NASA University Led Initiative: Electric Propulsion: Challenges and Opportunities

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NASA’s University Leadership Initiative (ULI) provides universities with opportunity to take greater role in identifying their own research challenges and proposing system-level solutions

ULI created to:

- Promote new, innovative ideas that can support NASA Aeronautics Research Mission Directorate (ARMD) portfolio and U.S. aerospace community;
- Help solve most complex challenges associated with strategic thrusts;
- Accelerate progress toward achievement of high impact outcomes;
- Leverage capability of universities to bring together best and brightest minds across many disciplines.
In 2016, NASA Aeronautics launched their University Led Initiative. Every university in the U.S. was encouraged to propose a program addressing one of the strategic thrust outlined by the agencies. In the 1st round, 81 universities proposed, 21 were selected. In the 2nd round, 5 were selected. The Ohio State team was notified that their proposal on “Transition to Alternative Propulsion and Energy” was selected for a 5 year $10M award.
Transition to Alternative Propulsion and Energy

- The world population is growing, up to 10B by 2100.
- Middle class is projected to double in the next 10 years. World GDP (Gross Domestic Product) in growing at the rate of 3% a year.
- The number of commercial airplanes will double in the next 20 years. CO₂ emissions will grow accordingly. Something needs to be done.
- In 2016, NASA chartered the National Academy of Engineering to assess what technologies could be developed to reduce carbon emissions for commercial aircraft.
- Committee was formed and determined that a 20% reduction in CO₂ and fuel burn on commercial aircraft could be attained with the incorporation of electric propulsion.
NASA University Led Initiative: *Electric Propulsion: Challenges and Opportunities*

- One key recommendation of the NAE committee was the development of research/engineering plans for the introduction of electric machines in the commercial fleet.
- Number of challenges were introduced:
  - System Integration
  - Ultra High Power Density Electric Machine and Power Electronics
  - Energy Storage
  - Advanced Control of Onboard Electric Power Systems
  - Research Infrastructure for More Electric Aircraft

High power team put in place to address these challenges
Power to Propulsion Configurations

Parallel Hybrid
- Electric Bus
- Turboprop
- Motor
- Battery

Turboelectric
- Turboshaft
- Electric Bus
- Generator
- Motor
- Distributed Fans

Series Hybrid
- Turboshaft
- Electric Bus
- Motor
- Battery
- Generator
- Distributed Fans

All Electric
- Battery
- Electric Bus
- Motor(s)
- 1 to Many Fans
Electric Propulsion Architecture

All Electric:

- Batteries for small aircraft, UAV’s
- High power electronics for commercial aircraft

• Hybrid/Turbo Electric:
Fully Integrated University Team Working Together
What We Set Out to Achieve?

Higher power density, Higher voltage, Higher altitude

- Electric Machines: > 14 kW/kg, efficiency >94%
- Power Electronics: > 25 kW/kg, efficiency >99%
- Voltage: > 2kV without partial discharge

Two stages of deliverables:

- 200 kVA high power density electric machine with off-the-shelf power electronics (Month 30th)
- 500 A Silicon Carbide (SiC) based power module (Month 30th)
- 1 MWA integrated drive (Month 60th)

The outcome of this university led project will be scalable to higher power.
Preliminary Concept for 1 MW Integrated Motor Drive

- 18-pole PM machine stator grouped into six 3-phase floating-wye groups, each excited by a 6-switch full-bridge inverter with SiC switches
- Inverters connected in series, so each inverter dc link voltage is 333 Vdc, totaling to 2000 Vdc

**IMD config. offers advantages including high power density and fault tolerance**
Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC)

What is WEMPEC?

Major university-industry consortium at UW-Madison dedicated to advancing the state-of-the-art of electric machines, drives, controls, and power electronics

- Founded in 1981
- > 85 international industry sponsors
- 9 UW-Madison faculty members
- > 60 graduate students
- ~ 10 Visiting Professors / Honorary Scholars
- > 15 undergrad/grad power area courses
OSU Center for High Performance Power Electronics

Profile

Faculty: 10
Visiting Scholars: 12
PhD Students: 38
MS Students: 25
Research Expenditures: $3.0 million/year

Major research areas

- Power Electronics
- Electric Machines
- Power System and High Voltage
- Smart Grid
- Electrification of Transportations

High Performance Power Electronics Lab

A multi-million dollar center geared towards advanced power electronics circuits and devices;

High Voltage Laboratory

A 3600 square feet facility that hosts the biggest arcs and sparks in the U.S. universities;

Distributed Real Time Simulation Platform

A DoE sponsored real time simulation platform for both the electrical and communication systems within a smart grid, featured in the New York Times on Dec. 30 2010.

Integrated Power Electronic Packaging Lab

An integrated cleanroom lab space, with the equipment for die handling, interconnection, and module encapsulation.
Power Electronics: State-of-the-arts and Future Trends

- Boeing 787 has four generators with a total electric power of 1.4 MW at a 540 V dc bus.

- Typical power density of current aerospace power electronics is around 2 kW/kg.

- Future hybrid propulsion will require much higher electric power (up to 22 MW) at a much higher voltage (up to 4.5 kV).

- To achieve higher power density for power electronics at higher voltage is becoming more urgent.
Challenge: Stability of the Electrical Power Network

Detailed Challenges:

- Coordination between multiple integrated drive systems.
- Transient stability issues of constant power loads (e.g. propulsion fans).
- Possible impact from pulsed power load to the electric power network.
- Survivability of electric power network to sudden loss of generation.
- Resiliency of electric power network to extreme/unexpected events.
Thermal Management

Patrick McCluskey  
*Univ of Maryland*

John Kizito  
*North Carolina A&T*

**Power Electronics**  
*OSU*

**Electric Machines**  
*U Wisc*

**System Integration**  
*GA Tech*

**Battery and Energy Storage**  
*Case Western OSU*
New Cooling Methods for Power Electronics

Thermoelectric Coolers

Spray Cooling

Microchannel Coolers

Jet Impingement Cooling

Heat Pipes and Vapor Chambers

New Cooling Methods for Electric Machines

- Heat Pipes and micro pumped fluidic systems
- Spray cooling hybrids with air cooling
- Fan/blower cooling systems
- Combined with two sided cooling of power electronics

Energy Storage Challenge to address.....

- To advance and transform aviation via *electric/hybrid electric propulsion*, reducing carbon emissions while improving operational efficiency;
- Team focus is on *energy storage system design, control and integration*:
  - Specific energy density must be increased at least by a factor of 3-5 compared to today’s technology (150-250 Wh/kg), to become useful;
  - Current research on high energy density cells (Li-metal and Li-S) promises a leapfrog improvement in theoretical capacity.
Advanced Battery to Enable Distributed Electric Propulsion

Our Approach: Develop High Performance & Safe Multifunctional Energy Storage/Power Modules integrated with individual aerospace components (fuselage, wings, tail, supports) – that can operate standalone, or work in tandem with fuel cells, turbo-electric generators, and/or conventional battery packs – Enable DEP and System-level Mass & Volume Savings

Challenges:
- Availability of High performance commercial battery
  - High capacity cells; high gravimetric and volumetric energy density
  - High discharge rates; Temperature exposure; High Cycle life
  - Conformal, Flexible and Safe
- Integration with the Structure (airframes). Need to be optimized for weight, volume and balance at the system and sub-system levels.

Leveraging expertise, core institutional facilities, and experience on our ongoing research programs on Multifunctional Structure-Integrated Battery Systems to guide the project
Battery Cell/Modules

Desired Battery Cell Attributes

➢ High-performance commercial battery cells
  • High capacity individual cells (20 Ah), high gravimetric energy density (>350 Wh/kg); Volumetric energy density (>600 Wh/L); High discharge rates (up to 20 C); Operational Temp - 20 to 100 °C; Long cycle life ~1000 cycles and inherently Safe
➢ Integration with the Structure – Conformal & Flexible --- pouch, cylindrical cells

Potential Battery Cell Chemistries

<table>
<thead>
<tr>
<th>Battery Technology</th>
<th>Theoretical Specific Energy (Wh/kg)</th>
<th>Technology Projection</th>
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<tbody>
<tr>
<td>Li-ion</td>
<td>390</td>
<td>250 Wh/kg (2013) to 350 Wh/kg (by 2020)</td>
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<tr>
<td>Zn-air</td>
<td>1090</td>
<td>400-500 Wh/kg (by 2025)</td>
</tr>
<tr>
<td>Li-O₂</td>
<td>3500</td>
<td>1050 Wh/kg (&gt;2025)</td>
</tr>
<tr>
<td>Li-S</td>
<td>2570</td>
<td>400 Wh/kg (2018) to 1250 Wh/kg (by 2025)</td>
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Potential Vendors: Oxis Energy, Sion, EaglePicher, American Lithium, Kokum, Solid Power
The facilities at CAR support research and development in electrochemical energy storage systems, ranging from coin cells to full-scale battery packs for electric vehicles:

**Coin Cell Prototyping/Material Characterization:**
- MBraun LABstar Glovebox Workstation
- MTI Coin Cell Fabrication/Disassembling Equipment
- Gamry Reference 600 Potentiostat
- Arbin Coin Cell Cycler, 16 channels (down to 100mA)

**Cell and Module Testing and Characterization:**
- Cell Cyclers 8 channels (0-8V, up to 400A)
- Module Cyclers, 8 channels (0-60V, up to 75A)
- Environmental Chambers (5)
- Isothermal Calorimeters (2)
- IR Cameras

**Battery Packs and EV Systems Integration:**
- AV900 Pack Cycler, 2 channels (up to 900V - 250kW)
- SIL and HIL Systems for BMS Prototyping
- Electric, PHEV and HEV Prototypes
Prof. Giorgio Rizzoni (Rizzoni.1@osu.edu); Prof. Marcello Canova (Canova.1@osu.edu)

- Buckeye Bullet (NiMH), 2000-2004, 315 mph
- Buckeye Bullet 2.5 (Li-ion), 2010, 308 mph
- Buckeye Bullet 3 (Li-ion), 2012-2017, 345 mph
- Buckeye Current: ECTA Land Speed Record; 3rd place IOM TT-Zero Race (2013, 2014); 3rd place Pikes Peak International Hill Climb - Electric Motorcycles (2015, 2016); 1st Place (6/25/2017)!!
NEAT—NASA Electric Aircraft Test Bed

- The NASA Electric Aircraft Testbed is a key enabler of flight-weight powertrain development.
- Its high power, remote location, large footprint, conditioned atmosphere, cryogenic infrastructure, and extensibility make it a unique testbed for fullscale aircraft powertrain development.
- It addresses and fills a unique role not currently available with existing test facilities.
- And when used in conjunction with the other government, industrial, and academic facilities, it provides an important next step in the path towards electrification of future single-aisle aircraft.

Ohio State faculty and students closely connected to NASA on planning and operation
The Product

- A MegaWatt System
- Will be demonstrated at the NASA NEAT Facility in Plumbrook, Ohio in 2022
- Will provide the right building blocks to power the commercial airplanes of the future
- Will lead creative new technologies for the nation and put us in a leadership position in the world:
  - Electrical Machines and Batteries for commercial and military aircraft
  - Innovative advanced airplane systems
  - Great motivation and education for students and faculty
THANK YOU!