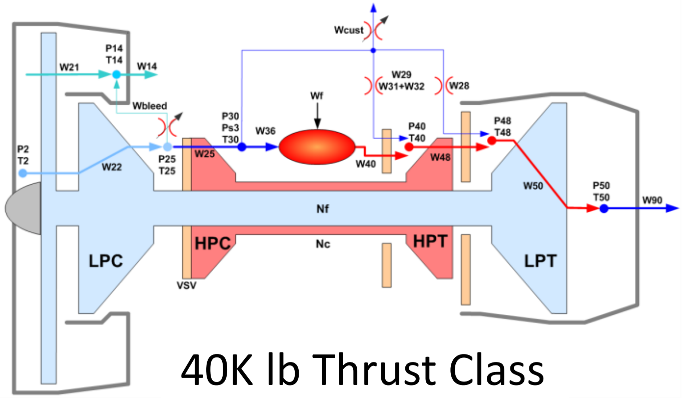
Parameterizable software components enable matching to data sheet or design specifications





90K lb Thrust Class



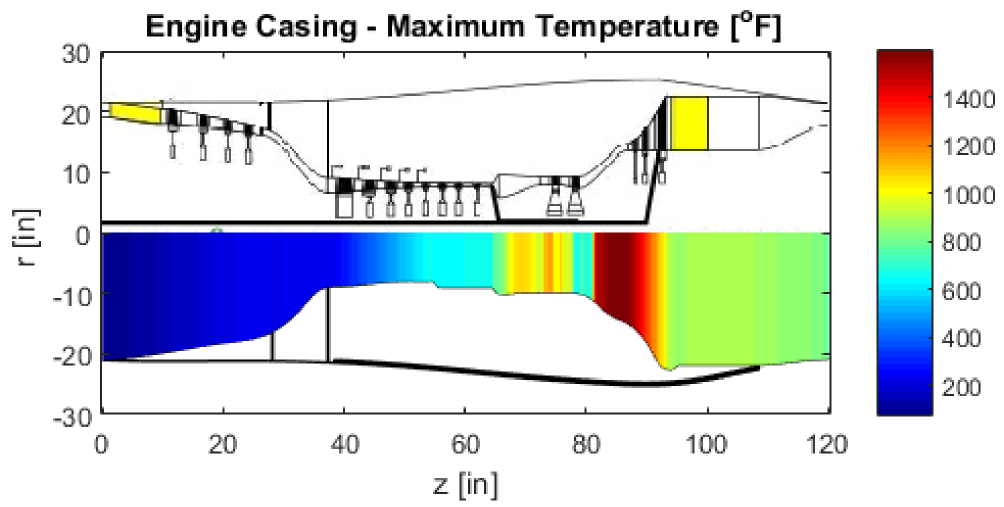


40K lb Thrust Class

EXAMPLE: Distributed Engine Control

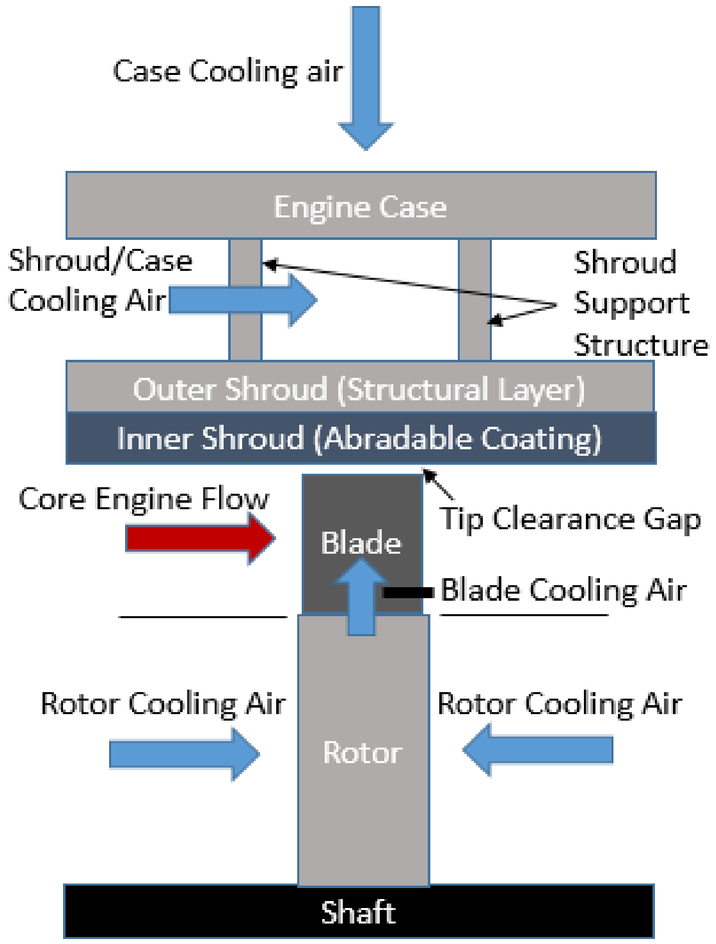
- Distributed Engine Control uses electronics to process data near each sensor location rather than the FADEC, saving many pounds of cable weight
- TSAT was used to predict engine case temperature throughout a flight to determine acceptable locations to mount electronics
- The work utilized the T-MATS-based dynamic closed loop AGTF30 model converted from an NPSS design to generate the gas path variables and physical dimensions determined from WATE++* code analysis

*WATE++ is an object-oriented computer code for gas turbine engine weight estimation; it calculates the weight and dimension of each major gas turbine engine component. It is used to create engine architecture that could achieve an engine thermodynamic cycle produced by a thermodynamic cycle code.

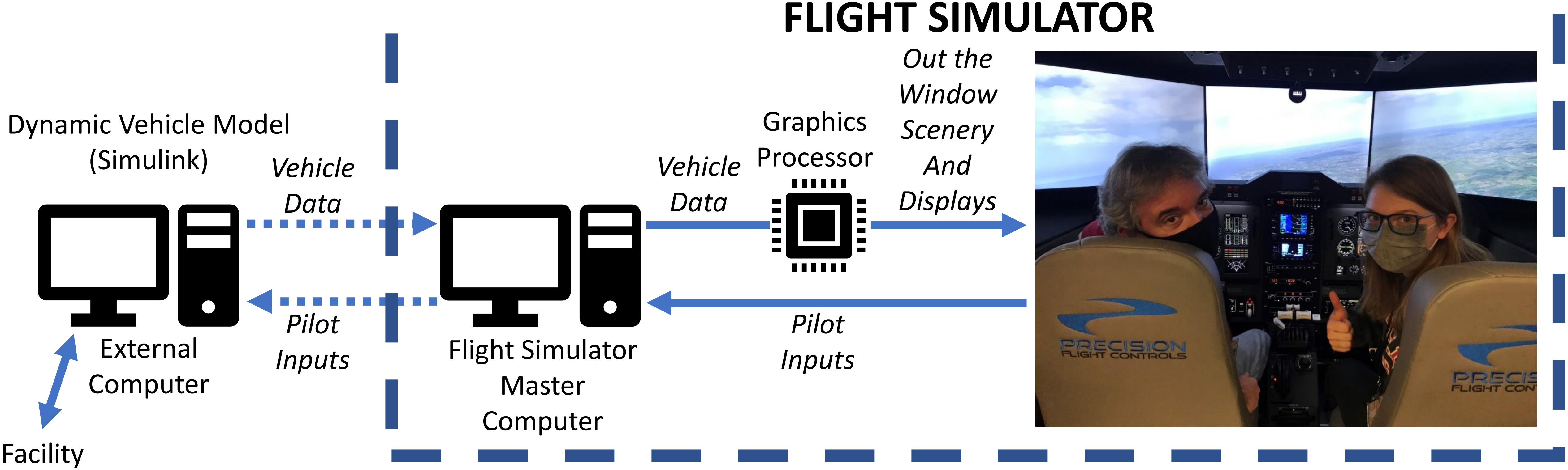


EXAMPLE: TURBINE TIP CLEARANCE

- Minimizing turbine tip clearance while avoiding rubs improves engine efficiency
- The Tip Clearance Modeling Library leverages TSAT to predict turbine blade and case expansion for a model-based tip clearance control
- Considers axisymmetric tip clearance variations due to centrifugal and thermal loads
- The work utilized the T-MATS-based dynamic closed loop AGTF30 model converted from an NPSS design to generate the gas path variables and physical dimensions determined from WATE++ code analysis
- Used to perform sensitivity studies related to bandwidth of tip clearance control approaches



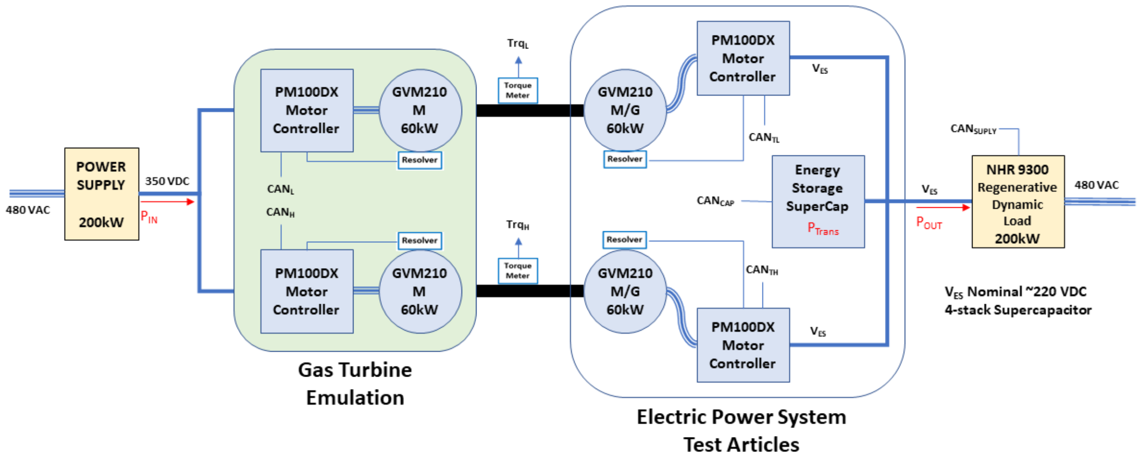
EXAMPLE: FLIGHT SIMULATOR PILOT-IN-THE-LOOP

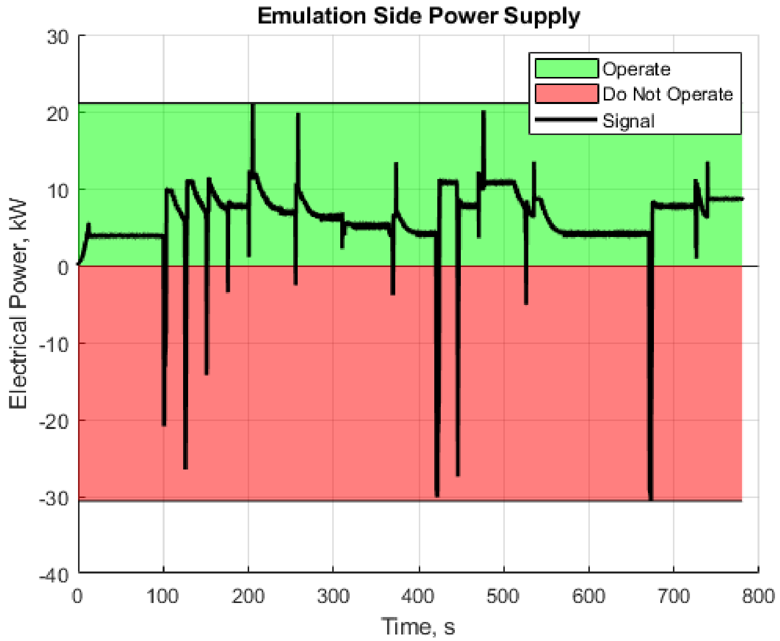


- Complete aircraft model, including powertrain, runs in real time on an external computer and pilot flies in the immersive environment of the flight simulator
- External computer can connect to another facility for piloted Hardware-in-the-Loop testing

EXAMPLE: DESIGN ANALYSIS/EVALUATION (1/2)

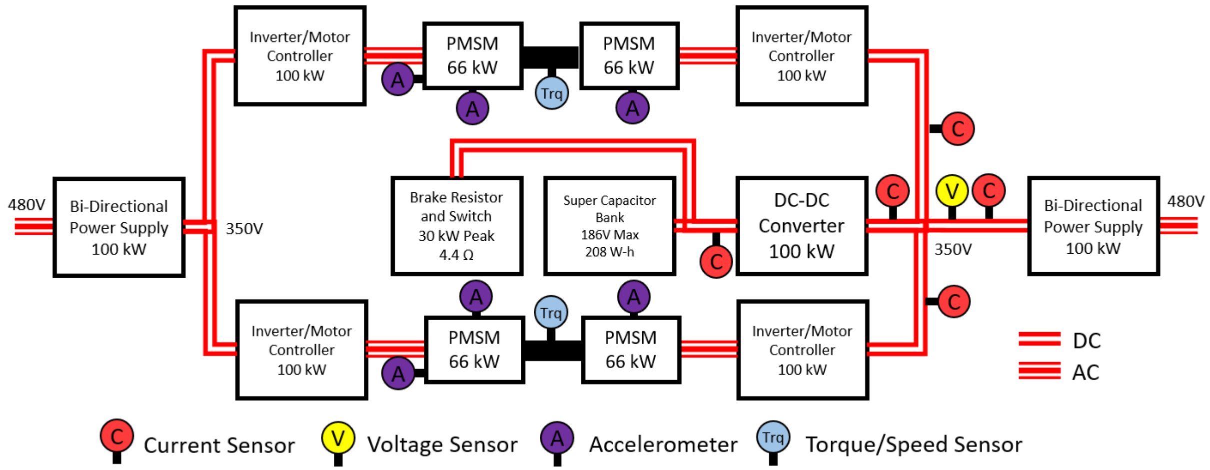
- Model and test/evaluate design before building to ensure that it performs as expected
- Created a dynamic model of a new motor lab (Hybrid Propulsion Emulation Rig (HyPER) lab) before the physical lab was built to gain understanding about its operation
- Simulation provided insight that pointed out a non-intuitive design flaw, forcing a redesign

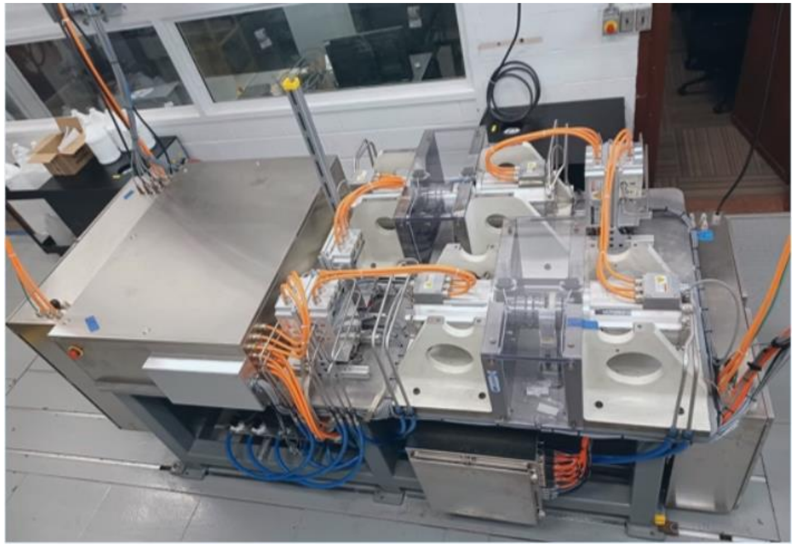




EXAMPLE: DESIGN ANALYSIS/EVALUATION (2/2)

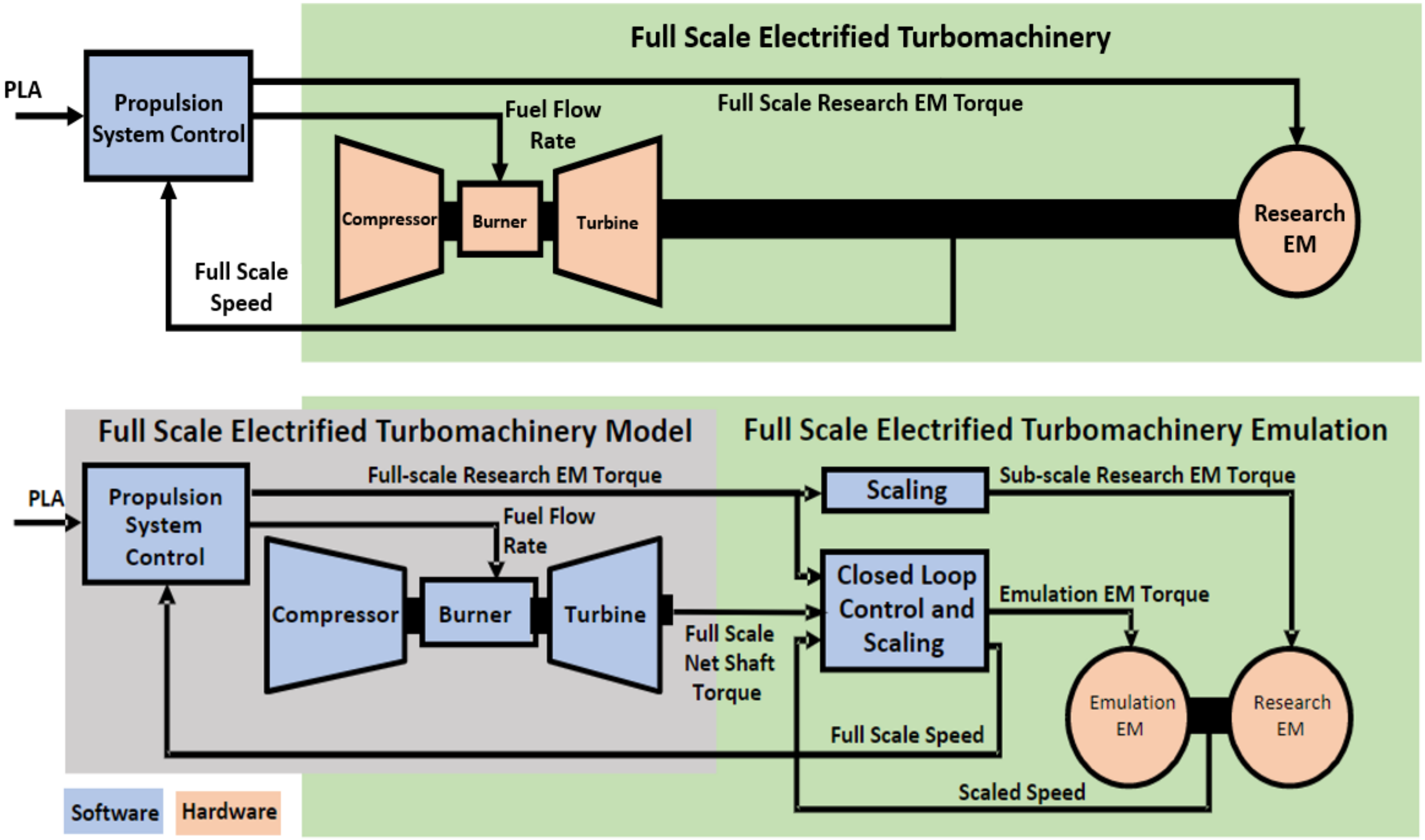
- Use of the dynamic model of the unbuilt system prevented a potential safety hazard and enabled redesign before buildup, saving time and money
- Now lab is built, pretest analysis continues to help set hardware limits and parameters





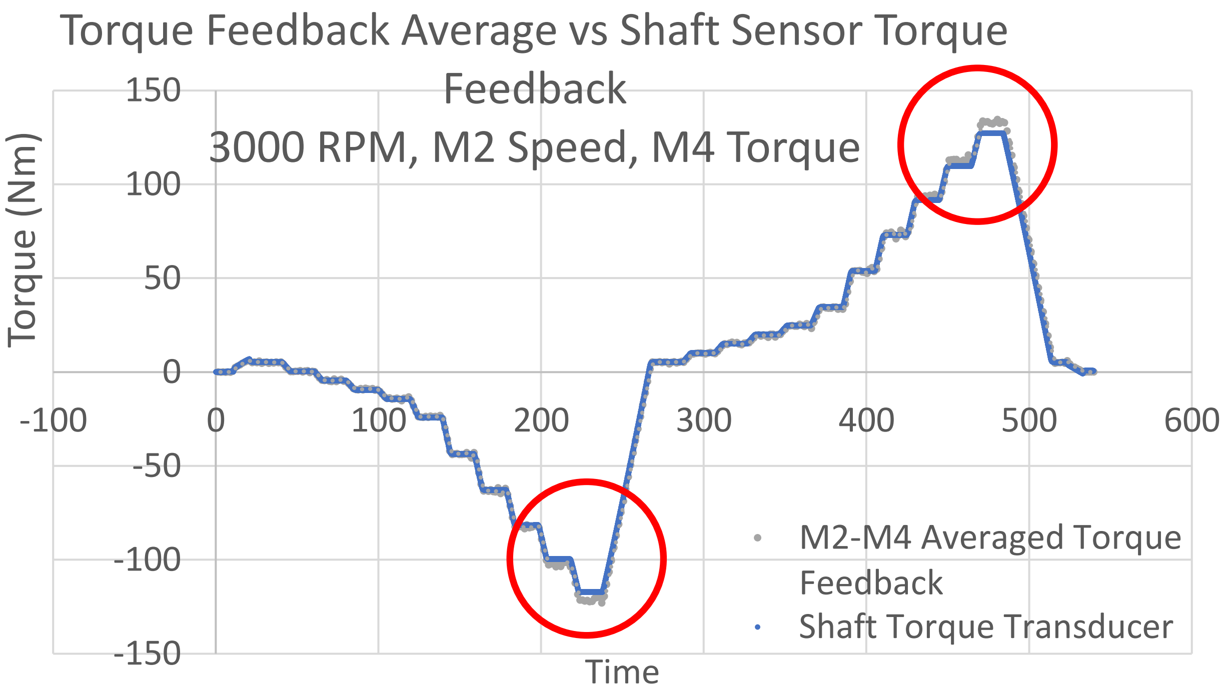
EXAMPLE: HARDWARE-IN-THE-LOOP

- Used in NASA Electric Aircraft Testbed (NEAT) Facility and Hybrid Propulsion Emulation Rig (HyPER) labs
- Enables testing of electrical hardware with simulated turbomachinery
- An innovative scaling technique allows small scale motor labs to represent full scale power systems



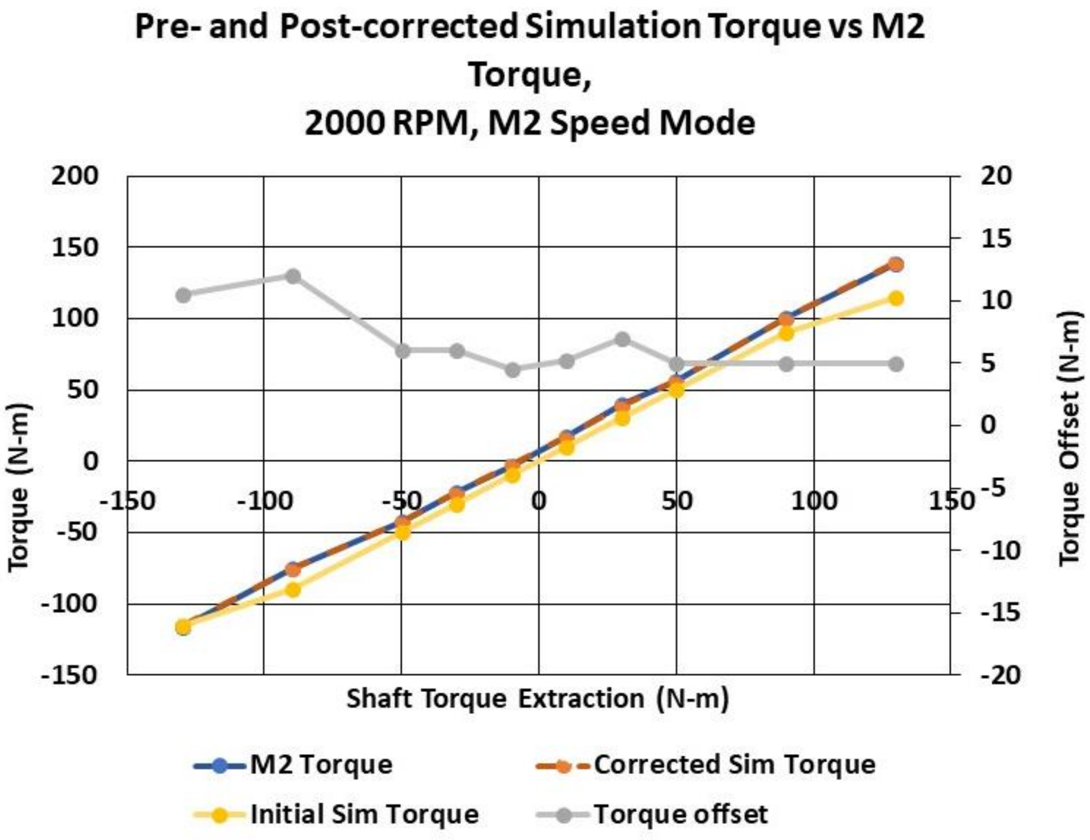
EXAMPLE: CHARACTERIZATION OF HARDWARE COMPONENTS (1/2)

- Can replicate conditions from spec sheet in the lab
- Validate component by running it in lab under the defined conditions
- Can set up a simulation of a whole system using data sheet specs
- In our case, the built-up system did not behave exactly as expected, we did not get torques expected based on simulation



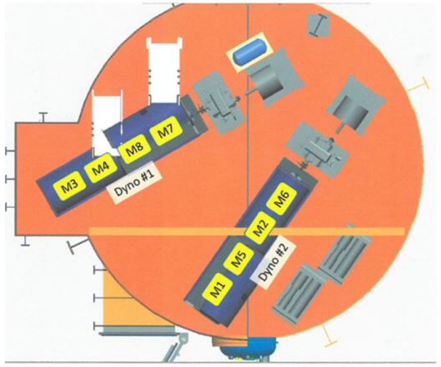
EXAMPLE: CHARACTERIZATION OF HARDWARE COMPONENTS (2/2)

- We could compare parts of the system and find the differences, helping to isolate the specific area of discrepancy
- Found repeatable unaccounted for damping torque, could be due to a motor or connection to shaft, etc., but isolated to one spot
- Allowed us to add a damping factor where necessary to match data well

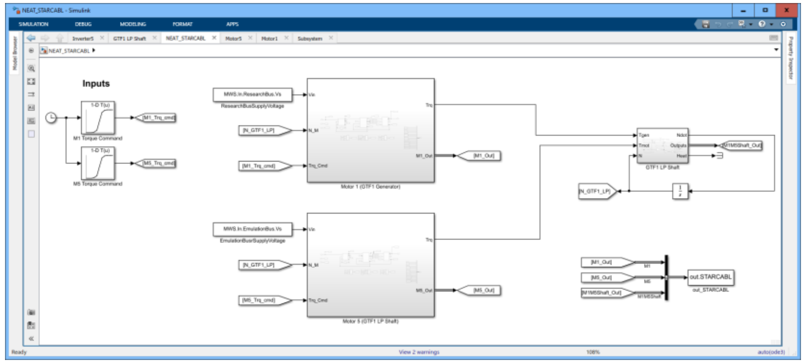


Digital Twin of EAP Power Train Components

- Provides “virtual representation” of actual electrical component hardware used for electrified aircraft propulsion (EAP) research
- Benefits of Digital Twin:
  - Provides models for controls research and development purposes
  - Serves as a health monitoring tool to detect system anomalies and degradation occurring over time
- Approach:
  - Baseline model of electric portion of EAP powertrain using EMTAT
  - Model parameters are determined via machine learning techniques applied to facility test data acquired from GRC EAP labs (NEAT and HyPER)
  - Will include automated approach for “tuning” model to track performance changes as additional data is acquired over time



NEAT Hardware Configuration

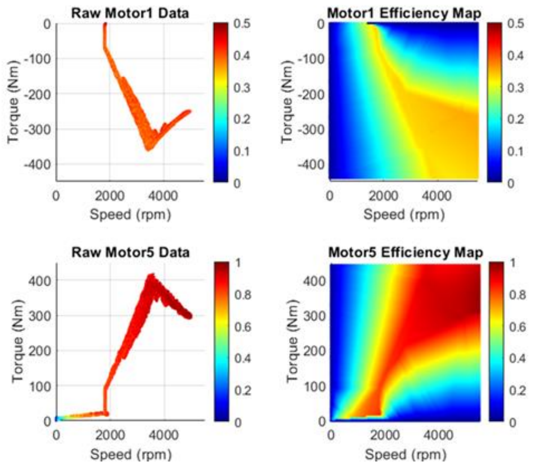


MATLAB™/Simulink™ EMTAT Digital Twin Model of EAP Powertrain

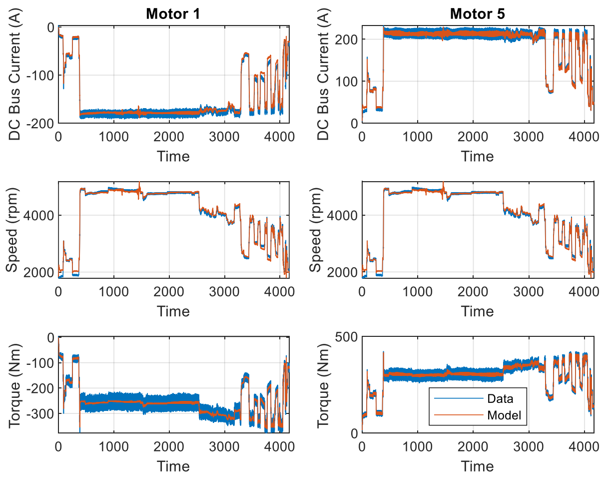
facility data

ML produced model parameters

Digital twin outputs



Model Parameters and Component Maps Determined by Machine Learning



Digital Twin Model Outputs Match Physical System Outputs

References

All the examples here and many more

- Litt, J.S., "Harnessing the Digital Transformation for Development of Electrified Aircraft Propulsion Control Systems," SAE Technical Paper 2023-01-1510, 2023, doi:10.4271/2023-01-1510; also NASA/TM-20230013301, October 2023.

AGTF30-e

- Kratz, J.L., "The Advanced Geared Turbofan 30,000 lbf – electrified (AGTF30-e): A Virtual Testbed for Electrified Aircraft Propulsion Research," AIAA 2024-3824, AIAA AVIATION FORUM AND ASCEND 2024, July 2024.

ADVANTAGES OF THESE TOOLS

- Built in industry standard MATLAB™/Simulink™
- Compatible with each other
- Completely customizable
- Created models are non-proprietary
- Compatible with MATLAB™/Simulink™ so all associated functionality is available
- Open source, free download

New Features Coming Soon

- T-MATS
  - Newton Raphson Solver with the Broyden Update Method
  - Volume Dynamics (increases the fidelity of the gas path dynamics)
  - Fuel Cell Modeling Capability (in addition to newly updated Cantera Interface)
- EMTAT
  - Updated Physics-based blocks
  - Thermal Management System Modeling Capability
- AGTF30-e with EMTAT Blocks

CONCLUSIONS

- Standard, reusable dynamic models and parameterizable powertrain components simplify new simulation development
- Efficient execution means that most models run faster than real time on a standard computer
- New capabilities are added as needed. User community can make a branch and add features, official versions are maintained by NASA
- For questions about the examples presented or the tools themselves, contact Jonathan Litt at jonathan.s.litt@nasa.gov

Acknowledgments

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- ARMD/TACP/TTT
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