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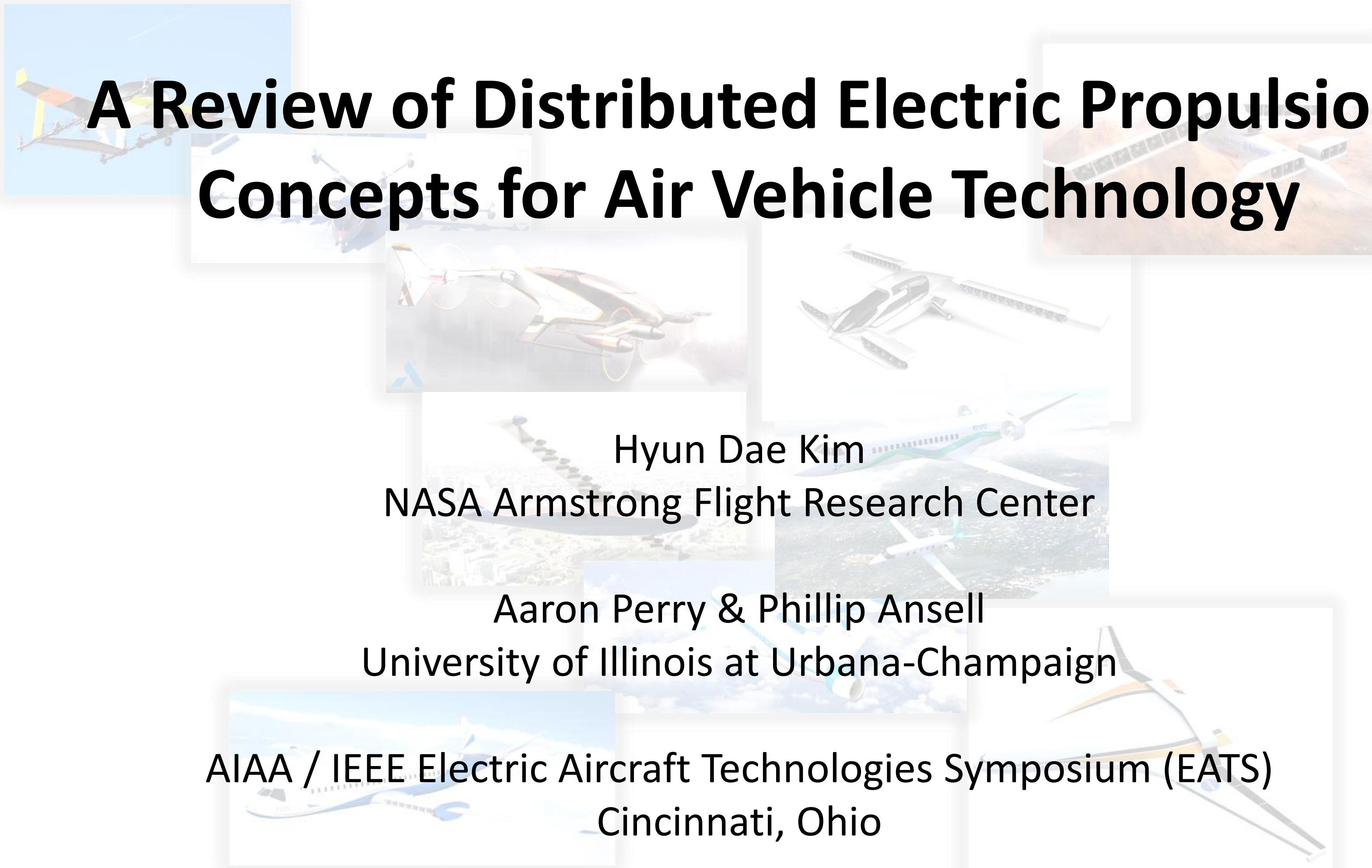

A Review of Distributed Electric Propulsion Concepts for Air Vehicle Technology

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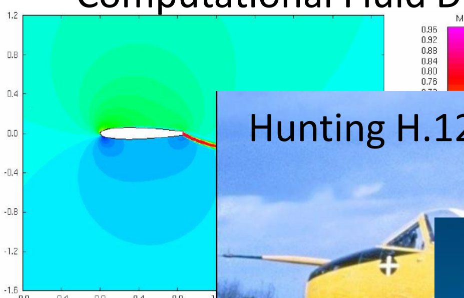
OUTLINE

1. Introduction to DEP concept
2. DEP aircraft (CTOL, STOL, & VTOL)
3. DEP/HE system research at NASA
4. Propulsion-Airframe-Integration (PAI) effects
    - Aero-propulsive coupling
    - Aircraft control
    - Noise reductions
5. R&D in electric components
6. Issues & Challenges
7. Conclusions

(DEP - Distributed Electric Propulsion, HE -Hybrid Electric)

- **What is Distributed Propulsion?** – No formal definition but,
  - Jet flap or distributed jet from one ore more engines
  - Multiple small independently powered propulsors
  - *Distributed propulsors driven by one or more power sources through various power transmission methods*

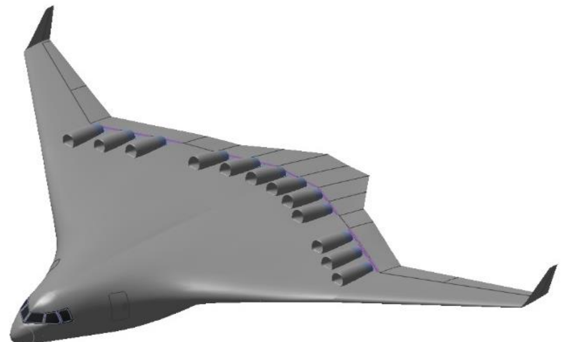
Computational Fluid Dynamics (CFD) simulation



Hunting H.126 (https://en.wikipedia.org)

F117 (http://www.af.mil)

YB-49 (http://www.nationalmuseum.af.mil)



Cruise Efficient Short Take-off and Landing (CESTOL) aircraft - NASA

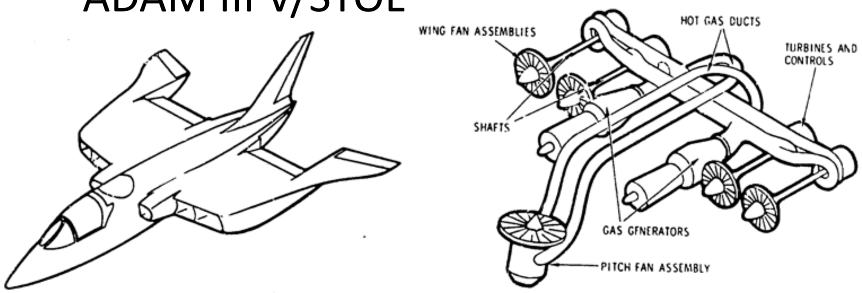
> **DP - Distributed propulsors driven by one or more power sources through various power transmission methods**

- Fluidically driven propulsor concepts
- Mechanically driven propulsor concepts
- ***Electrically driven propulsor concepts (D***

Silent aircraft by Cambridge-MIT Institute

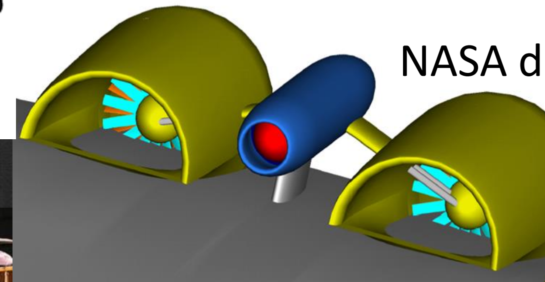
http://silentaircraft.org/sax40

ADAM III V/STOL



Winborn, B. R. Jr., “The ADAM III V/STOL Concept,” AIAA Paper 69-201

NASA dual-fan concept



Wright Flyer (http://www.nationalmuseum.af.mil)

What is Distributed Electric Propulsion (DEP)?

- A propulsion system where electrical energy sources are connected, via transmission lines, to multiple electric motor-driven propulsors

Key Features

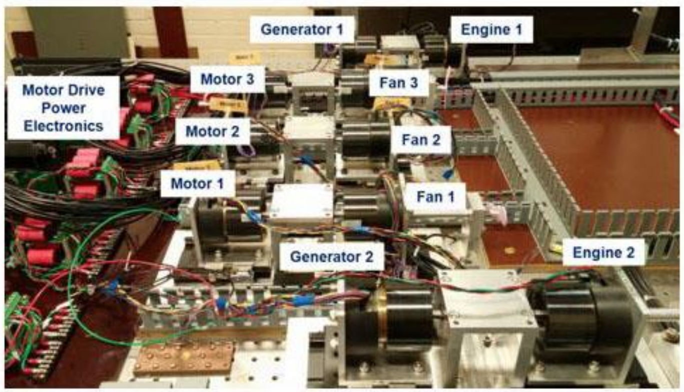
- Power sources can be any combination of electrical power-producing devices (i.e., electric generator, fuel cell, etc.) and/or energy storage devices (i.e., battery, capacitor, etc.)
- Propulsors can be any combination of thrust producing devices such as electrically-driven propellers or fans
- Decoupled feature between the power sources and propulsive devices enables flexibility in aircraft design and efficient operation ***if*** efficient & compact electric machines and transmission system are employed

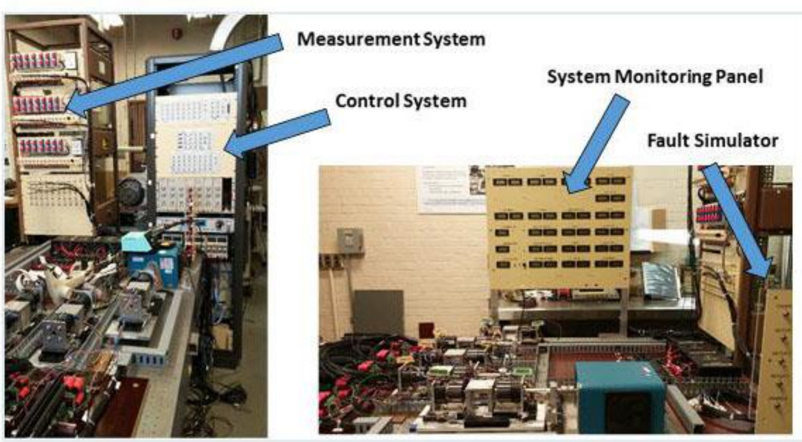
DEP Aircraft

(Images used with permissions)

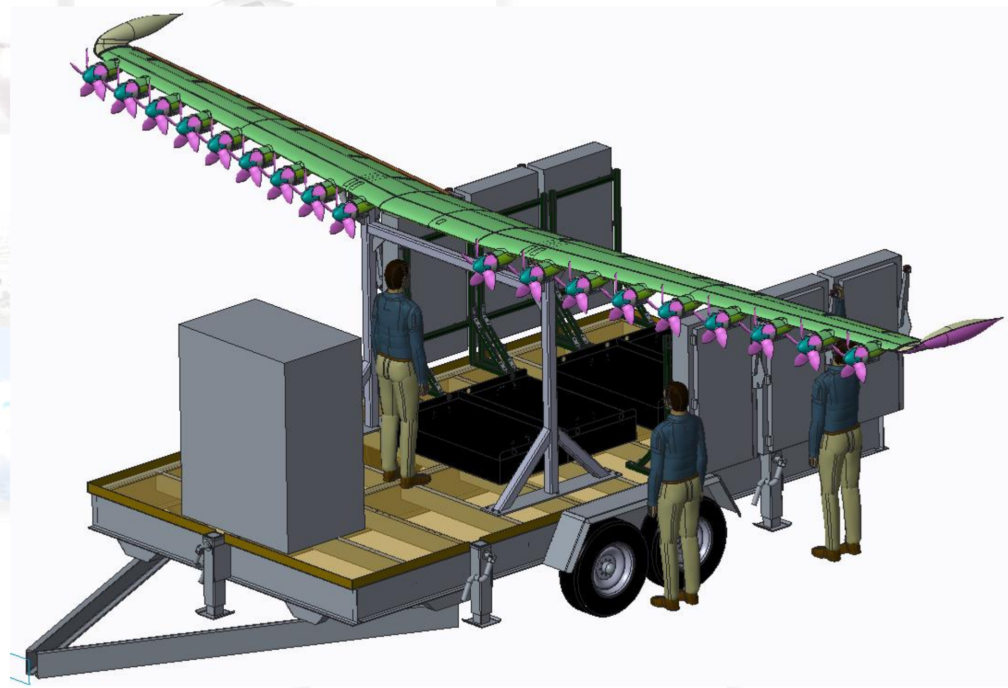
DEP/HE system research at NASA

Propulsion Electric Grid Simulator (PEGS) subscale electric power system for TeDP at NASA Glenn Research Center



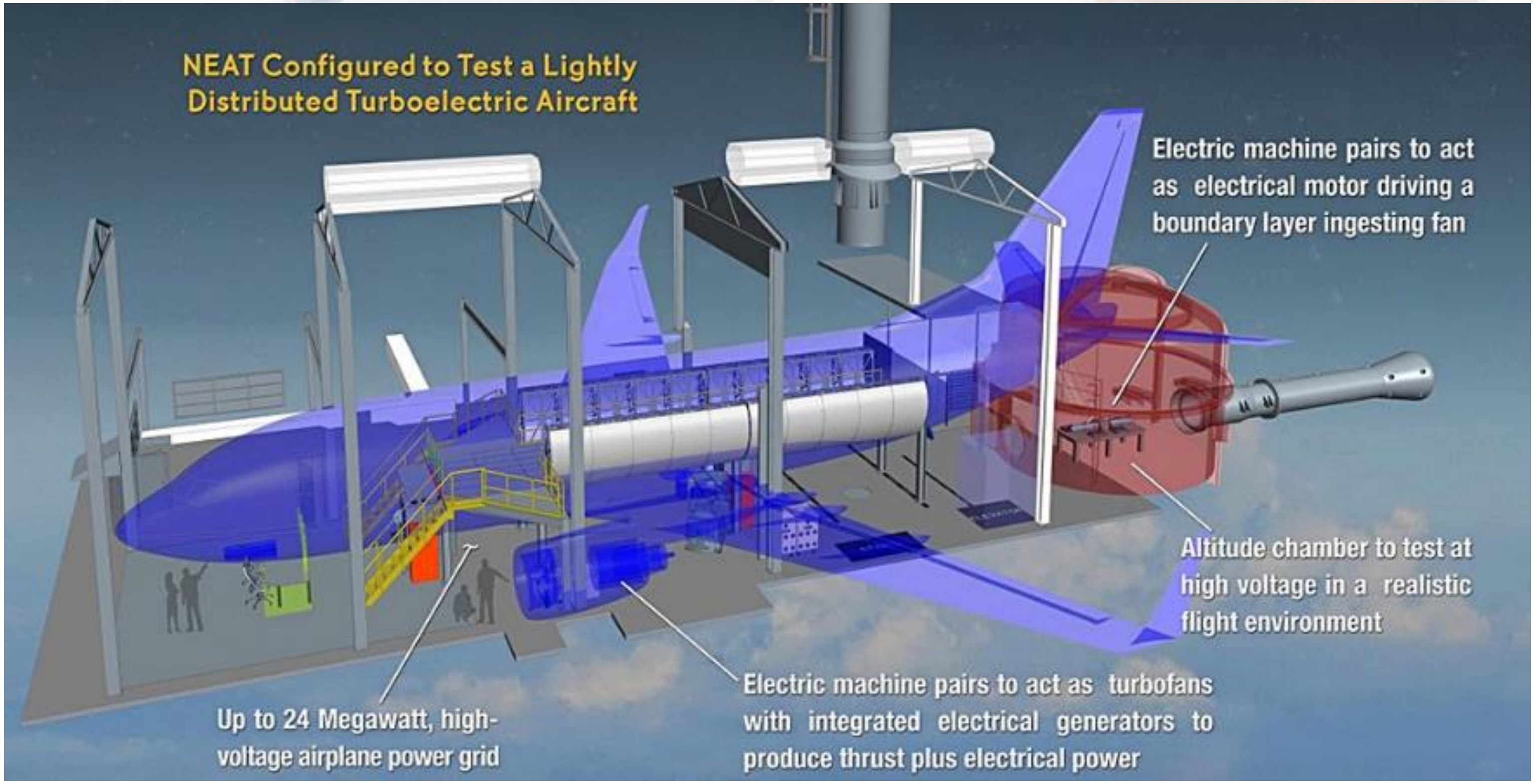


Hybrid-Electric Integrated Systems Testbed (HEIST) at NASA Armstrong Flight Research Center



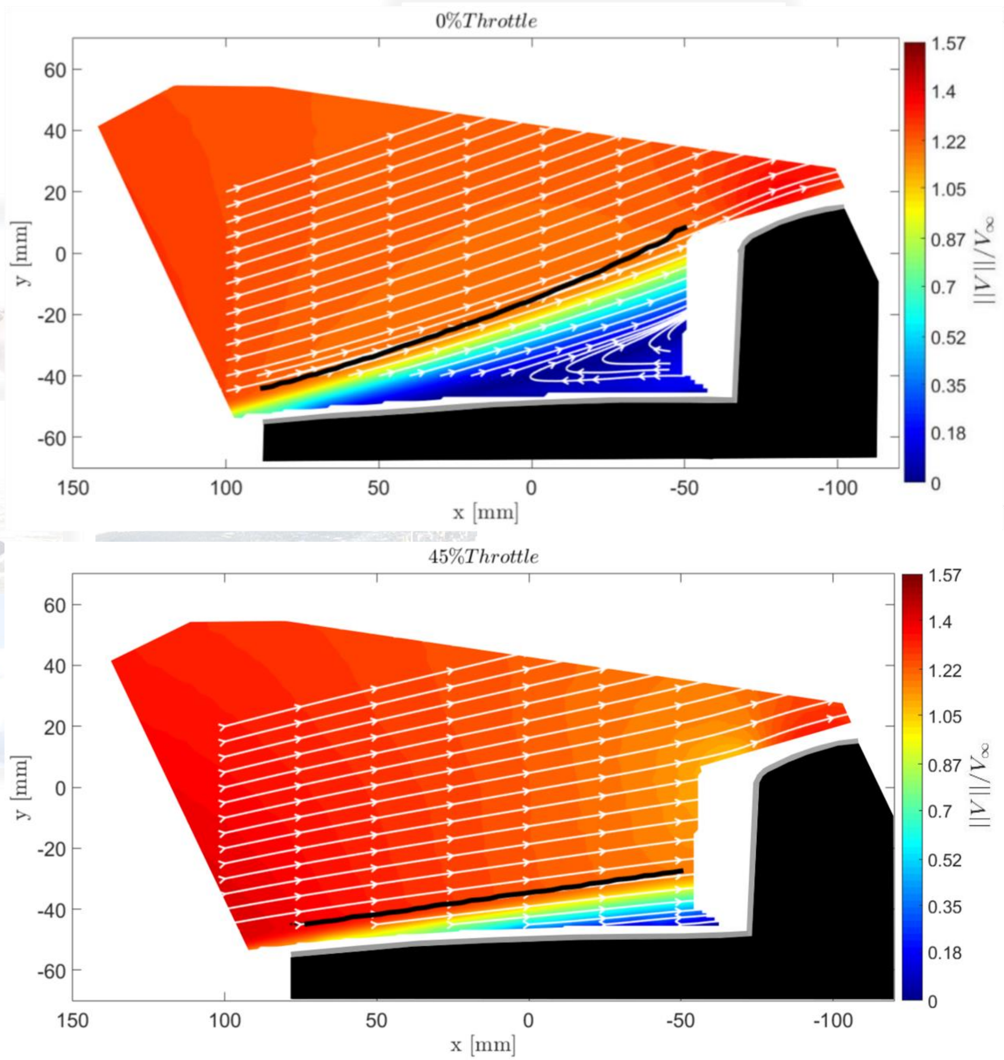
DEP/HE system research at NASA

NASA Electric Aircraft Testbed (NEAT) platform for full-scale turboelectric powertrain testing at NASA Glenn Research Center



Propulsion-Airframe-Integration (PAI) effects

- Aero-propulsive coupling
- Aircraft control
- Noise reduction



Aero-propulsive coupling

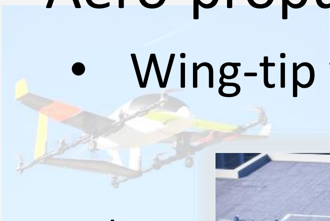
- Boundary layer ingestion (BLI) benefit – increased propulsive efficiency
- Wing-tip vortex suppression and wake-filling – reduced (induced) drag
- Enhanced lift or control authority


Lilium


NASA STARC-ABL


NASA N3-X

- Aero-propulsive coupling
  - Wing-tip vortex suppression – reduced (induced) drag



Joby S2

Airbus Vahana

NASA X-57

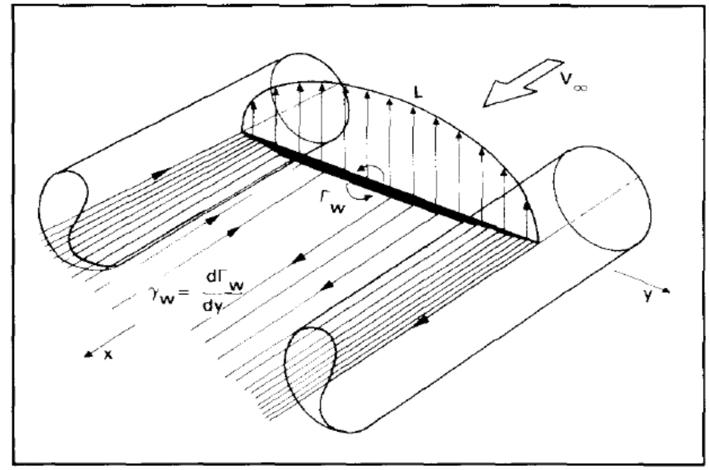
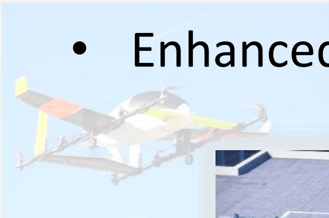


Figure 1. Vorticity Model of Wing-Propeller Combination

From Miranda, L. R. and Brennan, J. E., "Aerodynamic Effects of Wingtip-Mounted Propellers and Turbines," 1986.

NASA N3-X

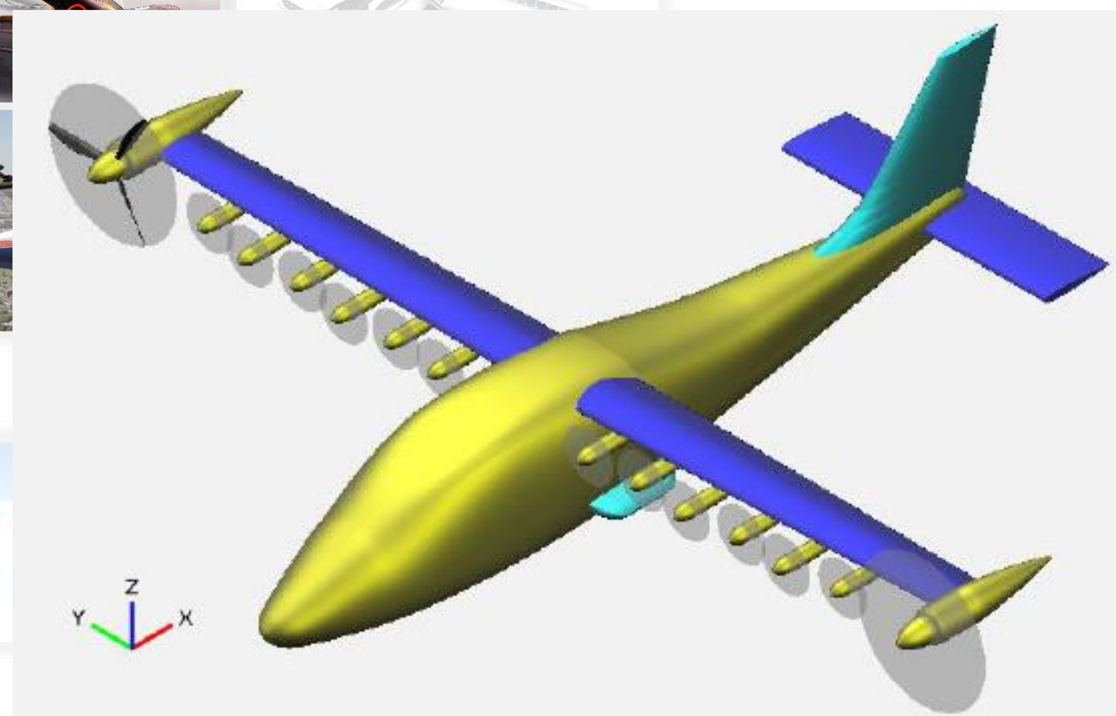
- Aero-propulsive coupling
  - Enhanced lift or control authority



Joby S2

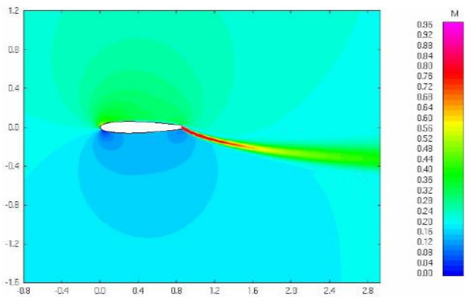
Airbus Vahana

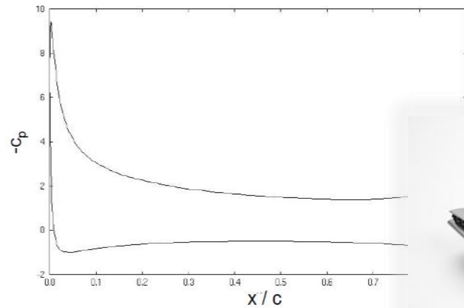
NASA X-57



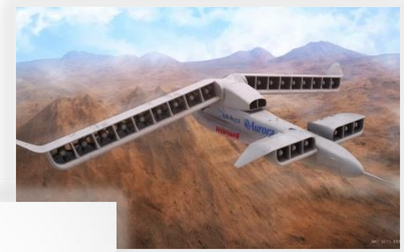
➢ Aero-propulsive coupling

- Enhanced lift or control authority





Aurora XV-24



Lilium

ESAERO ECO-150

unting H.126
ttps://en.wikipedia.org)

NASA N3-X

Aircraft Control

- Propulsion controlled aircraft origins (PCA)
  - 1989 DC-10 United Airlines Flight 232 accident in Sioux City, Iowa
  - Fault tolerant control (FTC)

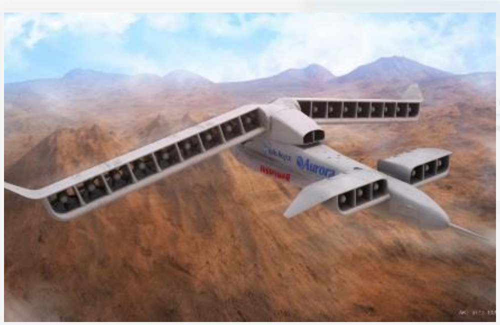
- Initial concept challenges
  - Development of MD-11 testbed
  - Slow gas turbine response time
- The bright future
  - DEP enabled control
  - Fast electric motor response time
    - Variable pitch blades, variable area nozzles

➢ DEP-based Aircraft Control

- Propulsion units as thrust-line control actuators
  - Thrust vectoring (Lilium)
- Enhanced control authority from blown surfaces
- Improved control redundancy/robustness to vehicle damage
- Reduction/elimination of traditional stabilizer/control surfaces
- Propulsion induced aeroelastic responses

Lilium

Aurora XV-24

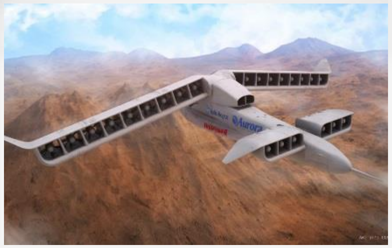


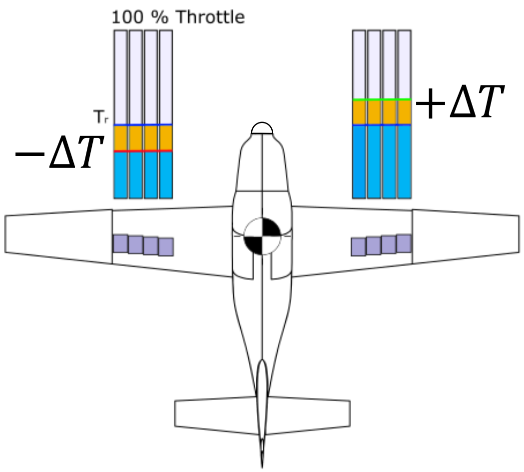
DEP-based Aircraft Control

- Several concepts exhibit DEP control
  - Thorough system identification tests for controller development (GL-10)
- Ongoing research at UIUC
  - Scaled Cirrus SR22 DEP variant
  - Flight tests – influence of propulsors on dynamics
    - Compare to baseline

Lilium

Aurora XV-24





Noise Reductions

- NASA Chapter 4 far term noise goal: cumulative margin 52EPNdB
- High effective bypass ratio for low FPR (N3-X margin of 32EPNdB)
- Shielding propulsion units from ground (N3-X margin of 64EPNdB)
- Electric machine noise
- X-57 Acoustic studies

R&D in electric components

- Current capabilities
  - Applicable to general aviation aircraft and UAVs
- Areas of research
  - Megawatt scale electrical machines (UIUC)
  - Hybrid electric systems
  - Power transmission architectures for DEP
  - Inverters, converters, power transmission

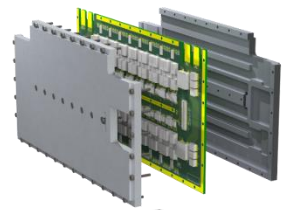


Table 1 Current electrical component capabilities for aircraft applications.

Motor Power Capability (MW)	Motor Specific Power (kW/kg)	Electronics Power Capability (MW)	Electronics Specific Power (kW/kg)	Battery Specific Energy (Wh/kg)
0.25	2.2	0.25	2.2	200-250

Issues & Challenges

- Inlet distortion from BLI (NASA GRC tests)
- Electrical component technology readiness
  - Weight, power ratings, certification, energy density
- Noise generation for eVTOL in urban environment
- Loss of propulsion units used for control/lift augmentation
  - Must be able to take off and land
  - Must be able to control vehicle


Distortion-Tolerant Fan Test (NASA GRC)

Conclusions

- Distributed Electric Propulsion
  - Electrical energy sources are connected to multiple electric motor-driven propulsors
  - Mechanical decoupling of power production and propulsive power expenditure
  - Use across CTOL, STOL, VTOL
- Advantages
  - Improved efficiency and performance
  - DEP-enabled vehicle control
  - Reduced operational noise
- Electrical Systems Research Thrusts
  - Components: motors, drives, electronics, energy storage
  - Power distribution architectures
  - System performance and control
- Challenges for Future Study
  - Inlet distortion
  - Redundancy and fault tolerance
  - Impact of VTOL and increased vehicle traffic on community noise
  - Battery systems and electrical components