BAT-6

Integrated 2 to 6 cell Li-Ion Battery System

For Micro- and Nano-Satellites

Features

- 2, 3, 4, 5, or 6 Li-Ion 18650 cells
- Automatic Cell balancing
- Short-circuit protection
- Over- and under-voltage protection
- Always-on ultra-low-power Real Time Clock
- Microcontroller for housekeeping and control
- CAN bus with CSP protocol
- Heater with automatic control
- High-reliability Micro-D connectors
- 2 Battery Bus connectors
- 2 inhibit connectors for either insert-before-flight or separation switches:
    - High-side and low-side raw battery
    - High-side and low-side MOSFET with external control lines
- Reliability
    - Radiation total dose tested EEE parts
    - Vibration rated for all launch vehicles
    - Redundant inhibit MOSFETs
- High-quality Enclosure
    - Min. 1.5 mm Al Shielding in all directions
    - PC-104 compatible mounting holes

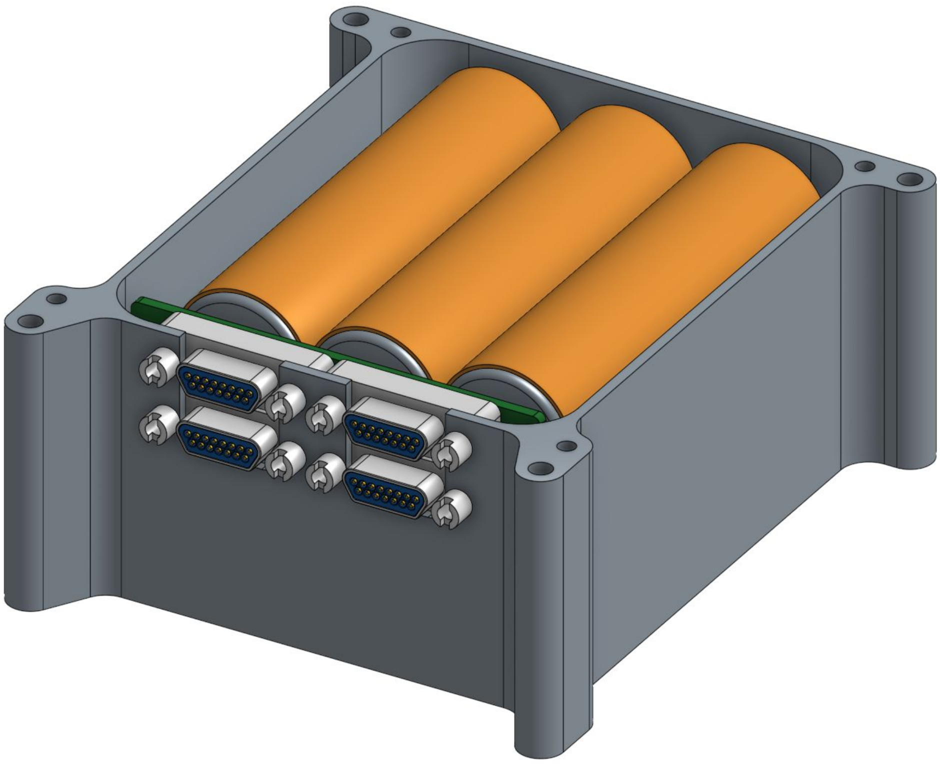
Description

The BAT-6 is a 2 to 6 cell Lithium-Ion battery system designed for battery life-time, easy integration, and safety. With a total of 8 different battery configurations and up to 59 Wh capacity, the BAT-6 is both flexible enough and sufficiently powerful for most nano- and small-satellite missions.

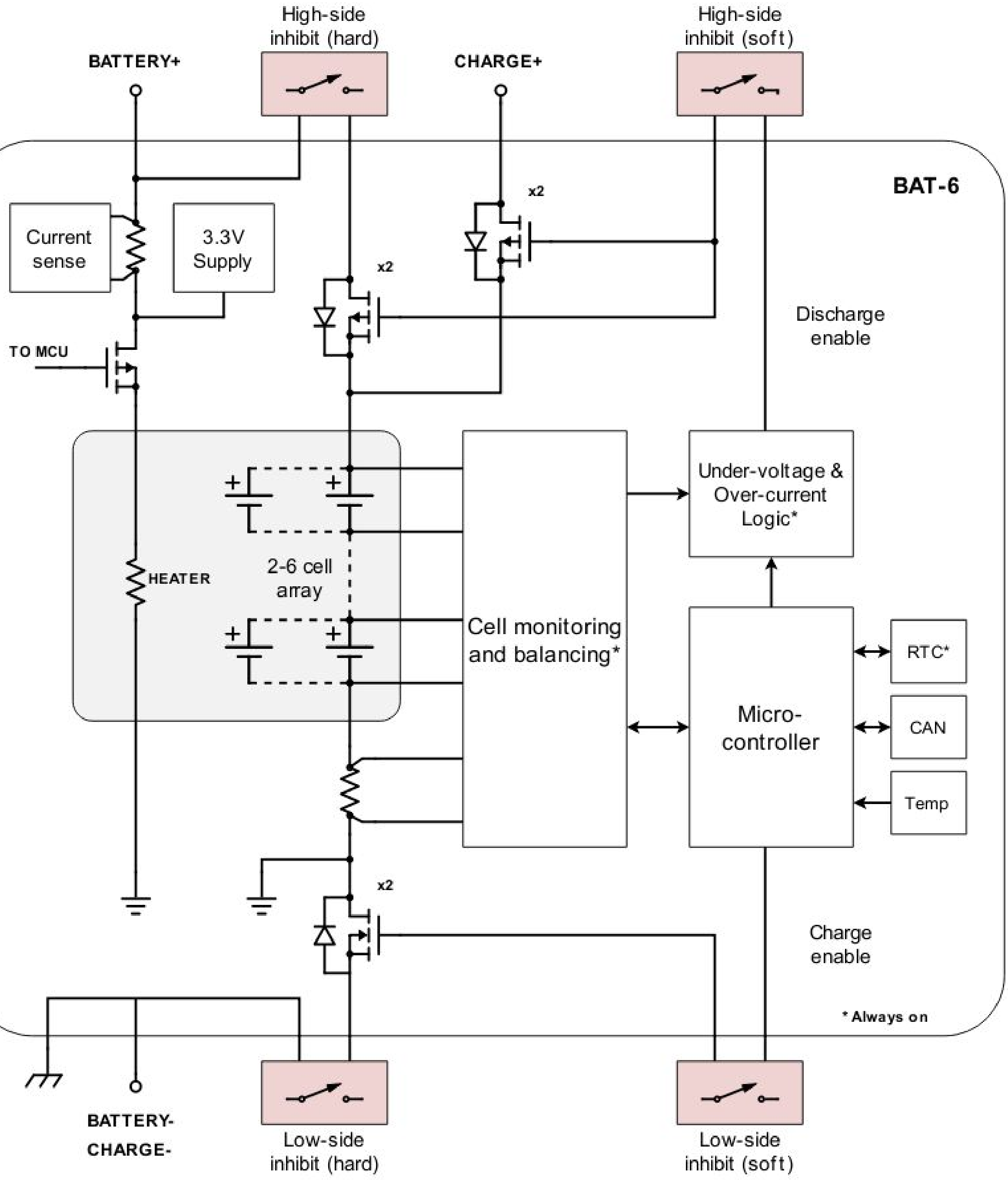
The automatic balancing circuit maximizes battery lifetime, and the automatic heater ensures optimal operational battery environment at all times. Short-circuit and over/under voltage detection circuits protects the batteries from damage. To accommodate different launch vehicle requirements, each module has connectors for both soft and hard inhibits.

The BAT-6 comes in a rugged and modular 1.5 mm Al enclosure, which both acts as on-orbit radiation mitigation as well as a practical short-circuit protection during satellite assembly.

An always-on ultra-low-power Real Time Clock provides timer-continuity during satellite shutdown.



Functional Description



Functional Block Diagram

Inhibit Circuit

The BAT-6 has two types of inhibits allowing compliance to all launch providers, including ISS launches. All inhibits can be used as either insert-before-flight or be routed through separation switches.

Inhibit low/high: These lines are connected in series with the cells and require the battery current to flow through the lines, so therefore the outgoing lines must be shorted to the return lines in order to make the circuit. There is a high-side and low-side inhibit and both must be closed for the battery to be enabled.

Inhibit low/high (MOSFET): These switches is connected in series with the discharge and charge MOSFET gate-signals, thereby preventing these MOSFETs from switching on when the inhibits are not closed. This type of inhibit does not carry battery current but only a very weak signal. There is a high-side MOSFET preventing discharging, and a low-side MOSFET preventing charging. Both inhibits must be closed for the battery to be enabled.

If any of these inhibits would fail open during operation, the battery will be disabled. Therefore, each inhibit is routed to 3 outgoing pins and 3 returning pins in parallel in order to mitigate this risk.

All four inhibits must be closed for the battery to be on. If some switches are not in use, a simple insert before flight connector can be added to permanently close the unused switch inputs.

Overcurrent and short circuit Protection

The total battery discharge current is monitored by a comparator which can quickly react to a short circuit and protect the cells and the circuits.

Undervoltage Protection

The cell voltage is monitored by a comparator that will disable battery discharging in under-voltage conditions. When in undervoltage, the microprocessor is also switched off in order to preserve as much power as possible. This means that the heater will also be disabled.

The battery undervoltage should only be used as a second line of defence as it can be harmful to the lifetime of the cells. Especially if the cells are both undervoltage and under temperature.

The recommended method to avoid an undervoltage condition is to gracefully shutdown subsystems as the battery voltage gradually lowers. This is typically performed in the power distribution unit.

Cell configuration

The BAT-6 supports up to 6 cells in series.

Option	Nominal	Max V	Capacity
2 cells (2s1p)	7.4 V	8.4 V	2600 mAh
3 cells (3s1p)	11.1 V	12.6 V	2600 mAh
4 cells (4s1p)	14.8 V	16.8 V	2600 mAh
4 cells (2s2p)	7.4 V	8.4 V	5200 mAh
5 cells (5s1p)	18.5 V	21 V	2600 mAh
6 cells (6s1p)	22.2 V	25.2 V	2600 mAh
6 cells (3s2p)	11.1 V	12.6 V	5200 mAh
6 cells (2s3p)	7.4 V	8.4 V	7800 mAh

Table 1: Battery voltage and configuration options

Overvoltage Protection

The overvoltage protection is built into the microprocessor. Please see the section below in the parameter description.

Real-Time Clock

The RTC is powered by the 3.3 V supply for the microprocessor in nominal mode. When the battery is switched off, the RTC is in ultra-low-power mode supplied directly from the battery through a 1 MOhm resistor. The quiescent power in this mode is 2 uA max. Thereby proving a long shelf-life while still maintaining the RTC clock.

Automatic Heater

The batteries perform best over 10 degrees Celsius. It can therefore be necessary to heat the cells in some circumstances. The microprocessor will monitor the temperature and switch the heater on when needed. The desired temperature can be controlled by a software parameter.

CAN Termination

The board features optional 120 Ohm CAN termination mounted to the customers specification.

Specification

Parameter	2s1p	2s2p	2s3p	3s1p	3s2p	4s1p	5s1p	6s1p	Unit
	Configuration								
System Ratings									
Nominal Voltage	7.2	7.2	7.2	10.8	10.8	14.4	18	21.6	V
Nominal Capacity	2.6	5.2	7.8	2.6	5.2	2.6	2.6	2.6	Ah
Nominal Energy	19	37	56	28	56	37	47	56	Wh
Maximum Instantaneous Power	18	36	54	27	54	36	45	54	W
Power Consumption									
Quiescent Current									
- Storage, Under-Voltage, Over-Current									
- - Typical[1]	59	59	59	63	63	67	70	74	µA
- - Maximum[2]	69	69	69	74	74	78	82	89	µA
- Nominal and Over-Voltage	4.2	4.2	4.2	2.8	2.8	2.1	1.7	1.4	mA
Efficiency[3]									
- Nominal	99.0	97.9	96.9	99.3	98.6	99.5	99.6	99.7	%
- Over-Voltage Mode	89.4	88.5	87.7	92.5	92.4	94.0	95.5	96.5	%
- Under-Voltage Mode	88.7	88.5	88.4	92.2	92.4	94.0	95.3	96.2	%
Shelftime[4]	743	743	743	694	694	652	617	585	Days
Inhibit MOSFET Switches[5]									
High-Side									
- On-State Resistance	25								mΩ
- Off-State Leakage	2								µA
Low-Side									
- On-State Resistance	5								mΩ
- Off-State Leakage	2								µA

[1] At nominal battery voltage and nominal system idle power consumption
[2] At maximum battery voltage and maximum system idle power consumption
[3] At maximum instantaneous power. The reduced efficiency in over- and under-voltage mode is because the battery is discharged and charged through the low and high-side MOSFET body diodes, respectively.
[4] Shelftime is defined as the typical time it takes to reduce the battery charge by 1000 mA due to quiescent current. Maximum 25 degree Celsius storage temperature is assumed. Reduction in storage capacity due to battery ageing is not accounted for.
[5] BOL and assuming redundant MOSFETs.

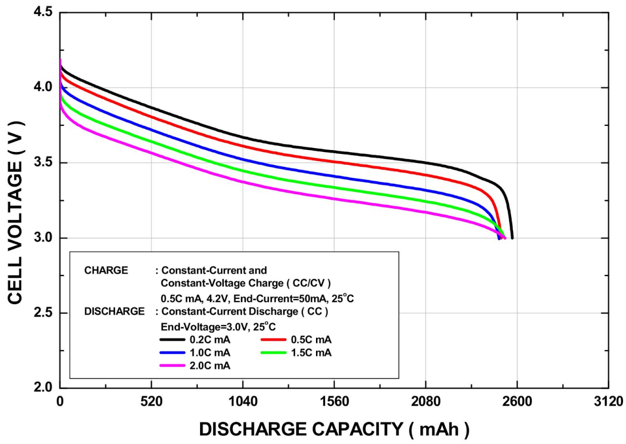
Parameter	Configuration								Unit
	2s1p	2s2p	2s3p	3s1p	3s2p	4s1p	5s1p	6s1p	
Battery Protection									
Under-Voltage Level	6.3	6.3	6.3	9.45	9.45	12.6	16.15	18.9	V
Under-Voltage Hysteresis	0.12	0.12	0.12	0.23	0.23	0.33	0.43	0.53	V
Over-Voltage Level	8.4	8.4	8.4	12.6	12.6	16.8	21	25.2	V
Over-Voltage Hysteresis	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.5	V
Over-Current Threshold	2.5	5	7.5	2.5	5	2.5	2.5	2.5	A
Over-Current Trip-Off Time									
- Typical	6.7								ms
- Maximum	7.4								ms
Over-Current Retrigger Interval									
- Typical	2.2								s
- Maximum	8.9								s

Battery Characteristics

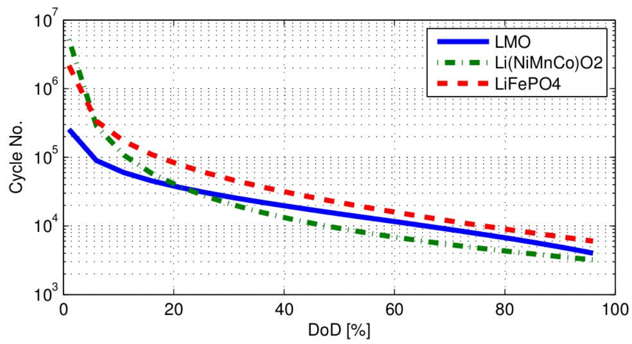
The BAT-6 uses up to six LG ICR18650B4 cells. These cells have proven to be very reliable in several space missions. The lifetime of the cells depends on the temperature, the charge and discharge rate and the total discharge depth. At full discharge depth, the cell remains at 90% capacity after 300 cycles at 40 degrees C. The cells will lose about 20-40% of its capacity when operating under 0 degrees C and discharge is not allowed. It is generally recommended to keep the cells above 10 degrees C.

Parameter	Condition	Specification
Capacity	Nominal	2600 mAh
Nominal voltage	Average	3.6 V
Max charge voltage		4.2 V
Max charge current		1 C
Max discharge current	-20 - +5 deg. C.	0.5 C
	5 - 45 deg. C.	2 C
	45 - 60 deg. C.	1.5 C
Operating temperature	Charge	0 - 45 deg. C
	Discharge	-20 - 60 deg. C
Storage temperature	1 month	-20 - 60 deg. C
	3 month	-20 - 40 deg. C
	1 year	-20 - 20 deg. C

Battery characteristics



Cell voltage as a function of battery capacity.



Battery lifetime as a function of depth of discharge (LG ICR18650B4 is equivalent to the green curve).

Battery lifetime considerations

Analysis of Li-Ion cells have shown how various parameters affected the battery lifetime.

There are three ways the lifetime can be improved for the BAT-6 system. (For further details see Xu et al.[6])

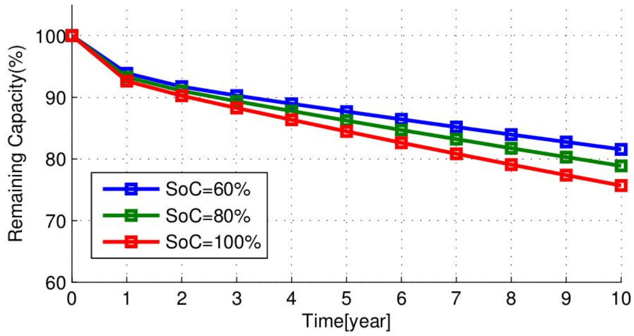
1: Temperature control: Keeping the cells below 35 degrees will keep the capacity above 80% after 5 years. In general the cooler the better. However the cells may not be charged at under 0 degrees C.

2: Reduce End of charge: Reducing the end of charge voltage from 100% SoC to 75% can greatly improve the amount of cycles before reaching end of life at around 80% capacity retention. This setting can be controlled in the battery charger by setting the `mppt_protect` parameter to a lower overall battery voltage.

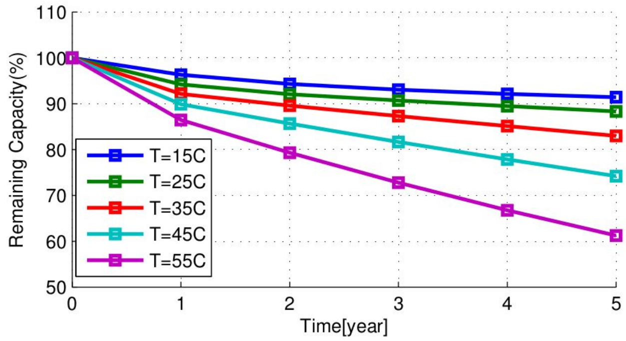
3: Reduce Depth of Discharge: Limiting the DoD to around 20% will increase the lifetime to around 50.000 cycles compared to a 75% DoD which gives only 4000 cycles. The DoD can be controlled with a Space Inventor PCDU-12 by gradually powering off subsystems, for example by entering lower power modes using the `dfl_vprotect` parameter.

Battery Storage

The optimal storage condition is at ~10 degrees C at 50% SoC.



Remaining storage capacity at different SoC levels at 25 degrees C.



Remaining storage capacity at different temperatures at 50% SoC

[6] Xu, Bolun & Oudalov, Alexandre & Ulbig, Andreas & Andersson, Göran & Kirschen, D.s. (2016). Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment. IEEE Transactions on Smart Grid. 99. 1-1. 10.1109/TSG.2016.2578950.

Parameters

The persistent configuration variables [conf_*] are stored in the external FRAM chip. The telemetry is updated each second.

Name	Type	Default	Unit	Description
Persistent configuration variables				
`conf_heater_auto`	uint8	1	true/false	Automatic heater control
`conf_heater_auto_on_at`	int8	10	degrees c	Automatic turn on at
`conf_heater_auto_off_at`	int8	15	degrees c	Automatic turn off at
`conf_ov_on_at`	uint16	8100	mV	Overvoltage on at (this will disable charging)
`conf_ov_off_at`	uint16	8000	mV	Overvoltage off at
`conf_balance_auto`	uint8	1	true/false	Automatic cell balancing
`conf_balance_thr`	uint16	50	mV	Automatic cell balancing threshold
State variables (on/off)				
`heater_on`	uint8	0	true/false	Current heater state, set to 1 to force turn on
`overvoltage_on`	uint8	0	true/false	Current overvoltage state, set to 1 to force turn on
`balance_cell`	uint8	0	1-6 or 0	Current cell balancing, 0 = off, 1-6 = on, set to force
Telemetry				
`tlm_temp`	int16	read only	degrees c	Temperature
`tlm_vcell`	uint16[6]	read only	mV	Individual cell voltages (up to 6)
`tlm_vpack`	uint16	read only	mV	Pack voltage
`tlm_ipack`	int16	read only	mA	Pack current (negative = charging, positive = discharging)
`tlm_isys`	uint16	read only	mA	Battery system own usage (including heater)
Trigger				
`powercycle`	uint8	0	magic	Set to magic value 123, to powercycle battery

List of parameters

Heater

The microcontroller continuously monitors the battery temperature and will enable its built-in heaters when the temperature reaches the value set in the `conf_heater_auto_on_at` parameter. The heater will turn off again when the temperature reaches the value set in the `conf_heater_auto_off_at` parameter. The automatic heater can be turned off by setting `conf_heater_auto` to zero.

The `heater_on` state variable shows the current state of the heater at any time. Setting this variable manually will switch the heater on or off.

Overvoltage

The microcontroller will disable battery charging when the voltage exceeds the value set in `conf_ov_on_at` and re-enable charging at `conf_ov_off_at`.

This is a second line of defence only which should not be used to limit the battery voltage because it will hard-disconnect the chargers. Running the battery in hard overvoltage protection for an extended amount of time will buildup extra heat in the protection switches and is therefore not recommended.

The recommended way of limiting the battery voltage is to switch off the battery chargers using their built-in overvoltage protection.

Cell Balancing

In order to prevent cell imbalance, the microprocessor monitors the individual cell voltage. If the difference between the highest and the lowest cell voltage is greater than 50 mV (default), a bleed-resistor is put in parallel to the battery with the highest voltage. The bleed current is 50 mA.

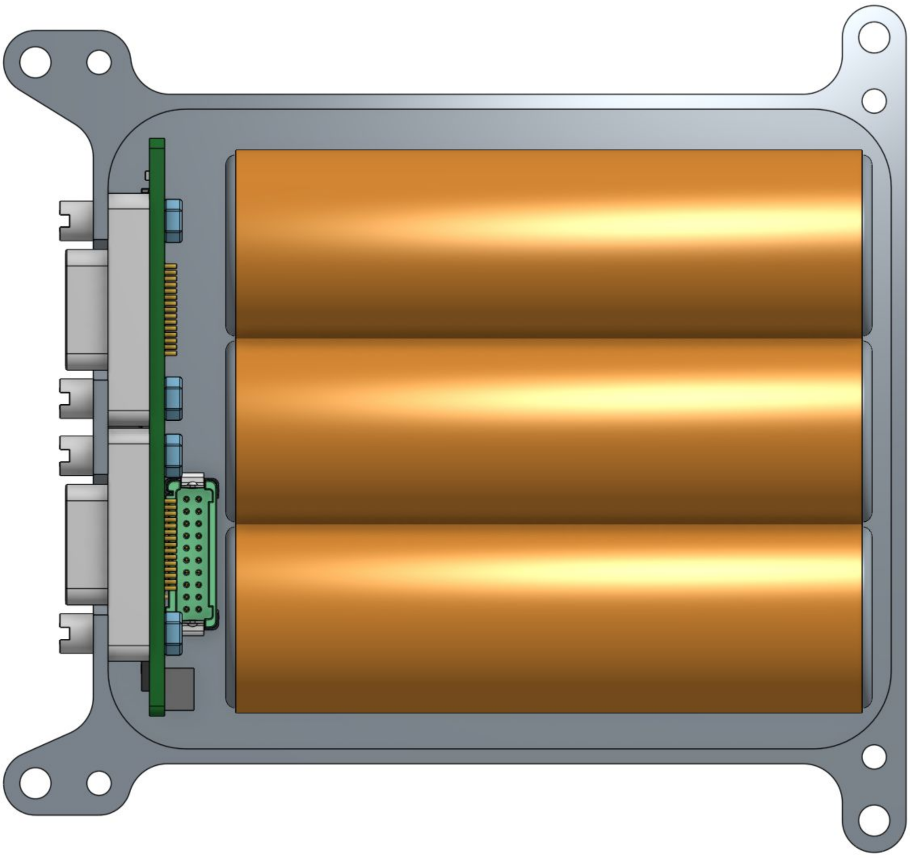
Individual cell voltages can be retrieved in the `tlm_vcell[6]` parameter. Automatic cell balancing can be disabled by setting `conf_blance_auto` to zero, and the threshold can be changed by setting `conf_balance_thr`.

The `balance_cell` state variable shows the current state of the balancer at any time. Setting this variable manually will force the balancer on at the given cell number (numbered 1-6). A setting to zero turns bleeding off.

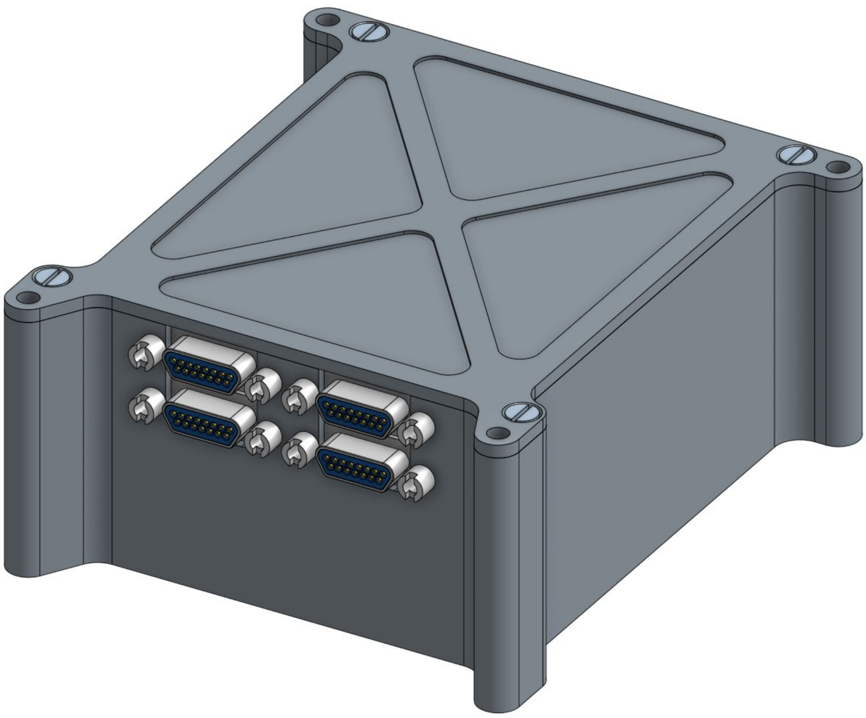
Power Cycle

In order to powercycle the battery output the variable `powercycle` should be set to 123. This will trigger the overcurrent protection and turn off the microcontroller and all battery discharging. When the microcontroller is powered off this will clear the powercycle condition, and the system will power up again.

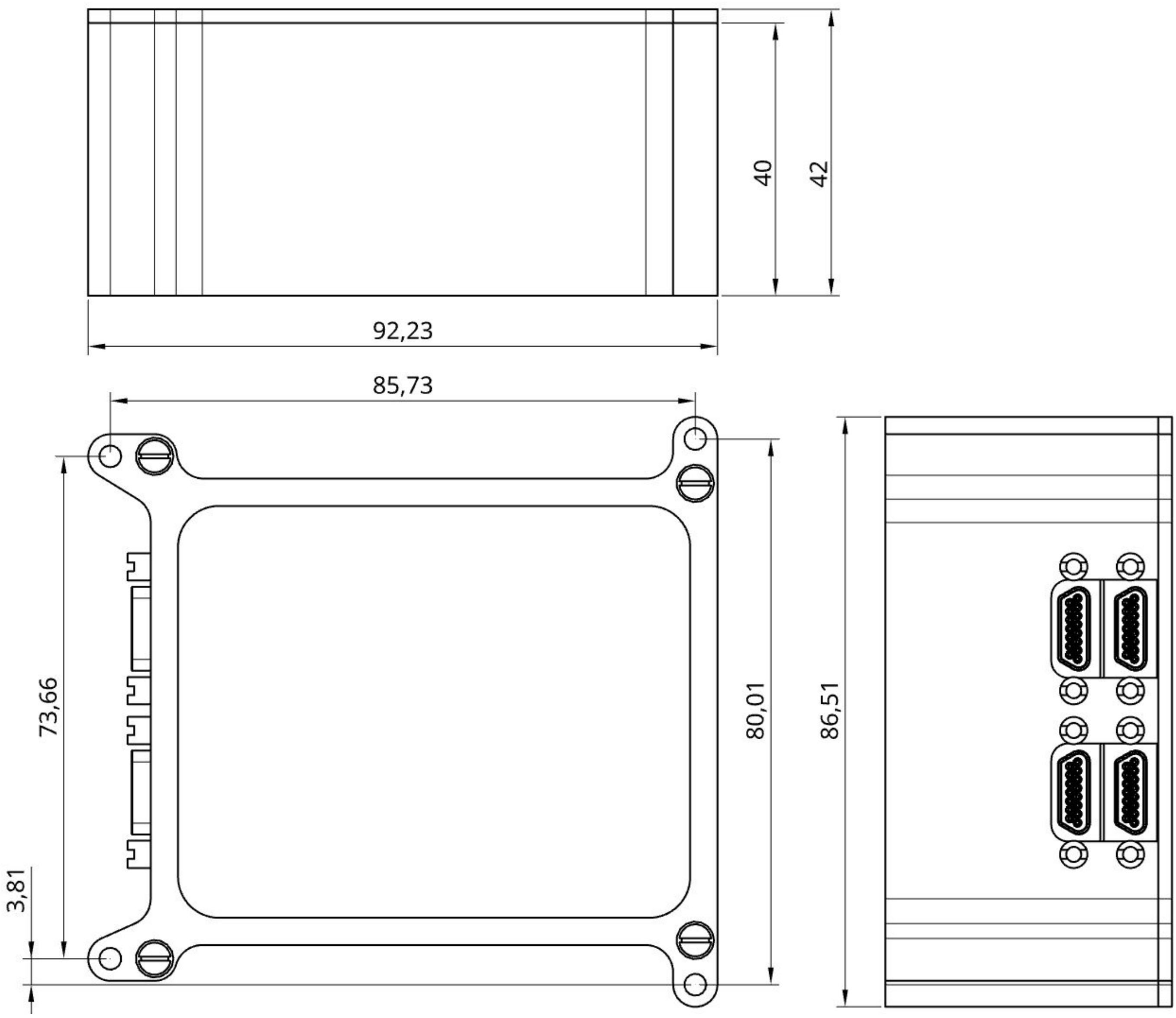
Mechanical Drawings



Top view



Isometric Rendering with 2mm Lid



Dimension Drawing

Pin-out

P1 to P4 are 15-pin Male Micro-D

Battery Bus Connectors

PIN	Function
1	CAN High
2	CAN Low
3	Do not connect
4	Do not connect
5-8	Battery
9	Do not connect
10-15	GND

Header P1

PIN	Function
1	CAN High
2	CAN Low
3	Do not connect
4	Do not connect
5-8	Battery
9	Do not connect
10-15	GND

Header P2

Inhibit Connectors

PIN	Function
1	Low side return
2	Low side return
3	Low side return
4	
5	
6	High side return
7	High side return
8	High side return
9	Low side out
10	Low side out
11	Low side out
12	
13	High side out
14	High side out
15	High side out

Header P3 - Raw battery

PIN	Function
1	Low side return
2	Low side return
3	Low side return
4	
5	
6	High side return
7	High side return
8	High side return
9	Low side out
10	Low side out
11	Low side out
12	
13	High side out
14	High side out
15	High side out

Header P4 - MOSFET signals