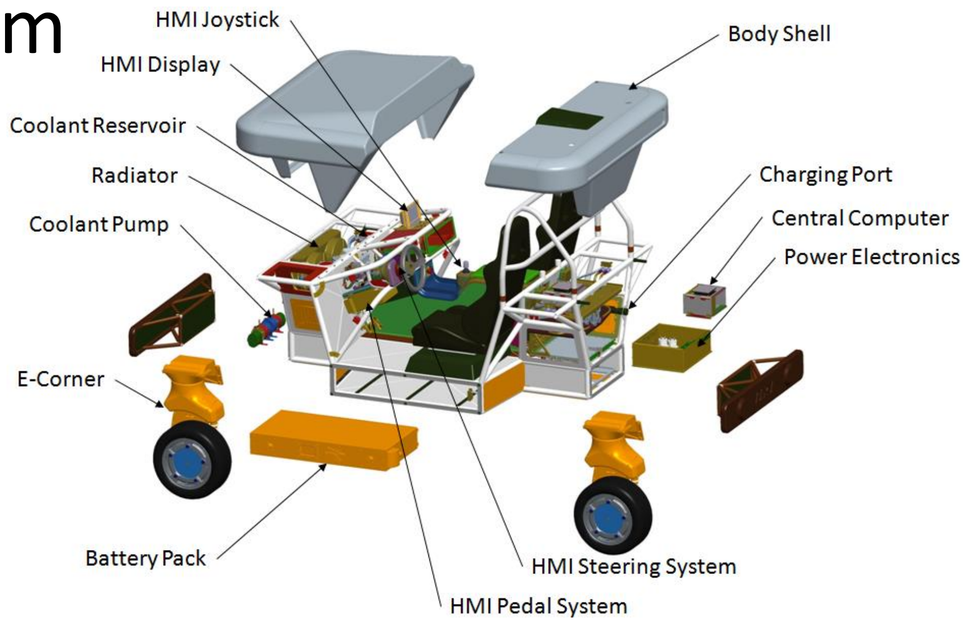
MRV and Robotic Systems Briefing

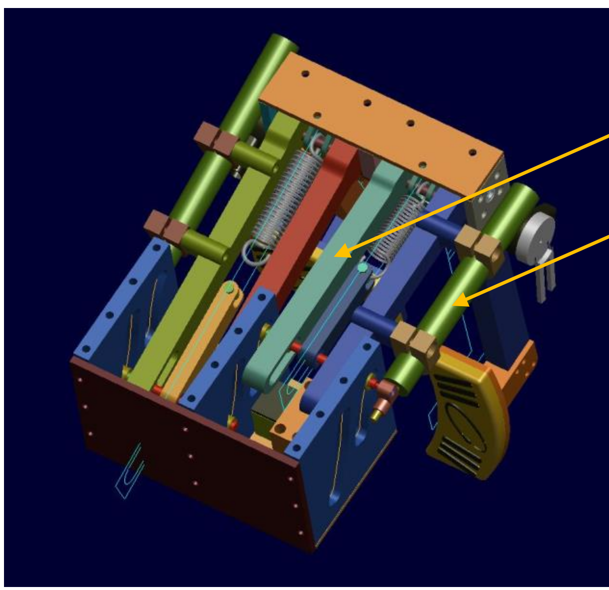
Introduction

MRV: Vehicle Specs

- Design speed: 64 kph (40 mph)
  - Currently computer limited to 25 kph
- Curb weight: 900 kg (2000 lb)
- Footprint: 2.15 x 1.55 m (7’ x 5’)
- By-wire without mechanical backup



Pedal-by-Wire Design



Rotation sensor (Prod Part)

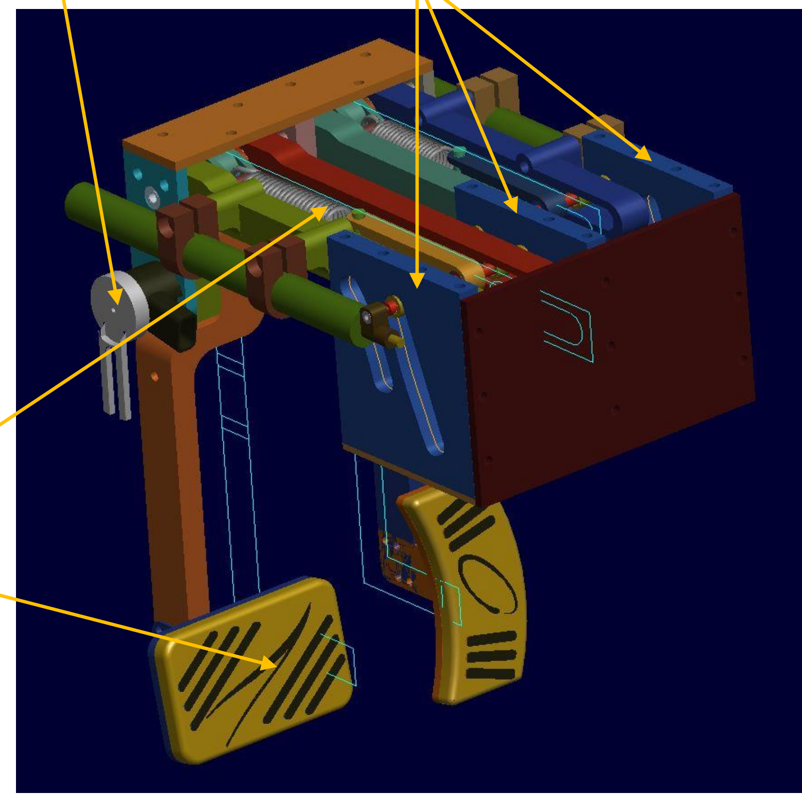
Cam profile plates

Level

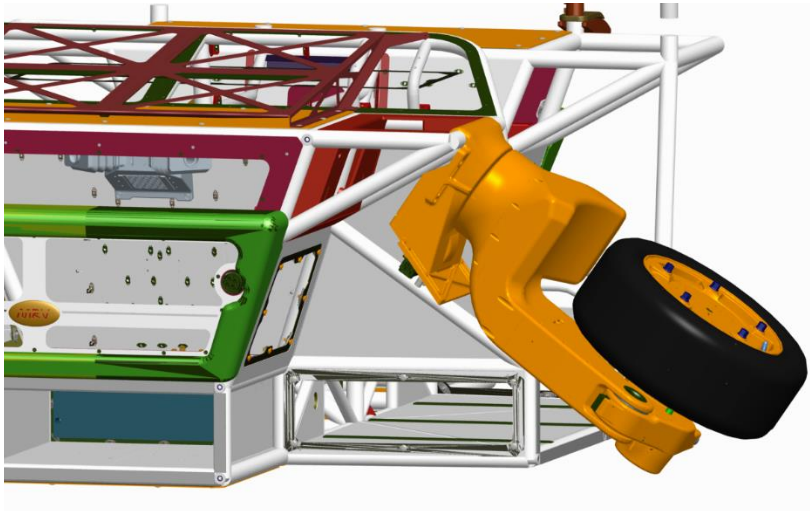
Linear Sensor

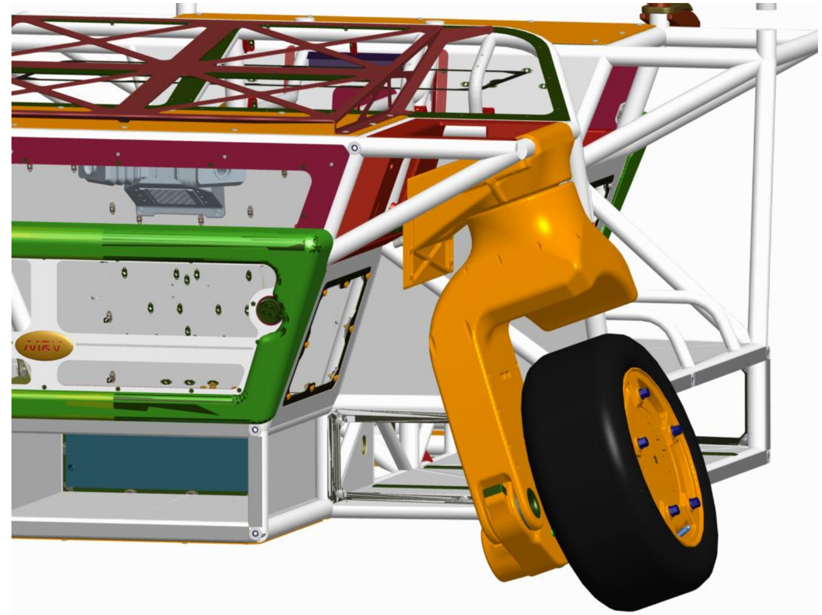
Spring

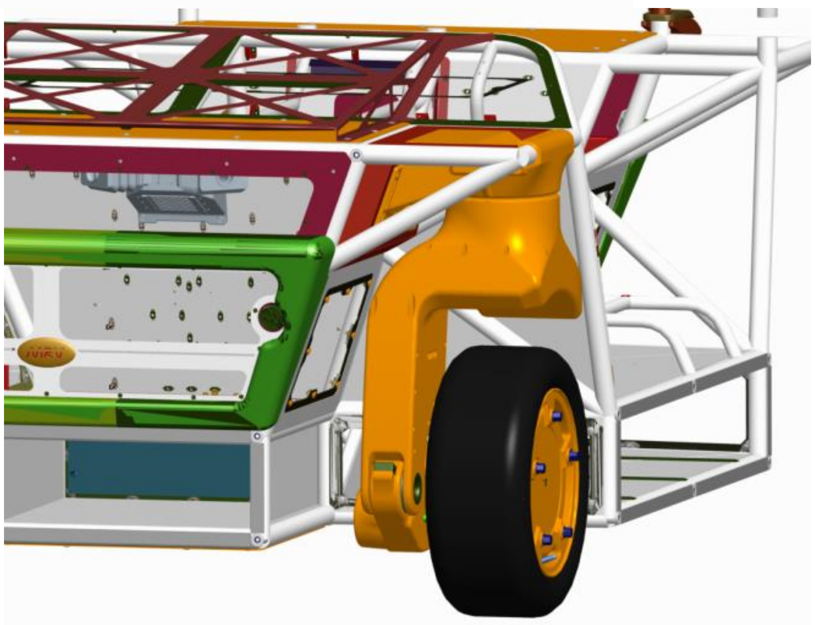
Pedal with
force sensor



Wheel Modules







MRV FMEA

DFMEA Driven - MRV Scenarios

Failure Type (FT)	Description
1. Power Bus: (HV, 12v)	All systems go off-line, emergency braking & steering system? Driver's input ignored
2. Hardware Failure:	Motor Failure, Mechanical or mechanism failure
3. Network Failure:	Network or a portion of network has failed (Node, Wiring, Connector)
4. Code Failure:	Program code and/or algorythim has failed or frozen
5. Operator:	Vehicle driver is unfamiliar and or confused in vehicle's operation

FUNCTION CRITICALITY (FC)

1. Loss of life or Loss of vehicle control
2. Unable to complete trip or journey, requires immediate attention: stop - repair
3. Unable to complete trip or journey, does not require immediate attention: reduced performance
4. Loss of component or system has no critical effect

Criticality Definitions from SSP 30234 (Rev F)

Category Definition

1 Single failure point that could result in loss of Space Station. Orbiter, or loss of flight or ground personnel.

1R Redundant items, all of which if failed, could result in loss of Space Station or loss of flight or ground personnel. When assigning criticality to an item whose failure results in the use of an emergency system, each safety system functional string shall be considered as redundancy that provides additional protection from a particular failure mode, e.g., a pressure tank is 1R for rupture when a relief valve exists.

1S A single failure point of the system component designed to provide safety or protection capability against a potentially hazardous condition or event or a single failure point in a safety or hazard monitoring system that causes the system to fail to detect, or operate when needed during the existence of a hazardous condition that could lead to loss of flight or ground personnel or Station (e.g., fire suppression, medical hardware).

1P A single failure point that is protected by a safety device, whereby the functioning of the safety device, would prevent the hazardous consequences of the failed (protected) component. This criticality category is no longer used as of Revision F of this document, but existing analyses will not be revised.

1SR Redundant components designed to provide safety or protection capability against a potentially hazardous condition or event, all of which if failed could cause the system to fail to detect, or operate when needed during the existence of a hazardous condition that could lead to loss of flight or ground personnel or Station; or redundant components within a safety or hazard monitoring system, all of which if failed could cause the system to fail to detect, or operate when needed during the existence of a hazardous condition that could lead to loss of flight or ground personnel or Station.

2 Single failure point that could result in loss of critical mission support capability, as defined below.

2R Redundant items, all of which if failed, could result in loss of critical mission support capability.

2N Single failure point that could lead to loss of function resulting in worst case effects not assessed as or deemed typical of Criticality 1 or 2, and more significant than Criticality 3. Also, a single failure point that could result in loss of a primary maintenance support system. These systems support/perform maintenance tasks for multiple ORUs whereas failure of the redundant ORUs could result in loss of critical Station functionality. Criticality 2N items are not categorized as critical items.

2NR Redundant items that could lead to loss of function resulting in worst case effects not assessed as or deemed typical of Criticality 1 or 2, and more significant than the Criticality 3. Also, redundant items that could result in loss of a primary maintenance support system. These systems support/perform maintenance tasks for multiple ORUs whereas failure of the redundant ORUs could result in loss of critical Station functionality. Criticality 2NR items are not categorized as critical items.

3 All others.

Fail Operational Matrix developed for supervisory & local definitions of failure scenarios and controlled reaction scenarios

Supervisory Control Architecture *

Priority

Steering System

IF	FT	FC	CR	Then	Indicator
1. Control Freezes - multiple corners (2+)	2,3,4	1	1	Controlled Stop	
2. Control Lost - multiple corners (2+)	1,2,3,4	1	1	Controlled Stop	
3. Angle Sensors Failure - single corner	2	2	1R	Controlled Stop	
4. Motor(x2) Failure - single corner	2	2	1R	Controlled Stop	
5. Erratic operation - single corner	2,3,4	1	1R	Controlled Stop	

Acceleration

IF	FT	FC	CR	Then	Indicator
1. Control is lost (Runaway)	2,3,4	1	1	Controlled Stop	
2. Control Lost (Fixed State)	3,4	1	1	Controlled Stop	
3. Control Lost (No Response)	1,2,3,4	1	1	Controlled Stop	
4. Control Lost (Erratic)	2,3,4	1	1	Controlled Stop	

Propulsion

IF	FT	FC	CR	Then	Indicator
1. Traction goes offline - multiple corners (3+; No Response)	1,2,3,4	2	2R	Controlled Stop	
2. Read Head Failure (Signal Lost)	2	3	2R	Use Remaining Propulsion	
3. Erratic operation (Response does not correlate with command)	3,4	1	1	Controlled Stop	
4. System Overheats	2	2	2	Controlled Stop	
5. Traction goes offline - single corner (No Response)	1,2,3,4	3	2R	Use Remaining Propulsion	

Braking System

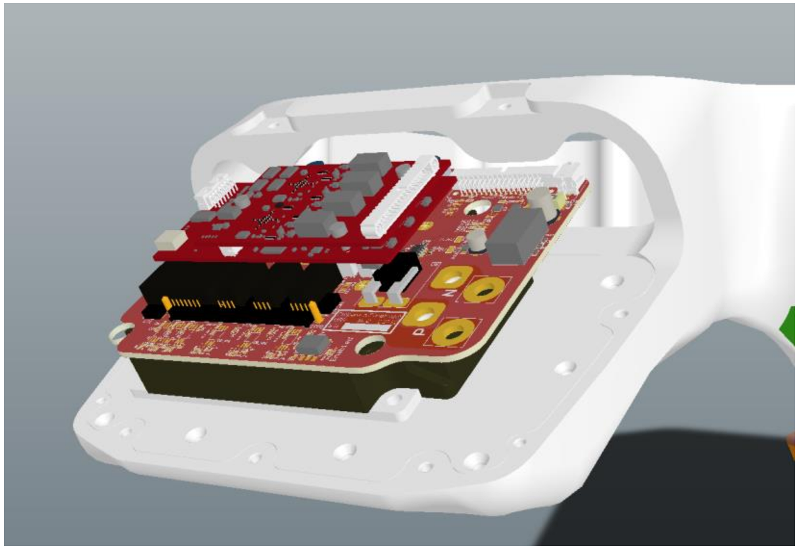
IF	FT	FC	CR	Then	Indicator
1. Control is lost - multiple corners (No Response)	2,3,4	1	1	Cotrolled Stop	
2. Control Freezes - single corner (Brakes Locked)	2,3,4	1	1	Cotrolled Stop	
3. Motor Fails - single corner (No Response)	1,2	3	1R	Use remaining brakes	

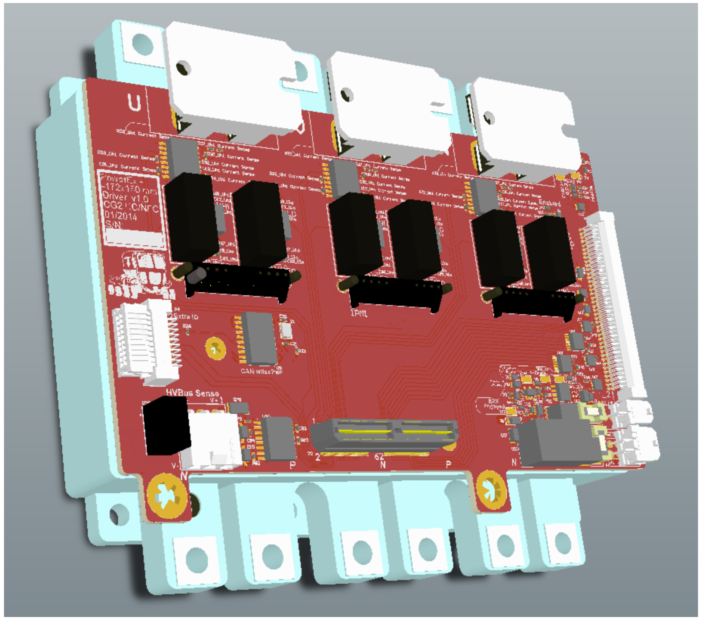
Electrical (HV) System

IF	FT	FC	CR	Then	Indicator
1. Battery Failure					
2. Battery Maintenance System Failure					
3. Power Distribution Failure					

Power Electronics

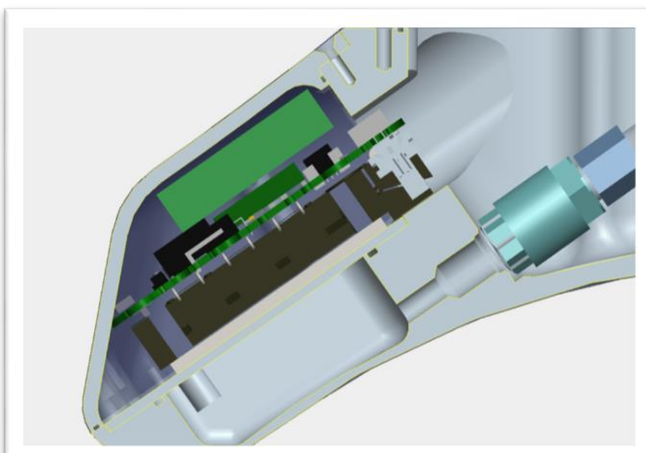
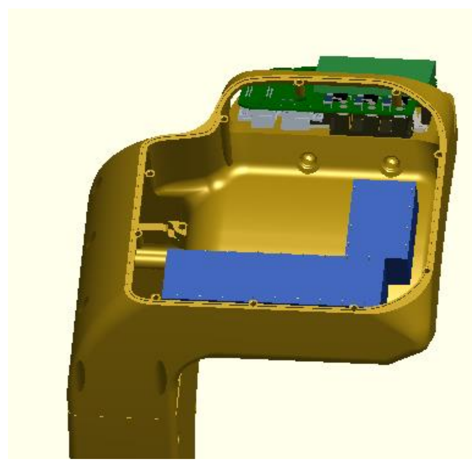
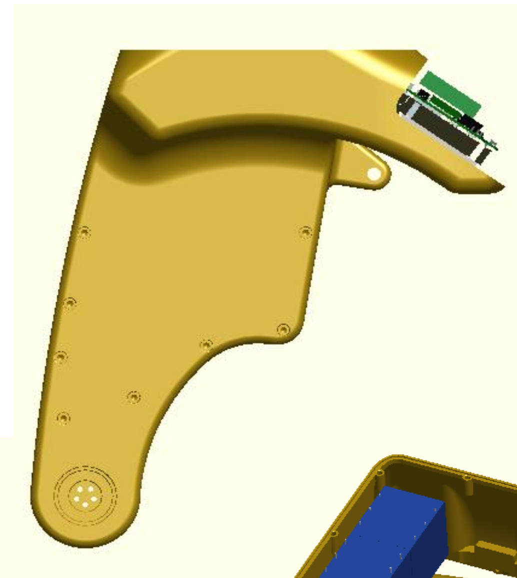
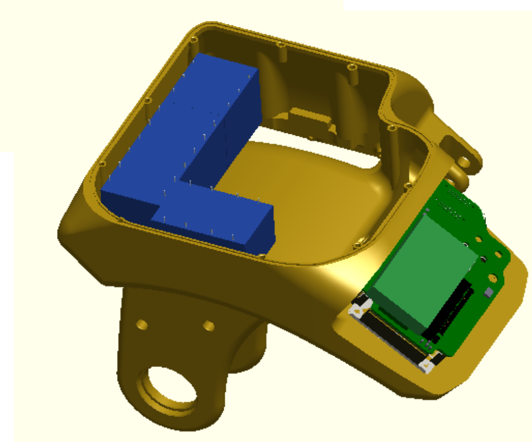
- Existing Power Classes
  - 600V (12kV IPM)
    - 75A (MRV)
    - 225A (CG2)
- Rugged IGBT switch technology
- Multi-loop embedded model-based control
  - Current, Velocity, Position
- Modular design enables rapid re-use





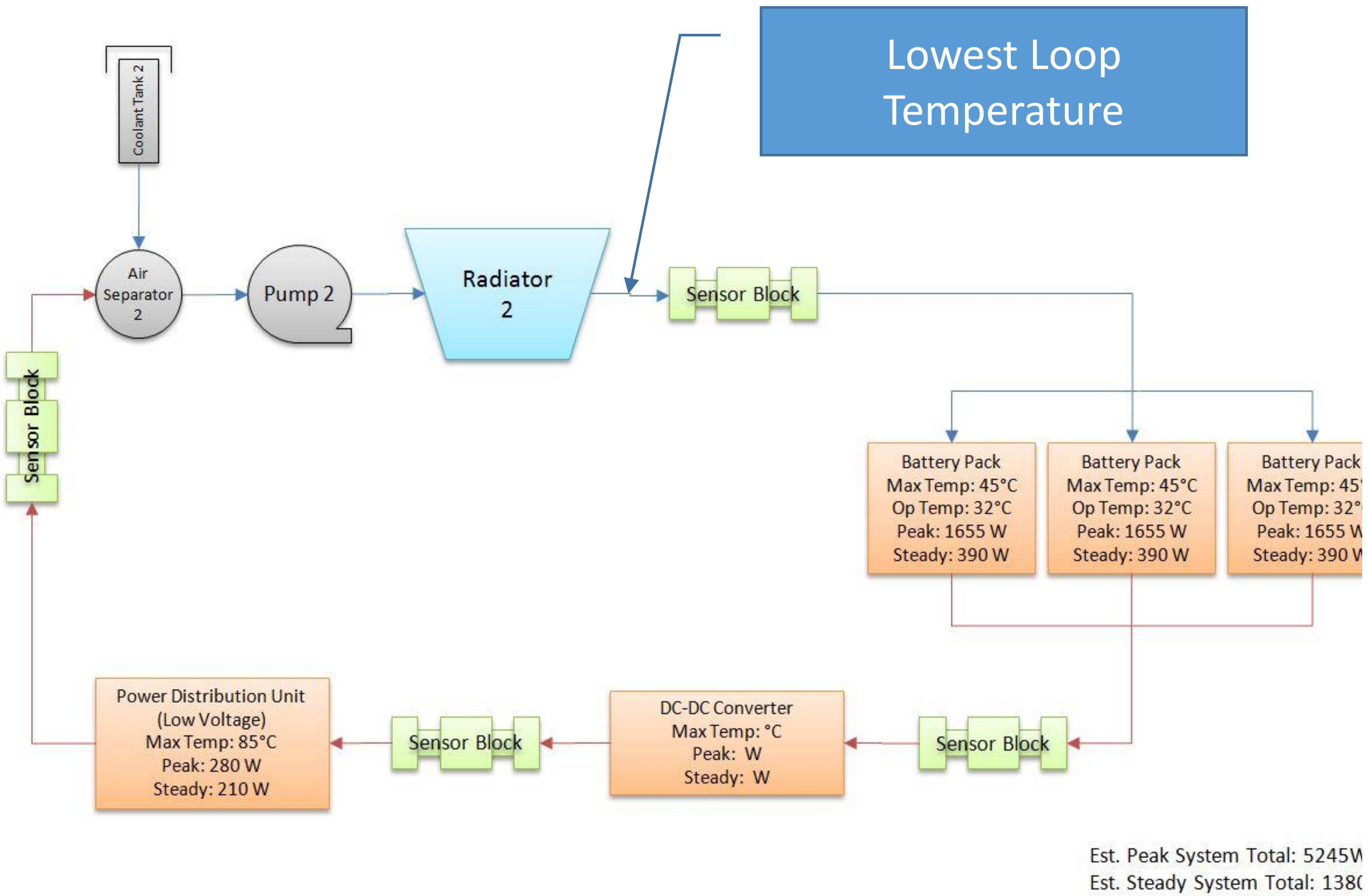
MRV Power Electronics Packaging

- Motor controller cold-plate integrated with structure
- Capacitor bank with bus bar connections

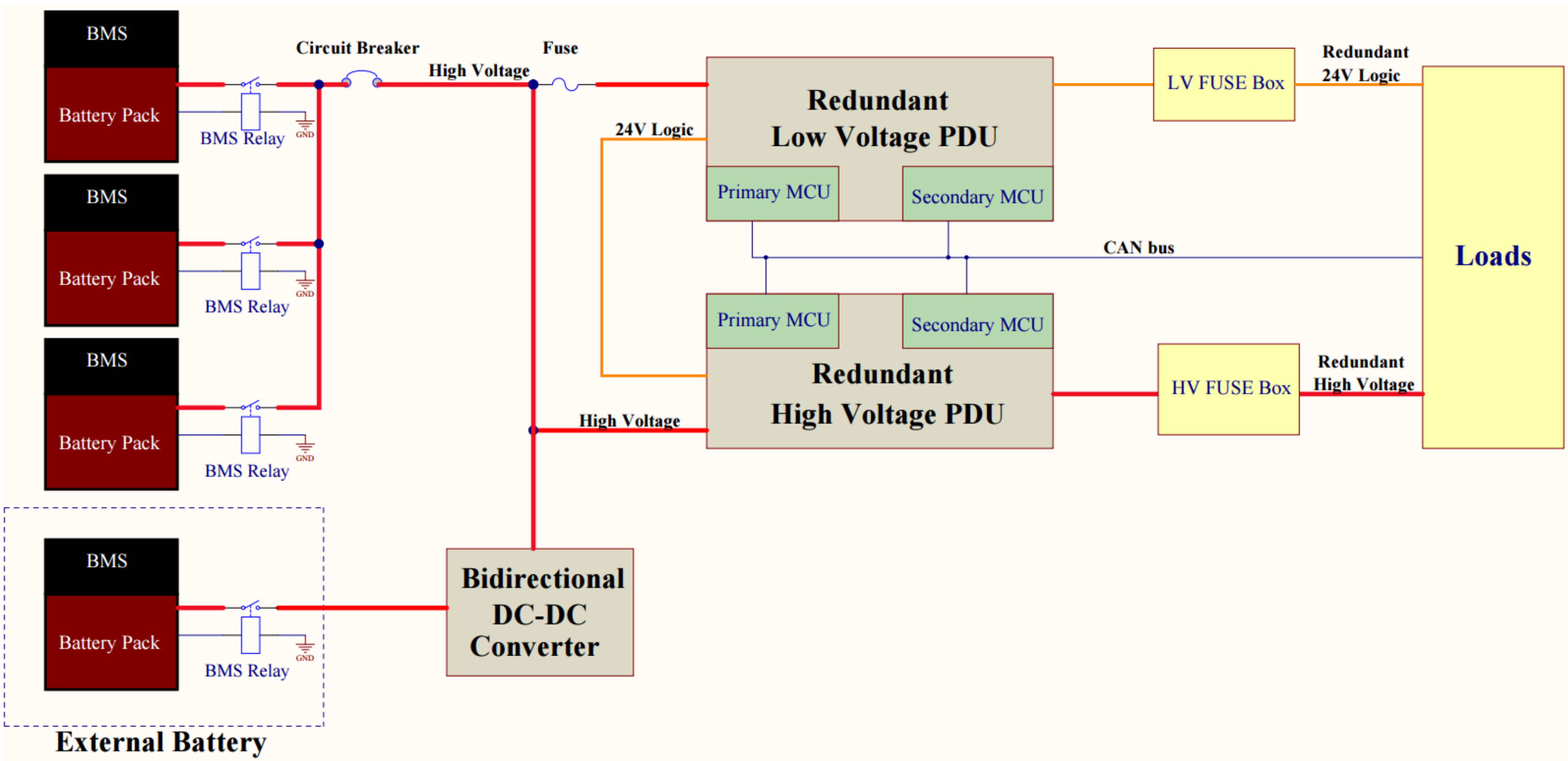
Next generation housing design incorporates new thermal design and process. Placement of motor controllers have taken advantage of cooling design efficiencies.

MRV Active Thermal Management



- Pre-cooling strategy
- High max pressure on radiator
- Lower initial temperature will increase heat removed

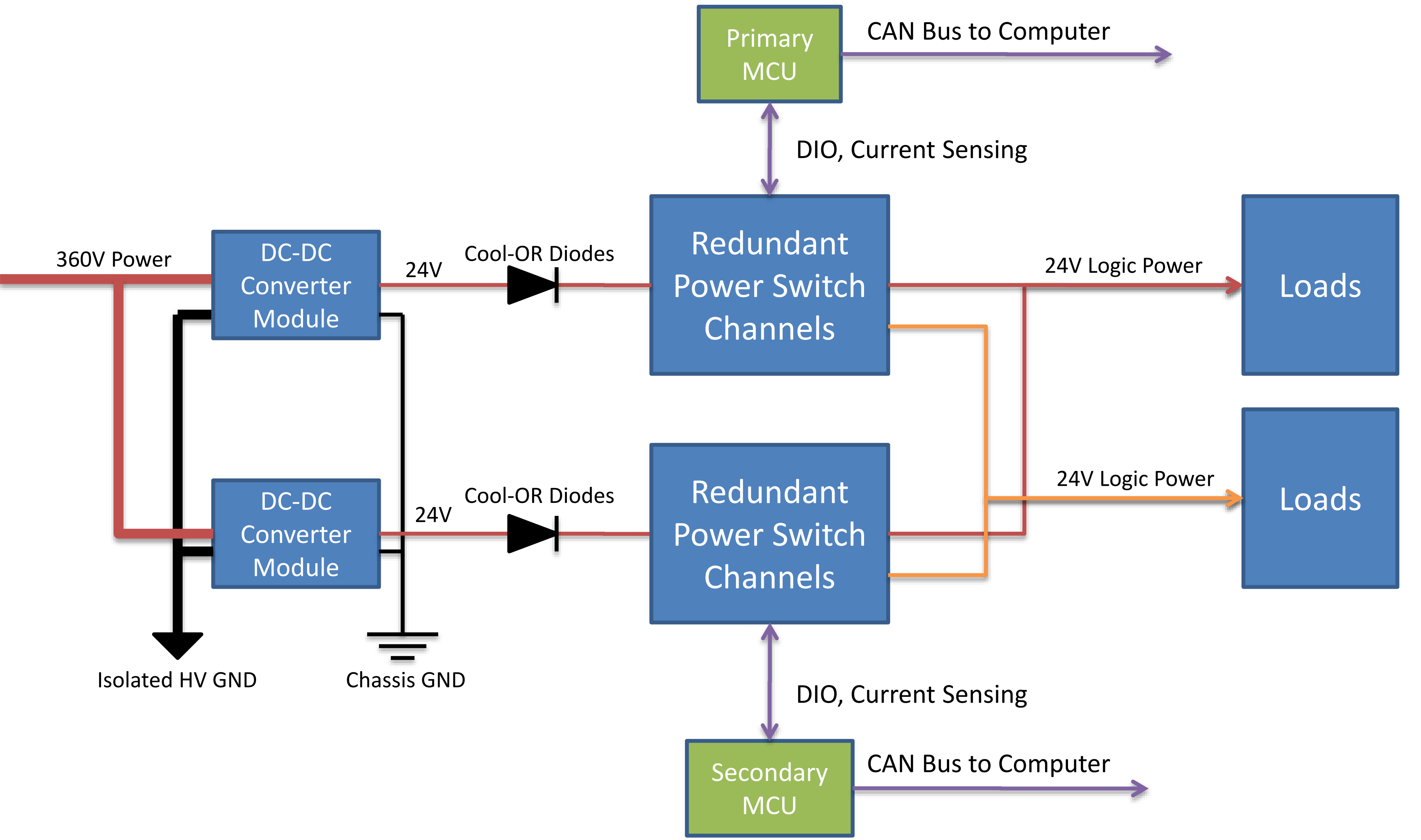
MRV Electrical Power System (EPS)



MRV Electrical Power System

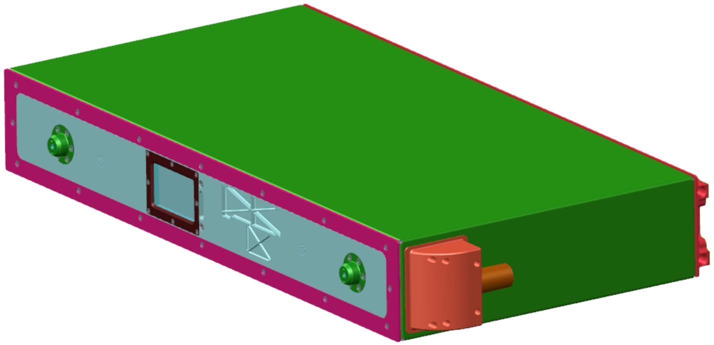
- **Low Voltage PDU**
  - PCM Board
    - Redundant DC-DC conversion from 300V to 24V
    - Fault Detection
  - PCS Board
    - Redundant MCUs
    - Redundant Low Voltage Power Switching
    - Current Sensing
    - Comm via CAN Bus, RS232, I2C
- **High Voltage PDU**
  - HVS Board
    - Redundant High Power Switching
    - Redundant MCUs
    - Fault Detection
    - Pre-charge control
    - HV Current Sensing
    - Comm via CAN Bus, RS232, I2C

MRV Redundant Low Voltage PDU



MRV Energy Storage

- MRV Battery Capacity – 18 kW hrs
- Cell Architecture - derived from Chariot 1
  - Large format cells
  - 292V nominal, 60 amp hr Lithium ion battery
  - Single series string of cells
  - 80 cells in series
  - Cells purchased from Gaia
- MRV used COTS Battery Management System
  - Manufactured by I+ME
  - Procured through a distributor, Lithium Technologies Corporation, Fairfax, VA



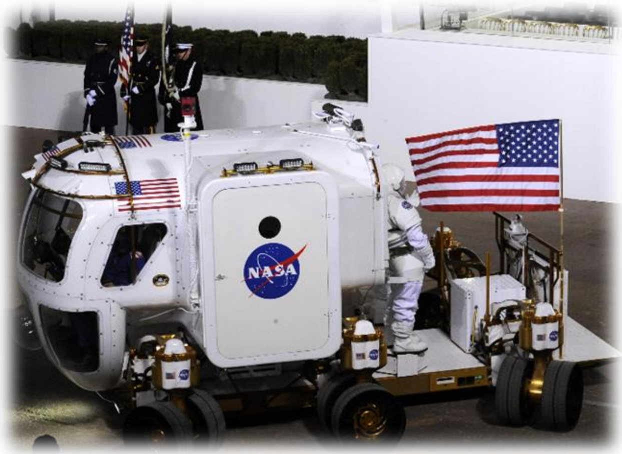
MRV Energy Storage

- Form factor/architecture – modules of 10 cells, easy to carry a module. BMS mounted in MRV, interfaced to each module
- Bus voltage – 292V, varies at the motor
- Thermal control – No thermal control for battery, minimal airflow
- Low capacity backup systems – Original plan in frame was to carry 3 batteries, this would give two fault tolerance. Large batteries ended up winning the day
- Charging
  - Interfaces – High voltage power supplies, constant current, constant voltage
  - Charge rates - nominal 0.2C or 11 amp; maximum 1.0C or 55 amps; to extend life, we've been doing < 5 amp
  - Non-mobility loads (HVAC, etc) –computers, pumps

MRV Energy Storage

- 50 amps per wheel, peak up to 60 kW propulsive power
- Static power draw 1.5 kW
- Not optimized for minimum power draw

Battery Design Experience

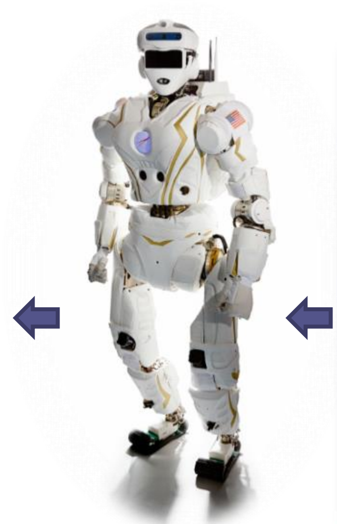


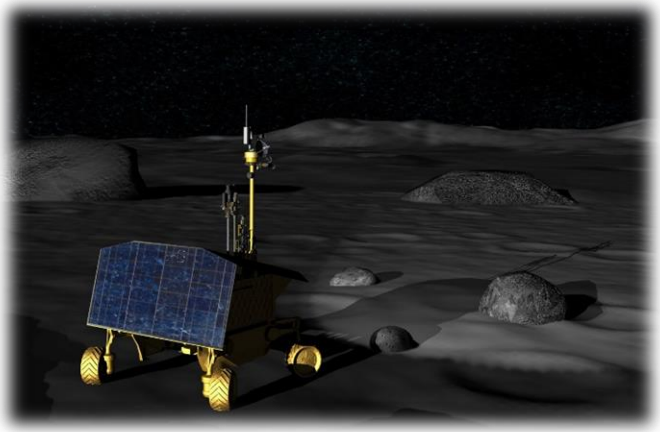
Space Exploration Vehicle

Centaur 2

MRV

Robonaut 2



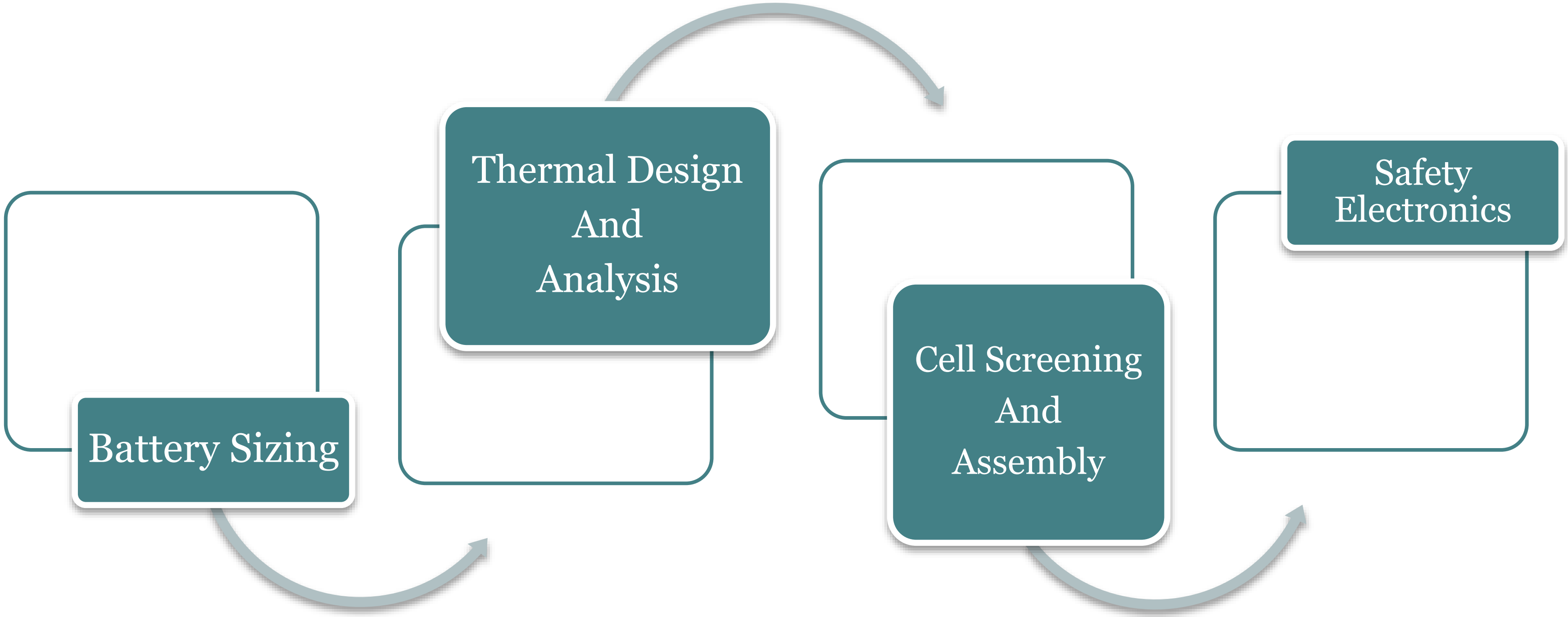


PLSS

Resource Prospector Rover

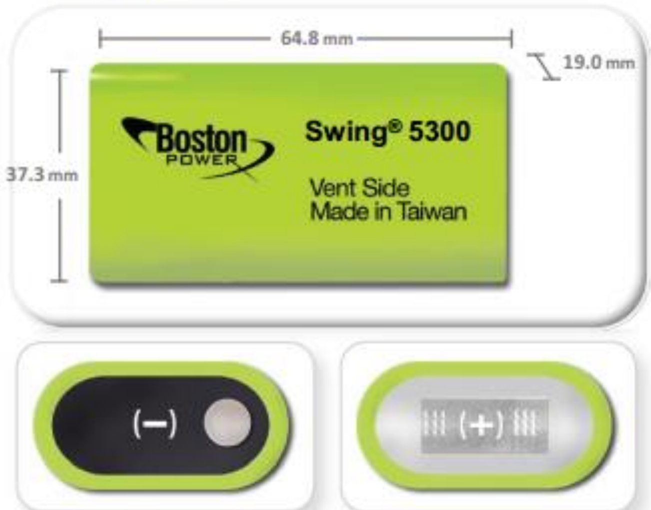
Valkyrie

Battery Management Design Strategy



Boston Power Lithium ion cells

Specifications



Nominal capacity [1]		5300 mAh
Nominal energy [1]		19.3 Wh
Nominal voltage		3.65 V
Energy density	Gravimetric	207 Wh/kg
	Volumetric	490 Wh/L
Nominal cell impedance		15.5 mΩ
Cycle life (1C discharge at 23°C)	100% DOD	>1000 cycles
	90% DOD	>2000 cycles
	80% DOD	>3000 cycles
Max continuous discharge rate (0 -100% SOC)		13 A
Allowable 10s pulse capability[2]		1000 W/kg
Standard charging method	Constant current (CC)	3.7A (0.7C) to 4.2V
	Constant voltage (CV)	4.2V to 50 mA
Max charge rate (continuous)		10.6 A
Nominal cell weight		93.5 g
Operating Temperature	Charge	-20 to +60 °C
	Discharge	-40 to +70 °C
Storage Temperature		-40 to +60 °C

[1] Standard discharge 0.2C to 2.75 V
[2] 50% to 100% SOC

5300 mAh

207 Wh/kg

>1000 Cycles to 100% Depth of Discharge

Certifications

UN 38.3, UL1642, IEC 62133, ROHS 2002/95/EC
In Process: Nordic Ecolabel

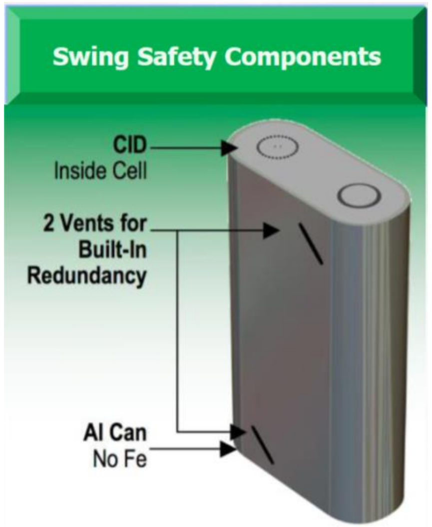
Cycle Life at 100% Depth of Discharge (DOD)

http://www.boston-power.com/sites/default/files/documents/940-0013-001_Swing_5300_DS_Rev_001_0.pdf

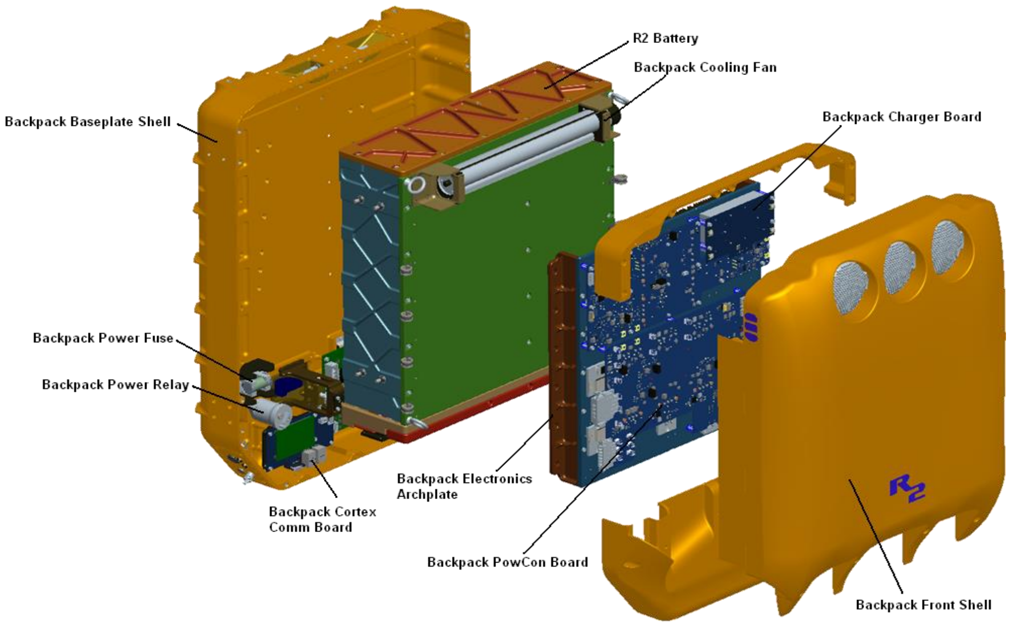
Boston Power Swing 5300 Features

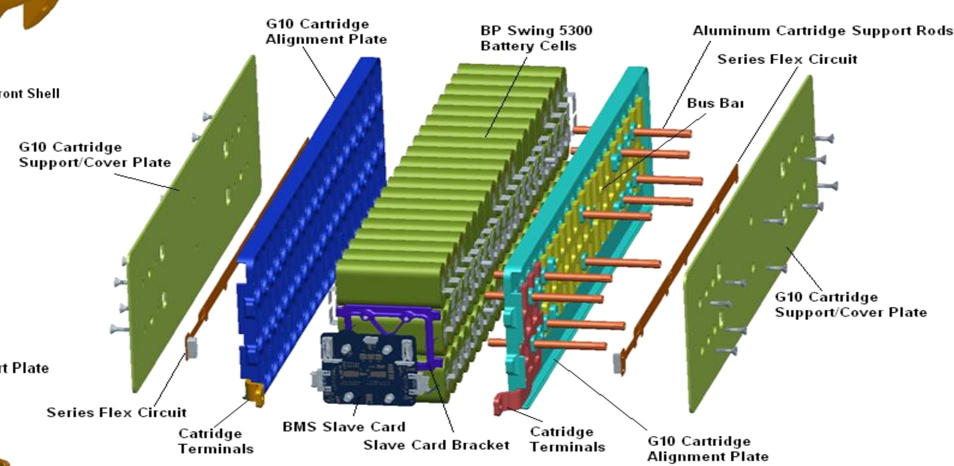
- Boston Power Swing 5300 Features
  - Small elliptical cell format
  - Nordic and Chinese Ecolable certification
  - Aluminum Can
    - High heat transfer rate vs cells using steel cans
    - Inherently lower venting pressure
    - Eliminates corrosion issues associated with Fe-containing cans

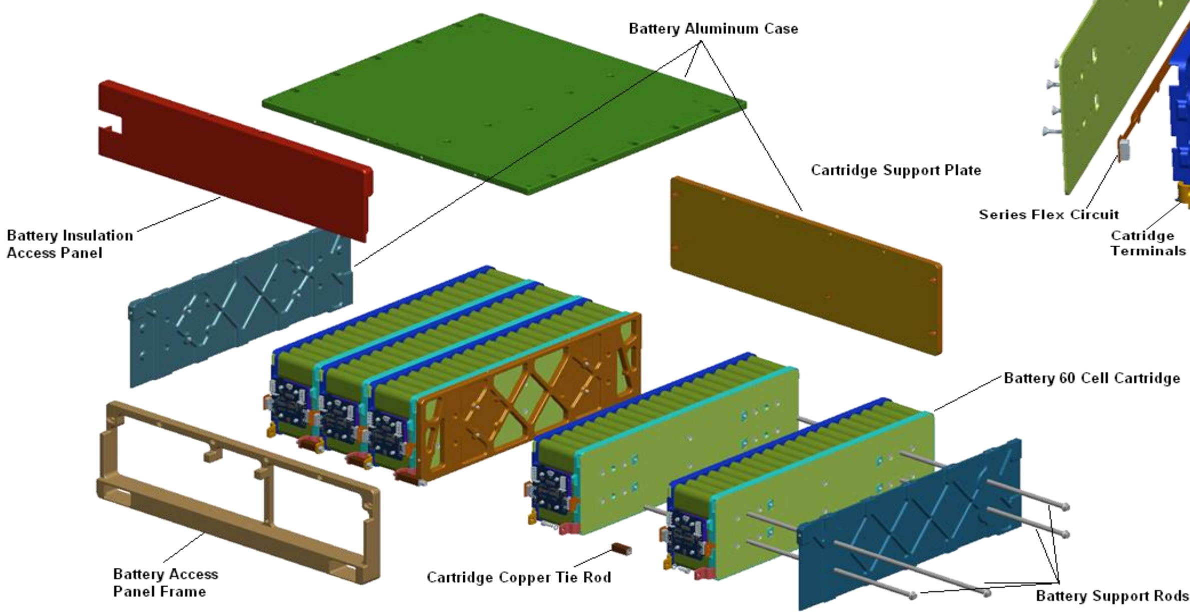
	Special separator	CID	Oriented Vent	Rupture
	3 layered separator	**C**urrent **I**nterruption **D**evice	Directed; redundancy	Less catastrophic
Mechanism	▪ Pores shut down at high temperature	▪ Pressure fuse ▪ Non-resettable ▪ Protect from pressure buildup	▪ Vent direction controllable ▪ 2 vents for redundancy	▪ Aluminum vs. steel for 18650
Devices Protects Against	▪ Overcharge ▪ Over temperature ▪ Internal shorts with temperature increase <150 °C	▪ Overcharge ▪ Over temperature	▪ Explosion ▪ Cascading (cell-to-cell runaway initiation)	▪ Explosion



R2 Batpack


R2 Battery
Backpack Cooling Fan
Backpack Baseplate Shell
Backpack Charger Board
Backpack Power Fuse
Backpack Power Relay
Backpack Electronics
Archplate
Backpack Cortex
Comm Board
Backpack PowCon Board
Backpack Front Shell


G10 Cartridge
Alignment Plate
BP Swing 5300
Battery Cells
Aluminum Cartridge Support Rods
Series Flex Circuit
Bus Bar
G10 Cartridge
Support/Cover Plate
G10 Cartridge
Support/Cover Plate
Series Flex Circuit
Catridge
Terminals
BMS Slave Card
Slave Card Bracket
Catridge
Terminals
G10 Cartridge
Alignment Plate


Battery Aluminum Case
Cartridge Support Plate
Battery Insulation
Access Panel
Battery 60 Cell Cartridge
Battery Access
Panel Frame
Cartridge Copper Tie Rod
Battery Support Rods

R2

Cell Configuration: 300 cells in full pack

- 5 Series connected cartridges
  - 5 Virtual cells in series per cartridge
    - 12 parallel cells per virtual cell

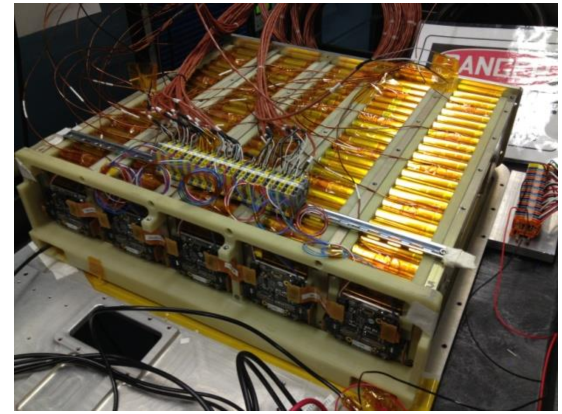
Energy: 5790 Wh

- Total Pack Assembly Weight = 37.421 kg
- Effective Energy Density = **<u>154.724 Wh/kg</u>**

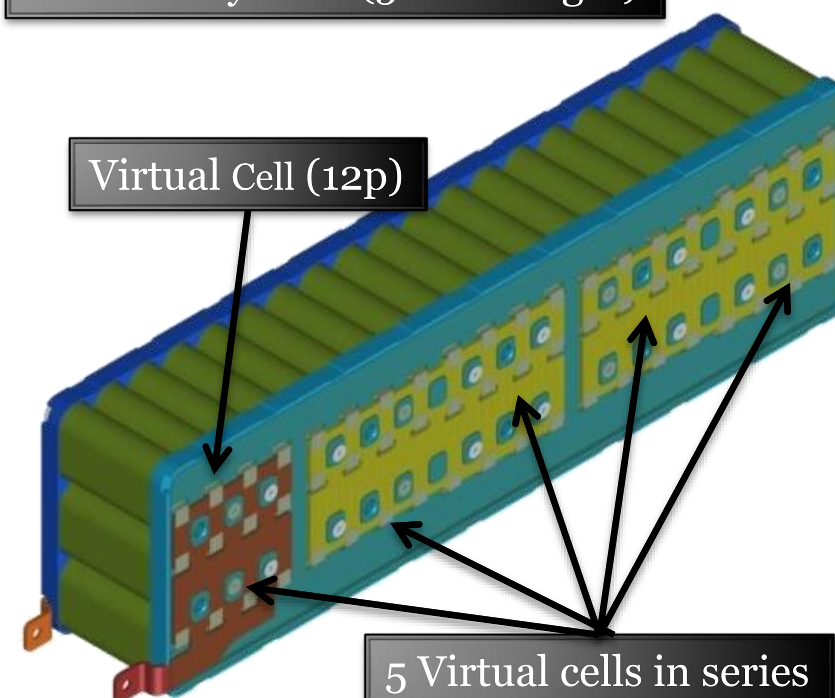
Operating Voltage: 105V – 65V

- Nominal pack voltage: 92.4V

Max Continuous Discharge: 156 A



Full Battery Pack (5s Cartridges)



Valkyrie

Cell Configuration: 96 cells in full pack

- 2 independent batteries for two power busses in one package
  - Four 24 cell cartridges
- Low voltage pack is one cartridge
  - 8 cell virtual cell
  - 3 series connected virtual cells
- High voltage pack is 3 series connected cartridges
  - 2 cell virtual cell
  - 36 series connected virtual cells

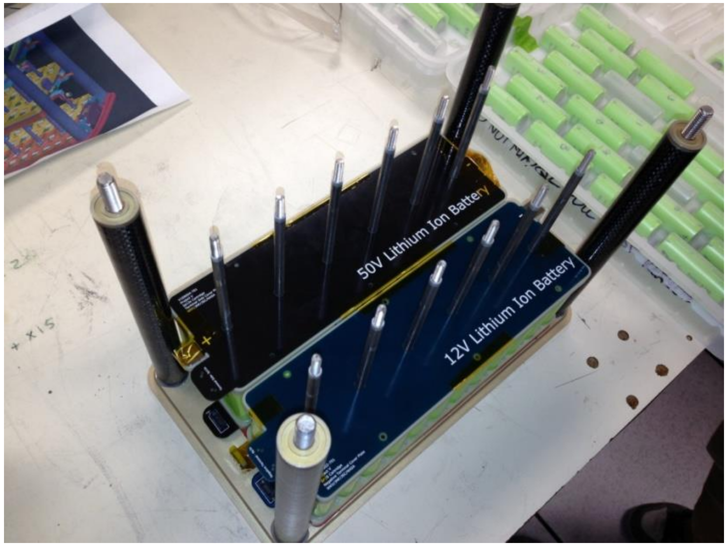
Energy: 1860 Wh

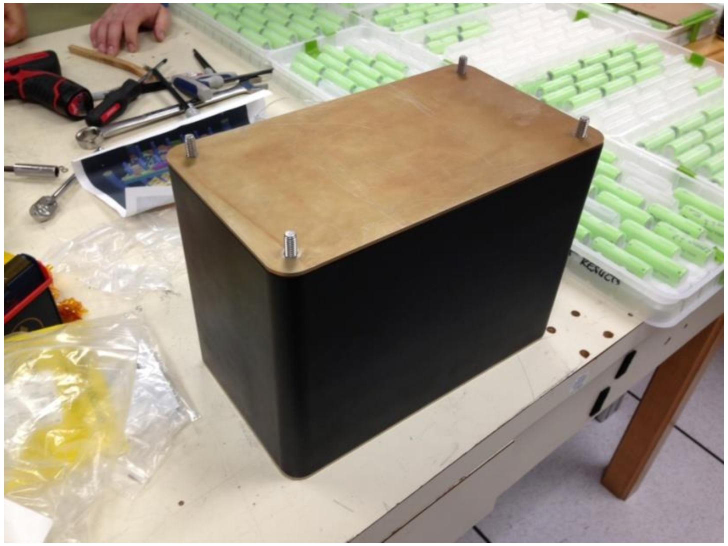
- Runtime: ~1 hour
- Energy Density ~**<u>133 Wh/kg</u>**

Operating Voltage

- Low Voltage pack (42 Ah)
  - Nominal 10.95V
  - Ranges from 9V to 12.6V
- High Voltage pack (10.6 Ah)
  - Nominal 131.4V
  - Ranges from 108 to 151V

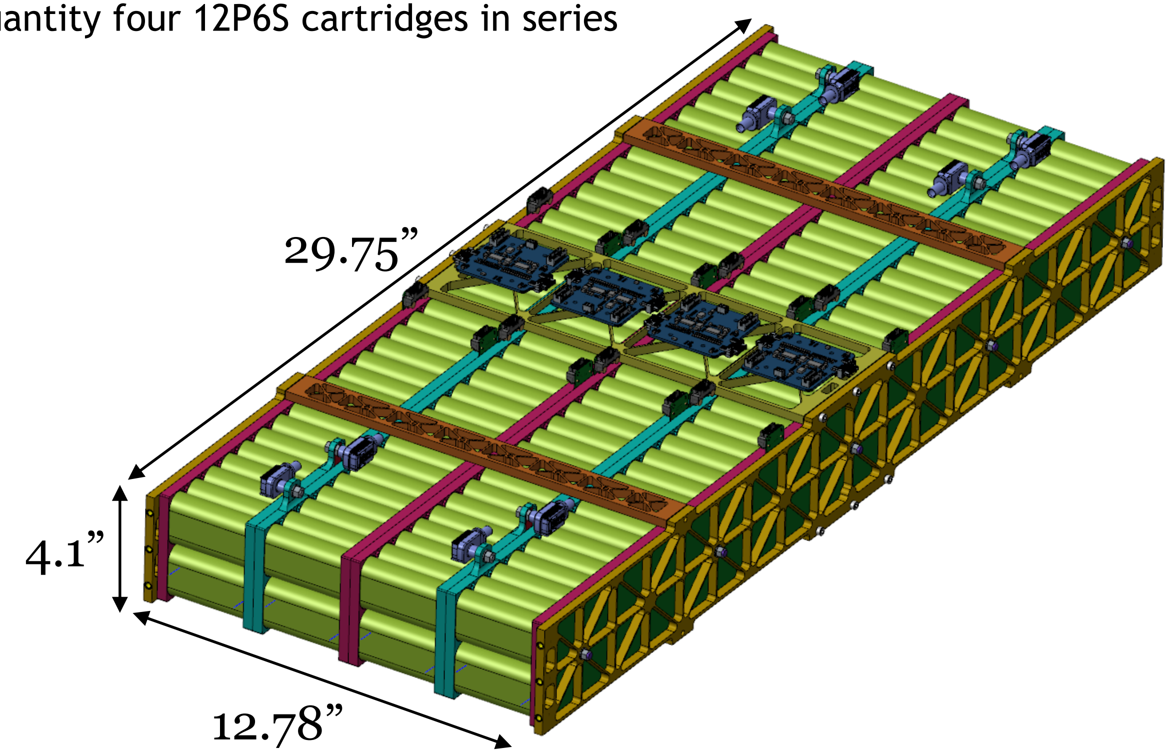
Max Continuous Discharge (HV): 30 A
Max Continuous Discharge (LV): 60 A





Resource Prospector (RP)

- RP Battery
  - Utilize Boston Power Swing 5300 cells
  - 12P24S layout consisting of quantity four 12P6S cartridges in series
  - 288 Cells
  - Voltage
    - Max: 100.8 V
    - Nominal: 87.6 V
    - Min: 72 V
  - Current
    - Max: 156 A
    - 1C: 64 A
    - 0.1C: 6.4 A
  - Power
    - Max: 13665 W
    - 1C: 5606 W
    - 0.1C: 560 W
  - Thermal Range (Cells)
    - Charge:-20 to 60C
    - Discharge: -40 to 70C
    - Storage: -40 to 60C
    - Significant Loss in capacity below 0C
    - Capacity Increases at higher temperatures
  - Energy: 5571 Wh (100% DOD)
  - Estimated Weight: 32 kg (70 lb)
  - Estimated Gravimetric Energy Density: **174 wh/kg**



Battery Safety

Catastrophic Hazards

- Conditions that lead to catastrophic failure (thermal runaway)
  - Overvoltage
  - Charging over discharged cells
  - Overcurrent
  - External heating (system design)
  - Internal Short

Safety Philosophy

- Our safety philosophy is to control against all catastrophic causes with two fault redundancy in detection and mitigation
- Action's based upon fault detection are flexible by design and vary depending on the application

*Additionally current testing and design efforts include working to prevent cell to cell propogation in the event of a single cell runaway

Safety Electronics

High Level: Operational Limits

Mid Level: Software/Firmware Limits

- *(Safety Critical Code adds cost and complexity)*

Low Level: Hardware Limits

- *(R2 hardware is 2 fault tolerant without software)*

Modular Battery Management System

BMS Slave Board

- Configurable to up to 12 series cells
- Stackable up to 31 boards (372 series cells)
- Over/Under Voltage Hardware Comparators
- Over/Under Temp Hardware Comparators
- Voltage and Temperature Monitoring
- All hardware safeties trip an interlock signal which can be used by the master as a hardware inhibit

BMS Master Board

- Communicates with slave boards via i2c interface
- Independent stack level Over/Under voltage monitoring
- Over Current Monitoring
- Disengages battery from system during any safety event

Battery Management System Telemetry

- Each Virtual Cell Voltage
- Min/Max/Avg Cell Voltage
- 12x Temp's/Cartridge
- Stack Voltage
- Current
- Error/Warning Flags
- Error/Warning Counters
- Cell Balancing Status
- BMS state machine state

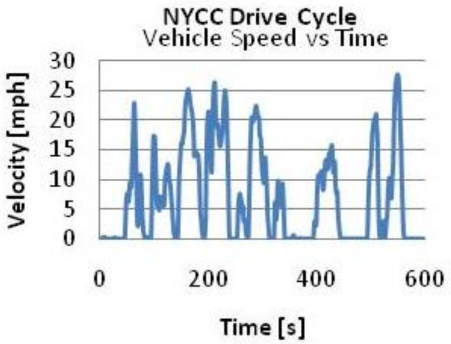
- Firmware Version
- Hardware Version
- Discrete input states
- Discrete output states
- ADC Sample Counters
- Local Power Supply Voltages
- Charger Control Parameters

Thermal Runaway Propagation

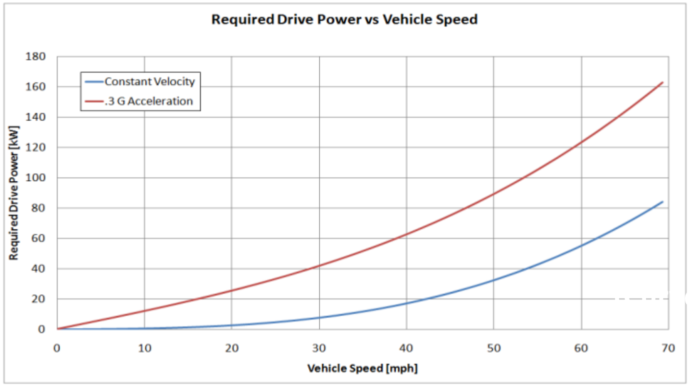
- Investigating materials for unique thermal properties
- Testing at the cell and pack level for propagation tolerance
- Coordinating with parallel NASA Engineering Safety Council and Space Suit Battery team work
- Developing thermal abuse models to aid with design of mitigation features

MRV Battery Power Estimation

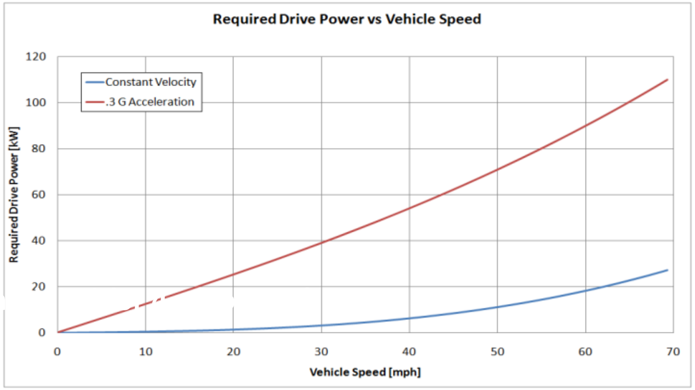
- Estimated Vehicle Power Requirements based on NYCC Drive Cycle
- Assumptions:
- 4 e-Corners
- Vehicle mass: 862Kg
- Hotel power load: ~1500W
- Acceleration: 0.3g
- Deceleration: 0.3g (-1.0g emergency)
- CD: 1.0



Power Profile with CD of 1.0



Power Profile with CD of 0.3

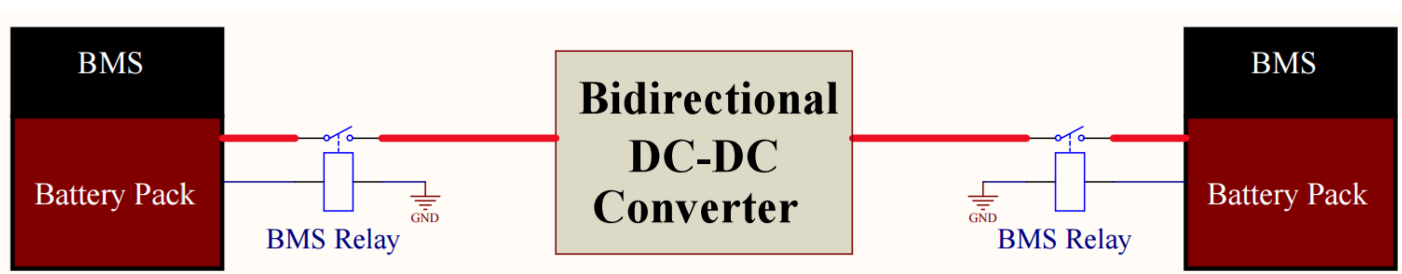


Hybrid Battery/Capacitor bank options

- NASA has investigated this approach for previous mobility system projects
- Looked at different convertors, approaches for connecting the capacitor to the batteries
- Initial architecture explored was large battery and large capacitor bank
  - This approach was influenced by size of Chariot rover design concept
- NASA bought a custom built bi-directional DC-DC converter device from US Hybrid for evaluation
- Initial evaluation was to send current back and forth between two batteries
- Goal was to charge one electric vehicle with another vehicle
- Other hybrid battery architectures explored involve pairing up a battery and a capacitor.

MRV Energy Transfer between Batteries

- Implemented bi-directional DC-DC Converter
- Directly applicable to Hybrid power systems
- Demonstrated power transfer in both directions
  - HV battery balancing
  - “Empty” one battery into the other in contingency
  - Arbitrary voltage and current setpoints (0-600V)



Power Management

- Low voltage “flavors” – many voltages used in MRV
- 24V - motor controller logic voltage, power thermal system, computers
- 12V – common for automotive systems
- Familiar with down conversion to lower voltages for many systems
- Dual redundant power systems in MRV

Power Electronics Modules

- Good success with COTS power modules
- R2 uses MS Kennedy, high reliability power electronics for military and aerospace. PowerEX also used, US manufacturer of power modules, relationship with Mitsubishi. R2 uses PowerEX in legs
- Sizing - expanding the top end range of power through the motor drives. Valkyrie fingers is smallest. Chariot 2 wheel module is largest power use, as implemented can accept 600V, deliver 225 amps
- De-rating – numbers above are derated 50%. Vendors recommend establishing limits through testing. Motorcycle dyno testing used for MRV.
- Supercar calls for lots of power, derating through modeling. Look to vendors for the models, we plug in our usage.
- For MRV and Chariot Gen 2, Mitsubishi has a model that shows loss value. Testing was very successful in establishing derating levels
- Commonality across subsystems – applied where feasible

Regenerative Braking

- NASA first implemented this with Chariot
- NASA implementation for MRV is a blending of mechanical and regenerative braking
- NASA sought motor which both a good motor as well as a good generator
- Design requirements of accelerating at 0.3 g, decelerating at 1 g were set for MRV. Acceleration requirement was accomplished in design, design for deceleration achieved 0.5g
- Regen power goes directly into MRV battery
- For battery/supercap architecture, trade study needed to determine what regen power goes to battery vs supercap

Regenerative Braking

- Shunting when fully charged - needed for systems with no large energy reservoir
- Robonaut 2 needed shunting
- Chariot has shunt regulator
- Our approach is to manage this operationally (don’t charge it up all the way)

MRV Regeneration and Mechanical Braking Contributions