System Health Management for a Series/Parallel Partial Hybrid Powertrain with Distributed Electric Propulsion

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AIAA SciTech Forum

January 8-12, 2024

Orlando, FL

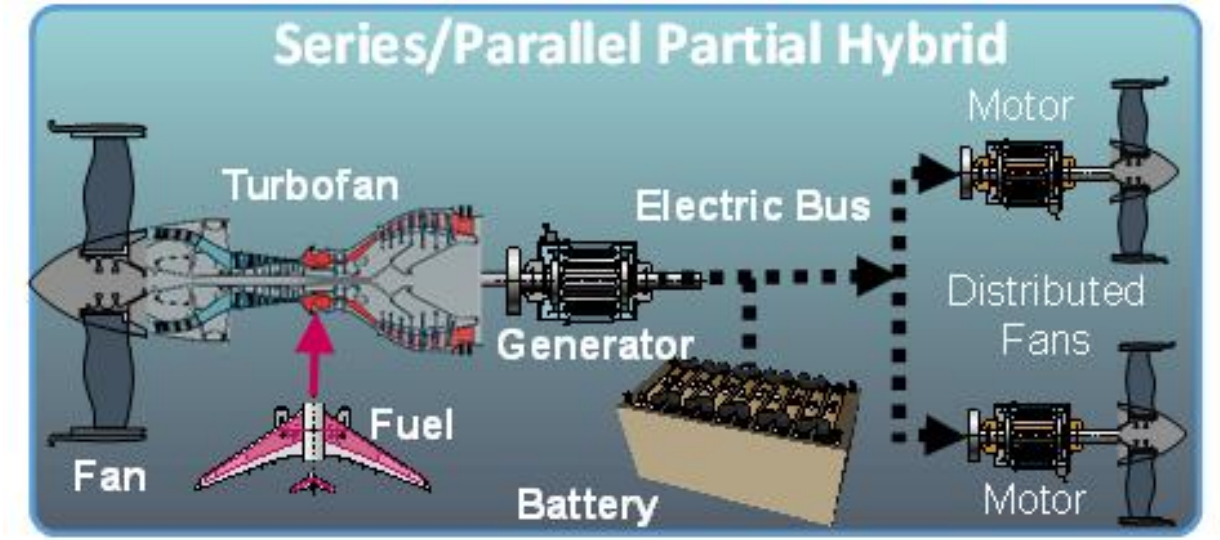
Overview

- Background/Definitions
- Examples
- Conclusions

SUbsonic Single Aft eNgine (SUSAN) Electrofan

- 2040 entry-into-service concept
- Single aisle 180 PAX regional jet
- Single Turbofan in the Empennage
- 16 Underwing Contrarotating Electric Fans or Electric Engines
- Series/Parallel Partial Hybrid Powertrain
- Small Reusable/Rechargeable (Secondary) Batteries Help Enable Electrification Benefits
- Single-Use (Primary) Batteries Provide Emergency Power, e.g., in the Case of a Turbine Engine Failure

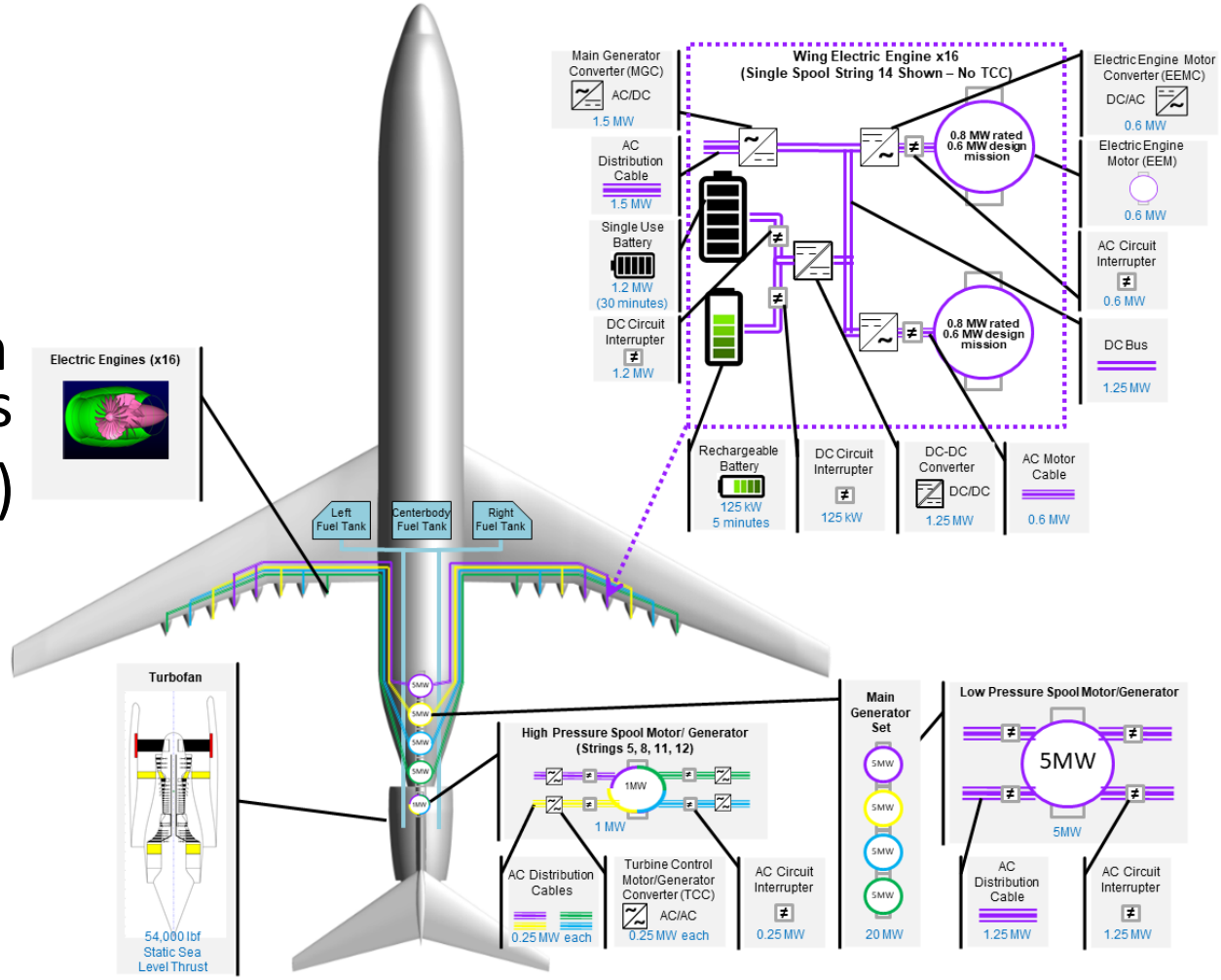




SUSAN Powertrain

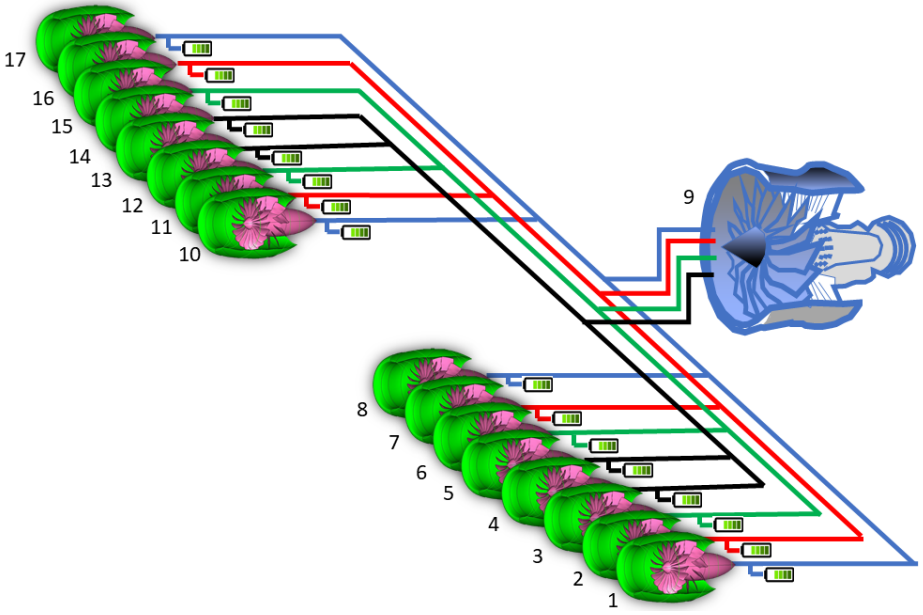
Detailed view of SUSAN powertrain

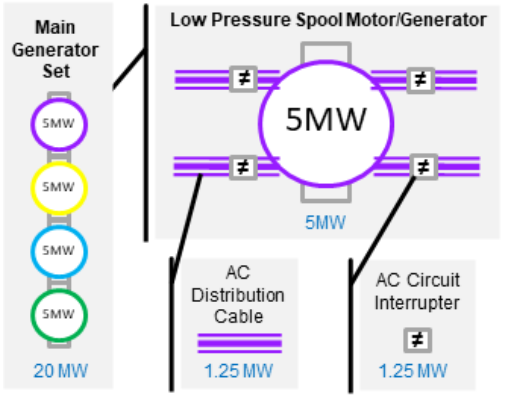
- One gas turbine engine
- 16 electric engines operated exclusively on power extracted from the gas turbine engine in most cases
- Distributed Electric Propulsion (DEP) can be used differentially to maneuver
- Four 5 MW generators on the low-pressure spool
- One 1 MW generator on the high-pressure spool

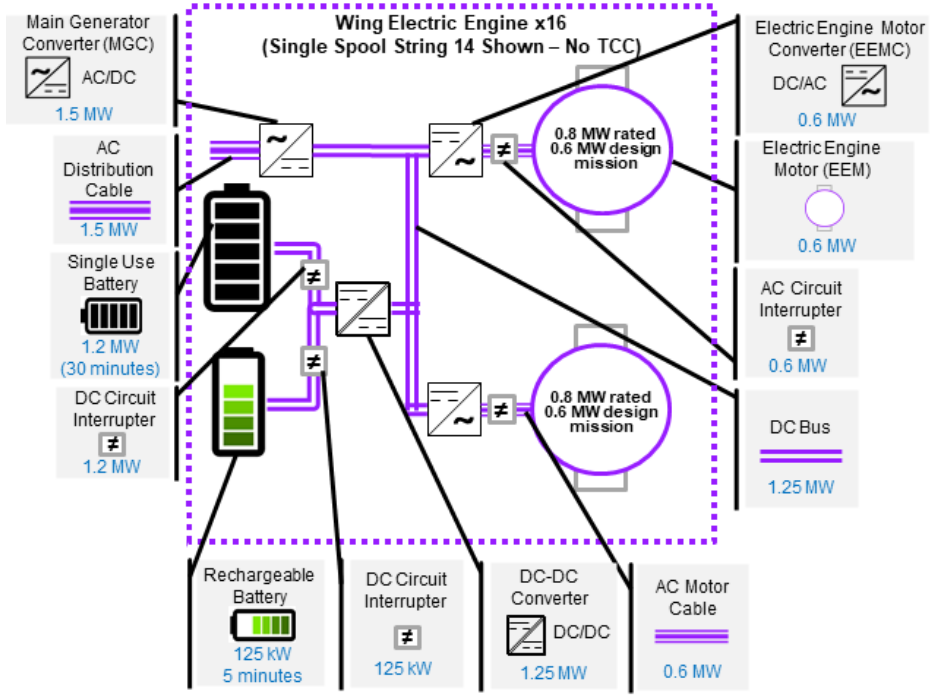


SUSAN Powertrain

- Simple representation of the powertrain (left)
- Main generator (center)
- Single electrical string shown from after the main generator up to and including the electric engine motor (right)







Integrated Vehicle Health Management

Descriptions of Integrated Vehicle Health Management (IVHM)

- IVHM requires a multi-disciplinary approach that enables automatic detection, diagnosis, prognosis, and mitigation of adverse events arising from component failures [1]
- A Self-Adaptive Health Management System that utilizes self-adaptive control and optimization to extend vehicle operation and enhance safety in the presence of potential or actual failures [2]

1. Divakaran, V.N., Subrahmanya, R.M., and Ravikumar, G.V.V, Integrated Vehicle Health Management of a Transport Aircraft Landing System, white paper, https://www.infosys.com/engineering-services/white-papers/documents/aircraft-landing-gear-system.pdf
2. SAE International, Integrated Vehicle Health Management, Rev. 2, April 2018.

IVHM to SHM

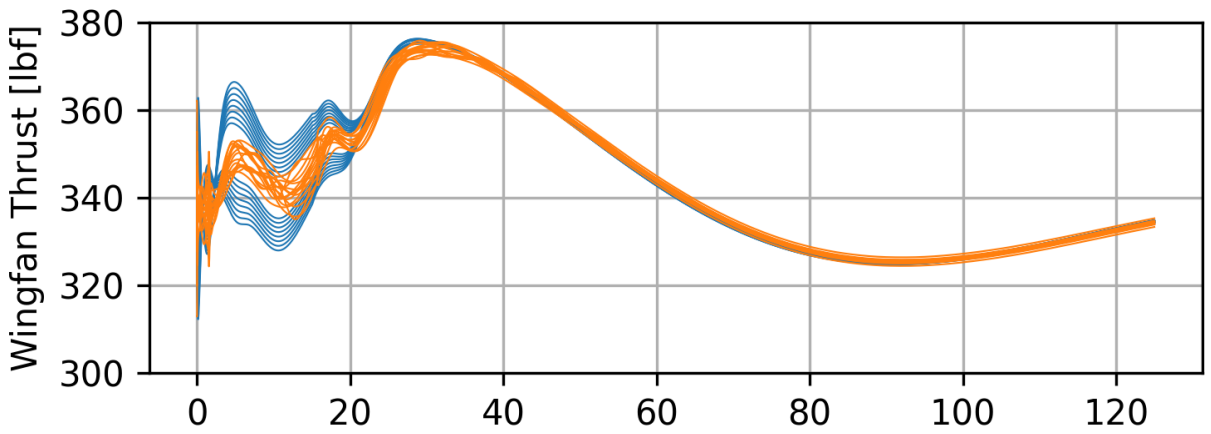
- Because the scope is limited to the powertrain, the term System Heath Management (SHM) is used here, but the previous descriptions remain valid
- Furthermore, there is the opportunity to expand the definition in the context of the electrified powertrain by accounting for degradation or other factors that shows up as an efficiency loss, even if it does not indicate an impending failure
- This way operation of a healthy powertrain can be optimized in terms of power

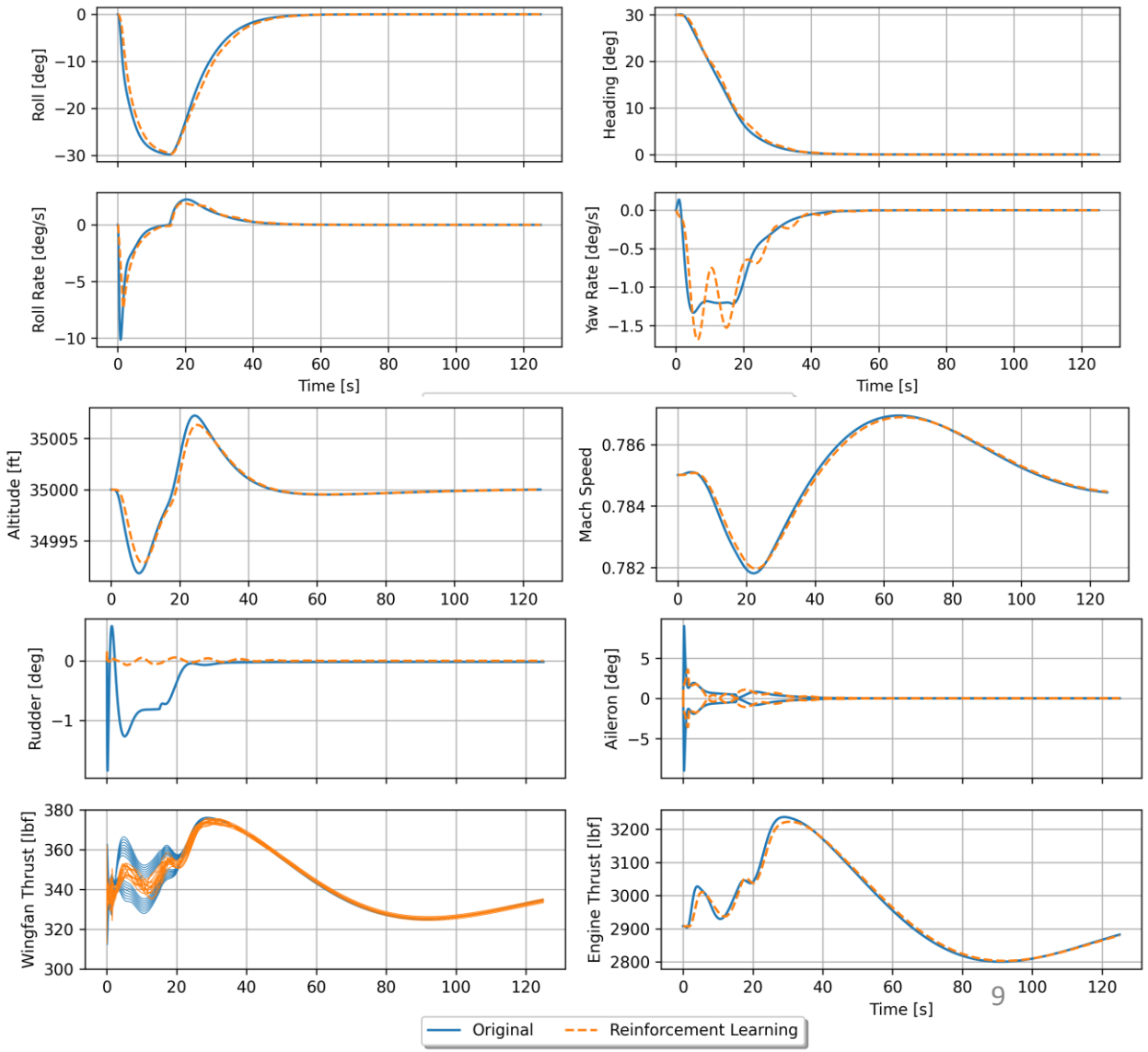
Examples

- Coordinated turn using machine learning
- Failure recovery using machine learning
- Failure recovery using pseudoinverse
- String efficiency estimation using machine learning
- Optimal power consumption and failure recovery using pseudoinverse

Coordinated turn using machine learning

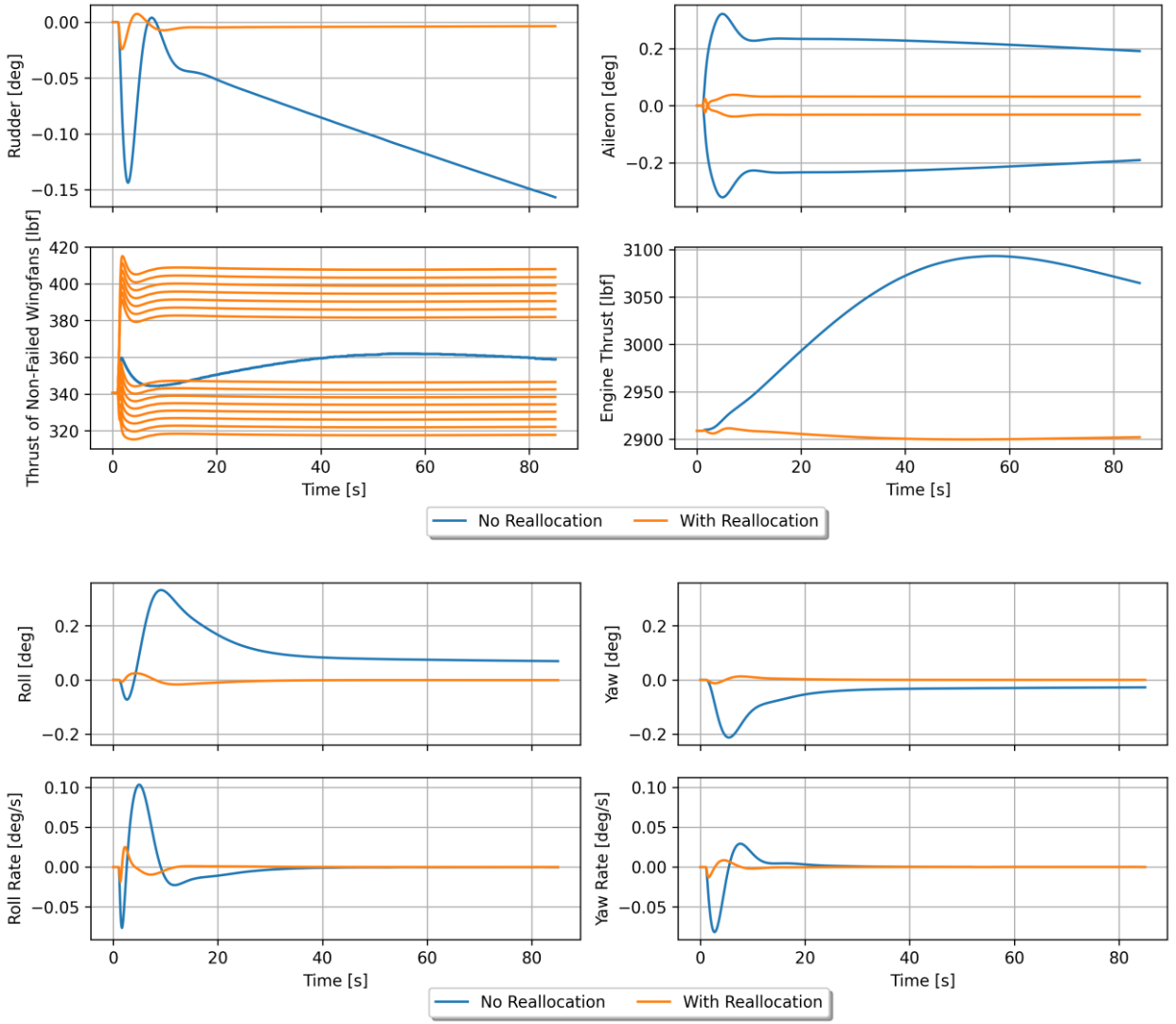
- Original flight control using rudder and DEP compared to coordinated turn using only DEP trained using reinforcement learning
- Objective to minimize control surface deflection
- Electric engines trained as individual differential pairs, thrust curves cross





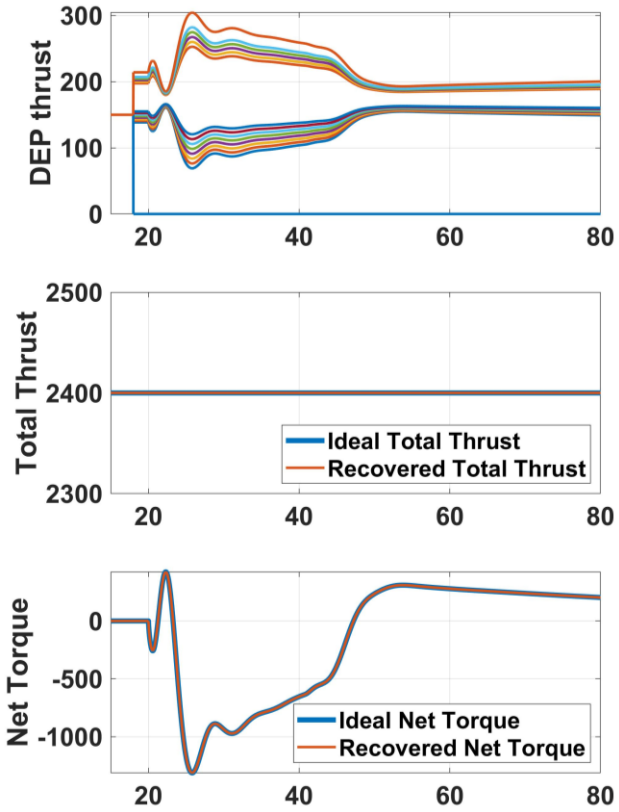
Failure recovery using machine learning

- Electric engine #1 (leftmost) failed
- Original flight control without thrust reallocation recovers attitude using surfaces after initial upset and lost thrust using throttle
- Reinforcement learning approach redistributes a portion of the lost thrust to the remaining electric engines, resulting in evenly spaced thrust levels



Failure recovery using pseudoinverse

- Using electric engines rather than rudder for a coordinated turn, but electric engines # 15 and 16 fail before turn is initiated
- Lost thrust is redistributed to remaining electric engines, matching total net thrust of unfailed powertrain
- Net torque on aircraft for turning matches net torque of unfailed powertrain

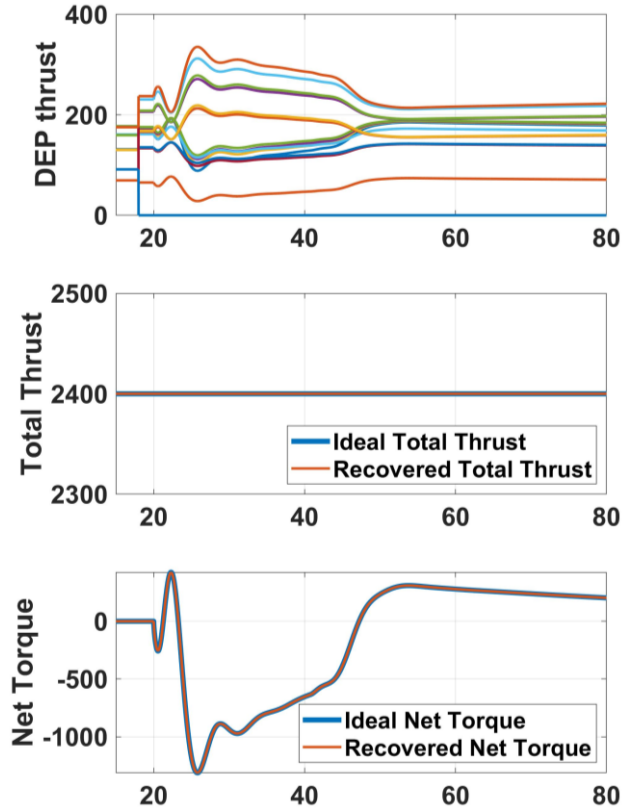


String efficiency estimation using machine learning

- Simulation of electrical engine strings incorporating representative component efficiencies produced data
- Overall, the string efficiencies tended to be above 90% based on the SUSAN requirements, with variation assumed due to manufacturing differences and other factors
- A deep learning artificial neural network was trained to estimate string efficiency from simulated sensed variables
- The estimation accuracy was within one percent

Optimal power consumption and failure recovery using pseudoinverse

- Accounting for efficiency of each string, more efficient strings are utilized more while less efficient strings are utilized less
- Using electric engines rather than rudder for a coordinated turn, but electric engines # 15 and 16 fail before turn is initiated
- Lost thrust is redistributed to remaining electric engines, matching total net thrust of unfailed powertrain
- Net torque on aircraft for turning matches net torque of unfailed powertrain

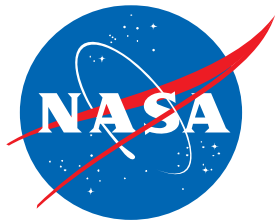


Conclusions

- Some preliminary examples of SHM algorithms were demonstrated
- The examples leveraged the redundancy within the powertrain to achieve continued safe flight after a failure occurred
- The complexity of the SUSAN powertrain and the interdependence of the parts means that the pilot will likely have no control over individual subsystems
- Powertrain SHM is critical to the safe operation of the vehicle
- The redundancy, reinforced by a robust health management system, should make the overall powertrain operation sufficiently reliable to ensure the SUSAN concept's feasibility

Acknowledgments

The Transformative Aeronautics Concepts Program (TACP) Convergent Aeronautics Solutions Project sponsors this work with the support of the Transformational Tools and Technologies Project, also under the TACP, and the Integrated Aviation Systems Program/Electrified Powertrain Flight Demonstration project, all of which are under the NASA Aeronautics Research Mission Directorate.


NASA