# ENHANCED ELECTRO-MECHANICAL POWERTRAIN SAFETY THROUGH DETERMINISTIC ONLINE MODEL ASSIMILATION

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EOL Energy Optimization Laboratory

# eVTOL SAFETY MUST BE #1

- Air transportation in heavily populated areas is considered high risk and even a single event can cause an industry to collapse.
- The eVTOL industry must look to the past to ensure proper safety, maintenance, and performance conditions for economic success.
- Nov. 12, 2023 – Joby flies first urban flight in NYC.

1977 helicopter wreck on PANAM building killed 5 & halted heliport services in NYC.

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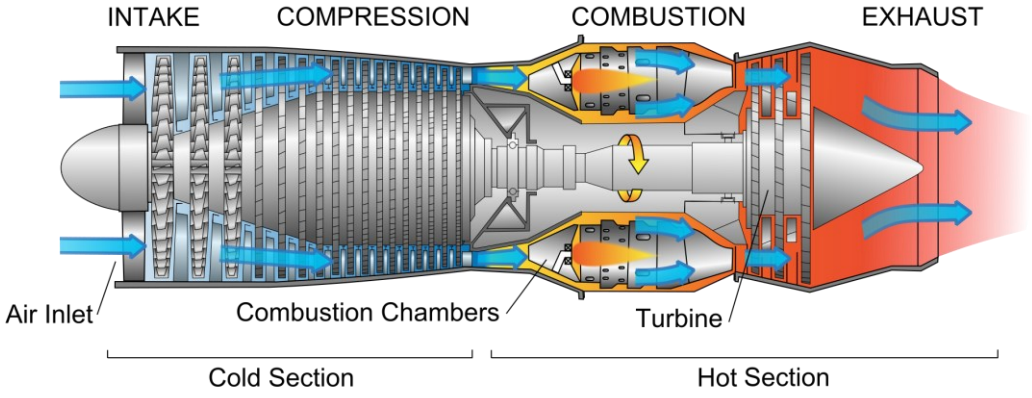
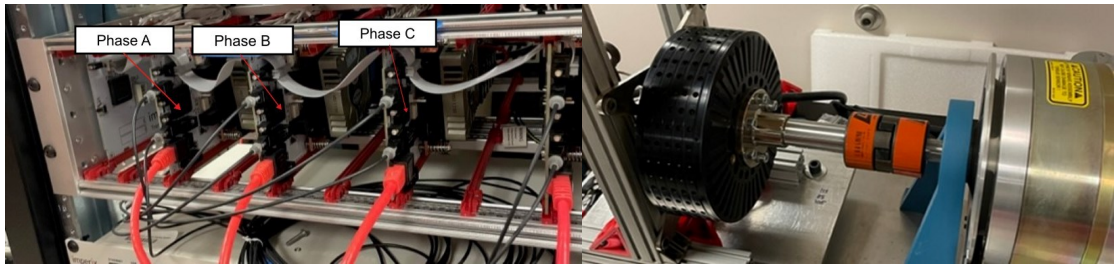
# THE SHIFT TO ELECTRIC AVIATION

## Jet Combustion Engine




## Electric Powertrain: Inverter + Electric Machine

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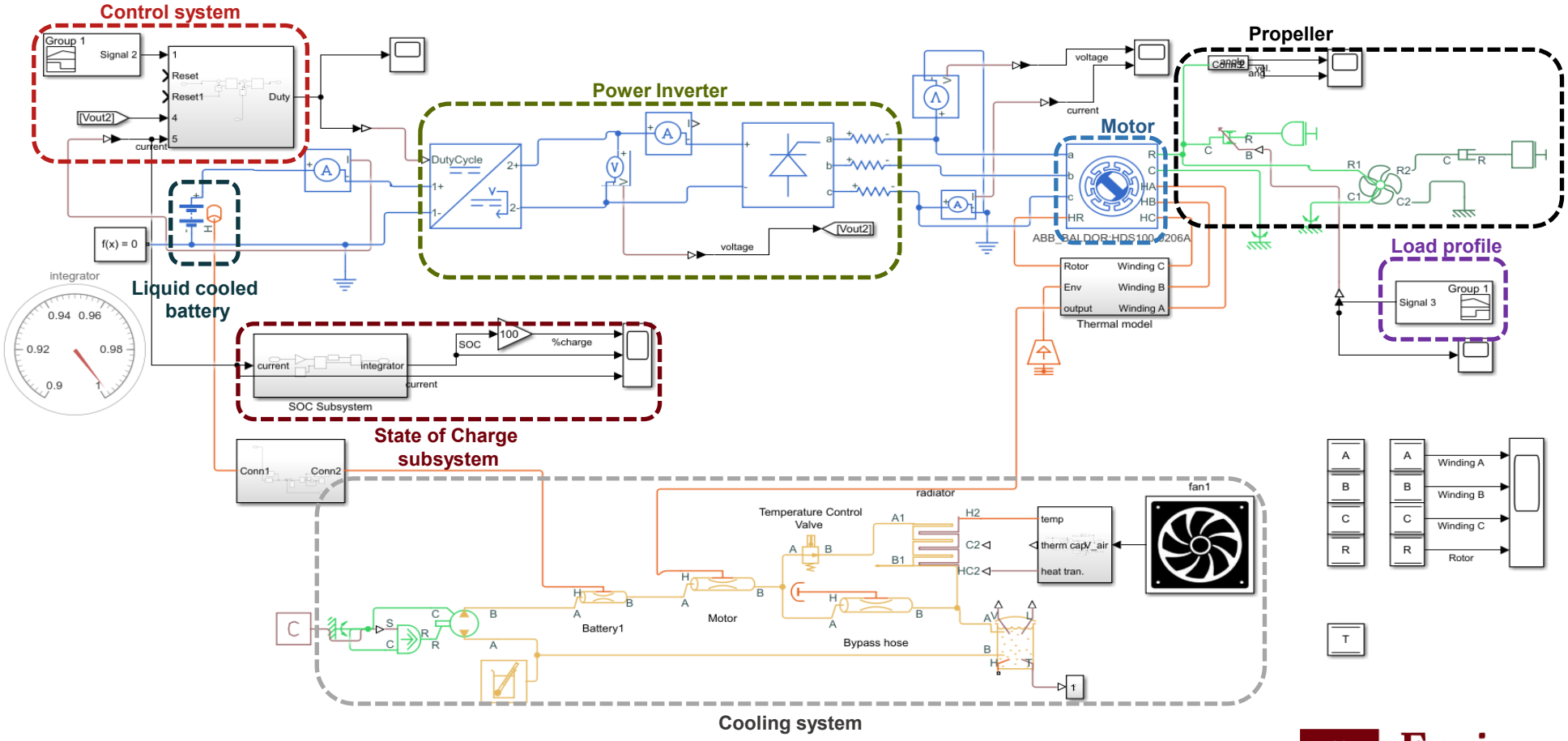
# FINAL REVIEW OUTLINE

- Full-scale eVTOL multi-domain modelling.
- Standardizing digital twin I/Os.
- Digital shadow: remaining useful life modelling.
  - Batteries & inverter components.
- Testbed overview and demonstration.
- Project conclusions.
- Future directions & discussion.

# SIMULINK MULTI-DOMAIN MODELING

- The Simulink model consists of the electrical, mechanical, and thermal components of the major system in the electric aircraft.
- An abridged version of a state of charge monitoring system was also added for the battery.
- With varying load profiles, results from different subsystems can be derived.

# MULTI-DOMAIN MODEL OF THE POWERTRAIN

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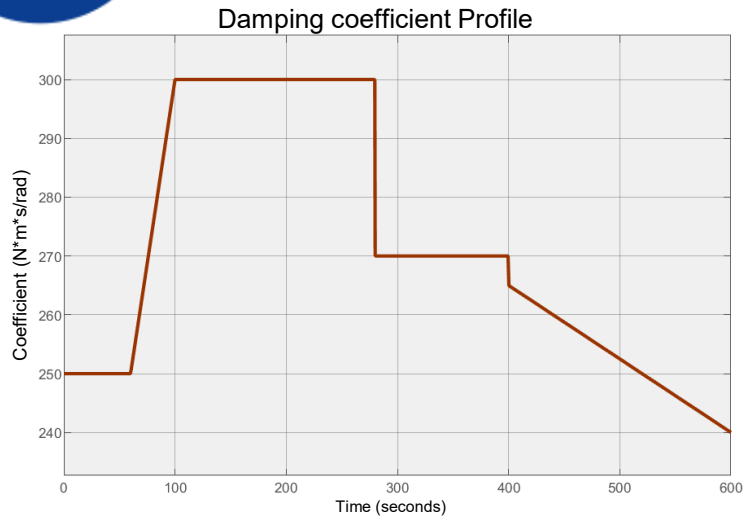
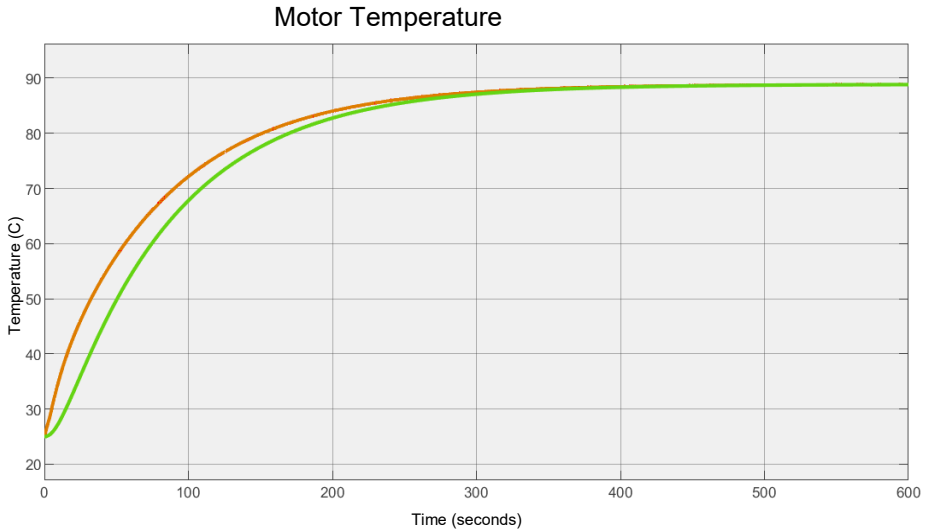
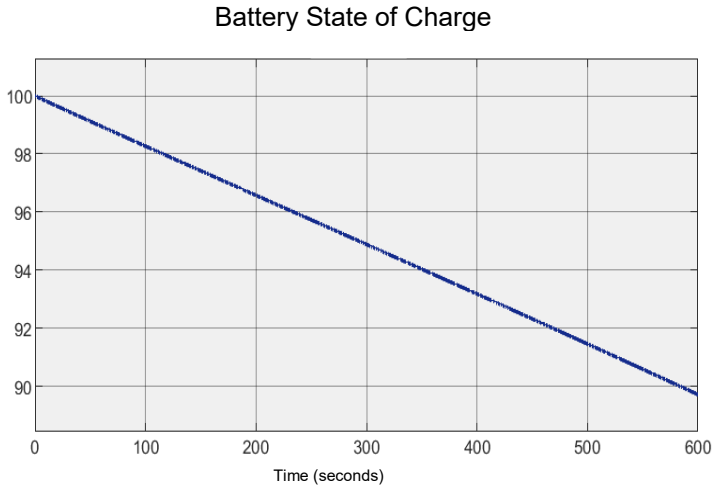
# SIMULATION RESULTS

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# STANDARDIZATION OF DIGITAL TWINS

**Digital Model:**

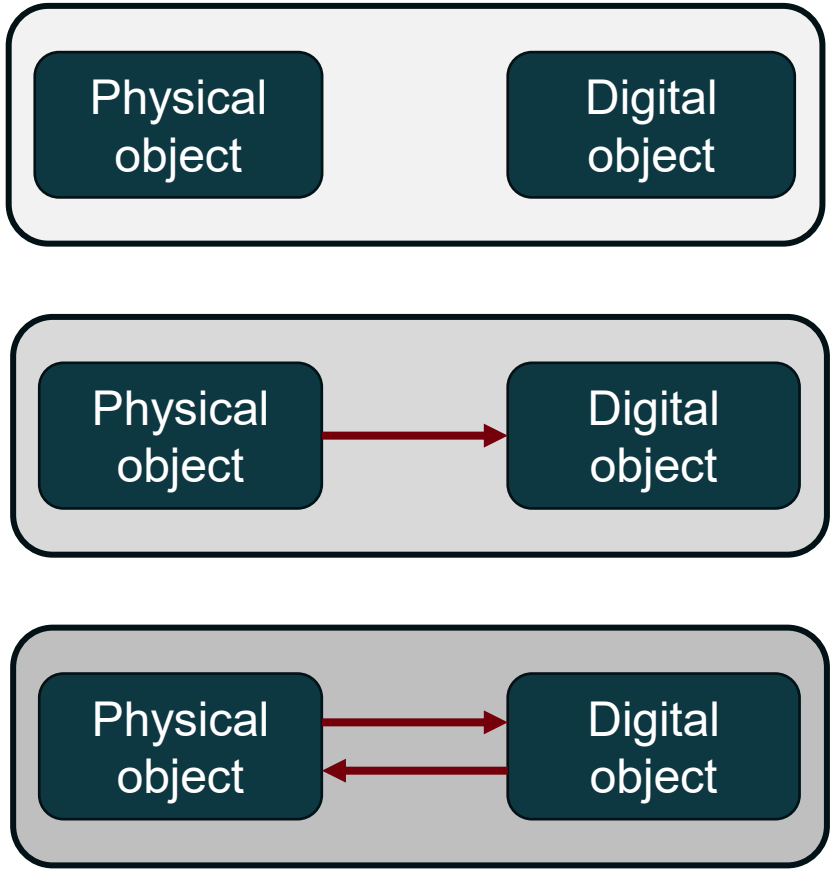
- No data flow, replication of condition.

**Digital Shadow:**

- Data exchange is unidirectional.

**Digital Twin:**

- Data exchange is bidirectional.

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# STANDARDIZATION OF DIGITAL TWINS

## Digital Twin (DT):

- It is an integrated representation that mirrors the lifecycle of a physical asset.
- Operates on any arbitrary timescale:

Slower than real-time | Real-time | Faster than real-time

## Physical Twin (PT):

- Is the physical asset, which can vary in complexity.

## Physical System:

- Is the system that encapsulates the physical twin and the edge computing devices for running DTs.

K. Booth, K. Sado, J. Hannum, J. Knight, and R. Dougal, “Introduction of Posture-Based Pre-Alignment for Naval Applications,” in 2023 IEEE Electric Ship Technologies Symposium (ESTS), 2023, pp. 1–4.

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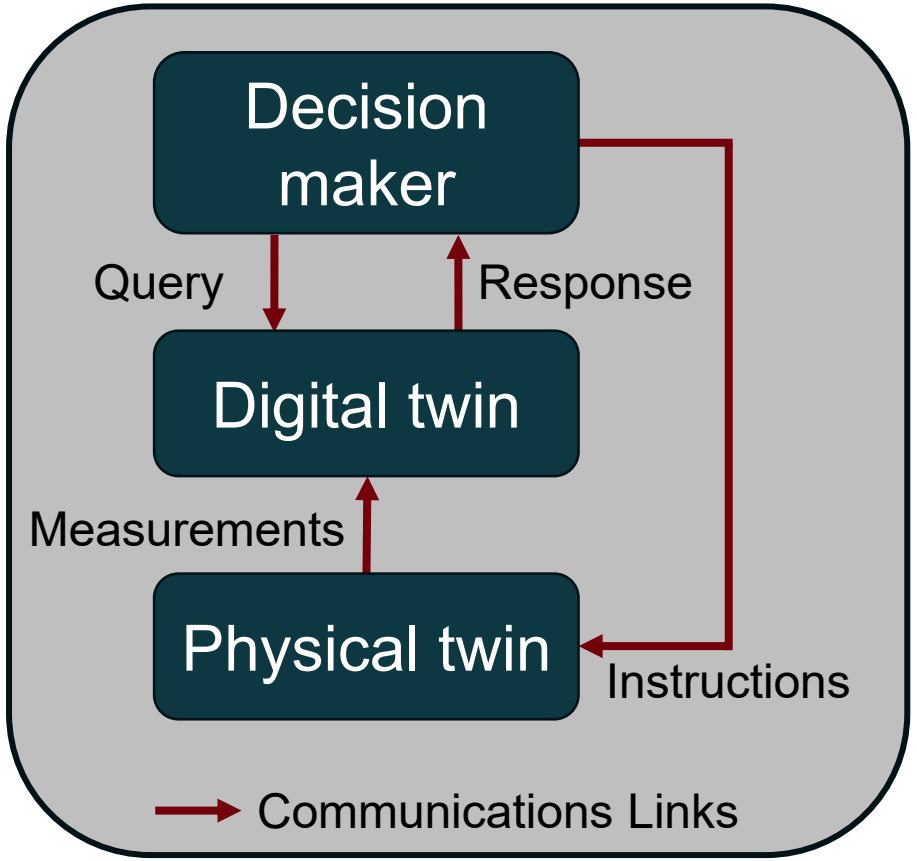
# STANDARDIZATION OF DIGITAL TWINS

**Decision Maker:**

- A control algorithm, operator, or a human-in-the-loop.
- Defines the desired response and constraints for system operation.
- Develops the goal or query for the digital twin to study.




K. Sado, J. Hannum, E. Skinner, H. L. Ginn and K. Booth, "Hierarchical Digital Twin of a Naval Power System," *2023 IEEE Energy Conversion Congress & Exposition (ECCE)*, Nashville, TN, USA.

K. Booth, K. Sado, J. Hannum, J. Knight, and R. Dougal, "Introduction of Posture-Based Pre-Alignment for Naval Applications," in 2023 IEEE Electric Ship Technologies Symposium (ESTS), 2023, pp. 1–4.

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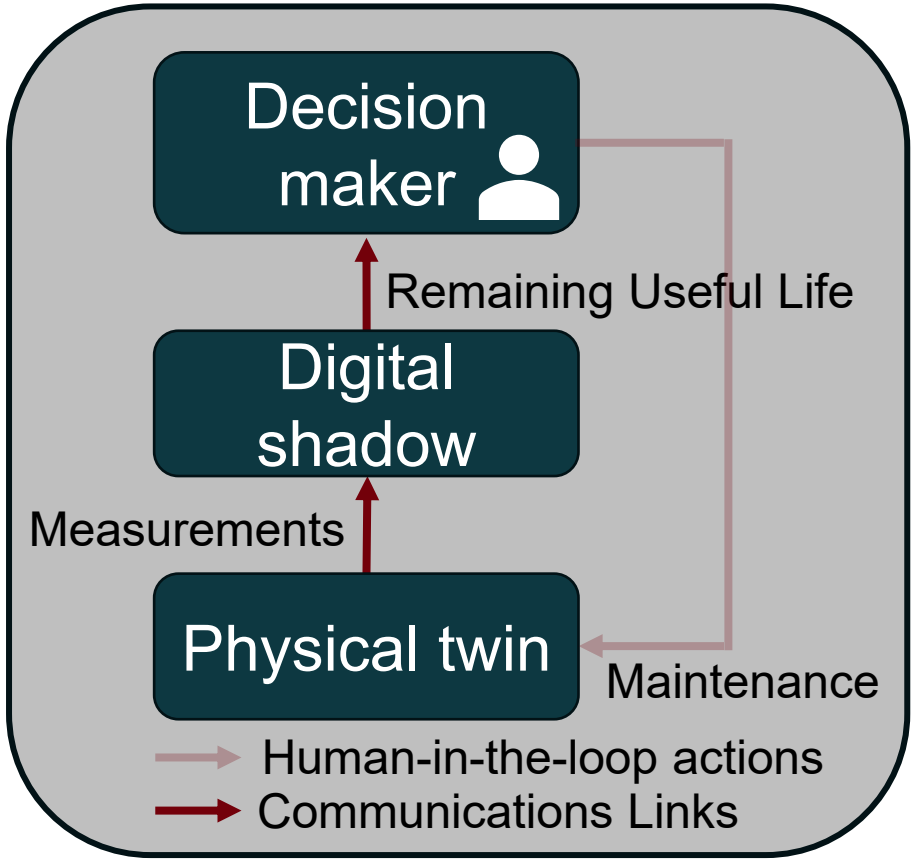
# POWERTRAIN DIGITAL SHADOW

- Focused on maintenance and replacement of parts.
- Monitors key aspects of the powertrain.
- Takes physical measurements and applies lifetime models to determine remaining useful life.
- Enables per-aircraft maintenance management.

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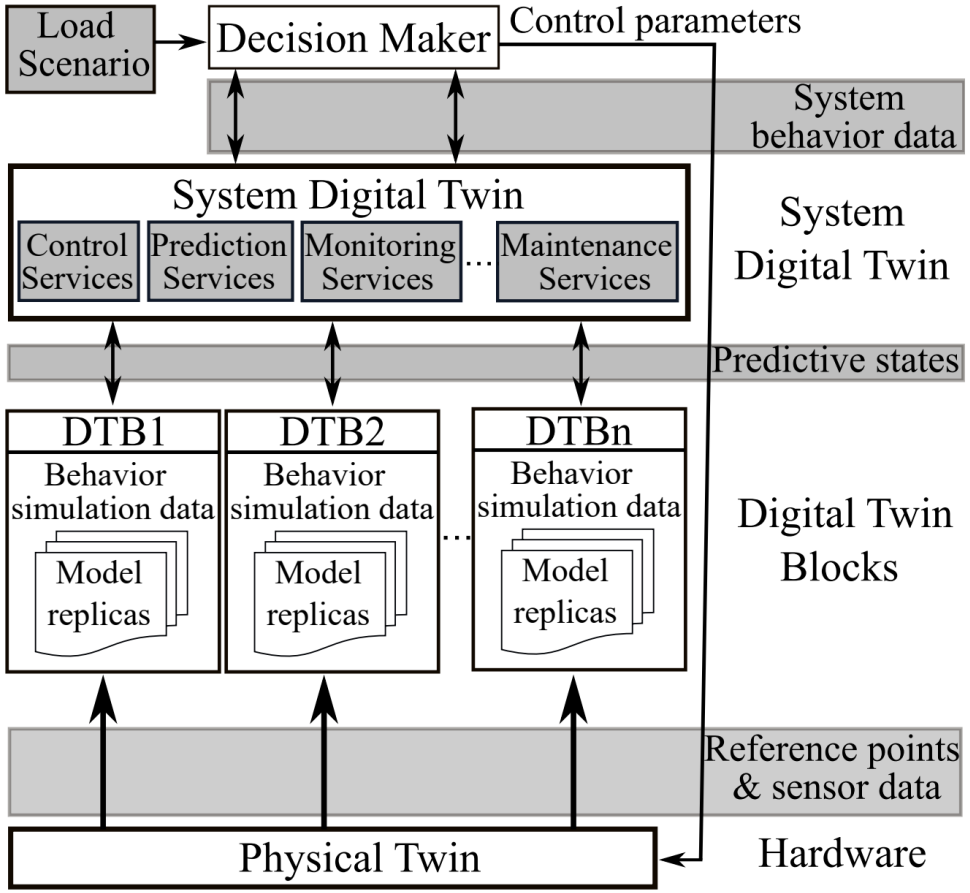
# POWERTRAIN TO POWER SYSTEM

- Powertrain digital twins can be collectively combined with other systems to create a hierarchical digital twin.
- Enables digital twin distributed computing with plug-n-play updates for asset maintenance, asset replacement, and DT model updating.

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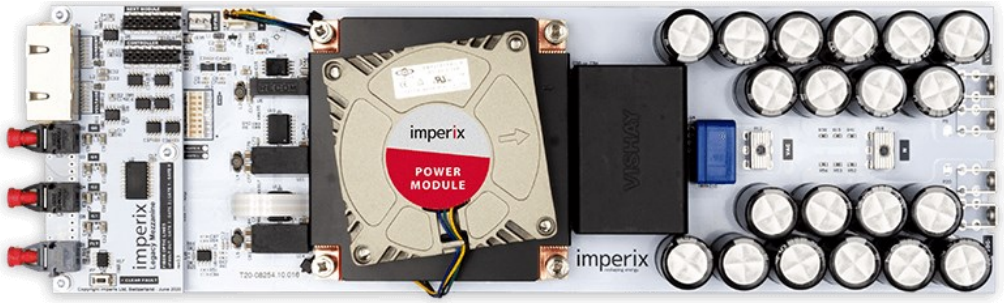
K. Sado, J. Hannum, H. Ginn, and K. Booth, "Hierarchical Digital Twin of a Naval Power System," 2023 IEEE Energy Conversion Congress and Expo (ECCE), Nashville, TN, Oct. 2023.

# REMAINING USEFUL LIFE MODELS

## Energy Storage

## Inverter Components




## Motor

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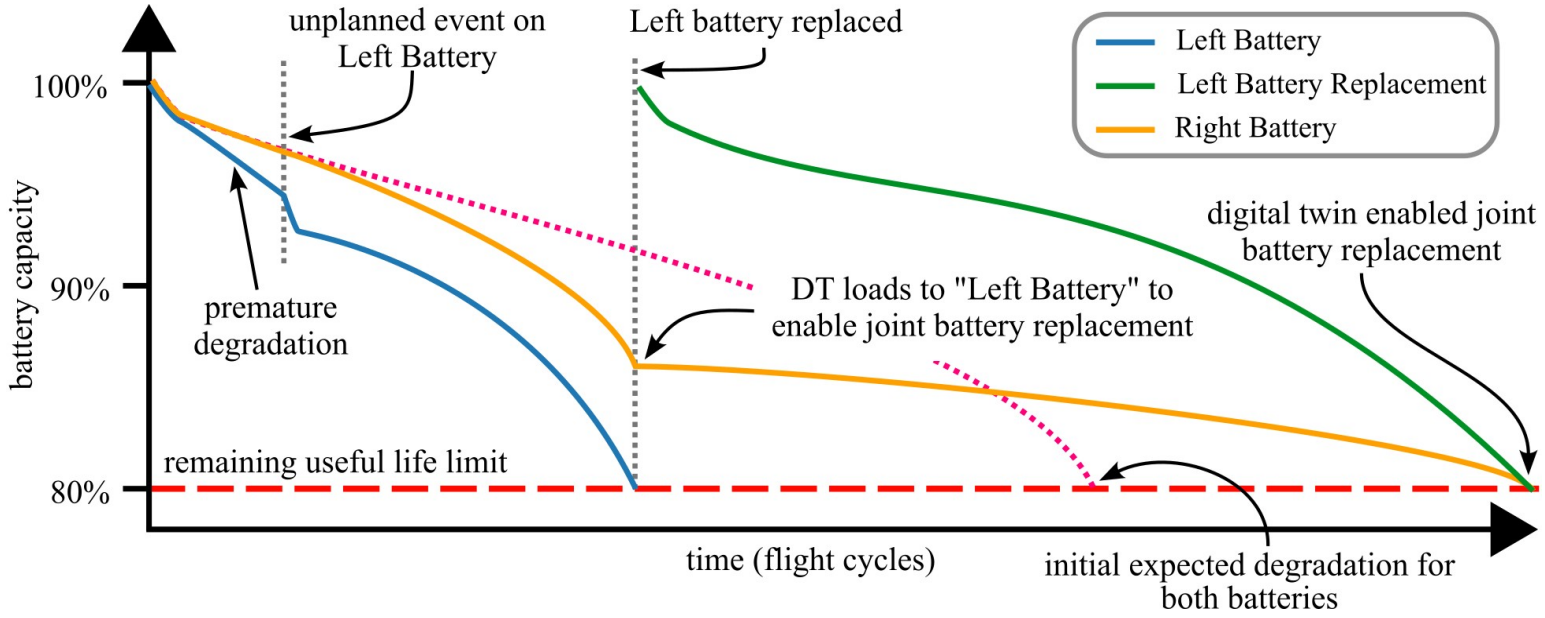
# BATTERY LOAD SHARING




An aircraft has a premature battery failure and replaces one of its batteries prematurely. The system will equalize the RULs to return to its original maintenance cycle.

G. Anthony, J. Peskar, N. Cooper, A. Downey, and K. Booth, “Extending Battery Life via Load Sharing in Electric Aircraft,” accepted to the 2024 American Institute of Aeronautics and Astronautics (AIAA) Conference, Orlando, FL, Jan. 2024.

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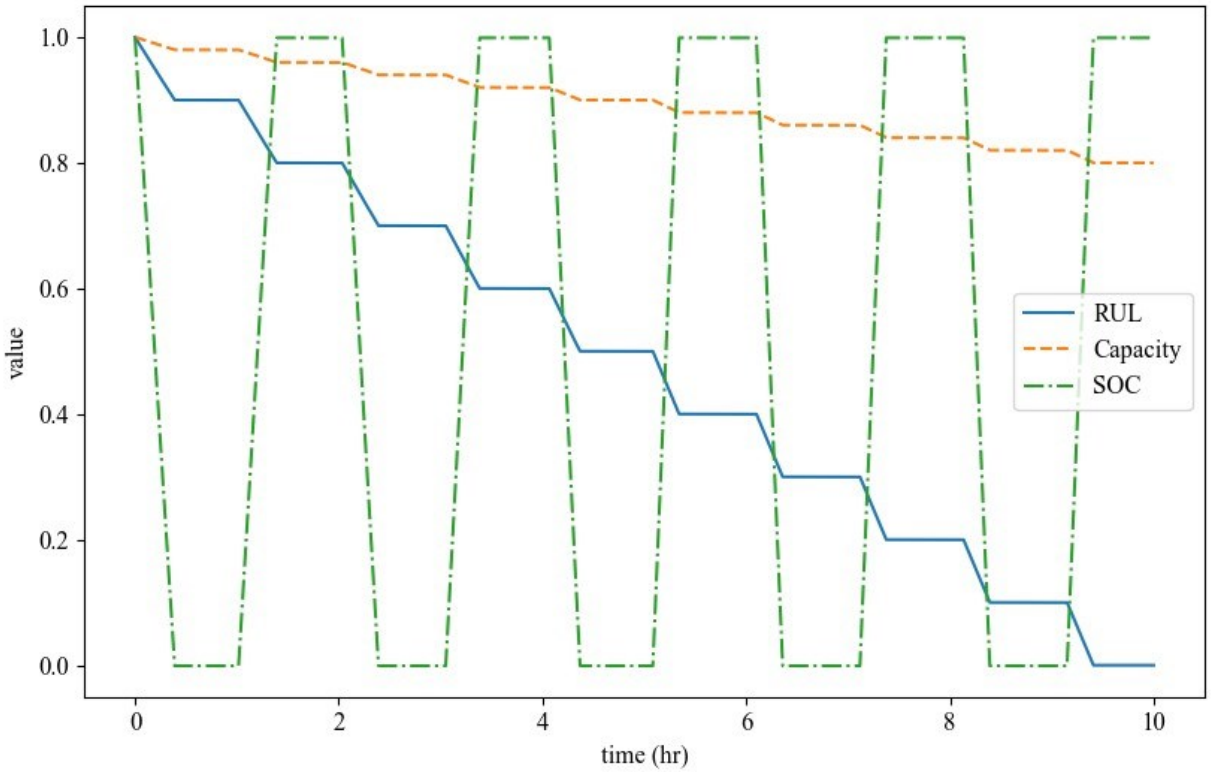
# BATTERY REMAINING USEFUL LIFE

- Tracks the battery's Remaining Useful Life (RUL) by recording current and comparing it to cycle life.
- As RUL approaches 0, the batteries capacity reduces to 0.8 its nominal capacity.




Simulated RUL decrease of a battery with 5 Cycle life.

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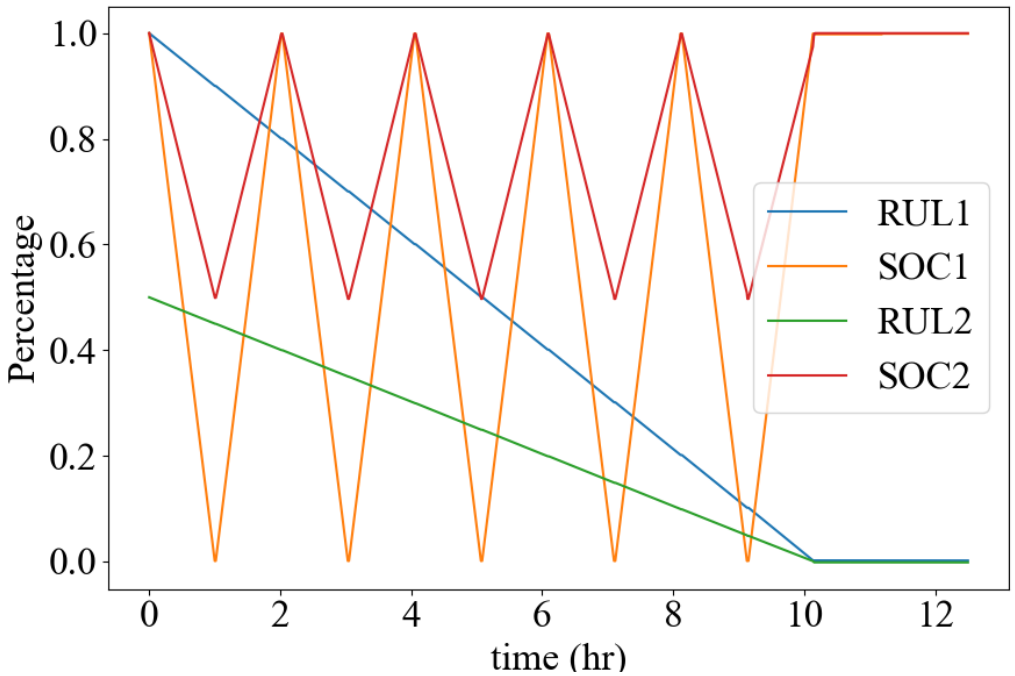
# LOAD SHARING EXAMPLE

- The adaptive agent prioritizes the battery with a higher RUL.
- By degrading one battery over the other it can match the RULs at zero.
- This allows for a normalized maintenance cycle going forward.




Batteries with starting RUL of 1 and 0.5 loadshare scenario

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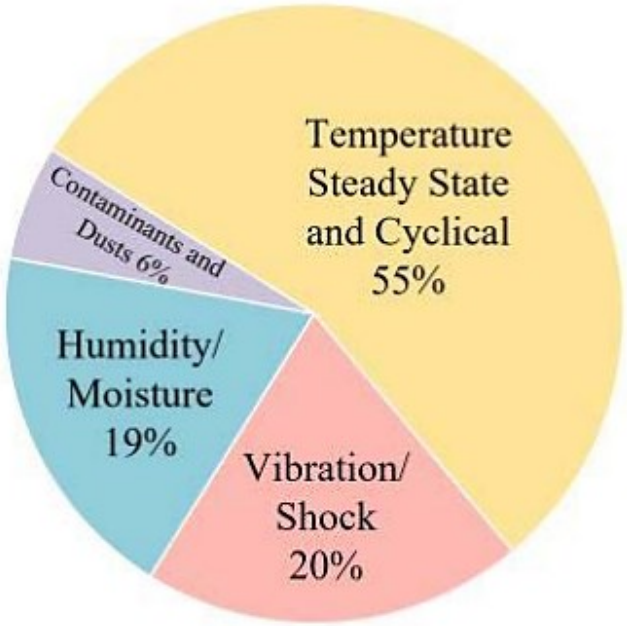
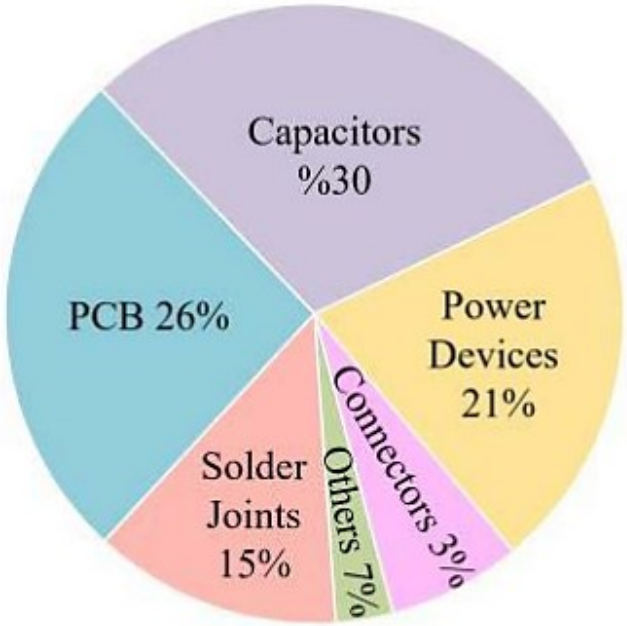
# FAILURE MODES OF POWER ELECTRONICS

Device level failure → Converter failure → System failure

- There is near zero tolerance for failure in various critical applications, including electric vehicles (EVs), aerospace, naval ships, and others.
- Temperature is one of the major sources contributing to the degradation of converters.




B. Wang, J. Cai, X. Du and L. Zhou, "Review of power semiconductor device reliability for power converters," in CPSS Transactions on Power Electronics and Applications, vol. 2, no. 2, pp. 101-117, 2017, doi: 10.24295/CPSSTPEA.2017.00011

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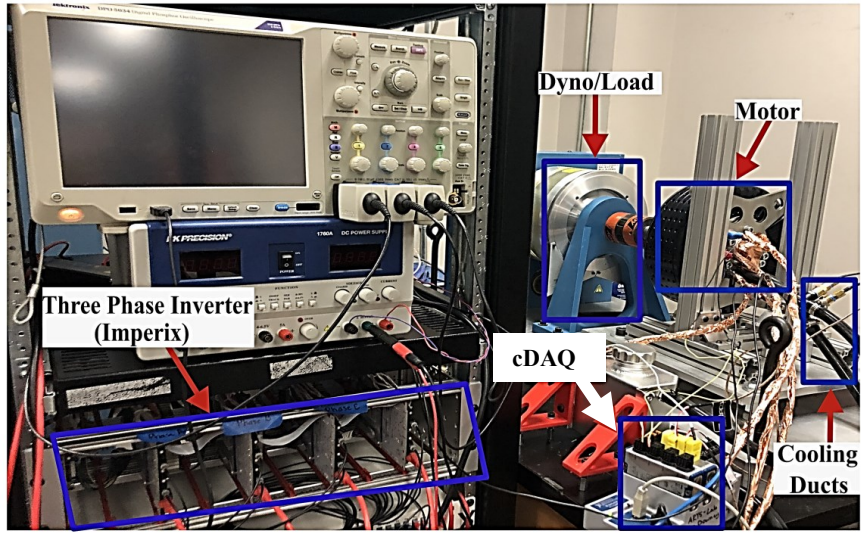
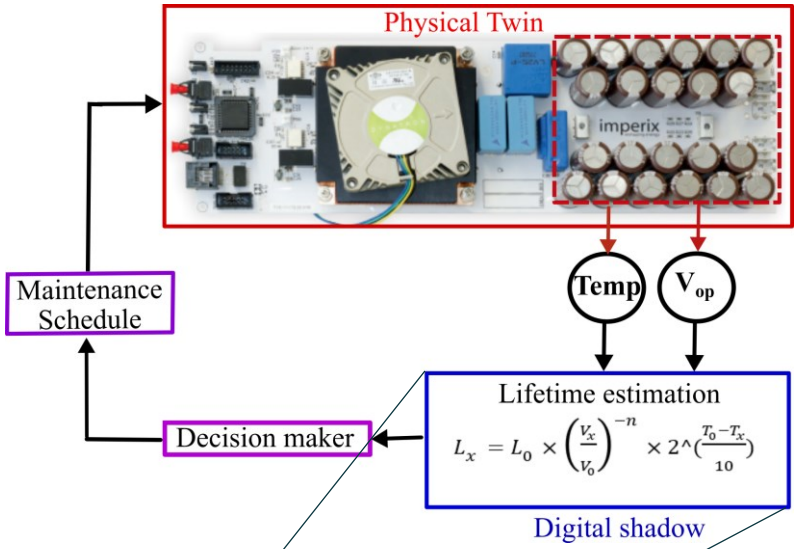
# CAPACITOR DEGRADATION MODEL




$$L_x = L_0 \times \left(\frac{V_x}{V_0}\right)^{-n} \times 2^{\frac{T_0 - T_x}{10}}$$

H. Wang and F. Blaabjerg, "Reliability of Capacitors for DC-Link Applications in Power Electronic Converters—An Overview," in IEEE Transactions on Industry Applications, vol. 50, no. 5, pp. 3569-3578, Sept.-Oct. 2014.

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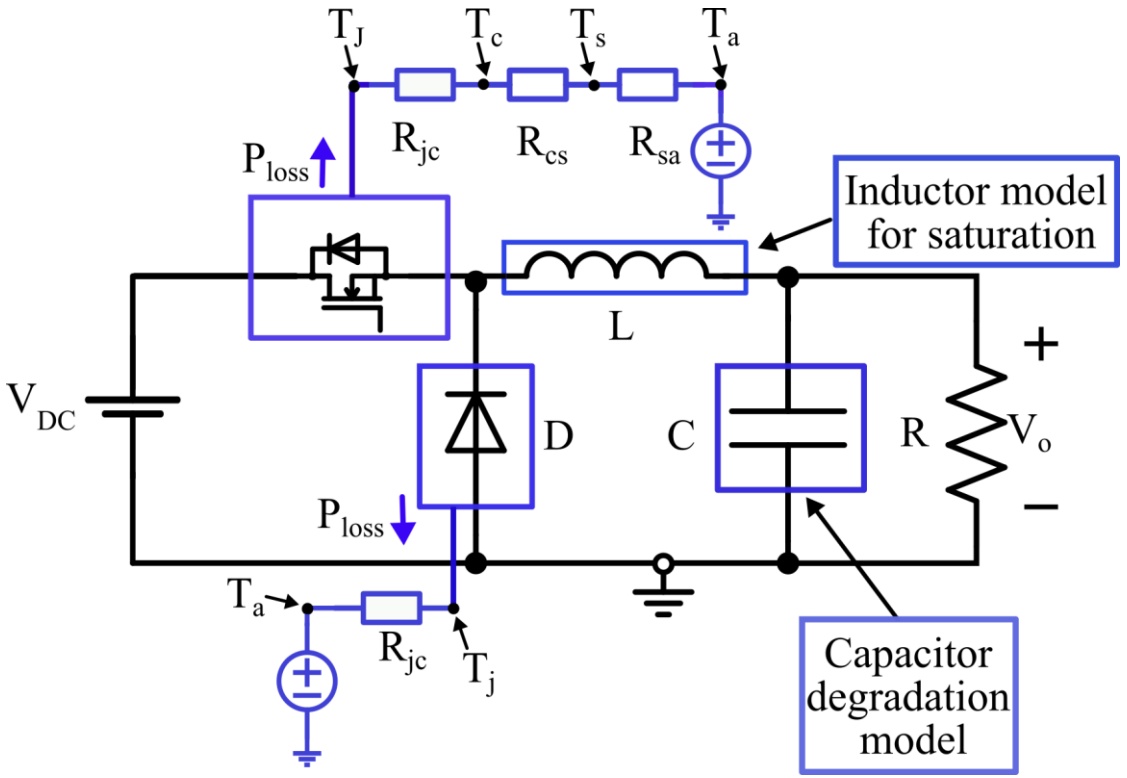
# FAILURE AVALANCHE AVOIDANCE




- A failure in one component can lead to an avalanche of failures throughout the system.
- A healthy component may be required to exert beyond its ratings.
- Digital twin can support emergency landing procedures for safe landing.

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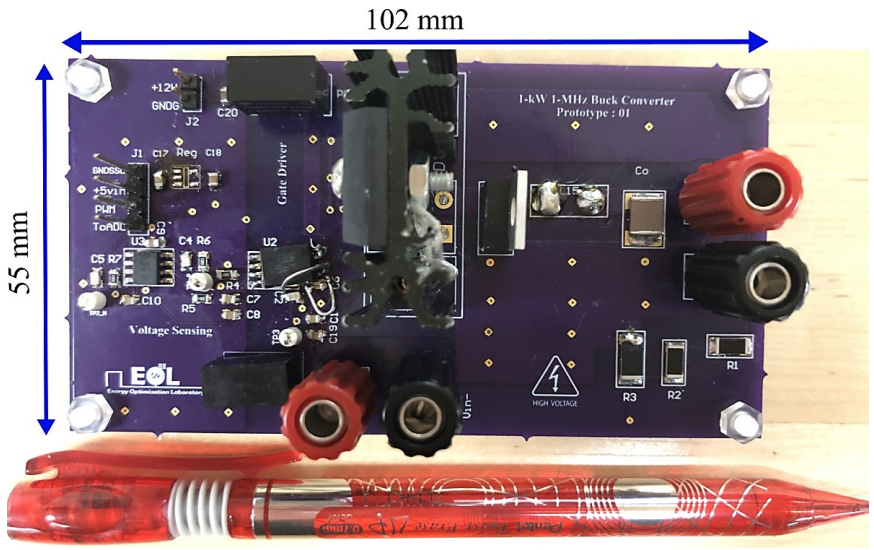
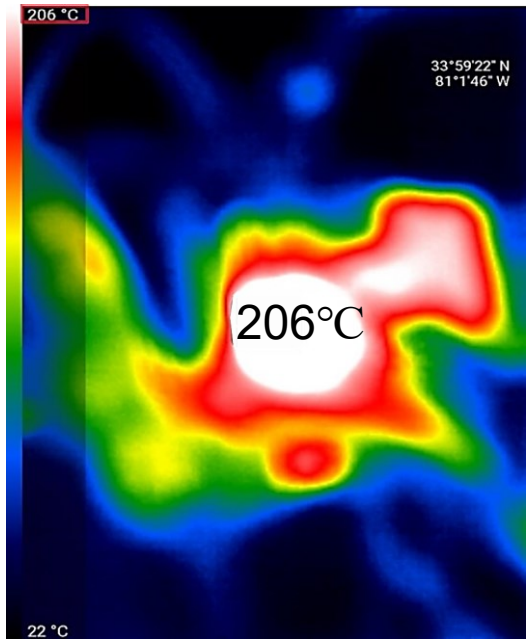
# CONVERTER OFF-NOMINAL TESTING




- PCB nominally designed for 4.5 A with 6.5 A max trace width.
- A stepping current was applied from 3.5 A to 7 A.
- Monitored devices' temperature and losses.

A. Hussain… "" in submission to ITEC…

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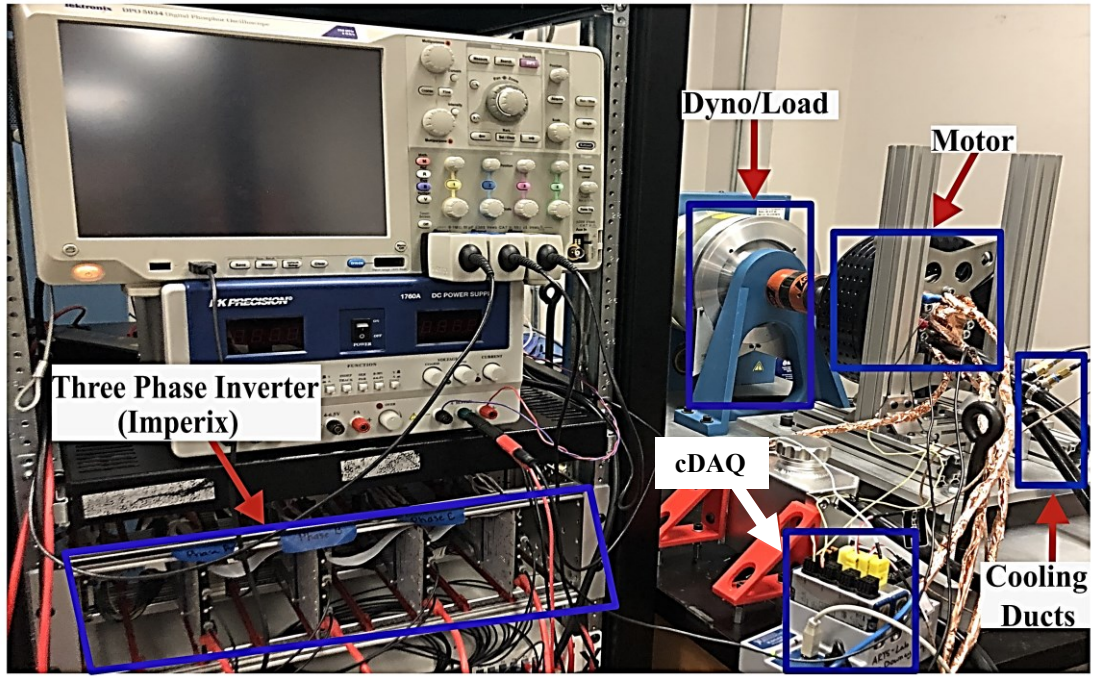
# TESTBED OVERVIEW

- 3-Phase Variable Frequency Drive- 3x Imperix IGBT Half-Bridge.
- Permanent Magnet Synchronous Machine- Emrax 228 MV CC.
- Digital Shadow of Motor + Inverter.
  - Implemented in real-time in Opal-RT.
- LabView Control Panel for real-time analytics.
- Imperix Cockpit for testbed, scenario control.

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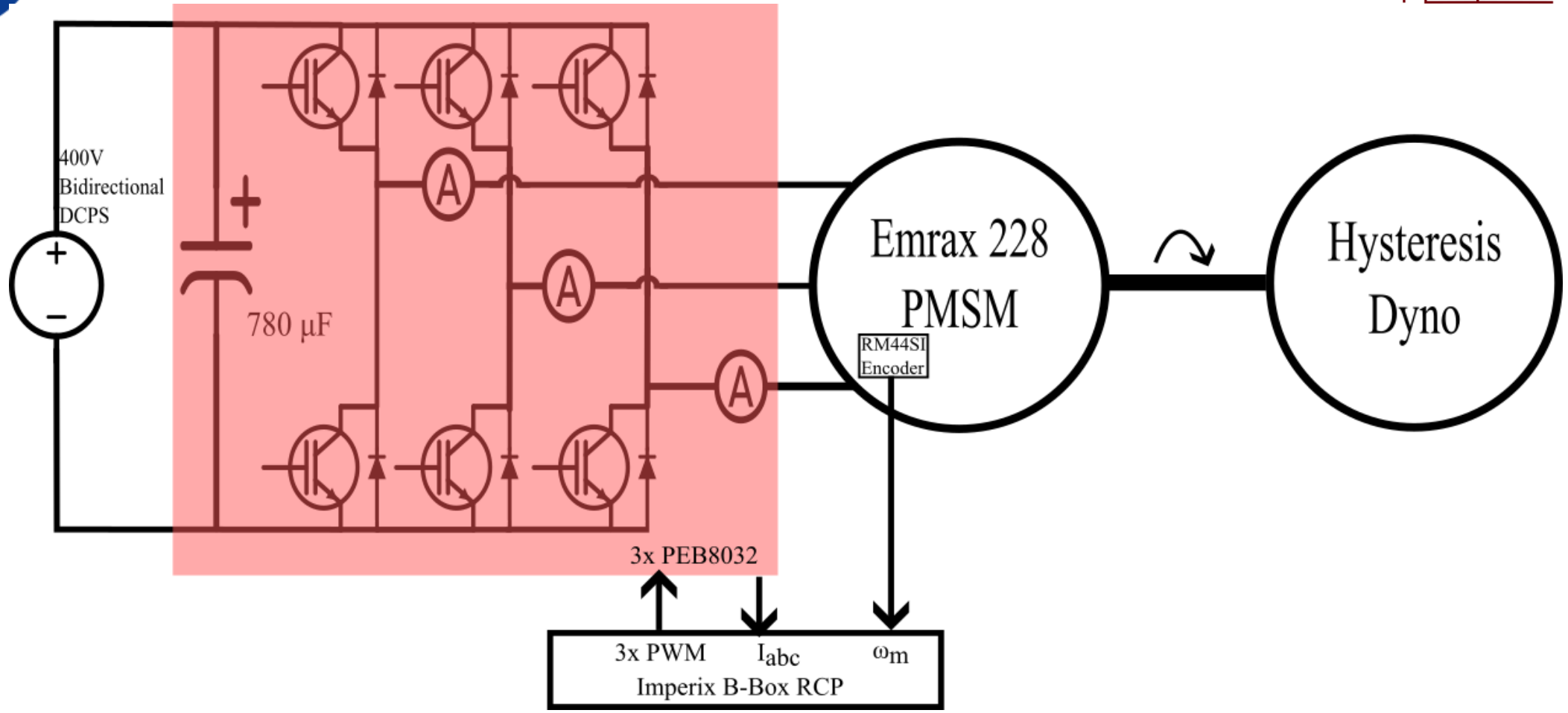
# TESTBED SCHEMATIC

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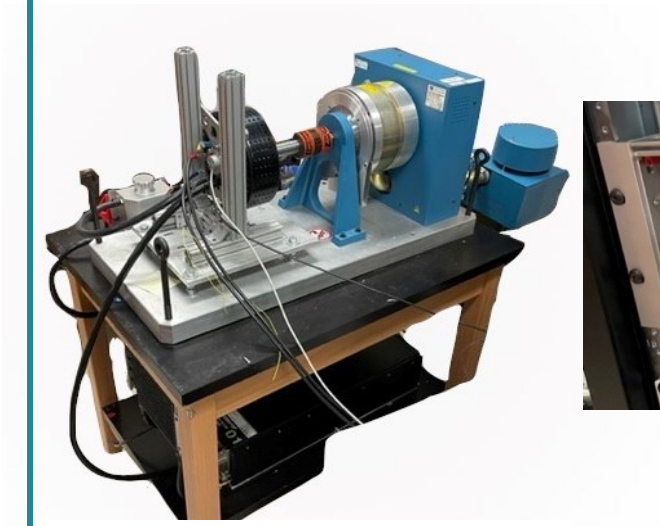
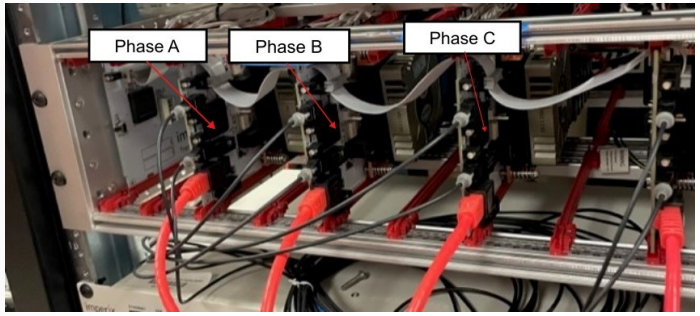
# PHYSICAL SYSTEM

## Physical Object



**Motor-Load Physical Twin**




**Inverter Physical Twin**

## Digital Object

- Model updates.
- Predictive modelling and maintenance scheduling.
- Remaining useful life of components.

Sensor Measurements via UDP

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# EVTOL FLIGHT PLAN

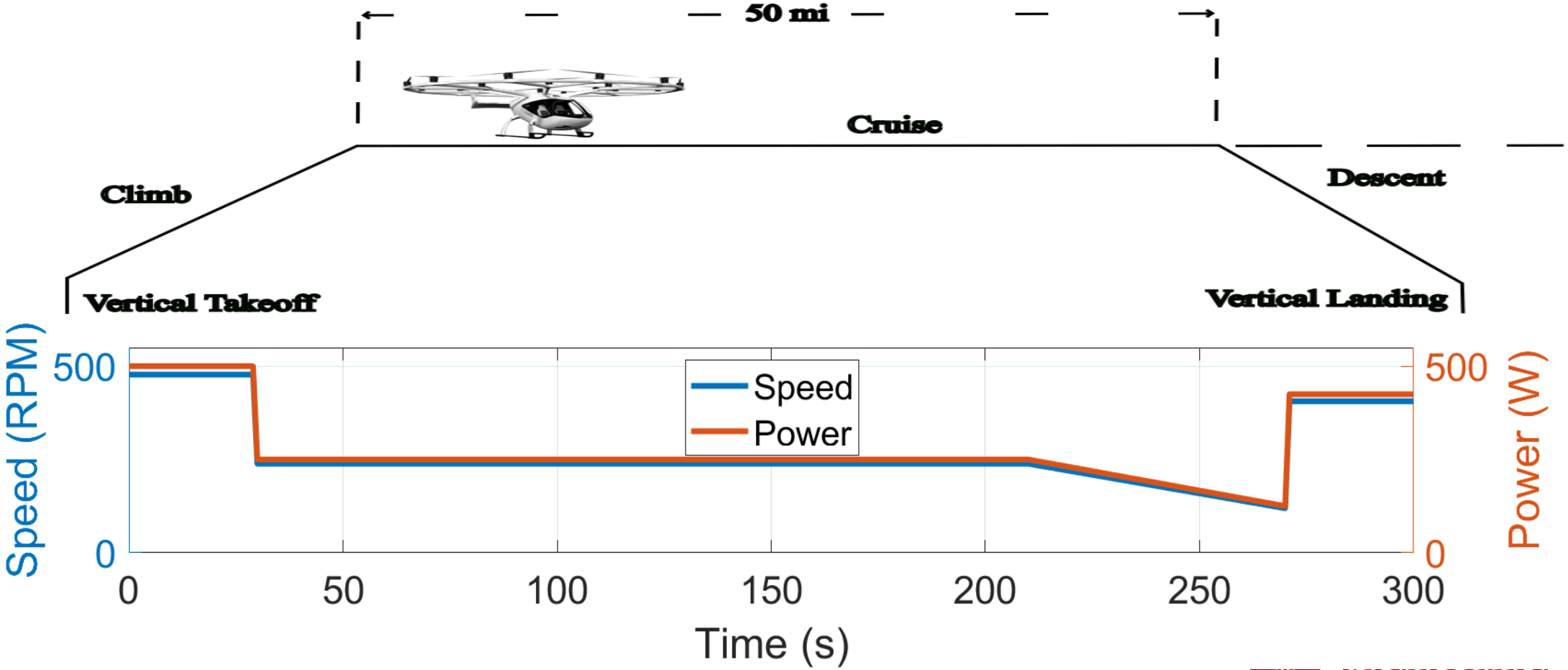


Image not to scale.

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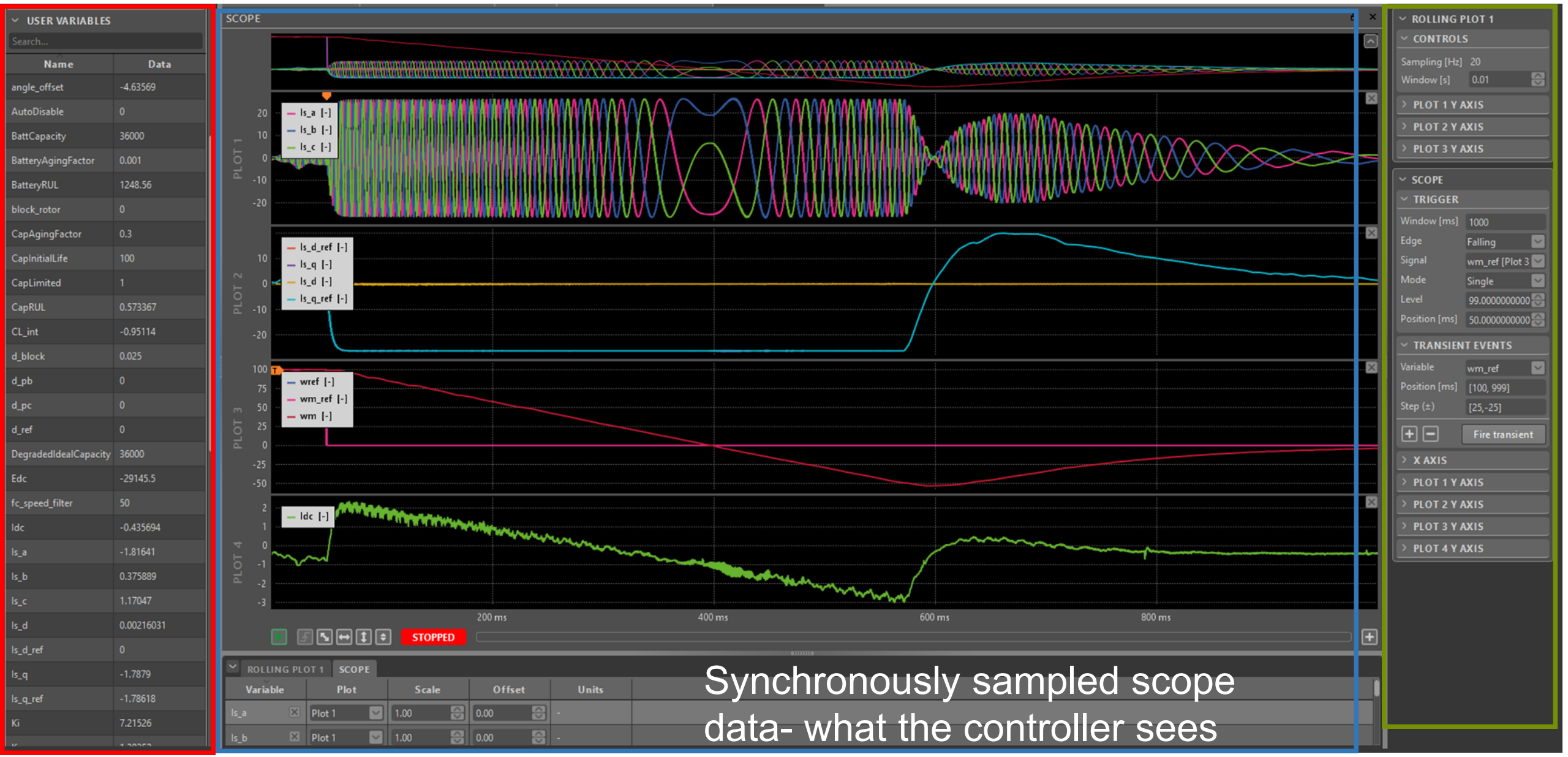
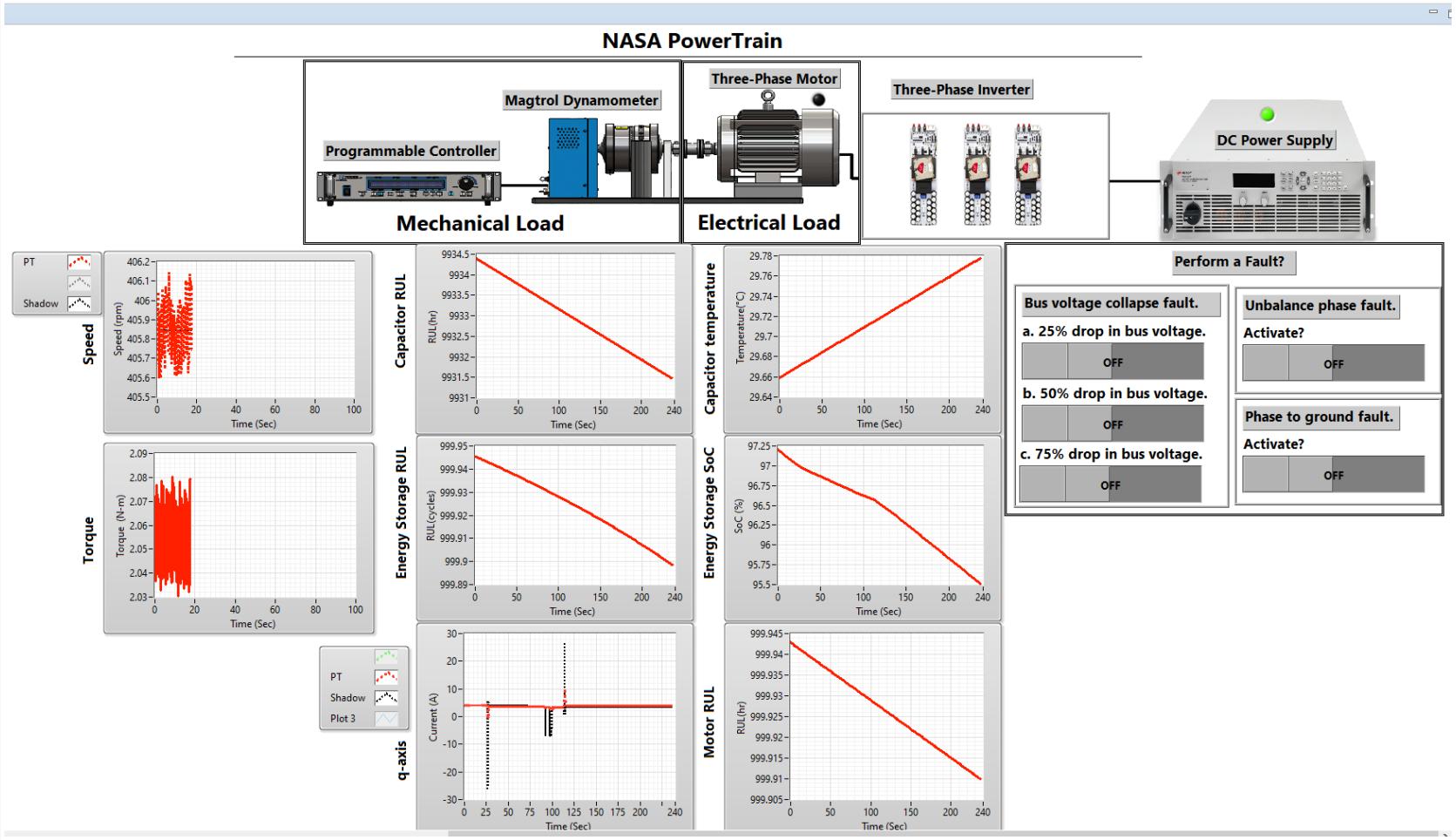



Synchronously sampled scope data- what the controller sees

Live tunable parameters for controllers, set-points & RUL calculation

Scenario Control- timed steps in speed to change motor power

# DIGITAL SHADOW PANEL




- Motor + inverter shadow.
- Capacitor RUL.
- ES RUL.
- Motor RUL.

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# RECORDED DEMONSTRATION

Click to play demo.

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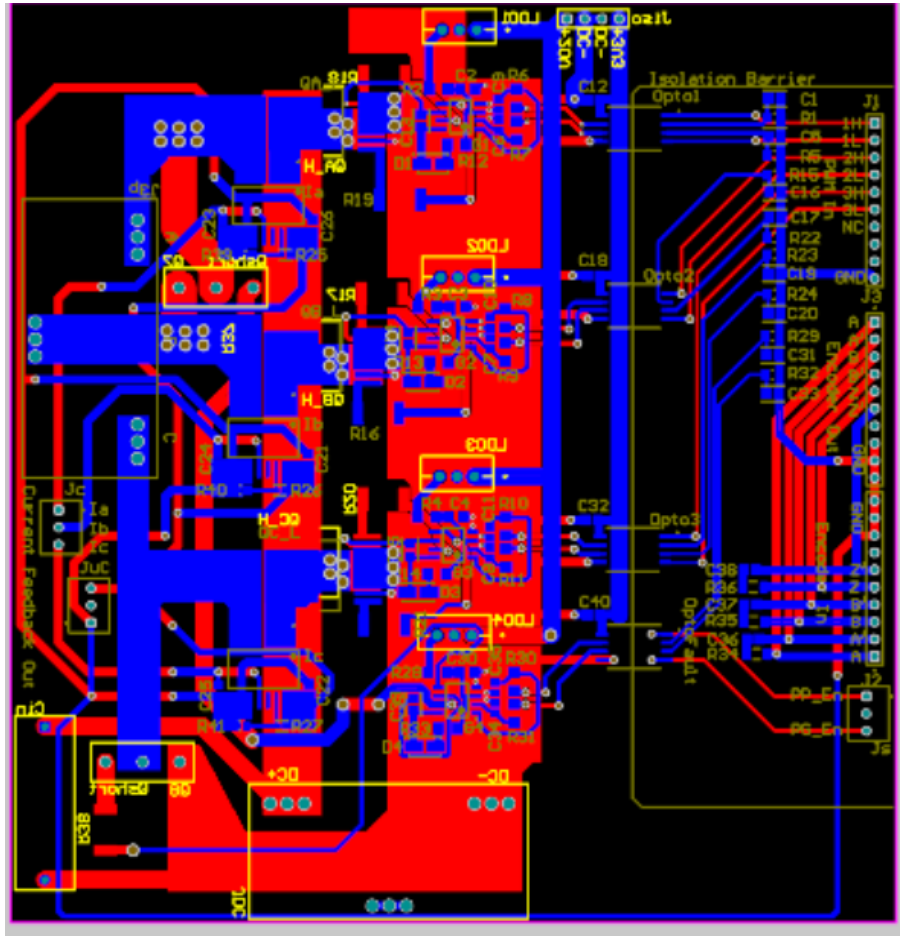
# PROJECT RESULTS

- Developed digital twin structure for eVTOL powertrain for RUL.
  - Can be extended to eVTOL power system.
- Full digital twin integration can modify system controls to aid maintenance scheduling.
- Improved maintenance management can mitigate potential for disastrous powertrain failures and eVTOL downtime in normal operating conditions.
- Off-nominal failures can exacerbate an emergency, and more studies are needed to avoid avalanche failure conditions.

# FUTURE WORK

- Inverter fault conditions:
  - Phase to phase asymmetric short.
  - Phase to ground/chassis short.
  - DC bus voltage collapse.
- Simulate and emulate faults via Opal-RT and PHIL for eVTOL.
- Fault in hardware on custom inverter board.
  - 500-kHz SiC MOSFET inverter designed – fab in process.

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# OPEN FLOOR DISCUSSION

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# Thank you to SC NASA EPSCoR Rapid Response Research funding & NASA Glenn Research Center.

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