In-Operando Variable Charge Rate Monitoring and Prognostics for Battery Safety

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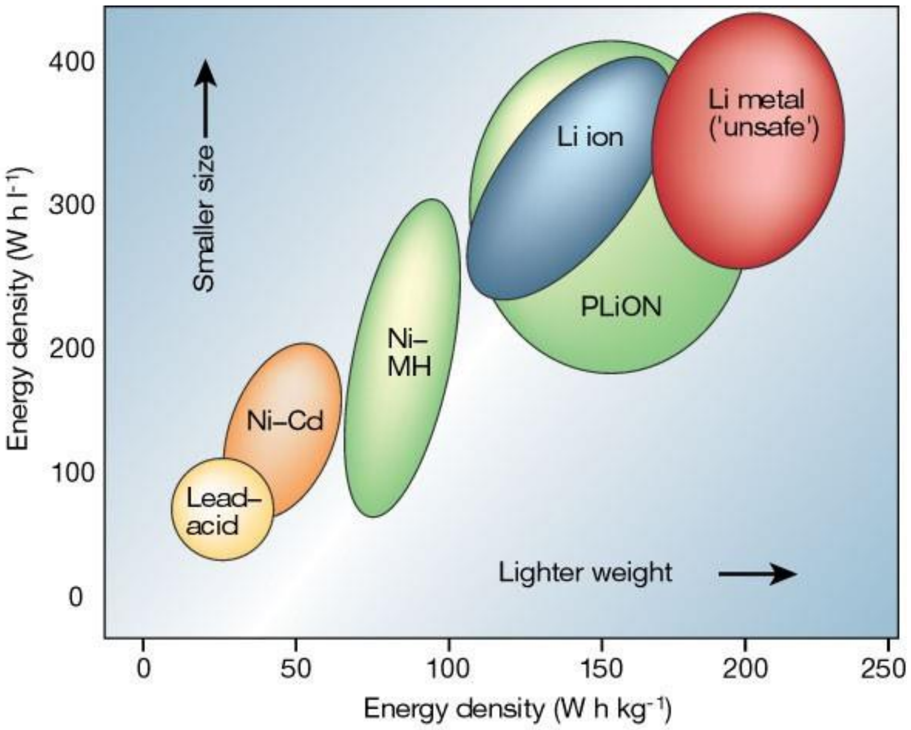
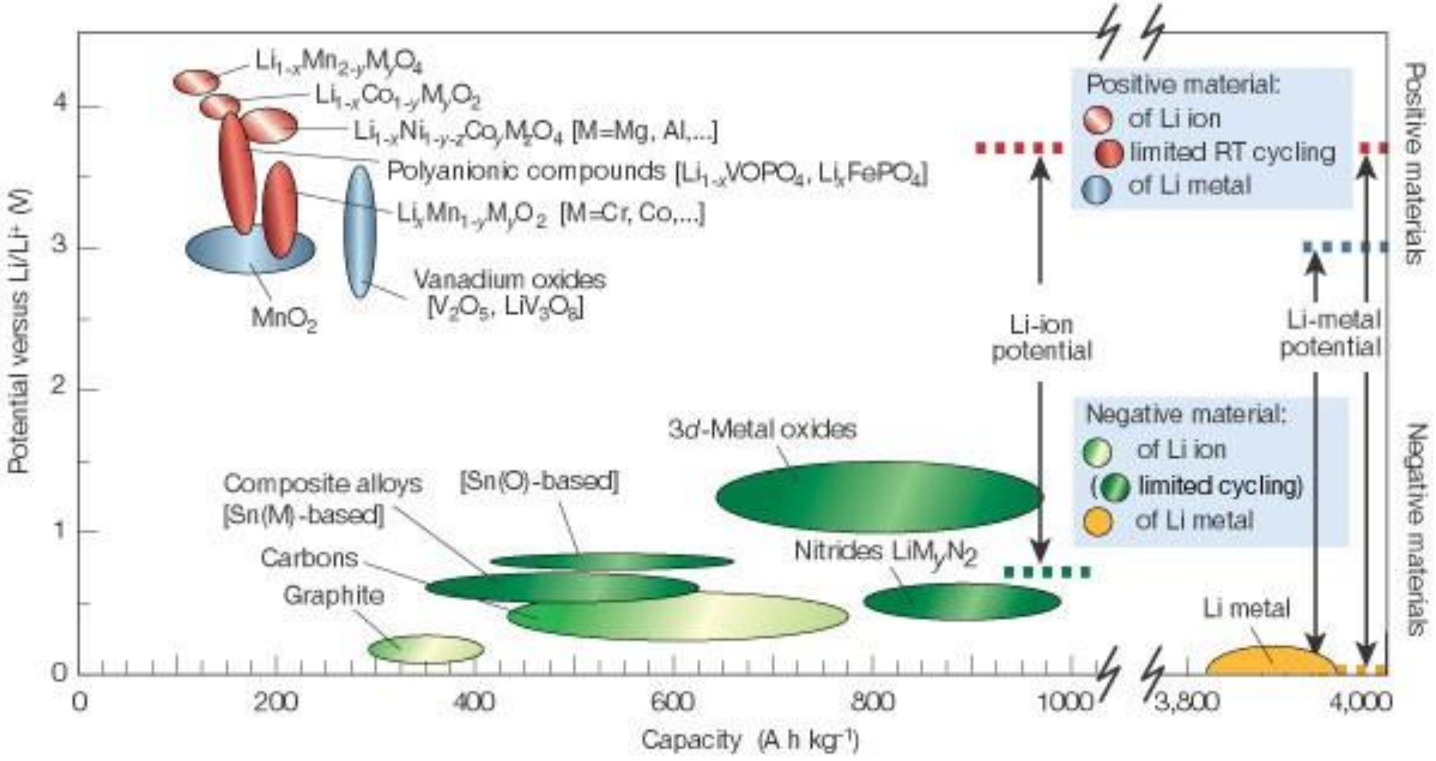
Benefits of Li-ion Batteries [1]





- Lithium-ion batteries have higher energy densities and greater design flexibility
- Different cell chemistries provide higher energy, power, and cycle life for different applications

[1] Tarascon, J. M., and Armand, M., 2001, "Issues and challenges facing rechargeable lithium batteries," Nature, **414**(6861), pp 359-367.

Potential Hazards of Li-ion Batteries

LIB shipment fire [2]

Boeing 787 [3]

USS Bonefish [4]

Samsung Galaxy Note 7 [5]

EV crash fire [6]

[2] “Lithium battery fire hazard in the aviation industry,” from http://www.lithiumsafe.com/lithium-battery-fires-in-aircraft/
[3] Lau, K., “Why the Boeing 787 Lithium-ion Battery System caught fire in 2013,” from https://everspring.net/?p=686
[4] NavSource Online: Submarine Photo Archive, from http://www.navsource.org/archives/08/08582.htm
[5] Lopez, R., 2017, “Here’s Why the Samsung Galaxy Note 7 Caught Fire,” from https://www.revu.com.ph/2017/01/samsung-galaxy-note-7-fire-reason/
[6] Isidore, C., 2018, “Are electric cars more likely to catch fire?,” from https://money.cnn.com/2018/05/17/news/companies/electric-car-fire-risk/index.html

Testing Standards

- NAVSEA 9310 [7], Sandia FreedomCAR [8], SAE International Surface Vehicle Recommended Practice [9], United Nations Manual of Tests and Criteria Section 38.3 [10]
  - Electrical abuse tests (overcharge/discharge, high rate charge/discharge, short circuit, separator integrity)
  - Thermal abuse tests (high temperature, thermal shock, thermal stability)
  - Mechanical abuse tests (penetration, drop, immersion, roll-over, mechanical shock, vibration, impact, pressure, crush)

[7] NSS Command, 2010, "Technical Manual for Navy Lithium Battery Safety Program Responsibilities and Procedures," Naval Ordnance Safety and Security Activity.

[8] Doughty, D. H., and Crafts, C. C., 2006, "FreedomCAR Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications," Sandia National Laboratories, Albuquerque, NM.

[9] *Surface Vehicle Recommended Practice*, 2009, SAE International, Warrendale, PA.

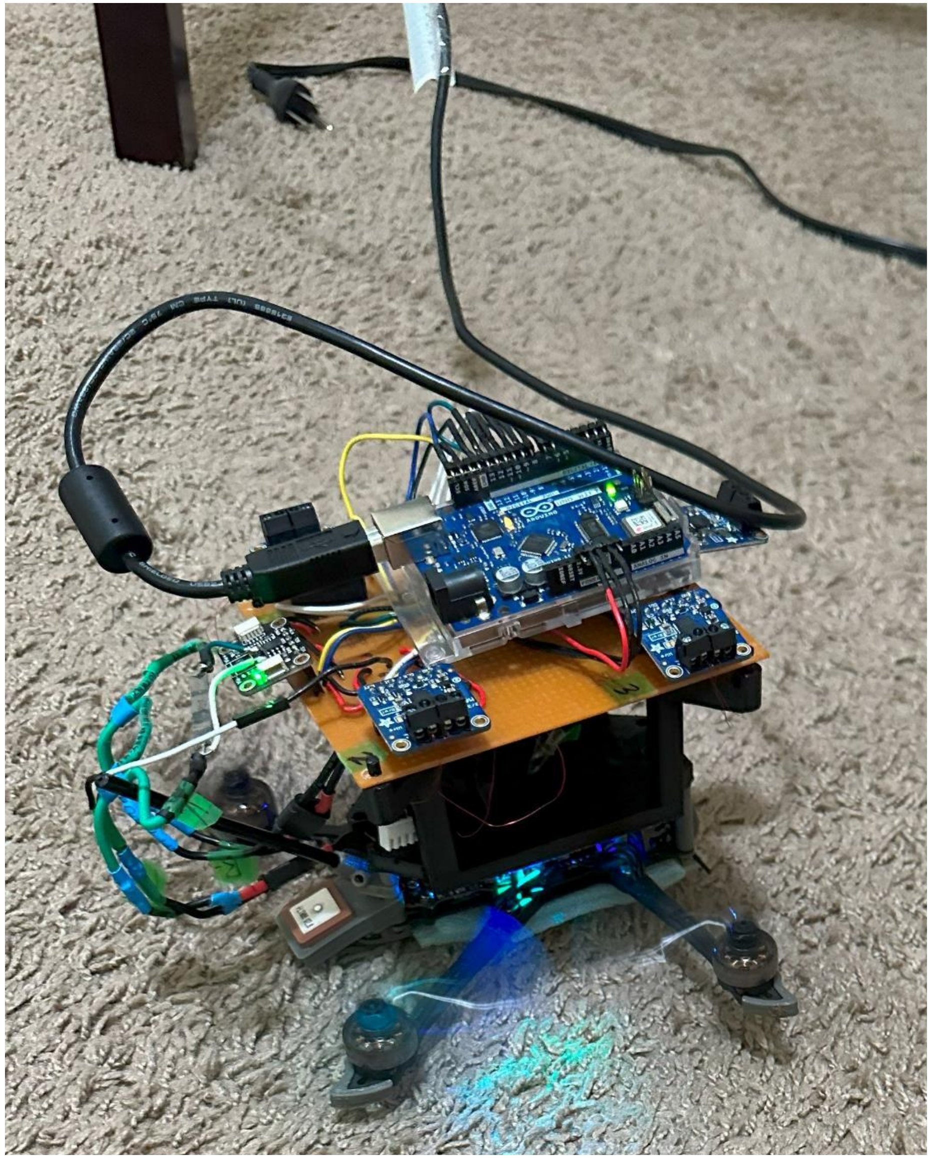
[10] *Recommendations on the Transport of Dangerous Goods*, 2015, United Nations Economic Council of Europe, Geneva, Switzerland.

Knowledge gaps

- Limited research on the use of machine learning algorithms for in-operando cycle life prediction of LIBs on a BMS incorporating accident effects.
- Limited investigation on the in-operando performance of machine learning models using public data for battery life prediction.
- Lack of publicly available datasets with high-quality data for training the neural network models for predicting battery capacity and life cycle.

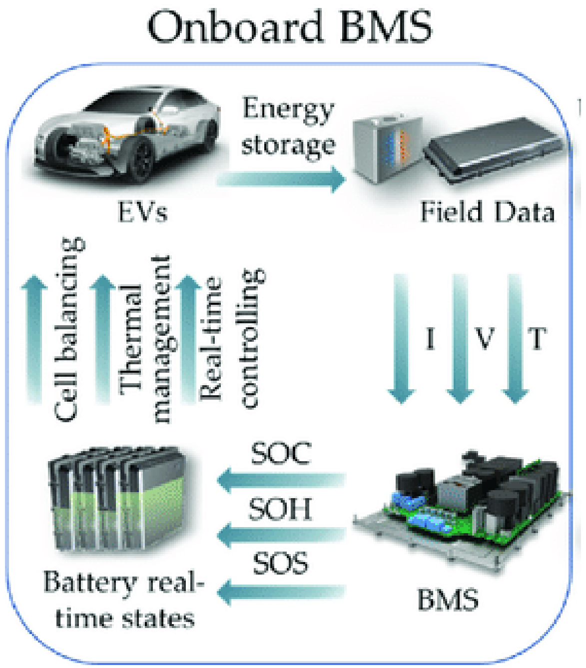
Outline

- Battery Health Monitoring System helps track
  - Voltage
  - Current
  - Temperature
- Prediction of LIB capacity
  - CD-Net model developed at Interfacial Multiphysics Laboratory.
- Edge-cloud communication
  - Advanced Encryption Standard (AES) encrypted data transfer



BMS and SOH

- SOC and SOH monitoring are the main concerns and the basis to improve reliability and ensure LIB safety.
- Online measurement of chemical parameters inside batteries is limited to inputs from BMS- [Current, Voltage, Temperature]
- SOH estimation infers if LIBs need to be replaced with new ones.
  - SoH is the maximum possible charge a battery can hold compared to the rated capacity



Zhao et al. 2022

$$\mathrm{SoH} = \frac{Q_{max}}{Q_{nominal}}$$

Q_{nom} : nominal capacity of the un-aged battery
Q_{max} : maximum available capacity in battery

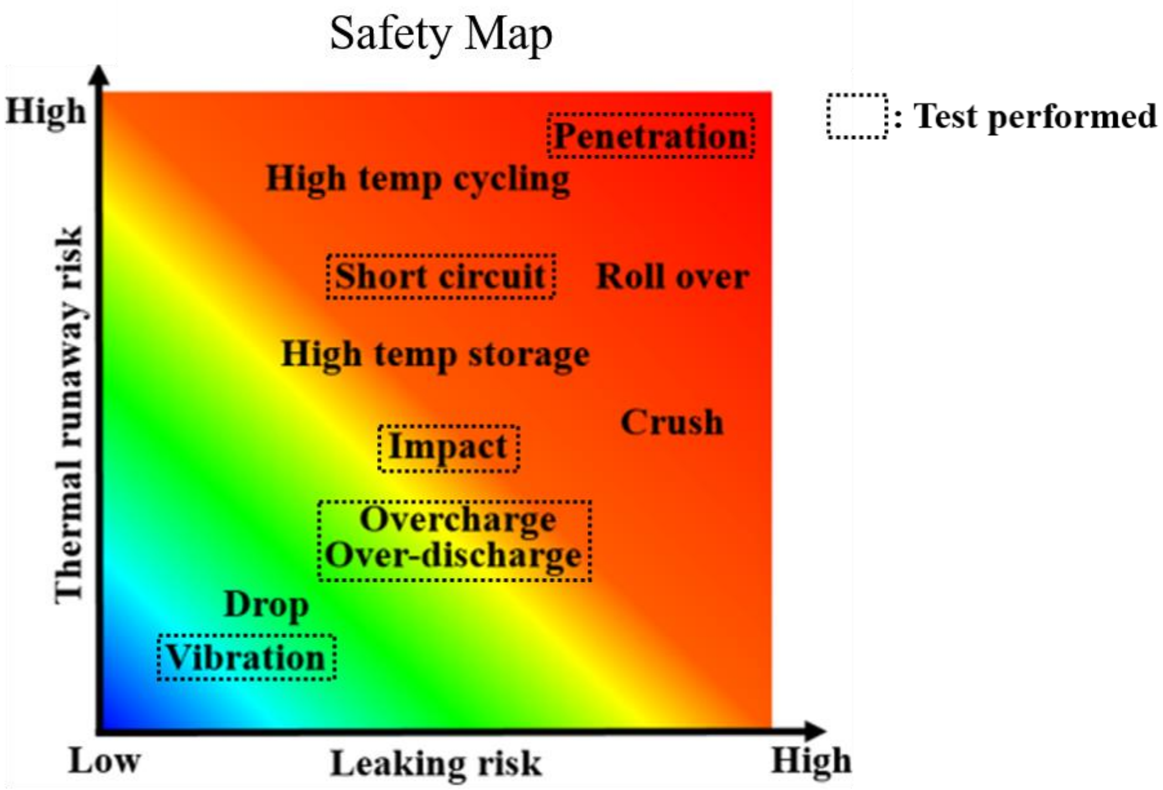
[11] Zhao, Jingyuan & Burke, Andrew, "Electric Vehicle Batteries: Status and Perspectives of Data-Driven Diagnosis and Prognosis. Batteries(2022) 8. 142. 10.3390/batteries8100142.

Safety Map – Lab Base Data

Risk Assessment Matrix

Probability ↕					
Expected	Med-low	Medium	Med-high	High	High
Likely	Low	Med-low	Medium	Med-high	High
Possible	Low	Med-low	Medium	Med-high	Med-high
Unlikely	Low	Med-low	Med-low	Medium	Med-high
Rare	Low	Low	Med-low	Medium	Medium
	Negligible	Minor	Moderate	Considerable	Significant

Severity ⟷



Background

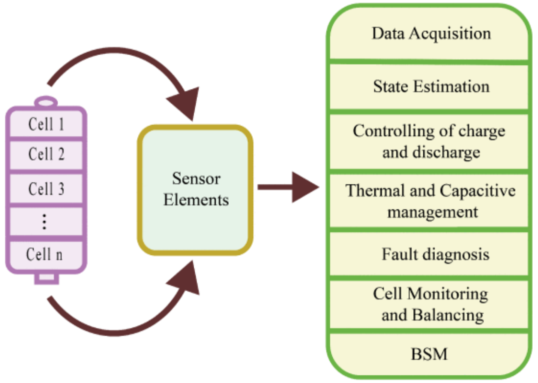
Predicting battery health is divided into three distinct styles [12]

- Experimental
- Physical Models
- Data-Driven Machine Learning

With recent advancements in machine learning and big data technology, data-driven algorithms have gained substantial popularity

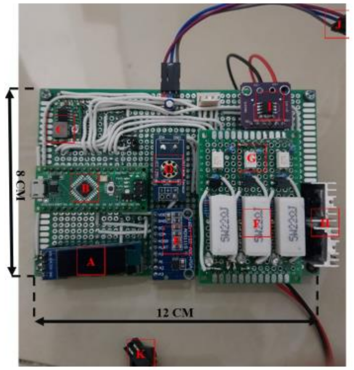
Requirements for modern RUL prediction approaches [13]

- Voltage
- Current
- Temperature

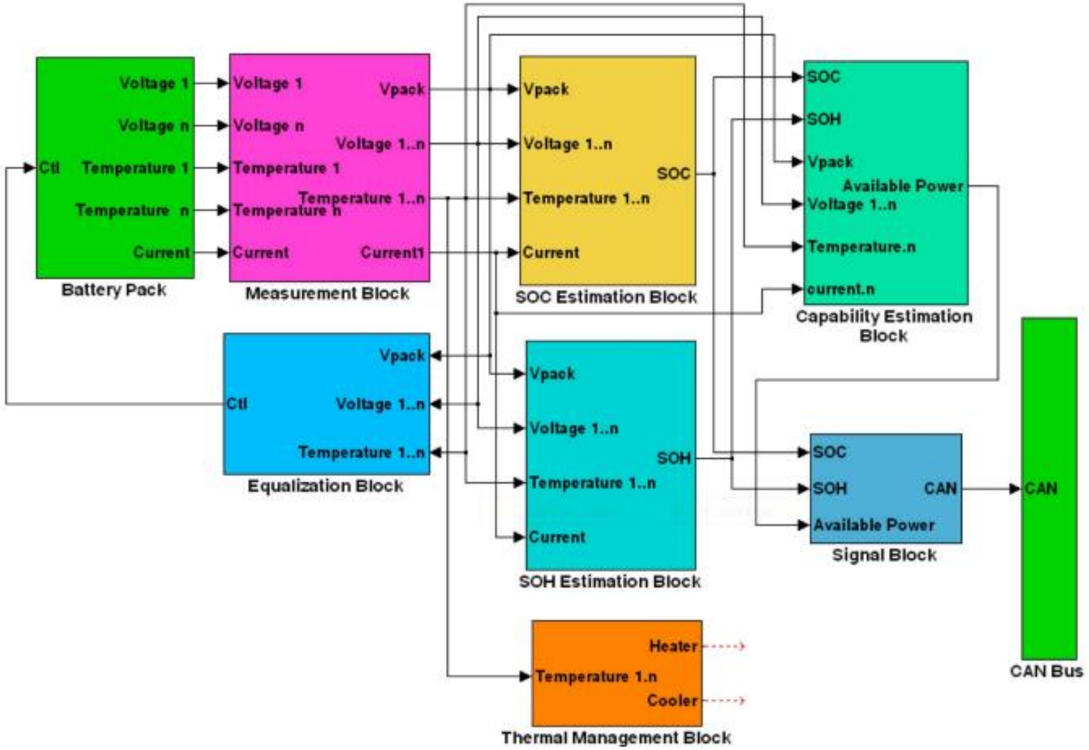


[12] Yan Ma et al, "State of Health estimation and Remaining Useful Life prediction for lithium-ion batteries by Improved Particle Swarm Optimization-Back Propagation Neural Network" in *Journal of Energy Storage , vol. 52, 2022, doi : https://doi.org/10.1016/j.est.2022.104750*
[13] S. A. Hasib et al., "A Comprehensive Review of Available Battery Datasets, RUL Prediction Approaches, and Advanced Battery Management," in IEEE Access, vol. 9, pp. 86166-86193, 2021, doi: 10.1109/ACCESS.2021.3089032.

Background : BMS



BMS for LIB[18]



Battery Management System for electric vehicles[17]

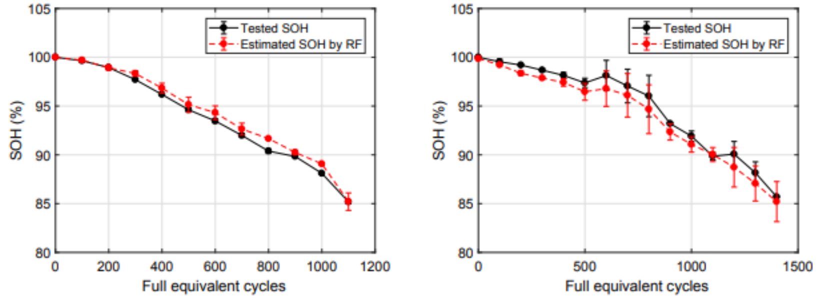
Disadvantages to modern designs [19]

- Limited local computing resources
- Lack of flexibility in usage
- Hard-programmed models

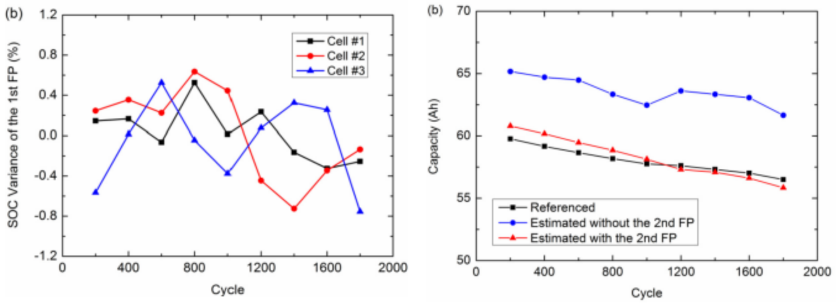
[17] K. W. E. Cheng, B. P. Divakar, Hongjie Wu, Kai Ding, and Ho Fai Ho, "Battery-Management System (BMS) and SOC Development for Electrical Vehicles," IEEE Transactions on Vehicular Technology, vol. 60, no. 1, January 2011.
[18] Muhammad Nizam, Hari Maghfiroh, Rizal Abdulrozaq Rosadi, Kirana D. U. Kusumaputri, "Battery management system design (BMS) for lithium-ion batteries," in AIP Conf. Proc., vol. 2217, p. 030157, April 13, 2020.
[19] T M.-K. Tran et al, "Concept Review of a Cloud-Based Smart Battery Management System for Lithium-Ion Batteries: Feasibility, Logistics, and Functionality" Batteries 2022, 8, 19. https://doi.org/10.3390/batteries8020019

Review of Recent Testing

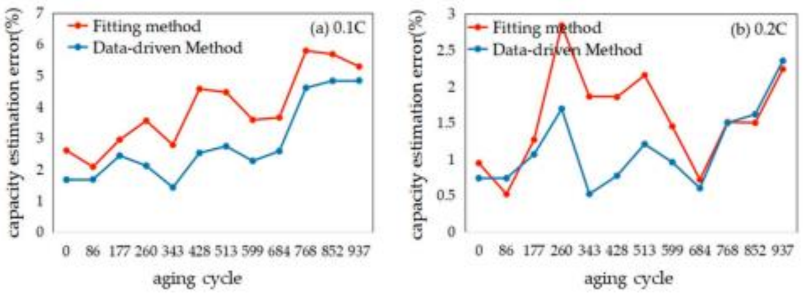
- Random forest regression [20]
  - Features from charging voltage and capacity measurements are used in a random forest regression to estimate capacity without requiring preprocessing
- Incremental capacity analysis for capacity estimation [21]
  - Incremental capacity peaks are used to develop a relationship with state of charge and estimate capacity
- Charging current for capacity estimation [22]
  - Adaptive capacity estimation method using incremental capacity curves from multiple charging conditions and cells with differing ages



Li et al. (2019)



Zheng et al. (2018)



Lin et al. (2021)

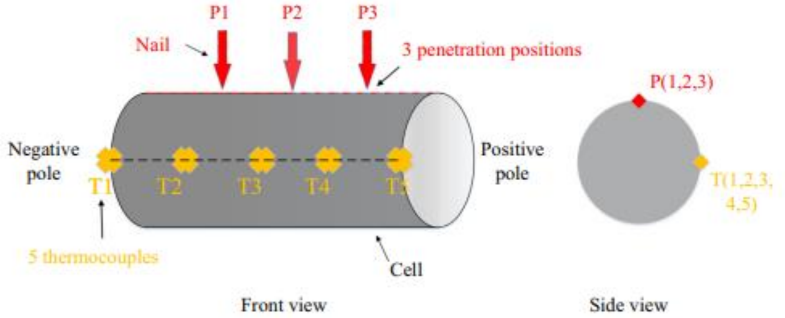
[20] Li, Y., Zou, C., Berecibar, M., Nanini-Maury, E., Chan, J. C. W., van den Bossche, P., Mierlo, J. V., and Omar, N., 2018, “Random forest regression for online capacity estimation of lithium-ion batteries,” Applied Energy, **232**, pp. 197-210.

[21] Zheng, L., Zhu, J., Lu, D. D., Wang, G., and He, T., 2018, “Incremental capacity analysis and differential voltage analysis based state of charge and capacity estimation for lithium-ion batteries,” Energy, **150**, pp. 759-769.

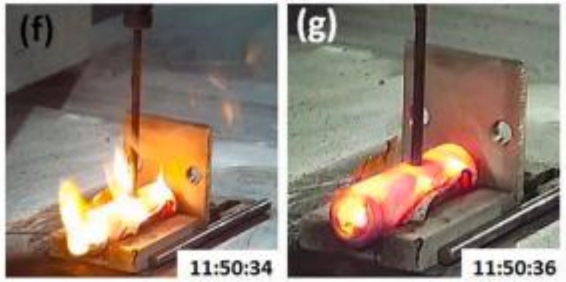
[22] Lin, Y., Jiang, B., and Dai, H., 2021, “Battery Capacity Estimation Based on Incremental Capacity Analysis Considering Charging Current Rate,” World Electric Vehicle Journal, **12**, 224.

Review of Recent Testing

- Failure mechanism during nail penetration [23]
  - Penetration at the center of a cell causes the most severe thermal runaway, surface temperature not positively correlated with penetration depth
- Thermal runaway induced by nail penetration [24]
  - Maximum temperature is higher and is reached in less time for radial penetrations as opposed to axial
- Deformation and failure under axial nail penetration [25]
  - Two possible failure modes (pinching or puncturing electrode layers), nail velocity has no clear effect on failure properties



Mao et al. (2018)

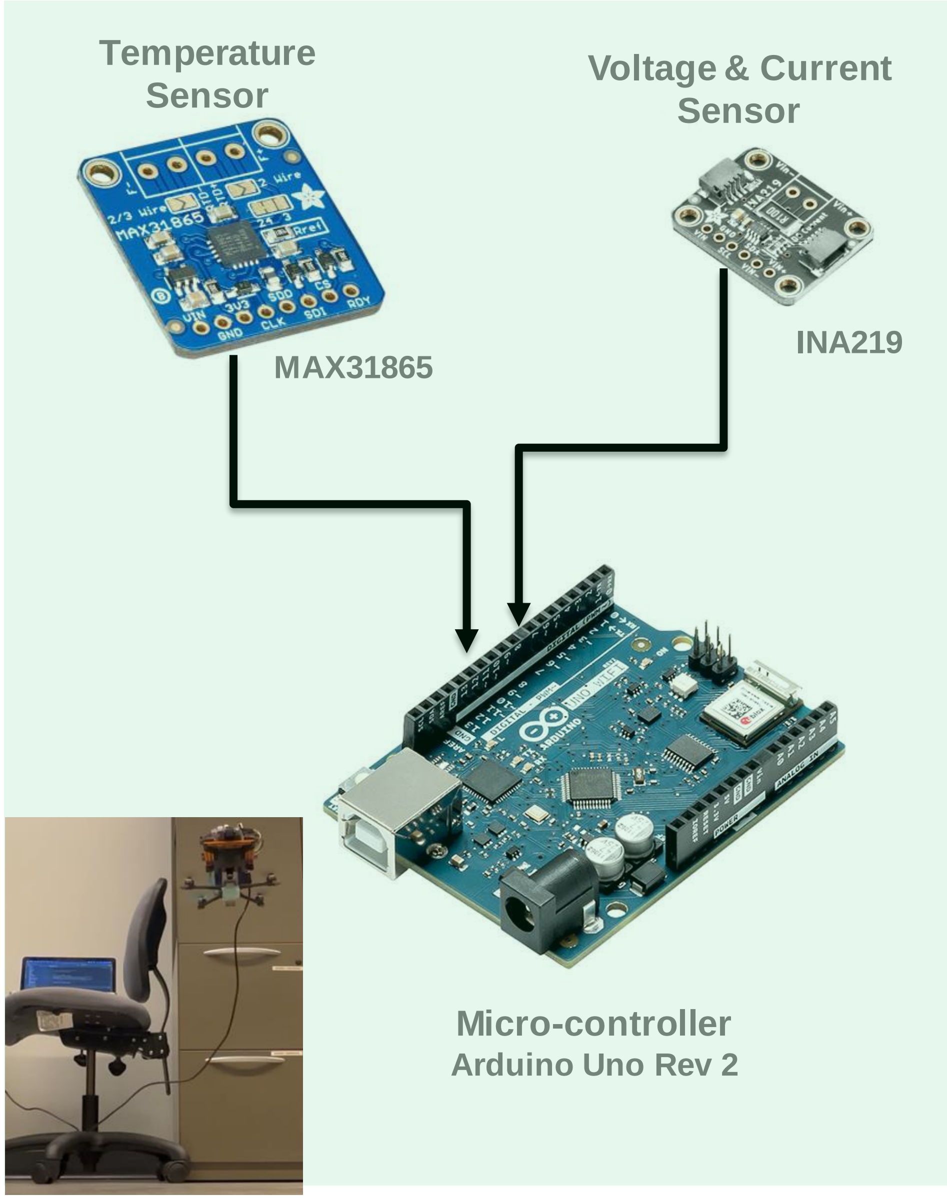


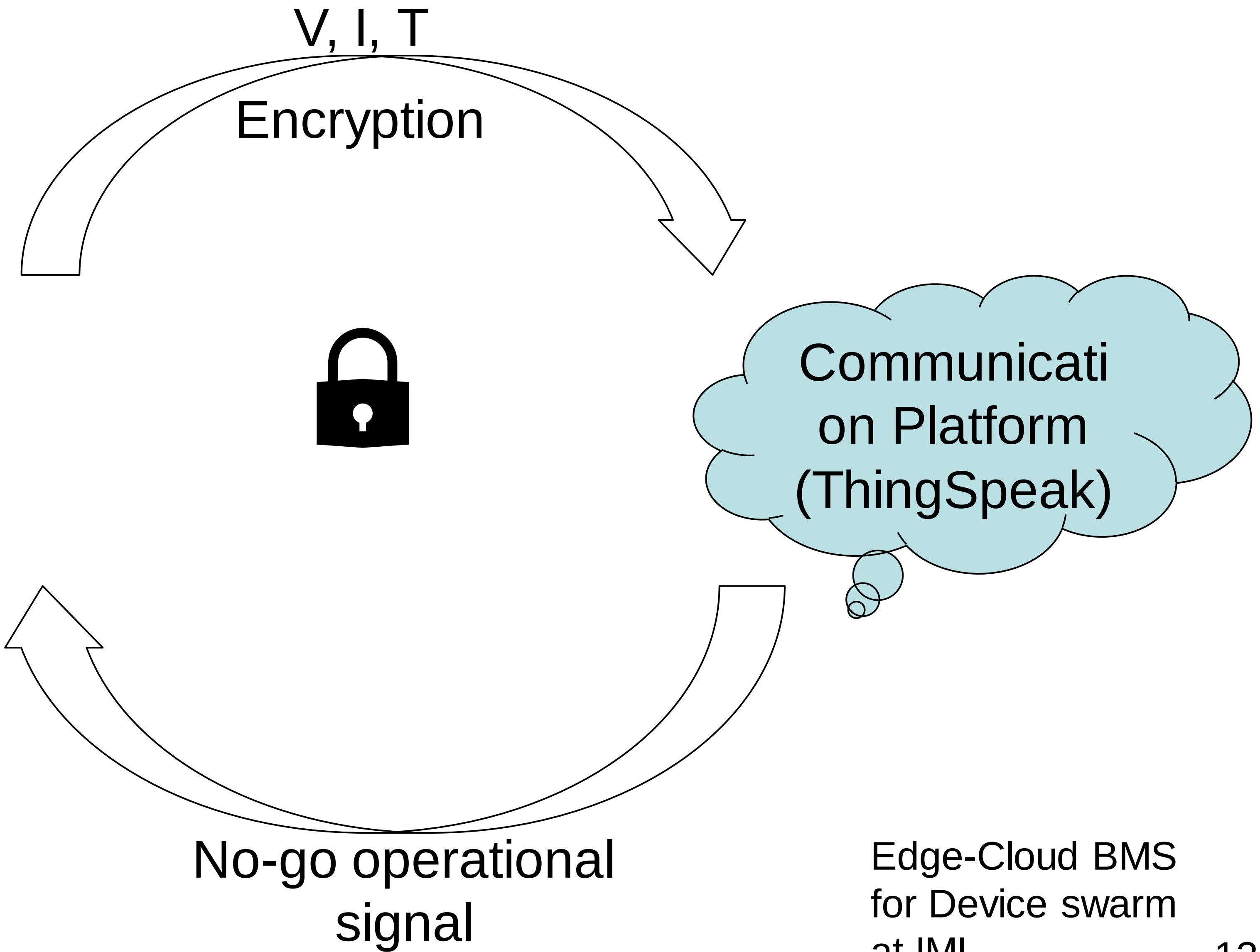
Shelke et al. (2022)

Wang et al. (2021)

[23] Mao, B., Chen, H., Cui, Z., Wu, T., and Wang, Q., 2018, "Failure mechanism of the lithium ion battery during nail penetration," International Journal of Heat and Mass Transfer, **122**, pp. 1103-1115
[24] Shelke, A. V., Buston, J. E. H., Gill, J., Howard, D., Abbot, K. C., Goddard, S. L., Read, E., Howard, G., Abaza, A., Cooper, B., and Wen, J., 2022, "Characterizing and predicting 21700 NMC lithium-ion battery thermal runaway induced by nail penetration," Applied Thermal Engineering, **209**, 118278.
[25] Wang, L., 2021, "Deformation and Failure Properties of Lithium-Ion Battery Under Axial Nail Penetration," Journal of Electrochemical Energy Conversion and Storage, **18**(2), 020906.

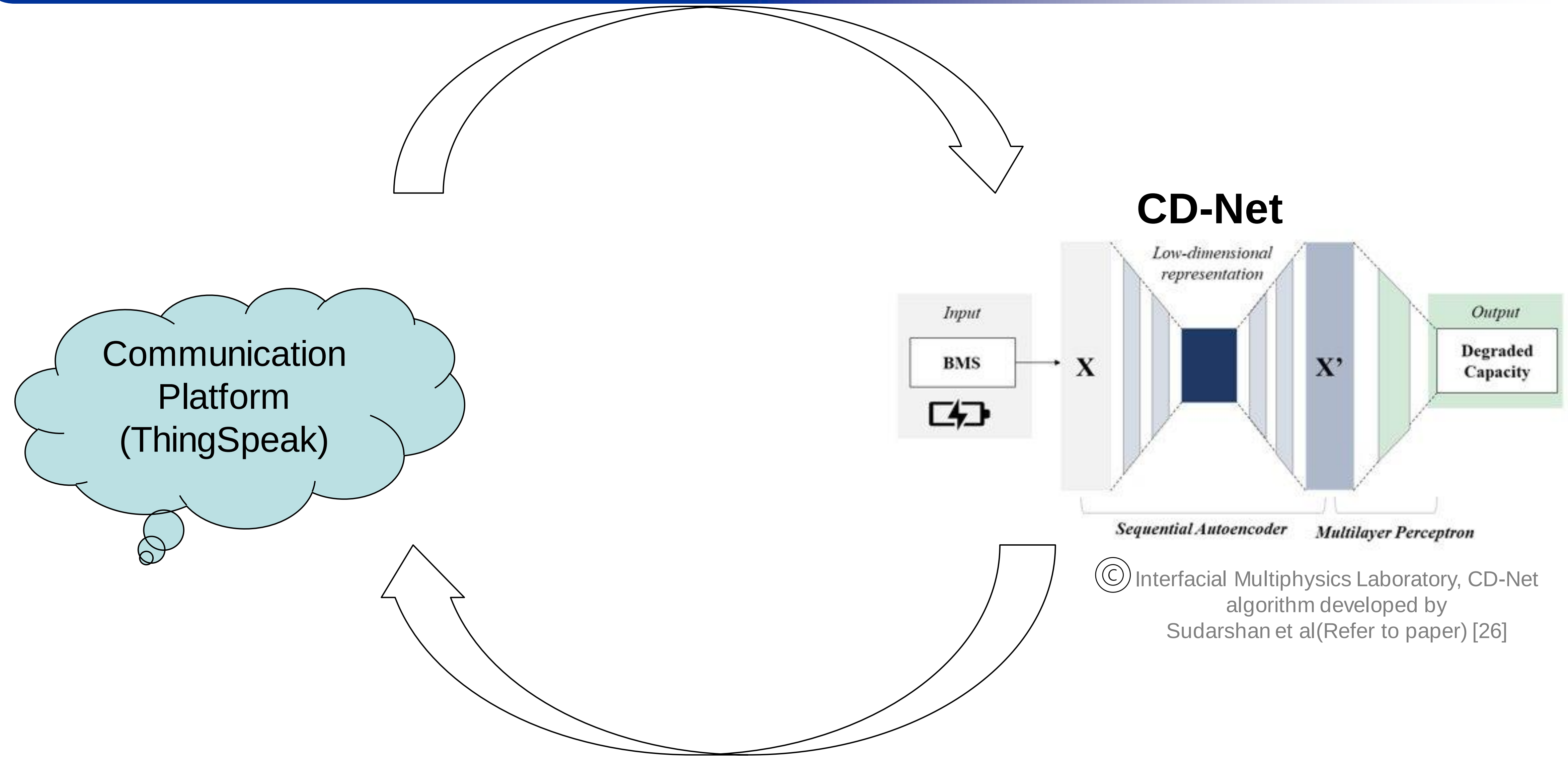
Battery Health Monitoring System





Edge-Cloud BMS for Device swarm at IML

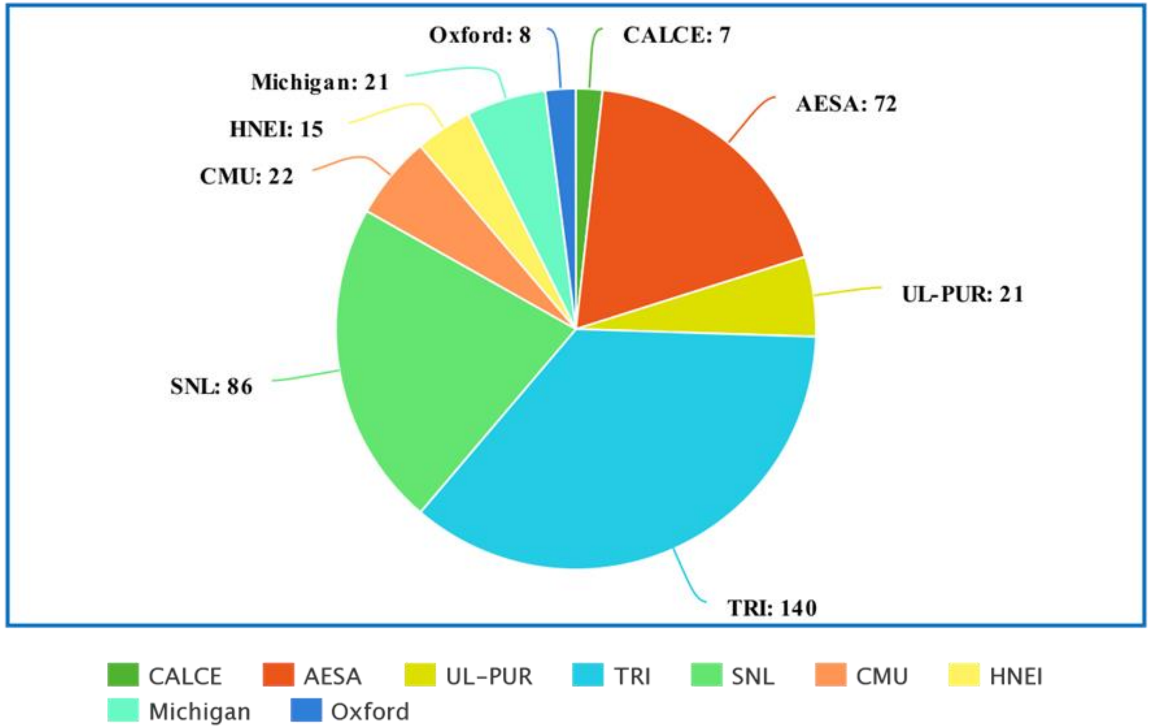
Battery Health Monitoring System



© Interfacial Multiphysics Laboratory, CD-Net algorithm developed by Sudarshan et al(Refer to paper) [26]

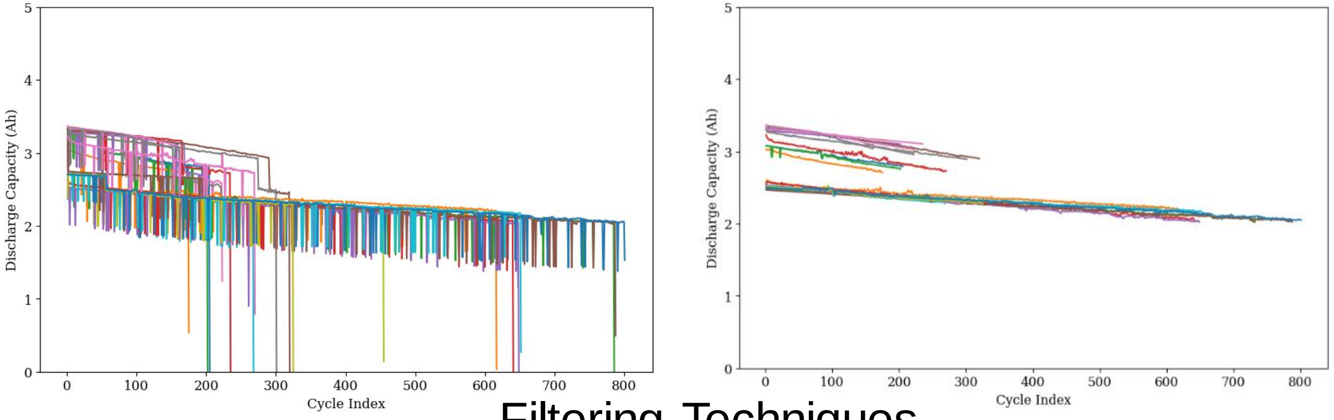
[26] Meghana Sudarshan, Alexey Serov, Casey Jones, Surya Mitra Ayalasomayajula, Edwin García, Vikas Tomar, "Data-Driven Autoencoder Neural Network for Onboard BMS Lithium-ion Battery Degradation Prediction", Journal of Energy Storage (Submitted)

CD-Net testing on open source



Unprocessed

Processed



Filtering Techniques

Unprocessed

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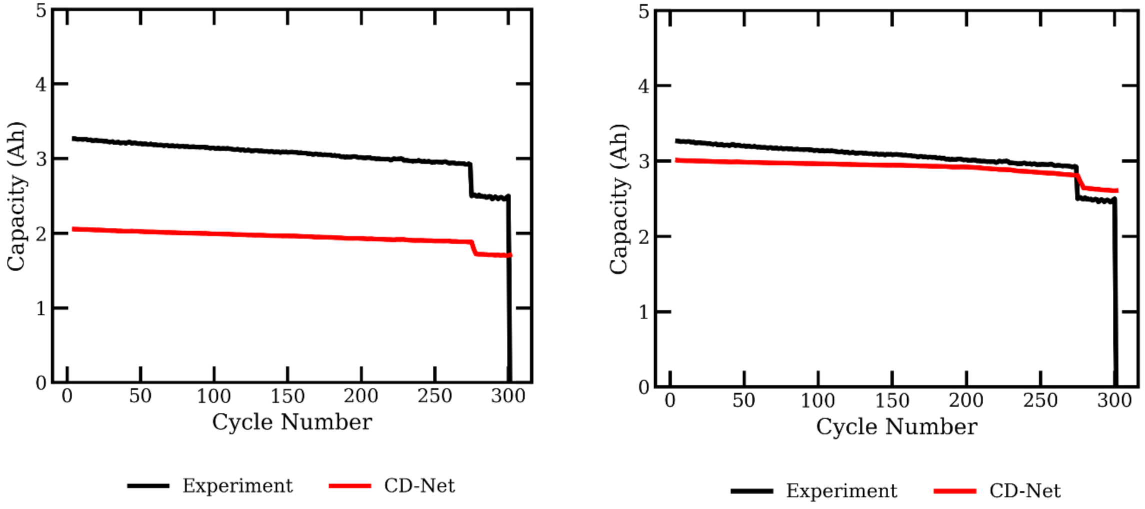
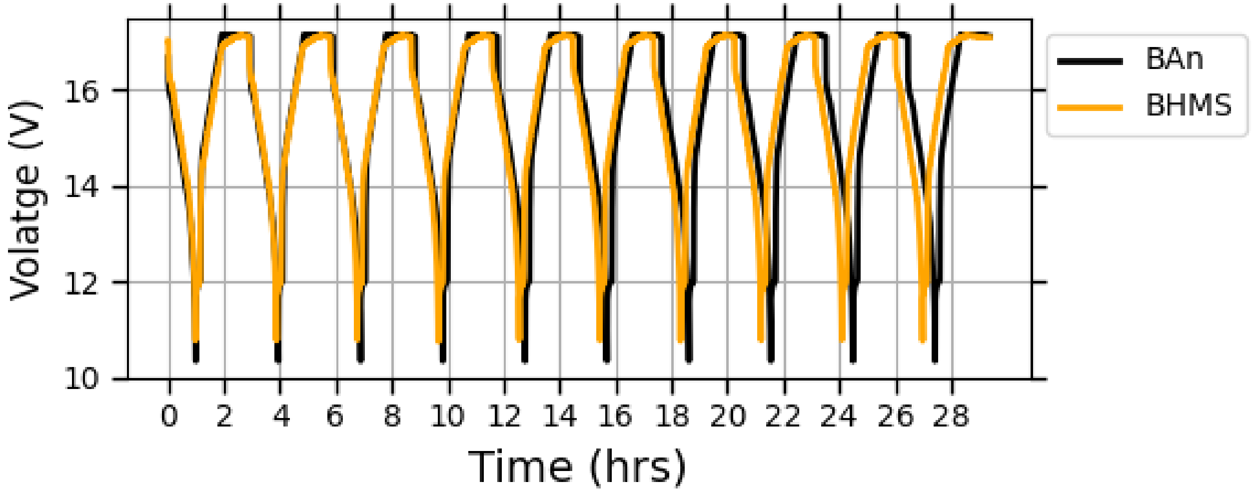
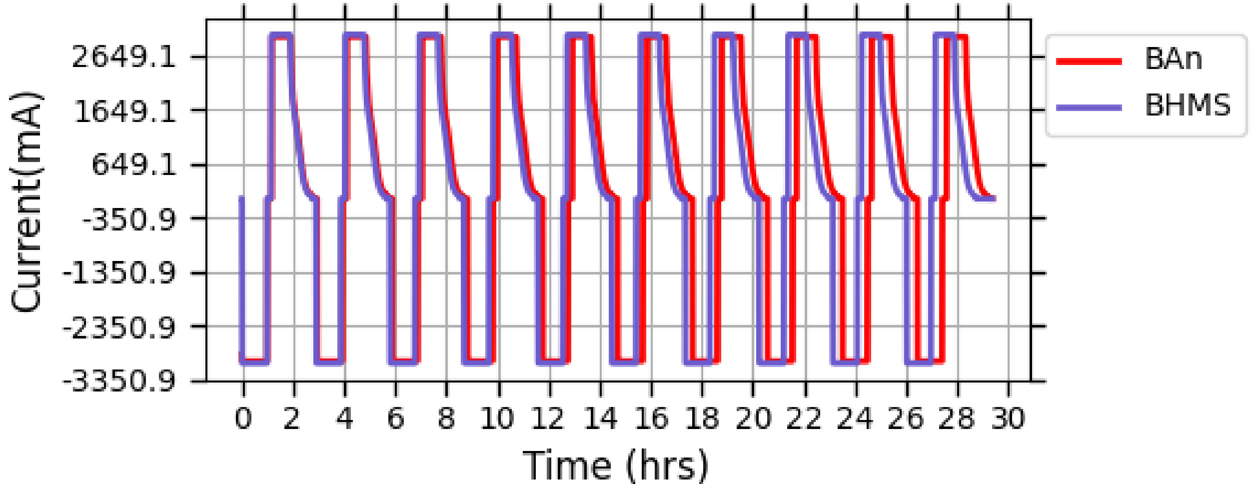
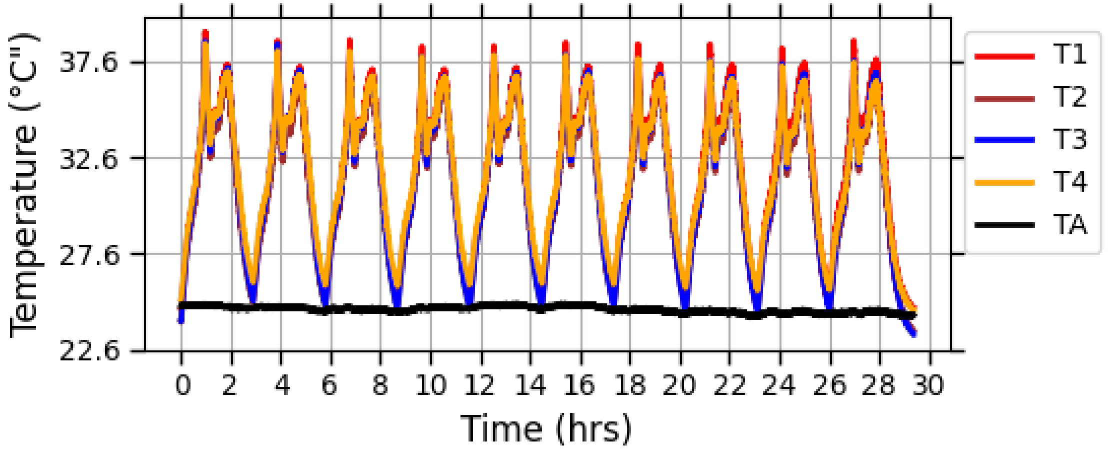


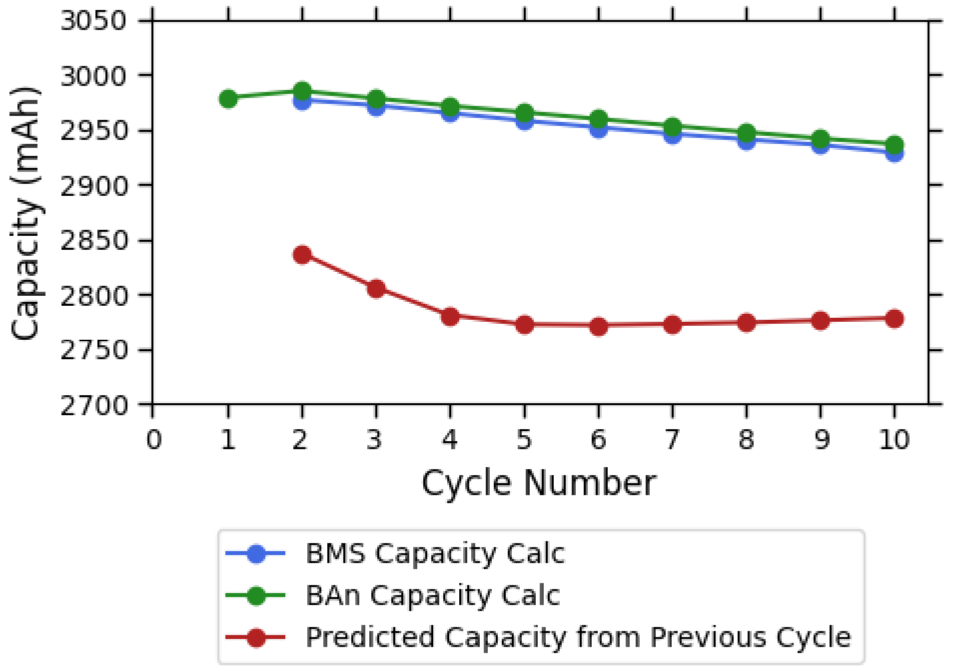
Prediction Improvement

Experiments - ground

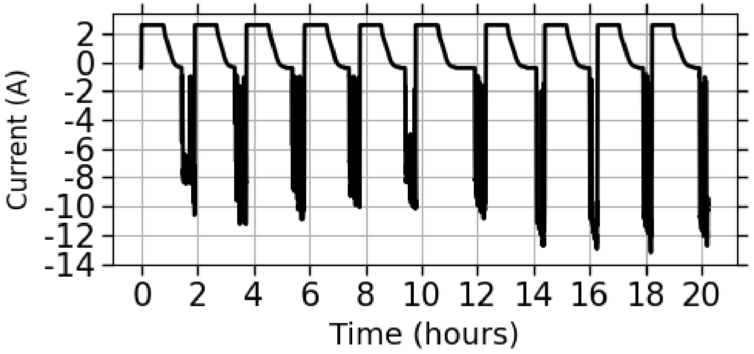


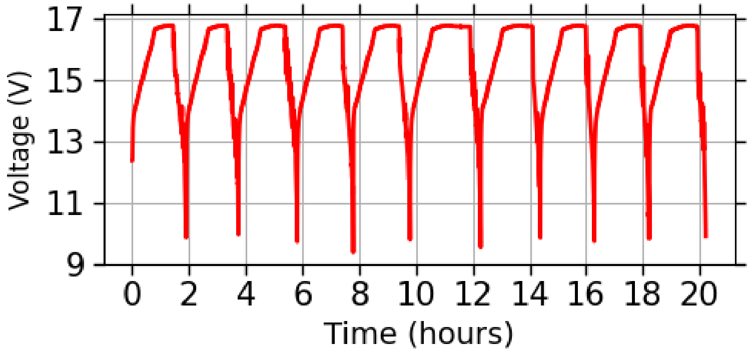


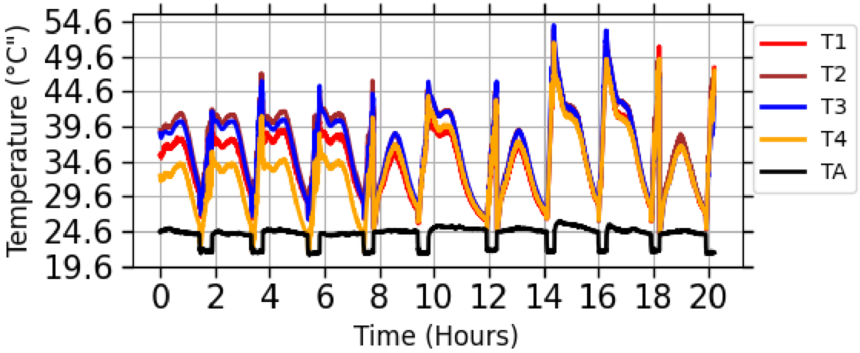


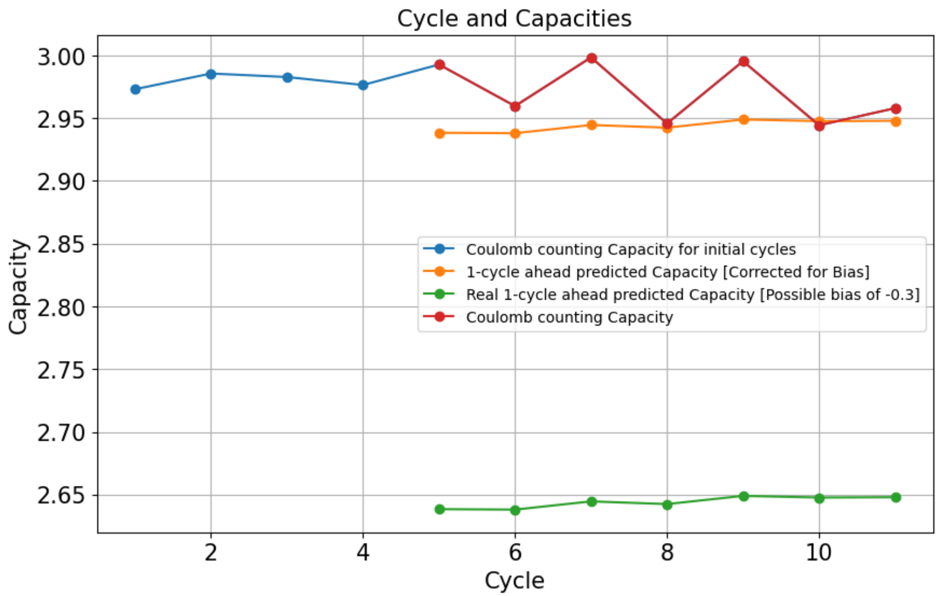


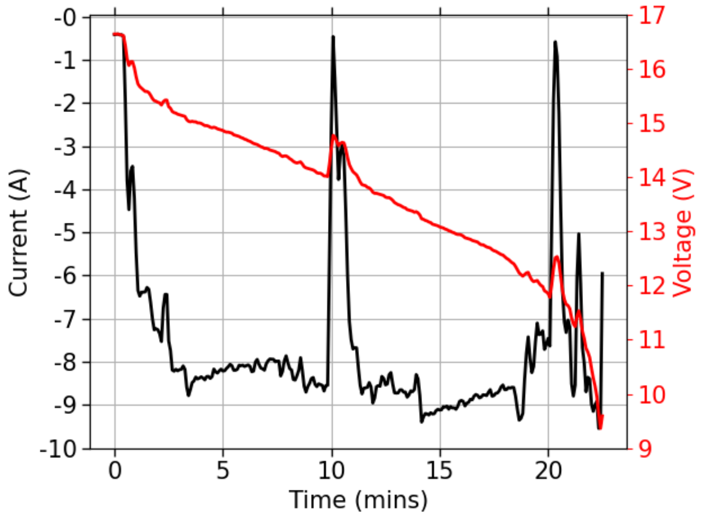
Experiment - Drone











Conclusion

BHMS

- BHMS showed close results to the Battery Analyzer values for the voltage and current.
- Edge and cloud communication was successfully established.

CD-Net

- Predicted capacity shows comparable values of capacity over the 10 cycles.
- By filtered data the prediction of CD-Net can be improved.

Drone versus ground

- Random current discharge were performed
- Discharge rate was at most 4C
- No-go signal based on SoC of battery

Acknowledgements

- Office of Naval Research (ONR)
- Dr. Tom Adams
- Dr. Corey Love
- Alex Serov, Meghana Sudarshan, Aishvarya Joshi, Dr. Casey Jones, Ritesh Gautam, Dr. Vikas Tomar (Interfacial Multiphysics Laboratory, Purdue University)

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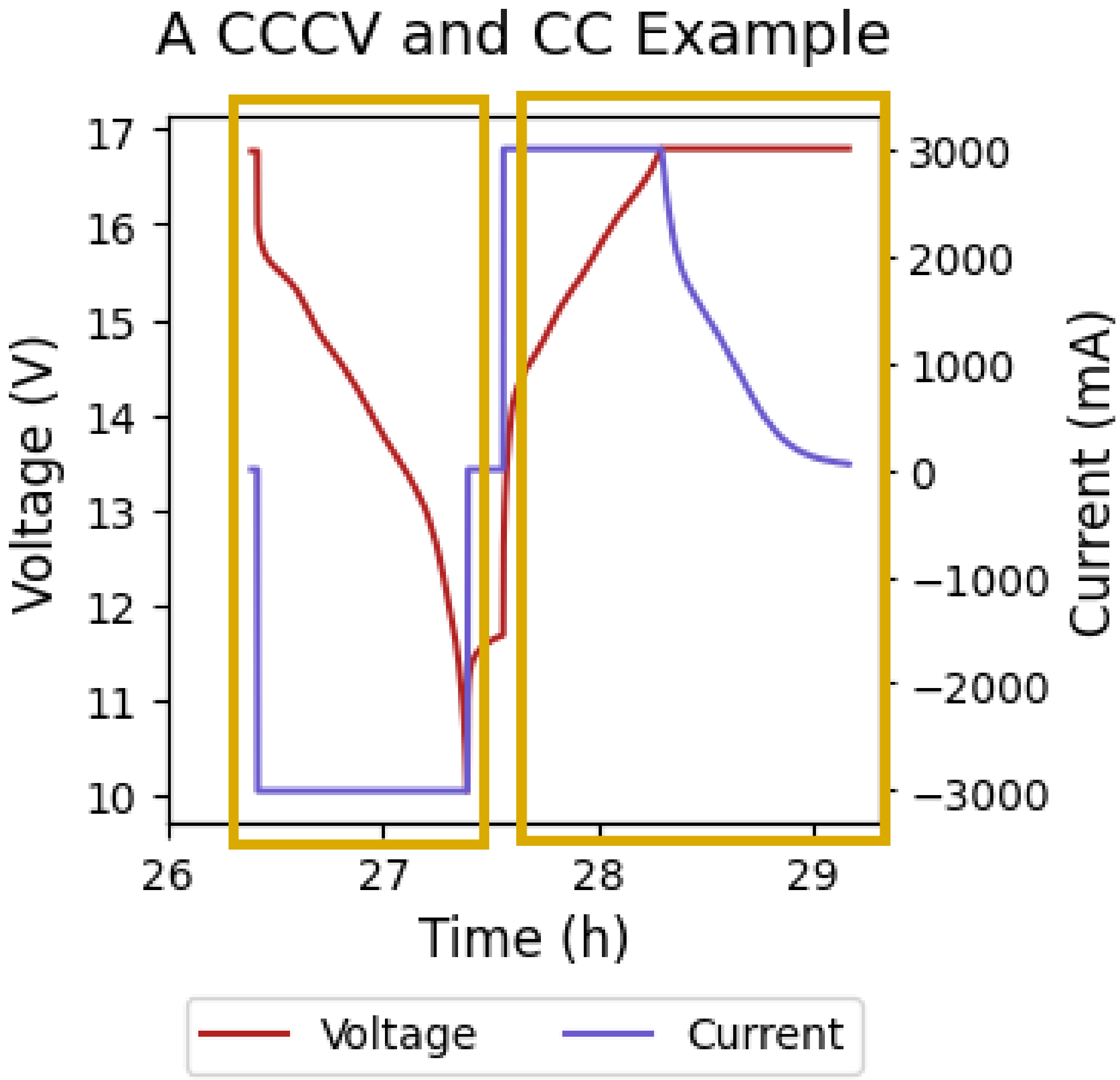
INTERFACIAL MULTIPHYSICS LAB

Questions?

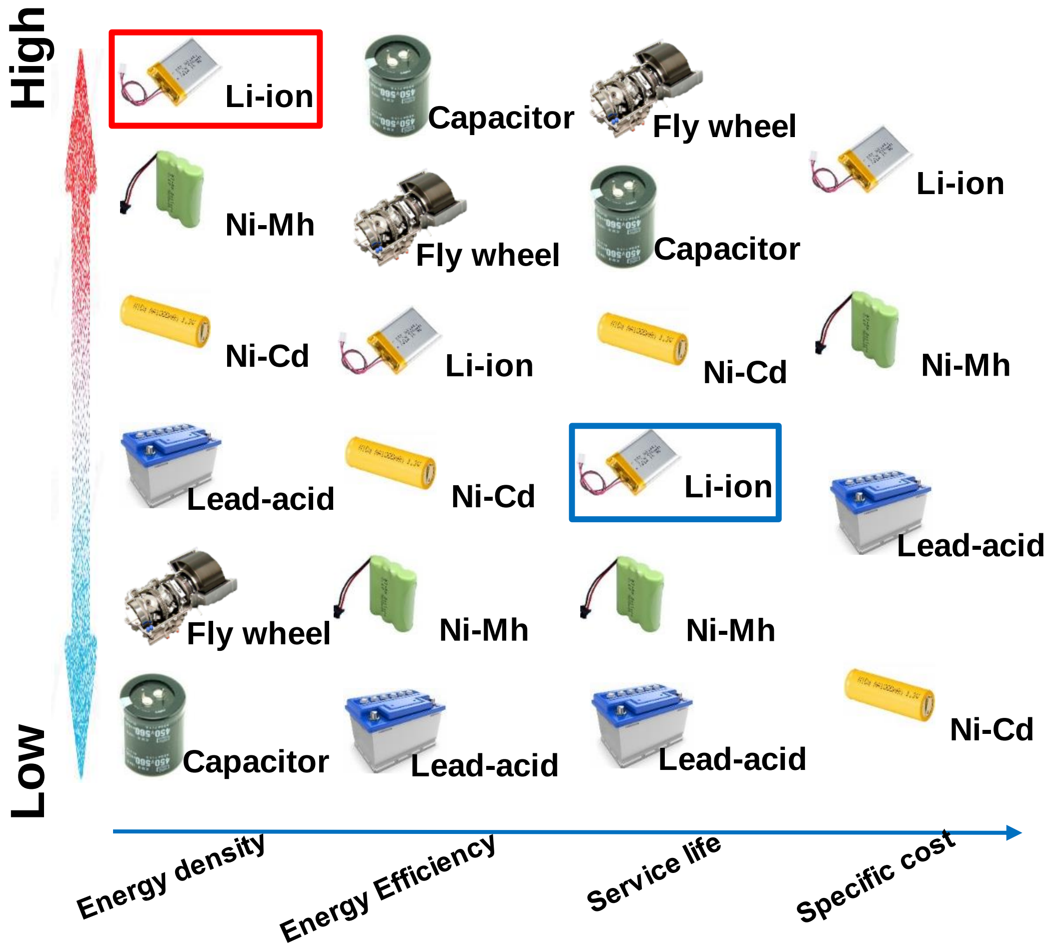
Background : Battery Cycling

Lithium-ion batteries degrade over time as they cycle

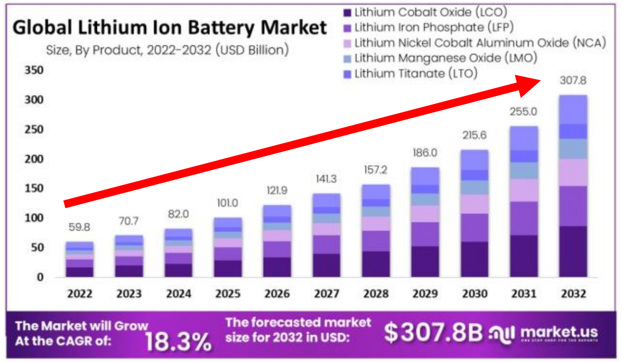
- A full cycle consist of a discharge and charge
- CC and CCCV are common charge algorithms
- C-rate of a battery



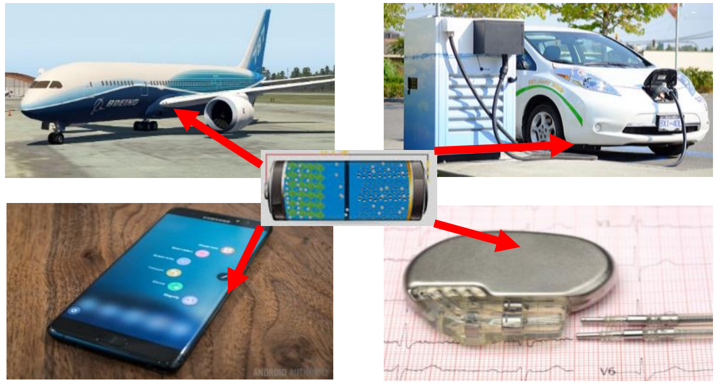
Lithium-ion Battery: Benefit and Market



Energy Storage System Comparison[1]



Lithium-ion Battery World Markets: 2022-2032[2]



[1] Figure by Multiphysics Lab, data from http://batteryuniversity.com/learn/archive/whats_the_best_battery
[2] https://www.globenewswire.com/en/news-release/2023/02/28/2617605/0/en/Lithium-Ion-Battery-Market-is-Slated-to-be-Worth-USD-307-8-Billion-by-2032-Market-Us.html

Background

- To practice safe operation of LIB batteries
  - State of Health needs to be examined during battery abusing operations.
  - Thermal runaway needs to be detected.
- Continuous monitoring of LIB is necessary!

Lithium-ion battery fires in New York on March 9, 2023 [4]

[4] https://www.cnn.com/2023/03/09/tech/lithium-ion-battery-fires/index.html#:~:text=The%20problem%20with%20lithium%20batteries&text=All%20lithium%2Dion%20batteries%20use,catastrophic%20explosion%2C%20according%20to%20Khoo.

Background : Related Dataloggers

Data loggers (DAQs) exist, but they are bulky, expensive, and application-specific

- National Instruments
- Omega Eng
- Battery Analyzers (BAn)

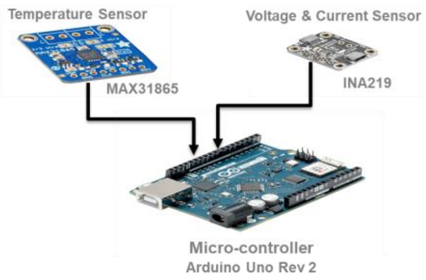
Figure : Neware BTS400 Battery Analyzer **[14]**

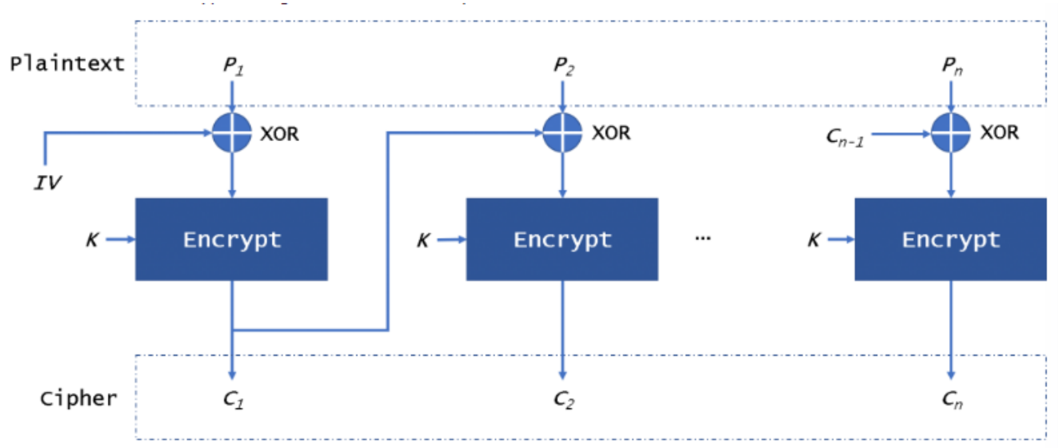
Figure : omega Engieering USB DAQ **[16]**

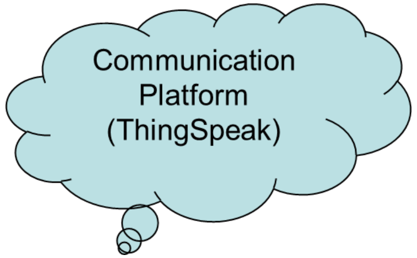
Figure : National Instruments DAQ options **[15]**

[14] https://cdn.shopify.com/s/files/1/1976/6951/products/tesla-model-s-lithium-ion-18650-ev-module-22-8-volt-5-3-kwh_590x_dc1c084f-894c-4a41-977e-8e936bb8bcef_720x.jpg?v=1601997995
[15] https://newarebattery.com/wp-content/uploads/2017/02/BTS4000-5V-series.png
[16] https://assets.omega.com/images/communication-and-connectivity/data-acquisition-modules/OMB-DAQ-2408_l.jpg?imwidth=450

Edge-Cloud communication



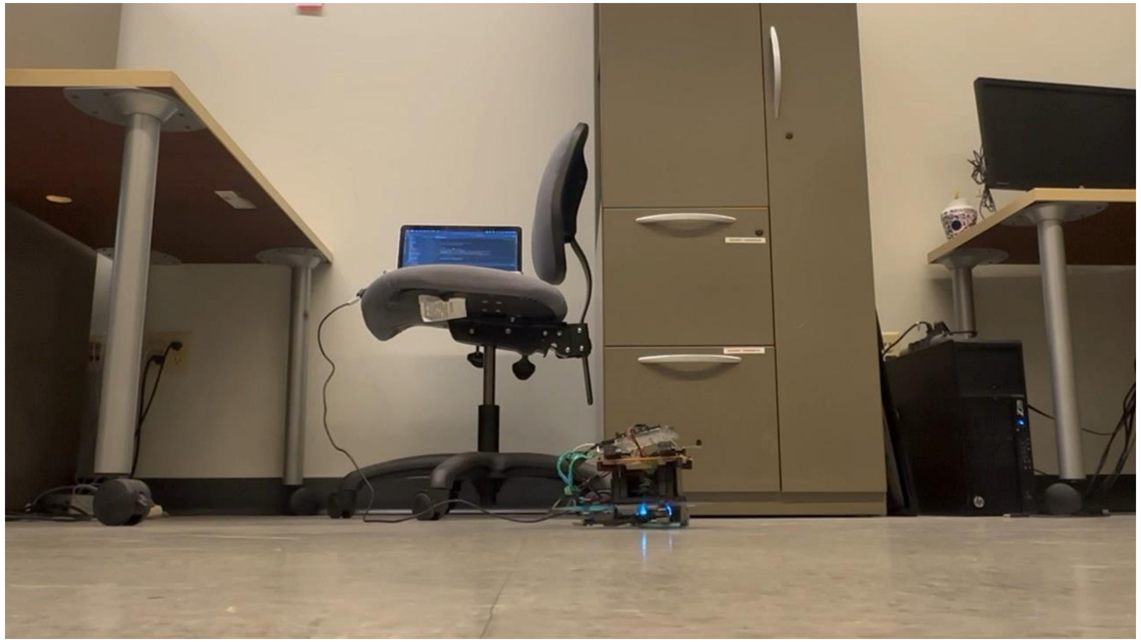




CBC encryption [1]

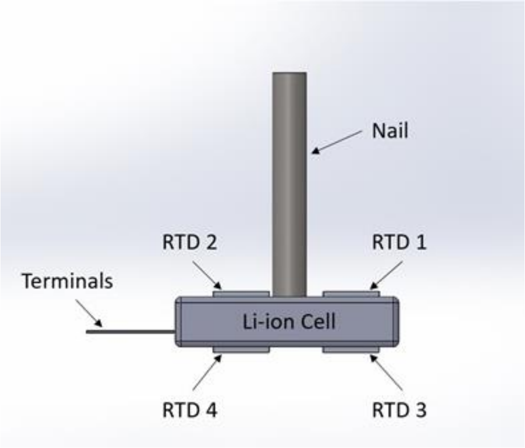
Data transfer from edge and cloud is Encrypted with AES.

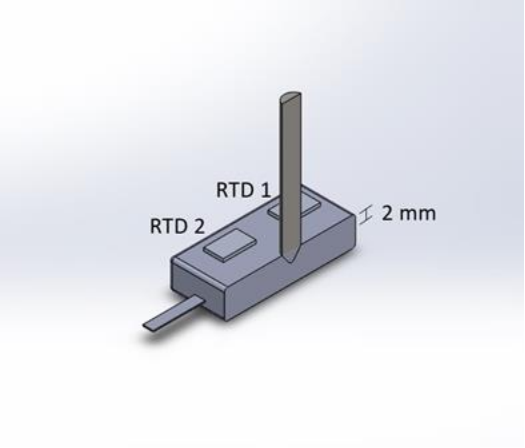
[7] https://www.highgo.ca/2019/08/08/the-difference-in-five-modes-in-the-aes-encryption-algorithm/

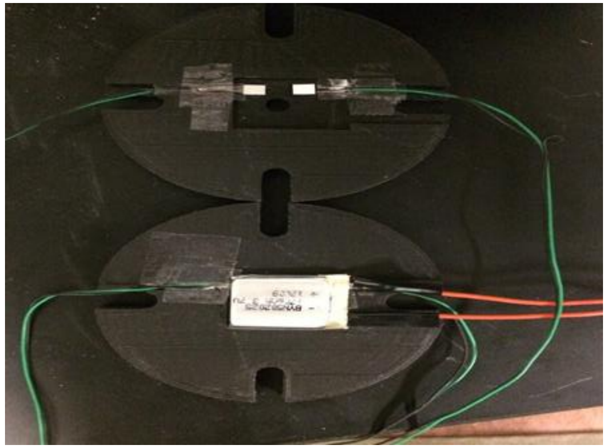


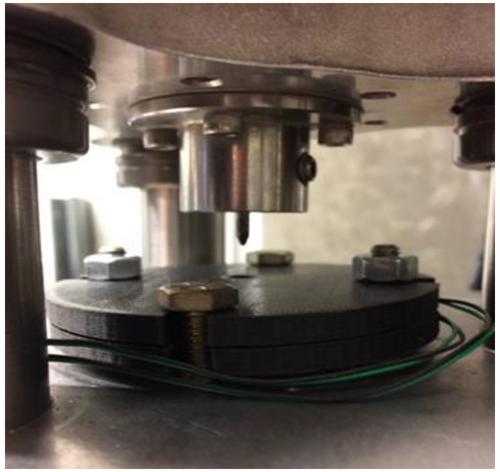
Integrating LIB abuse

- Mechanical abuse testing, nail penetration
  - Previous study by Dr. Casey at Interfacial Multiphysics Lab
- Future work-
  - use nail penetration integrated with BHMS.









Jones, C., Li, B., and Tomar, V., "Determining the Effects of Non-Catastrophic Nail Puncture on the Operational Performance and Service Life of Small Soft Case Commercial Li-Ion Prismatic Cells," eTransportation 8 (2021): 100109