Development of a Coupled Electro-thermo Battery Emulator for Ground Test Platforms

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Thermal Runaway

- Thermal runaway is a self feeding process that can lead to combustion of the batteries.
- Better cooling methods and testing at the extremes will help mitigate this risk.
- A battery emulator is proposed to be a helpful tool for developing better cooling methods at the extremes of battery use.

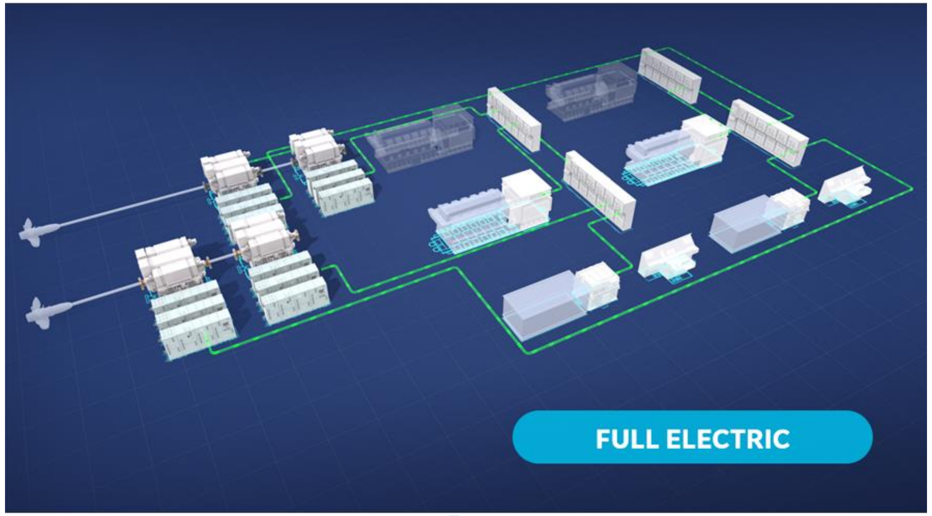
Tesla car in Oslo 2016 [1]

Tesla Megapack in Australia 2021 [2]

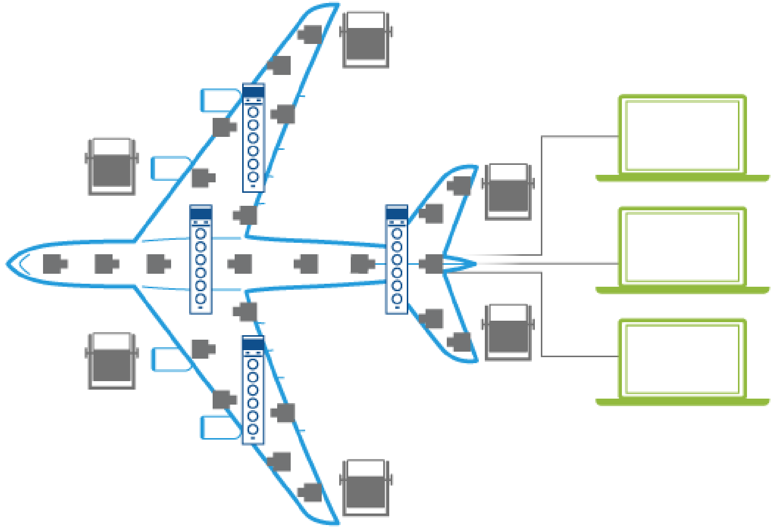
[1] Mauger, Alain & Julien, Christian. (2017). Critical review on lithium-ion batteries: are they safe? Sustainable?. Ionics. 23. 10.1007/s11581-017-2177-8.
[2] Ben. “Why Thermal Runaway Is the Real Killer in Battery Fires.” *Zenaji*, 31 Jan. 2022, https://zenaji.com/why-thermal-runaway-is-the-real-killer-in-battery-fires/.

Emulator Applications

- Will be able to work on any system that a physical battery can attach too.
- Being developed to work with digital twin test bed for naval propulsion at University of South Carolina.
- Looking to be used in ground testing/ digital twins of electric aircrafts.



[3]



[4]

[3]“Solutions - Naval Electric Power & Propulsion.” *GE Power Conversion*, https://www.gepowerconversion.com/product-solutions/Naval-Electric-Power-Propulsion.
[4] “Knowledge.” *Ground Vibration Testing - Vibration Simulation* | *Brüel & Kjær*, https://www.bksv.com/en/knowledge/applications/structural-dynamics/ground-vibration-test.

Battery Emulator

- Goal:
  - Enable safe exploration of distributed energy resources under extreme (equipment threatening) conditions
  - Emulate characteristics of large battery at all system connections -- electrical terminals and fluid ports -- based on actual behavior of a single cell of the type used in the battery
  - Investigate thermal and electrical coupling effects at system level
- Real-time Operations:
  - The single cell experiences V, I, and thermal stresses scaled-down from the system interface. The system experiences V, I and thermal stresses scaled up from the single cell response.
  - Real-time interface between cell and system includes a fully-sensorized and actuated digital twin of the battery, based on Simulink models, that runs on NI edge computing device.

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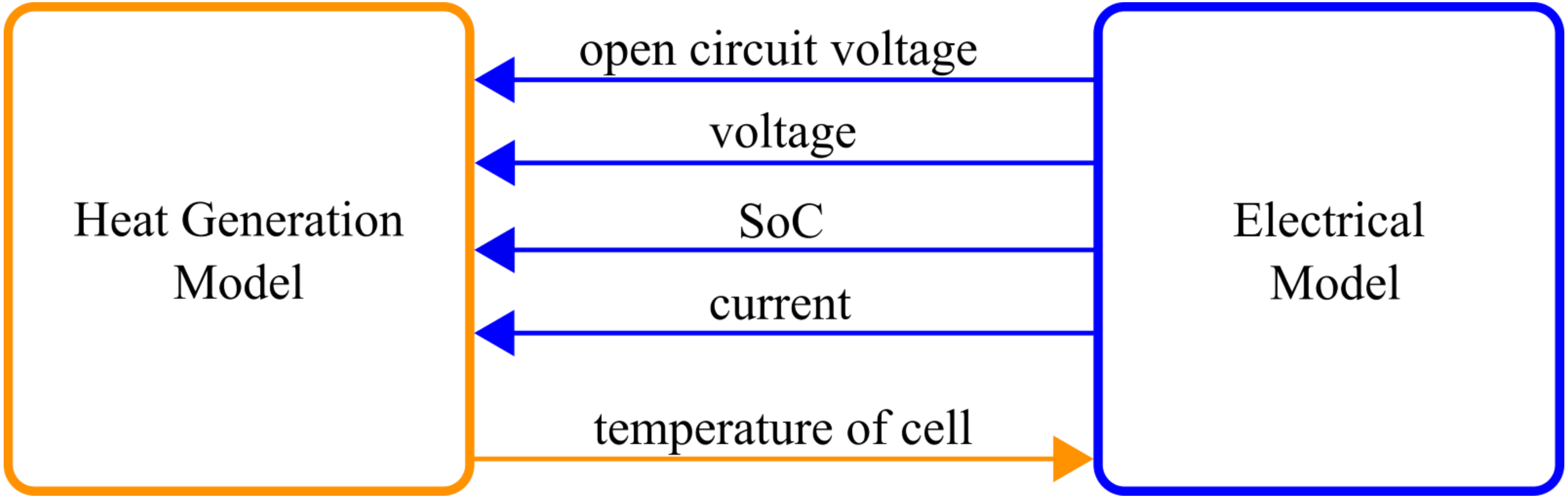
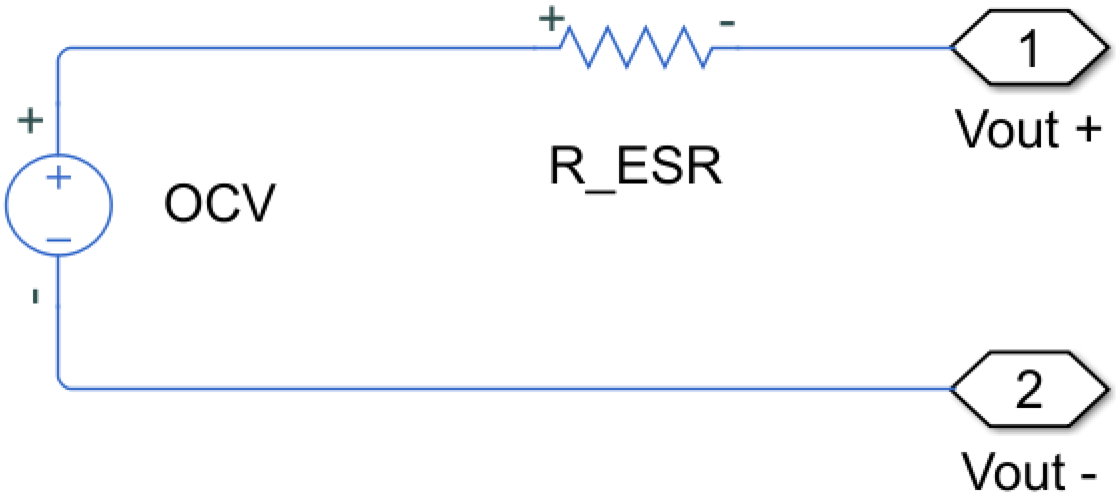
Battery Model

- A coupled electro-thermal model
- Parameters are dependent on each other



Coupled Electrical Model

- Equivalent electrical circuit:
  - Simple equivalent circuit used initially
  - Later can add more dynamics by replacing ESR with RC circuit



- Governing equation:
  - $V_{\mathrm{out}}(t) = OCV(SoC, T) - i(t_0)R_{\mathrm{ESR}}(SoC, T)$
  - Open Circuit Voltage (OCV) and Equivalent Series Resistance (ESR) values are organized into lookup tables

Coupled Thermal Model

- An isothermal reduced order heat generation model.

Original Eq [1]:

$$\dot{Q} = I\left(U_{\mathrm{avg}} - V\right) - IT\frac{\partial U_{\mathrm{avg}}}{\partial T} + \sum_{l} \Delta H_{l}^{\mathrm{avg}} r_{l} + \int \sum_{j} \sum_{i} \left(\overline{H_{ji}} - \overline{H_{ij}^{\mathrm{avg}}}\right)\left(\frac{\partial c_{ij}}{\partial t}\right) dv$$

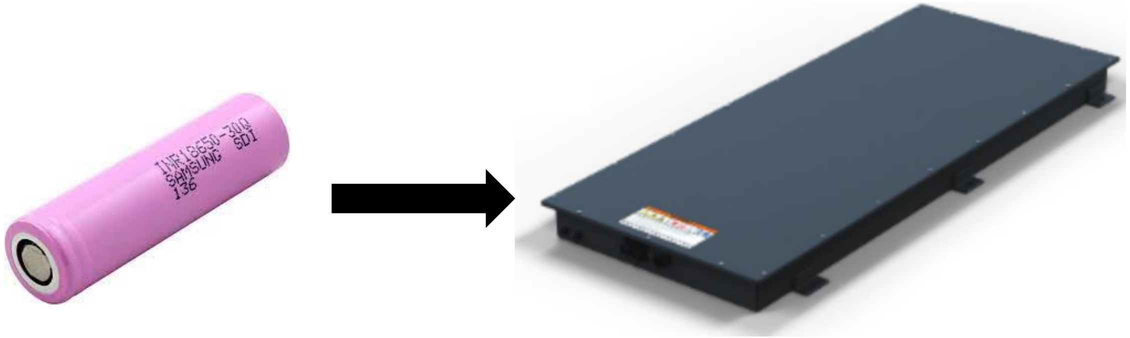
Implemented Eq (added natural convection and liquid cooling):

$$\dot{Q} = I\left(U_{\mathrm{avg}} - V\right) - IT\frac{\partial U_{\mathrm{avg}}}{\partial T} - Ah\left(T_{\mathrm{cell}} - T_{\mathrm{amb}}\right) + \dot{m}_{\mathrm{liquid}} c_{\mathrm{liquid}}\left(T_{\mathrm{in,\,liquid}} - T_{\mathrm{out,\,liquid}}\right)$$

- Equation Assumes uniform current density, uniform heat generation and no mass transport limitations
- Works well with low charge/discharge rates
  - At low rates side reactions and mixing is negligible

[5] Y. Zeng, D. Chalise, S. D. Lubner, S. Kaur and R. S. Prasher, "A review of thermal physics and management inside lithium-ion batteries for high energy density and fast charging," *Energy Storage Materials,* vol. 41, pp. 264-288, 2021

Scalability



- Can scale up single cell to represent the larger battery packs such as a Lithos battery pack:
  - 350V 36Ah, up to 10C discharge (360 Amps)

- Battery model is electrically and thermally scalable
  - Electrically:
    - OCV obtained by multiplied by number of cells in series
    - Capacity/current obtained by multiplying by number of cells in parallel
    - Terminal resistance by equivalent resistance of the parallel and series arrangement
  - Thermally:
    - Thermal mass of all cells and case sum together
    - Convective surface area scaled to surface area of the fluid interface

- Assumptions:
  - Uniform heat, SOC, and current in all cells of the battery

Data Gathered

- Data from a Samsung 30Q 18650
- Experiments used to find electrical parameters.
- Heat transfer coefficient and heat capacity values taken from literature.
- dU/dT parameter found by fitting a 2nd order polynomial to the OCVs with respect to the temperature range at each SOC step.
- Currently do not have a liquid cooled battery to take parameters from.

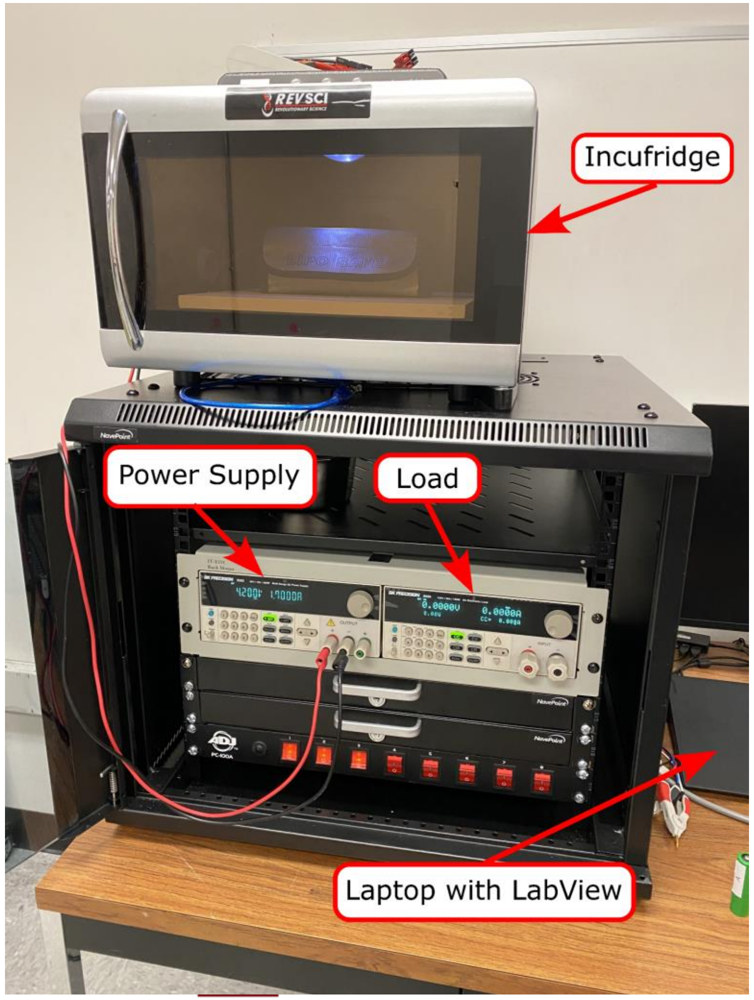
	Parameters need
Electrical	nominal voltage
	capacity (T)
	open circuit voltage (SoC, T)
	terminal resistance (SoC, T)
Thermal	open circuit voltage (SoC, T)
	dU/dT (SoC, T)
	surface area
	convective heat transfer coefficient [5]
	mass
	specific heat capacity [6]
Liquid cooling (Not found yet)	pipe wall thickness
	pipe length
	pipe thermal conductivity
	pipe cooling contact area
	pipe hydraulic diameter
	pipe cross-sectional area
	mass flow rate of liquid
	density of liquid

[6] X. Zhang *et al.*, “Evaluation of convective heat transfer coefficient and specific heat capacity of a lithium-ion battery using infrared camera and lumped capacitance method,” *Journal of Power Sources*, vol. 412, pp. 552–558, Feb. 2019, doi: 10.1016/j.jpowsour.2018.11.064.

[7] J. C. Chin, S. L. Schnulo, T. B. Miller, K. Prokopius and J. Gray, "Battery performance modeling on maxwell x-57," *AIAA Scitech 2019 Forum,* 2019.

Battery Tester

- Built in house to perform Pulsed Power Characterization (PPC) testing
    - Composed of a load, power supply, incufridge, thermocouples, and a laptop with LabVIEW.



Pulse Power Characterization

- Get parameters from pulse response of battery. Equations and profile from [7]

$$R_0 = \left(\frac{u_0 - u_1}{i}\right)$$

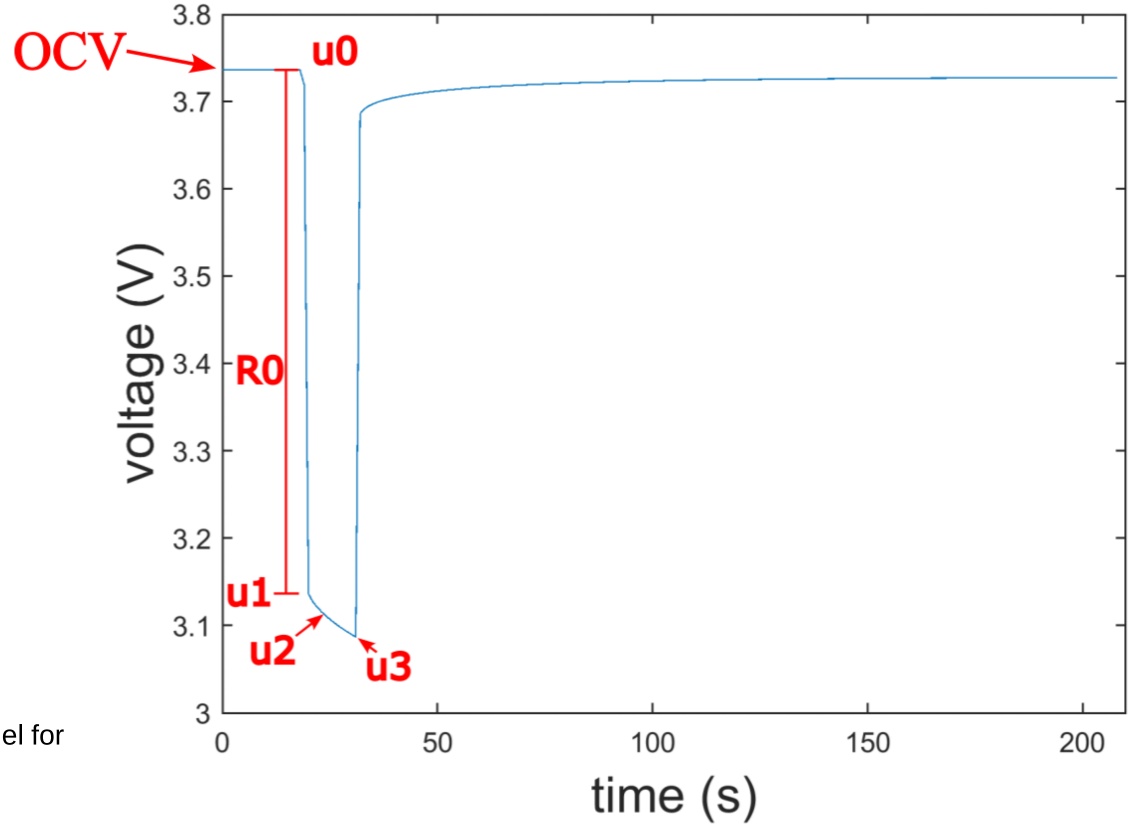
For 2-time constant dynamics:

$$R_1 = \left(\frac{u_1 - u_2}{i}\right)$$

$$R_2 = \left(\frac{u_3 - u_2}{i}\right)$$

$$t_1 = R_1 C_1$$

$$t_2 = R_2 C_2$$

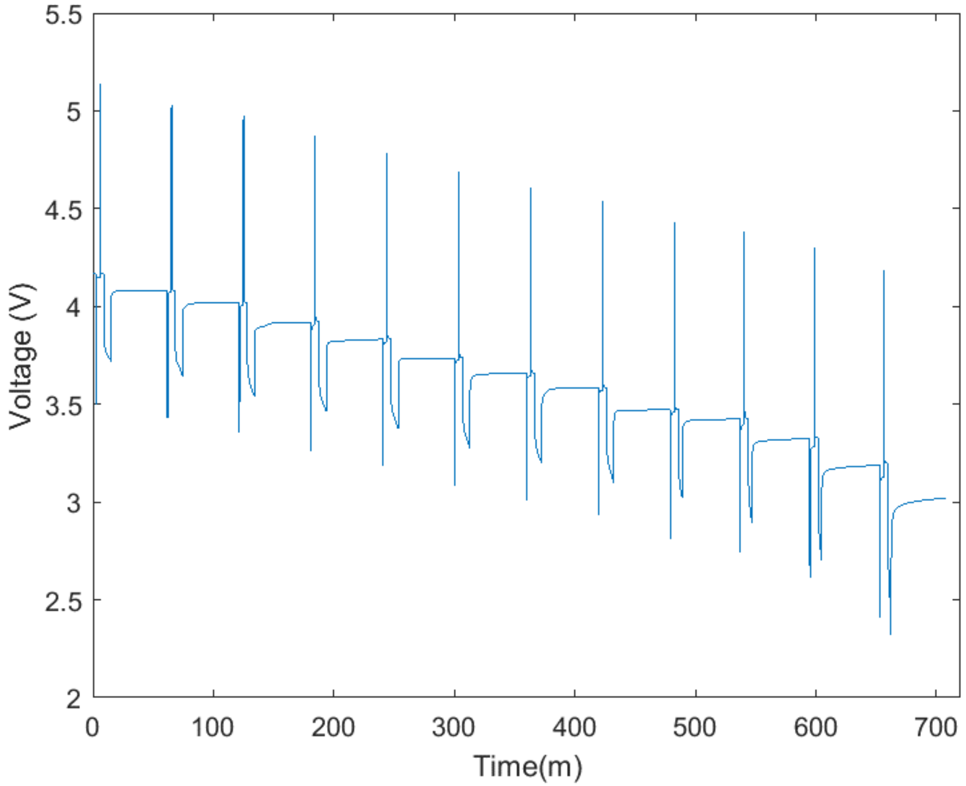


[8] S. Thanagasundram, R. Arunachala, K. Löffler, T. Teutsch and A. Jossen, "A cell level model for battery simulation," in *European Electric Vehicle Confrence*, 2012.

Pulse Power Characterization

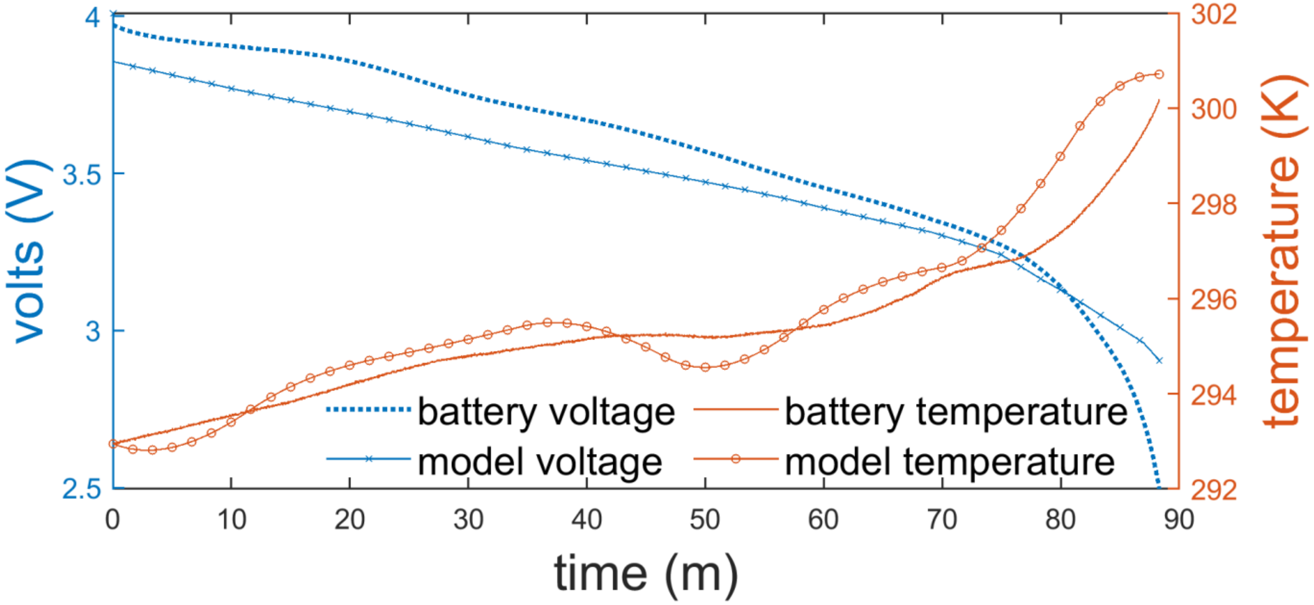
- Profile: 2C discharge pulse (10 sec), 3 min wait, 2C charge pulse (10 sec), 3 min wait, discharge to next SoC step, rest 1 hr.
- Repeat pulse discharge/ charge events at every 10% decrement of SoC from 100% to 20% and at every 5% decrement from 20%-0%
- Temperature range: 13,20,30,40, and 48 °C

A PPC test run at 20ºC



Model Result (Air convection only)

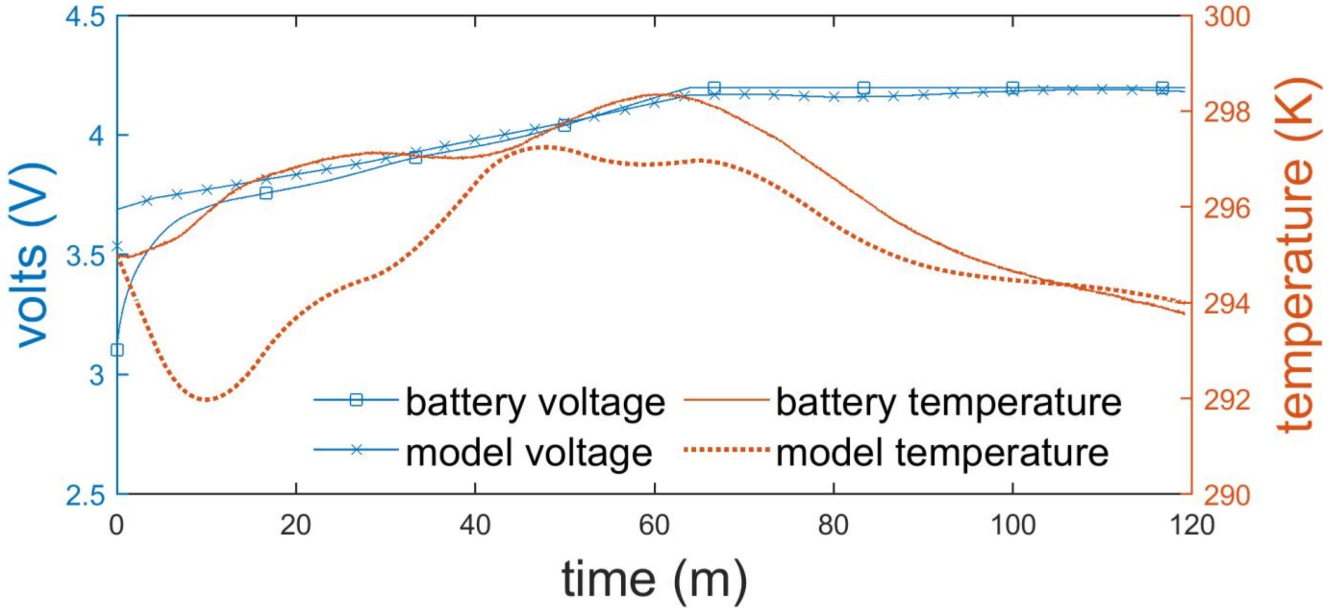
- 0.5C discharge to 2.5V cutoff
- Modeled voltage with 2.93% average absolute error.
- Modeled temperature with 0.10% average absolute error.



*Note, these tests recorded only the battery surface temperature.
Core temperature can be up to 10ºC hotter than the surface.

Model Result (Air convection only)

- 4.2V 0.5C CC-CV charge to 150mA cutoff
- Modeled voltage with 1.10% average absolute error.
- Modeled temperature with 0.43% average absolute error



*Note, these tests recorded only the battery surface temperature. Core temperature can be up to 10ºC hotter than the surface.

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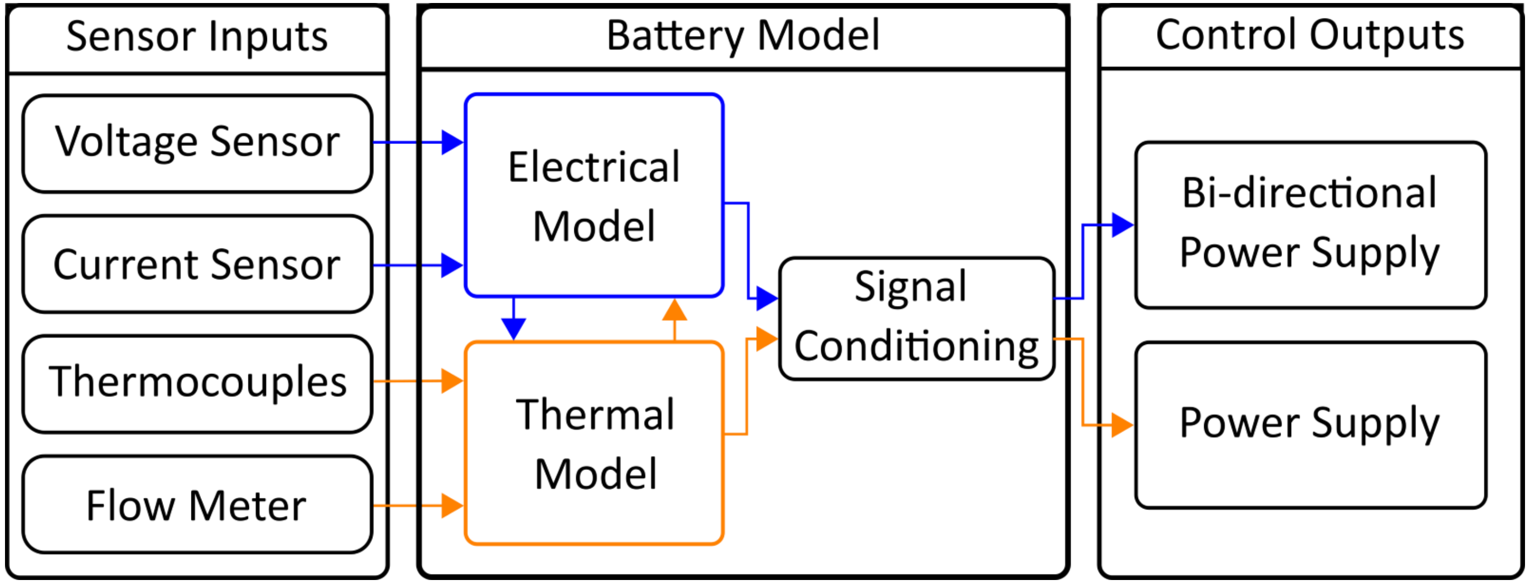
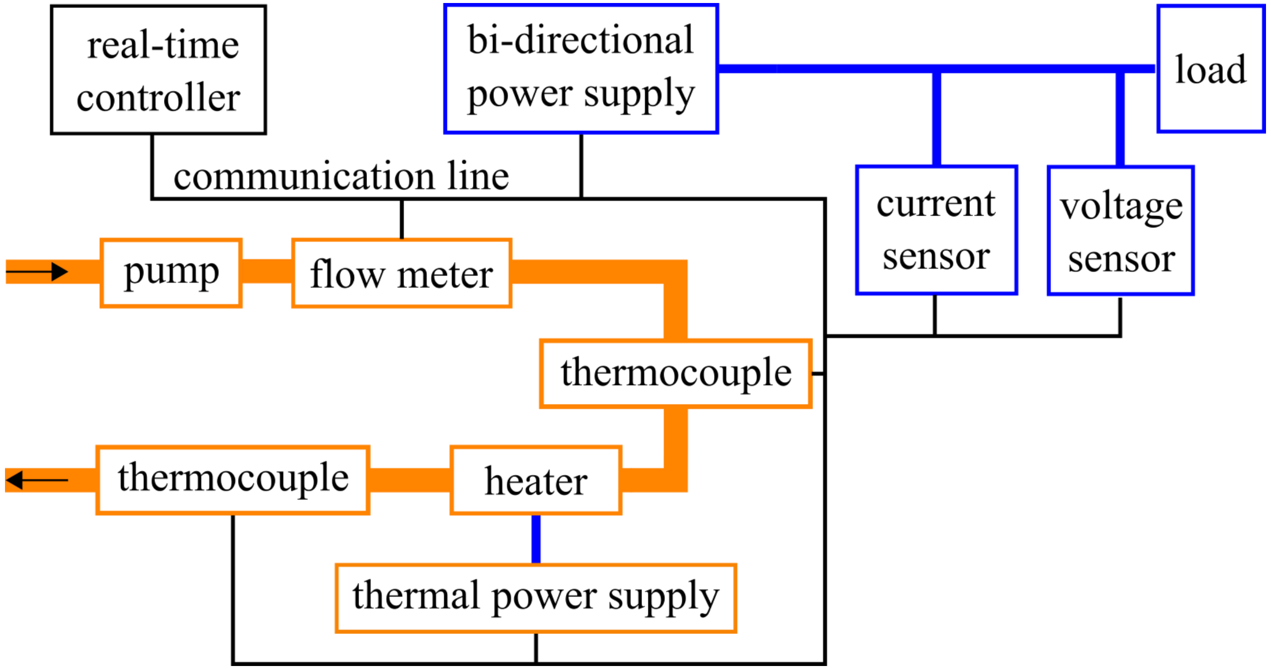
Model Implemented on Hardware

- Real-time controller (cRIO-9054)
  - Receives real-time data from sensors.
  - Outputs real-time control signals to power supplies
- Control Scheme will be uploaded to real-time controller:

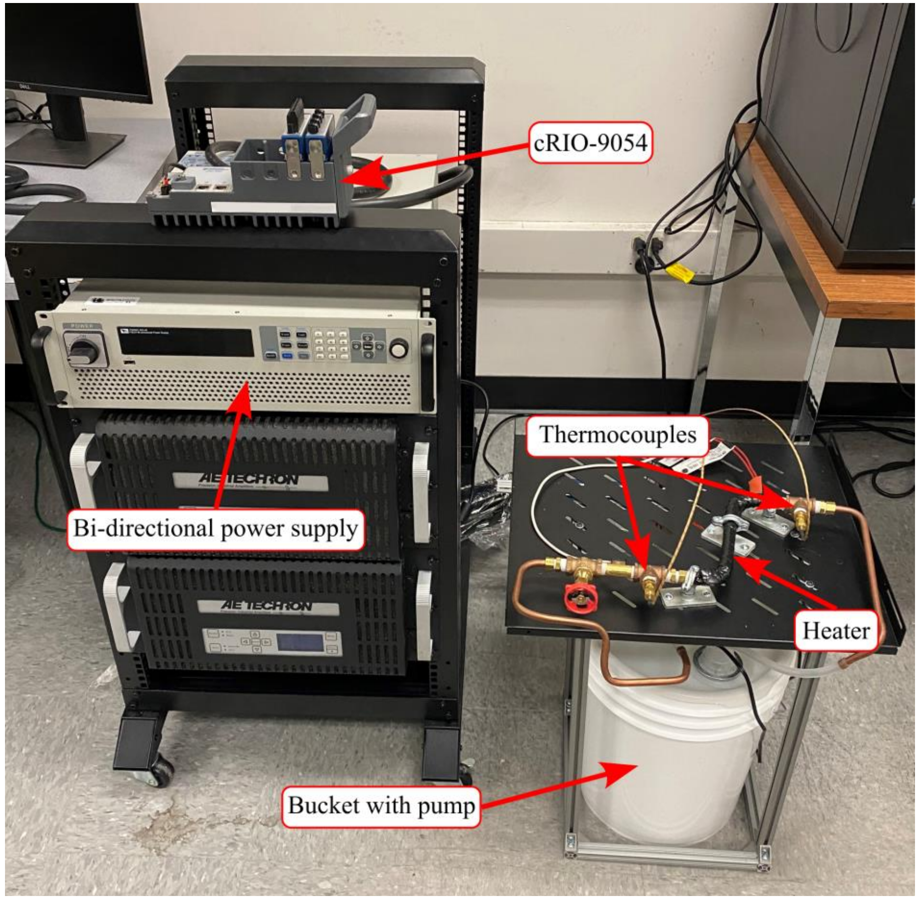


Hardware Setup

Diagram of complete setup:



Physical Setup:



Discussion

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Conference Abstract

Lithium-ion batteries are the dominant battery in various industries due to their high power to weight ratio and limited memory effect. However, one challenging aspect of Lithium-ion batteries is their potential for thermal runaway. If these batteries are heated above 60 ºC, they will begin a positive feedback loop of reactions within their structure. These reactions will eventually combust the battery and are a major safety issue for batteries used incorrectly. This work reports progress on the development of a continuous 6 kW electro-thermal lithium-ion battery emulator being developed for integration into test platforms. A unique feature of the emulator in development is that it replicates the thermal response of the batteries enabling the ground-based validation of cooling methodologies. This enables the testing of how batteries under extreme loads interact with both the electrical and thermal aspects of an electrified propulsion system under test. The physical battery emulator is composed of three parts: electrical, thermal, and control. The electrical component is made up of a bidirectional power supply that connects to any grid or system the same way as a real battery would connect and emulates battery response post battery management system. The thermal liquid cooling loop is comprised of a heater, pump, thermocouples, and a flowmeter and emulates the heat released from the battery and allows for cooling techniques to be employed. The real-time controller receives sensor data from the thermal loop and electrical components and runs the battery model to generate the batteries electro-thermal response. The model that runs on the real-time controller is a coupled electro-thermal model built off characterizing a considered test cell using hybrid pulsed-power testing. The coupled electrical model is an equivalent electrical circuit representation of a battery composed of a voltage source and a resistor. The coupled thermal model is a modified version of the isothermal reduced order model commonly used for batteries. Preliminary results for a Samsung 30Q cell show that the coupled electro-thermal model for a cell under a standard discharge of 0.5 C has achieved 2.93% and 0.10% average absolute error for the voltage and temperature, respectively. Moreover, under standard constant current constant voltage (CCCV) charging it achieved 1.10% and 0.43% average absolute error for the voltage and temperature, respectively. A discussion of current hardware, its integration into an electro-thermo testbed for a naval propulsion application, and limitations of the current system are provided.