Optimal Design and Control of Battery Energy Storage Systems for Hybrid Propulsion and Multi-Source Systems for Aerospace Applications

2019 NASA Aerospace Battery Workshop

Dr. Matilde D’Arpino
Senior Research Associate
Center for Automotive Research

Prof. Marcello Canova
Associate Professor
Department of Mechanical and Aerospace Engineering

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Characterization and benchmarking of automotive battery (Li-ion, beyond Li-ion, lead acid, NMH,…)

Electro-thermal characterization
Aging characterization

Model and control development (SoC, SOH, SoX)

Testing facilities for cells, module, pack

Modeling, Control, Diagnostics & Prognostics

Prototyping

- State of the art battery cyclers (µA to 1000A; up to 900V)
- Thermal management testing and design
- HIL/SIL capabilities and BMS testing and calibration;
AGENDA

1. Introduction to the Center for Automotive Research (CAR)
2. Potential benefits and issues of Li-ion batteries in aerospace applications
3. Numerical strategies for co-optimization of design and control for multi-source systems
4. Case study: NASA ULI Electric Propulsion Challenges and Opportunities
   1. Program introduction
   2. Cell characterization and modeling
   3. Design and energy management for hybrid turboelectric aircraft for commercial aviation via dynamic programming
1. **System efficiency** - decoupling the energy generation from the load;

2. **Emissions** - enabling optimal control of fuel-based power generation;

3. **Management of Uncontrollable Sources** - e.g. renewable sources and regenerative braking;

4. **Controllability & Power Quality** – facilitating the management of complex multi-source systems;

5. **Reliability at the System Level** – providing back up;

6. **Weight** - 10 kg weight reduction for an aircraft will result in the saving of 17,000 tonnes of fuel and 54,000 tonnes of carbon dioxide emission per year for all air traffic worldwide (DOI: 10.1049/iet-est.2016.0019)

7. **Delay System Expansion / Investments**;

8. **Flexibility & Modularity**.

**Lithium-ion batteries represent a more sustainable and cost-effective energy solutions when compared to other energy storage devices.**
Energy Management Prospective:

1. **cost** (initial, operational, maintenance, replacement);
2. **high energy/power density** battery cells (especially for propulsive and space);
3. **charging/discharging rate** limits (fast charging capabilities);
4. **weight overhead** of electronics, packaging, and cooling required for operating lithium-ion batteries.


System Integration Prospective:

5. **SAFETY**;
6. **reliability & durability** of cell performance over time and capability of **prognosis and diagnosis**;
7. **complexity** of large-size high-voltage battery pack (aviation and stationary).

![Battery Pack](Source: Nasa.gov)
LITHIUM-ION BATTERY IN AEROSPACE APPLICATIONS

Satellites
Moon/Mars exploration
Launch vehicles

More Electric Aircraft
Electric/Hybrid commercial aviation
UAV

Sources: nasa.gov; safran-group.com

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LITHIUM-ION BATTERY IN AEROSPACE APPLICATIONS

Satellites

- 10-15 year calendar life
- Up 35,000 cycles at 25% DOD

Durability & Reliability
- Oppy: 5111 sols of operation and has travelled over 45 km on Mars’ surface
- Wide temperature range (-20ºC to +30ºC)
- Energy density

Moon/Mars exploration

- Cost
- Energy/power volumetric/gravimetric density
- -40ºC to +70ºC temperature range (DO-160)
- Degradation and reliability
- Altitude operation
- Complexity of large scale battery packs
- HV operation

Launch vehicles

- Volumetric/gravimetric energy/power density of cells
- Packaging/cooling weight
- Degradation

More Electric Aircraft

Electric/Hybrid commercial aviation

UAV

Sources: nasa.gov; safran-group.com

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DOI: 10.1109/BCAA.2002.986382
doi.org/10.1016/j.electacta.2018.02.020
LITHIUM ION BATTERY TECHNOLOGIES

Spider plots of prevalent battery technologies

Projected Cost for a 100kWh, 80kW Automotive Battery Pack

Note: These are the best case projections (all chemistry problems solved, performance is not limiting, high volume manufacturing), and do not include extreme fast charge capability.

Irena report

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**BATTERY PACK DESIGN STRATEGIES FOR MULTI-SOURCE SYSTEMS**

Co-optimize *design and control* of *battery pack* given a mission profile:

**Mission profile vs. Time**

**Design**
- Chemistry/format selection
- Number of cells and configuration
- Chemistry combination (if hybrid storage)
- Thermal management system
- Current/voltage/power limits

**Objective**
*Minimize:* overall weight, capital cost, operating (lifetime) cost, degradation, thermal requirements

**Control**
- Power and thermal limits control
- Dynamic power split between the different sources
- Power split between different ESS

**Question:** how do we approach this complex coupled design and control optimization problem?
Design and control optimization for HEV applications results in multi-objective optimization problem with a coupling between the physical system and the control algorithm.

Problem complexity increases with size of design space.

**Coordination architectures to solve system level optimization:**

1. **Alternating:** optimize plant first, then control (iterative method, weak/no coupling between parameters)
2. **Nested:** control design nested within plant design (fully optimize control for every plant configuration, some coupling between parameters)
3. **Simultaneous:** plant and control optimized in one step (strong coupling between parameters)

**Common objective functions to minimize:**
1) Fuel consumption
2) Total cost (capital and lifetime)
3) Vehicle weight

*DP typically used as benchmark solution for online control optimization strategies*
NASA ULI ELECTRIC PROPULSION: CHALLENGES AND OPPORTUNITIES
Distributed electric propulsion is a leading architecture for measurable CO₂ reduction on large commercial aircraft - regional, single aisle, and twin aisle.

- Two turbo-generators to supply electrical power to distributed motors
- Eight motors with embedded power electronics
- Integrated thermal management system
- Battery energy management can be charge-depleting or charge-sustaining; battery thermal management system is separate from powertrain

**Challenge 1 System Integration**  
**Success Criteria:** Vehicle energy and CO₂ >20% improvement over existing solutions

**Challenge 2 Ultra-High Power Density Electric Machine and Power Electronics**  
**Success Criteria:** Electric machines > 14 kW/kg, power electronics > 25 kW/kg, efficiency > 99%, bus voltage up to 2kV without partial discharge

**Challenge 3 Energy Storage**  
**Success Criteria:** Power density and reliability (desired 450 Wh/kg)

**Challenge 4 Advanced Control of Onboard Electrical Power Systems**  
**Success Criteria:** System remains stable at 20% voltage sag and 200% step load change

**Challenge 5 Research Infrastructure for More Electric Aircrafts**  
**Success Criteria:** Sub-system and component prototyping and testing at elevation – 2 kV, 1 MW, 20 kRPM drive tests

Research on thermal management system design is integrated in every aspect of the project.

Benefits of Battery Turboelectric Hybrid Aircrafts

Turboelectric Distributed Propulsion

Benefits:
- Enable new aero efficiencies
- Improve propulsion efficiency
- Freedom in engine design
- Enable Power Sharing between fans
- Degree of freedom in using residual thrust from the turboshift

Challenges:
- High efficiency electric machine and power converters
- Weight -> increase energy density of the electric drive
- System integration

Distributed Series Hybrid Turboelectric

Benefits:
- As turboelectric solution
- Use battery as buffer and peak shaving
- Optimize power split battery/turboelectric
- Improve dynamic stability of the electric bus

Challenges:
- System integration
- Increase system complexity
- Weight -> increase energy density of the battery packs (cells and system integration)
- Safety, reliability, and lifetime

Selected for the OSU NASA ULI

Benefits of Battery Turboelectric Hybrid Aircrafts

**Baseline Aircraft (CRJ 900)**

- **Fuel Burn Reduction at 600 nmi and typical payload**
  - 8%

**Next Generation Aircraft (A220)**

- **Distributed Hybrid Turbo Electric**
  - 15% improvement to Next Gen (A220)

- **Use of Hybrid Propulsion**
  - 9%

- **BLI/Optimized Power management**
  - 6%*

- **Distributed Propulsion**
  - 5%

**Detailed Analysis**

- **BLI = Boundary Layers Ingestion**
- **BR = Power split between Batteries and Turboshaft**
- *Assumes 200 Wh/kg batteries used at rate of 30% of overall propulsive power during climb and 20% during cruise @ 600 nmi.

Feasibility Analysis

Missions simulated in GT-HEAT with a 93% efficient electric powertrain, no battery power limits, constant power split during climb and cruise.

200 Wh/kg battery

300 Wh/kg battery

Fuel burn reduction compared to the Turboelectric solution with Distributed Energy Propulsion.
Feasibility Analysis

Design of a 2MWh battery pack for the 600nmi. 30% climb – 20% cruise mission profile.

<table>
<thead>
<tr>
<th>Cell</th>
<th>Cell 1</th>
<th>Cell 2</th>
<th>Cell 6</th>
<th>Cell 7</th>
<th>Cell 8</th>
<th>Cell 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Format</td>
<td>18650 Cylindrical</td>
<td></td>
<td></td>
<td></td>
<td>Pouch</td>
<td></td>
</tr>
<tr>
<td>Chemistry</td>
<td>LMO</td>
<td>NMC</td>
<td>NMC</td>
<td>Li-S</td>
<td>Li-Metal</td>
<td>Li-S</td>
</tr>
<tr>
<td>Energy Density assessment [Wh/kg] (@1C, 23°C)</td>
<td>237</td>
<td>215</td>
<td>224</td>
<td>336</td>
<td>(478)</td>
<td>(363)</td>
</tr>
<tr>
<td>Experimentally Tested?</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔSoCavail</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(10-95)%</td>
</tr>
<tr>
<td>m_en_e - Total Cell Number</td>
<td>176,472 (516s x 342p)</td>
<td>196,560 (504s x 390p)</td>
<td>51,816 (508s x 102p)</td>
<td>54,752 (472s x 116p)</td>
<td>27,608 (476s x 58p)</td>
<td>66,990 (770s x 87p)</td>
</tr>
<tr>
<td>Max C-rate (discharge)</td>
<td>2.20</td>
<td>2.26</td>
<td>2.16</td>
<td>2.15</td>
<td>2.28</td>
<td>2.06</td>
</tr>
<tr>
<td>Heat Generation (kW) (Peak/Average)</td>
<td>672 / 66</td>
<td>357 / 42</td>
<td>438 / 41</td>
<td>330 / 24</td>
<td>74 / 7</td>
<td>-</td>
</tr>
<tr>
<td>Efficiency [%] (Min/Average)</td>
<td>88 / 97</td>
<td>90 / 97</td>
<td>92 / 98</td>
<td>94 / 98</td>
<td>94 / 98</td>
<td>-</td>
</tr>
<tr>
<td>Pack Weight (Tons)</td>
<td>8.39</td>
<td>9.26</td>
<td>8.88</td>
<td>5.91</td>
<td>4.16</td>
<td>5.69</td>
</tr>
</tbody>
</table>
Design & Control Optimization Problem

Series/Parallel Battery-Hybrid Turboelectric with Distributed Propulsion

Design Factors:
• Cell chemistry
• Number of cells (S/P)

Control variables:
Electric power split

External Inputs:
• Mission profile (time, MN, altitude)
• Aircraft assembly (mass tracking)

Pack Design Objectives:
• Pack weight and volume
• Pack cost
• Operating costs (degradation and replacement)

Energy Management Objectives:
• Fuel burn over mission / total energy use
• Cost of total energy (fuel+electrical)
• Overall CO2 production

\[ n_f = 8 \]
\[ n_{TG} = 2 \]
Modeling Overview

**PLANT DESIGN**

**Design**: Energy Storage System selection and sizing
Iterate design between different chemistry and weight
Constraint: maximum take off weight

**Initial conditions**: initial fuel estimation
Optimize initial weight of the aircraft and ensuring the mission serve fuel

**Input**: Mission Profile
Consider different climb rate with respect to the aircraft weight

**CONTROL DESIGN**

Map-based quasi-static component models

- **Fan (GT, NPSS)**: thrust as function of MN, altitude, motor torque, and speed
- **Turboshaft (GT, NPSS)**: fuel burn, shaft power, and thrust as function of MN, altitude, FAR, and electric power slip
- **Generator (TBD)**
- **Motor (UW)**: Torque-speed curve and efficiency map as function of torque and speed
- **Electric Distribution (OSU CAR)**: Power losses on wiring and distribution components
- **Battery (OSU CAR)**: voltage, state of charge, heat generation, aging estimated by equivalent circuit model
- **Power Converters (OSU CHPEE)**: Conversion efficiency as function of DC link voltage, power request
- **Airframe (GT, FLOPS)**: Aerodynamic perf., Maximum Take Of Weight (MTOW)

**Powertrain architecture & Optimal Power Flow Control**

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

**Minimize Fuel Burn & Battery Aging**
Constrained by: max battery power, components maximum power, thermal limits

**Co-optimization of Design and Control Strategy**

Nested approach: control design nested within plant design
(fully optimize control for every plant configuration, some coupling between parameters)

**Nested approach**: control design nested within plant design
(fully optimize control for every plant configuration, some coupling between parameters)
Model Architecture

Series/Parallel Battery-Hybrid Turboelectric with Distributed Propulsion

Control input (engine Power Code)

Operating conditions (Altitude, MN)

Design specs (chem, weight)

<table>
<thead>
<tr>
<th>Power flow</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric</td>
<td></td>
</tr>
<tr>
<td>Fluid</td>
<td></td>
</tr>
<tr>
<td>Mechanical</td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td></td>
</tr>
</tbody>
</table>

Turboshaft (engine)

Turbogenerator, \( n_{TG} = 2 \)

Fuel tank

High speed compressor

Burner

High speed turbine

Low speed turbine

Free turbine

Nozzle

AC-DC rectifier

Generator

DC link

DC-DC converter

ESS

Motor

DC-AC inverter

Fan assembly, \( n_f = 8 \)

Ducted fan

Operating conditions (Altitude, MN)

\( P_{DC} \)

\( P_{ESS} \)

\( P_{TG} \)

\( P_{EM} \)

\( m_{fuel} \)

\( \tau_m, N_m \)

\( n_f F_f \)

\( F_{req} \)

Airframe dynamic model

Operating conditions (Altitude, MN)
Battery Cell/Pack Model - Overview

- Prediction model to analyze **weight**, **battery life** and **thermal requirements**
- Dynamic estimation of power limits
- Thermal model of the pack including TMS solutions
- Degradation models

**Calibration for several state of the art (TRL>7) and advanced (low TRL) lithium-ion cells**

**Experimental Tests:**
- 0, 10, 23 and 50°C
  - Multi-rate capacity - Energy density assessment
  - Dynamic Pulse testing - HPPC/RCID
  - Performed on multiple samples and cell models for benchmarking

**Experimental Tests:**
- Non-isothermal thermal tests
  - Capacity and dynamic profile
  - Temperature rise on cell skin is measured for modelling
  - Cell to pack analysis

https://doi.org/10.2514/6.2019-4469
Model-Based Control Design Strategies

- **Causal energy management strategies:**
  - Use a reference signal and the current system output (example, SOC) to make a decision on the control input.
  - Easy to implement, but suboptimal!

- **Non-Causal energy management strategies (Dynamic Programming):**
  - Guaranteed optimal solution!
  - Require the knowledge of the future (backward algorithm).
  - Complexity grows exponentially with the number of control inputs and states (e.g., battery SOC).
  - **Dynamic Programming (DP)** is a numerical method based on the Bellman’s Optimality Principle
  - The algorithm is based on a recursive process that uses a **discretized version of the problem**

DOI: 10.1109/CCA.2009.5281131
The battery pack is used during climb, charged during part of cruise and then used at the end of cruise. 

Peak current of 10C is required during climb.
DP Results 600nmi mission
(ESS mass of 10,000kg and GED of 200Wh/kg, with Power Limits)
**Summary** for ESS mass of 10,000kg and GED of 200Wh/kg

*Fuel burn reduction compared to the Turboelectric solution with Distributed Energy Propulsion*

<table>
<thead>
<tr>
<th>Mission</th>
<th>Setup</th>
<th>Fuel Burn</th>
<th>Battery Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mass [kg]</td>
<td>Reduc. [%]</td>
</tr>
<tr>
<td>Length: 600 nmi</td>
<td>No ESS</td>
<td>1413</td>
<td>-</td>
</tr>
<tr>
<td>Climb: 13.4 min</td>
<td>27 Climb, 18 Cruise</td>
<td>1358</td>
<td><strong>3.9</strong></td>
</tr>
<tr>
<td></td>
<td>Rule based control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cruise: 30 kft</td>
<td>DP w/o Limits Optimal control</td>
<td>1265</td>
<td><strong>10.5</strong></td>
</tr>
<tr>
<td>0.8 MN</td>
<td>DP w/ Efest Optimal control</td>
<td>1339</td>
<td><strong>5.2</strong></td>
</tr>
</tbody>
</table>

(*) Difference due to “efficiency” related to when (SOC) / how (magnitude) power is used and corresponding resistance.
**Summary** for ESS mass of 6,900kg and GED of 300Wh/kg

*Fuel burn reduction compared to the Turboelectric solution with Distributed Energy Propulsion*

<table>
<thead>
<tr>
<th>Mission</th>
<th>Setup</th>
<th>Fuel Burn</th>
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<tr>
<td></td>
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</tr>
<tr>
<td>Length: 600 nmi</td>
<td>No ESS</td>
<td>1413</td>
<td>-</td>
</tr>
<tr>
<td>Climb: 13.4 min</td>
<td>30 Climb, 20 Cruise Rule based control</td>
<td>1273</td>
<td>9.9</td>
</tr>
<tr>
<td>Cruise: 30 kft 0.8 MN</td>
<td>DP w/o Limits Optimal control</td>
<td>1176</td>
<td>16.8</td>
</tr>
<tr>
<td></td>
<td>DPM w/ Efest Optimal control</td>
<td>1258</td>
<td>11.0</td>
</tr>
</tbody>
</table>

(*) Difference due to “efficiency” related to when (SOC) / how (magnitude) power is used and corresponding resistance.
Design/Control Optimization of Hybrid Turboelectric Generator System - Next Steps

• Perform analysis considering multiple factors:
  1. Evaluate impact of different cell chemistries
  2. Evaluate impact of battery thermal model for dynamic evaluation of the power limits, thermal management analysis and degradation estimation
  3. Consider different climb rate and mission profiles
  4. Consider impact of electric driveline efficiency
  5. Extend weight analysis

• Analyze different Objective Functions:
  1. Include battery operating cost due to degradation
  2. Include cost-to-cool for the energy storage

• Develop “online” energy management strategy to implement in HIL for prototype testing.
Thank You for Your Kind Attention!

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Dr. Matilde D’Arpino
Senior Research Associate
darpino.2@osu.edu

Prof. Marcello Canova (canova.1@osu.edu)
Prashanth Ramesh (ramesh.47@osu.edu)