Loon LLC Hydra Battery Design

Overview

Hydra is the 3rd-generation Loon battery pack used to power Loon systems in flight. To serve the dynamic requirements of different types of Loon flights, Hydra implements a modular battery pack concept for flexibility and reliability.

Hydra compared to previous 2nd-gen battery

Hydra is a significant departure from previous monolithic single-pack designs used for Loon previously. Hydra also incorporates comprehensive self-management electronics and custom firmware, whereas previous batteries used only off-the-shelf fuel gauges.

- Scalable modular design:
  Up to 16 Hydra packs operate as one battery system to power a flight.
- More or fewer packs can be used to balance power vs. mass on a per-flight basis
- Increased operational reliability via redundancy and local SoC estimation
- Improved power density
- Comprehensive management electronics
  - Management MCU
  - Loon CAN-bus avionics network support
  - Intelligent power on/off control
  - Fault detection and tracking
  - Pack Heater
  - Cell-balancing
  - Shipping shock detection
  - In-system firmware upgradable

Hardware Design

A Hydra pack is composed of these parts:

- 24 round cells configured as 12S2P
- Battery Management Unit PCBA
- Strip heater
- Lightweight plastic frame
- Shrink-wrap outer insulation

Software Design

Hydra is built on the Loon Avionics MajorTom infrastructure (the Loon Avionics embedded OS). This allows Hydra to participate in the Loon Avionics CAN bus network. Unlike most batteries which are managed over SMB/I2C, Hydra is capable of monitoring itself and actively pushes telemetry, status, and error information over CAN. Building on top of MajorTom infrastructure also enables Hydra to provide an RPC service, which is used to manage manufacturing information, configure batteries, and update battery firmware.

In contrast with off-the-shelf batteries, Hydra firmware is entirely built by Loon, and we can customize the battery SoC algorithms and protection policy to fit our needs. Most notably, this allows us to push the batteries to their limit to save a flight in extreme situations, at the risk of sacrificing some of the batteries. Custom firmware and electronics also allows defining our own safety policy to reduce the risk of harm to personnel or destructive failure.

Spec/Requirements Table

Specification	**Value**	**Comments**
General Requirements		
Battery Voltage	50.4V	at full charge
Battery Capacity	273.6 Wh typical	11.4Wh per cell
Pack Topology	12S 2P	12 series, 2 parallel
Mass	1.4 kg	
Specific Energy	200 Wh/kg nominal	175 Wh/kg derated to flight conditions
Continuous Charging	3.15 A	
Continuous Discharge	6.3 A	
Cell Type	18650 Form Factor	
Cell Capacity	3.2 Ah	
Cell Voltage (nominal)	3.65 V	
Certification	Must meet UN38.3 certification requirements	
Mechanical / Thermal		
Form Factor	Prismatic	
Shock	150g in all 3 axes, with no loss of cell containment or short-circuit	half-sine, 6 millisecond duration

Vibration	3 hours vibration in each axis with no loss of cell containment or short circuit	sinusoidal sweep 7Hz → 200Hz → 7Hz in 15 minute cycles (12 cycles total per axis)
Thermal Survival Power	1% capacity per hour	to maintain battery temperature at +15C +/- 5C in -20C environment
Thermal Matching	temperature of all cells within 5C	
Control and Monitoring		
System Communication	CAN 2.0B 125 kbps	
System Controller	High Performance MCU	
Temperature Sensing	3x sensors in pack, accuracy +/-2C over -40 to +60C	
Fuse	15 A fast-blow	
Voltage Monitoring	+/-50 mV	
Coulomb-counting current sense	+/-10 mA	
Cell Balancing Method	1% per hour discharge, cell-selective	using resistive shunts
Self-Protection	Overtemperature, Undertemperature Overvoltage, Undervoltage Overcurrent, Short circuit	disconnect battery charge or discharge path as appropriate

Key Features

Status LEDs

There are five LEDs on the battery pack, next to the 1x8 connector. Four of them are green and show the current state of charge:

- 1 LED on: 0-30%
- 2 LEDs on: 30-60%
- 3 LEDs on: 60-90%
- All LEDs on: 90%+

If the battery is charging, in addition to the LEDs showing the state of charge, the next higher LED blinks.

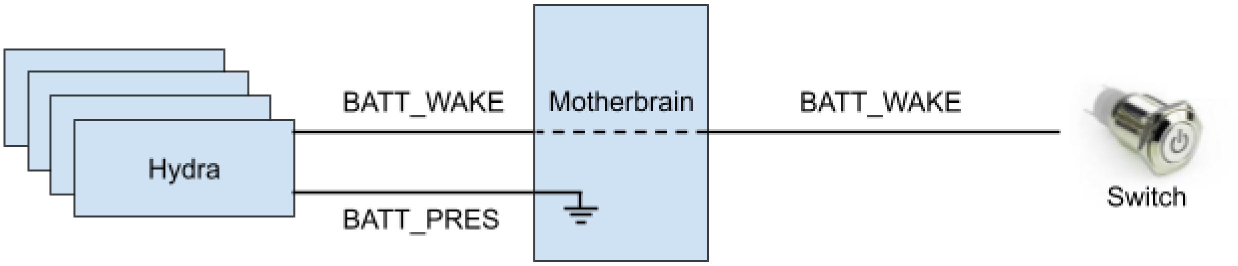
The other red LED is a fault indicator and lights up when the battery is in at least one fault condition. Note that the fault LED being on does NOT mean the power paths are definitely disabled. If the fault is a charging fault, the discharge path may still be on, and vice versa.

Battery Heater

Loon's operating environment includes ambient/payload temperatures that range from -80C to +50C. To keep the battery's cells performing well and maintain access to the greatest available charge, the Hydra battery incorporates a resistive strip heater situated between the cells, and three thermistor temperature sensors. The heater is controlled via an adjustable software thermostat accessible and settable remotely by Loon Avionics. The thermostat mode and setpoint is chosen to balance energy used for heating vs. improved energy availability and efficiency due to a warmer battery.

Robust On/Off Switching

It's crucial that the batteries remain always on in flight yet can be turned on/off easily by users as intended on the ground. A switch is provided on the payload for the users to turn on/off the batteries, and the signal goes through the Motherbrain board, as shown in the following diagram. We call this signal BATT_WAKE. Another signal that goes between Hydra and Motherbrain is the BATT_PRES signal, which is pulled up on Hydra and tied to ground on Motherbrain. BATT_PRES is used to detect if a Hydra is connected to a payload. If it is, BATT_PRES is forced low by Motherbrain; otherwise, it's pulled high by Hydra itself.



The cables connecting Hydra batteries to their load (MotherBrain) are fully contained and strain-relieved inside the payload enclosure, and thus have only a modest chance of failing. However, the switch is partially exposed on the outside of the payload, so the switch and the cable connecting the switch to Motherbrain have a higher risk of failing short or open.

The goals of Hydra's on/off switching behavior are:

- Multiple Hydra packs in a payload can be turned on/off together with a single switch.
- A flight never loses power even if the switch or the cable fails.
- Hydra must disable its power output if it is disconnected from a payload.

The scheme we use to achieve these goals is:

- If BATT_PRES is high, Hydra always turns off, regardless of the state of BATT_WAKE.
- If BATT_PRES is low, Hydra monitors BATT_WAKE and measures the width of any pulses on BATT_WAKE signal. At the beginning of a pulse, Hydra turns on. When the pulse ends, Hydra turns off if the pulse width is between 2 to 10 seconds. In other words, a pulse shorter than 2 seconds or longer than 10 seconds turns on the battery, and a pulse with width in between turns off the battery.

To avoid bouncing on BATT_WAKE accidentally waking a battery, a Schmitt trigger is added on the signal path.

With this scheme, if the switch fails in flight, we would get a level change on BATT_WAKE but not a correctly-timed pulse, and therefore the batteries stay on.

Long-Term Sleep Mode

Between when a Hydra battery is manufactured and when it is put into a payload, it may sit in a warehouse for quite some time. Without a built-in bootstrapping mechanism, if the battery cells are drained too much, the battery will need to be taken apart and refurbished. Therefore, we want to keep the power consumption of the battery management unit (BMU) as low as possible, so as to extend the shelf life of Hydra to its maximum.

When Hydra is turned off, whether because it is detached from a payload or because it is turned off manually with the switch, the BMU enters low power mode. In this mode, the onboard microcontroller enters its lowest power state and loses all its state. The heater is also turned off, even if the temperature of the cells is too low.

BATT_WAKE signal is tied to the wake-up input signal of the microcontroller. When the user turns on the battery with the switch, it wakes the microcontroller and it resumes control of the battery.

Health Self-Assessment and Cell Protection

When Hydra is on, it monitors the battery health and activates appropriate protection immediately if a fault condition is met. At the same time, the fault condition is captured and reported in telemetry back to MC, and an alert in MC is triggered to notify relevant team members. With this, we are able to spot any battery irregularity within 20 minutes of it happening in flight.

Name	Fault Condition	Trigger Timeout	Affected Power Paths	Recovery Condition	Recovery Timeout
Cell undervoltage	One cell goes below 2.5V	1 s	Discharge	All cells go over 2.75V	5 s
Cell overvoltage	One cell goes over 4.25V	1 s	Charge	All cells go under 4.2V	5 s
Overcurrent discharging	Discharge current over 20A	160 ms	Discharge	Discharge current below 0.1A	1 s
Short-circuit	Discharge current over 40A	400 us	Discharge	Discharge current below 0.1A	5 s
Overcurrent charging	Charge current over 6.3A	1 s	Charge	Charge current below 0.1A	30 s
Under temperature	One temperature sensor reads below 0C	1 s	Charge	All temperature sensors read over 5C	5 s
Over temperature charging	One temperature sensor reads over 45C	1 s	Charge	All temperature sensors read under 40C	5 s
Over temperature discharging	One temperature sensor reads over 60C	1 s	Discharge	All temperature sensors read under 55C	5 s
Hardware error	Unexpected hardware error	Immediately when detected	Charge and Discharge		

The active faults are reported in ‘battery*_pack_error’ reports. Each bits in the report corresponds to a fault, and the mapping is:

0x001: Charge inhibited (Usually because of some charging faults)
0x002: Discharge inhibited (Usually because of some discharging faults)
0x004: Overcurrent charging
0x008: Overcurrent discharging
0x010: Short circuited
0x020: Cell overvoltage
0x040: Cell undervoltage
0x080: Overtemperature charging
0x100: Under-temperature
0x200: Unexpected hardware error
0x400: Overtemperature discharging

The health monitoring includes:

- Temperature monitoring: charging/discharging at extreme temperature may damage the battery cells.
    - If the temperature reaches 45°C, charging is disabled.
    - If the temperature reaches 60°C, discharging is disabled.
    - If the temperature goes below 10°C, charging is disabled.
    - Discharging is not disabled at low temperature, so that we have a chance to save a flight by tuning down the heater when power runs low in the night.
- Voltage monitoring
    - If a cell reaches 4.25V, charging is disabled to avoid cell damage and potential safety hazard.
    - If a cell goes below 3.0V, discharging is disabled.
- Current monitoring: If charging or discharging current is too high, current flow is disabled.
- Battery analog frontend (AFE) health monitoring: If the AFE reports an error, Hydra passes the error back to MC.

Shipping Shock Detection

During transportation, we try to avoid dropping the batteries or bumping them into anything in any way. Still, we want to be sure that the batteries we fly are not damaged by physical shock.

Hydra has an on-board shock detector capable of detecting shock up to 400-g (i.e. 3920 m/s^2). When the battery is on, the microcontroller constantly polls the detector and records the maximum shock. To also detect shock when the microcontroller is off, it programs the shock detector to look for a range of preset shock levels. If a shock is detected, a bit is set in the shock detector. When the battery is turned on the next time, the microcontroller checks for the bit and updates the maximum shock accordingly.

While this means we don’t get the exact magnitude of the shock when the battery is off, this approach is enough for us to determine if a battery is okay to fly, and it doesn’t require us to keep the battery always on.

SoC Estimation

SoC stands for “state of charge”. It tells us when we’re going to run out of juice. While there exists commercially-available hardware and publicly-available algorithms to track the SoC of a battery, we can’t use these because:

- Our operating temperature varies dramatically
    - Temperature ranges between -20C and 50C in flight are common
    - Temperature has tremendous impact on the battery chemistry, voltages, and available energy
- We don’t reach full charge every day
    - Many approaches correct for bias when the battery is full
- We don’t “idle”
    - Many approaches use idle (ie, no load) conditions to get clean measurements
- We want to utilize as much capacity as possible
    - Battery charge equates to LTE coverage

For example, the 2nd-gen battery used a SoC gauging algorithm by TI. It performed poorly- in one case we saw 20% error. It didn’t compensate for temperature, and it could only un-bias when we reach full charge. We had to include a ~15% buffer as a conservative thermal prorating.

The Model

- SoC ***is approximately*** $\frac{charge\ left}{total\ charge\ that'll\ fit}$
- More precisely, we define SoC as $\frac{charge\ we\ could\ extract\ at\ training\ temp,\ current}{max\ charge\ we\ could\ extract\ at\ training\ temp,\ current}$
    - This is normally in the range 0 to 1.
- This value does not change discreetly with temperature- we do thermal prorating by moving around SoC_{min} and SoC_{max}. See Thermal Prorating.

A Note on Units

SoC is unitless. Joules, coulombs, and even percent are very useful units for making decisions (eg, do I have enough left to run until morning?). However, the percent capacity (or the number of coulombs, or joules) you can get out of a battery depends on the conditions of the discharge. What kind of load? What temperature? This unitless number, along with simulation, can be used to answer specific questions (eg, “How long until my battery dies if I continue discharging at the same power and temperature?”).

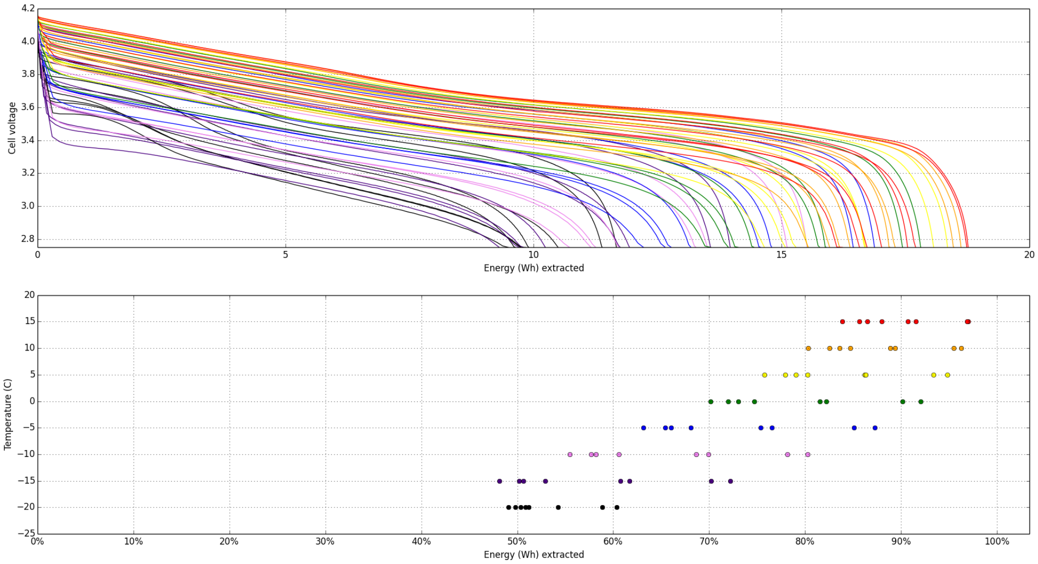
We often use $SoC_{percent}$ and $SoC_{coulombs}$. $SoC_{percent}$ is corrected for temperature, and goes from 0% when the pack is empty to 100% when the pack is full. $SoC_{coulombs}$ is basically the same, going from 0 when empty to the thermally-prorated pack capacity when full.

Cell Characterization

Cell data is available from manufacturers and earlier pack designs, but that data is insufficient. We want to characterize:

- Capacity
- Cell to cell variation
- Voltage dependence on load, temperature, and SoC

In order to fit the voltage model we do offline training. We discharge a suite of cells at constant current in a thermal chamber at a set of different temperatures and loads.



Example set of discharge curves for our Gen-2 cells.

Our SoC algorithm works better near one temperature and current. We picked “hotel load” as our training current- that’s the current required to run only critical electronics- because that is our typical nighttime load. We picked our nighttime operating temperature as the training temperature. For the test, we considered 6 currents and 5 temperatures around training conditions, and discharged 4 cells for each choice of current and temperature.

How Do We Track SoC?

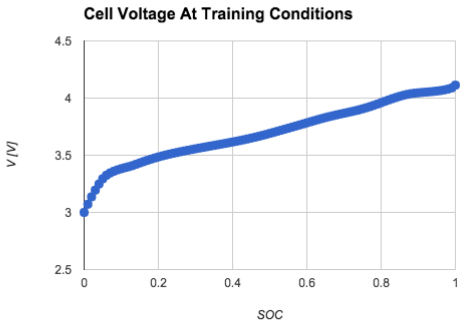
We track SoC by counting coulombs, and correct for bias with voltage measurements. We fuse the two methods in a Kalman filter. Then, we do thermal prorating by moving around the discharge floor and charge ceiling.

Dead Reckoning / Coulomb Counting

Batteries are mostly charge efficient (in ≅ out). On the time scale of hours, we can figure out how much charge is left in the battery by adding how many coulombs go in, and subtracting how many coulombs come out. This is supported by hardware, to be very precise.

“Stateless” Voltage Based Model

To zeroth order, battery terminal voltage is a function of that battery’s SoC: $V_{terminal} \approx V_{train}(z)$ where z is SoC and $V_{terminal}$ is the battery’s terminal voltage (which we can measure).



Cell voltage at training conditions (constant current discharge, i=100mA and T=10C).

The zeroth order approximation might be sufficient for 10% accuracy, but we seek to be more accurate than that. We correct current and temperature differences by taking the Taylor series expansion of terminal voltage to first order, centered around “training” discharge conditions, for each SoC:

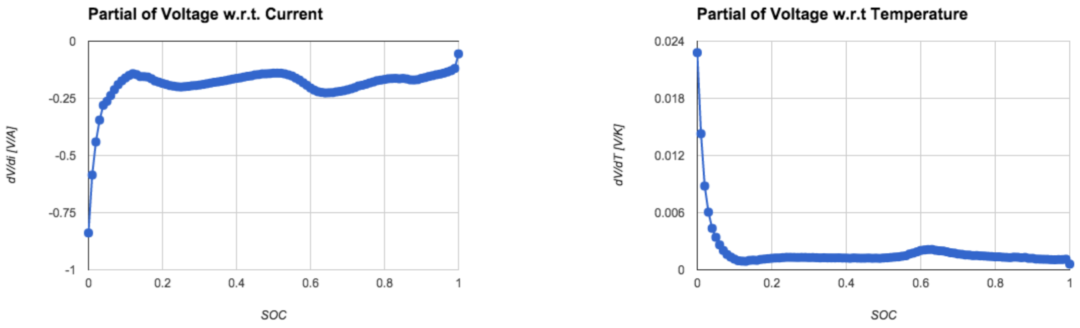
$$V(z,\ i,\ T)\ \approx V_{train}(z)\ +\ \frac{\partial V}{\partial i}\Big|_{training}(z)\ *\ \Delta i\ +\ \frac{\partial V}{\partial T}\Big|_{training}(z)\ *\ \Delta T\ +\ O(\Delta^2),$$

where

$$\Delta i\ =\ i\ -\ i_0,\ \Delta T\ =\ T\ -\ T_0,$$

$\frac{\partial V}{\partial i}\Big|_{training}(z)$ = Partial of steady state voltage wrt current, at training conditions [V/A=Ω], and

$\frac{\partial V}{\partial T}\Big|_{training}(z)$ = Partial of steady state voltage wrt temperature, at training conditions [V/K].



Cell voltage correction terms for current and temperature.

Voltage also depends on other variables:

- Time
    - Time effects are near zero mean (our pack appears to have some capacitance, for example), and fast (tens of minutes). These are absorbed by our Kalman

filter.

- Cell-to-cell variations
  - Negligible. System SoC is the average of hundreds of cells with relatively tight tolerances (probably within 5% individually, less than 1% taken in aggregate).
- State of health (degradation due to use)
  - Neglected. Current flights are short, but for longer flights SoH can degrade capacity by about 10%, and we'll need to add this to our model.

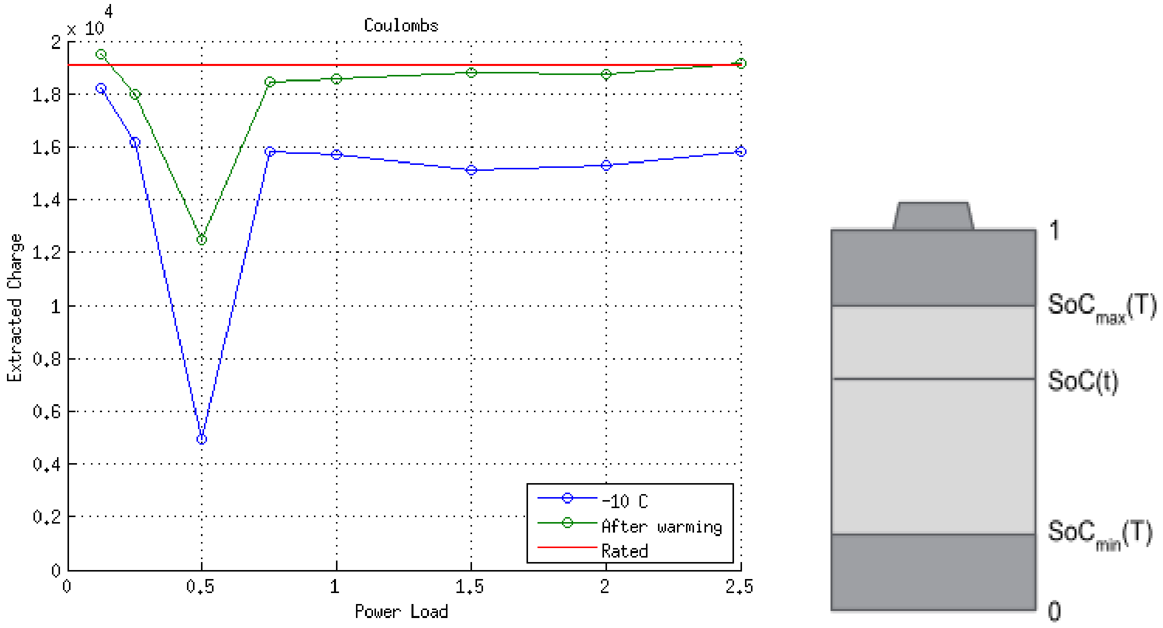
Kalman Filter

We chose the parameters of our filter to meet a few requirements:

- Converge quickly when it starts.
  - By initializing the SoC variance with a huge number, the packs effectively enter a learning cycle when first booted.
- Trust coulomb counting in the time frame that it's accurate (on the order of hours).
- We want to trust the voltage measurement more when we're near training conditions.
  - As we get further from training, our linearized model starts breaking down.
  - Variance of the voltage based SoC guess is chosen to be quadratic in both Δi and ΔT, capturing the error in our linearization of voltage.

Thermal Prorating

There are two intuitive models for how extractable charge is a function of temperature: decreased efficiency in the cold, or some "frozen" capacity. To choose between them, we tested "If we discharge the batteries cold, and then heat them up, can we get the rest of the charge out?".



Extracted Charge

Note that the 0.5A test is anomalous, and should be ignored.

Left: After warming we were able to extract close to 100% of the nominal cell capacity.

Right: This model can be thought of as an inaccessible or frozen reserve of charge.

Implementation

We have implementations of this algorithm in both firmware and in Fleet Management System.

In Firmware

We store all model parameters (nominal capacity, training conditions, filter parameters, etc) as well as lookup tables for $V_{train}(z)$, $\frac{\partial V}{\partial i}|_{training}(z)$, and $\frac{\partial V}{\partial T}|_{training}(z)$ in the Hydra firmware. Each pack averages the cell SoC and reports the data to PFC. PFC averages the pack SoC into flight SoC. Both pack SoC and flight SoC are sent back to MC.

Note that this average is weighted by capacity. However, the current model doesn't include cell-by-cell capacity differences, so all cell capacities are equal and all pack capacities are equal.

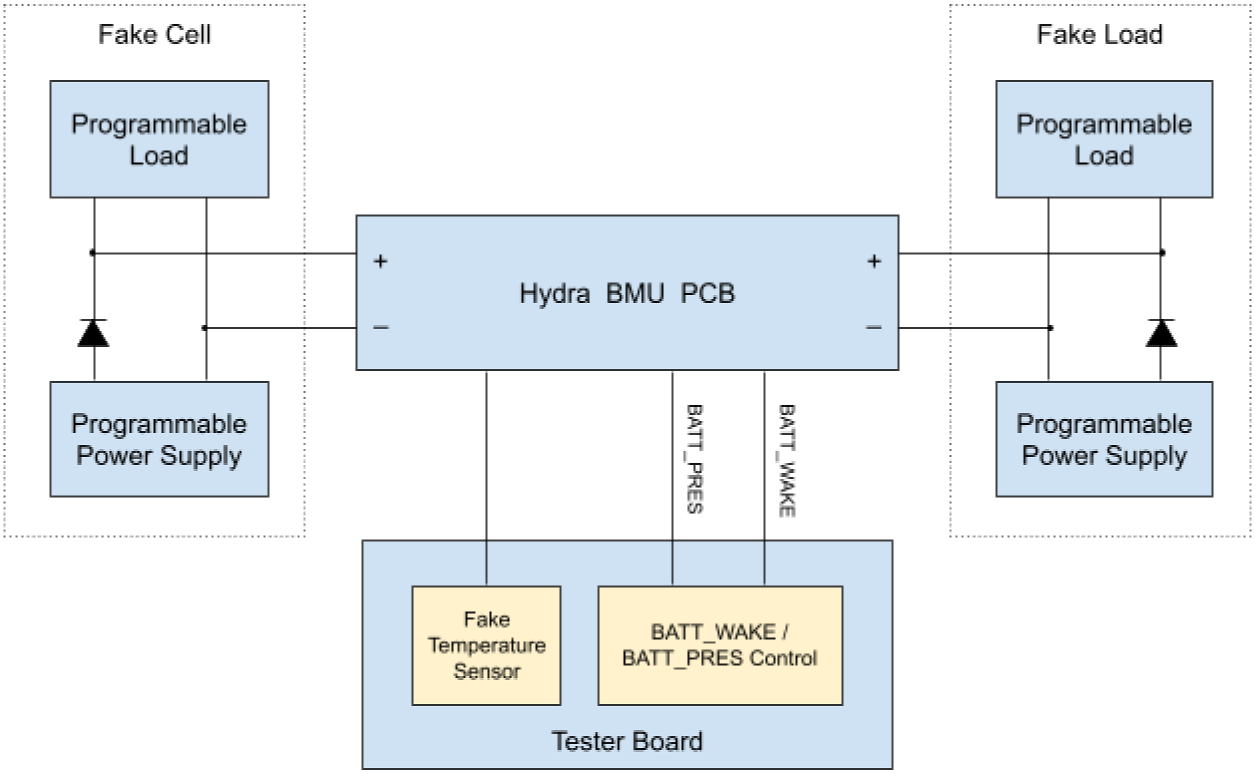
In Fleet Management System

For redundancy, for algorithm development, and for historical analysis these algorithms are reproduced in MC's estimation service. Note that avionics makes measurements every ~250 ms, but telemetry with current, voltage, and temperature only comes back every ~20 minutes. Some care was taken to ensure that this approach is still accurate. For example, this filter derives current from a charge integrator in avionics telemetry.

Testing

Testing occurs at various stages between when a battery is manufactured and when it is ready to fly. The following sections describe our testing process.

PCB Manufacturing Tests



When a BMU board is built, we run tests on it in a test fixture. The test fixture includes:

- A set of programmable load and programmable power supply to simulate the battery cells.
- A set of programmable load and programmable power supply to simulate the load. The load may be consuming power (discharging the battery) or providing power (charging the battery.)
- A tester board to exercise various BMU functions. Most notably, the tester board includes a fake temperature sensor to exercise the undertemperature and overtemperature protection. It also has control of BATT_WAKE and BATT_PRES signal to verify the functionality of battery on/off control.

With this test fixture, we can run the following tests in a fully automatic manner:

- Voltage measurement accuracy test
- Current measurement accuracy test
- Charging overcurrent protection test
- Discharging overcurrent protection test
- Short circuit protect test
- Undervoltage protection test
- Overvoltage protection test
- Load detach test: checks battery powers off when detached from the payload
- Power off test: checks battery can be powered off and back on with the switch

- Undertemperature protection test
- Overtemperature protection test

Battery Assembly Test

Tested BMU boards are sent to battery pack CM and assembled with the cells, among other things, into a battery pack. The battery packs are first put into a battery cycler to perform full charge/discharge cycles. During the process, the battery cycler monitors the voltage and current and fails if the reading is abnormal.

Once the battery passes the cycling test, it is tested with a test kit we provided to:

- Program the serial number in the non-volatile memory
- Verify battery on/off switch
- Check for cell imbalance

Preflight Test

After batteries are put into a payload, they are tested inside the payload before the payload flies. The tests include:

- Voltage check: checks battery are charged to expected level
- Temperature sensor tests
- Battery error check: checks no battery fault is reported
- Heater test
- Power path test

Software Test

In addition to tests that verify the hardware, software regression tests are automatically run on every submitted CL in the test trays to ensure Hydra firmware functionality and quality.