Lithium-Sulfur Batteries: Steps towards a Practical Reality

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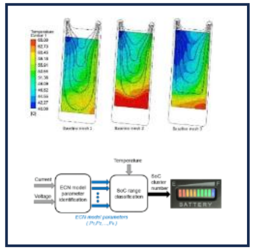
Cranfield University

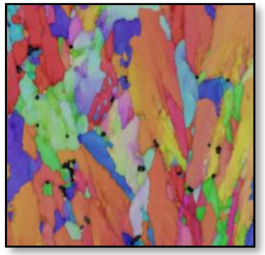
- Specialist postgraduate university
- Approx. 5000 students p.a. from over 100 countries.
- Close links to industry + global reach and influence.

- Well known for aerospace inc. electric aviation.
- Active in automotive since 1960s – offering six MSc courses.
- Battery Systems since before 2013.
- Lithium-sulfur since early 2014 (REVB).

Batteries @ Cranfield



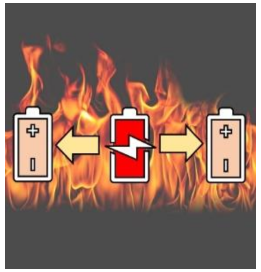
Battery modelling, management and systems integration



Sustainable multivalent batteries, advanced electrolytes & coatings

Lithium-sulfur batteries
Li-S

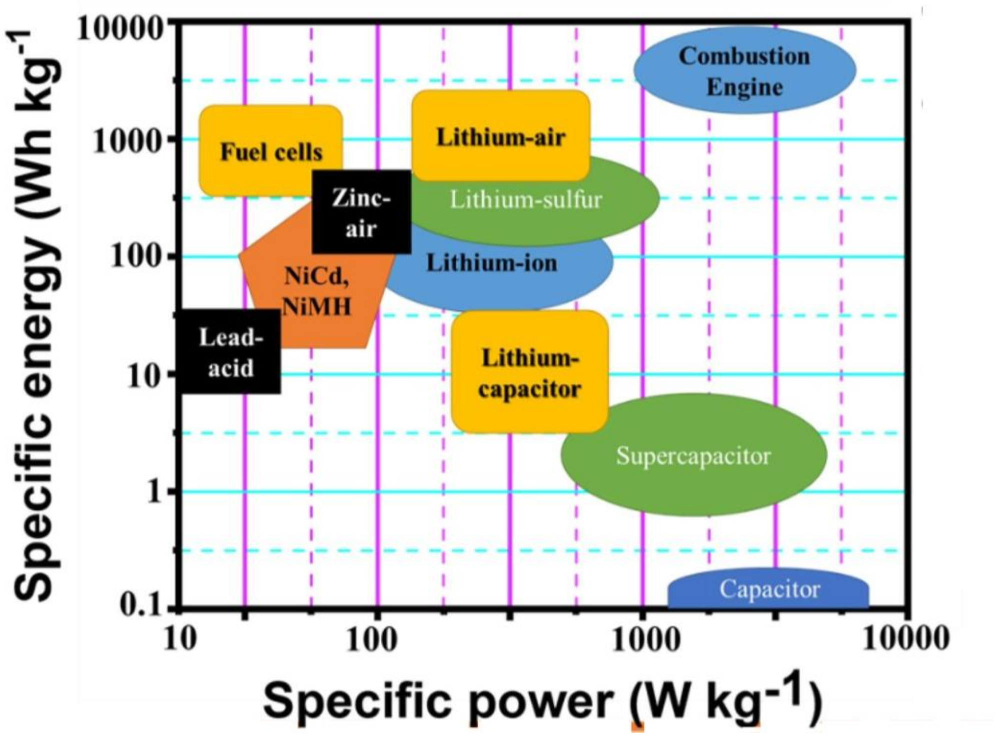
Advanced thermal modelling + bioinspired cooling



Detection and management of thermal runaway

Aircraft electrification – propulsion, integration and certification

Lithium sulfur – great when weight is a key driver



- safe … depending on detail
- avoid conflict minerals
- cheap at scale

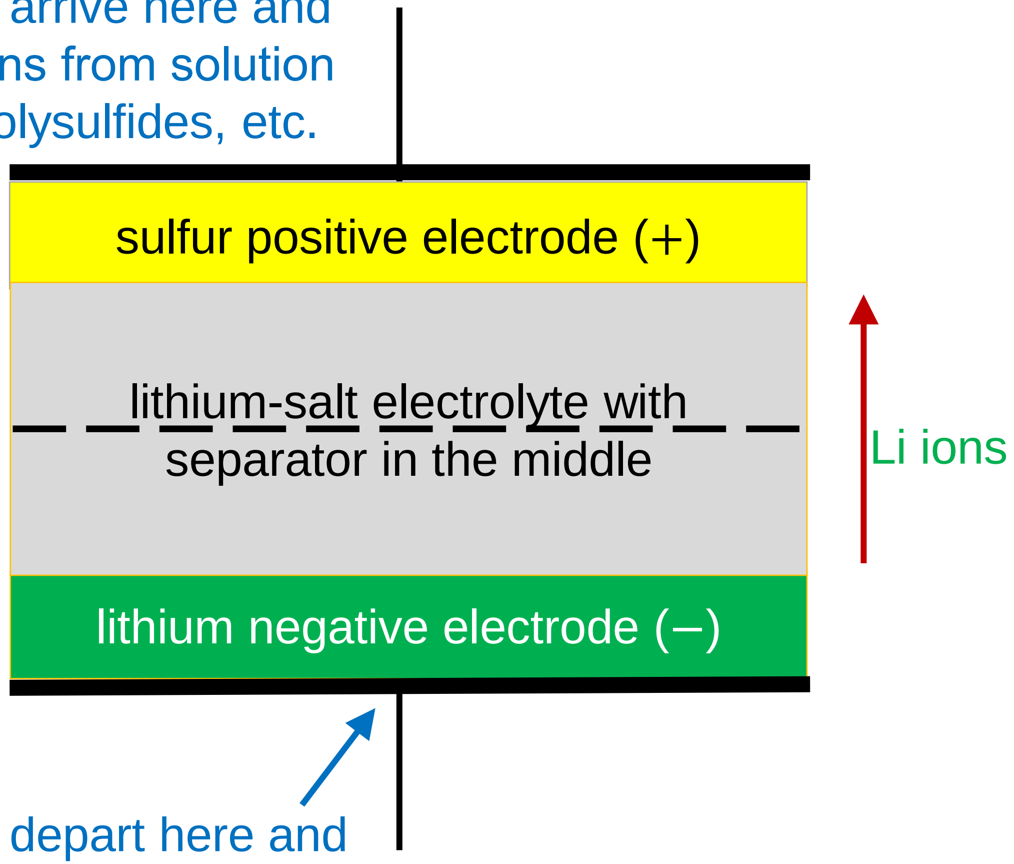
Today's UK-based cells can produce:

- Up to 400 Wh/kg for 200 cycles.
- Up to 1 C discharge – though reduces cycle life.

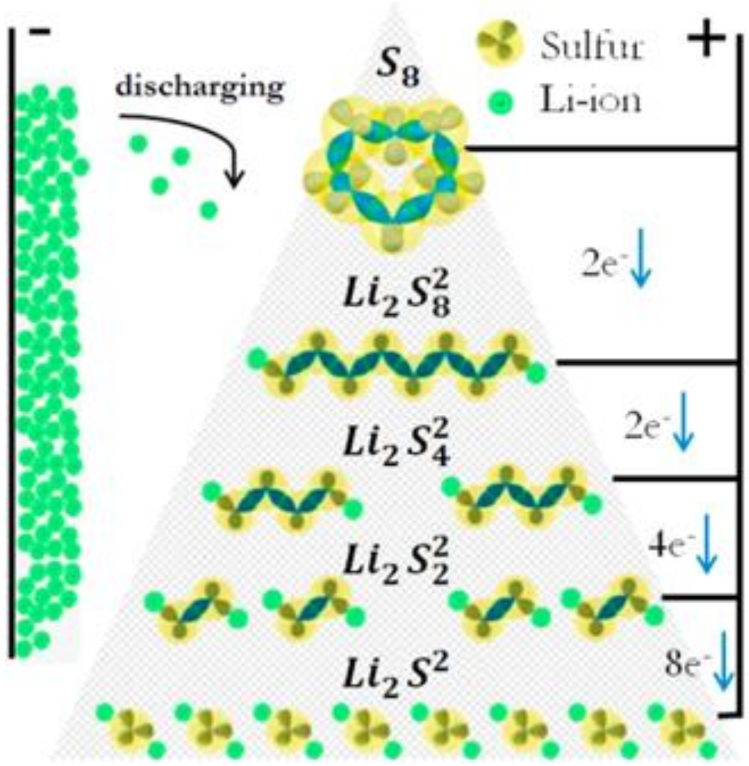
Haruna et al (2022), https://doi.org/10.1016/j.elecom.2022.107248. Open Access.

Li-S redox reactions are complex

when discharging, electrons arrive here and ‘pull’ Li ions from solution to form polysulfides, etc.

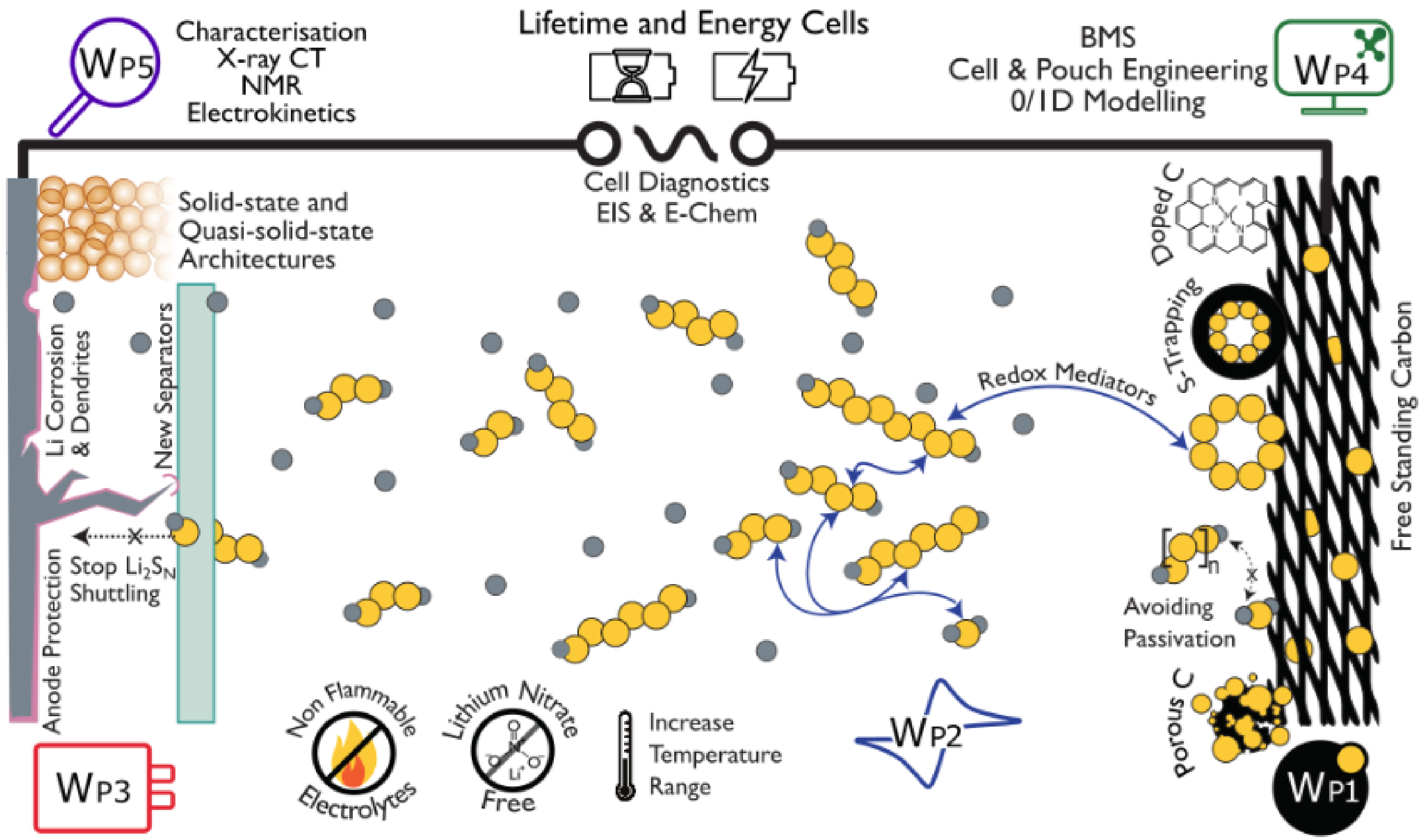


electrons depart here and ‘push’ new Li ions into solution



Propp *et al* 2016, doi:10.1016/j.jpowsour.2016.07.090

The LiSTAR Project



Composed of five parallel work streams, each tackling fundamental challenges relating to the development of Li-S batteries, the WPs and structure of LiSTAR is shown in this diagram.

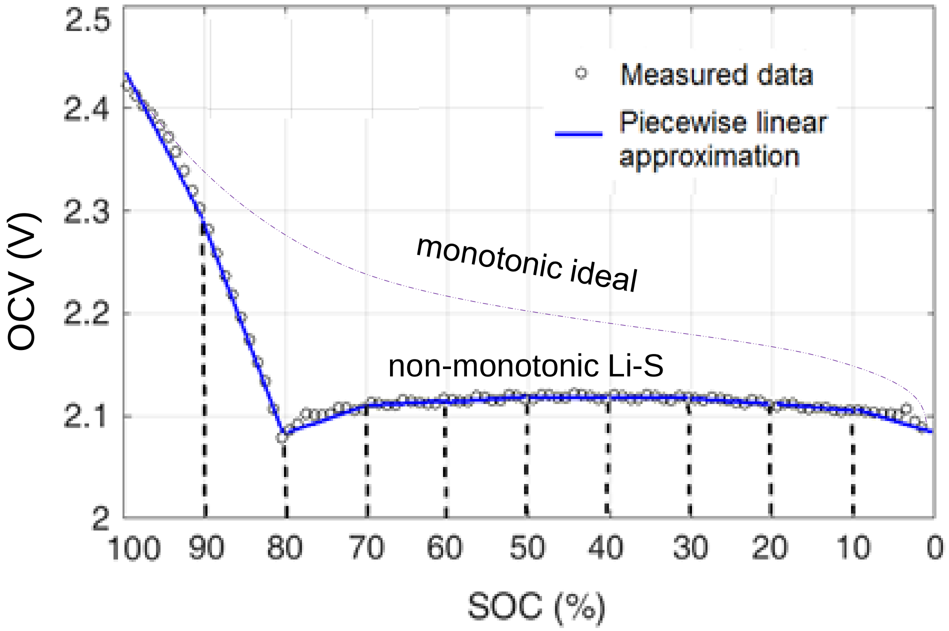
LiSTAR Key Facts

- Funder – The Faraday Institution
- PI: Prof. Paul Shearing (Oxford)
- Project Lead:
  Dr James Robinson (UCL)
- A collaboration between several universities across the UK.

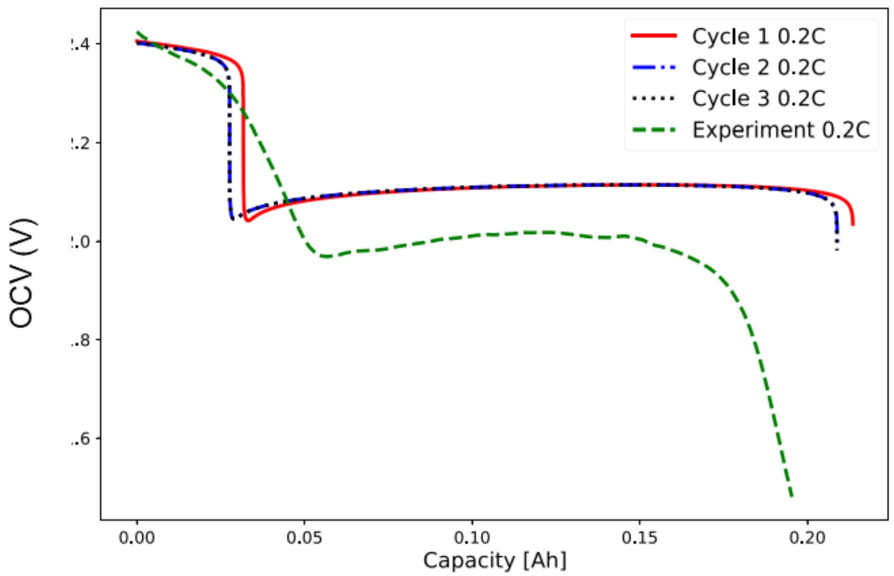
https://www.listar.ac.uk

Why state estimation of Li-S is challenging

Voltage curve is “difficult”

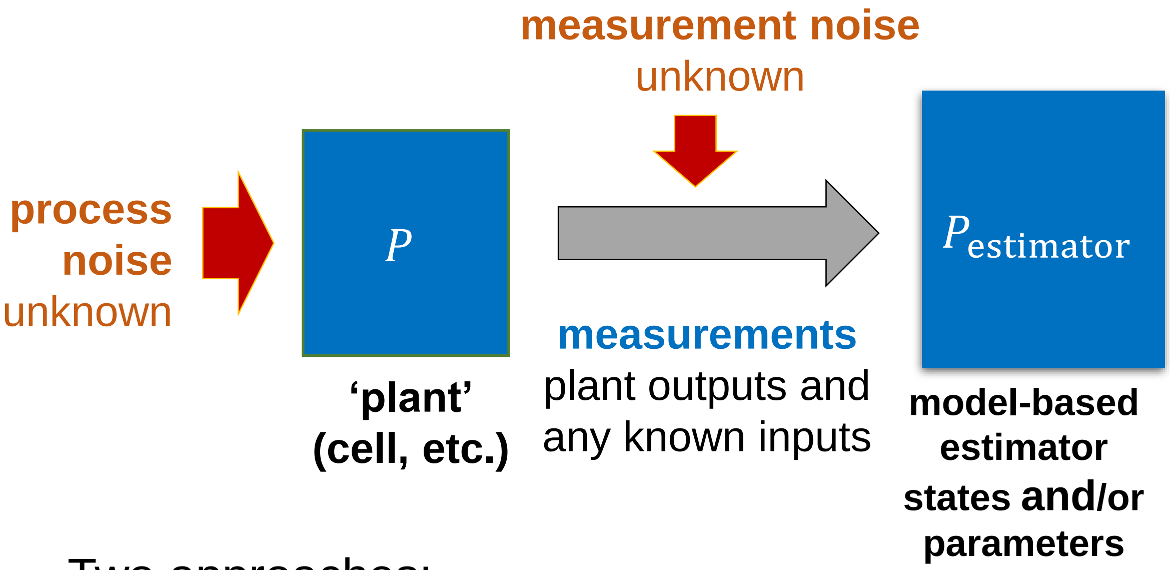


Reduced order models not at the same level of maturity as li-ion



Cornish & Marinescu 2022, https://doi.org/10.1149/1945-7111/ac7750

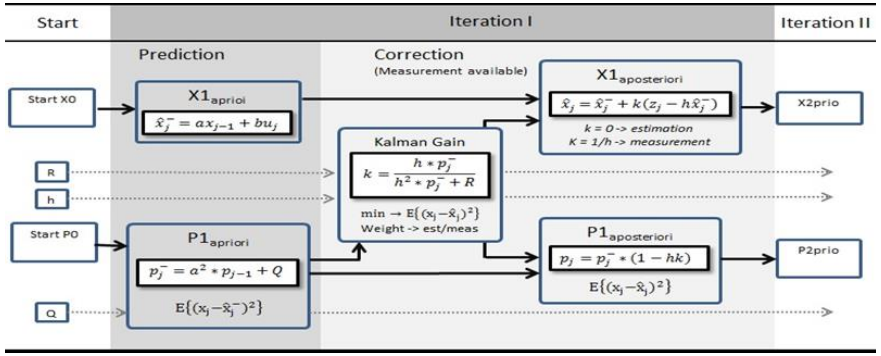
How we are meeting the challenge



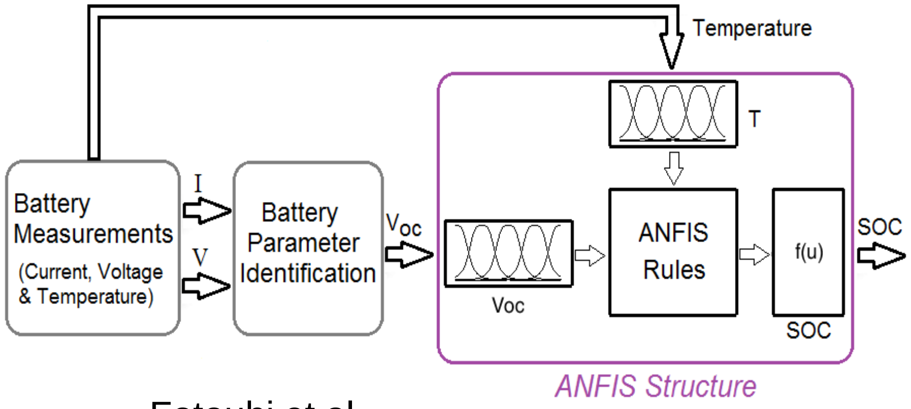
Two approaches:

- **physics/dynamics informed**
- **data-driven**

Physics-informed is the gold standard
Data-driven is highly practical
Usually combine both



Propp et al,
doi: [10.1016/j.jpowsour.2016.12.087](https://doi.org/10.1016/j.jpowsour.2016.12.087)



Fotouhi et al,
doi: [10.1109/TSMC.2016.2599281](https://doi.org/10.1109/TSMC.2016.2599281)

BMS Modelling – Collaborative work in LiSTAR

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Hardware-in-the-loop testing @ Cranfield

LiSTAR cell
from Coventry
University

prototype cells (pre scale-up)

measurements

Real-time interface
simulates vehicle dynamics providing duty cycles at cell level

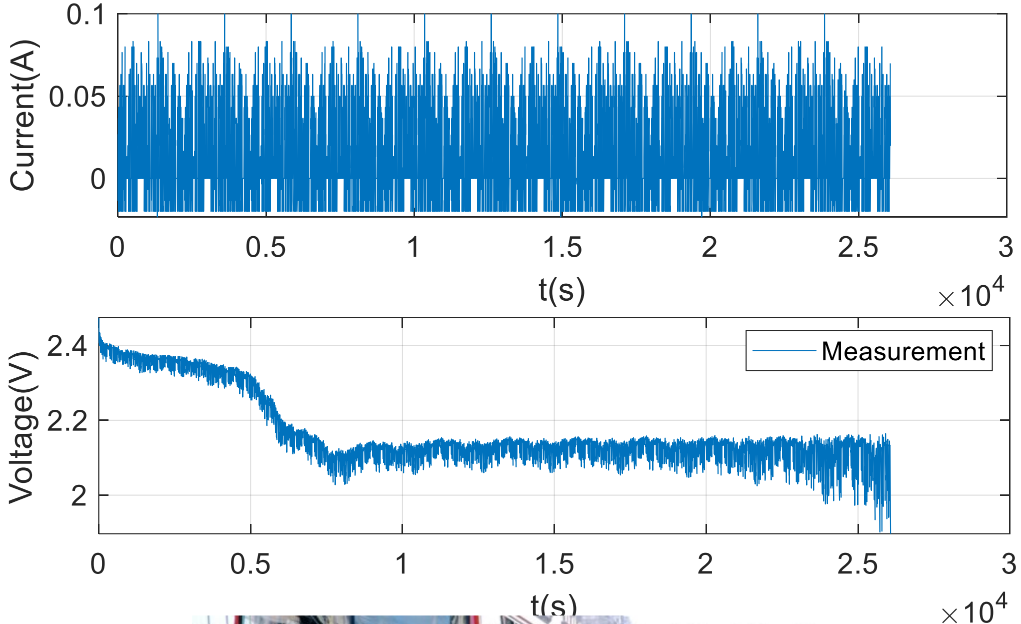
control signals

bidirectional power source specified for compatibility with cells of interest

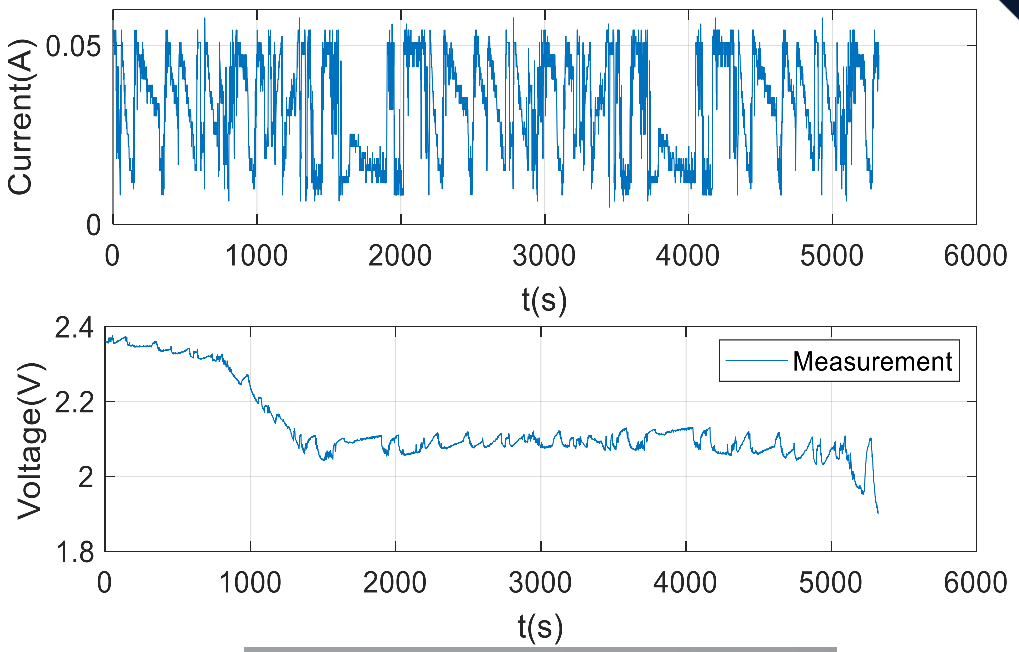
application duty cycles at cell level

Duty Cycles

Heavy-duty automotive



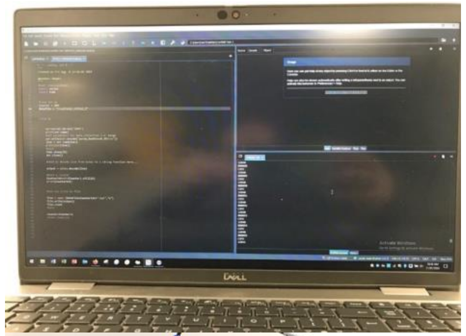
Light aircraft

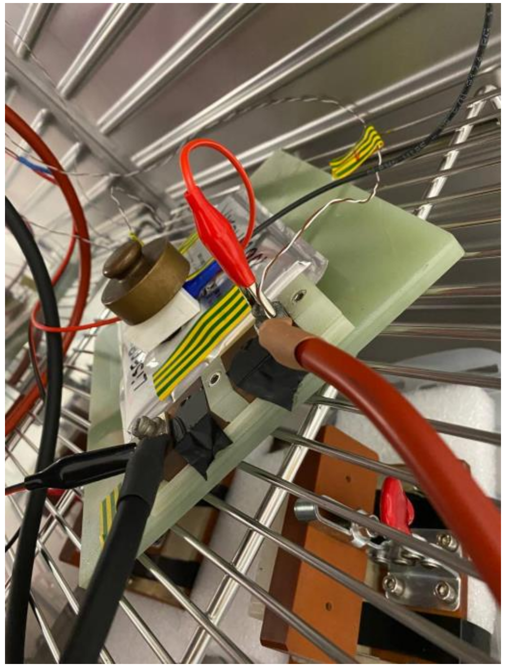


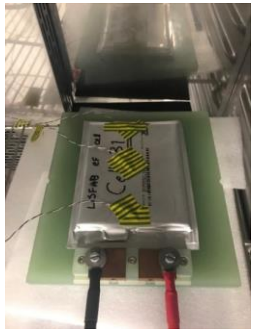
Incorporation of acoustic sensors and heat-generation methods

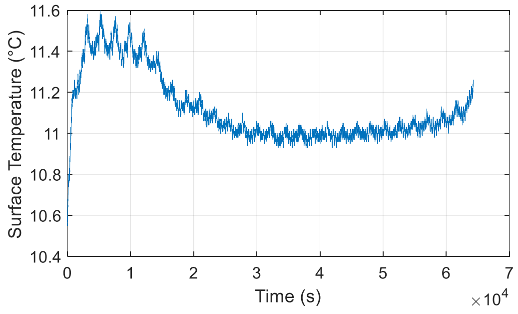
- Acoustics - collaboration with UCL
- Techniques demonstrated for Li-ion
- Does it work for Li-S?

- Temperature fluctuations
- Appearing in the literature for Li-ion
- Again, does it work for Li-S?









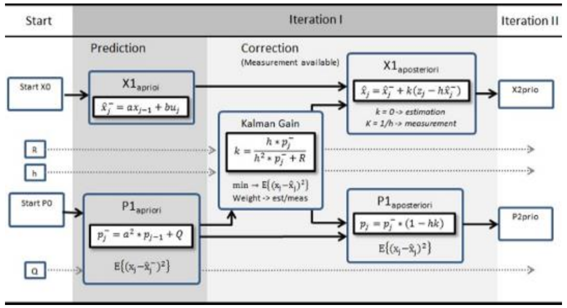
In-application determination of state of charge

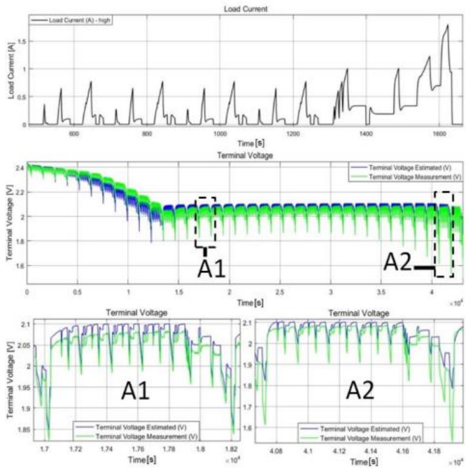
SoC estimators for BMS

- doi:10.1016/j.jpowsour.2016.12.087
- doi:10.1049/iet-pel.2016.0777
- doi:10.1109/TSMC.2016.2599281
- doi:10.1016/j.ifacol.2016.08.008
- doi:10.1109/TPEL.2017.2740223
- doi:10.3390/en11082133
- doi:10.1016/j.est.2019.100943
- doi:10.1109/TVT.2020.3045213

Control Theory techniques

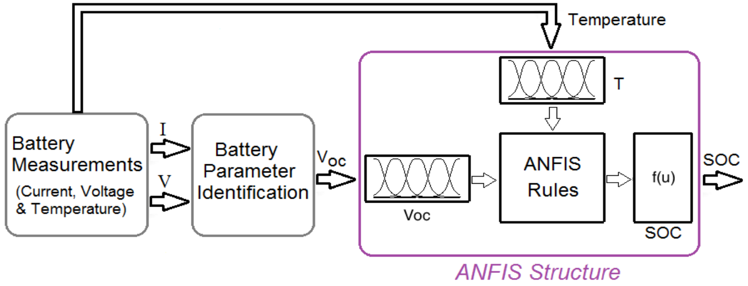
- Uncertain system dynamics.
- Fast system identification methods, e.g. Prediction Error Minimization, grey-box model identification.
- Optimal state estimation, e.g. Kalman filter derivatives, robust observers.

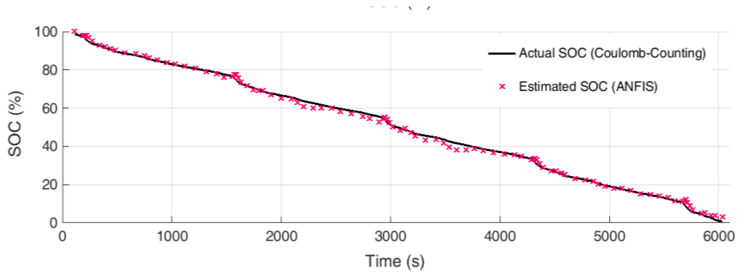




Computer Science techniques

- Trained expert systems.
- Adaptive Neuro-Fuzzy Inference Systems (ANFIS).
- Implementation trade-offs – computational cost versus accuracy.



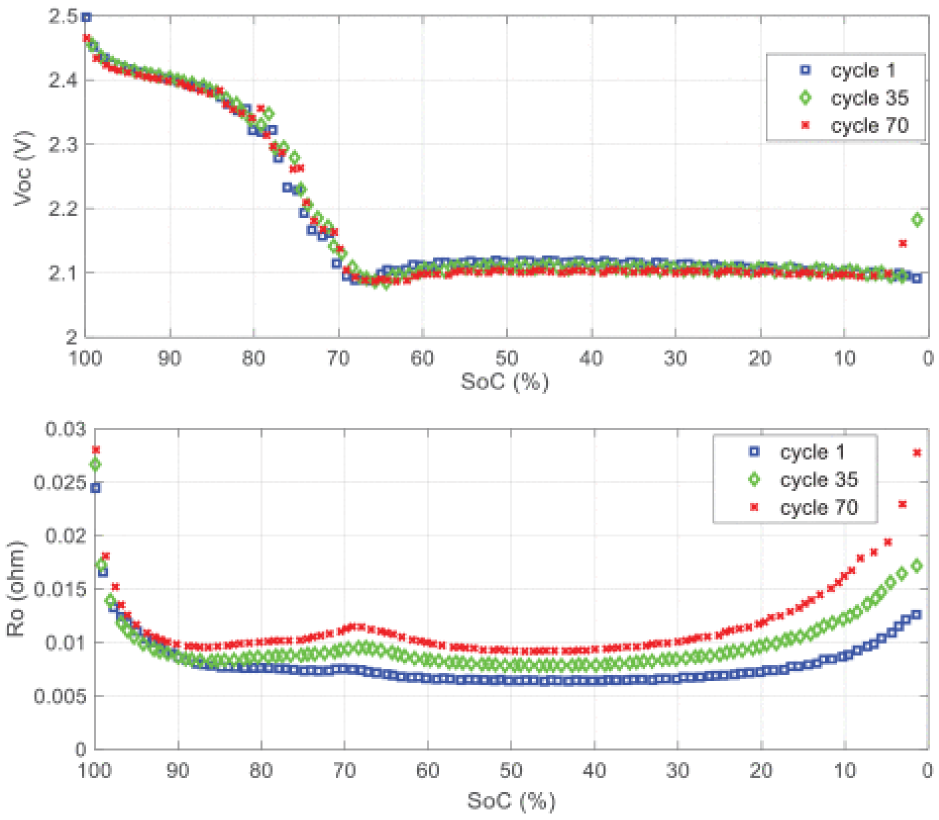


In-application determination of state of health

Relate observable features to state of health.

- Lots of features *might* tell us.
- Electrochemistry and observations suggest possibilities.
- Testing these tells us what works.

- For Li-S, two successful techniques::
    - **AI-based (support vector machine)**
    - **Nonlinear parameter curve fitting**



doi:10.1109/TTE.2021.3059738

Key takeaways

- Li-S offers extreme light weight, but there are obstacles to exploitation. The LiSTAR project is working to overcome these.
- State/health estimation hard because physics-based models are still in development – but we can solve these.
- Despite this, control theory and AI enable us to get great results.
- Physics-informed models will ultimately enable us to do even better in future.

Acknowledgements:

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- Innovate UK
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- Our LiSTAR collaborators:
  - University of Oxford
  - UCL
  - Coventry University
  - Imperial College London
  - Cranfield Centre for Aeronautics

Thanks for listening!