National Aeronautics and Space Administration

Enabling Electric Propulsion for Flight

Hybrid Electric Aircraft Research at AFRC

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Transformational Flight - Electric Propulsion Development and Testing
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ARMD Goals for System Level Metrics (last updated in 2010)

CORNERS OF THE TRADE SPACE	N+1=2015*** Technology Benefits Relative To A Single Aisle Reference Configuration	N+2=2020*** Technology Benefits Relative To A Large Twin Aisle Reference Configuration	N+3=2025*** Technology Benefits
Noise (cum below Stage 4)	-32 dB	-42 dB	-71 dB
LTO NO_x Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-50%**	better than -70%
Peformance: Field Length	-33%	-50%	exploit metroplex* concepts

*** Technology Readiness Level for key technologies = 4-6
** Additional gains made be possible through operational improvements.
* Concepts that enable optimal use of runways at multiple airports within the metropolitan area

- Challenge goals will require non-traditional approaches to aircraft efficiency at both the component and system levels.
- Incremental improvements to existing architectures won't be sufficient to meet these targets.
- Solutions will integrate new technologies and techniques from many fields (propulsion, structures, controls, etc.).

The Big Picture / Elec. Prop. Research Pathway at AFRC

Airvolt

Airvolt Hybrid

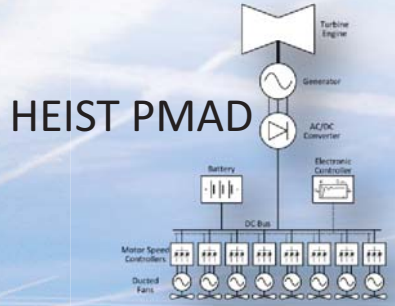
Motor Generator Advances

2 MW Testbed

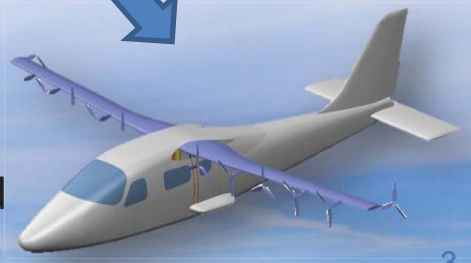
HEIST LEAPTech

Hardware-in-the-Loop Sims

Iron Birds



HEIST PMAD



Advanced Flight Testbed Or Experimental Vehicle

Challenges to Advancing Electric Propulsion System TRL

- **System Integration**: Unexpected complexities surface on flight-like systems:
  - Will DC buses remain stable with high-frequency loads?
  - What grounding issues will only emerge when airframe installation compromises are considered?
  - Will EMI/EMC effects emerge in volume/weight constrained applications?
- **Standards Development**: System design and implementation standards needed:
  - What measurement techniques and sensor technologies are necessary or ideal?
  - What V&V methodologies are most effective?
  - What physics-based issues/phenomena cannot be predicted with simulation?
  - How should subsystem performance be monitored?
- **Size**: Components are needed at higher energy/power density and smaller volume
  - How will thermal management become a design driver at high power density?
  - How will battery management and quality be affected by high energy density systems?
- **Funding**: Limited budgets in aeronautics R&D drive a spiral development approach
  - How can we achieve the most research objectives with limited budgets?

Challenges

SysInt

Standard

Size

Funding

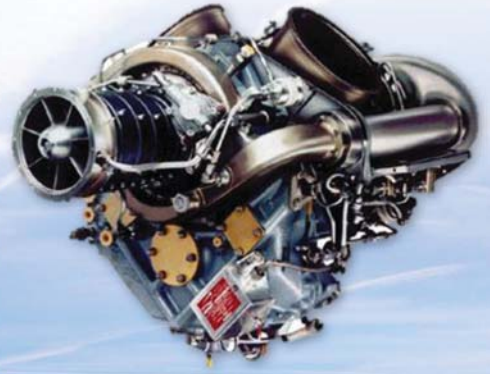
AirVolt: Single String Propulsion Test Stand

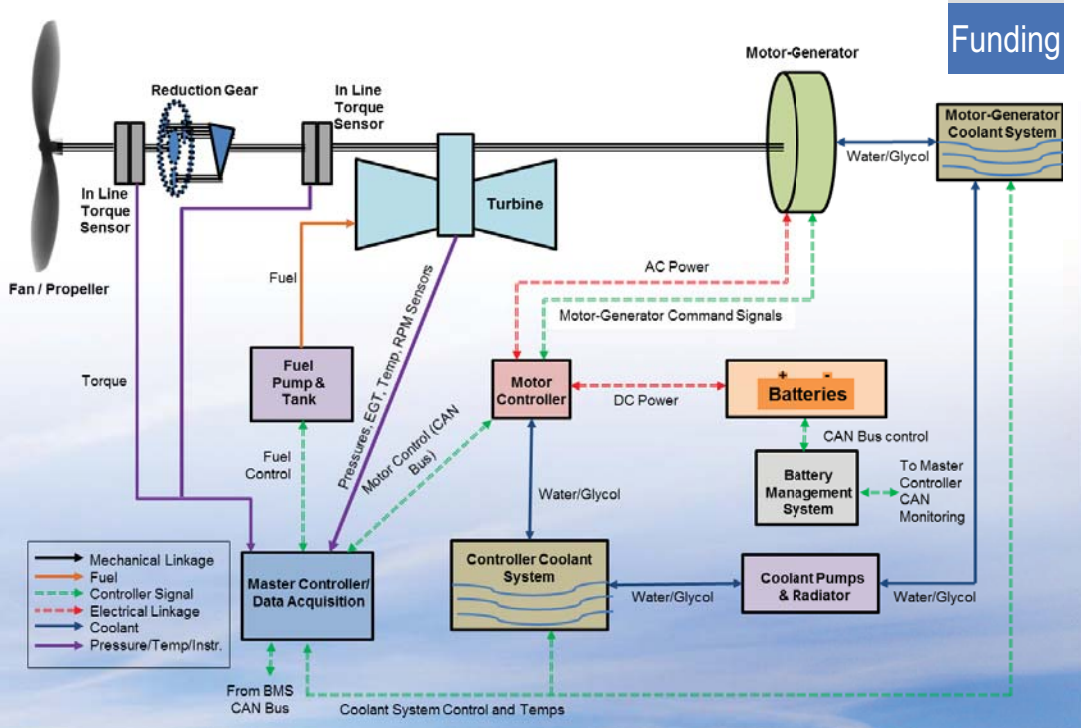
- **Motor Power**: up to 500 VAC, 500 A *(200 kSPS)*
- **ECU Power**: up to 500 VDC, 500 A *(200 kSPS)*
- **Thrust**: Up to 500 lbs *(measured at 5 kSPS)*
- **True Air Speed**: Up to 120 fps *(100 SPS)*
- **Torque**: -50 to +150 ft-lbs *(5 kSPS)*
- **P_{BARO}, Temp, Humidity** *(100 SPS)*
- **Motor Speed**: up to 3,000 rpm
- **Propellers**: up to 6' diameter
- **Total power**: up to 40 kW

Hybrid Airvolt

Challenges
- SysInt
- Standard
- Size
- Funding

- Investigate power transfer stability challenges
- Initial concept reviews complete.
- Targeting 317 HP/230 kW config
- Major System Components
  - › Allison 250 turbine
  - › Motor & Controller
  - › Batteries and BMS

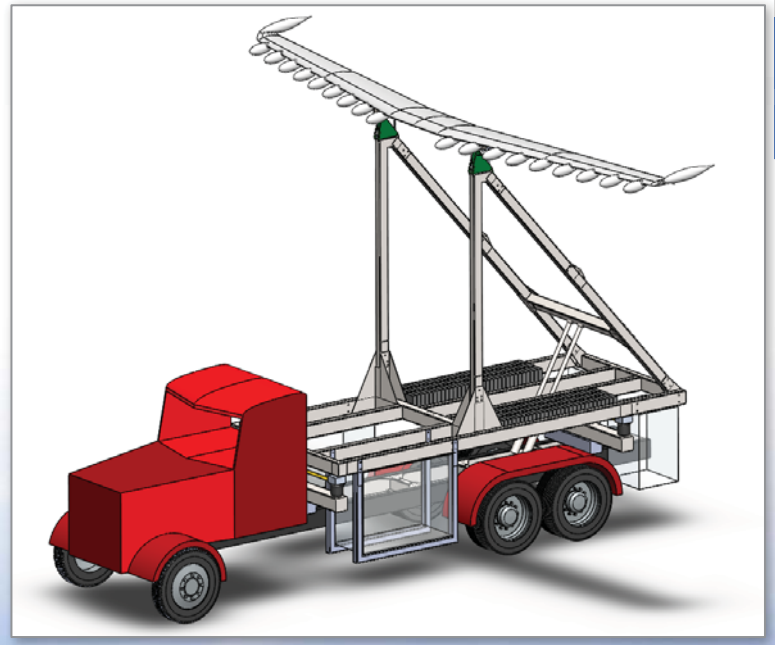




Hybrid-Electric Integrated System Testbed (HEIST)

Challenges
SysInt
Standard
Size
Funding

- **Leading Edge Asynchronous Propeller Technology (LEAPTech):**
  - First experiment to be conducted at Armstrong, Nov 2014
  - Funded by ARMD Team Seedling competition (partnership between AFRC, LaRC, ARC, GRC)
  - Obtain data to validate CFD tools for designing and optimizing distributed propulsion configurations
    - Measure real flow physics associated with the proposed configuration
    - Develop phase 2 test objectives for higher fidelity test points and measurement goals



NASA E|S|AERO JOBY AVIATION

LEAPTech: Major Roles & Responsibilities

Challenges
SysInt
Standard
Size
Funding

- NASA AFRC
  - Oversight / Host
  - Requirements Management
  - Master motor controller
  - Test Execution
  - Safety Review Process
- NASA LaRC
  - LEAPTech lead (PI)
  - Wing aero design
  - CFD analysis
  - Structural analysis
- ESAero-Small Business Contractor (Prime)
  - Top level engineering
  - Instrumentation
  - System Integration
- Joby Aviation (Subcontractor)
  - Wing Manufacturer
  - Motors, motor speed controllers, propellers
  - Test Rig (truck platform) fab, force balance design

Hybrid-Electric Integrated System Testbed (HEIST)

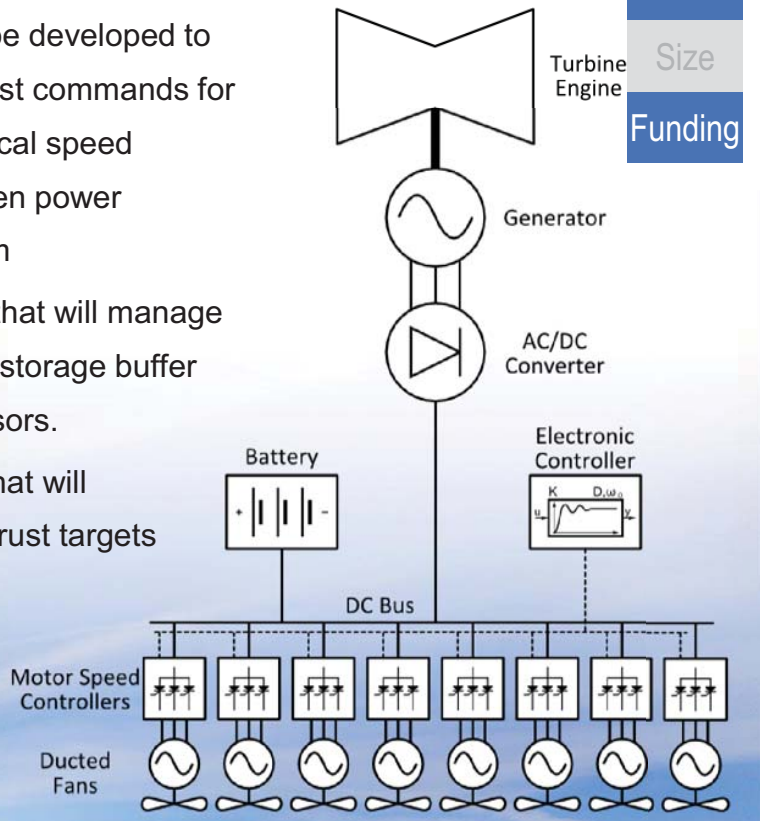
Challenges
SysInt
Standard
Size
Funding

- **Power Management and Distribution (PMAD):**
  - Second experiment on the HEIST, Feb 2016
  - Static propulsion test stand co-located with Airvolt
  - Evaluate inherent issues with parallel-hybrid electrical bus architecture (bus stability given many dynamic loads and sources)
  - Characterize aggregate thrust control of many motors in parallel (including coupling effect and reaction to motor-out scenarios)
  - Research control approaches for integrating hybrid-generator
  - Investigate algorithms for thrust augmented yaw control
  - Assess power generation/consumption problems (incl. catastrophic load shedding)

HEIST: Power Management and Distribution Research

Challenges
SysInt
Standard
Size
Funding

- **Distributed Propulsion Electronic Controller**: A novel controller will be developed to translate the thrust targets with simulated pilot inputs into individual thrust commands for each of the propulsors (Propulsive Yaw Control, expanded take-off vertical speed envelopes). This controller will also need to manage the balance between power generation, storage and consumption of this electrical propulsion system
- **Power Management Algorithm**: A control algorithm will be developed that will manage the loading of the power generator, the real-time capacity of the energy storage buffer (e.g., battery system) and the power demand of the collection of propulsors.
- **Thrust Distribution Algorithm**: A control algorithm will be developed that will synthesize individual propulsor commands based on the total system thrust targets established by the pilot and the generator and stored power availability. Apply advanced control strategies (Peak Seeking Controller).
- **Embedded Flight Control Computer**: A research flight control computer will be developed to host the hybrid electric distributed propulsion control algorithms



Pathway to High Fidelity Simulators

- **Based on initial teststand data**:
  - Derive models of power system component performance
  - Formulate more detailed requirements for these complex systems based on lessons learned on initial tests
  - Build more advanced data acquisition and analysis systems
- **Simulate flight environments and mission constraints**
  - **Hardware in the Loop**: Integrate flight-like electric propulsion system hardware into simulated electric aircraft flight controls, real-time feedback on component loading (dynamometers)
  - **Aircraft in the Loop / Ironbird**: Include control surfaces, flight-ready control system, flight-like energy storage components

Modular Electric Propulsion Flight Test Platform

- 1-2 MW vehicle; modular architecture to allow for multiple configurations (TeDP / Hybrid / All-electric; serial or parallel buses)
- Address actual implementation effects:
  - › Real-world volume and weight constraints
  - › Address failure modes and recovery strategies
  - › Identify and resolve interdependencies between propulsion and other systems
  - › Validate aero-propulsive efficiency gains over traditional propulsion/airframe designs
  - › Demonstrate realistic performance benefits due to propulsion airframe integration
- This coordinated research and development strategy will:
  - › Increase electric vehicle technology readiness
  - › Identify key multidisciplinary integration challenges
  - › Enable industry partners use of these lessons as a springboard for accelerated commercial development.

Hybrid Electric Propulsion Research Collaboration

Airvolt

Propulsor Dynamic Performance

Hybrid-Electric

Single String Efficiency

SBIR/METIS

Turbo-generator

Phase II

SBIR/ESAero/GA

ePHM

Phase II

HEIST

Phase III

STTR/RHRC

A/C Conversion Study

LEARN/RHRC

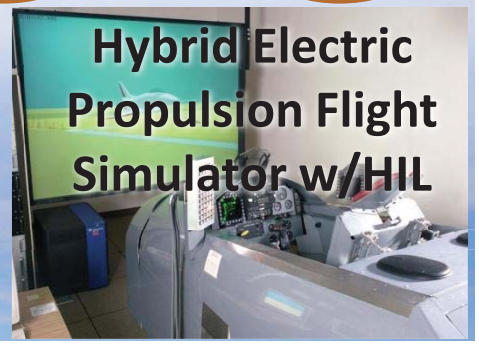
Boundary Layer Ingestion efficiency

Phase II

Ground Test Data/Airvolt/ HEIST

6DOF Aero Model/ Seedling

GRC/Georgia Tech/NPSS



HEIST - TeDP

PMAD Instrumentation and Feedback

Distributed Propulsion Controller

High Voltage Distribution System

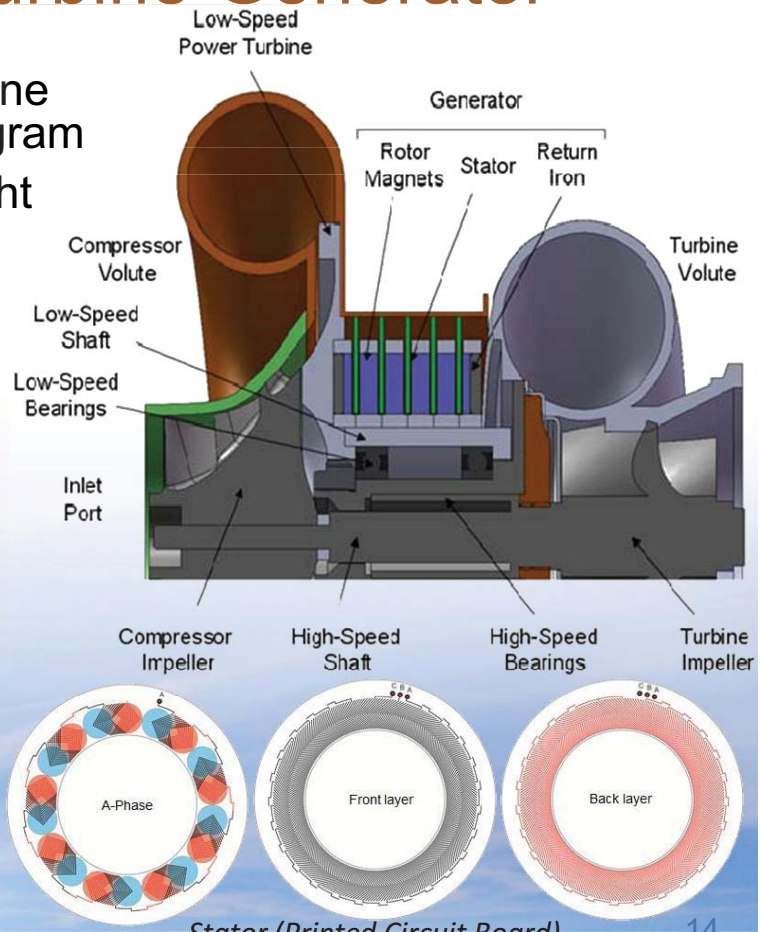
Generator vs Battery transient handling

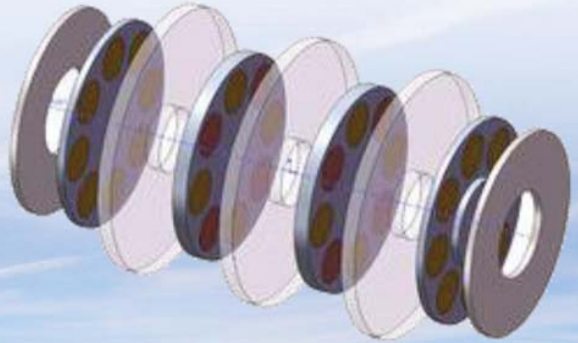
Adjacent Propulsor Inlet Interaction

Armstrong Flight Research Center

SBIR: Lightweight Small-Scale Turbine Generator

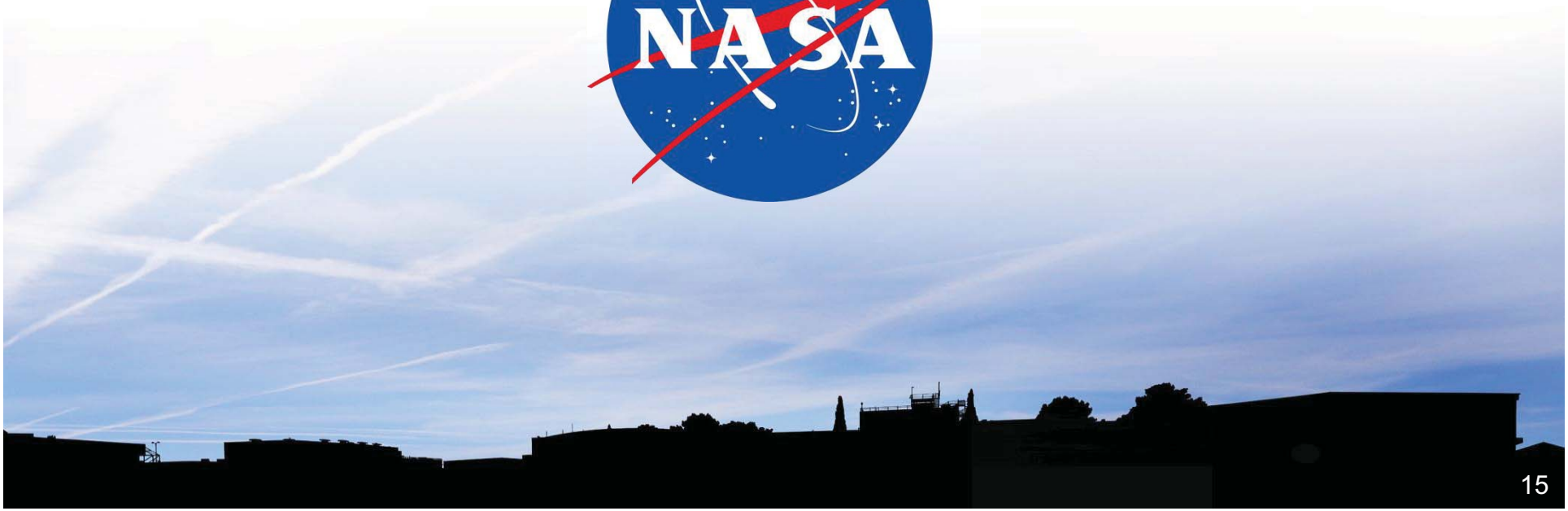
- **Metis Design Corporation**; builds on a two-spool turbine concept demonstrated on the DARPA Transformer program
- Objective is to perform a preliminary design a lightweight turbine generator and demonstrate the key innovative elements of the generator concept (40 kW)
- So far: intermediate-speed testing has been performed (16 krpm, 50% full speed) to improve modeling of the system losses
- Phase II kickoff June 2014





Rotor (axial layout with N52 Nd magnets)

Stator (Printed Circuit Board)

[The purpose of flight research] is to separate the real from the imagined problems and to make known the overlooked and the unexpected.

— Hugh L. Dryden