

Hybrid Electric Aircraft with Unlike Engine Degradation Using Model Predictive Control

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Turning hybrid electric commercial aircraft into reality

nasa.gov



Agenda



- Background
- HEALED Decentralized Control
- System Models
- Model Predictive Control
- HEALED Centralized Control
- Simulation
- Results
- Conclusion



Background

Hybrid-electric aircraft technology may lead to more fuel-efficient flight.

- NASA researching different applications for hybrid-electric
- Electrifying turbomachinery leads to new opportunities for control and improved propulsion performance
- Hybrid-electric aircraft technologies are best used in tandem



Credit: NASA

magniX demonstrator aircraft for the Electrified Powertrain Flight Demonstration (EPFD) project taking off from Moses Lake, WA.

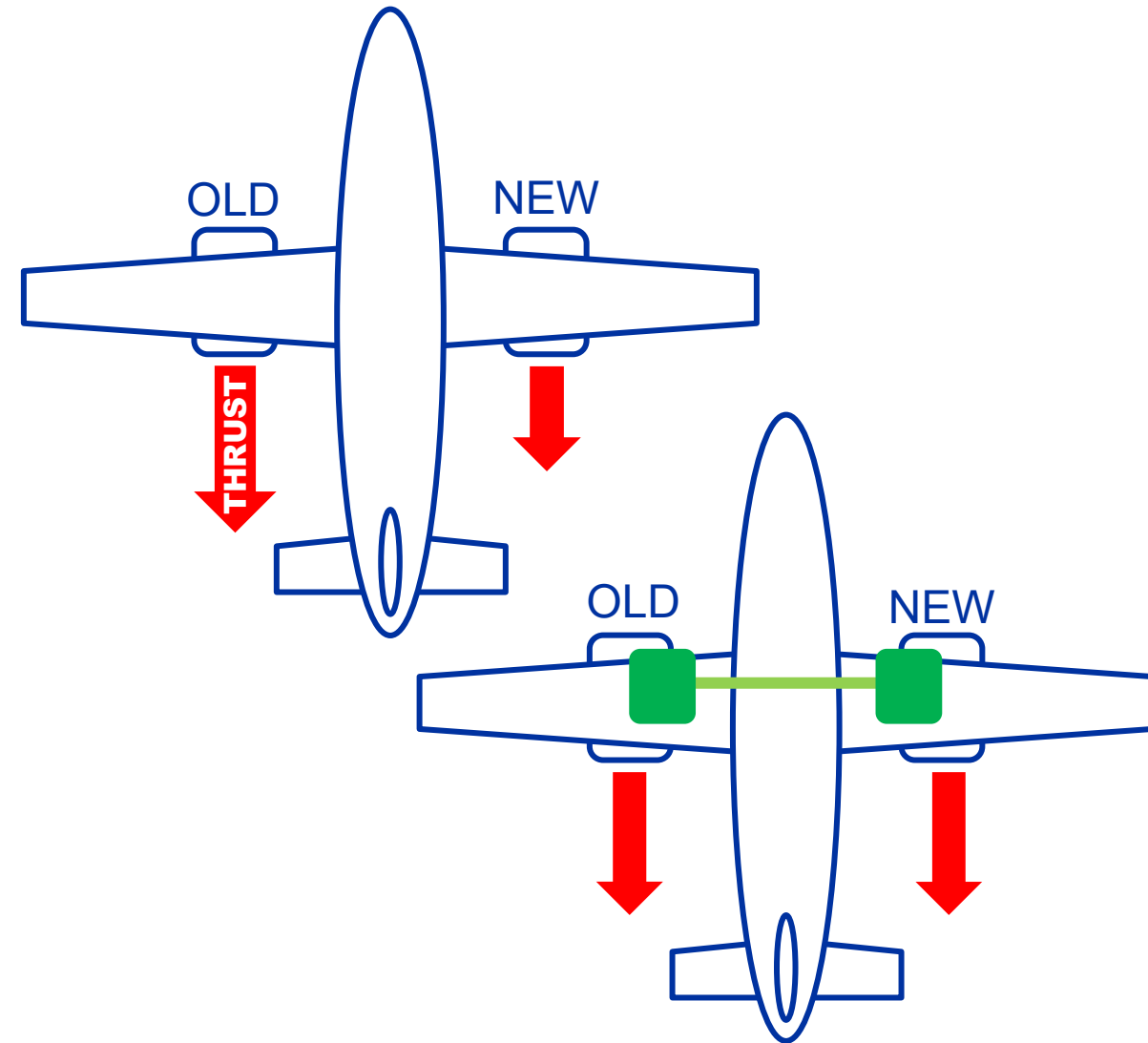
Hybrid Electric Aircraft with Unlike Engine Degradation (HEALED)

Problem = Multi-engine aircraft with different levels of degradation

- Asymmetric degradation leads to asymmetric thrust
- Turbofan thrust estimated for control based on corrected fan speed (N1c)
- A degraded engine will produce more thrust at the same throttle setting.
- Today compensate with rudder (drag, fuel burn, etc.)

Solution = HEALED

- Assuming an already hybrid-electric aircraft
- Electric machines (motor/generator) extract or insert power to assist the more-degraded engine with power from the healthier engine

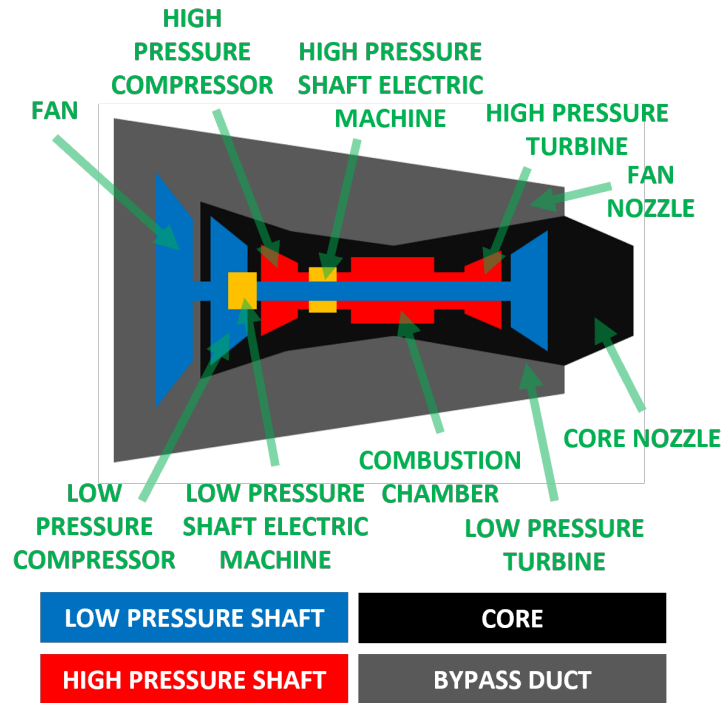


Asymmetric Thrust is balanced with HEALED Control

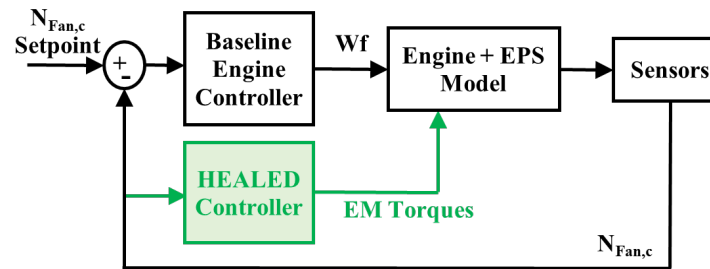
“Hybrid Electric Aircraft with Unlike Engine Degradation” Buescher and Connolly, ASME Turbo Expo 2024.

System Models

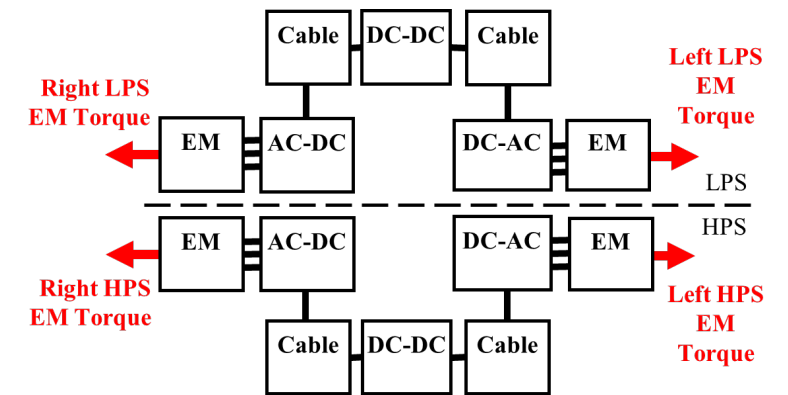
Electrified Advanced Geared Turbo Fan 30k pound thrust class engine (AGTF30-e)



Baseline control with HEALED for a hybrid-electric aircraft. Augmentations to the baseline shown in green.



Electrical power system (EMTAT) used to demonstrate HEALED control.



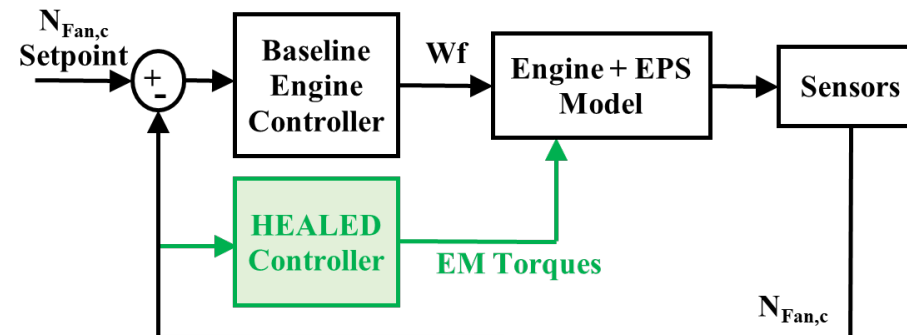
All models are built in MATLAB/Simulink.

HEALED control is applied to a hybrid-electric aircraft power and propulsion system model.

HEALED 1.0 – Decentralized Control

Proportional-Integral (PI) Control

- HEALED 1.0 utilized a decentralized control scheme made of PI controllers for the electric machines.
- Torque commanded for power extracted/inserted based on ratio of shaft speeds
- Instead of increasing fuel flow, HEALED assisted the more-degraded engine with electrical power.
- A centralized control scheme could improve system level performance.



HEALED PI was able to eliminate thrust asymmetry using the hybrid-electric powertrain.

Model Predictive Control (MPC)

Model Predictive Control (MPC)

- Model-based, optimal control scheme.
- Leverages system knowledge to generate optimal control trajectories subject to state, input, or output constraints.
- Centralized MPC architecture consolidates control authority into one controller.
- Offers sophisticated alternative to decentralized scheme previously implemented.

HEALED 2.0 – Centralized Control

Model Predictive Control

Optimal control problem:

$$\min_{\delta u_k} J_k = \frac{1}{2} \sum_{j=1}^{N_p} \|\delta \tilde{y}_{k+j}\|_Q^2 + \frac{1}{2} \sum_{j=0}^{N_u-1} \|\Delta u_{k+j}\|_R^2$$

subject to

$$\delta y_k = y_0$$

$$\delta x_{k+1} = A_d \delta x_k + B_d \delta \Omega_k$$

$$\delta y_k = C_d \delta x_k + D_d \delta \Omega_k$$

$$\delta x_k \in X - x_{trim}$$

$$\delta u_k \in U_{2:3} - u_{trim,2:3}$$

$$\delta y_k \in Y - y_{trim}$$

$$k \in 1, \dots, N$$

where

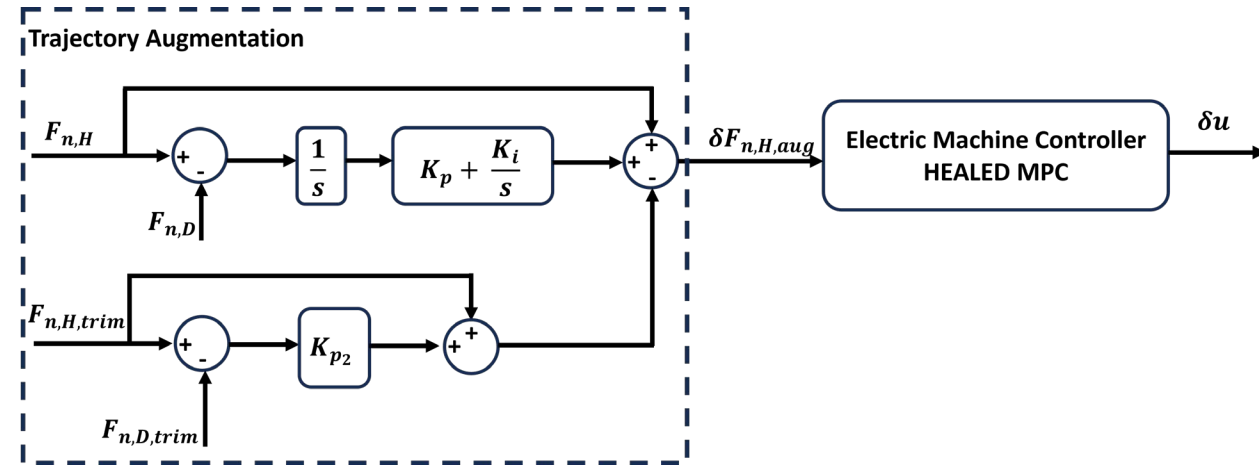
$$\tilde{y} = F_{n,D} - F_{n,H}$$

$$\Delta u_{k+j} = \delta u_{k+j} - \delta u_{k+j-1}$$

$$\Omega_k = [w_{f,H,0} \quad M_{LPS,H,k} \quad M_{HPS,H,k}]^T$$

Tracking

Rate
Penalty



HEALED MPC with Trajectory Augmentation

- Controller actuates healthy engine, thus no knowledge of degradation
- Trajectory augmentation added to compensate for steady-state error.

Simulation

- HEALED MPC is verified at cruise (35k ft, MN = 0.8, standard day)
- Two degradation cases (50% and 100%)
- Compared to Baseline Control and HEALED PI
- Input constraints on electric machines. Designed to restrict torques to power extraction.
- Output constraints on shaft speeds, turbine inlet temperature (T_{45}), and stall margins (SM) selected for standard operating limits.
- Constraint adherence demonstrated using turbine temperature, T_{45} .
 - In unconstrained condition, set to standard operating limit.
 - In constrained condition, reduced based on degradation level.

Results (1/3)

Adherence to system constraints on T45 (°R)

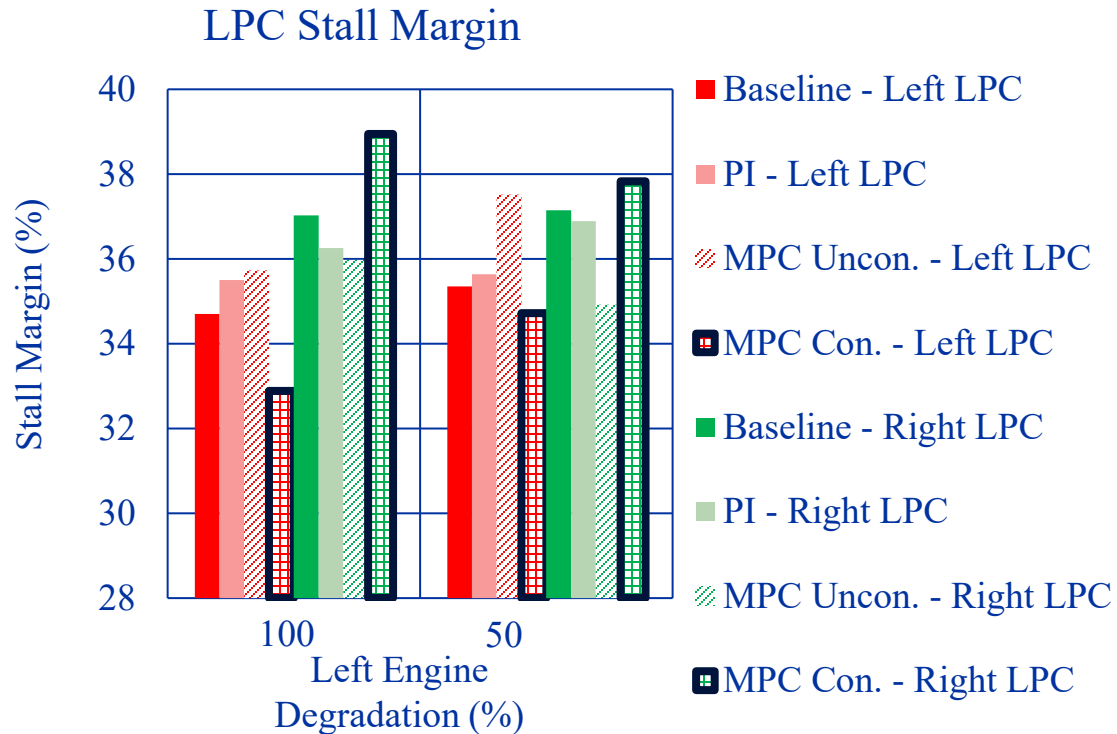
- 50%: T45 < 2205 °R
- 100%: T45 < 2225 °R

	Degraded Engine Condition (%)	T ₄₅ (°R)	
		Degraded Eng.	Healthy Eng.
Baseline	0	2191	2191
	50	2244	2190
	100	2321	2187
HEALED MPC (Unconstrained)	0	2191	2191
	50	2223	2211
	100	2279	2229
HEALED MPC (Constrained)	0	2191	2191
	50	2231	2203
	100	2287	2221

T45 (°R)

HEALED MPC successfully adhered to system constraints on T45.

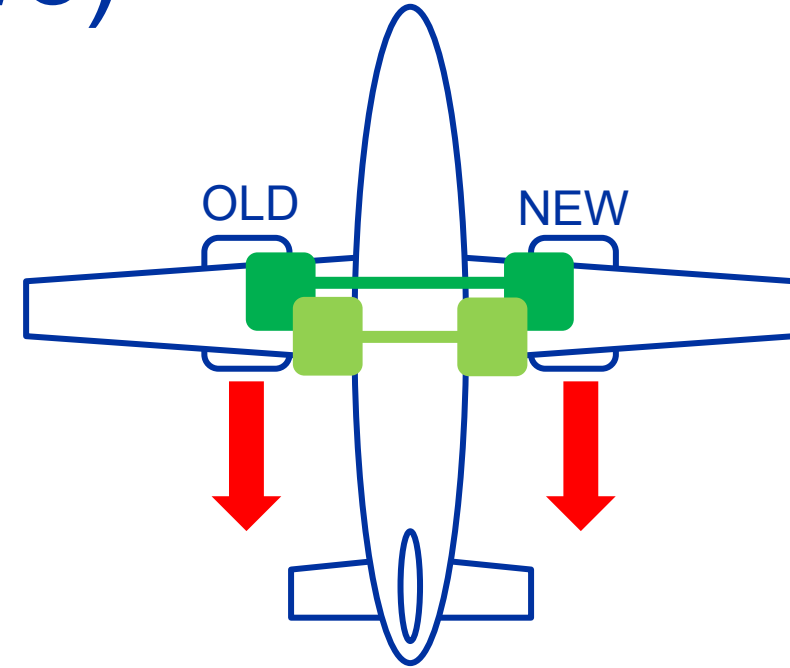
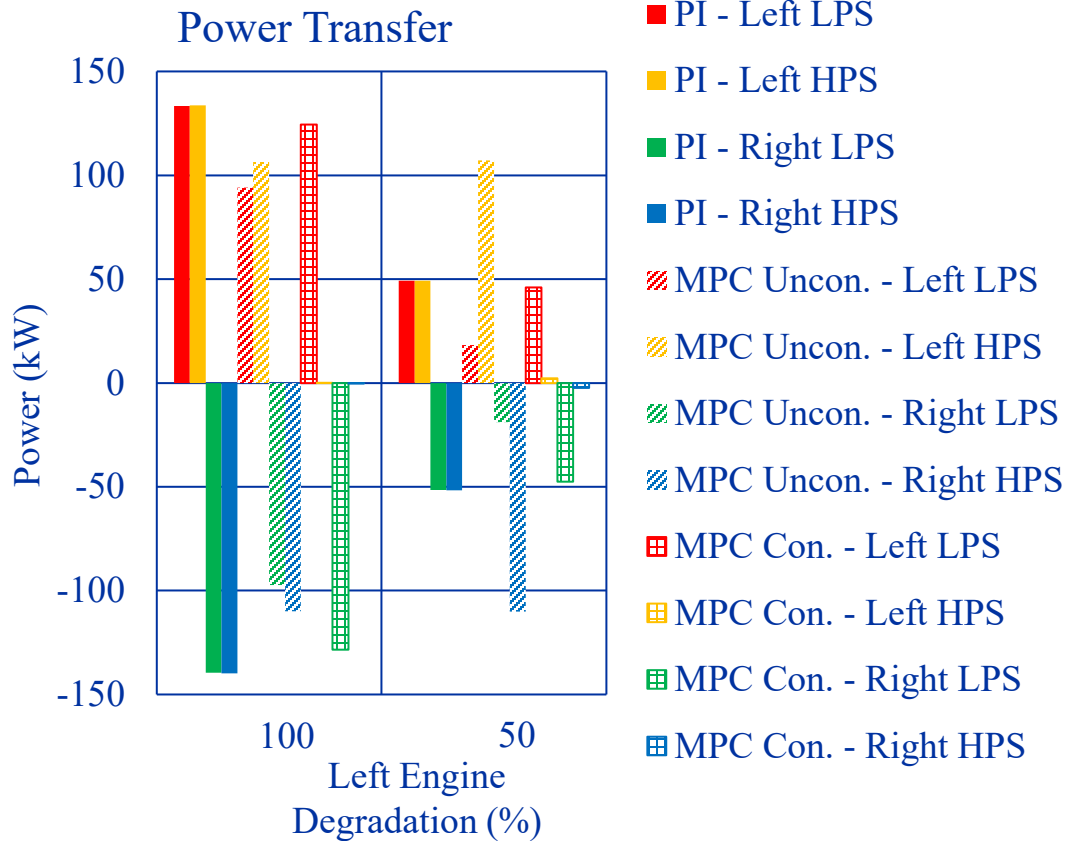
Results (2/3)



- HEALED 2.0 low-pressure compressor (LPC) stall margin (SM)
- $8\% < SM_{LPC} < 40\%$
- Unconstrained cases, green LPC SM decreases and red LPC SM increases with HEALED.
- Added constraints, the opposite happens.

HEALED MPC adheres to the constraints, but the constraints should be adjusted.

Results (3/3)



- HEALED PI – even distribution of power extraction.
- HEALED MPC – uneven distribution of power extraction.
- Constrained MPC commands power transfer primarily from the low-pressure shaft (LPS).

Culley, D., et. Al. "Turbine Electrified Energy Management (TEEM) for Enabling More Efficient Engine Designs," AIAA Propulsion and Energy Forum, Cincinnati, Ohio. 2018.

Conclusions

- HEALED with MPC adheres to system constraints while achieving the goal of balancing asymmetric thrust.
- HEALED with MPC commanded power extraction from the healthier engine to be inserted upon the more-degraded engine.
 - Constraints are applied to the healthier engine to preserve performance.
 - MPC determines optimal ratio of power extraction between high-pressure and low-pressure shaft electric machines.
- Fuel burn reduction was not a goal, so it was not reduced.

Future work:

- Add fuel flow reduction to the MPC goals.
- A shared electrical bus connecting the low- and high-pressure electric machines would allow more nuanced power extraction ratios.

HEALED with MPC balanced asymmetric thrust while adhering to system constraints.

Acknowledgements

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- Electrified Powertrain Flight Demonstration (EPFD) project
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Questions?

