



# A Review of Distributed Electric Propulsion Concepts for Air Vehicle Technology

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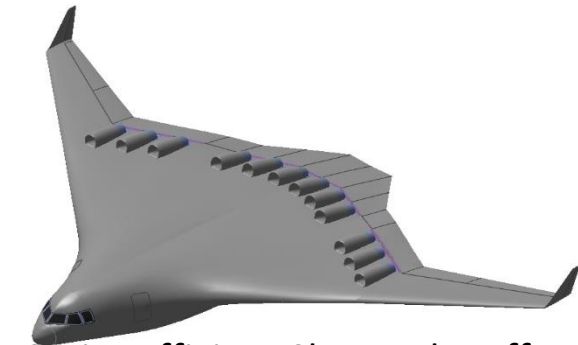
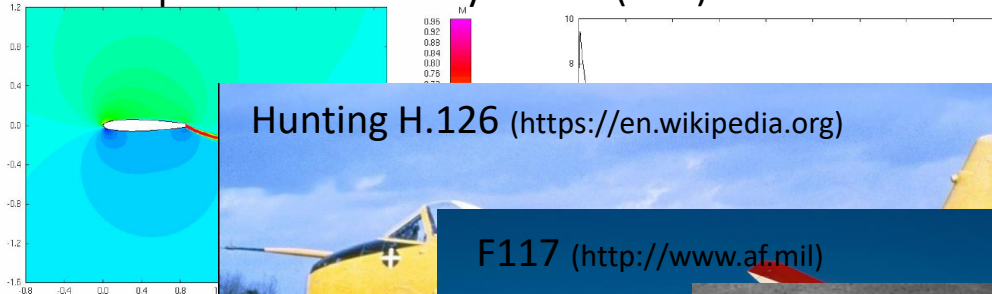
## OUTLINE

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 or 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

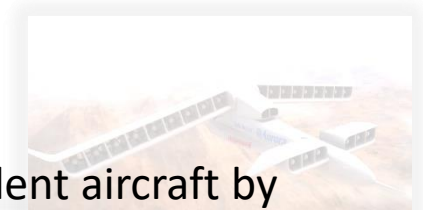


Cruise Efficient Short Take-off and Landing (CESTOL) aircraft - NASA



➤ 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 (E-DEP)**

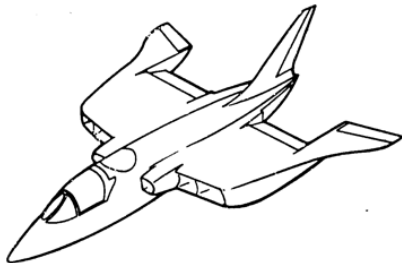


Silent aircraft by Cambridge-MIT Institute

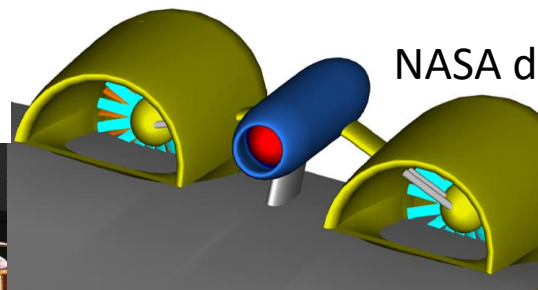
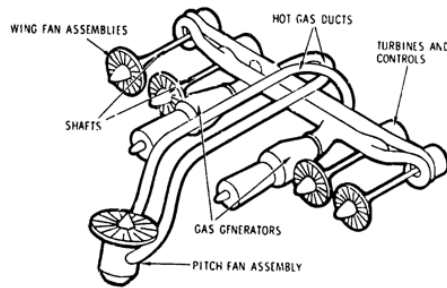


<http://silentaircraft.org/sax40>

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



# A Review of Distributed Electric Propulsion Concepts for Air Vehicle Technology

## DEP Aircraft

Aurora eVTOL



Joby S2



Airbus Vahana



Lilium



Aurora XV-24



### VTOL Configurations

NASA X-57



Zunum Regional Aircraft



ESAERO ECO-150



NASA STARC-ABL



NASA N3-X

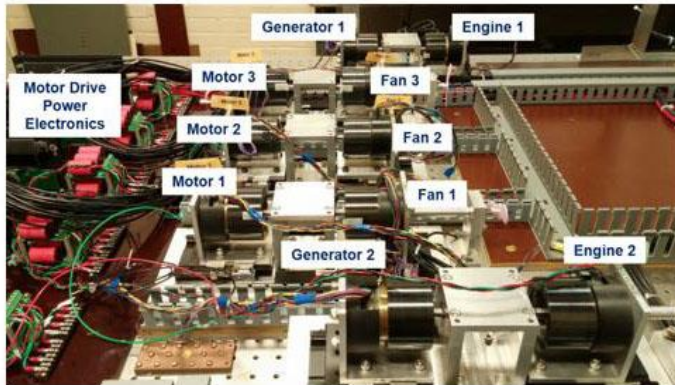


### CTOL Configurations

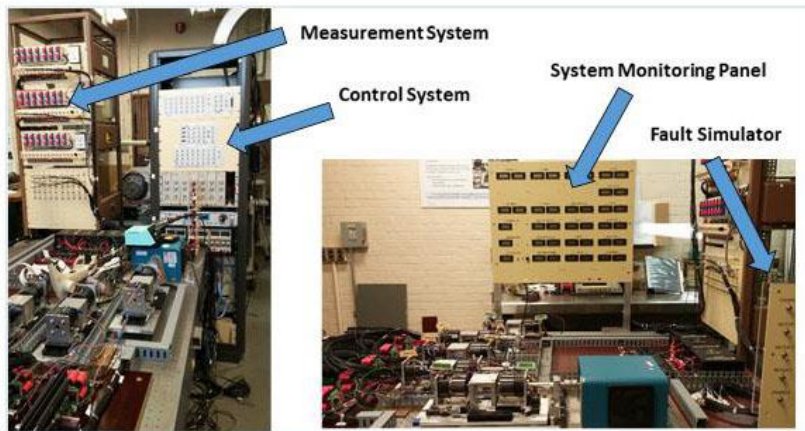
(Images used with permissions)

## 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

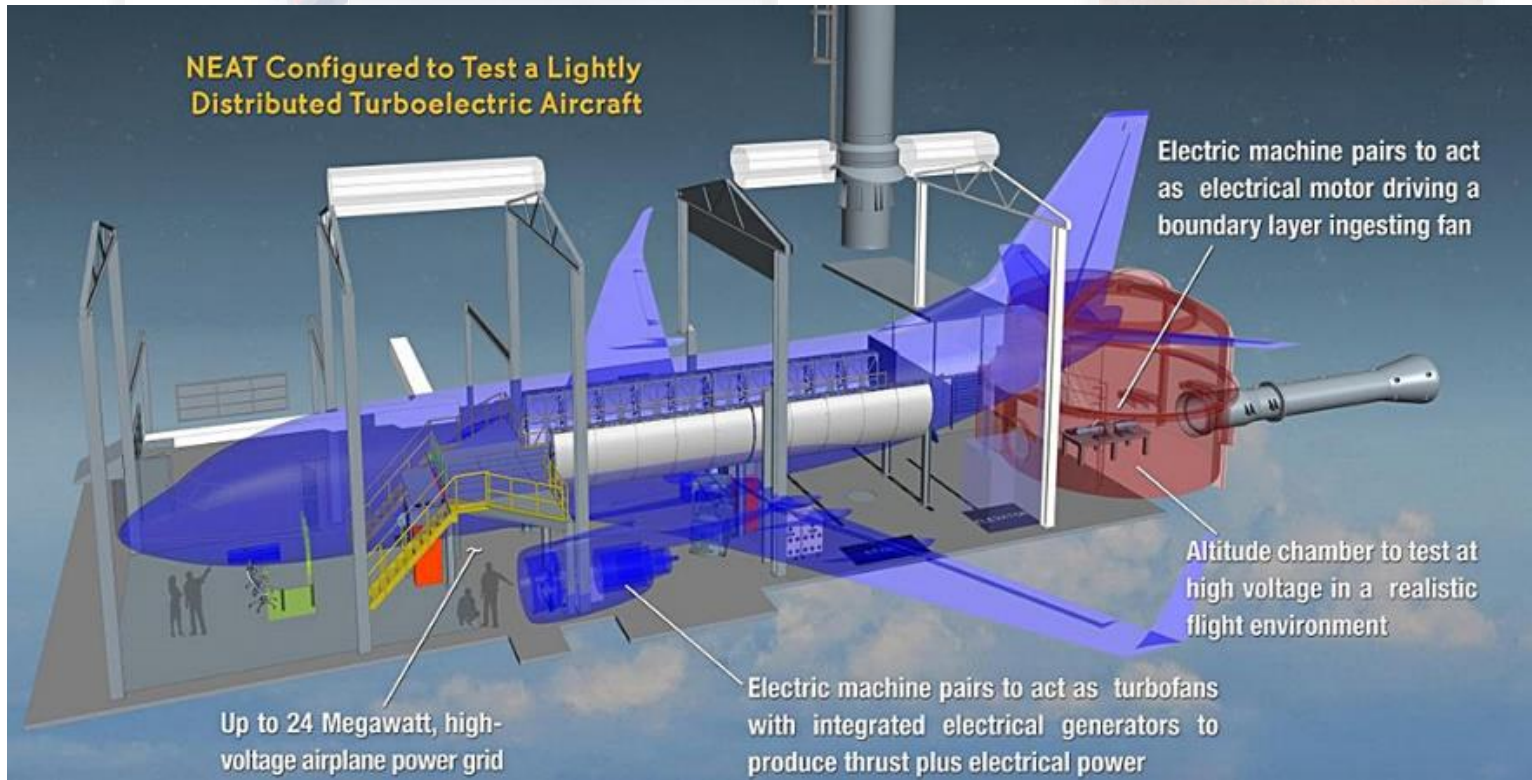
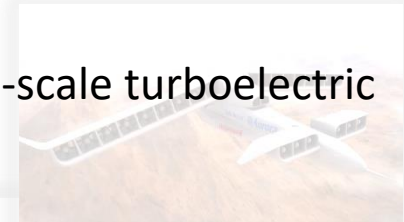




## DEP/HE system research at NASA



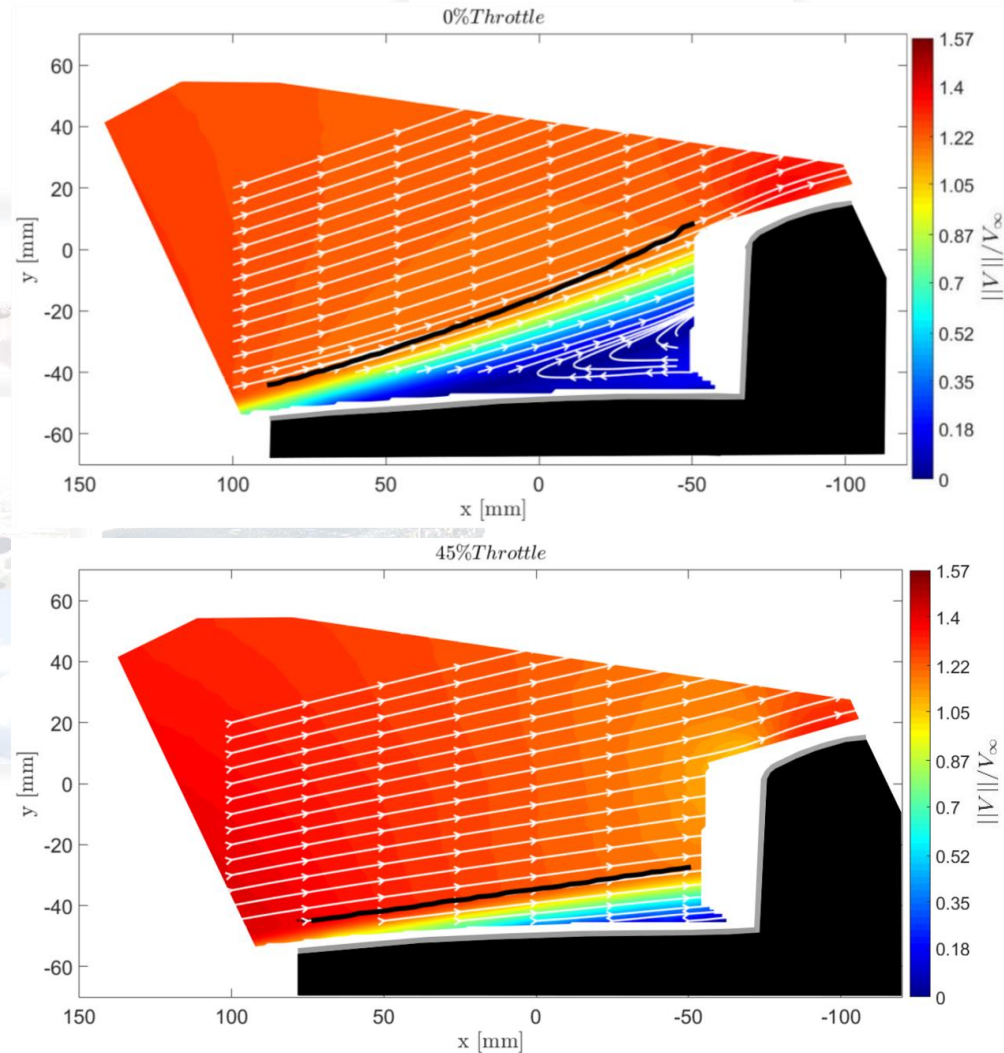
NASA Electric Aircraft Testbed (NEAT) platform for full-scale turboelectric powertrain testing at NASA Glenn Research Center





## Propulsion-Airframe-Integration (PAI) effects

- Aero-propulsive coupling
- Aircraft control
- Noise reduction



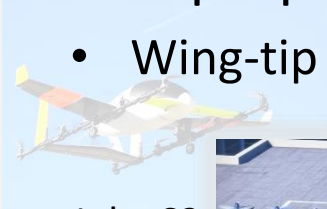
## ➤ Aero-propulsive coupling

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



## ➤ Aero-propulsive coupling

- Wing-tip vortex suppression – reduced (induced) drag



Joby S2



Airbus Vahana



NASA X-57



NASA  
N3-X

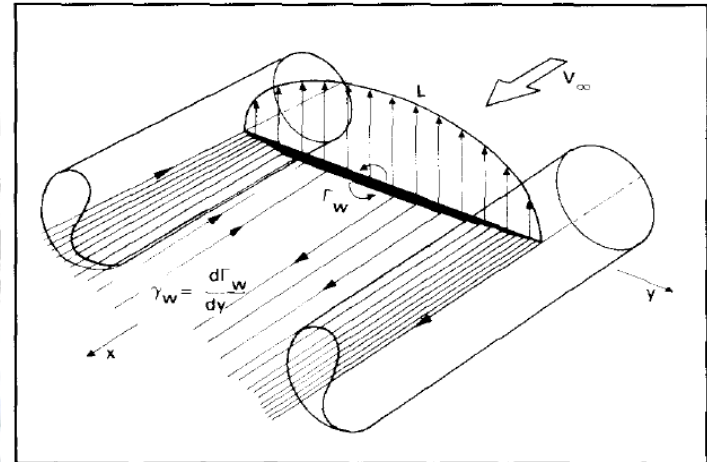


Figure 1. Vorticity Model of Wing-Propeller Combination  
From Miranda, L. R. and Brennan, J. E., "Aerodynamic Effects of Wingtip-Mounted Propellers and Turbines," 1986.



## ➤ Aero-propulsive coupling

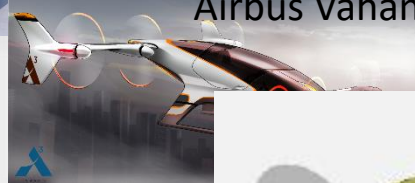
- Enhanced lift or control authority



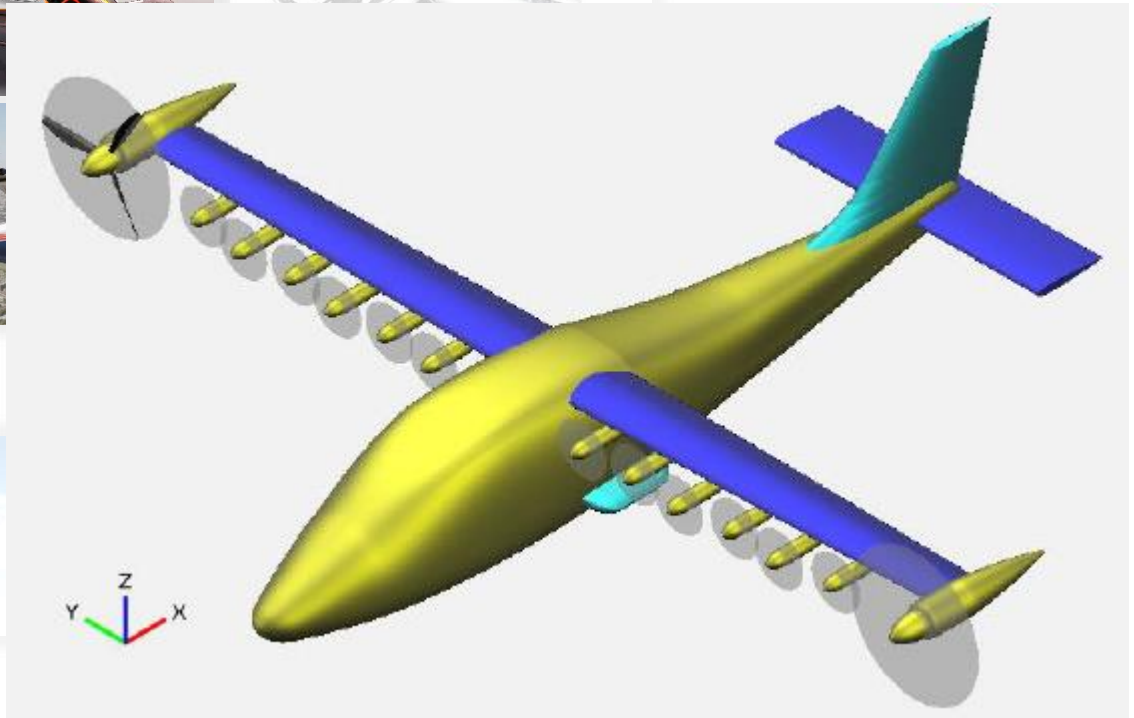
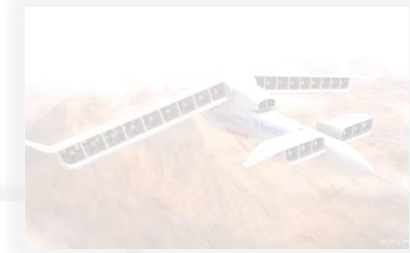
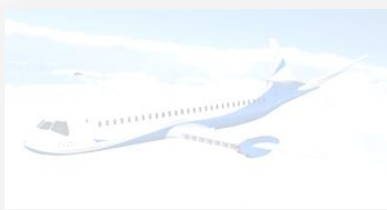
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Airbus Vahana

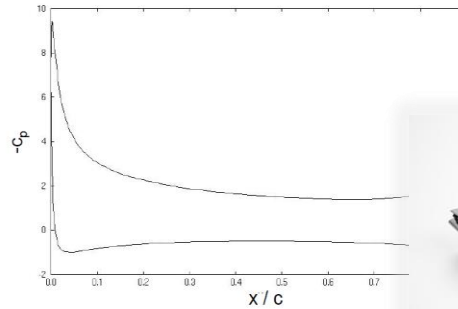
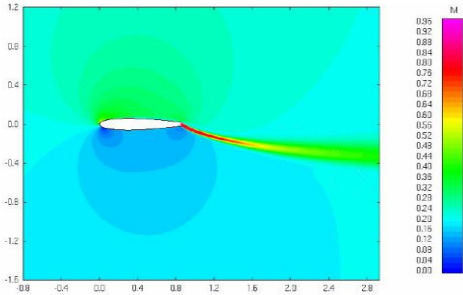


NASA X-57



## ➤ Aero-propulsive coupling

- Enhanced lift or control authority



Aurora XV-24



Lilium



ESAERO ECO-150



Hunting H.126  
<https://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





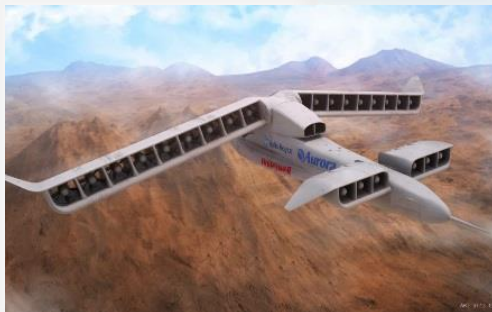
## ➤ DEP-based Aircraft Control

- 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

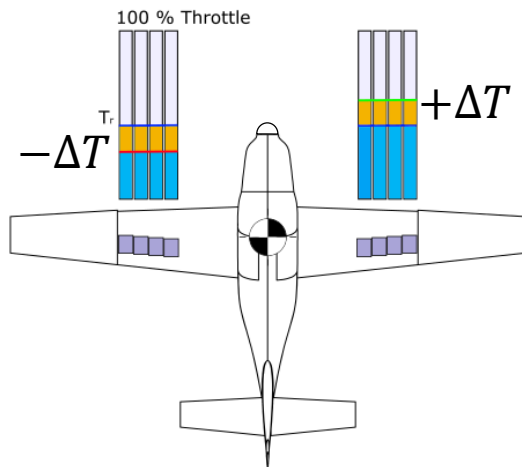


Aurora XV-24



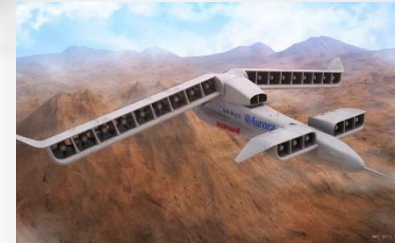
## ➤ DEP-based Aircraft Control

- 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

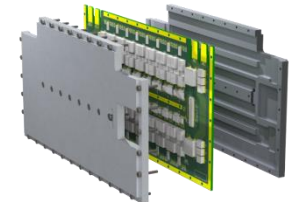
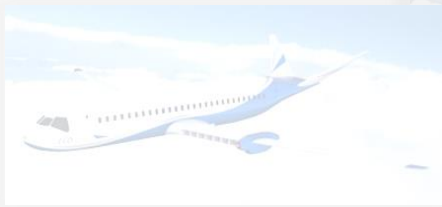


Table 1 Current electrical component capabilities for aircraft applications.

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