NASA's X-57 High Lift Motor Controller: Detailed Design, Test Results, and Outcomes

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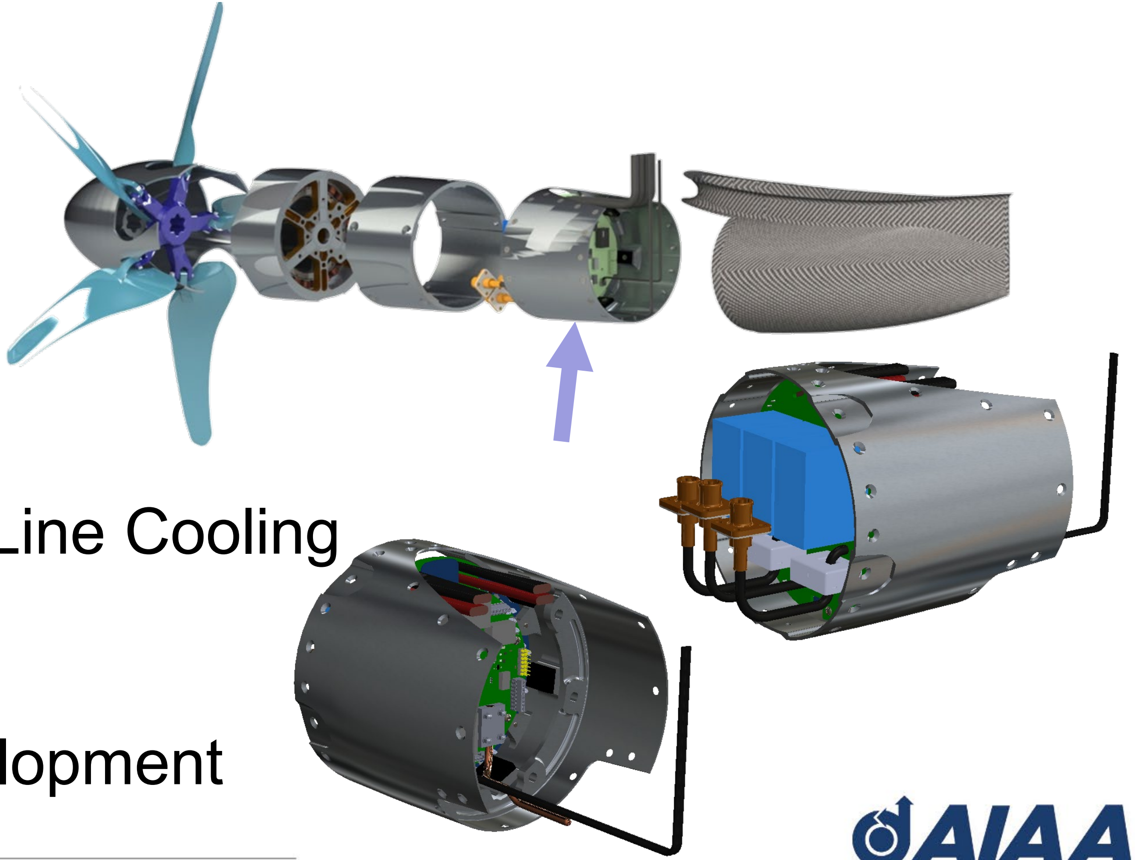
Distributed Electric Propulsion (DEP)

- X-57 Maxwell uses a DEP architecture
  - Benefits in aerodynamics, control, and reliability
  - 12 high-lift motors (HLM) and controller/converters (HLMC)
  - Does not increase pilot workload substantially

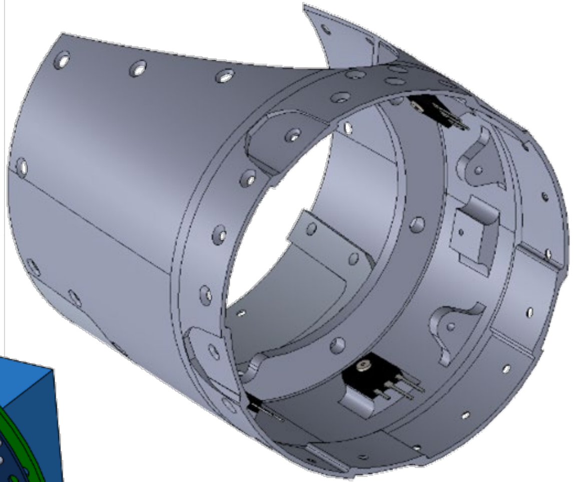
High Lift Motor Controller (HLMC) Key Objectives

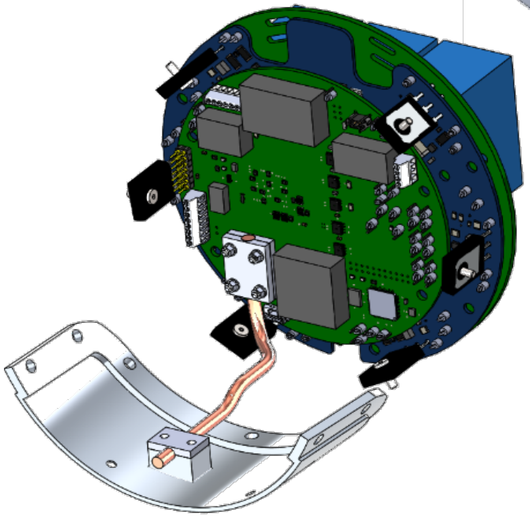
- 14 kW Output
- <330 W of loss
  - >97% Efficiency
- Mass ≤ 1kg
- Passive, Outer Mold Line Cooling
- Fiber Optic Ethernet
- Rapid Software Development



HLMC Thermal and Mechanical Design

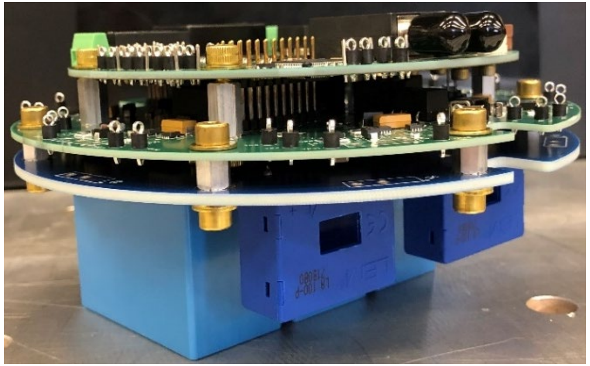
- Radially mounted MOSFETs
- Two isolated heatsinks – conform to outer mold line and provide mechanical support
- COTS heat pipe on secondary heatsink
- Thermal copper layers internal to circuit boards

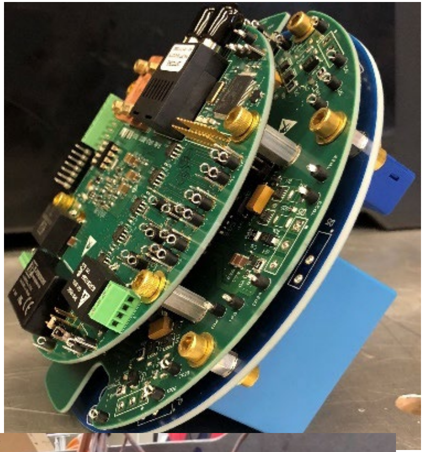


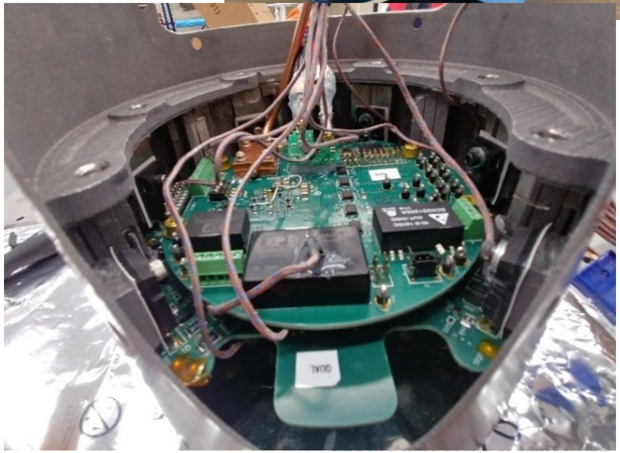


HLMC Electrical and Mechanical Design

- 3 circular printed circuit boards (PCBs)
- Minimal inductance between the MOSFET driver and gate
- Low coupling capacitance between high power and low power electronics

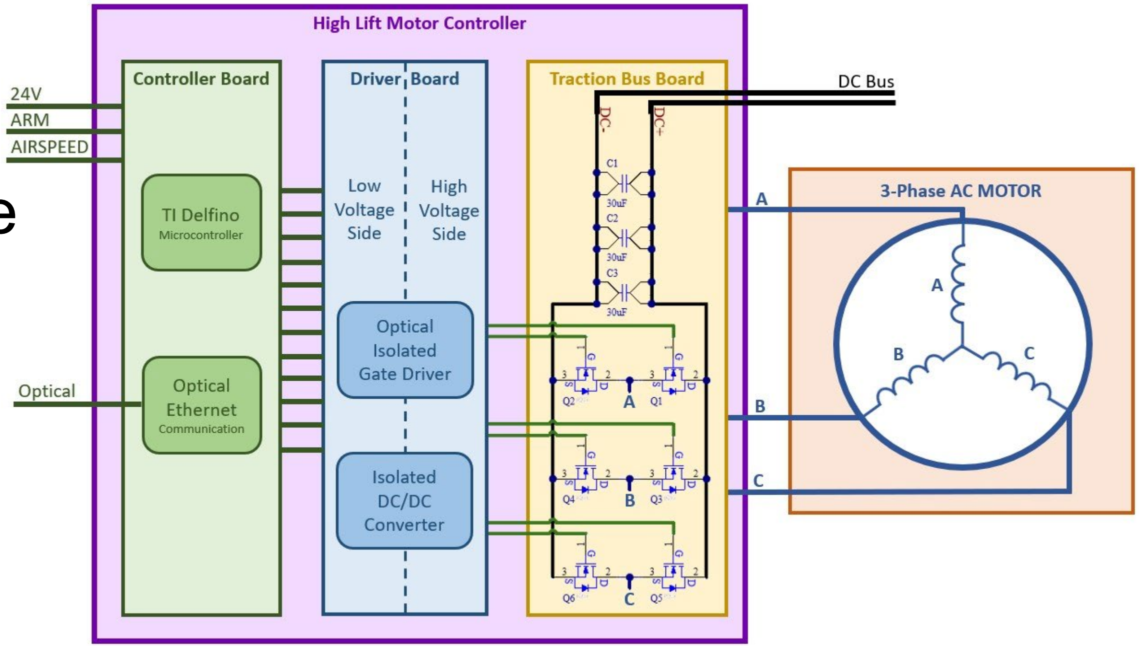






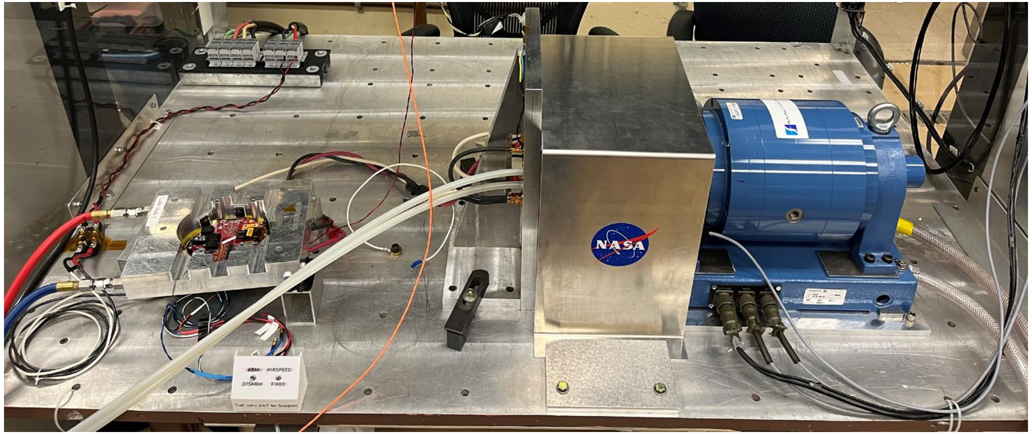
HLMC Electrical Design

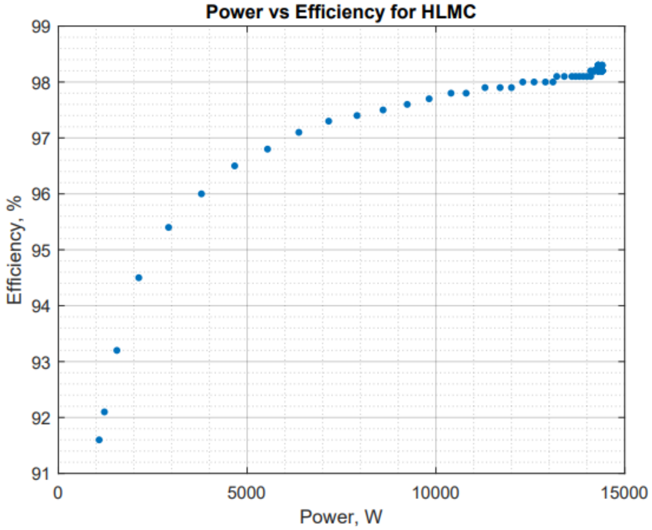
- DC bus filter
- Silicon Carbide (SiC) MOSFET switches
- Optically isolated gate drivers
- Fiber optic ethernet
- TI Delfino microprocessor
- Code generation



HLMC Power and Efficiency Testing

- Motor testing with propeller and dynamometer loads
- Full power (14 kW) reached with 98.3% efficiency
- Less than 330 W of loss from 6 – 14 kW output

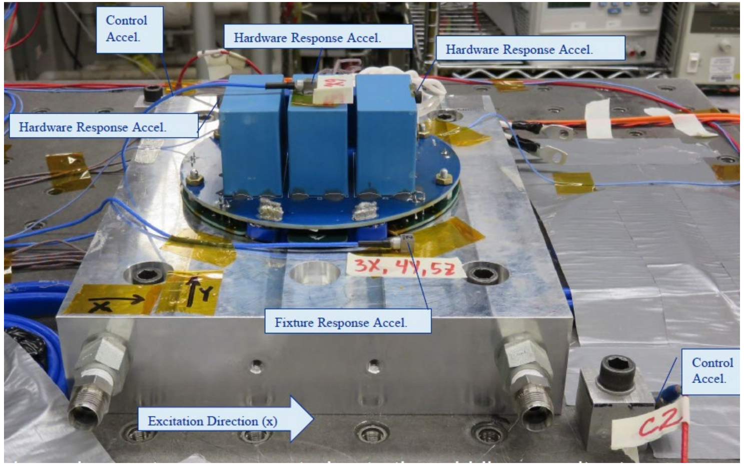


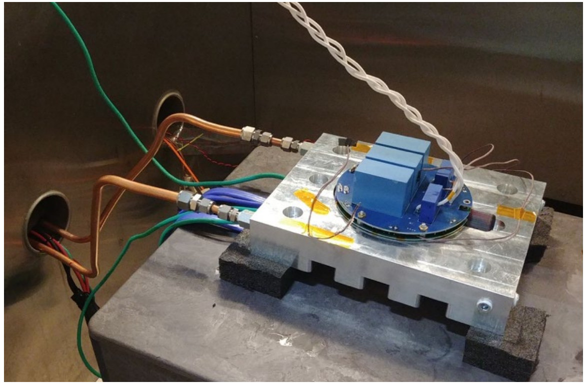


HLMC Qualification Testing

- Random vibration test
- Shock test
- Thermal cycle test

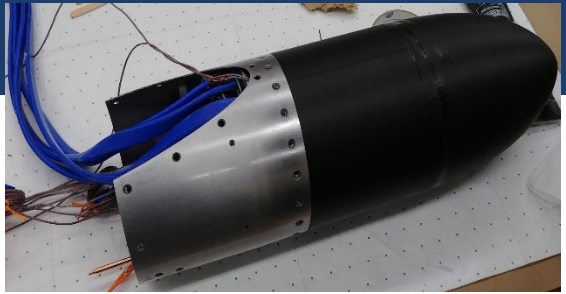
Vibration	Shock	Static Thermal
10.9 Grms	DO-160 Sec. 7	16 – 20 Thermal Cycles
20 min each axis	6 g	> 95% Defect Precipitation
10 Hz – 2 kHz	11 ms pulse	-40 to +60 ° C Air
Low power operation after each axis	Low power operation after each axis	Low power operation at extreme temperatures

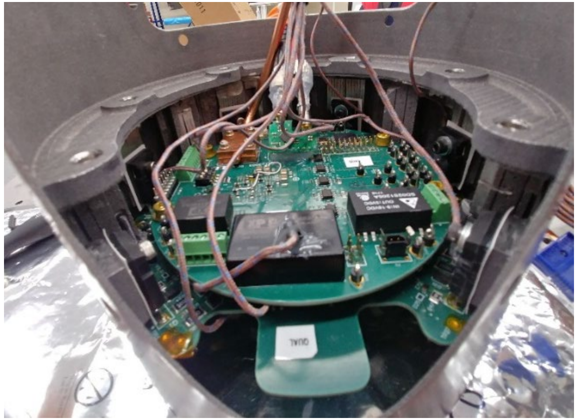


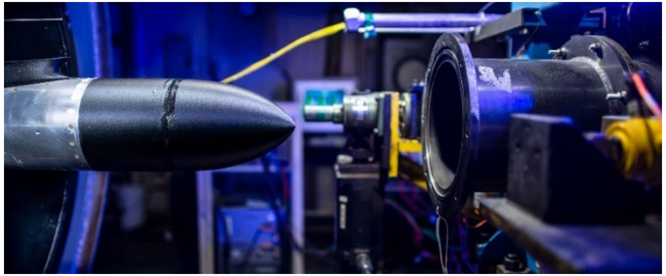


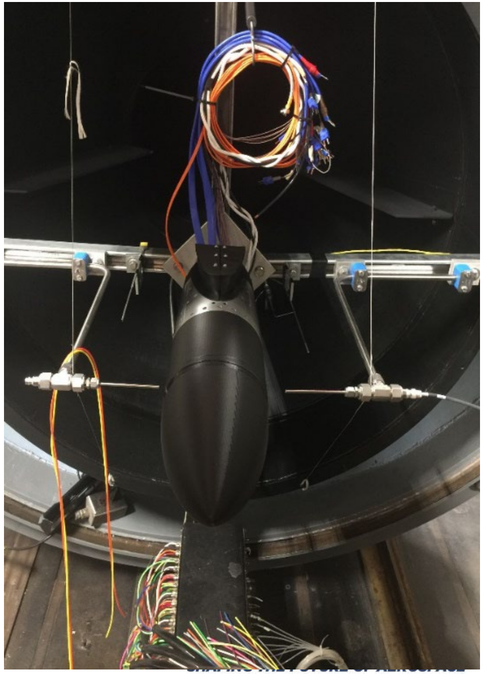
HLMC Wind Tunnel Testing

- High power testing
- Passive nacelle heatsink
- 20 to 50 m/s free-stream air velocity
- +60 °C air operation
- 15,000 ft altitude









Lessons Learned - Mechanical

- Use 3D CAD to ensure fit between PCBs and mechanical hardware
- Considerations when affixing MOSFETs to the heatsink:
  - Ensure the heatsink surface is flat with no sharp edges
  - Do not over-torque MOSFET screws as it will damage the MOSFET and cause more potential for protrusions through thermal interface material
    - Vibrations can cause MOSFET screws to loosen if thread locker is not used (even in lab unit). Loose screws will lead to MOSFET over-temperature failure.
- Any “large/heavy” PCB parts should be staked with epoxy to prevent breakage during vibration

Lessons Learned - Electrical

- Use LC filters on low voltage microcontroller supply pins
- Isolate high and low voltage electronics to reduce the impact of noise
  - Use optical coupling electronics where possible
  - Minimize coupling capacitance of isolated components
  - Create no-copper zones through all layers of a circuit board at boundaries
- Minimize inductance in the MOSFET gate by keeping trace lengths short
- Tune desaturation over-current protection for the MOSFET current limit
- Use sufficient DC bus filtering capacitance to reduce ripple
- Ensure proper clearance in the PCBs for the voltage level at altitude

Conclusions

- NASA GRC has developed a flight-weight highly configurable motor controller that can power 3 phase, 14 kW motors.
- The knowledge gained through this integrated approach to electronic power train design has been used as a guide for ongoing new electric power train component development.

Acknowledgments

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