



OPTIMAL CONTROL ALLOCATION FOR DISTRIBUTED ELECTRIC PROPULSION IN A SERIES/PARALLEL PARTIAL HYBRID POWERTRAIN

GT2024- 122380

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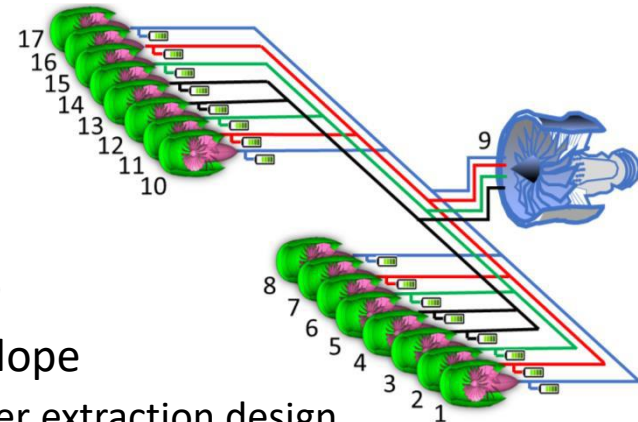
NASA Glenn Research Center

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SUBsonic Single Aft Engine (SUSAN) Electrofan



- NASA concept aircraft
- 2040 entry into service
- 180 passenger
- 50% reduction in emissions
- Single gas turbine engine (GTE)
 - GTE sized for cruise
- Generators attached to GTE power 16 electric engines (EEs)
 - Four main generators power four EEs each
- Single-use batteries in case of GTE or generator failure
- Small rechargeable batteries enable electrification benefits
 - The rechargeable batteries provide boost power at top of climb
- GTE provides 35% of thrust, EEs 65% throughout flight envelope
 - The GTE and EE thrust setpoints are tied together through power extraction design



Objective

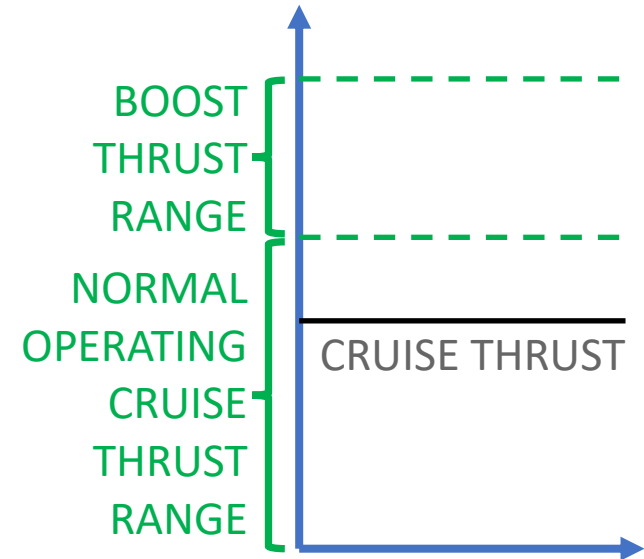


- Determine EE setpoint commands to:
 - Minimize power required for normal operation
 - Optimally reallocate unmet thrust commands due to failure or saturation
- Ultimately determine number and location of EE failures that can be accommodated before resorting to using single-use emergency batteries

Boost



- Engine sized for cruise
- Boost is envisioned as a 2 MW augmentation (125 kW per EE) for 5 minutes at top of climb using power from the rechargeable batteries
- Boost is the only phase of flight during which the standard 35%/65% thrust split is not adhered to, i.e., the EEs produce more than 65% of the total thrust during boost
- Thus, as the aircraft approaches cruise altitude and speed, the EEs are running faster and generating more thrust than would be possible through power extraction alone
- This provides a margin at the upper end of the EE speed range that can be leveraged to optimize non-boosted flight



Electrical String Efficiency

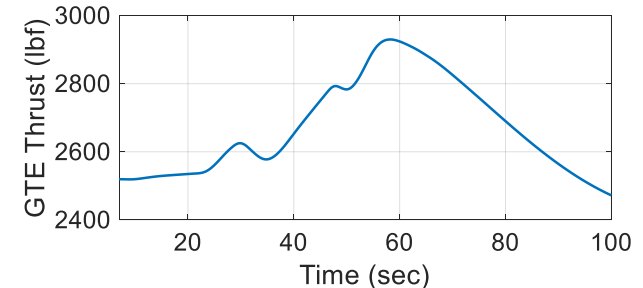
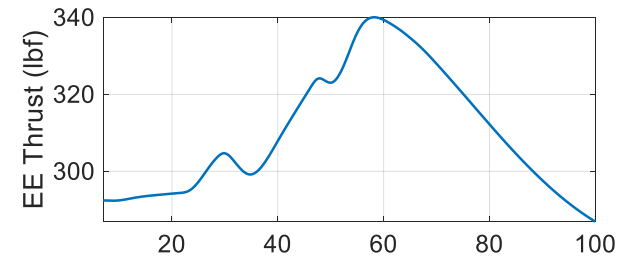
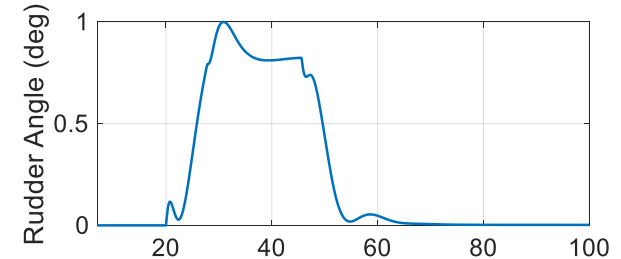
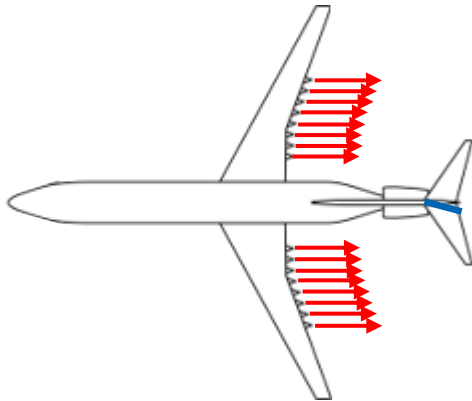


- Each electrical string comprises all components from the generator attached to the GTE to the EE motors
- There are 16 such strings, one for each EE
- The overall efficiency of each string is assumed to be between 90% and 99%
- We assume that the efficiency of the i th string, η_i , can be estimated and thus is known

Coordinated Turn at Cruise



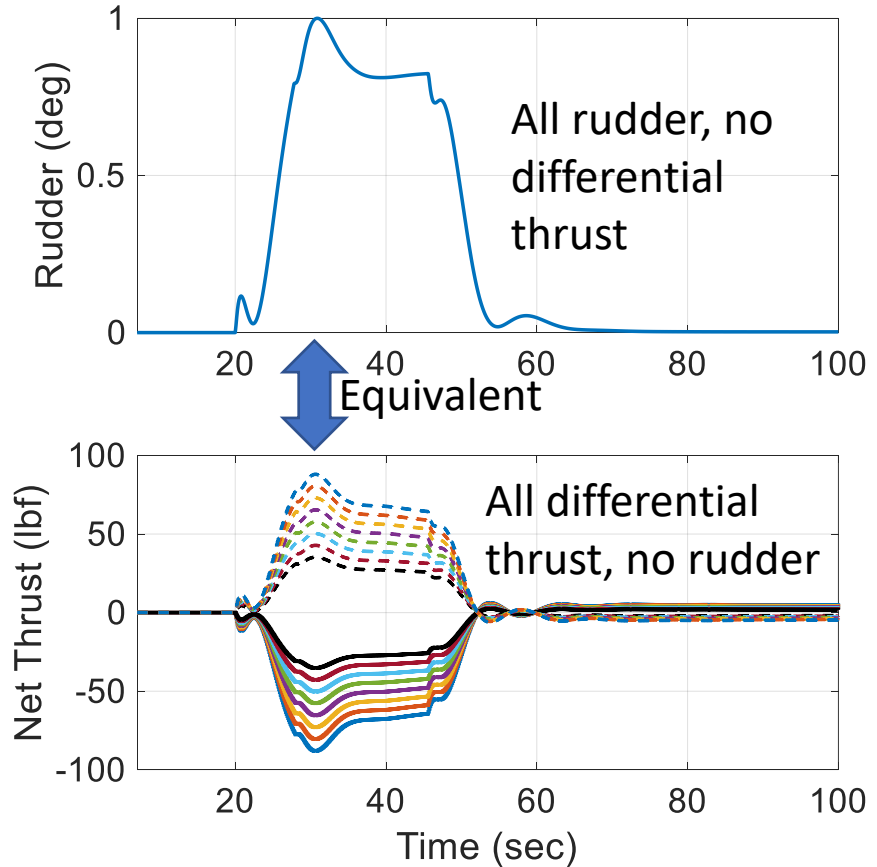
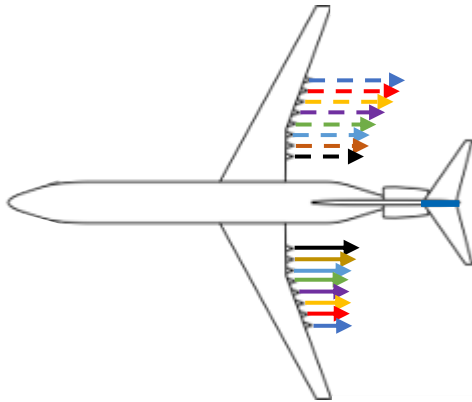
- A coordinated turn is a turn without sideslip
- The rudder is used to prevent sideslip
- This example was generated using the autopilot
 - In this example, the thrust is temporarily increased to maintain altitude during the turn
 - The EEs thrust tracks the GTE thrust to maintain the 65/35 EE/GTE thrust ratio



Coordinated Turn at Cruise

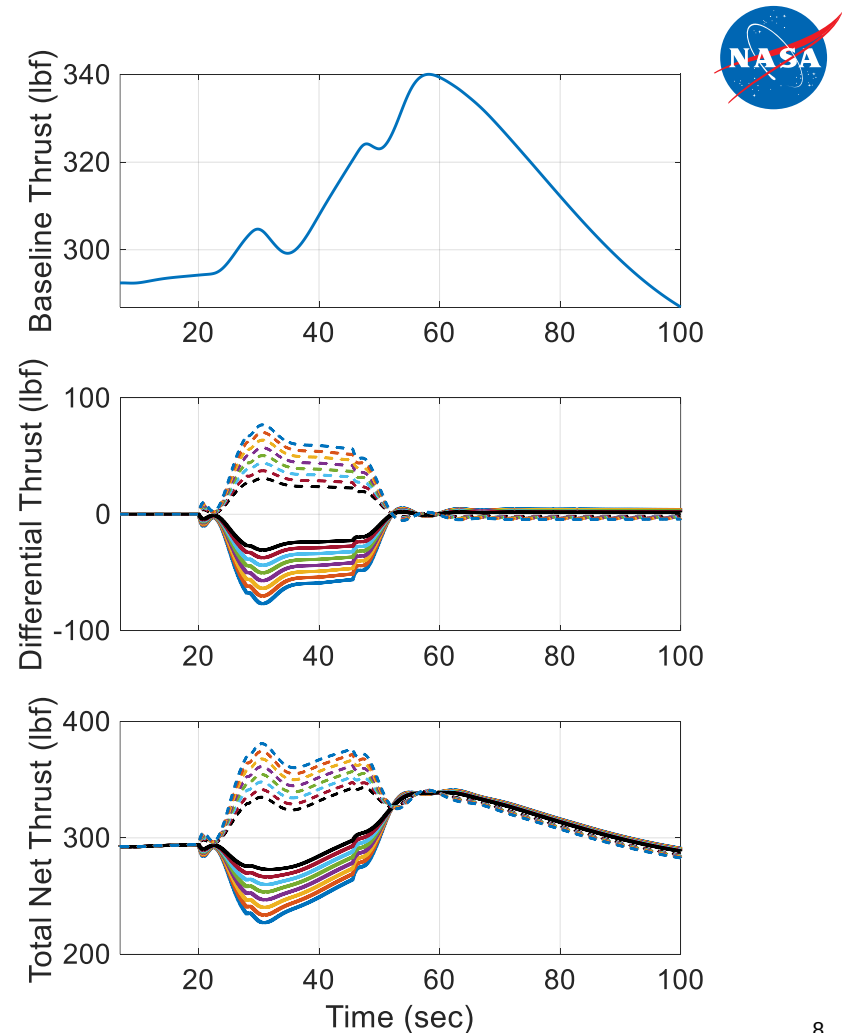
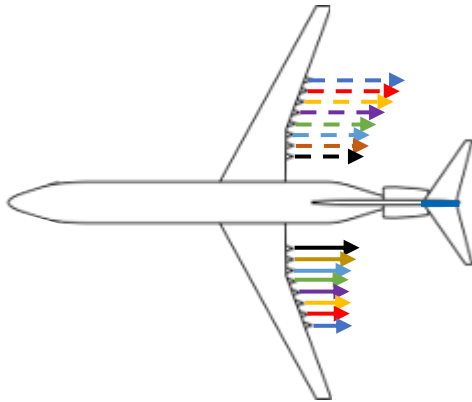


- The flight control system can assign a portion of the rudder function to the EEs in the form of incremental differential thrust commands
- Replacing rudder function with Distributed Electric Propulsion (DEP) enables reduction of size of rudder and associated actuators, saving weight

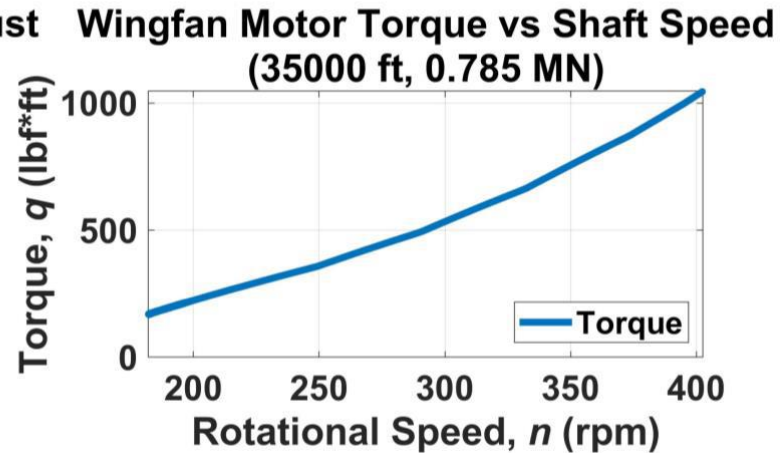
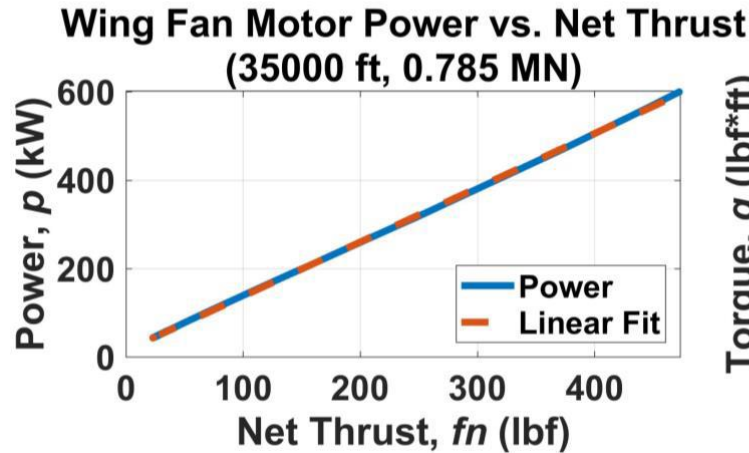
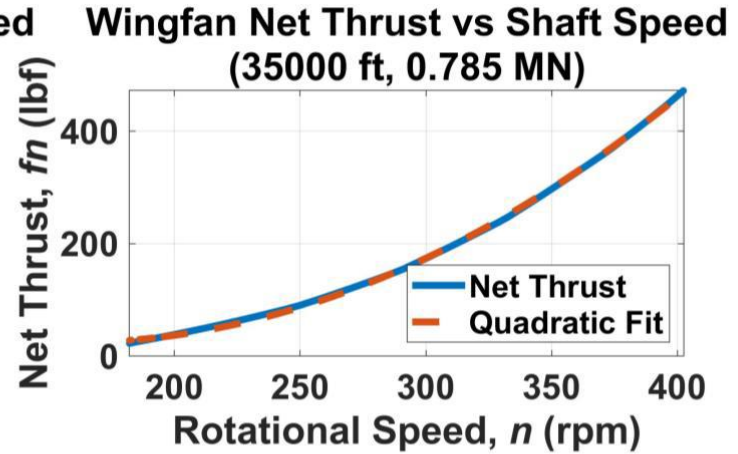
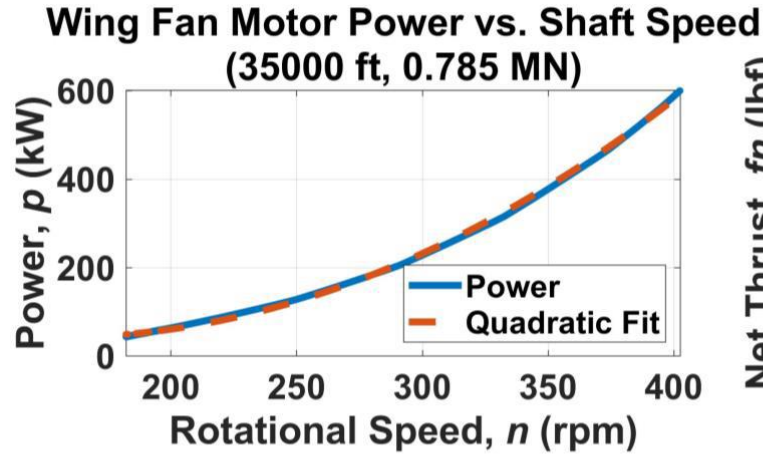


Coordinated Turn at Cruise

- Adding the incremental differential thrust commands to the nominal thrust command allows the DEP to replace the rudder function
- Use of differential thrust commands maintains average thrust, so power extraction also remains about the same



Electric Engine (Wingfan) Data at Cruise



Problem Setup



Power in terms of thrust

$$p_i = a_1 f n_i + a_2$$

Constraint

$$Ax = b$$

where

$$A = \begin{bmatrix} 1 & \cdots & 1 \\ r_1 & \cdots & r_n \end{bmatrix} \quad b = \begin{bmatrix} Fn \\ Q \end{bmatrix}$$

p_i = power consumed by i th EE motor

$f n_i$ = net thrust of the i th EE

$$x = [f n_1, \dots, f n_n]^T$$

r_i = distance of i th EE from centerline

$Fn = \sum f n_i$, total net thrust

$Q = \sum (r_i \times f n_i)$, net torque due to EEs

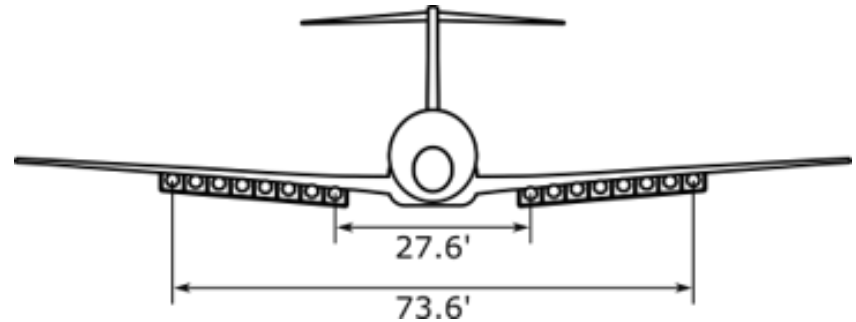
η_i = efficiency of the i th electrical string

$$P = [p_1, \dots, p_n]^T$$

$$H = \text{diag}(\eta_1, \dots, \eta_n)$$

Redefine H as H^2 for convenience

$$J = \frac{1}{2} (H^{-1/2} P)^T H^{-1/2} P + \lambda^T (b - Ax)$$



Solution

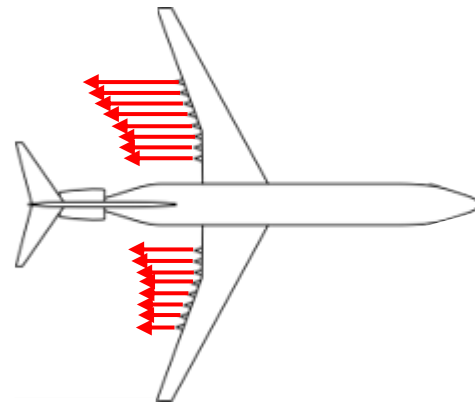


$$x = HA^T(AHA^T)^{-1}b + \frac{a_2}{a_1}(HA^T(AHA^T)^{-1} - I)[1 \dots 1]^T$$

Recall that

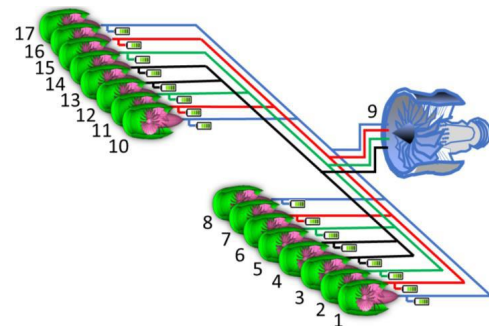
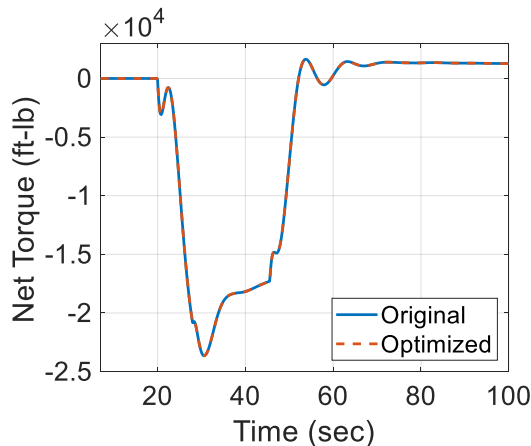
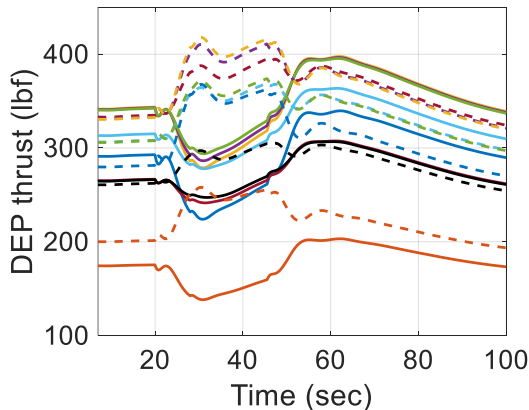
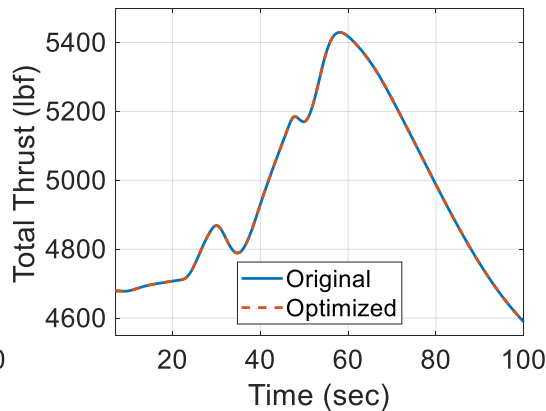
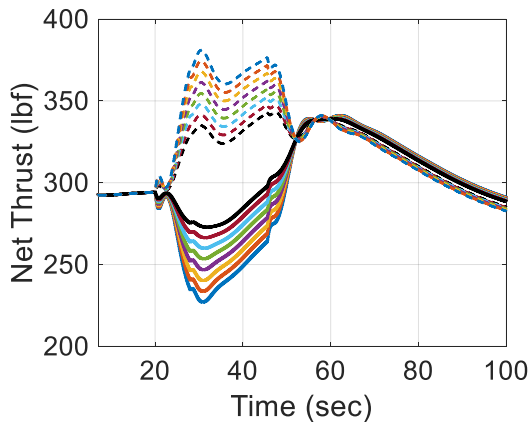
$$x = [fn_1, \dots, fn_n]^T$$

$$b = \begin{bmatrix} Fn \\ Q \end{bmatrix}$$



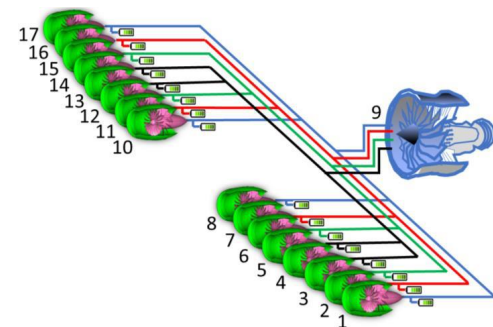
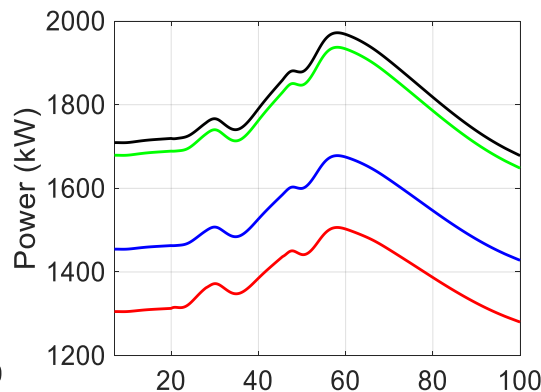
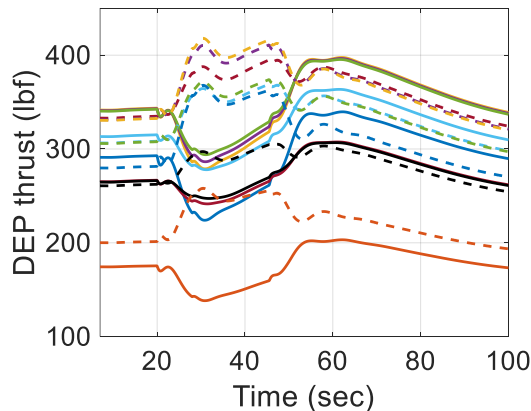
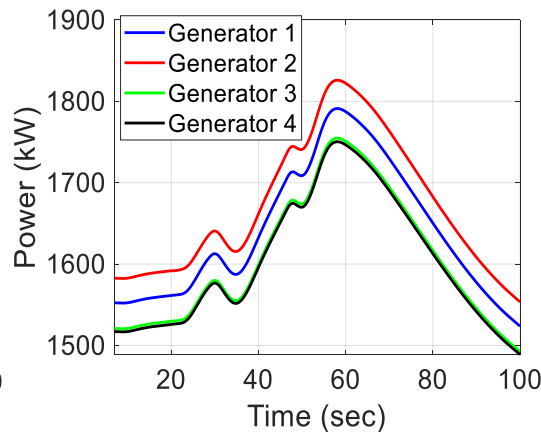
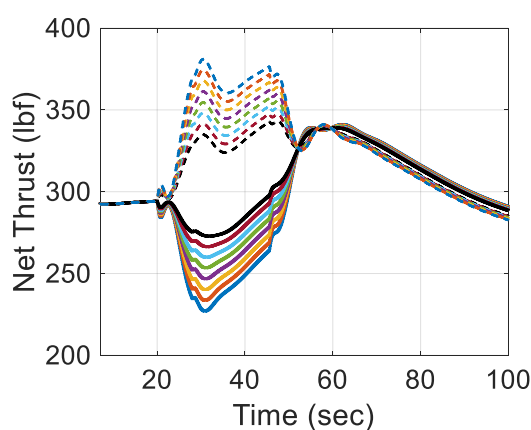
- Assumes that the original flight control commands produce the “ideal” response
- At every control interval, inserting the total thrust and net torque from the original EE commands produces the equivalent optimal commands
- Can redefine H in solution to provide a greater penalty on the use of less efficient strings

Control Optimized to Minimize Power Consumption

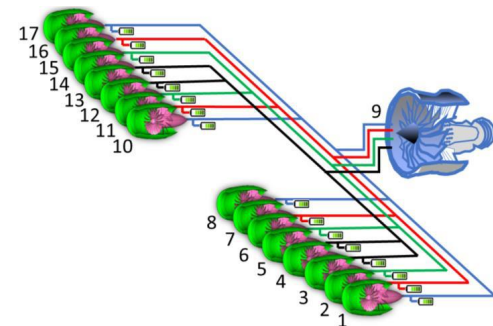
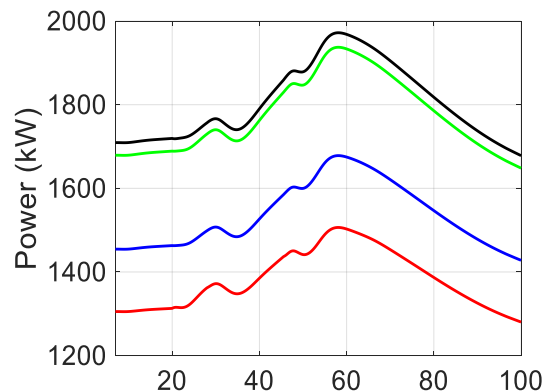
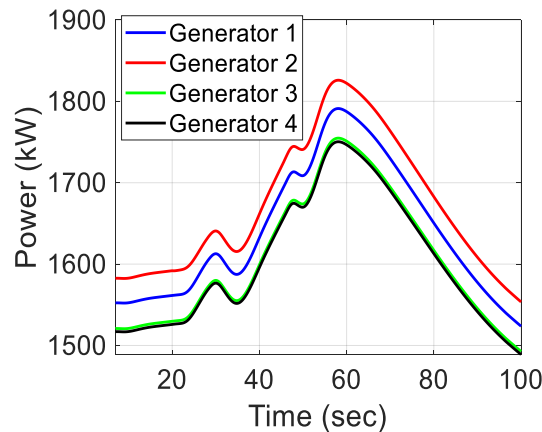
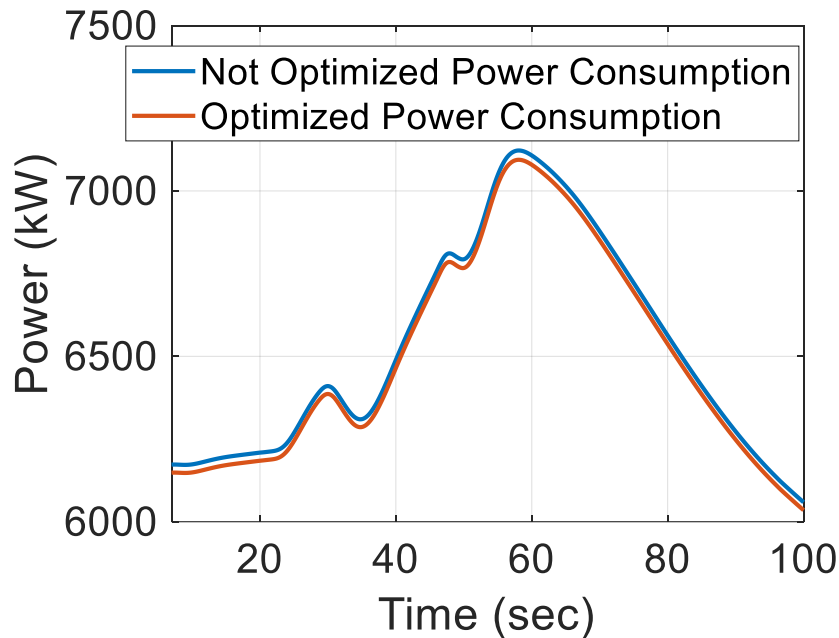


Here H is redefined as H^8 to enhance the separation between the most and least efficient strings

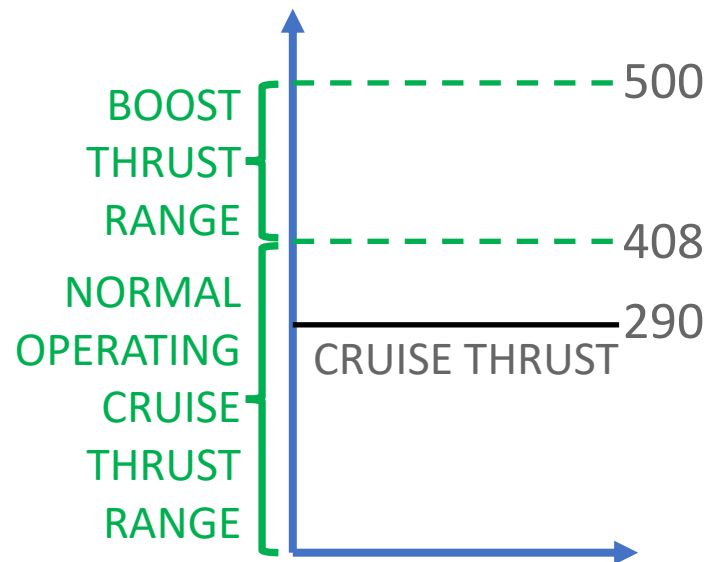
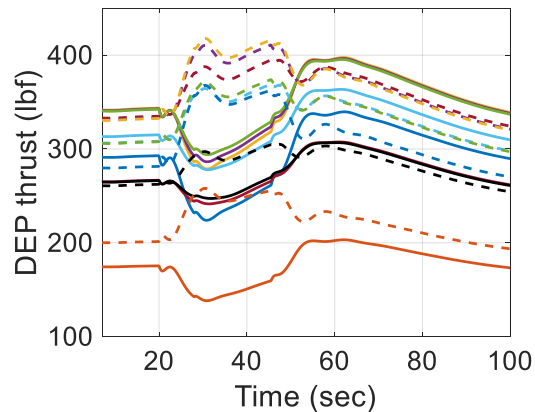
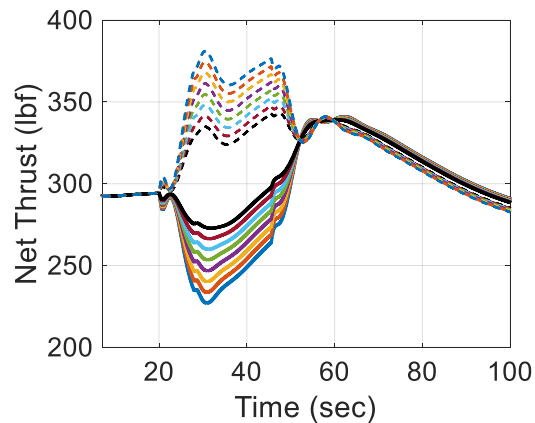
Control Optimized to Minimize Power Consumption



Control Optimized to Minimize Power Consumption



Thrust Reallocation for Saturations and Failures



Thrust Reallocation for Saturations and Failures



- When an EE cannot meet its demand, either through saturation or failure, the unmet portion, u , is reallocated to other EEs through an incremental command, w

$$w = Gu$$

where

u = vector of the unmet thrust demand from the individual EEs

$$G = [g_1 \dots g_n]$$

$$g_i = I^* H A^T (A H I^* A^T)^{-1} A I_i$$

I_i = the i th column of the identity matrix (corresponding to nonzero elements of u)

I^* = the identity matrix with the dimension of the number of EEs with the columns corresponding to the failed EEs zeroed

- Only columns corresponding to EEs with unmet demand are defined

Thrust Reallocation for Saturations and Failures

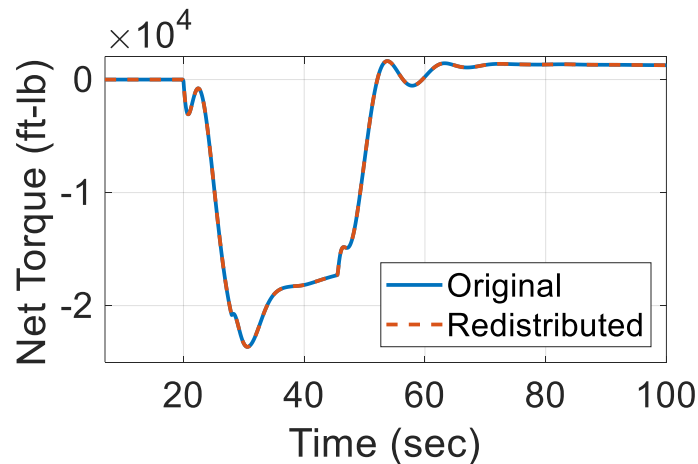
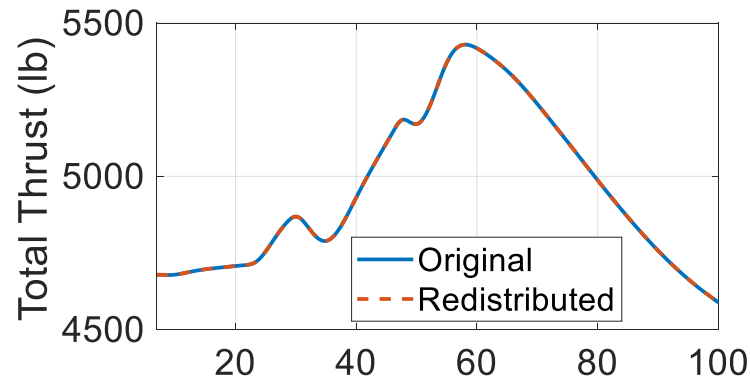
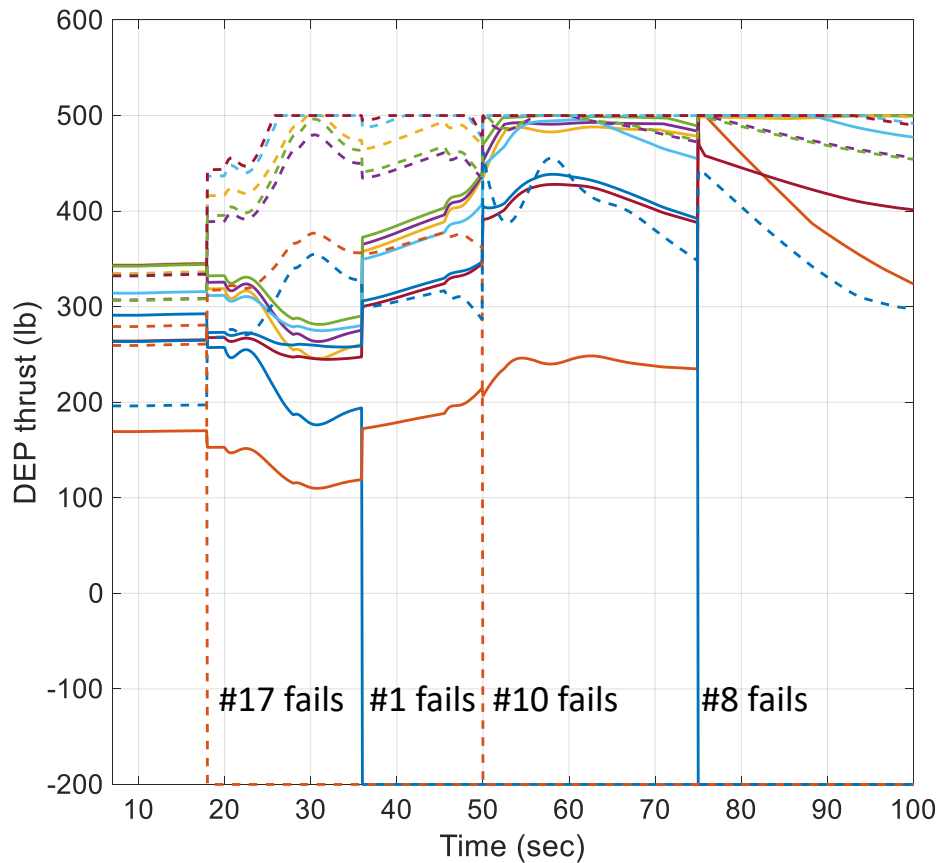


Assumptions

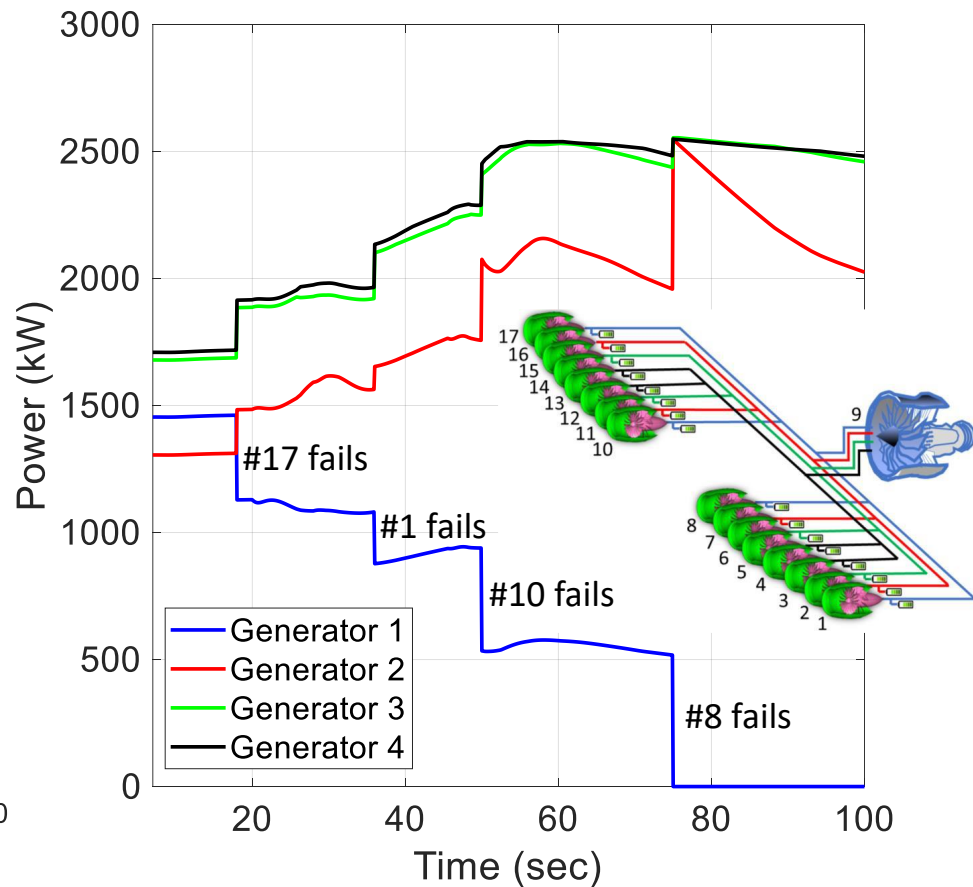
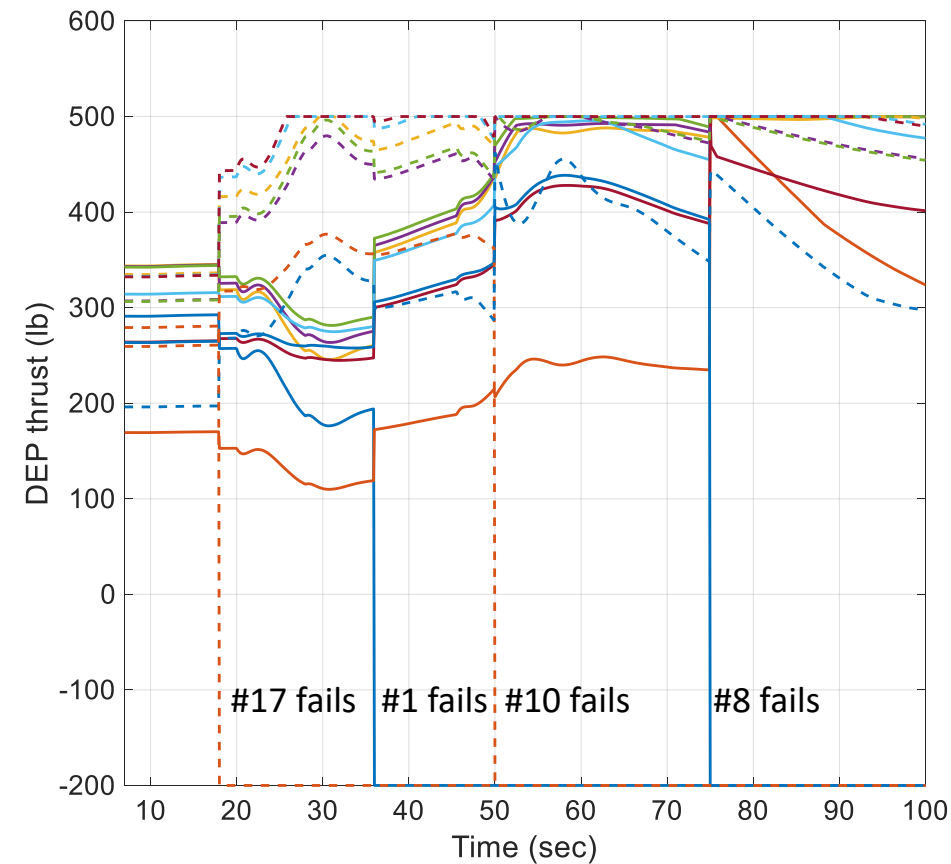
- An EE failure is the result of a component failure within the corresponding electrical string
- EE failures are abrupt and total
- Instant failure detection and isolation allowing immediate reallocation
- Drag of each failed EE is 200 lbf (there is a lot of uncertainty on this crucial value)

Again, H is redefined as H^8 to enhance the separation between the most and least efficient strings

Thrust Reallocation for Saturations and Failures



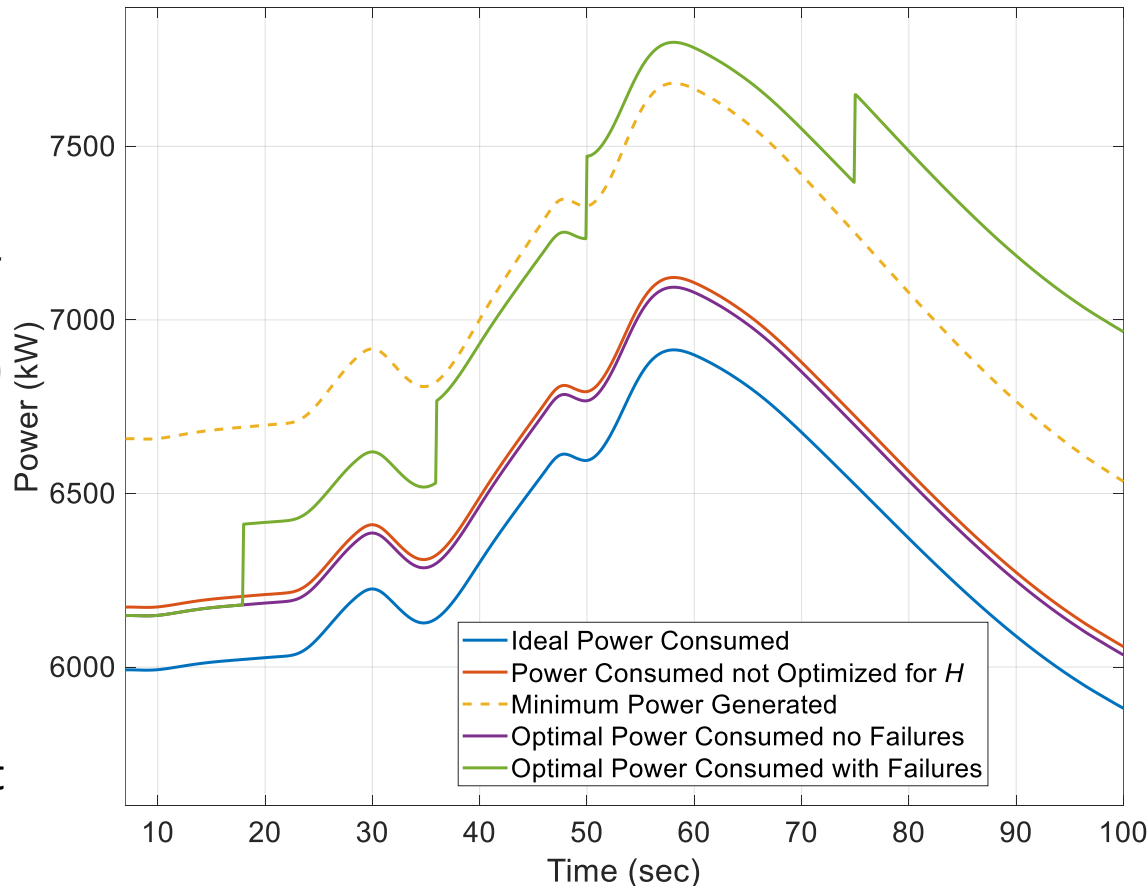
Thrust Reallocation for Saturations and Failures



Discussion



- Based on assumed efficiency range, power requirement is above blue line potentially up to dashed yellow line
- Optimal commands accounting for string efficiency reduce power requirement (red and purple lines)
- Power extraction requirement increases with failures due to need to offset additional drag (green line)
- Higher thrust requirement of individual EEs due to drag of failed EEs and need to replace lost thrust brings them closer to saturation



Conclusions



- Demonstrated approach that optimally distributes thrust setpoint commands to minimize power consumption by accounting for electrical string efficiency
- Methodology also recovers lost EE thrust due to failures or saturations
- The ideal thrust and torque can be maintained up to the limits of the powertrain, i.e., as long as there are enough available degrees of freedom (unsaturated actuators)
- The problem formulation allows the number and location of EE failures for which the thrust and torque can be maintained to be investigated, which has implications for certification
- The drag of failed EEs results in an increased power extraction requirement
- The ability to downsize components to save weight, which is enabled by redundancy and benefits of electrification, is somewhat offset by the requirement for safe operation in failure scenarios and graceful degradation

Acknowledgments



This work was funded by the Transformative Aeronautics Concepts Program (TACP)/Convergent Aeronautics Solutions Project of the NASA Aeronautics Research Mission Directorate. The author thanks the SUSAN team for informative discussions on a variety of aspects related to the design and on aircraft operation in general. The author especially thanks Jonah Sachs-Wetstone and Jeff Chapman of NASA Glenn Research Center and Andrew Patterson of NASA Langley Research Center for providing model data and associated explanations.



