System-Level Modeling, Estimation and Control of Battery System

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Outline

- **System-level battery management**
  - Temperature estimation of battery system
  - Reduced battery voltage sensing
- **Physics-based Investigation and Modeling**
  - Neutron Imaging
- **Work Experiences at Ford Motor Company**
  - EV DC fast charging system
  - University collaboration

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Li-ion Cells : Human Like

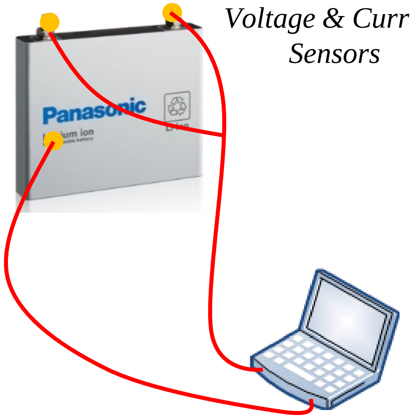
- Poke them and they can *bleed* and burst into *flames*
- Hate to be over-worked
- Picky about temperature
- Diversity
- All cells must die

They need to be taken care of!
Battery Management:

- **State Estimation**
  - State of charge (SOC)
  - State of health (SOH)
  - Power capability
- **Thermal Management**
  - Temperature control
  - Temperature imbalance control
- **Cell Balancing**…

Existing Studies on Battery Management

State of Art: Cell-level Battery Management



Voltage & Current Sensors

Temp Sensor

BMS:
States Estimation
Thermal Management
Cell Balancing
…

Reality: Battery systems come in packs.

Nissan Leaf: 192 cells

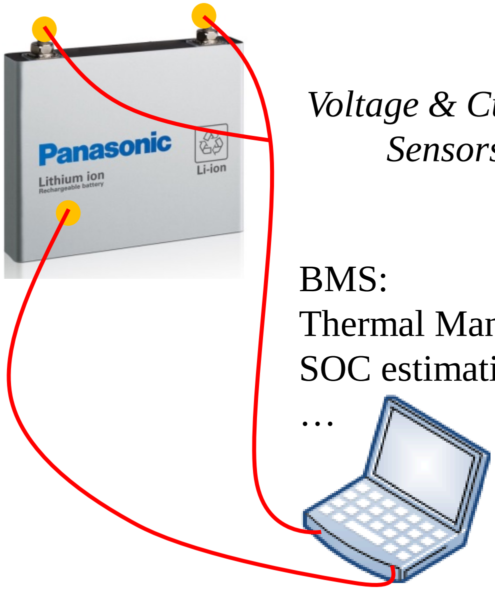
Chevy Volt: 288 cells

Tesla Model S: >7000 cells

Goal: System-level BMS

Battery Cell

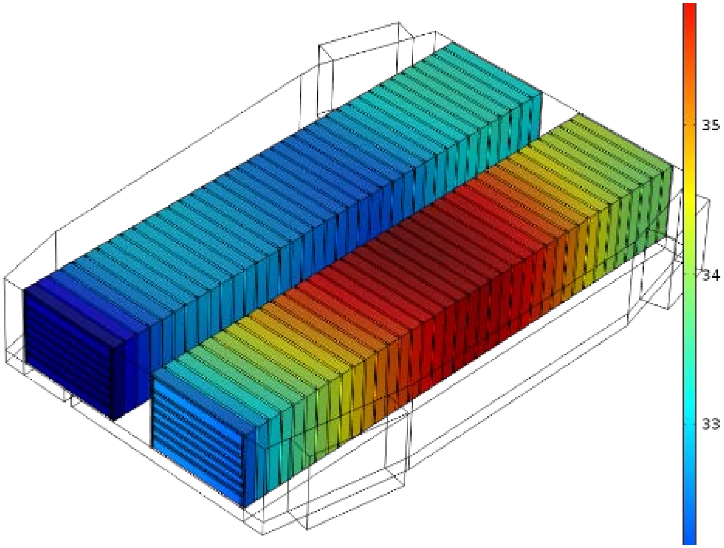
Temp Sensor



Voltage & Current Sensors

BMS:
Thermal Management
SOC estimation
…

Battery System



Cell-Level Battery Management with Full Sensing

System-Level Battery Management under Sparse Sensing, Limited Computational Capacity and System Uncertainty

A lesson learned from Industry

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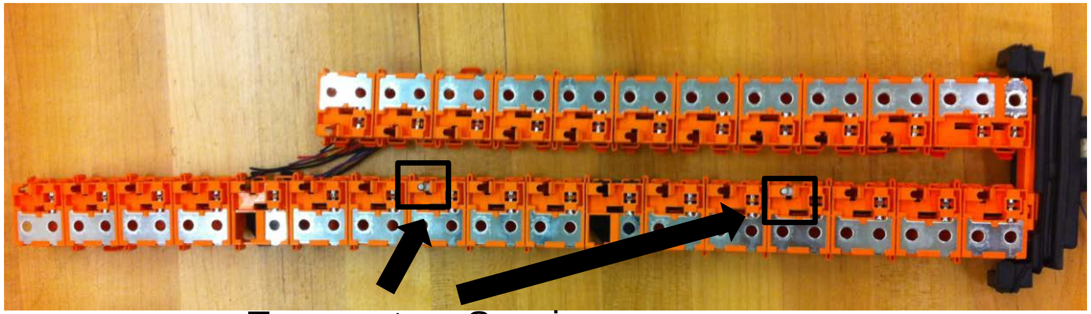
Temperature Estimation of Battery System



Temperature Sensing

Issue: ineffective temperature sensing:

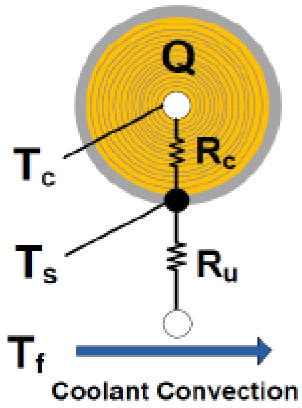
- Limited number of sensors: ~ 1 in every 10 cells
- Only measuring surface but not the internal cell temperature

Solution: combining sparse sensing with model-based estimation

Modeling → ***System Identification*** → ***State Estimation***

Sponsored by US Army TARDEC

Single-Cell Model and Identification

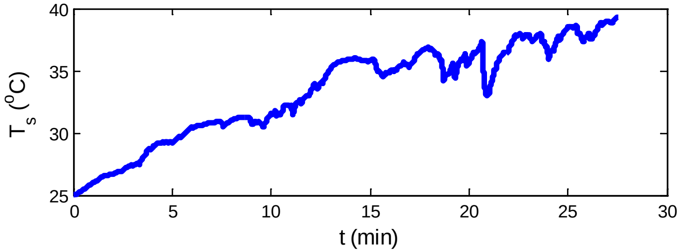


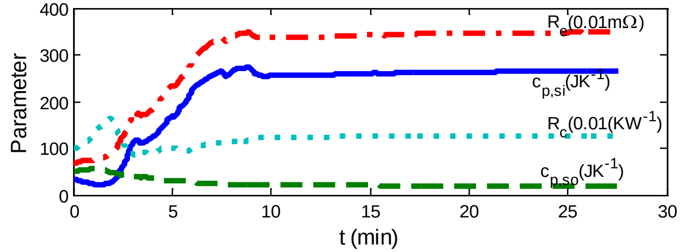
Core temp T_c

$$C_c \frac{dT_c}{dt} = I^2 R_e + \frac{T_s - T_c}{R_c}$$

Surface temp T_s

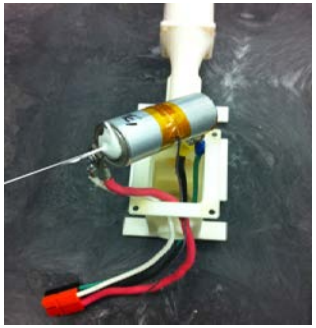
$$C_s \frac{dT_s}{dt} = \frac{T_f - T_s}{R_u} - \frac{T_s - T_c}{R_c}$$

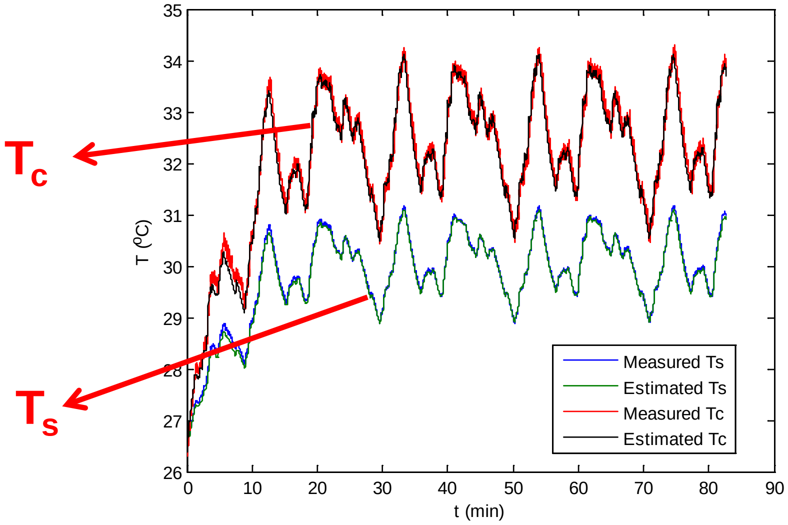




System Identification

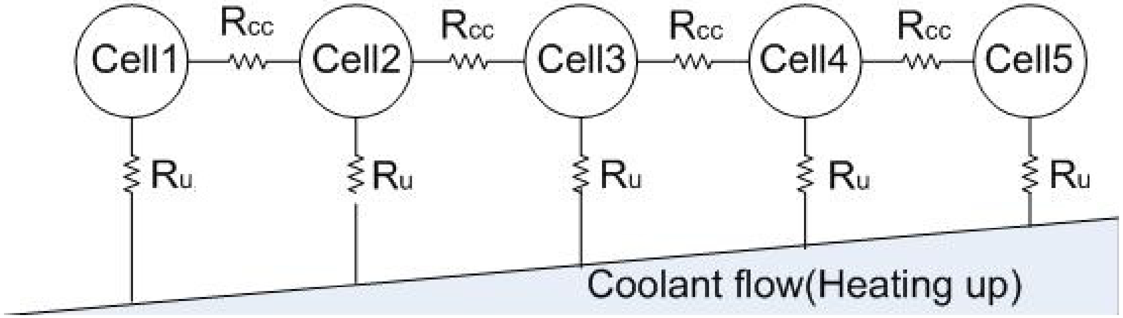
- To determine model parameters
- Online ID using T_s and I
- Experimental validation





Lin, et al., IEEE Transaction, Control Systems and Technology 2013
Lin, et al., American Control Conference 2012

Battery System Thermal Model



Single Cell Model

Cell to Cell Conduction

$$C_c \frac{dT_{c,i}}{dt} = I^2 R_e + \frac{T_{s,i} - T_{c,i}}{R_c}$$

$$C_s \frac{dT_{s,i}}{dt} = \frac{T_{f,in,i} - T_{s,i}}{R_u} - \frac{T_{s,i} - T_{c,i}}{R_c} + \frac{T_{s,i-1} + T_{s,i+1} - 2T_{s,i}}{R_{cc}}$$

$$T_{f,in,i} = T_{f,out,i-1}$$

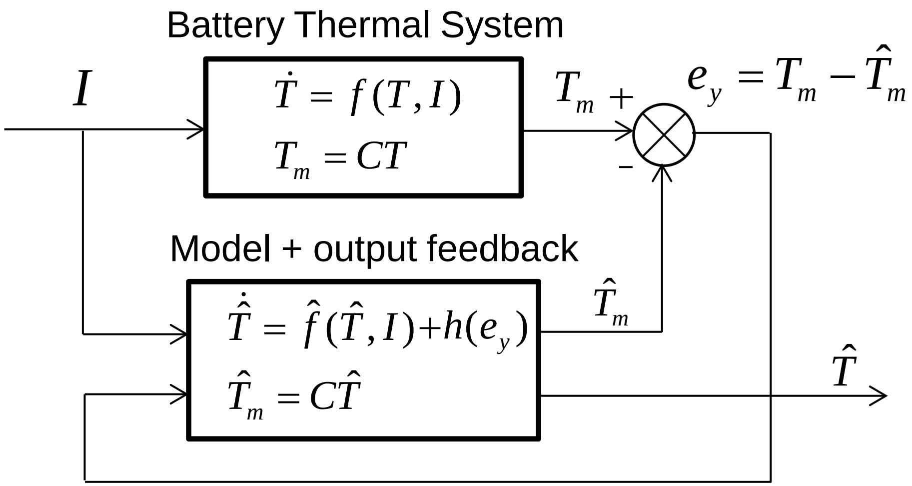
$$T_{f,out,i} = T_{f,in,i} - \frac{T_{f,in,i} - T_s}{R_u c_{p,air}}$$

Coolant Flow Dynamics

Lin, et al., IFP RHEVE 2011
Lin, et al., Journal of Power Sources 2014

Model-based Observer Design

- **Observer for Temperature Estimation**



$$T = \begin{bmatrix} T_{c1} & T_{s1} & T_{c2} & T_{s2} & \dots & T_{cn} & T_{sn} \end{bmatrix}^T \qquad T_m = \begin{bmatrix} T_{s1} & \dots & T_{sj} \end{bmatrix}^T$$

- **Issue caused by sparse temperature sensing:** $n \geq 10j$
  - Inaccurate model parameters for cells with no sensor

$$f \neq \hat{f}$$

Problem Formulation

Battery thermal model in state-space representation:

$$\dot{T} = AT + BI^2$$

$$T_m = CT$$

$$B = \frac{R_e}{C_c} = \frac{1}{C_c}\begin{bmatrix} R_{e,1} & 0 & R_{e,2} & 0 & \ldots & R_{e,n} & 0 \end{bmatrix}^T$$

Model uncertainty: resistance imbalance among cells

$$\Delta R_e = R_e - R_{e,0} = \frac{1}{C_c}[\Delta R_{e,1}, 0, \Delta R_{e,2}, 0 \ldots \Delta R_{e,n}, 0]^T \qquad |\Delta R_{e,i}| \leq 0.1 R_{e,0}$$

Goal: to design an optimal “worst-case” observer

$$\mathsf{F}: \; \dot{\hat{T}} = A_h \hat{T} + B_h I + G T_m$$

$$\hat{y} = C_h \hat{x}$$

$$e = T - \hat{T}$$

$$\min_{\mathsf{F}} \max_{\Delta R_e} J\left(e(\Delta R_e)\right)$$

$$\Delta R_e = \begin{bmatrix} \Delta R_{e,1} & 0 & \Delta R_{e,2} & 0 & \cdots & \Delta R_{e,n} & 0 \end{bmatrix}^T,$$

$$s.t. -0.1 R_{e,0} \leq \Delta R_{e,i} \leq 0.1 R_{e,0}, \quad i = 1, 2, \cdots, n$$

Guarantee minimized worst-case error under all possible degree of uncertainties!

Method: Robust H∞ Observer

Robust H_∞ observer: solving linear matrix inequality (LMI)

$$\min_{\mathrm{F}} \max_{\omega\in[0,+\infty),\Delta R_e} \left\| G_{eu}(j\omega) \right\|_2$$

If ΔB belongs to a polytope: $\Delta B = \sum_j^q \alpha_j B_j, \quad \alpha_j \geq 0, \quad \sum_j^q \alpha_j = 1,$

$$\min_{R,X,M,N,D_h,\gamma^2} \gamma^2$$

$$s.t. \begin{bmatrix} RA + A^T R & RA + A^T X + C^T Z^T + M^T & R\Delta B_j & W^T - C^T D_h^T - N^T \\ * & A^T X + XA + C^T Z^T + ZC & XB + ZD & W^T - C^T D_h^T \\ * & * & -\mathbf{I} & -D^T D_h^T \\ * & * & * & -\gamma^2 \mathbf{I} \end{bmatrix} < 0,$$

$$\forall j = 1, 2, \ldots q$$

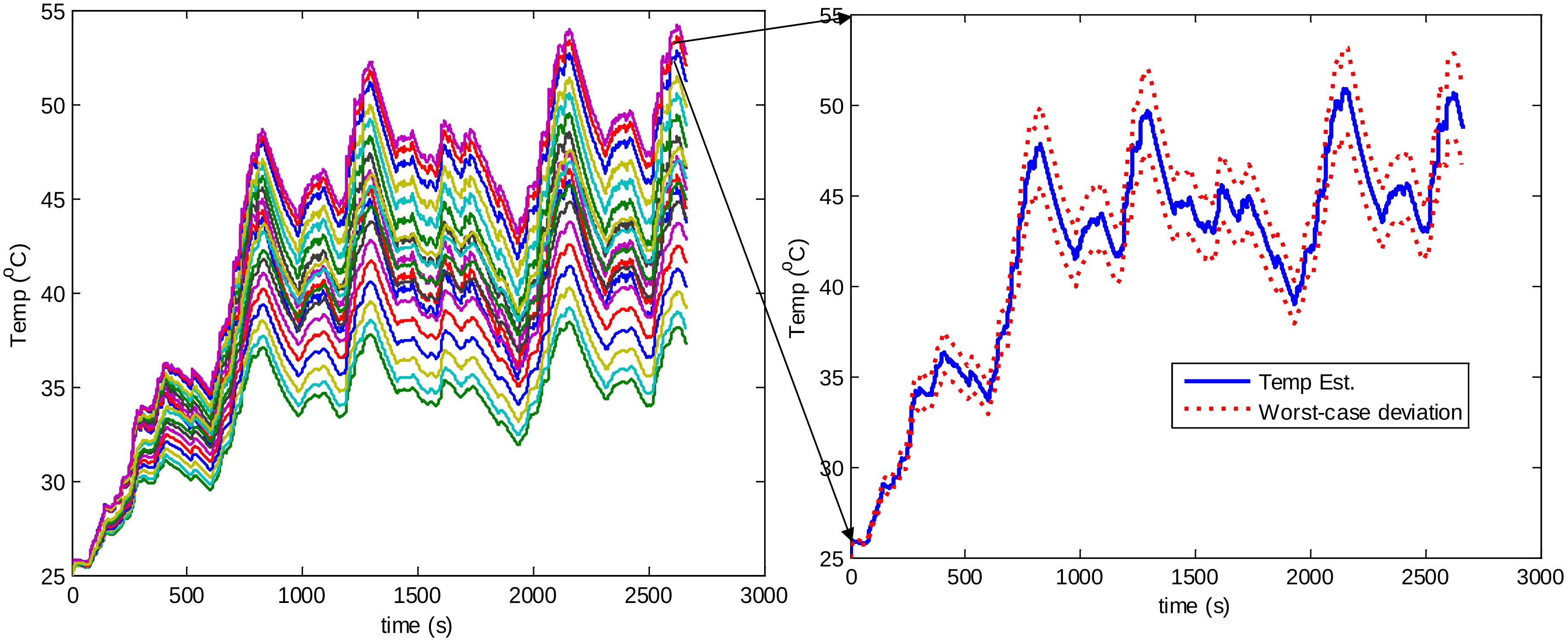
$$R - X < 0$$

In our case: $\Delta B_j = \dfrac{1}{C_c} \begin{bmatrix} \Delta R_{e,1} & 0 & \Delta R_{e,2} & 0 & \cdots & \Delta R_{e,n} & 0 \end{bmatrix}^T,$

$$\Delta R_{e,i} \in \{0.1R_{e,0}, -0.1R_{e,0}\}, \quad i = 1, 2, \cdots, n$$

Lin, Ph.D. Dissertation
Lin, et al., ASME DSCC 2014

Observer Performance



Estimated Temperature Distribution in the pack (core and surface T of each cell)

Worst-case Estimation Deviation Under the 10% Resistance Uncertainty

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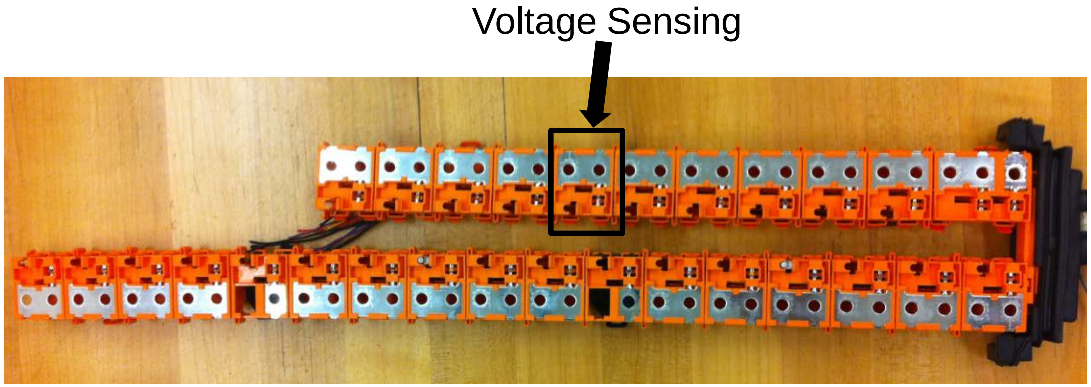
SOC Estimation Under Reduced Voltage Sensing



- **Issue: Too much voltage sensing**
  - Need to measure the voltage of single cells
  - For overvoltage protection
- **Disadvantages:**
  - High cost and complexity
  - Difficulty for maintenance

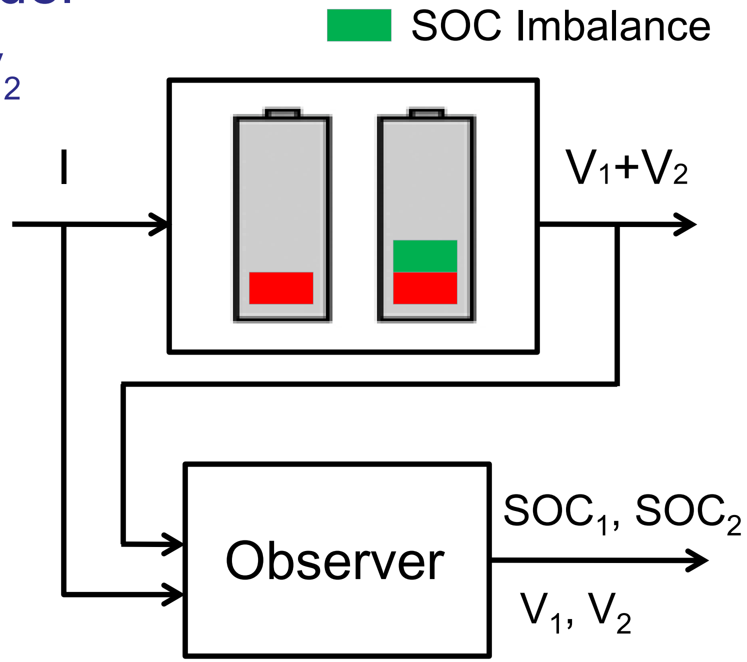
Are sensors such a big deal?
Yes for auto industry!

- **Solution: reduced voltage sensing**
  - Measuring the total voltage instead of cell voltage
  - Estimating the cell voltage from the total voltage

Problem Formulation

Two cells in series

- x_1 ‡ x_2 (SOC: state of charge)
- Analysis using a battery electrical model
- Goal: to estimate x_1, x_2 based on $V_1 + V_2$



🟩 SOC Imbalance

I

V_1+V_2

Observer

SOC_1, SOC_2

V_1, V_2

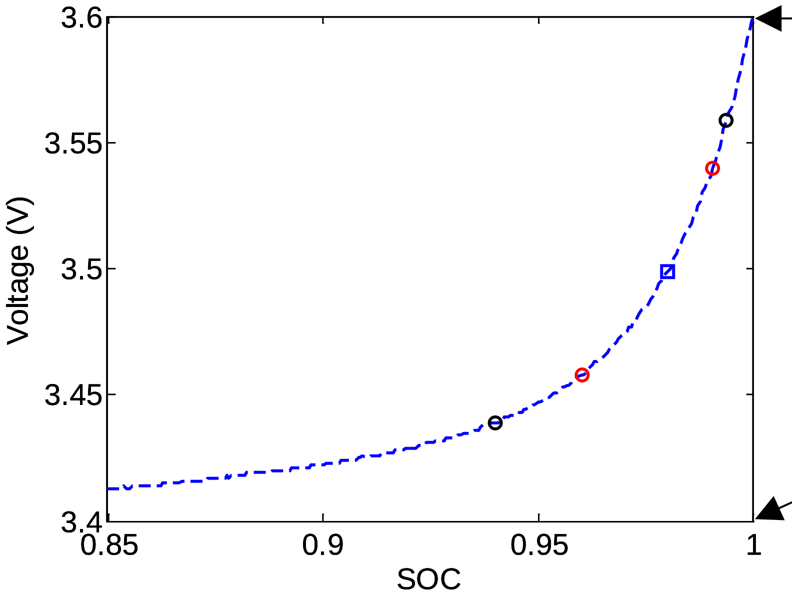
$$x_{1,k} = x_{1,k-1} + \frac{I_{k-1}\Delta t}{Q}, \quad V_{1,k} = g(x_{1,k}) + IR$$

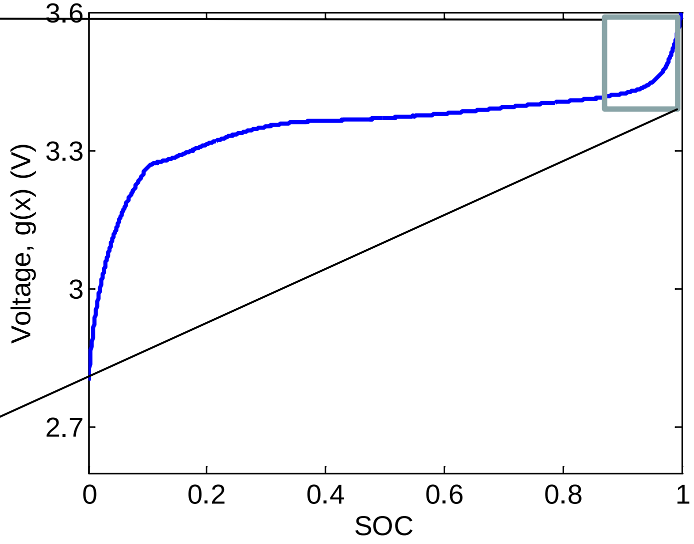
$$x_{2,k} = x_{2,k-1} + \frac{I_{k-1}\Delta t}{Q}, \quad V_{2,k} = g(x_{2,k}) + IR$$

$$x_{str,k} = \begin{bmatrix} x_{1,k} & x_{2,k} \end{bmatrix}^T$$

$$V_{str,k} = V_{1,k} + V_{2,k} = g(x_{1,k}) + g(x_{2,k}) + 2IR$$

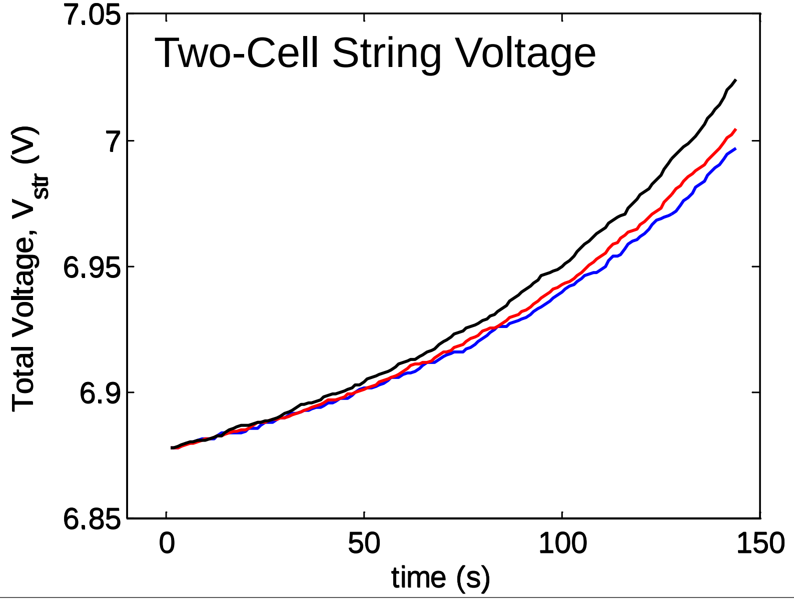
Feasibility?





Consider 3 combinations:

- □ $SOC_1 = SOC_2 = 0.94$
- ○ $SOC_1 = 0.92$, $SOC_2 = 0.952$
- ○ $SOC_1 = 0.9$, $SOC_2 = 0.958$



Single point: indistinguishable.
Trajectory: distinguishable.

Math Underpinning: Observability

Total voltage trajectory based on the string model

$$\begin{bmatrix} \delta V_{str,k} \\ \delta V_{str,k+1} \end{bmatrix} = \begin{bmatrix} g'(x_{1,k}) & g'(x_{2,k}) \\ g'(x_{1,k} + \frac{I_k \Delta t}{Q}) & g'(x_{2,k} + \frac{I_k \Delta t}{Q}) \end{bmatrix} \begin{bmatrix} \delta x_{1,k} \\ \delta x_{2,k} \end{bmatrix}$$

$$= O(x_{str,k}) \delta x_{str,k}$$

To be observable, $\delta x_{str,k}$ and ($\delta V_{str,k}$, $\delta Vx_{str,k+1}$) needs to be an one-to-one mapping, meaning that $O(x_{str,k})$ should be of full rank.

$$O(x_{str,k}) = \begin{bmatrix} g'(x_{1,k}) & g'(x_{2,k}) \\ g'(x_{1,k} + \frac{I_k \Delta t}{Q}) & g'(x_{2,k} + \frac{I_k \Delta t}{Q}) \end{bmatrix}$$

Observability Matrix

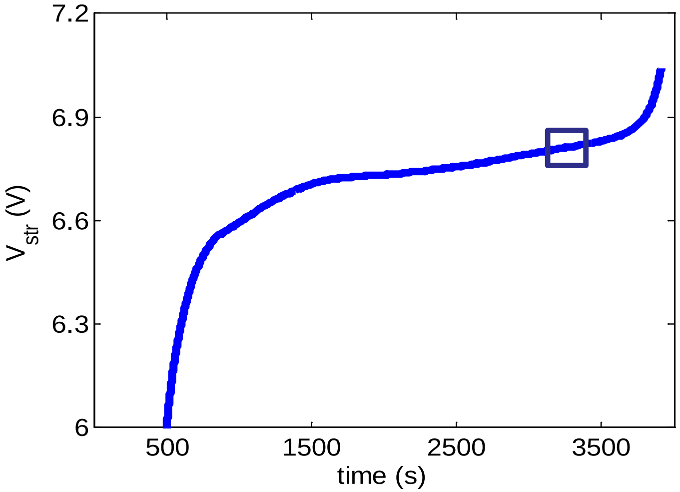
$$\Leftrightarrow \begin{bmatrix} g'(x_{1,k}) & g'(x_{2,k}) \\ g''(x_{1,k}) \frac{I}{Q} & g''(x_{2,k}) \frac{I}{Q} \end{bmatrix}$$

Nonlinear observability:
2nd order gradient of g(x)

Algorithm

Trajectory-based method: Moving Horizon Observer

$$\begin{bmatrix} V_{str,0} \\ \cdots \\ V_{str,k} \end{bmatrix} = \begin{bmatrix} g(x_{1,0}) + g(x_{2,0}) \\ g(x_{1,0} + \frac{I_0 \Delta t}{Q}) + g(x_{2,0} + \frac{I_0 \Delta t}{Q}) \\ \cdots \\ g(x_{1,0} + \frac{\sum_0^{k-1} I_i \Delta t}{Q}) + g(x_{2,0} + \frac{\sum_0^{k-1} I_i \Delta t}{Q}) \end{bmatrix} = H(x_{str,0})$$



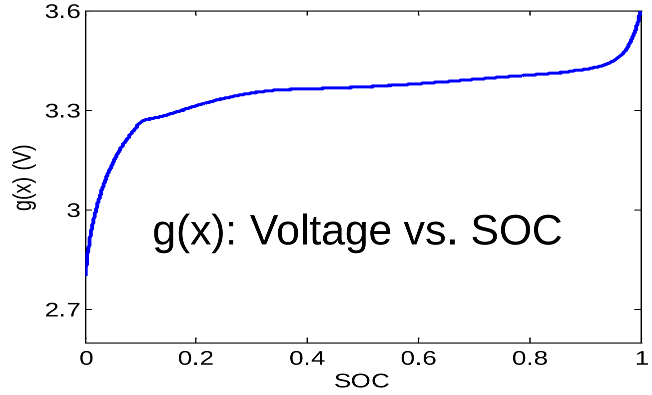
Use Newton's method to calculate $x_{str,0}$ iteratively:

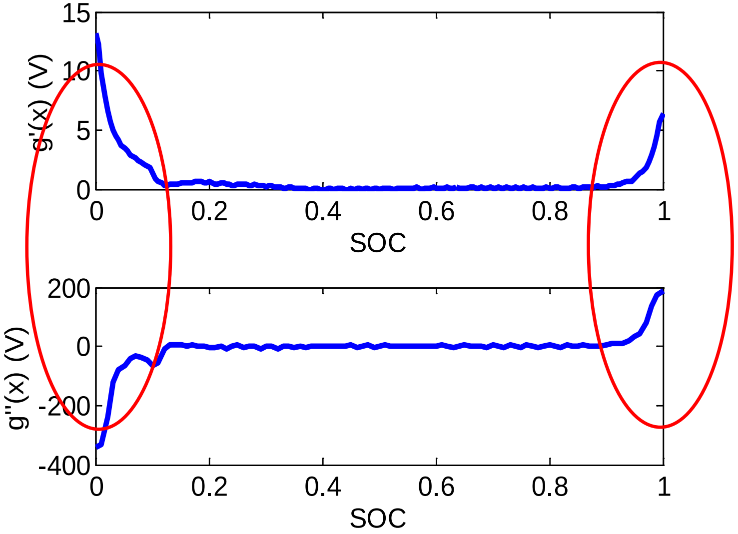
$$\tilde{x}_{str,0}^{j+1} = \tilde{x}_{str,0}^{j} + \left[\frac{\partial H}{\partial x_{str,0}}(\tilde{x}_{str,0}^{j}, I_{[0,k]})\right]^{-1} \left(V_{str,[0,k]} - H(\tilde{x}_{str,0}^{j}, I_{[0,k]})\right)$$

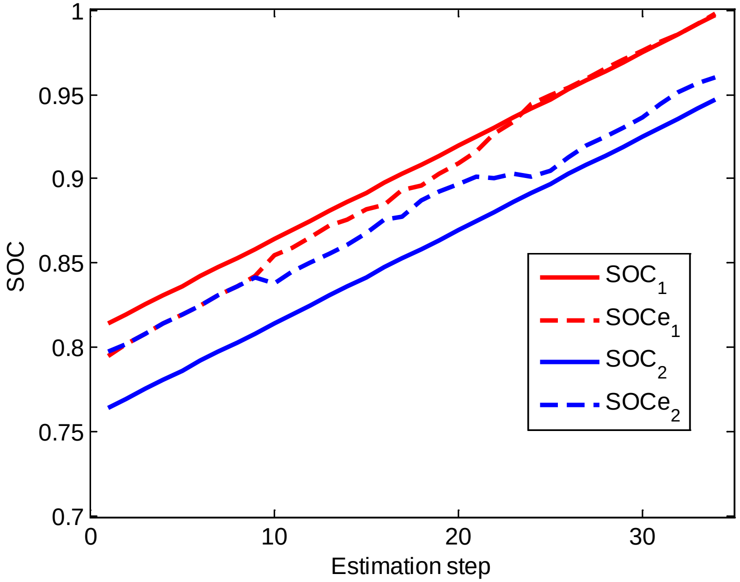
Lin, et al., IEEE Control Systems and Technology 2014
Lin, et al., American Control Conference 2013

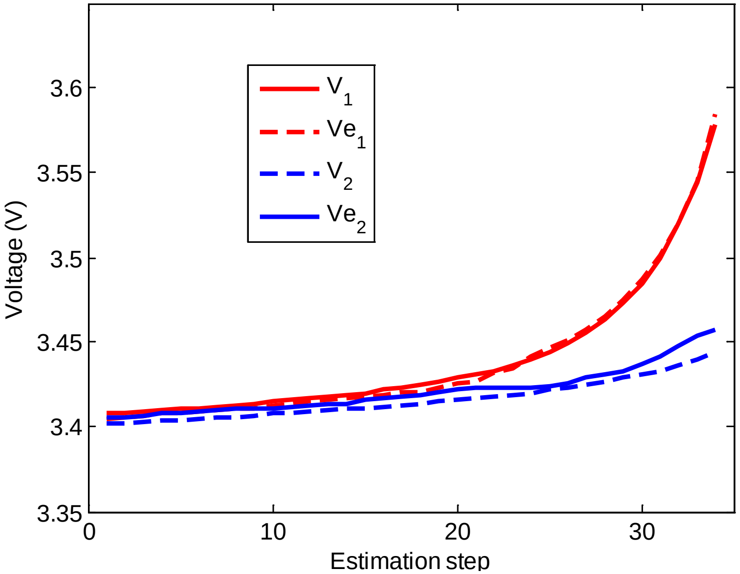
Application to Actual Battery

A123 LiFePO4 battery:









The SOCs are observable in high and low SOC ranges due to non-zero 2nd order gradient!

Summary: System-Level Battery Management

Battery Pack Temperature Estimation

- Thermal Model:
  - Capture surface and core temperatures of all cells in the pack
- Online parameter ID algorithm:
  - Determine parameters by using onboard signals
- Robust Observer design:
  - Guarantee minimized worst-case estimation error under uncertainty

SOC and Voltage Estimation under Reduced Voltage Sensing:

- Observability Analysis:
  - Establish the conditions for the cell SOCs to be observable
- Nonlinear Observer Design:
  - Trajectory-based moving horizon observer …
- Extension to cell capacity and resistance estimation

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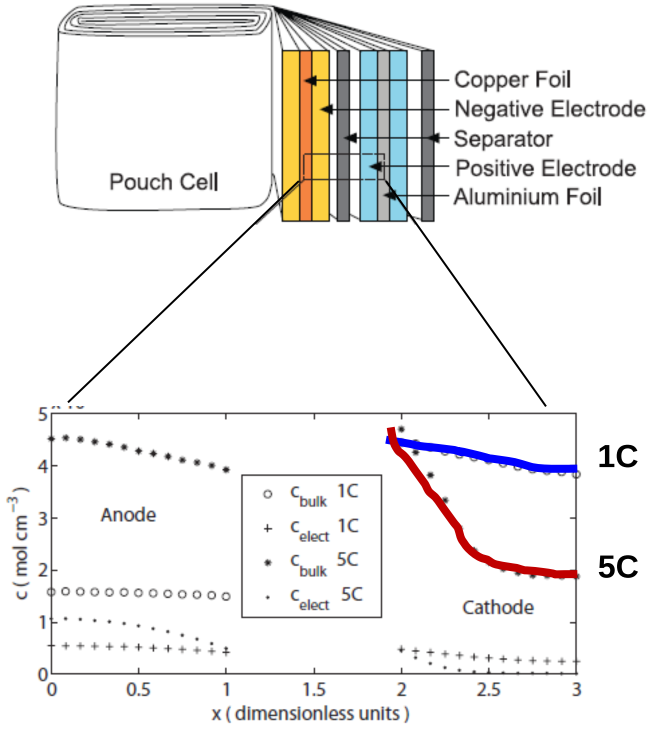
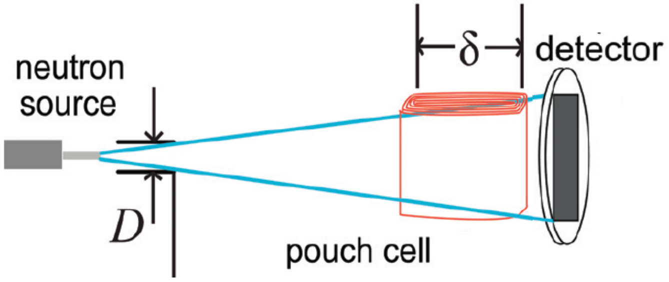
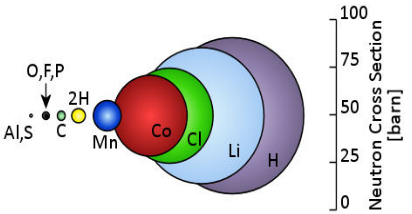
Neutron Imaging of Li-ion Battery

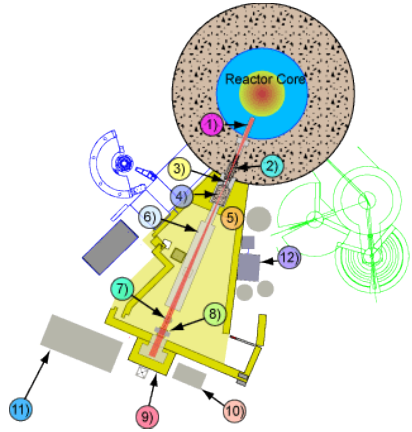


lithium distribution inside battery

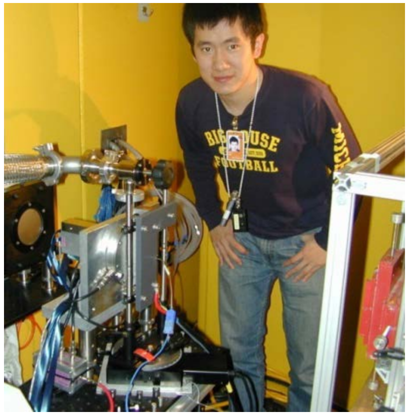
Siegel, Lin, et al., J. Electrochemical Soc. 2011
Siegel, Lin, et al., American Control Conference 2011
Siegel, Lin, et al., American Control Conference 2012







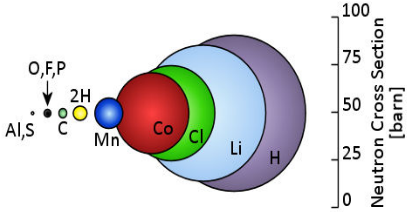
- 1) Neutrons from reactor
- 2) Tapered colimation
- 3) Bismuth filter
- 4) Rotating Drum
- 5) Wax and shot fill
- 6) Evacuated flight tube
- 7) Sample position
- 8) Neutron camera
- 9) Beam stop
- 10) Small fuel cell test stand
- 11) Large fuel cell test stand
- 12) Hydrogen generator



Design and Fabrication of Battery Cells

Why we made our own cells?

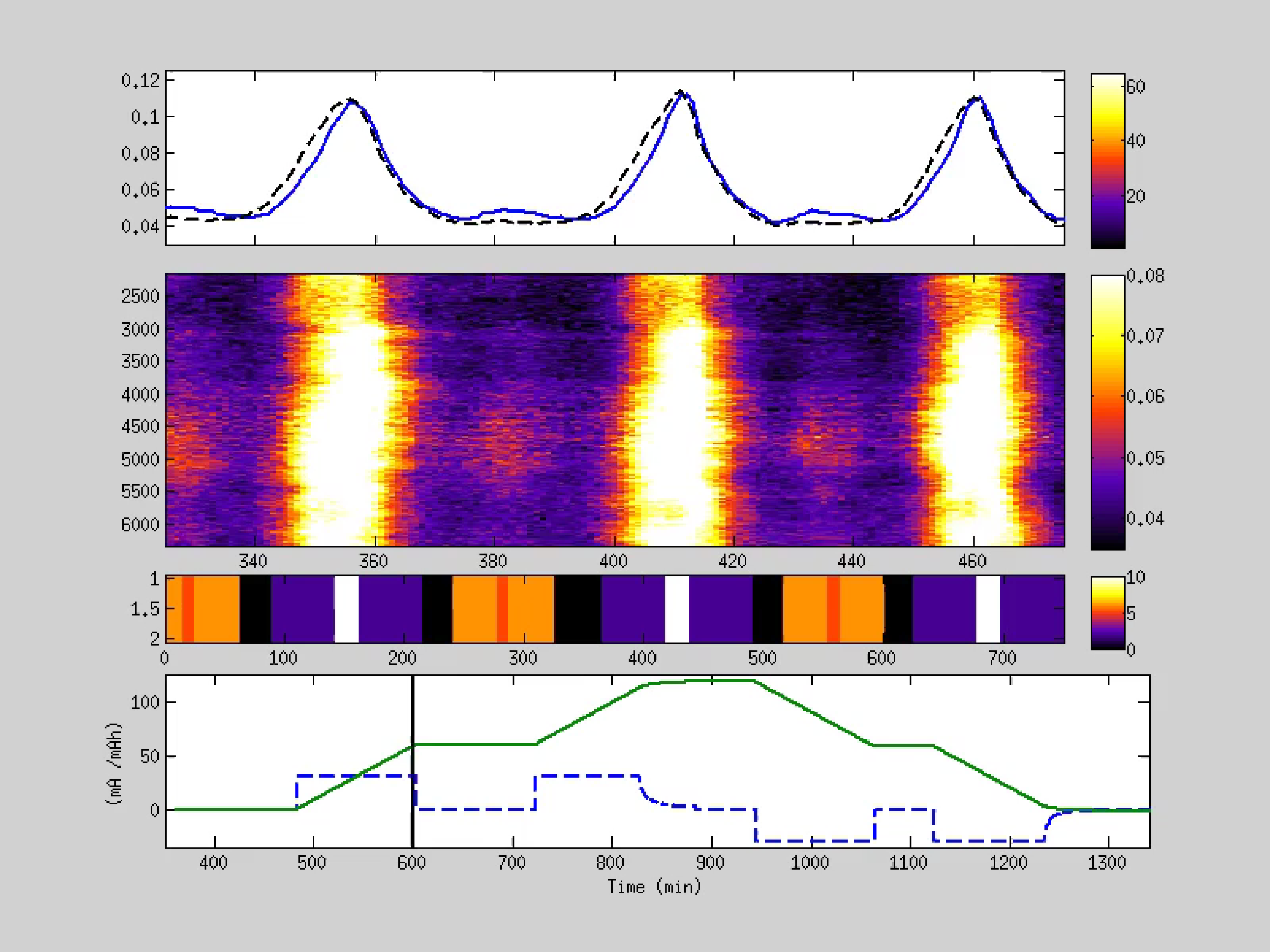
- customize shape/dimension
- to know/control composition
- need special materials



Procedures:

- Start with: LMO, graphite…
- Mix and Grind
- Dissolve and make paste
- Paste on the mold
- Bake and dry up
- Assemble inside glove box

Processed Lithium Concentration



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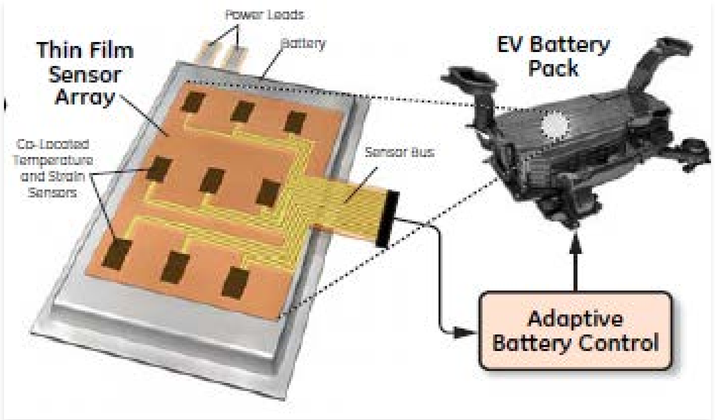
Work Experiences at Ford

- **Applying the system-level BMS to EVs**

- **EV systems and components development**
  - EV DC Fast Charging System
    - Charging 80% range in 20 minutes

- **University Collaboration:**
  - UMich, GE: ARPA-E AMPED
    - Battery control based on strain/temp sensing
  - Ohio State: Ford URP
    - Aging propagation in battery packs



Questions?