



Piloted Evaluation of a Fault Recovery System for an Aircraft with Distributed Electric Propulsion

Jonathan S. Litt
*NASA Glenn Research
Center*

T. Shane Sowers
HX5, LLC

Sophia M. Bricker
INSA Lyon

Jonah J. Sachs-Wetstone
*NASA Glenn Research
Center*

A. Karl Owen
NovaTek Engineering

Anna Schaldenbrand
Cornell University

AIAA SciTech Forum
January 6-10, 2025
Orlando, FL

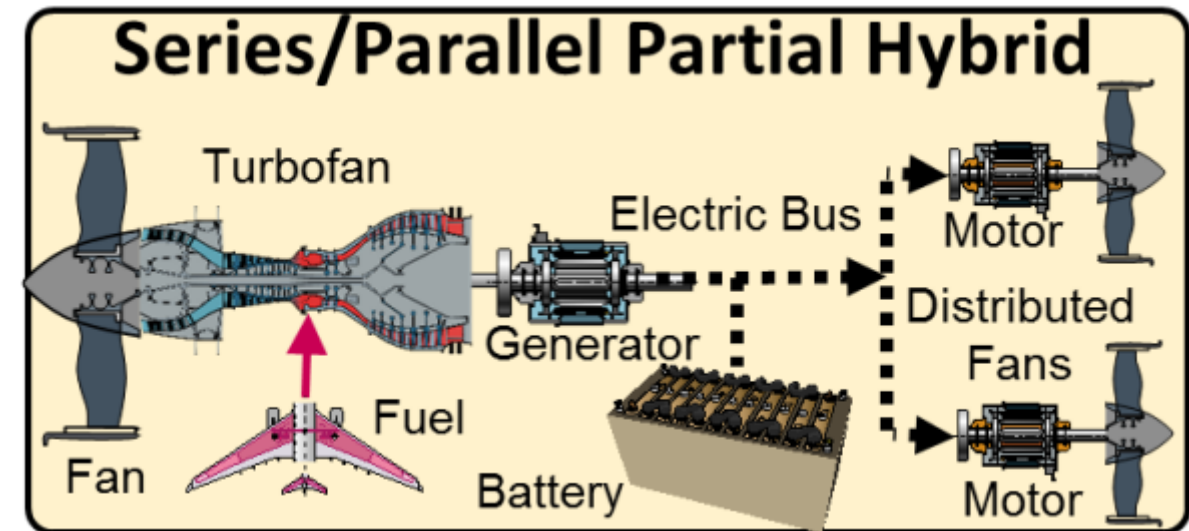


Overview

- Background
- Objective
- Examples
- Conclusions

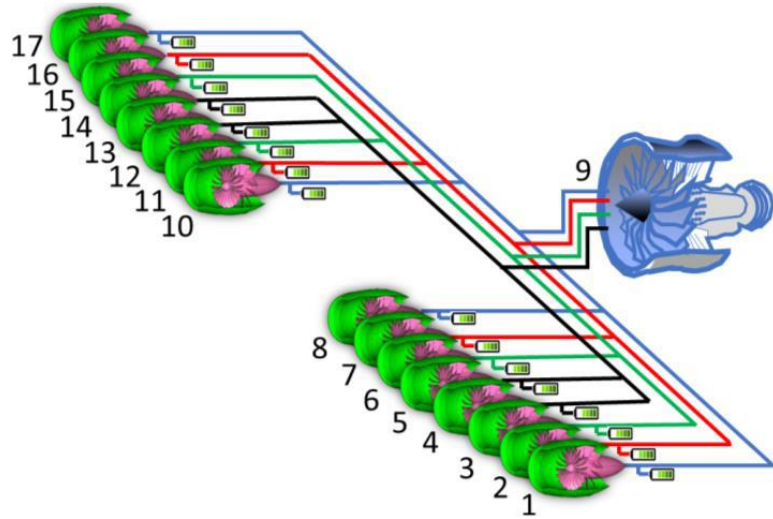
SUBsonic Single Aft eNginE (SUSAN) Electrofan

- 2040 entry-into-service concept
- Single aisle 180 PAX regional jet
- Single turbofan in the empennage provides 35% of the thrust and power for the electric engines
- 16 underwing electric engines provide 65% of the thrust
- The 16 underwing engines comprise a distributed electric propulsion system that can aid in maneuvering
- Series/Parallel Partial Hybrid Powertrain
- Small reusable/rechargeable (secondary) batteries help enable electrification benefits

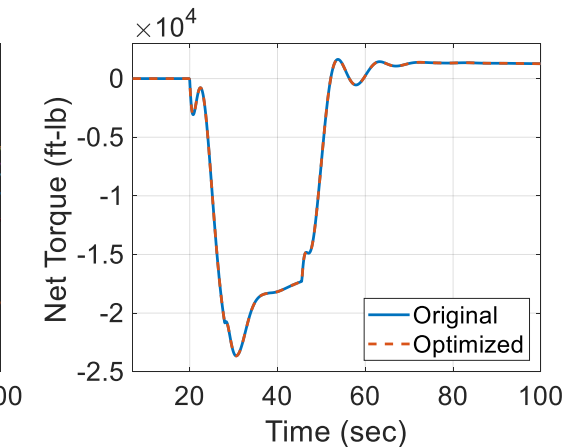
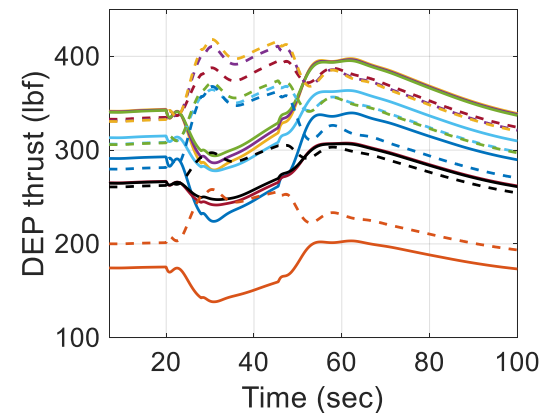
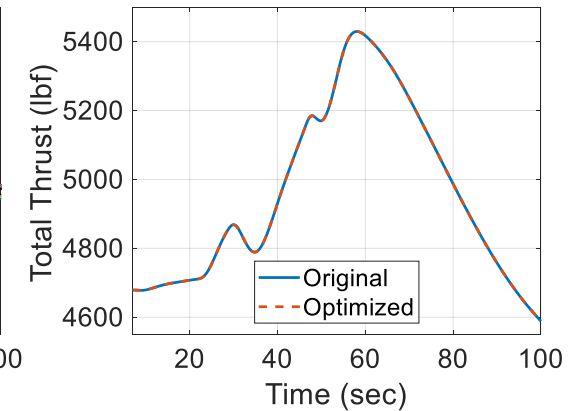
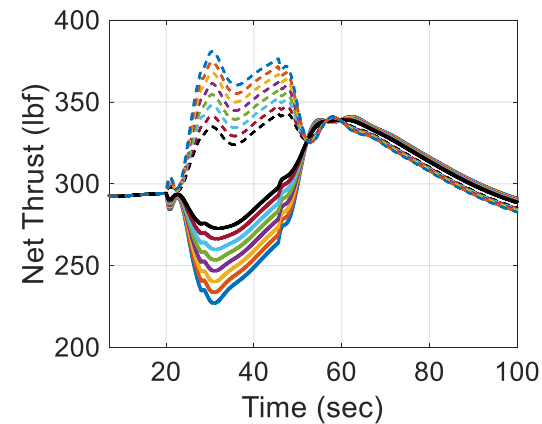


Past Work

- Developed an optimal thrust setpoint reallocation algorithm that modifies baseline flight control commands to the electric engines to minimize power consumption

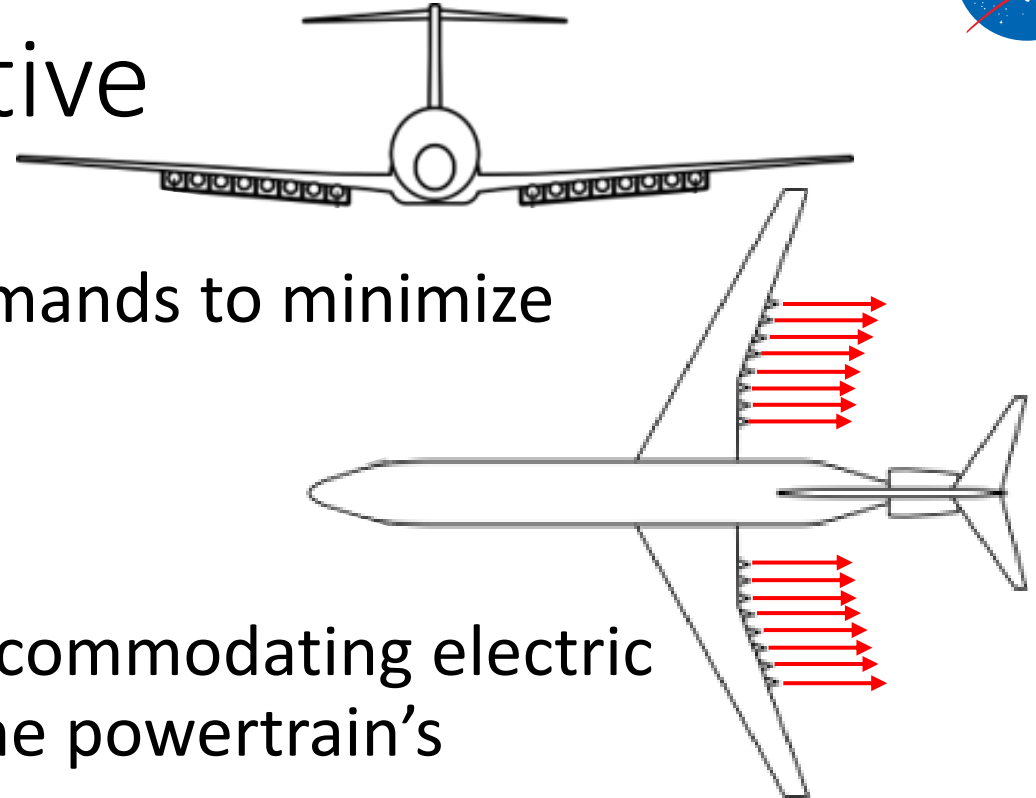


- Demonstrated in the yaw axis



Thrust Reallocation Objective

- To optimize electric engine thrust commands to minimize power consumption while maintaining
 - required total thrust
 - required net torque on the aircraft
- To maintain thrust and torque while accommodating electric engine failures and saturations using the powertrain's inherent redundancy
- To accommodate electric engine saturations by reallocating thrust commands in a continuous manner
- To degrade gracefully when insufficient redundancy remains





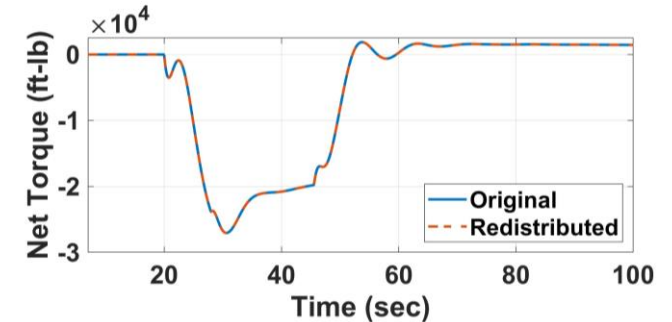
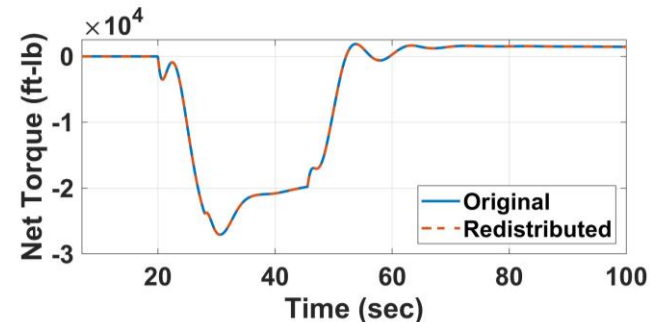
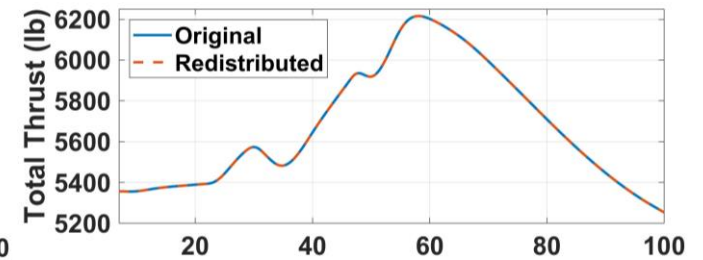
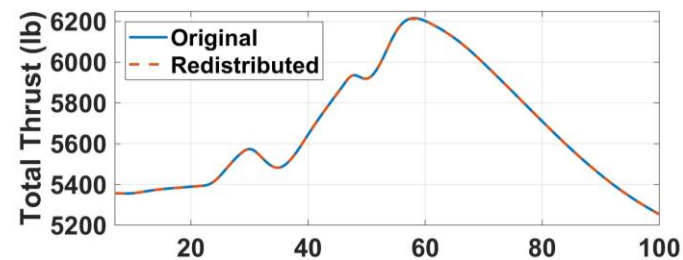
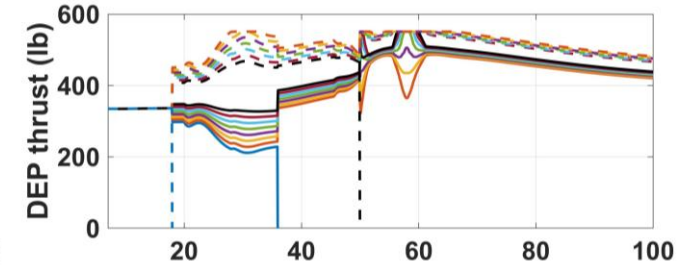
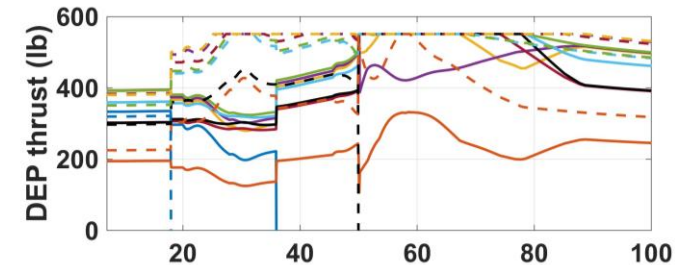
Current Work – Piloted Demonstrations

- The objective of the tests reported here was for the pilot to evaluate the aircraft behavior with electric engine failures and recovery in a 3DOF flight simulator
- No flight control, no autopilot
 - Aircraft reacts to failures without automatic correction
- Four electric engine failures were injected sequentially
 - Here a failure is represented by commanding the electric engine to idle
 - Thrust setpoint reallocation occurs at the instant of the idle command
 - The simulation includes the aircraft and electric engine dynamics:
 - “Failed” electric engines dropping to idle
 - Remaining electric engines reacting to thrust command reallocation

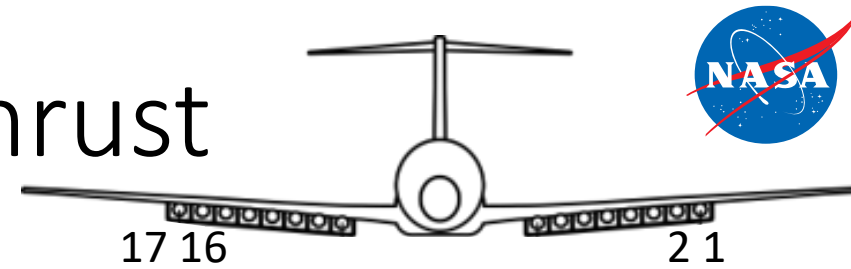
Approach to Examples

- For visual clarity
 - the efficiencies of all electrical strings are assumed to be equal
 - there is no commanded differential thrust

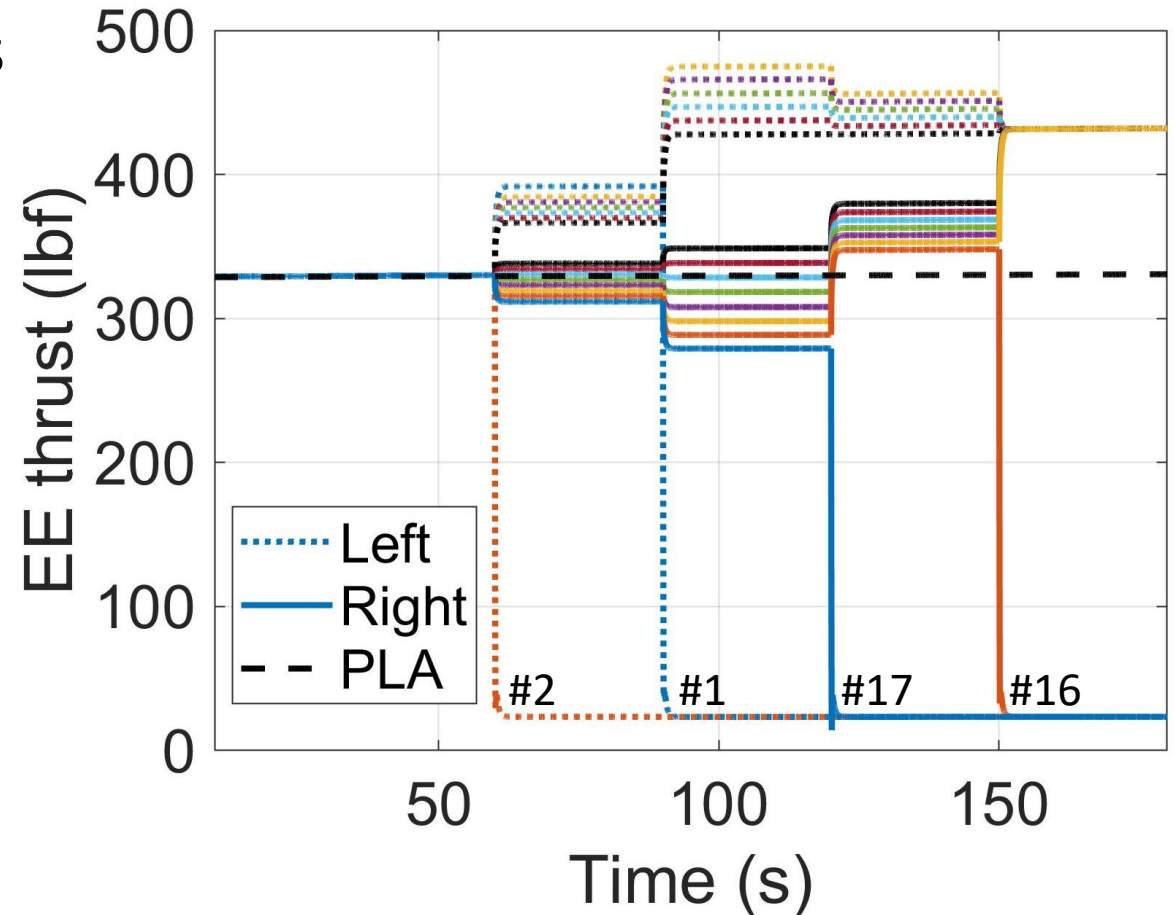
Although there is differential thrust commanded in both figures here (after 20 s), in the figure on the right the efficiencies are equal, and it is much easier to see the saturation accommodation



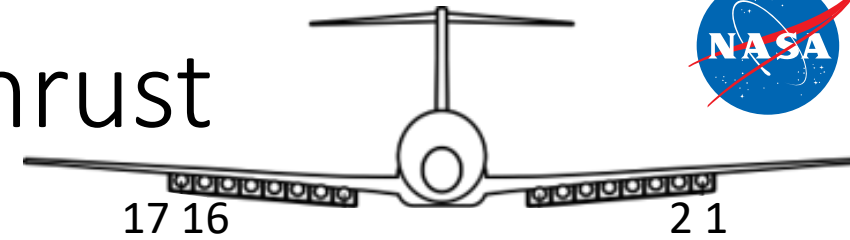
Example 1: Demonstration of Thrust Reallocation



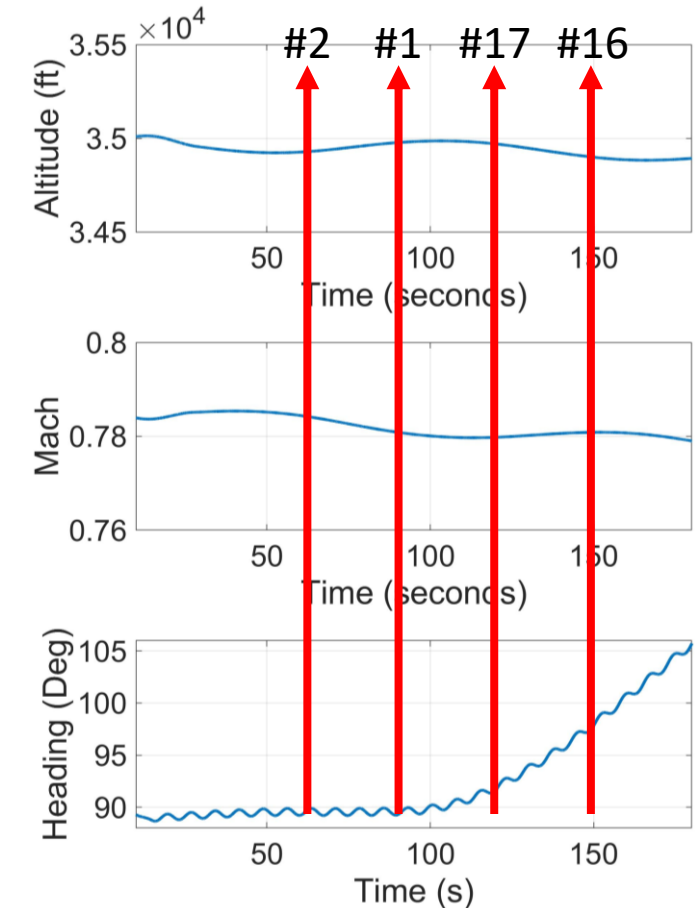
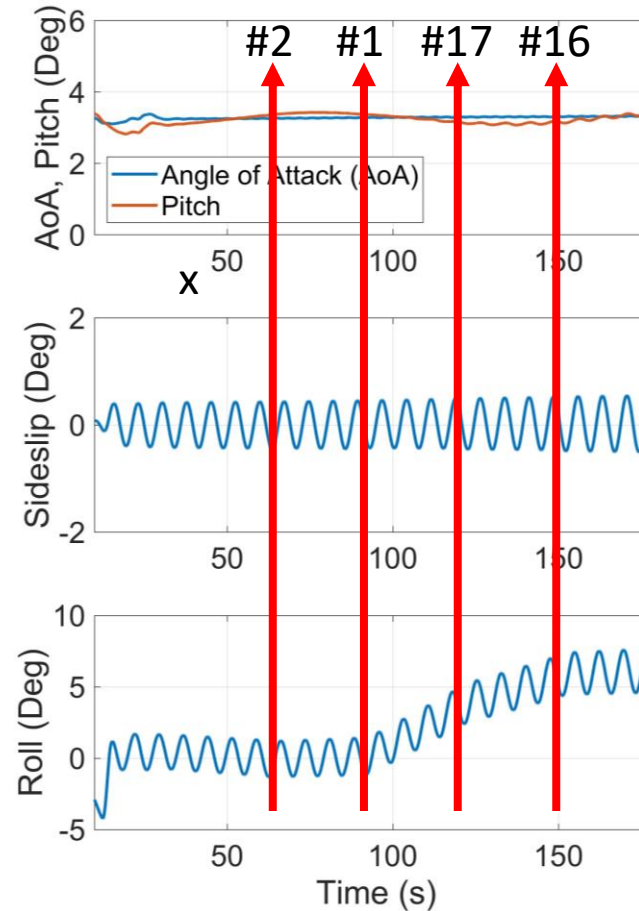
- Failures at 60 s, 90 s, 120 s, 150 s
- Thrust setpoints are reallocated to maintain desired total thrust and net torque on the aircraft
- When the failures are asymmetrical, the setpoints separate
- When the failures are symmetrical, the setpoints converge



Example 1: Demonstration of Thrust Reallocation



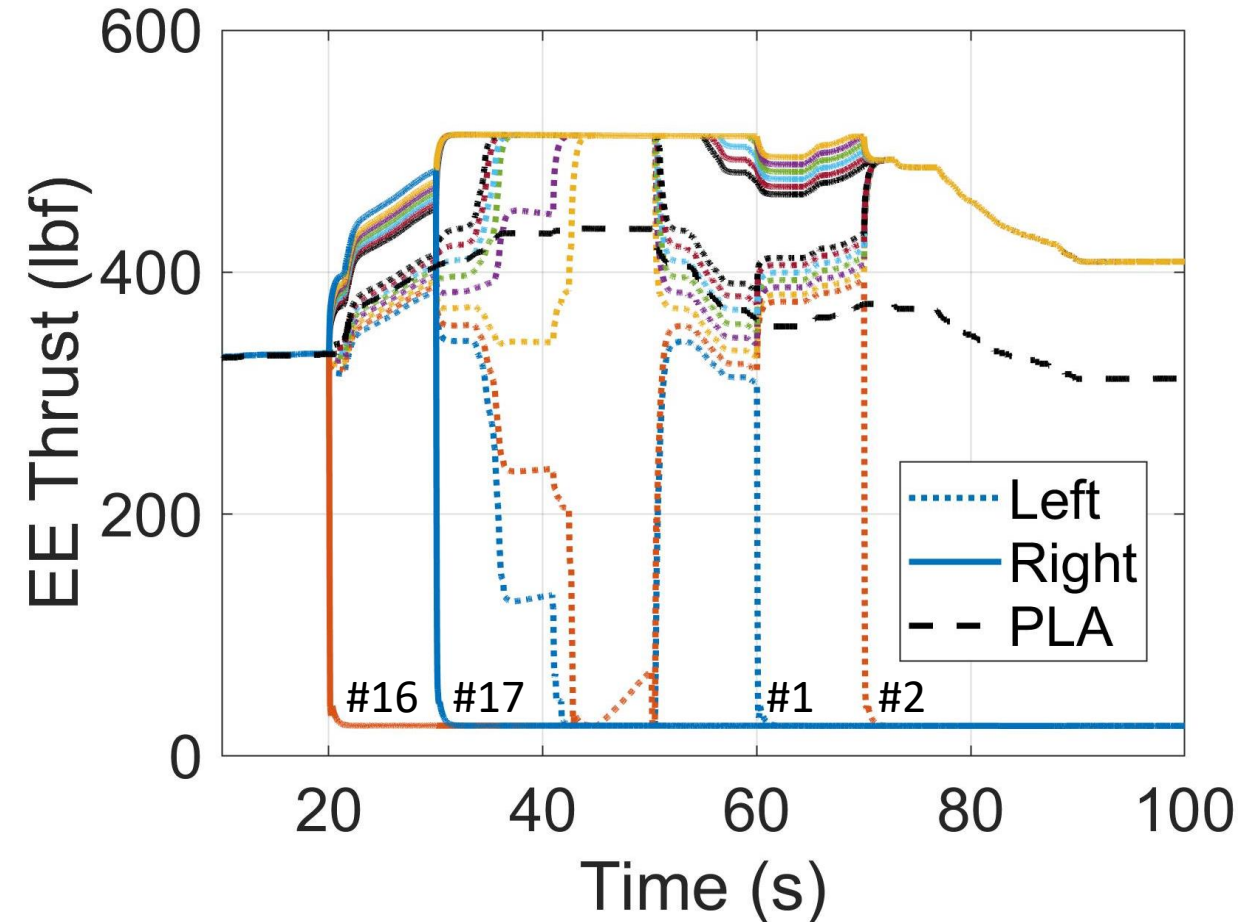
- Failures at 60 s, 90 s, 120 s, 150 s
- Dutch roll and phugoid start immediately
- After second failure, the aircraft starts rolling to the right
- The aircraft stops rolling once the thrusts are symmetrical



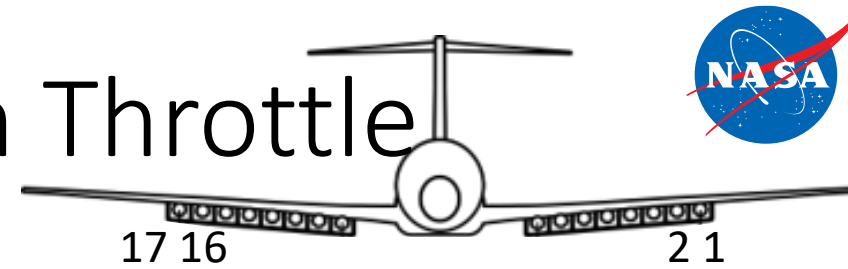
Example 2: Demonstration With Throttle Movements



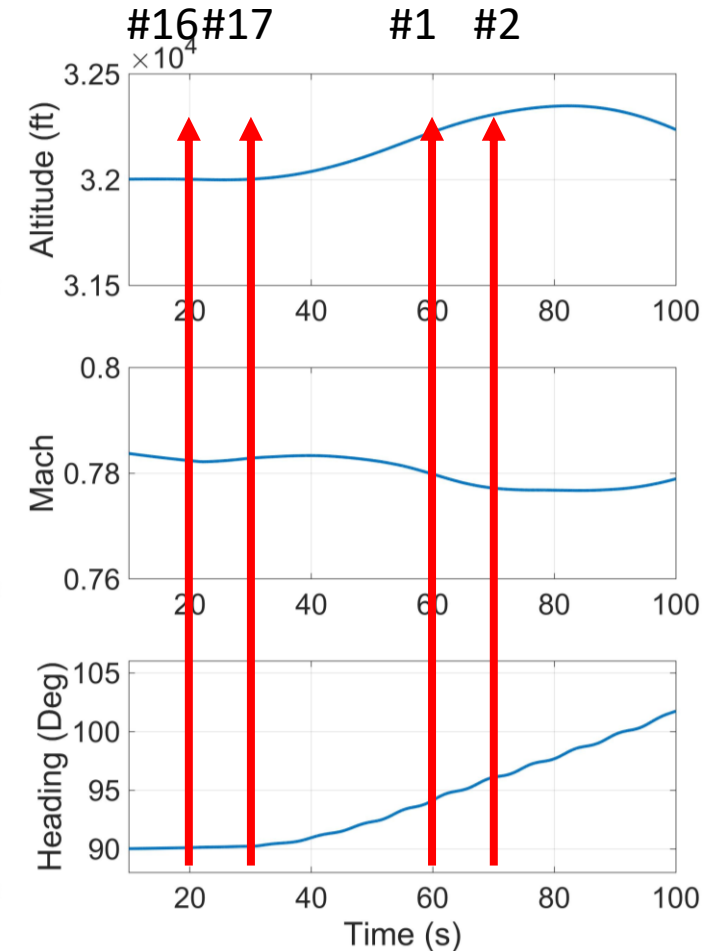
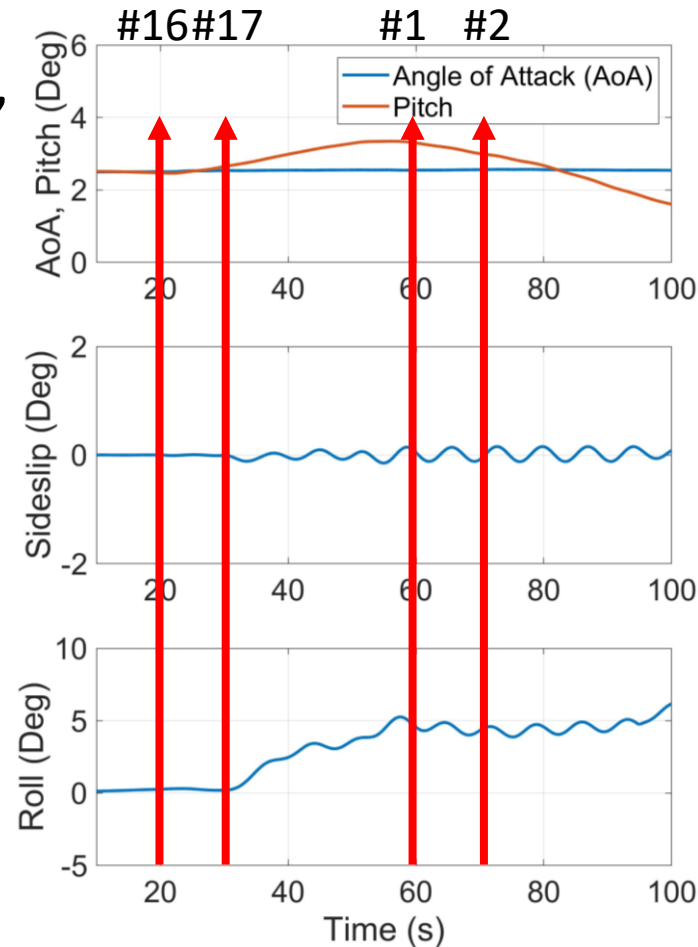
- Failures at 20 s, 30 s, 60 s, 70 s
- Thrust setpoints are reallocated to maintain desired total thrust and net torque on the aircraft
- When the failures are asymmetrical, the setpoints separate
- When the failures are symmetrical, the setpoints converge
- After the second failure, and even more when the pilot increases the throttle, electric engines saturate



Example 2: Demonstration With Throttle Movements



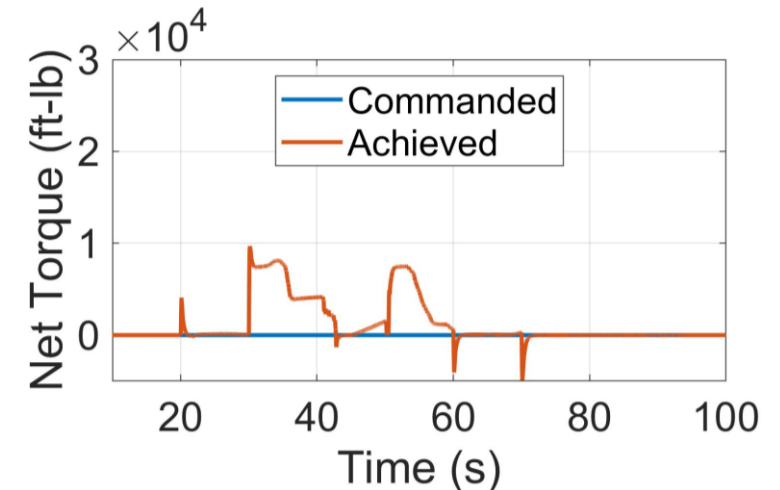
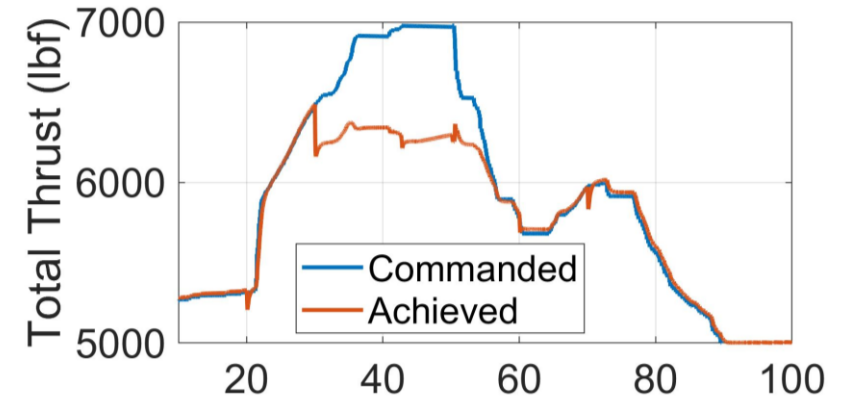
- Failures at 20 s, 30 s, 60 s, 70 s
- Dutch roll starts after second failure
- After second failure, the aircraft starts rolling to the right
- The aircraft stops rolling after the third failure



Example 2: Demonstration With Throttle Movements

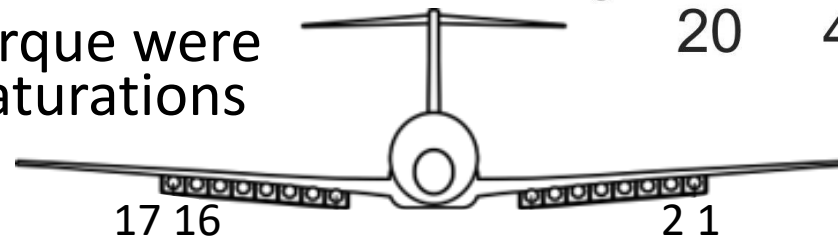
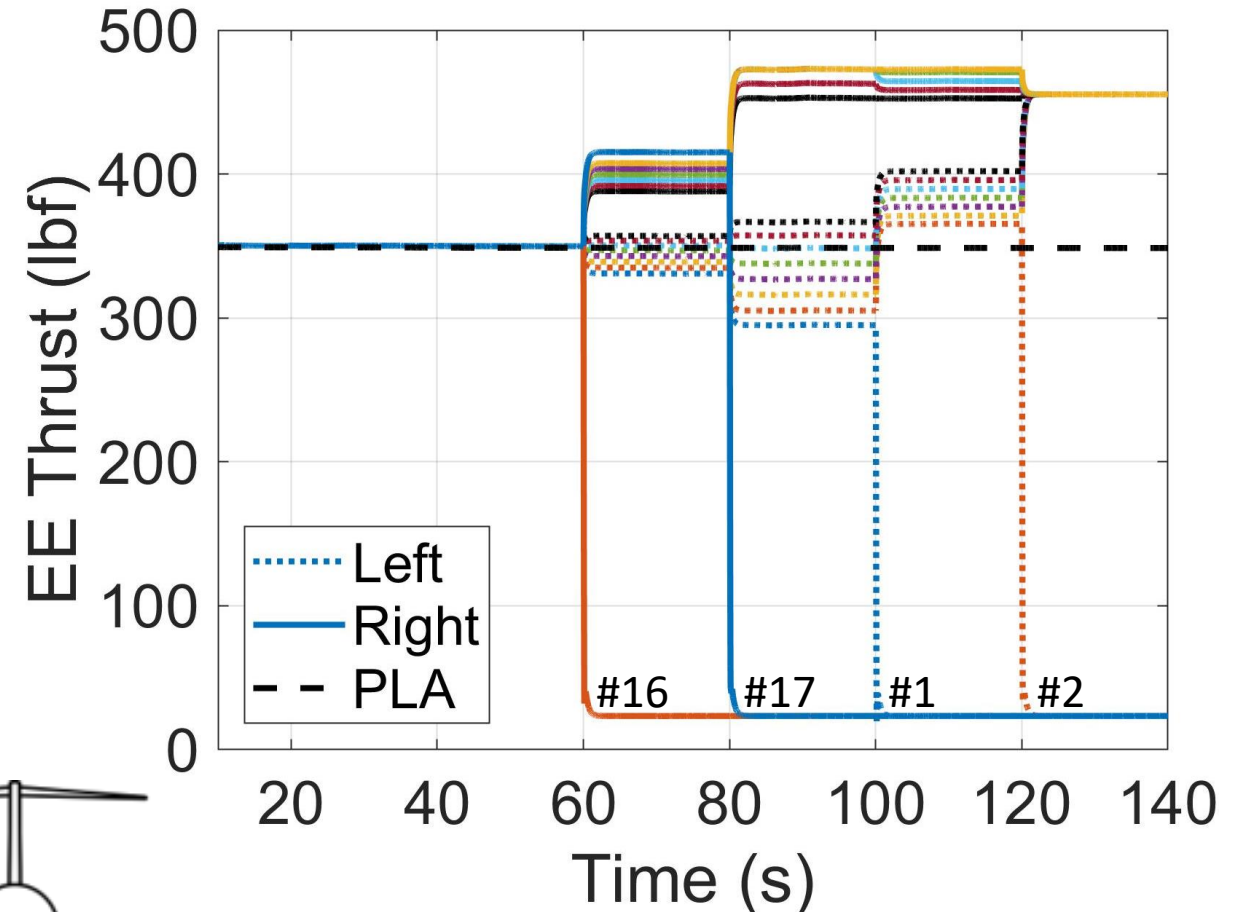


- Failures at 20 s, 30 s, 60 s, 70 s
- Aircraft rolled to the right although initial failures were on the left, the opposite of the previous example
- There is a total thrust and/or net torque error between 30 s and 60 s due to the saturations
- The reallocation algorithm tries to balance the constraints when one or both cannot be met; this caused the roll to the opposite side
- Error spikes at the times of the failures are due to the electric engine dynamics



Example 3: Demonstration With the Pilot Actively Trying to Maintain Straight and Level Flight

- Failures at 60 s, 80 s, 100 s, 120 s
- Thrust setpoints are reallocated to maintain desired total thrust and net torque on the aircraft
- When the failures are asymmetrical, the setpoints separate
- When the failures are symmetrical, the setpoints converge
- Saturations occur after the second failure, but disappear after fourth failure
- Total thrust and net torque were not impacted by the saturations



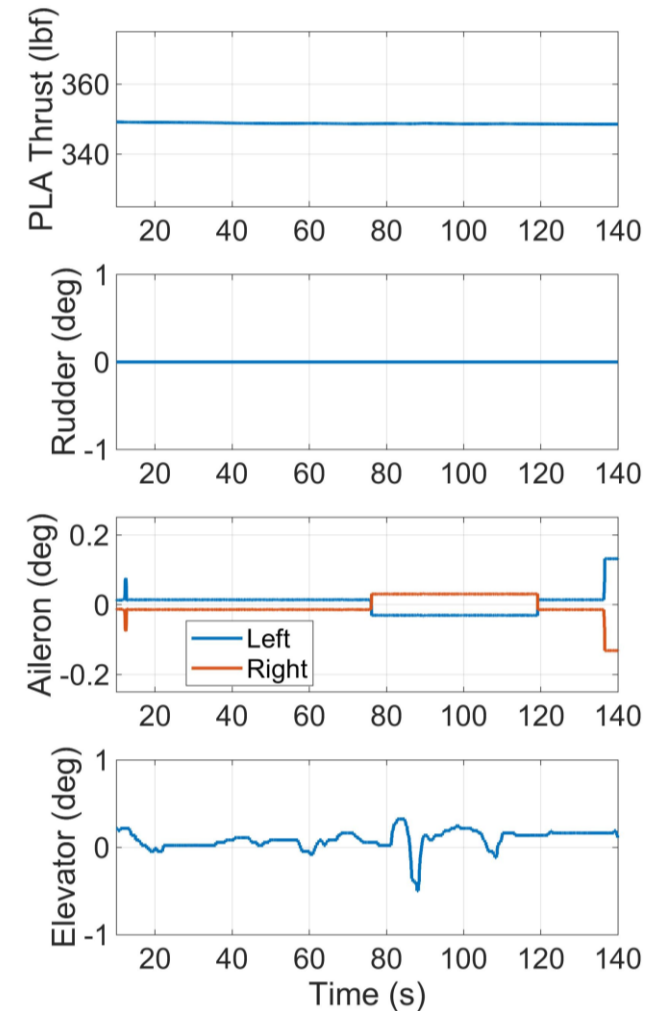
Example 3: Demonstration With the Pilot Actively Trying to Maintain Straight and Level Flight

The pilot used the displays and horizon to make adjustments



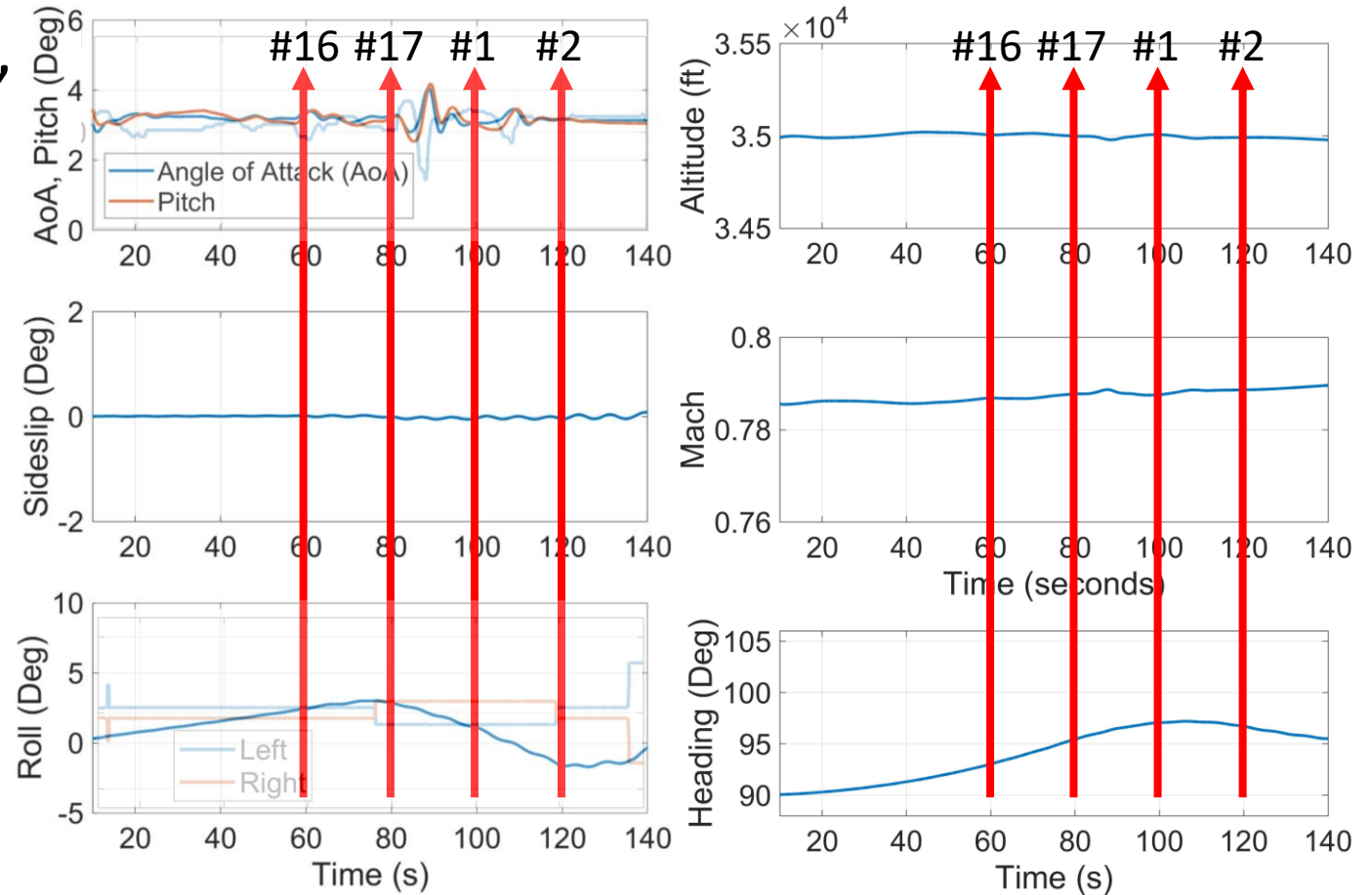
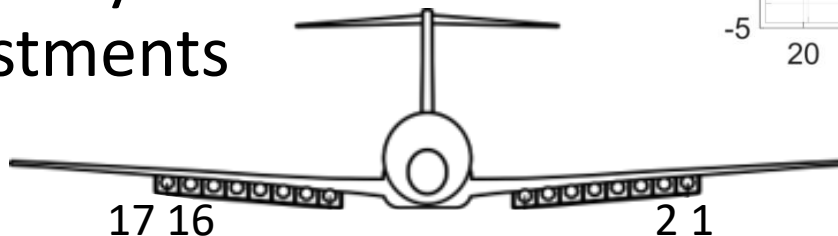
Example 3: Demonstration With the Pilot Actively Trying to Maintain Straight and Level Flight

- The aircraft was initially well trimmed
- The pilot did not touch the throttle or rudder pedals
- The pilot only made small adjustments to the aileron and rudder trim



Example 3: Demonstration With the Pilot Actively Trying to Maintain Straight and Level Flight

- Failures at 60 s, 80 s, 100 s, 120 s
- Elevator position is overlaid on pitch plot
- Aileron position is overlaid on roll plot
- The pilot was able to keep the aircraft close to trim with only minor trim adjustments





Conclusions

- The examples of recovery from in-flight electric engine failures in the SUSAN concept aircraft demonstrated that the thrust reallocation algorithm works as designed
- The resulting minor attitude changes could be easily compensated by an autopilot
- The examples leveraged the redundancy within the powertrain to achieve continued safe flight after a failure occurred
- The thrust reallocation algorithm maintains total thrust and net torque to the extent possible, and then gracefully degrades. Once redundancy is exhausted, it balances the constraints in a way that safely approximates a fully functional system
- The complexity of the SUSAN powertrain and the interdependence of the parts means that the pilot will have limited control over individual subsystems, so a powertrain control that automatically takes advantage of the inherent redundancy to be robust to failures is critical to the safe operation of the vehicle



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.

