Vehicle-level thermal safety of lithium-ion batteries: Experimental analysis and method

Changfu Zou, *Associate Professor*
Department of Electrical Engineering
Chalmers University of Technology, Sweden

Scandinavian Conference on System and Software Safety
Göteborg | 20 November 2024

Outline

- Our BMS research group at Chalmers
- Literature review
- Vehicle-level experiments and analysis
- Our further research toward safety

Our BMS group at Chalmers

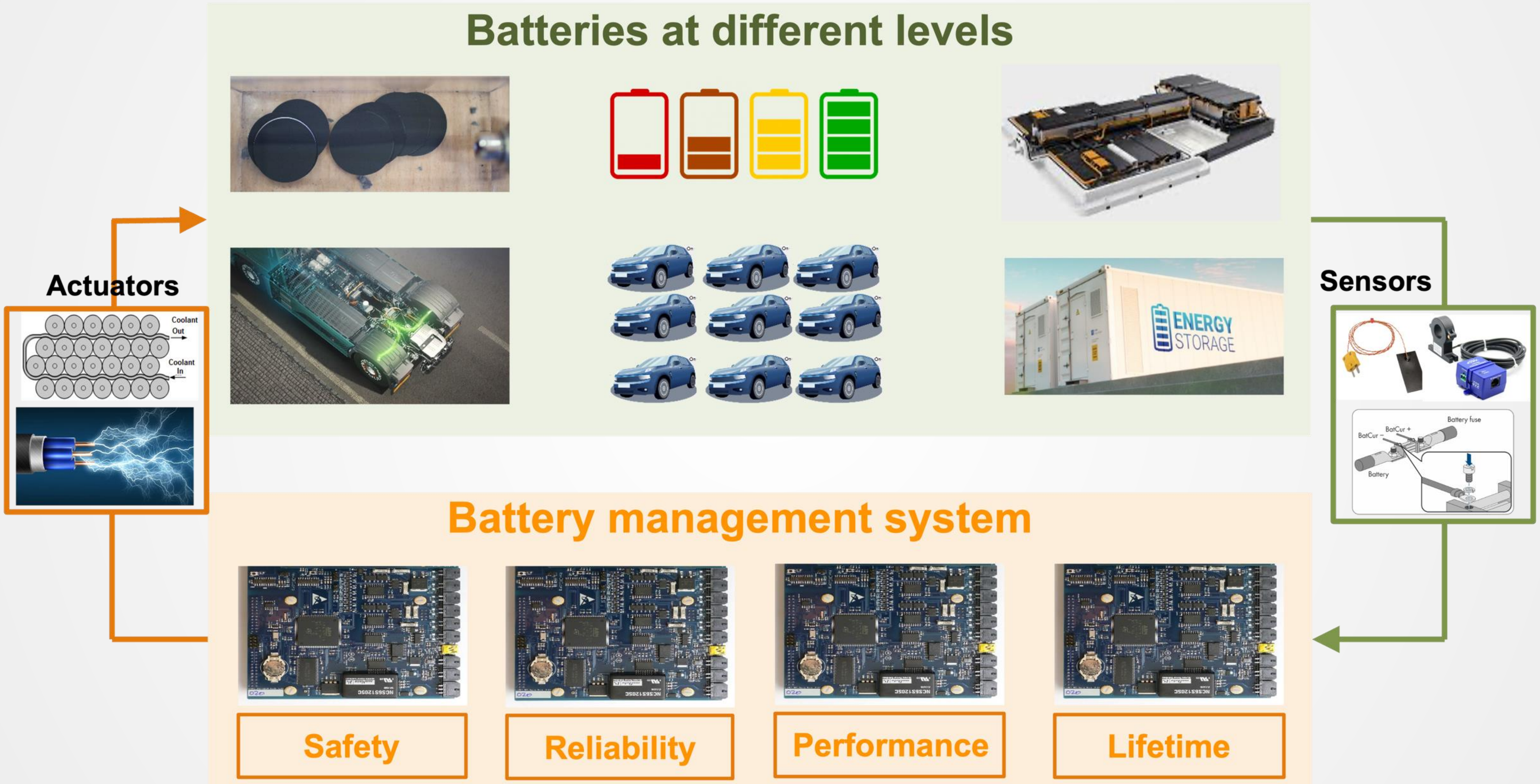
Professors:
- Prof. Torsten Wik (~80% on battery)
- Assoc. Prof. Changfu Zou (100%)

Members:
- 5 researchers/postdocs (4 Marie Skłodowska-Curie Fellows)
- 10 full-time PhD students
- ~10 MSc thesis projects/year

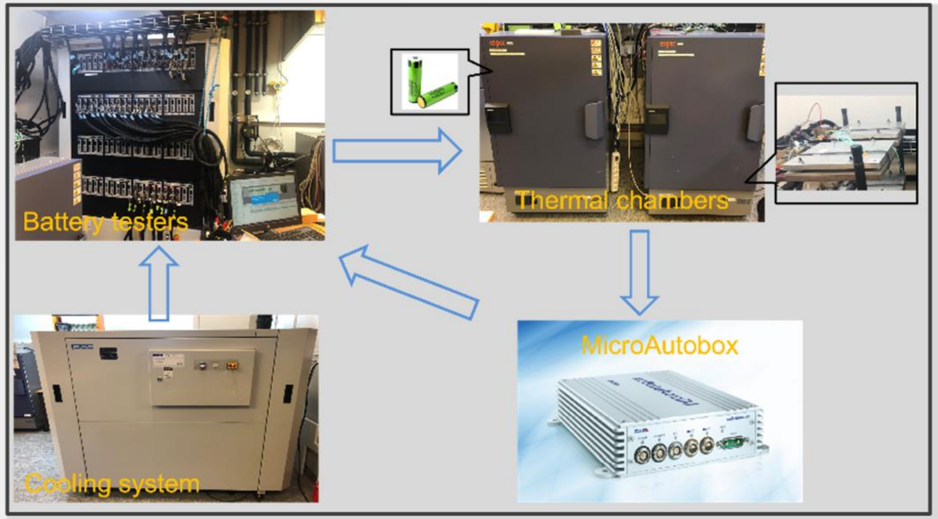
Main funders:
- Swedish Energy Agency (FFI, Batterifond, SEC, SESBC)
- Swedish Research Council
- Swedish Innovation Agency (incl. BASE)
- EU Commission

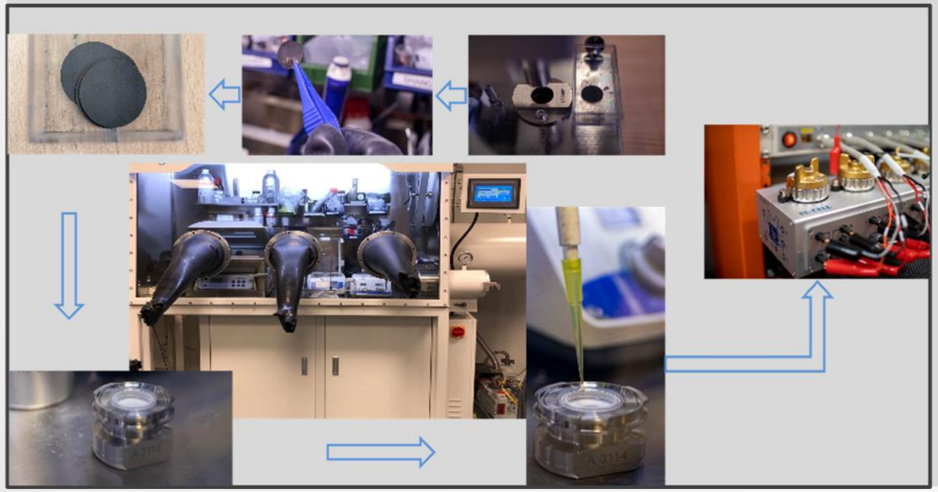



Our research interest



Our research activities: in the real world





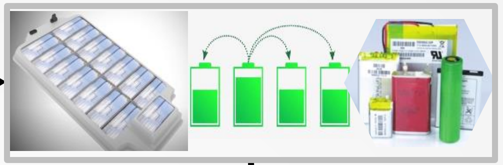
Our research activities: mainly computer-based

Optimizer

Ref.

Controller
(or with RL)

Actuator



Sensor
(External/Internal)

Environment
Usage Info

Feedback

Data log
(Cloud/Local)

Monitor & Predictor
(Digital Twin)

Battery models are needed everywhere (physics-based [16-17], physics-based ECM [18], data-based [5,19], or hybrid [20])

Strain, fiber optic, gas [1], and graphene-based electrochemical sensors

SoC [2], SoP (cell- and pack-level [3-4]) SoH, RUL [5], physical variables [6]

Optimization in slow-time scale or on the system (vehicle) level [7-9]

Control of fast charging [10-12], SoC balancing [13-14], cooling system, and configuration [15]

[1] *Bian X., et al.*, Under review.
[2] *Zou C., et al.*, IEEE TIE, 2018.
[3] *Zou C., et al.*, JPS, 2018.
[4] *Han W., et al.*, IEEE TTE, 2022.
[5] *Zhang Y., et al.*, IEEE TTE, 2023.
[6] *Li Y., et al.*, IEEE TII, 2021.
[7] *Hu X., et al.*, IEEE TPEL, 2020.
[8] *Lee C.F., et al.*, IFAC, 2023.
[9] *Zhu Q., et al.*, IEEE TTE, 2024.
[10] *Zou C., et al.*, IEEE T-MECH, 2018.
[11] *Li Y., et al.*, IEEE T-EC, 2022.
[12] *Li Y., et al.*, IEEE T-CST, 2023
[13] *Tang X., et al.*, IEEE TPEL, 2020.
[14] *Ouyang Q., et al.*, IEEE TII. 2020.
[15] *Han W.*, et al., IEEE TSG. 2020.
[16] *Zou C., et al.*, IEEE T-CST, 2016.
[17] *Xie Y., et al.*, IEEE TPEL, 2019.
[18] *Li Y., et al.*, IEEE TTE, 2022.
[19] *Zhang Y., et al.*, JPS, 2022.
[20] *Huang Y., et al.*, IEEE TPAMI, 2024.

TRA445
Advanced Battery Modelling and Control

Tracks Project Course (7.5 credits)

Battery Management Systems (BMS) are essential for ensuring the safe and efficient operation of batteries, particularly in electric vehicles and energy storage systems. This course covers key aspects of BMS, including modelling, state estimation, and control.

BACKGROUND

Students will explore techniques such as equivalent circuit modelling, physics-based insights, and data-driven methods, along with practical exercises on state-of-charge (SOC), state-of-health (SOH) estimation, cell balancing, and power-limiting strategies.

Lecturers

Torsten Wik
Changfu Zou
Xiaolei Bian
Yicun Huang
Industrial guest lecturers

Course Structure

Pre-requisites: basic course in automatic control, basic knowledge in electrical engineering and linear algebra, and experience in programming.

Duration (provisional): Study period 3 (Jan-March) 7 weeks (10*2h Lectures + 9*2h Computer labs + 2*3h Hands-on labs)

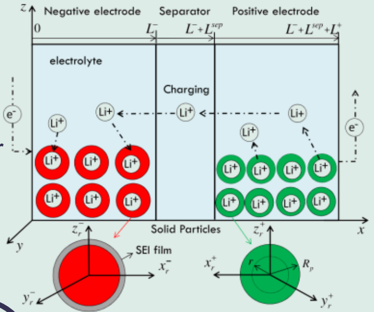
Format: Lectures, exercises, labs and final assignment

Introduction

BMS fundamental components **and its functionalities**

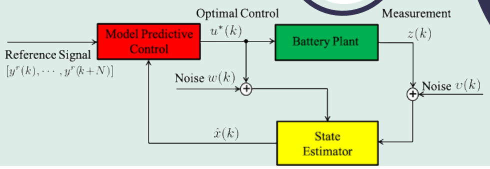
Modelling & Estimation

- **Equivalent circuits**
- **Electrochemical and thermal models**
- **Kalman filter and state estimation**
- **Battery pack dynamics, constant power and voltage simulations**



Control & Diagnostics

- **Model-based optimal control**
- **Data-driven battery aging diagnostics and prognostics**



Battery pack

- **Cell balancing techniques**
- **State of power and voltage-based power limit estimation**

FINAL PROJECT

Comprehensive BMS Simulation and Control

Interested?

Apply between November 12–26 through the application systems NyA and antagning.se for the track course. PhD students, alumni, and professionals should apply via email directly to the examiner, Prof. Changfu Zou, at changfu.zou@chalmers.se.

CHALMERS UNIVERSITY OF TECHNOLOGY

Battery course is open for both academia and industry

Application deadline: **Nov 26, 2024**

Delivery: Spring 2025

Chalmers Course: TRA445 Advanced Battery Modelling and Control

Changfu Zou
21 Nov 2024

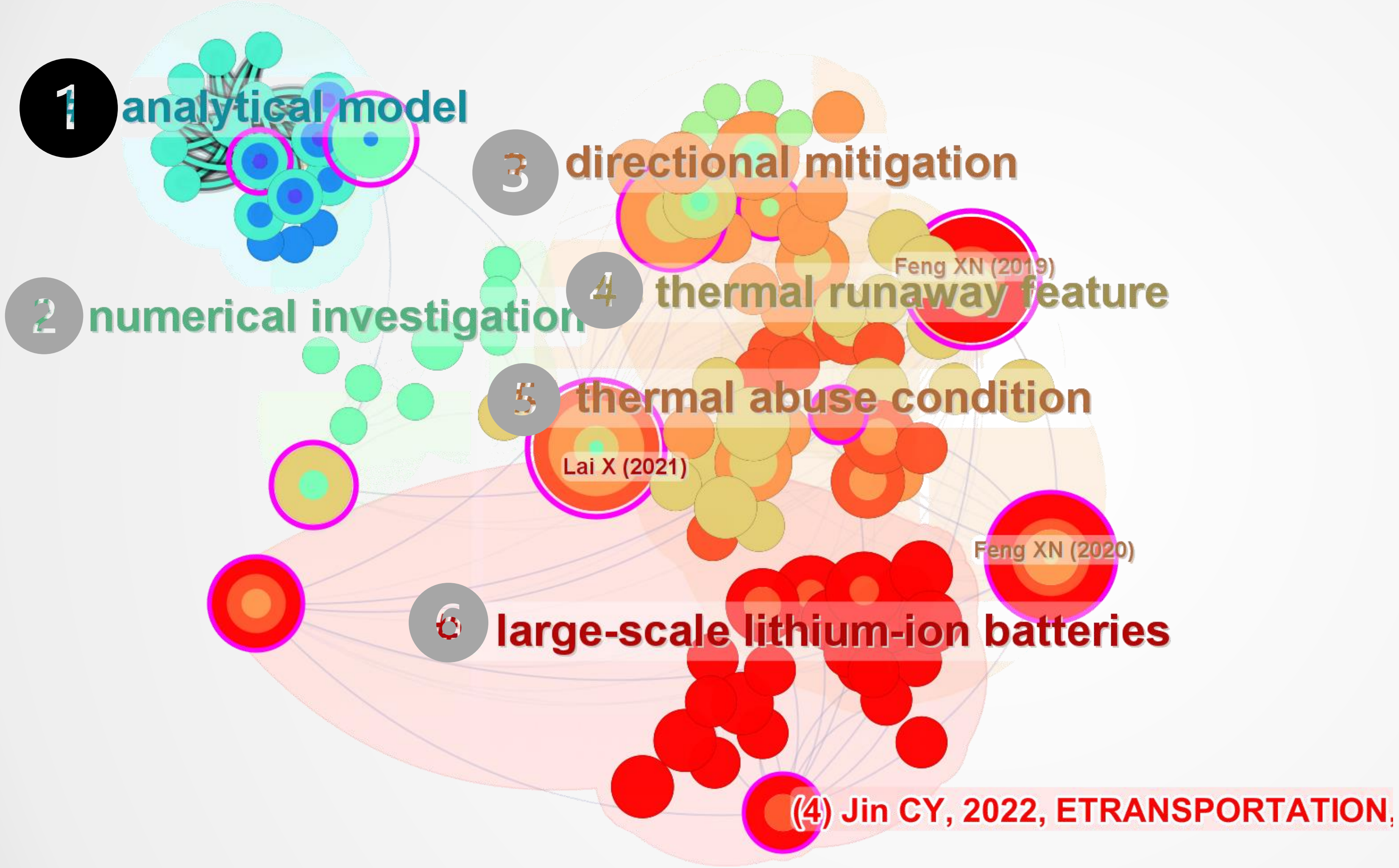
ESOC Energy Systems and Optimal Control Lab

CHALMERS UNIVERSITY OF TECHNOLOGY

Outline

- Our BMS research group at Chalmers
- Literature review
- Vehicle-level experiments and observations
- Our further research toward safety

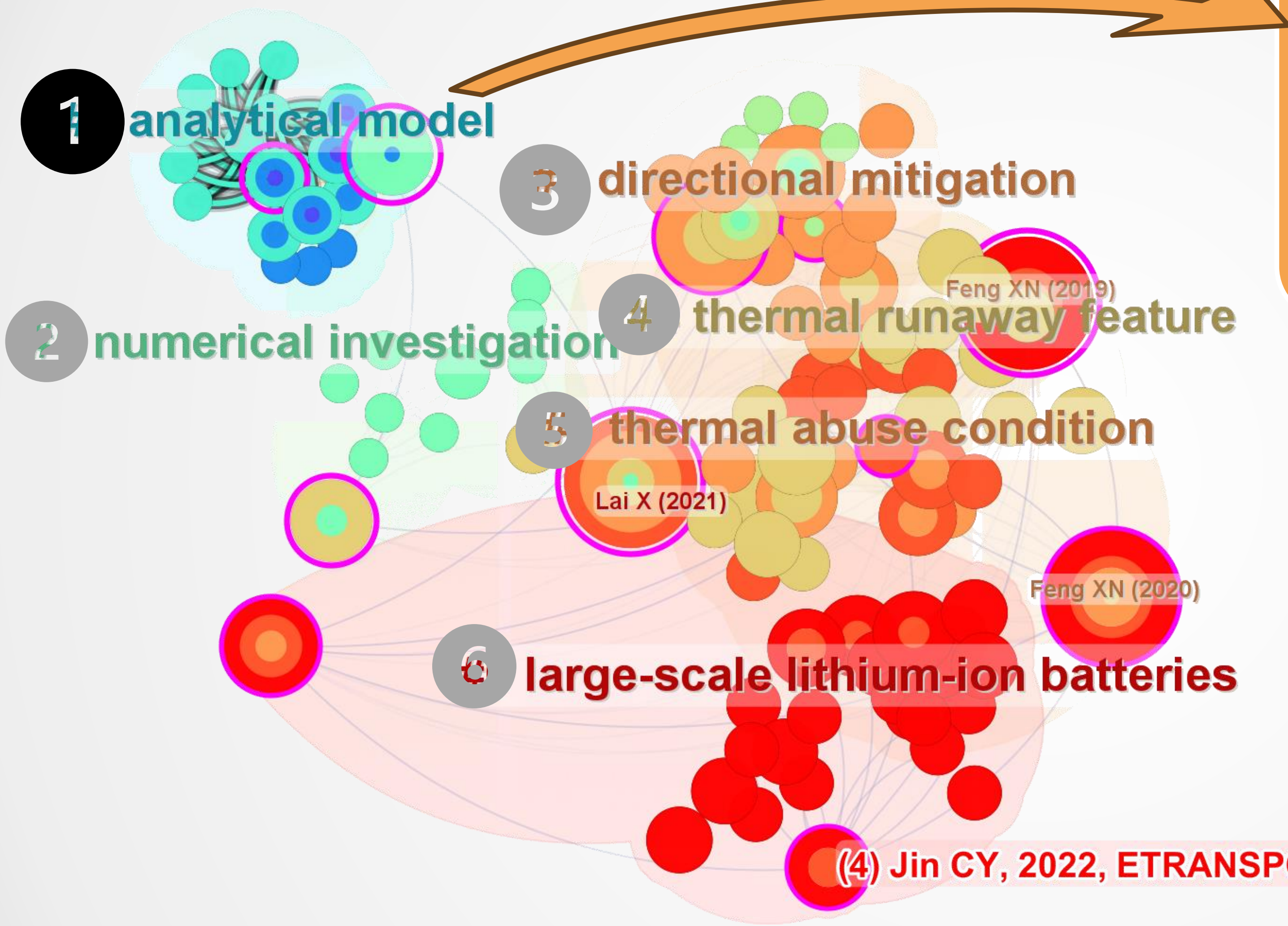
State of Research: Battery thermal safety



Yicun Huang, *Researcher and MSCA Fellow*

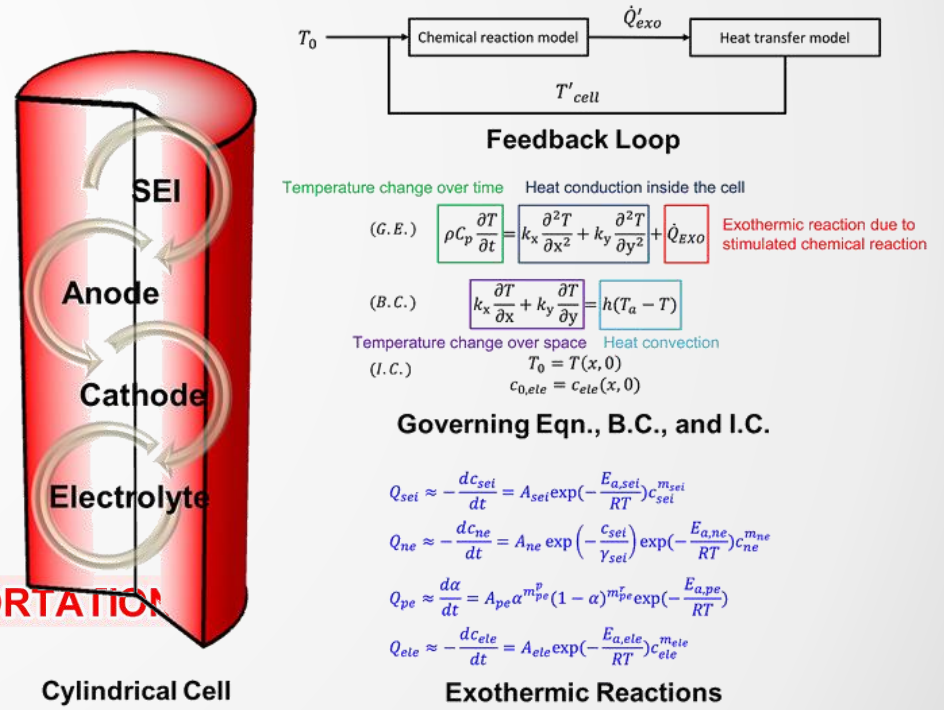
Sources: Web of Science and CiteSpace

State of Research 2014-2018



Analytical Modeling of Idealized Systems

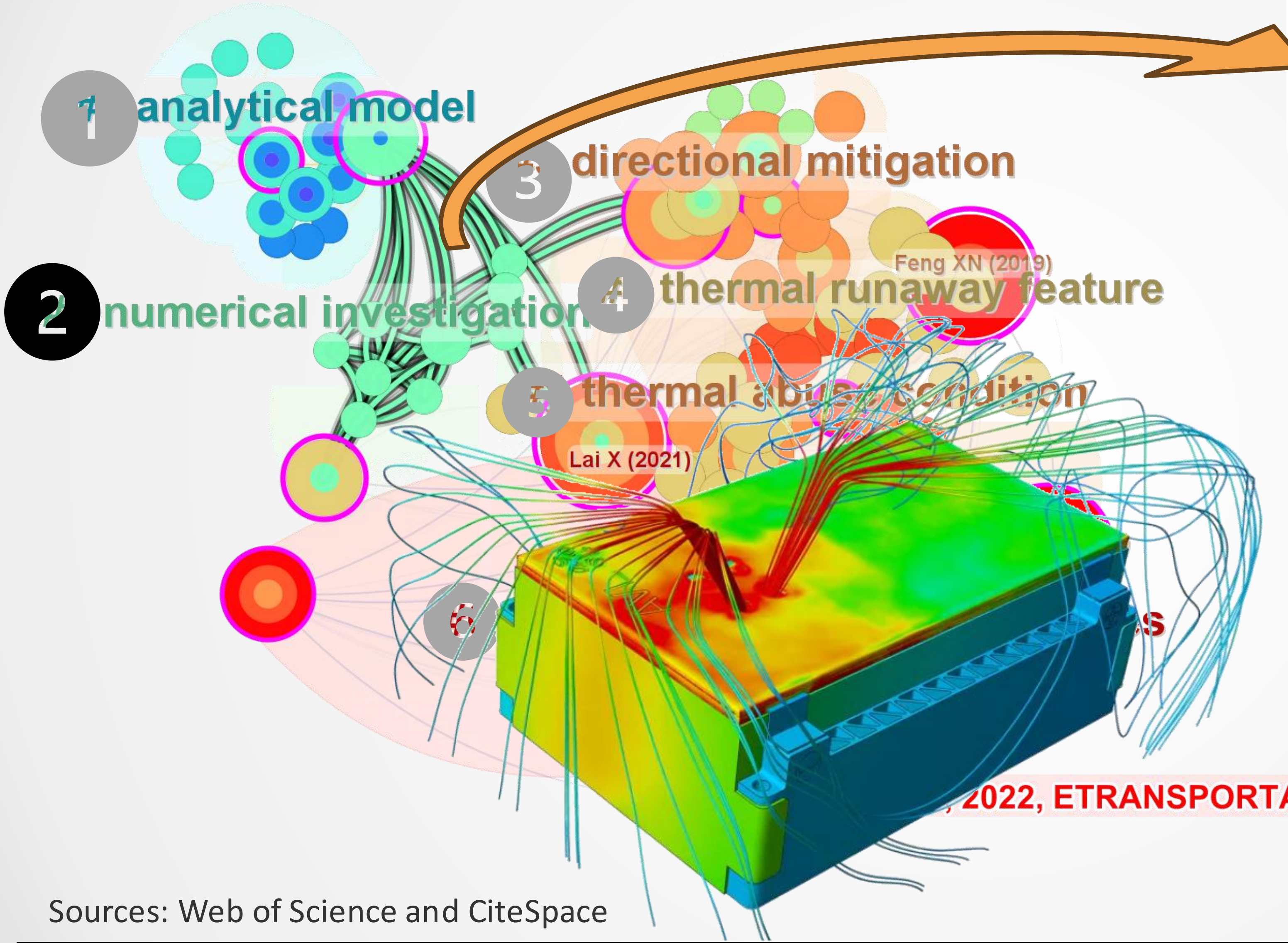
- Simplified to the underlying thermal dynamics within LIBs
- Foundational understanding of the critical parameters
- Does not capture real-world behaviors



Kim et al. Modeling and prediction of lithium-ion battery thermal runaway via multiphysics-informed neural network

Sources: Web of Science and CiteSpace

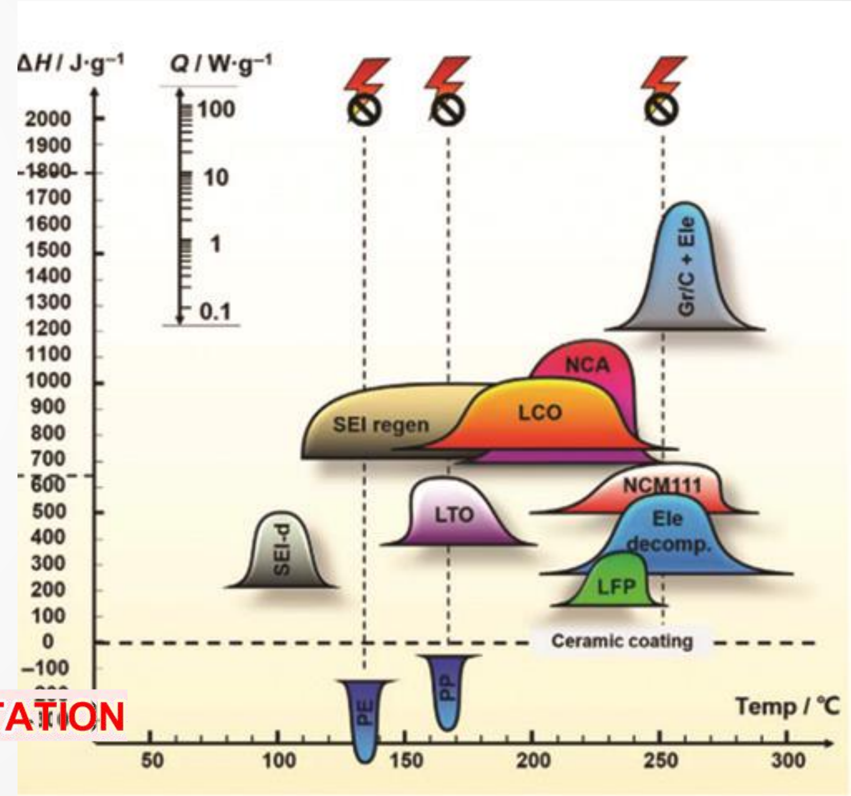
State of Research 2019



Sources: Web of Science and CiteSpace

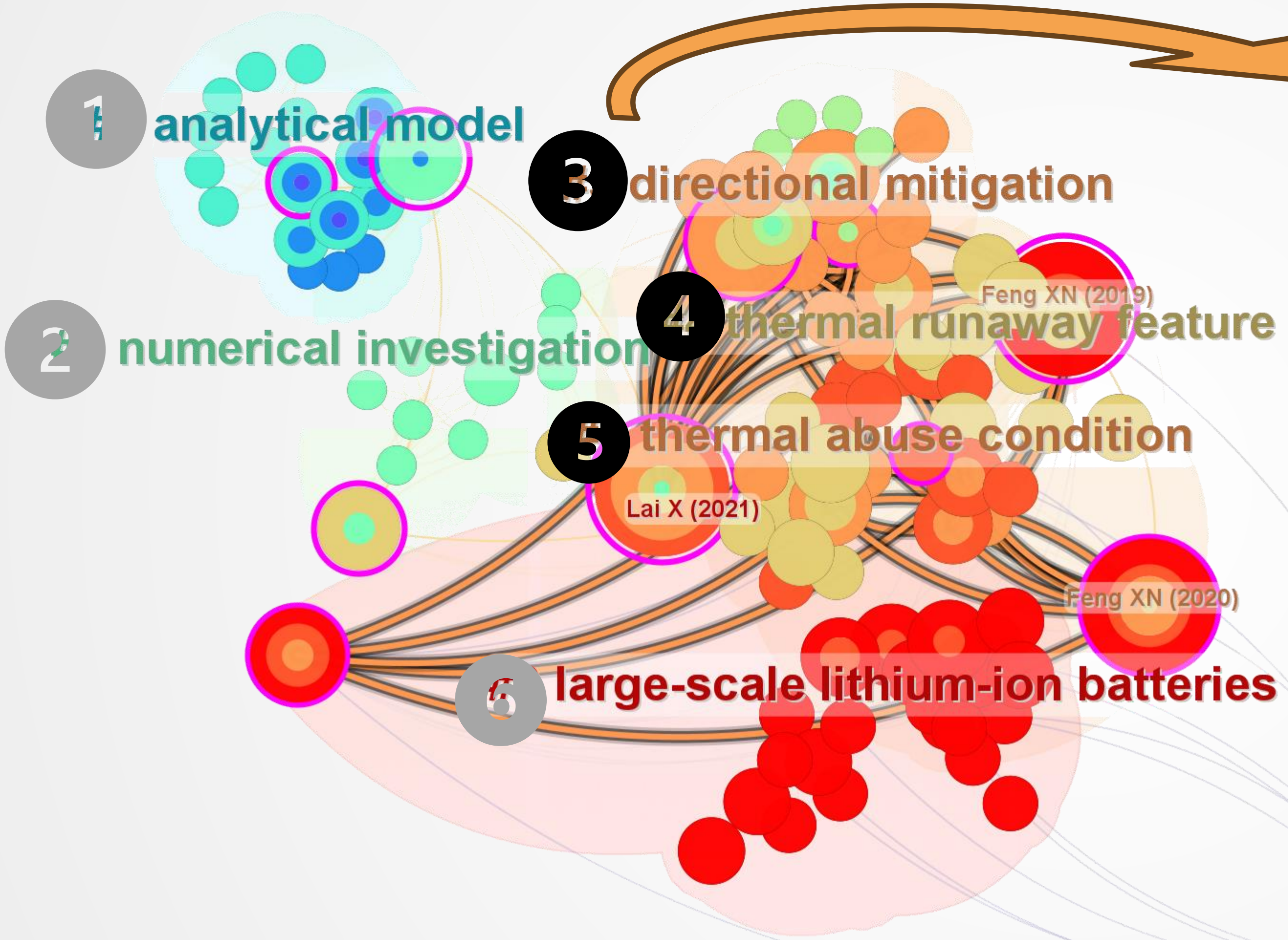
Numerical Modeling

- Localized temperature variations
- Multi-phase reactions
- Spatial heterogeneities



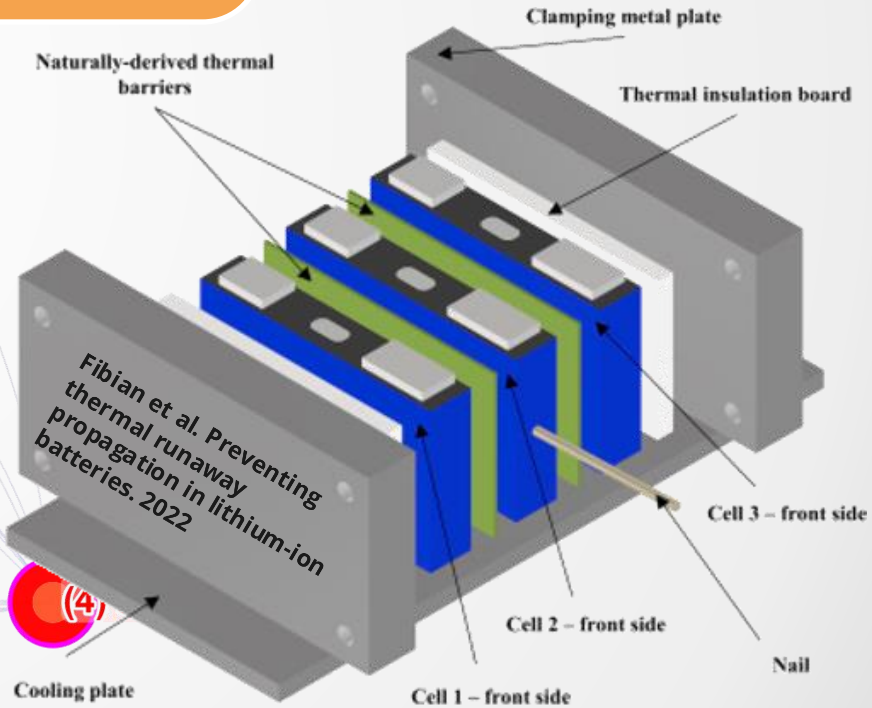
Zhang et al. A Critical Review of Thermal Runaway Prediction and Early-Warning Methods for Lithium-Ion Batteries. 2023

State of Research 2020-2022



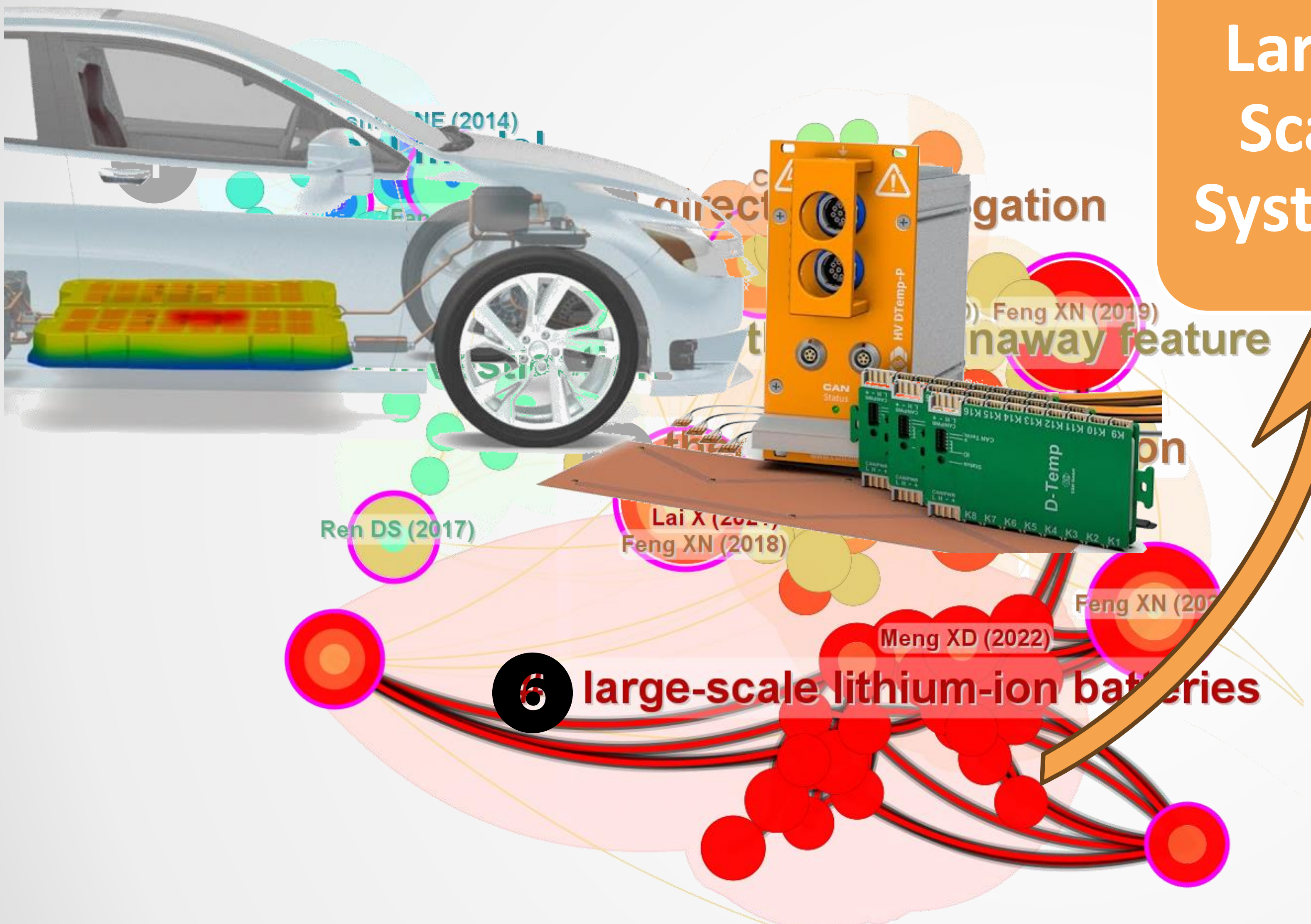
Directional Mitigation & Thermal Runaway Features

- Thermal barriers, cooling channels, and phase change materials
- Temperature thresholds, pressure buildup, and gas emissions
- Thermal abuse tests



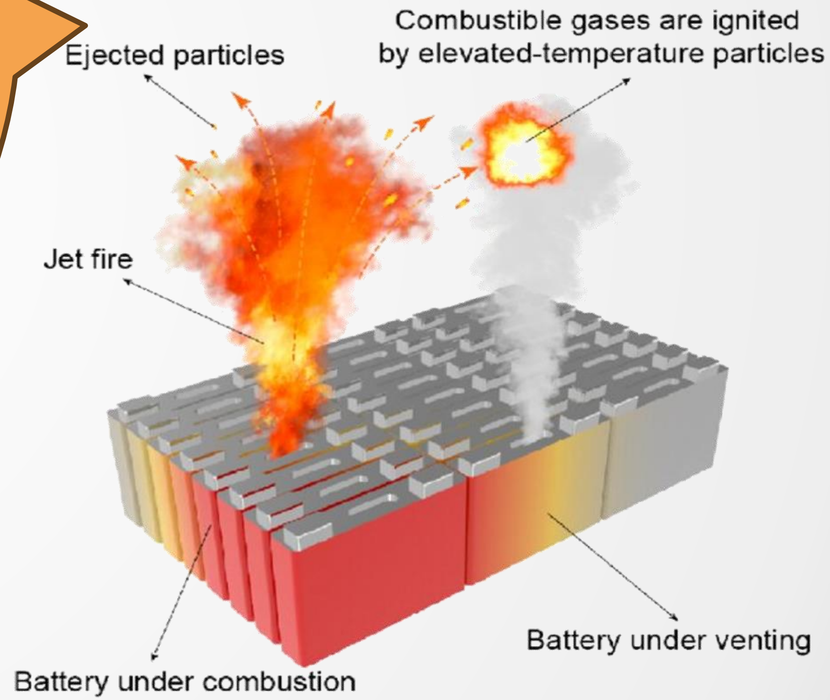
Sources: Web of Science and CiteSpace

State of Research 2023 to present



Large-Scale Systems

- Interactions across 100+ of cells within a confined space
- Propagation control and containment
- Multiscale modeling, fire-resistant materials and venting designs



Sources: Web of Science and CiteSpace

Wang et al. Revealing particle venting of lithium-ion batteries during thermal runaway. eTransportation. 2023

Outline

- Our BMS research group at Chalmers
- Literature review
- Vehicle-level experiments and analysis
- Our further research toward safety

Background

Research project

RESEARCH.chalmers.se

Thermal safety management for vehicle battery systems

Research Project, 2020 – 2023

VINNOVA
Sweden's Innovation Agency

Paper manuscript

Electric Vehicle Thermal Runaway: Insights from Vehicle-Level Experiments and Analysis

Jinghan Zhang[a,b,c], Qingbo Zhu[c], Zhenpo Wang[a,b], Peng Liu[a,b,*], Yicun Huang[c], Tengfeng Jiang[a,b], Ni Lin[a,b], Quan Sun[d], Zhiwei Zhao[d], Zhu Yana[a,b], Shengxu Huang[a,b], Zirun Jia[a,b], Torsten Wik[c], Changfu Zou[c,**]

[a]*National Engineering Research Center for Electric Vehicles, Beijing Institute of Technology, Beijing, 100081, China*

[b]*School of Mechanical Engineering, Beijing Institute of Technology, Beijing, 100081, China*

[c]*Department of Electrical Engineering, Chalmers University of Technology, Gothenburg, 412 96, Sweden*

[d]*Viridi E-mobility Technology (Ningbo) Co., LTD., Ningbo, 315336, China*

Torsten Wik
Professor at Chalmers

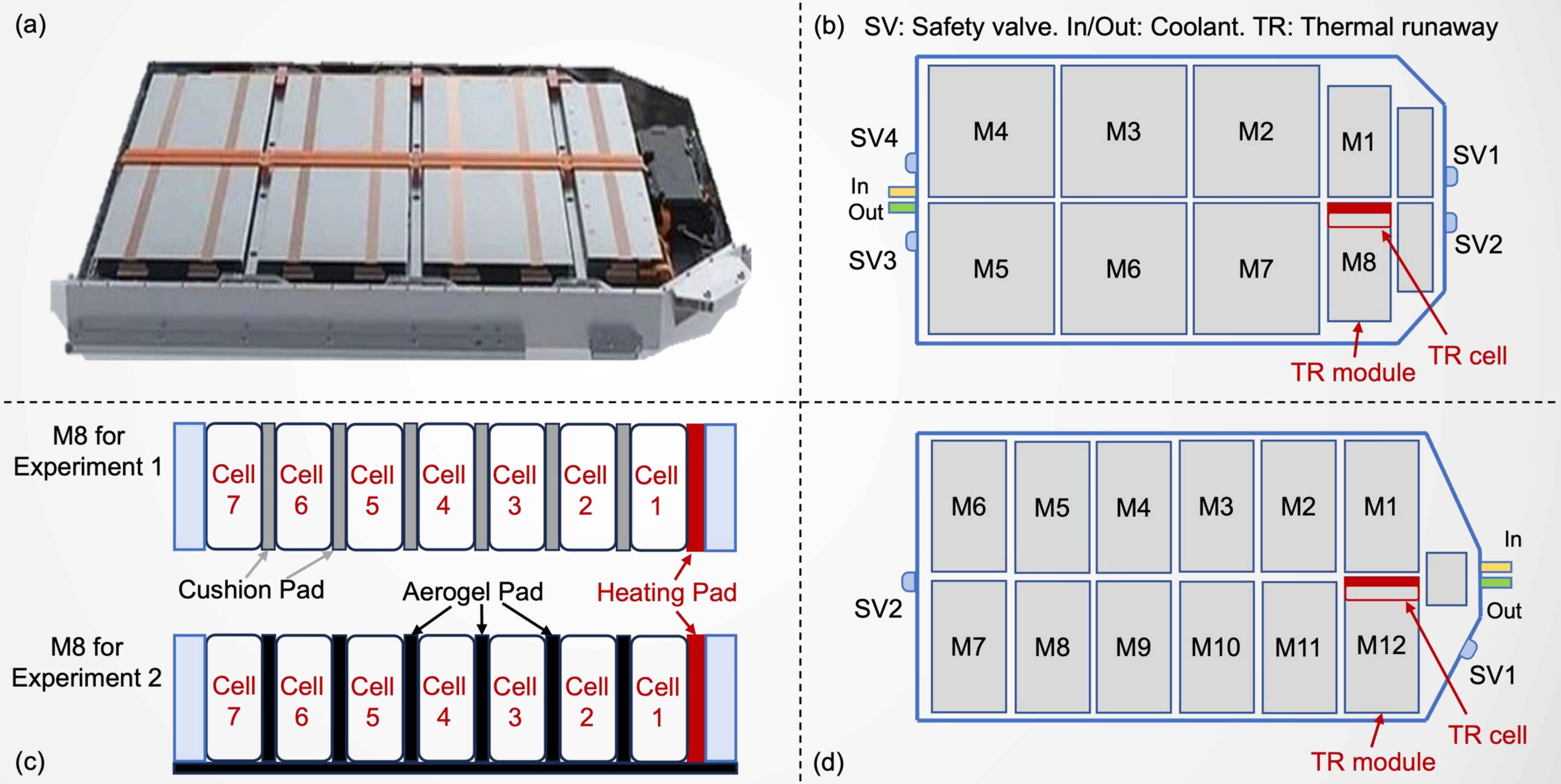
Jinghan Zhang, PhD from BIT
Visiting PhD at Chalmers

Zhang, J., et al. Electric vehicle thermal runaway: Insights from vehicle-level experiments and analysis (under review).

Vehicle-level experiments: Vehicle and battery

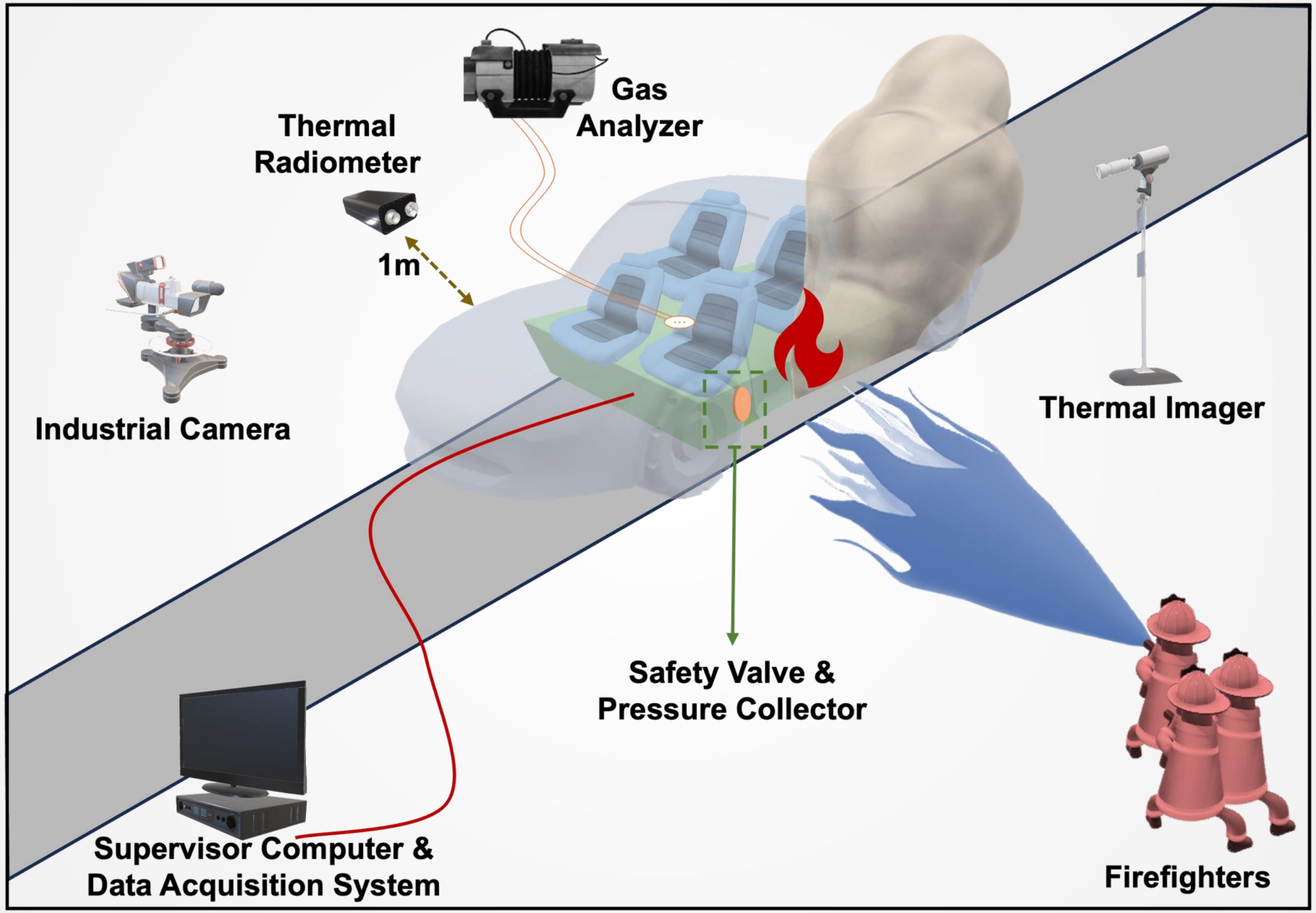
Battery packs from 2 SUVs (same type and model)

Cells arranged in the module



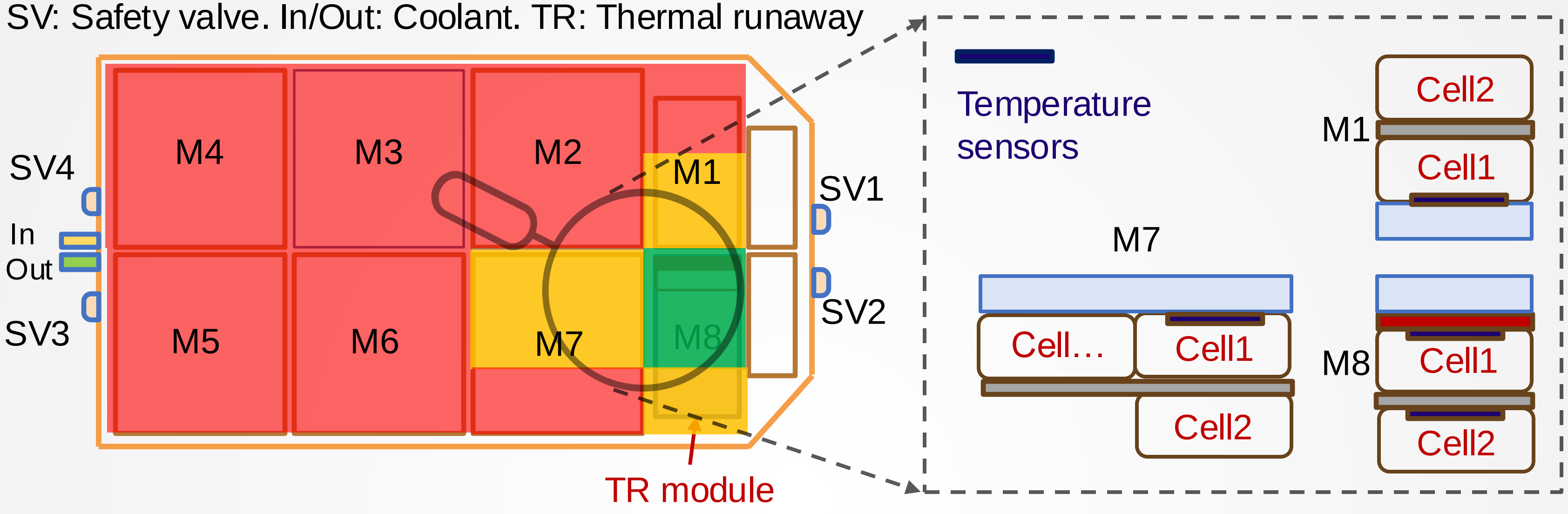
Changfu Zou
21 Nov 2024

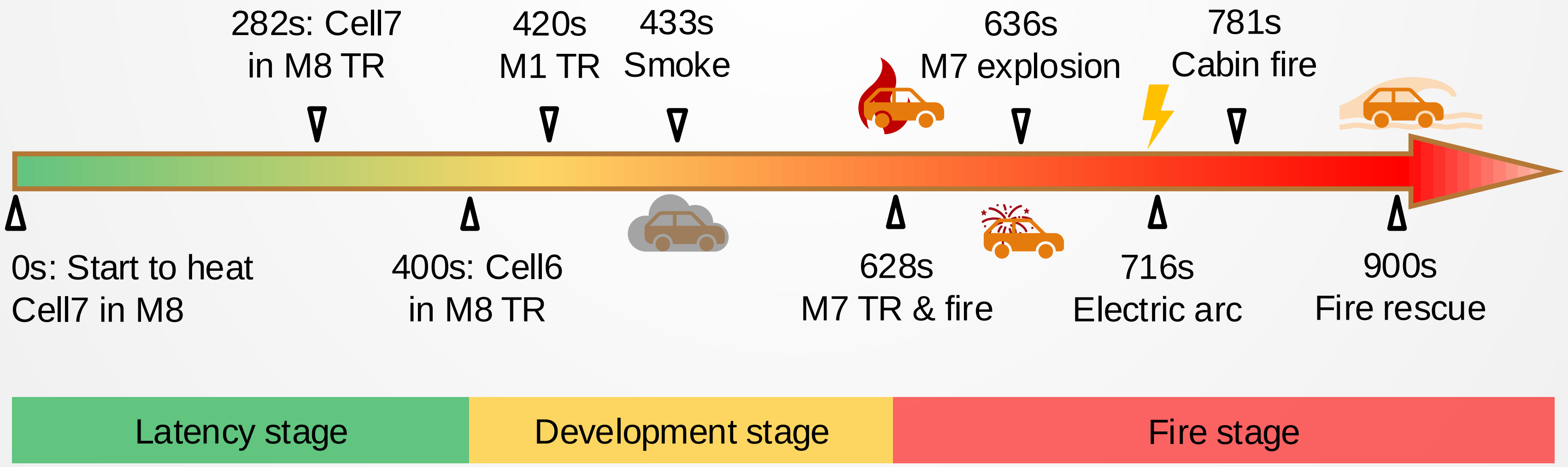
Vehicle-level experiments: Equipment setup



Vehicle-level experiments: Observations

SV: Safety valve. In/Out: Coolant. TR: Thermal runaway



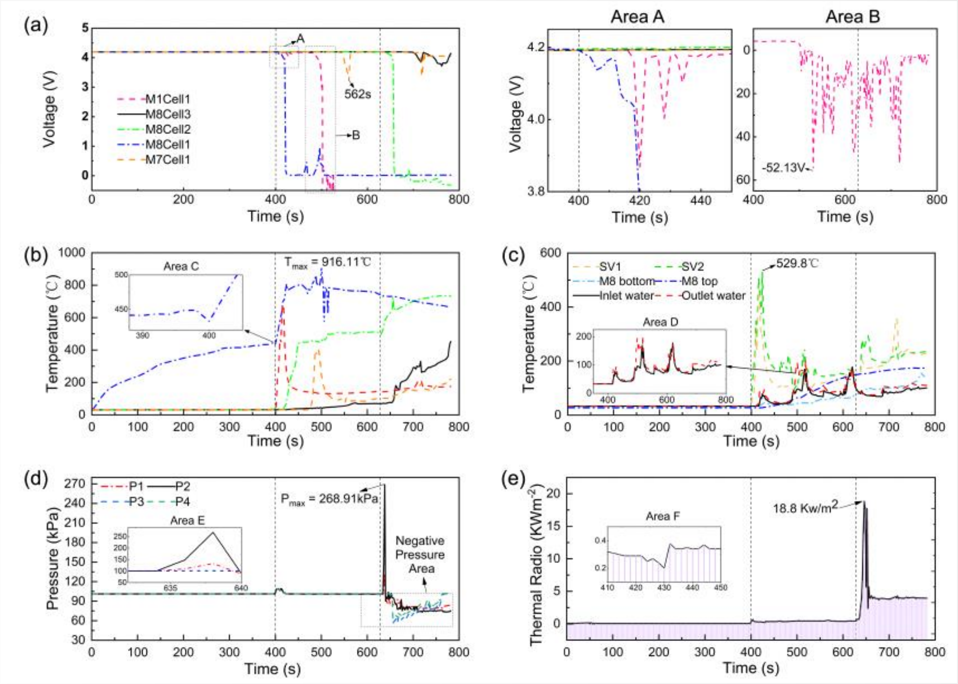


Changfu Zou
21 Nov 2024

Vehicle-level experiments: Analysis

Latency stage of EV thermal runaway:

- Cell voltage remained stable initially, with minimal pack-level impact.
- Surrounding cells showed no visible damage.
- Timely isolation minimized losses, enabling potential vehicle recovery.

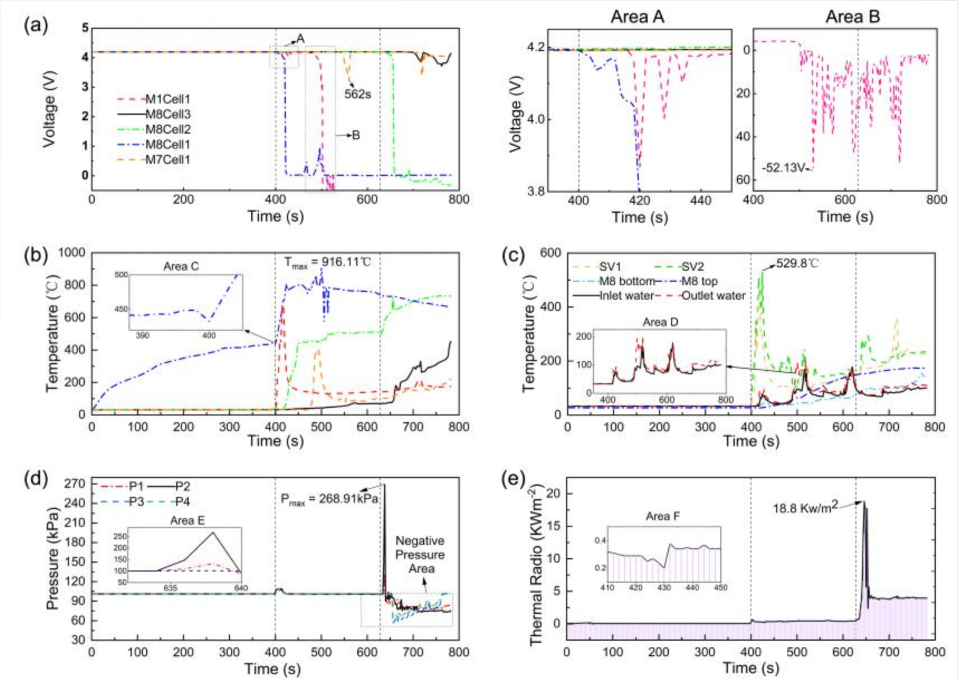


Changfu Zou
21 Nov 2024
ESOC Energy Systems and Optimal Control Lab
CHALMERS UNIVERSITY OF TECHNOLOGY

Vehicle-level experiments: Analysis

Development stage of EV thermal runaway:

- Internal pressure rose rapidly, >100 kPa within 10s due to gas generation;
- Pressure relief valves activated, delaying the explosion;
- Internal short circuits caused sharp voltage drops;
- Active cooling system initially slowed propagation but reached saturation.



Changfu Zou
21 Nov 2024

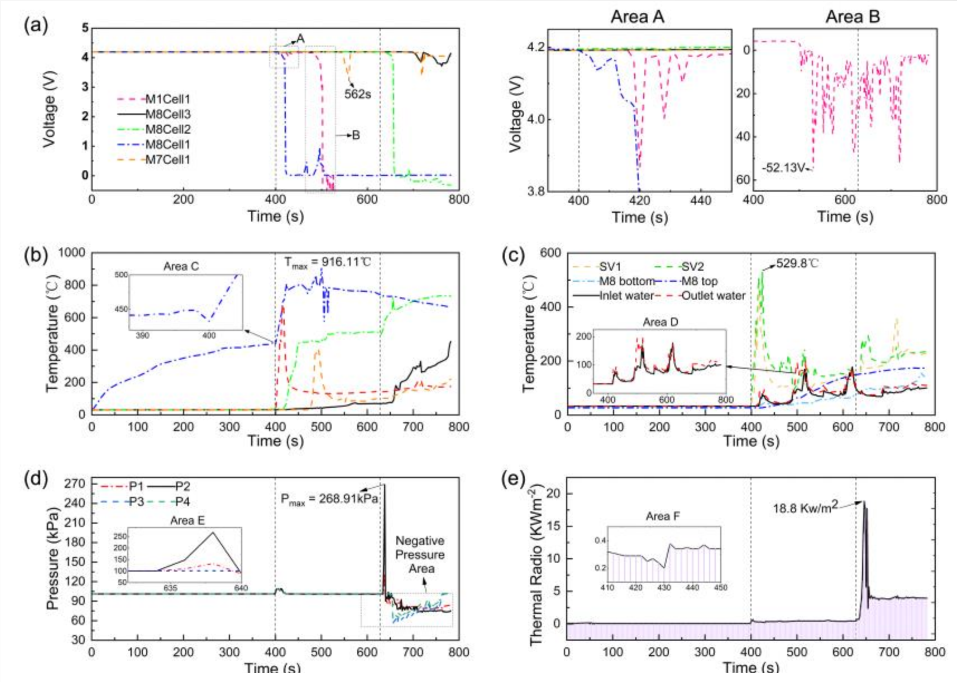
ESOC Energy Systems and Optimal Control Lab

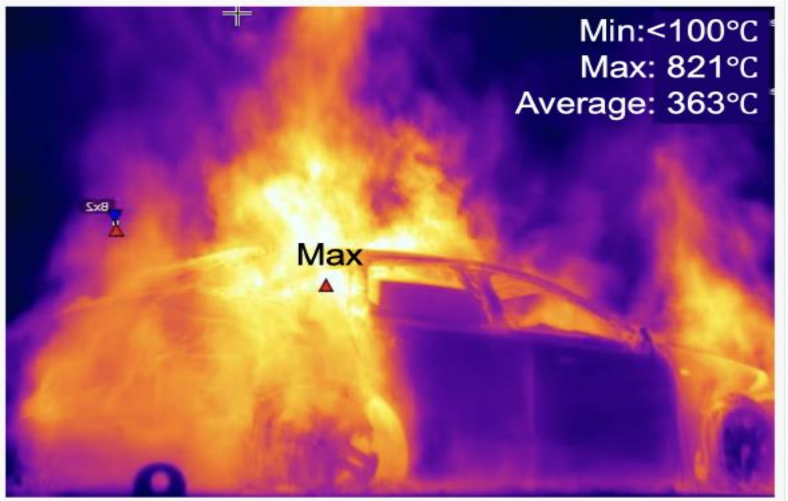
CHALMERS UNIVERSITY OF TECHNOLOGY

Vehicle-level experiments: Analysis

Fire stage of EV thermal runaway:

- The maximum temperature >800^{o}C, thick black smoke, large flames, and explosions;
- Negative voltage in cells due to electrical arcing (tires insulated, no grounding);
- Negative pressure in the pack (<atmospheric pressure).





Changfu Zou
21 Nov 2024

Outline

- Our BMS research group at Chalmers
- Literature review
- Vehicle-level experiments and observations
- Our further research toward safety

Further research toward safety: Optimized cooling

arXiv > eess > arXiv:2409.08974

Search...

Help | Adv

Electrical Engineering and Systems Science > Systems and Control

[Submitted on 13 Sep 2024]

Thermal Modelling of Battery Cells for Optimal Tab and Surface Cooling Control

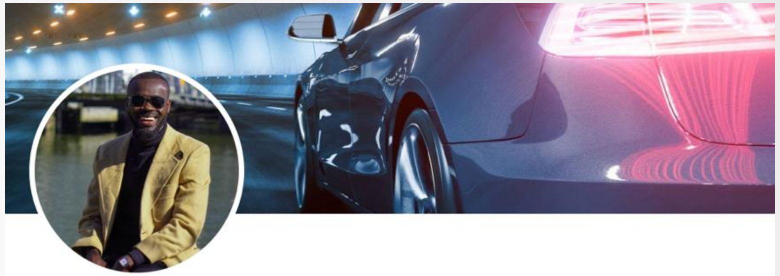
Godwin K. Peprah, Yicun Huang, Torsten Wik, Faisal Altaf, Changfu Zou

Optimal cooling that minimises thermal gradients and the average temperature is essential for enhanced battery safety and health. This work presents a new modelling approach for battery cells of different shapes by integrating Chebyshev spectral-Galerkin method and model component decomposition. As a result, a library of reduced-order computationally efficient battery thermal models is obtained, characterised by different numbers of states. These models are validated against a high-fidelity finite element model and are compared with a thermal equivalent circuit (TEC) model under real-world vehicle driving and battery cooling scenarios. Illustrative results demonstrate that the proposed model with four states can faithfully capture the two-dimensional thermal dynamics, while the model with only one state significantly outperforms the widely-used two-state TEC model in both accuracy and computational efficiency, reducing computation time by 28.7\%. Furthermore, our developed models allow for independent control of tab and surface cooling channels, enabling effective thermal performance optimisation. Additionally, the proposed model's versatility and effectiveness are demonstrated through various applications, including the evaluation of different cooling scenarios, closed-loop temperature control, and cell design optimisation.

Model Predictive Cooling Control of Cylindrical Battery Cells Through Tab and Surface Channels

Godwin K. Peprah, Torsten Wik, Yicun Huang, Faisal Altaf, Changfu Zou

Manuscript 690 submitted to 2025 American Control Conference (ACC).
Received October 2, 2024.



Godwin K. Peprah

PhD Student - Thermal System Design and Control of Vehicle Battery System

Gothenburg, Västra Götaland County, Sweden ·

Chalmers University of Technology

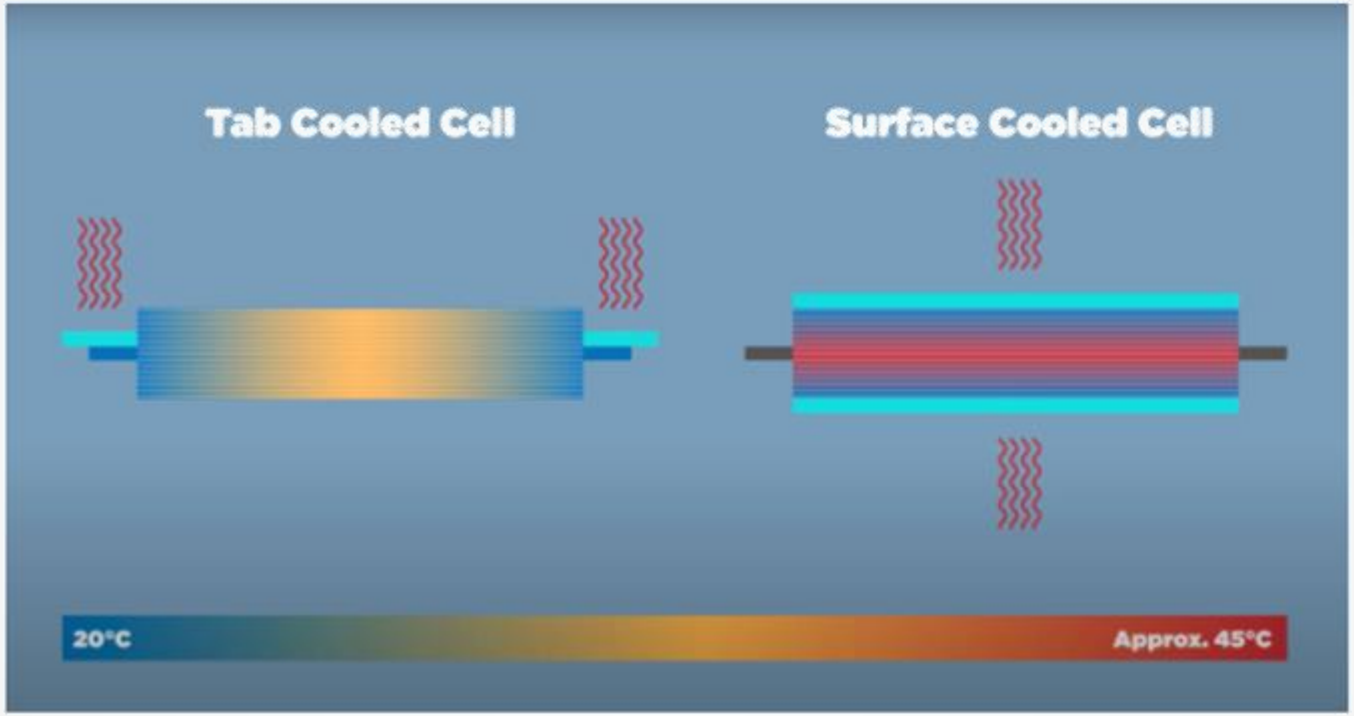
VOLVO
VOLVO GROUP

SCANIA

Swedish Electromobility Centre

Swedish Research Council

Further research toward safety: Optimized cooling

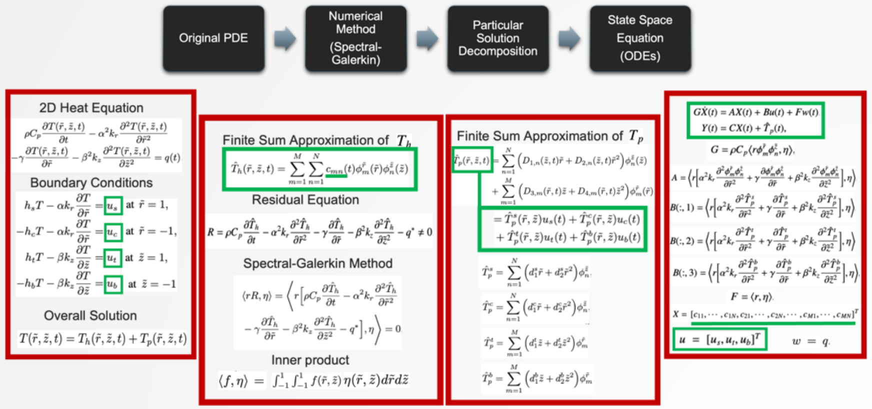


- High thermal conductivity, low thermal gradient
- More homogeneous usage of active electrode materials

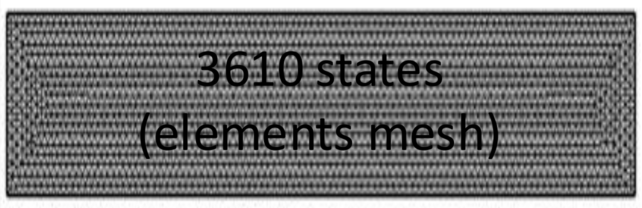
- Large cooling area, low average temperature
- Mitigated ageing mechanisms such as solid-electrode interface (SEI) growth

Further research toward safety: Optimized cooling (modeling)

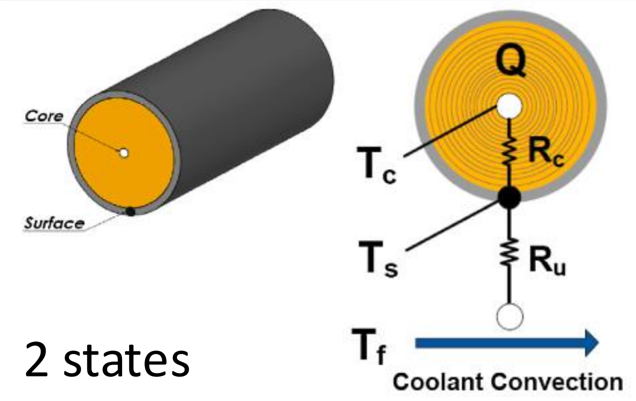
Our model

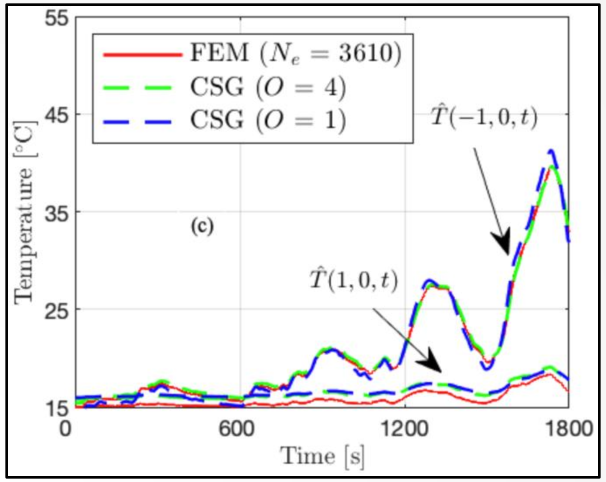


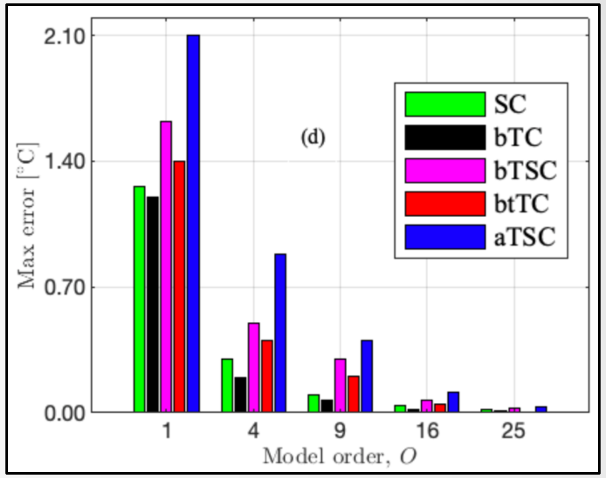
Benchmark 1
Finite element model

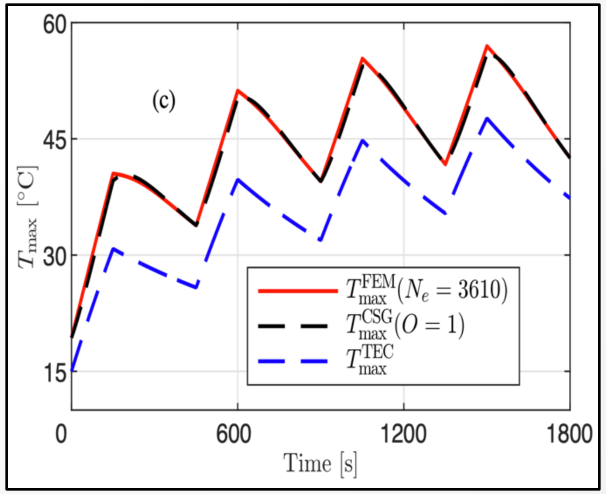


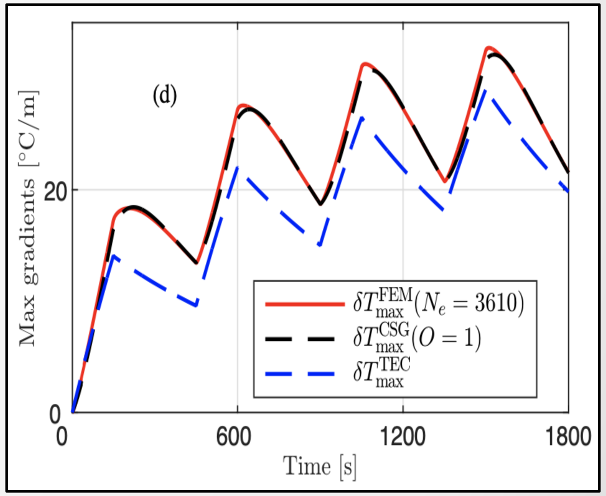
Benchmark 2
Thermal equivalent
circuit model





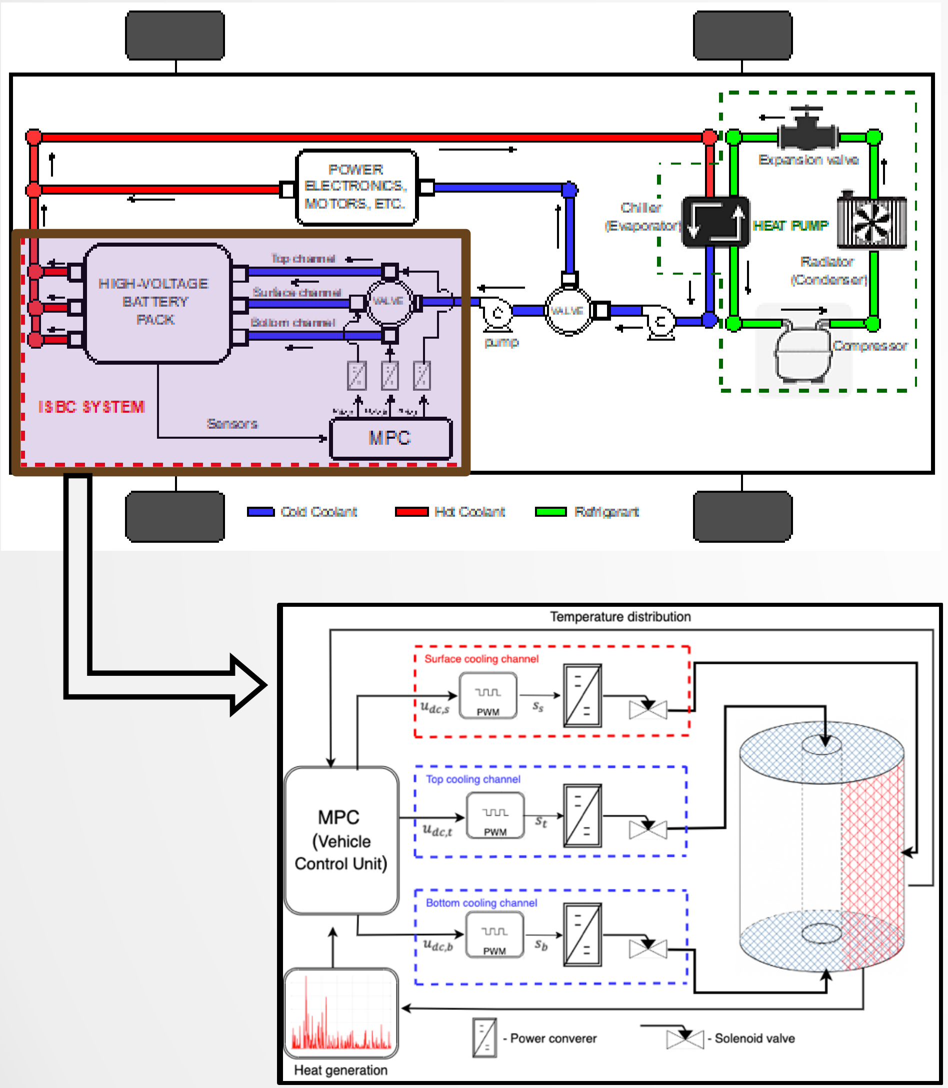




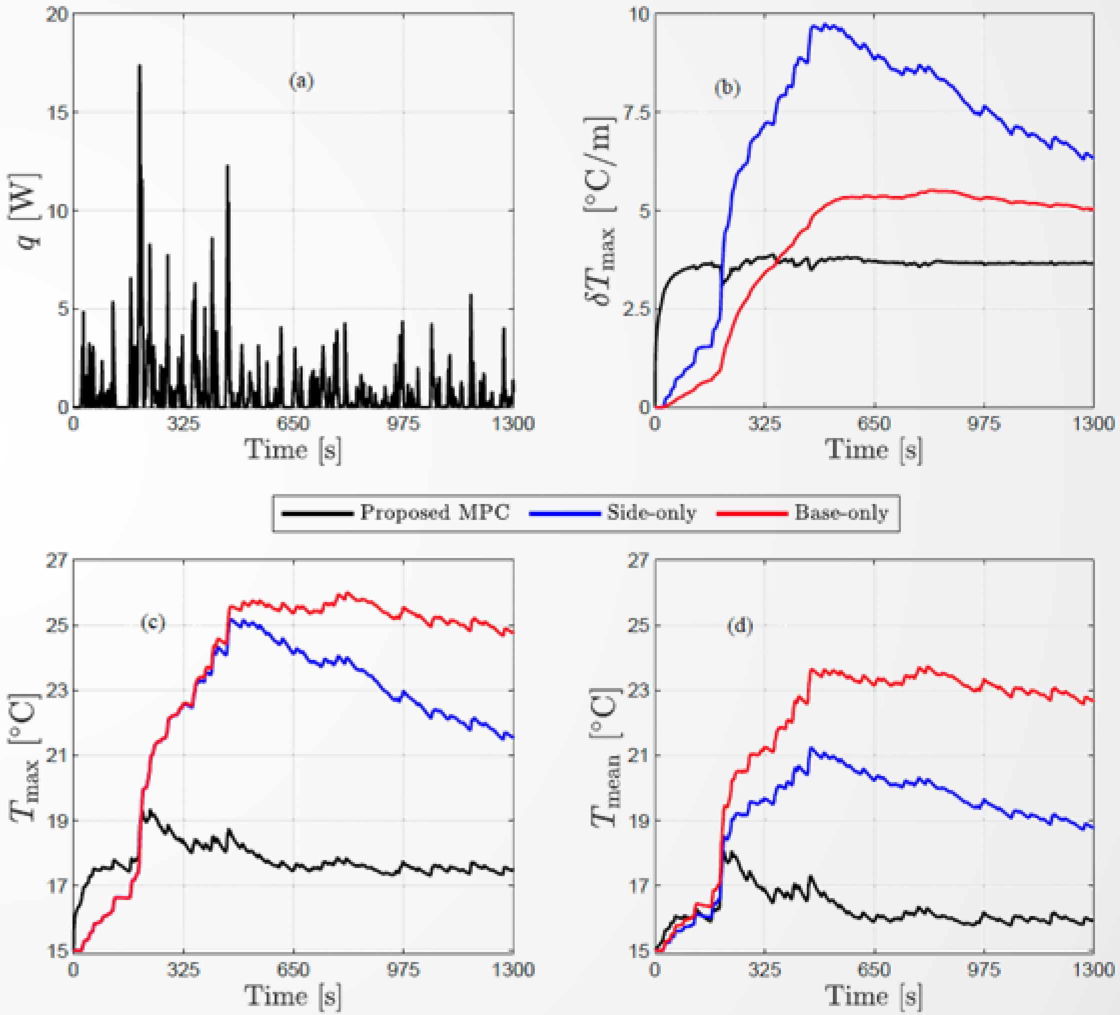


Changfu Zou
21 Nov 2024

Further research toward safety: Optimized cooling (control)

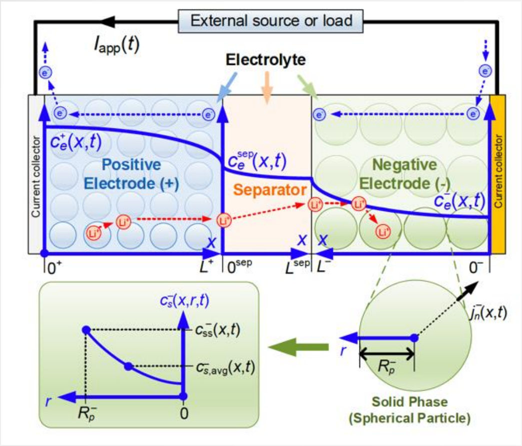


Simulation results on cell level



Changfu Zou
21 Nov 2024

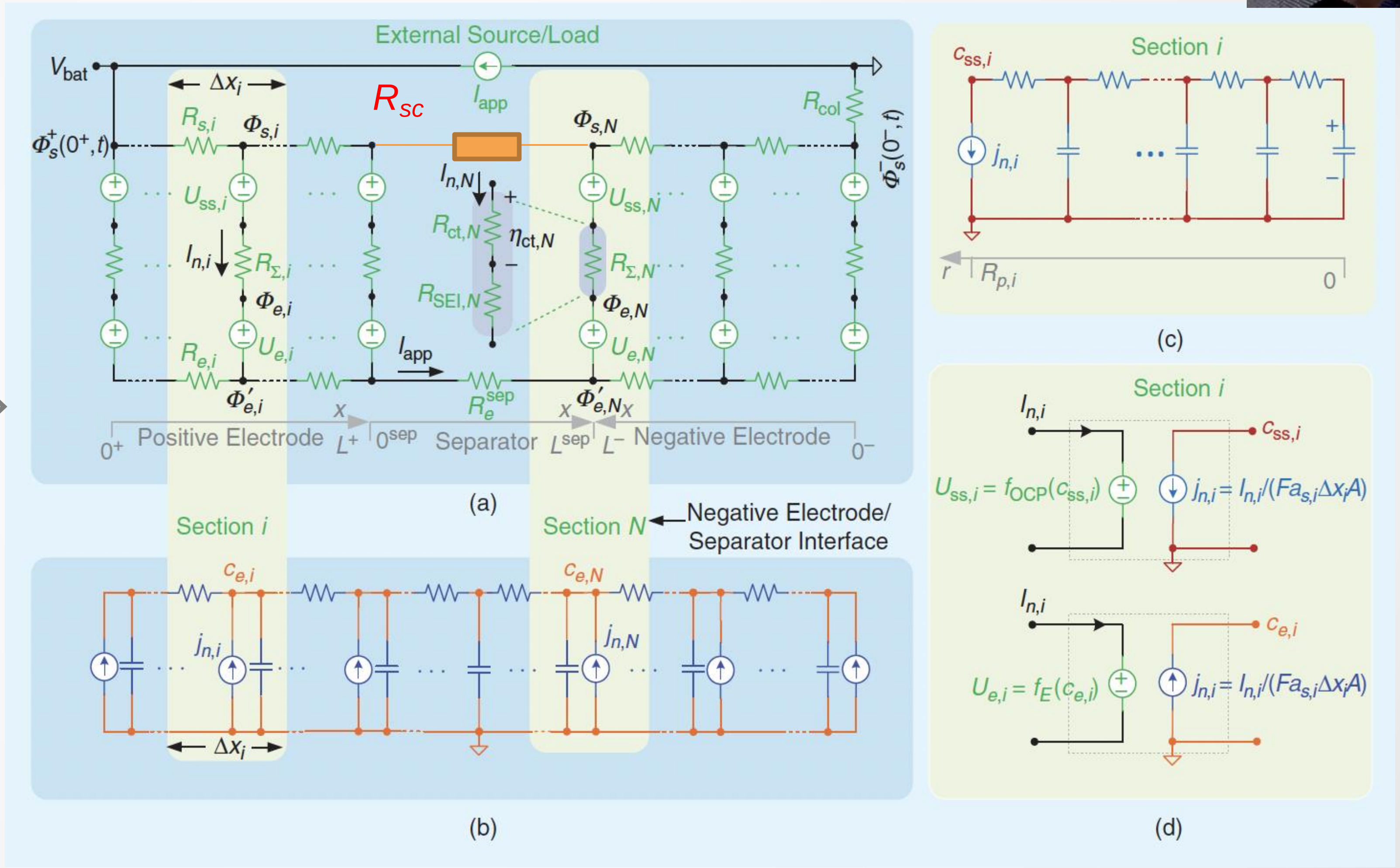
Further research toward safety: Simulator of short circuits

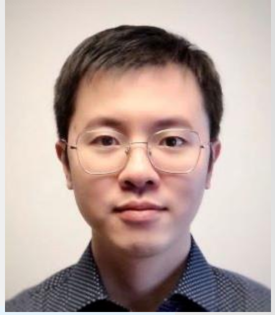


P2D

Spatial discretization

Physically insightful ECM





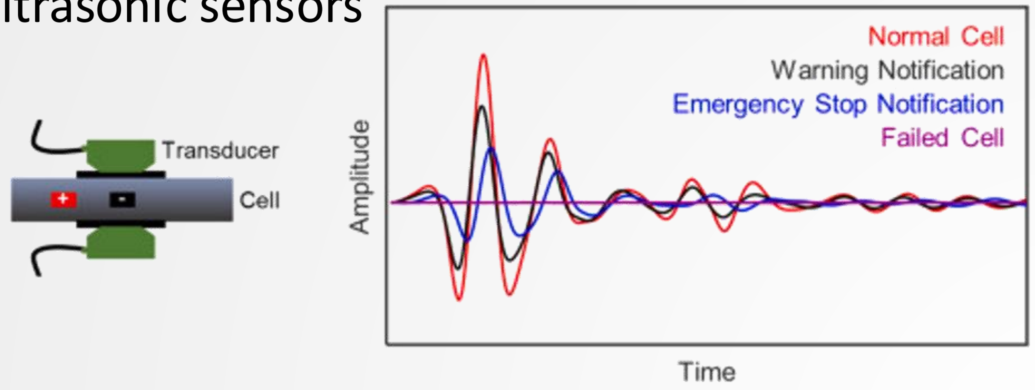
We can emulate (micro) ISC straightforwardly and then analyze its effects comprehensively!

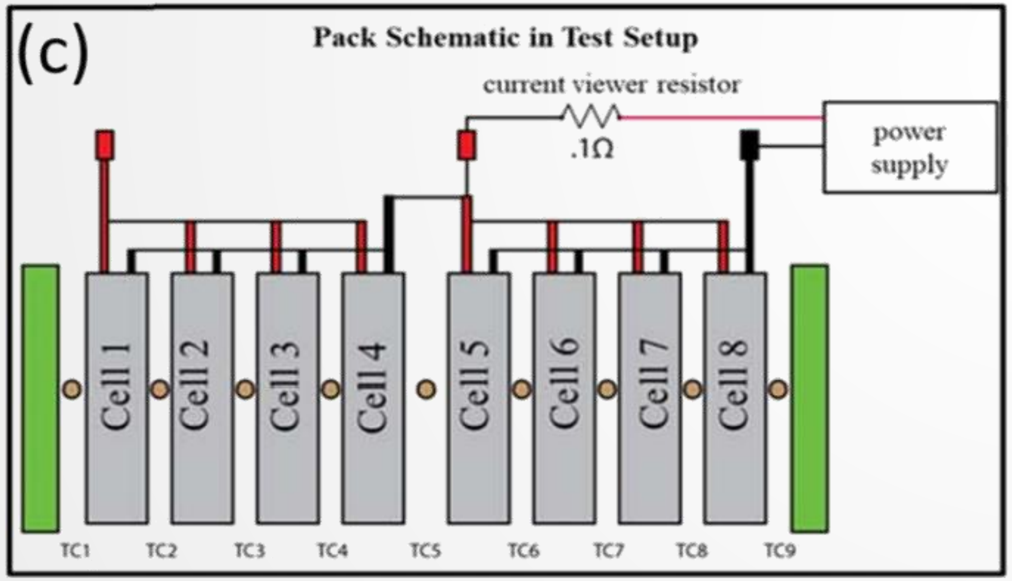
Li, Y., ..., & Zou, C. (2022). IEEE Industrial Electronics Magazine. 16 (3), 36-51.

Changfu Zou
21 Nov 2024
ESOC Energy Systems and Optimal Control Lab
CHALMERS UNIVERSITY OF TECHNOLOGY

Further research toward safety: advanced sensing (literature)

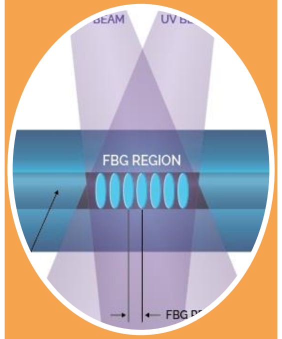
Ultrasonic sensors





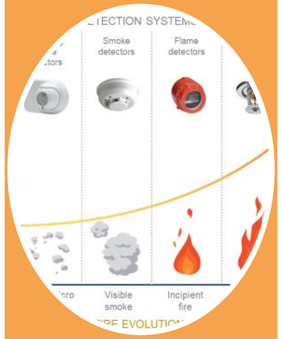
Electrochemical Impedance Spectroscopy (EIS)

Torres-Castro et al. (2024). J. Electrochem Soc, 171(2), 020520.



FBG and FPI-type sensors measure internal temperature and pressure

Safety warning range and early warnings

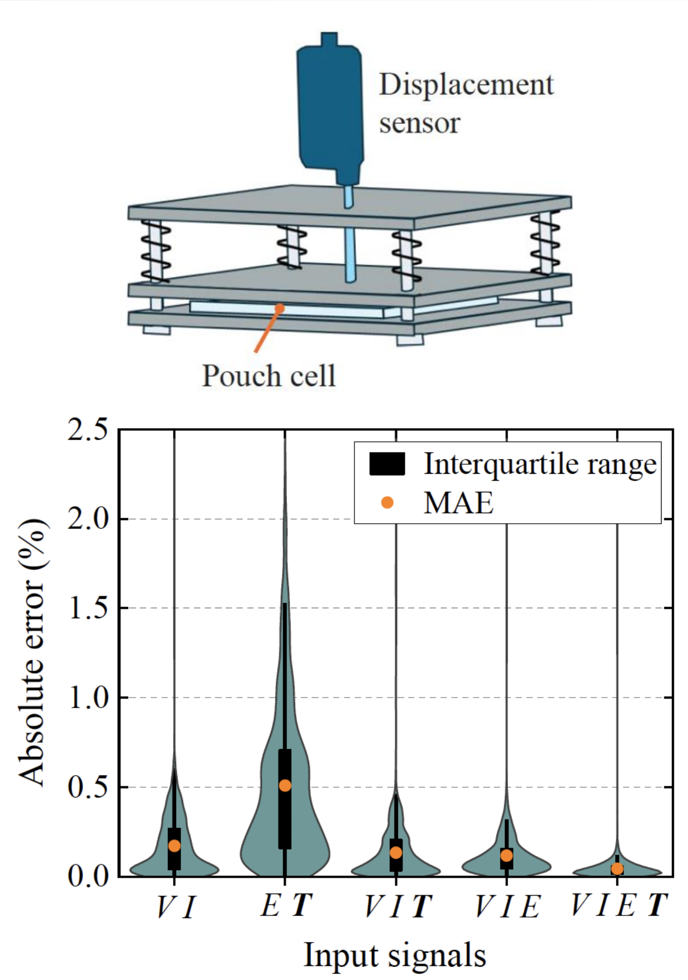


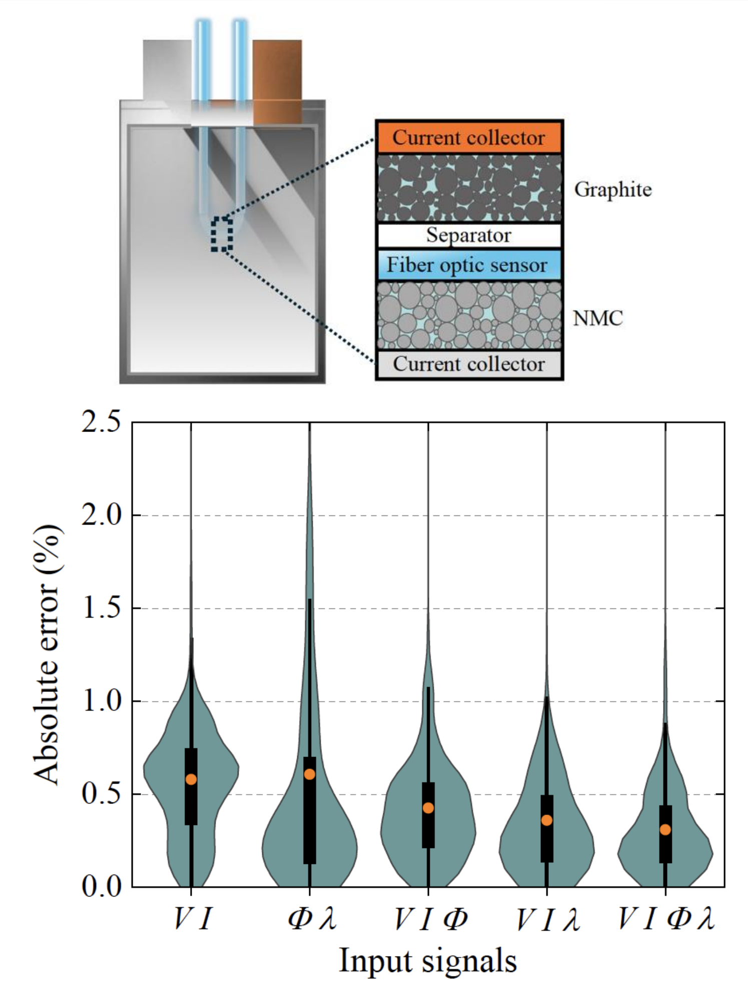
It distinguishes critical phases

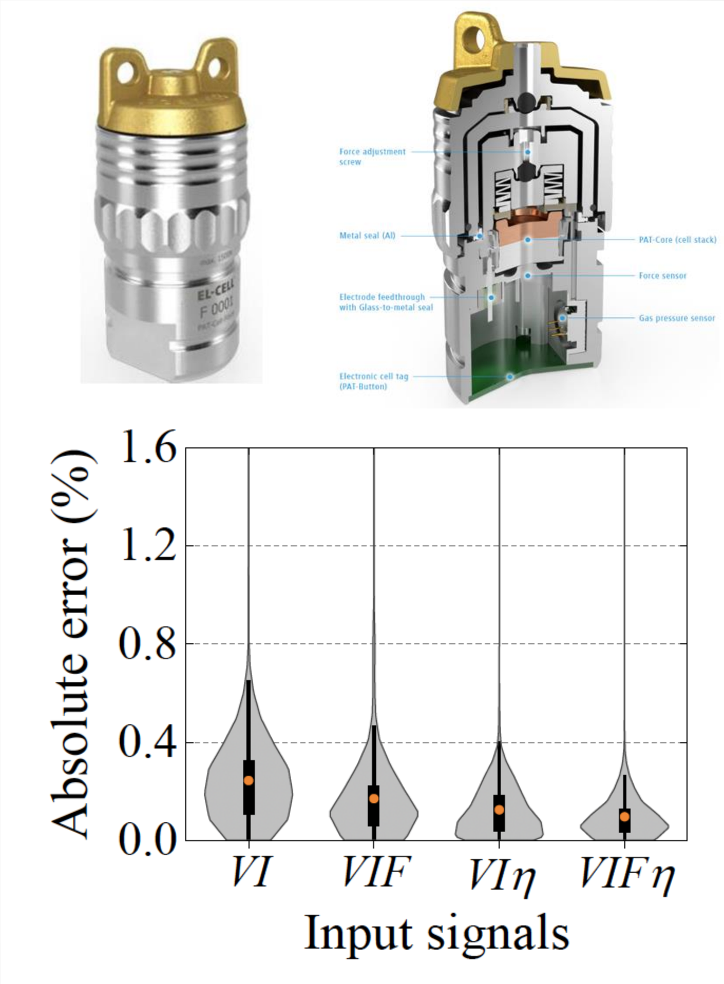
[1] Appleberry et al. (2022). J. Power Source, 535, 231423.
[2] Mei et al. (2023). Nature communications, 14(1), 5251.

Further research toward safety: advanced sensing

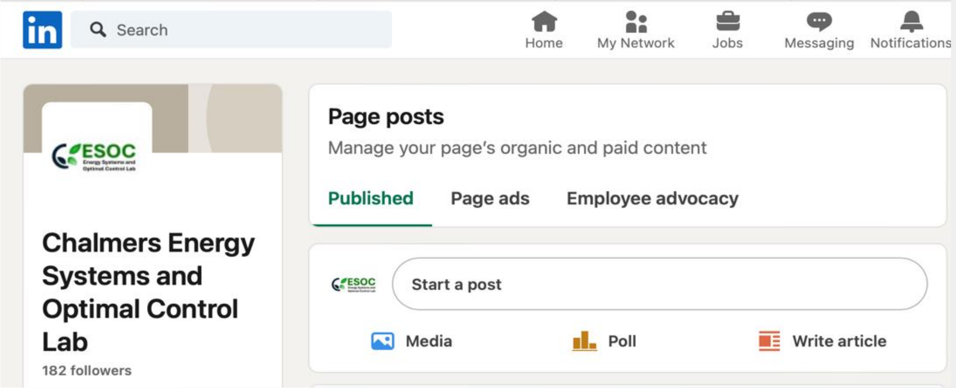
- We collected 3 datasets from diverse cells (different sizes and chemistries).
- Developed explainable machine learning models to fuse different signals, e.g. for SOC estimation.







Bian, X. et al. Breaking the accuracy barrier in battery state-of-charge monitoring (under review).



Acknowledgements and how to reach us

Contact:
Maskingränd 2, Göteborg 412 58, Sweden
Phone: +46 (0)31-772 3392
Email: changfu.zou@chalmers.se

Chalmers webpage:
https://www.chalmers.se/en/persons/changfu/
Personal webpage:
https://sites.google.com/view/changfu