Estimation and Control of Battery Electrochemistry Models: A Tutorial

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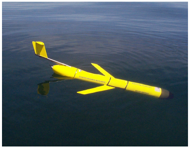
54th IEEE Conference on Decision and Control | Osaka, Japan

energy, controls, & applications lab

A Golden Era

IS-1
ST. JUDE MEDICAL
Sylmar, CA USA
ACCENT SR RF
PM1210 SSR
IS-1
ST. JUDE MEDICAL
Sylmar, CA USA
ANTHEM RF
PM3212 DDDRV



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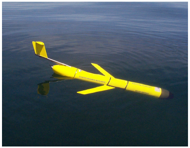

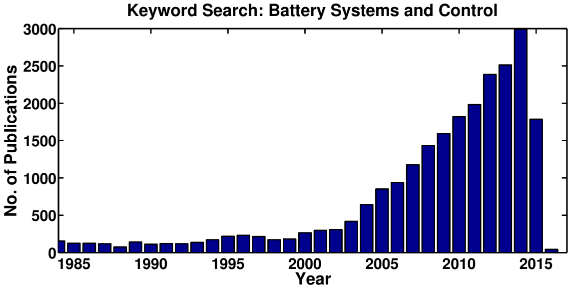

Keyword Search: Battery Systems and Control
No. of Publications
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500
1000
1500
2000
2500
3000
1985
1990
1995
2000
2005
2010
2015
Year

The Battery Problem

Needs: Cheap, high energy/power, fast charge, long life

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Some Motivating Facts

EV Batts	1000 USD / kWh (2010)*
	485 USD / kWh (2012)*
	350 USD / kWh (2015)**
	125 USD / kWh for parity to IC engine
	Only 50-80% of available capacity is used
	Range anxiety inhibits adoption
	Lifetime risks caused by fast charging

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Two Solutions

Design better batteries (materials science & chemistry)	Make current batteries better (estimation and control)

*Source: MIT Technology Review, "The Electric Car is Here to Stay." (2013)
**Source: Tesla Powerwall. (2015)

Outline

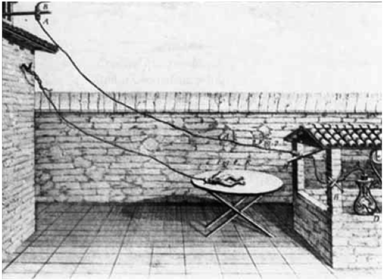
History

Luigi Galvani, 1737-1798,
Physicist, Bologna, Italy

"Animal electricity"
Dubbed "galvanism"

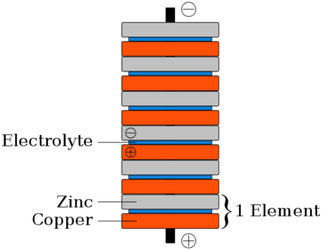
First foray into
electrophysiology

Experiments on frog legs



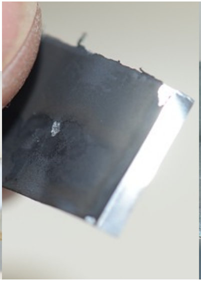
Alessandro Volta, 1745-1827
Physicist, Como, Italy

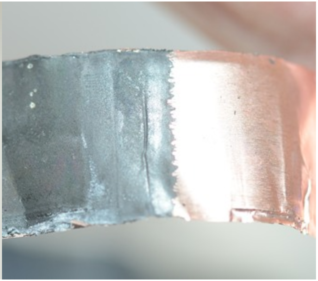
Voltaic Pile



Monument to Volta in Como

Cell Assembly - Jelly Roll





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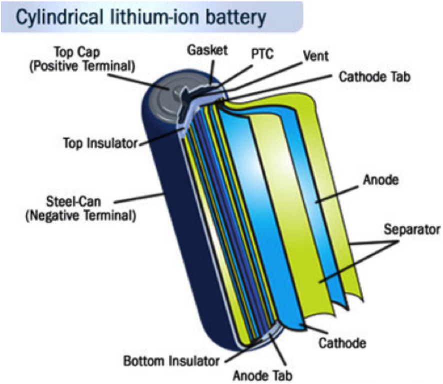
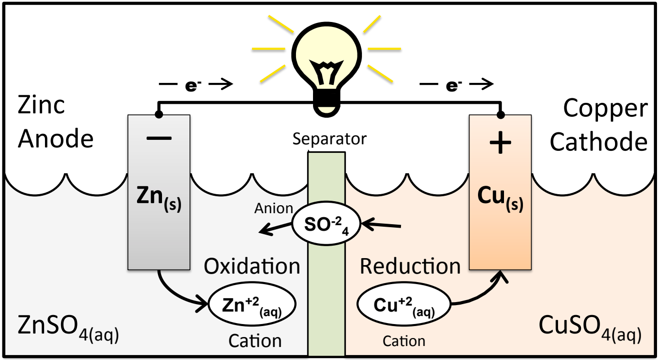


Battery Cell Anatomy

Principles of Operation



Anode Half Cell:

$$Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2e^-$$

Cathode Half Cell:

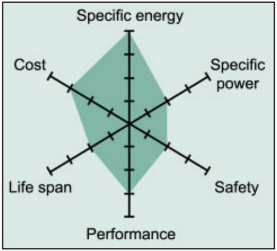
$$Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$$

Total Rxn:

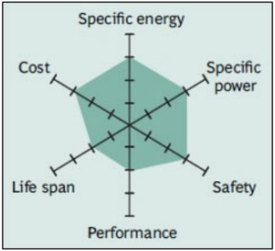
$$Zn_{(s)} + Cu^{2+}_{(aq)} \rightarrow Zn^{2+}_{(aq)} + Cu_{(s)}$$

Comparison of Lithium Ion (Cathode) Chemistries

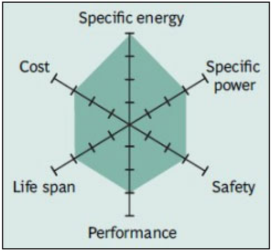
Lithium Cobalt Oxide ($LiCO_2$)



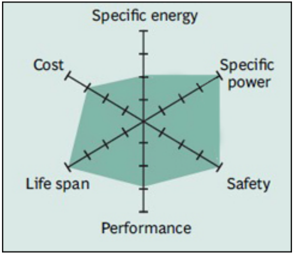
Lithium Manganese Oxide ($LiMn_2O_4$)



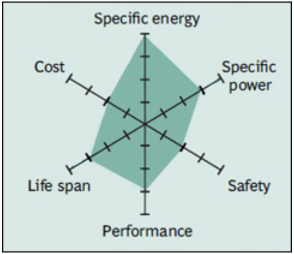
Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$)



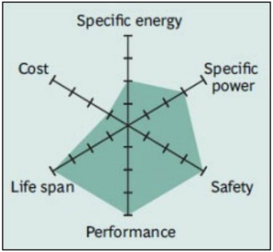
Lithium Iron Phosphate ($LiFePO_4$)



Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$)

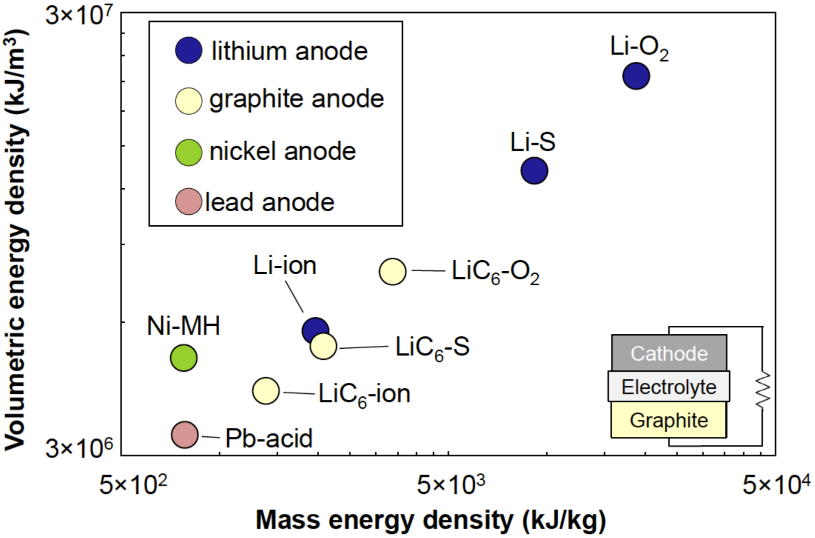


Lithium Titanate ($Li4Ti_5O_{12}$)



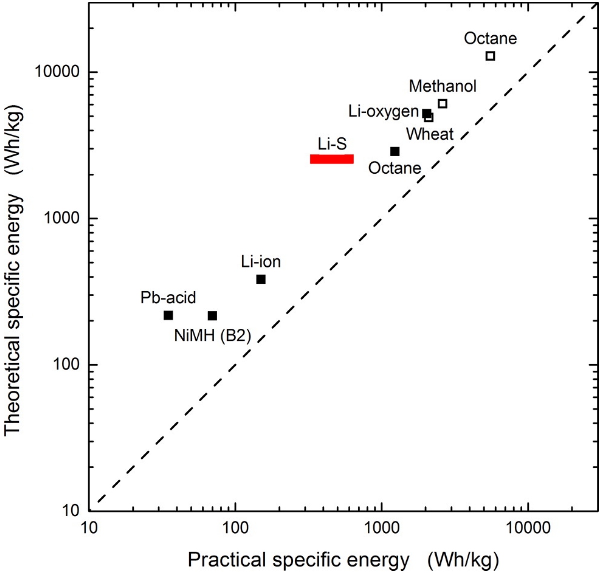
Source: `http://batteryuniversity.com/learn/article/types_of_lithium_ion`

Energy Density



Source: Katherine Harry & Nitash Balsara, UC Berkeley

Energy Density

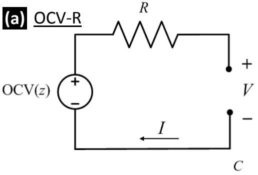


N. P. Balsara, and J. Newman, “Comparing the Energy Content of Batteries, Fuels, and Materials”, Journal of Chemical Education, 90 (2013), 446-52.

Outline

Equivalent Circuit Model

(a) OCV-R



Battery Models

Equivalent Circuit Model

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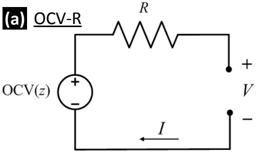
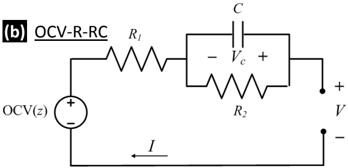
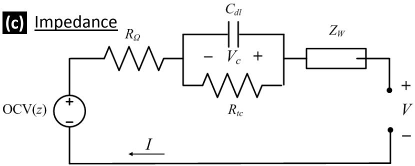


(b) OCV-R-RC



(c) Impedance



Battery Models

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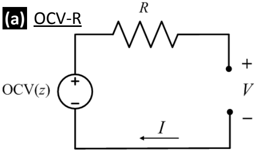
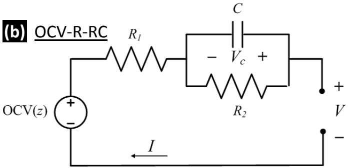
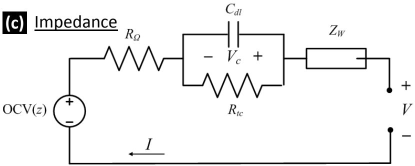
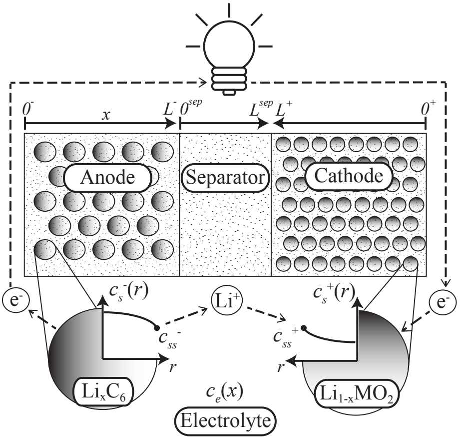


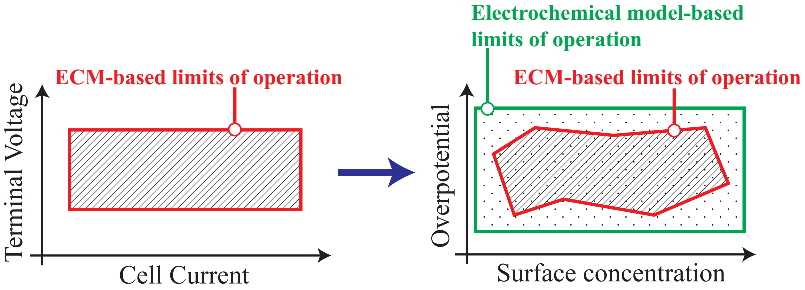




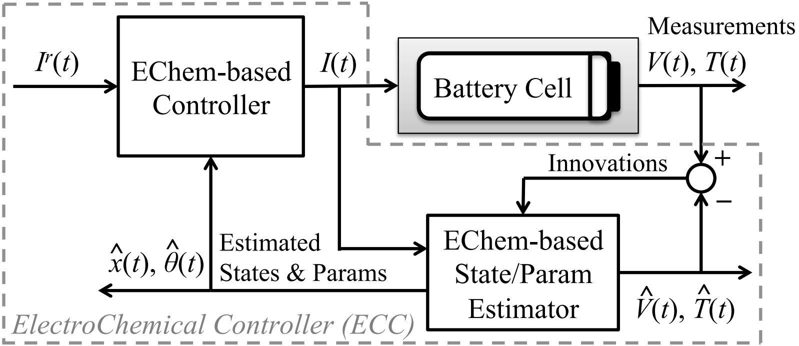
Electrochemical Model

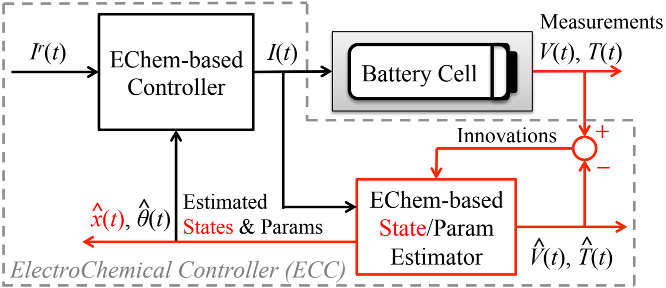


Safely Operate Batteries at their Physical Limits



ElectroChemical Controller (ECC)

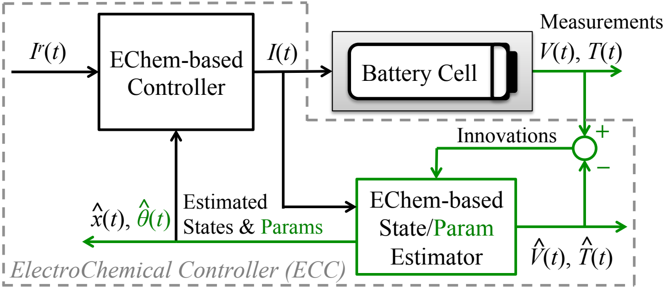




The State (a.k.a. SOC) Estimation Problem

Given measurements of current $I(t)$, voltage $V(t)$, and temperature $T(t)$, estimate the electrochemical states of interest. Exs:

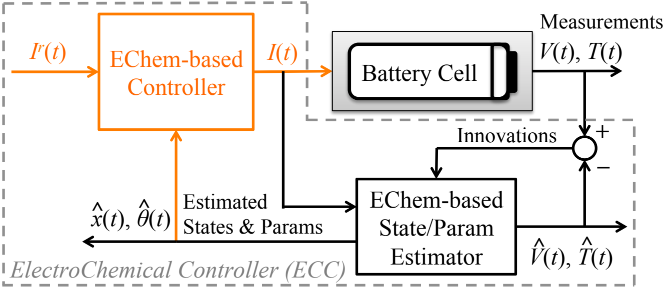
- bulk solid phase Li concentration (state-of-charge)
- surface solid phase Li concentration (state-of-power)



The Parameter (a.k.a. SOH) Estimation Problem

Given measurements of current $I(t)$, voltage $V(t)$, and temperature $T(t)$, estimate uncertain parameters related to SOH. Exs:

- cyclable lithium (capacity fade)
- volume fraction (capacity fade)
- solid-electrolyte interface resistance (power fade)

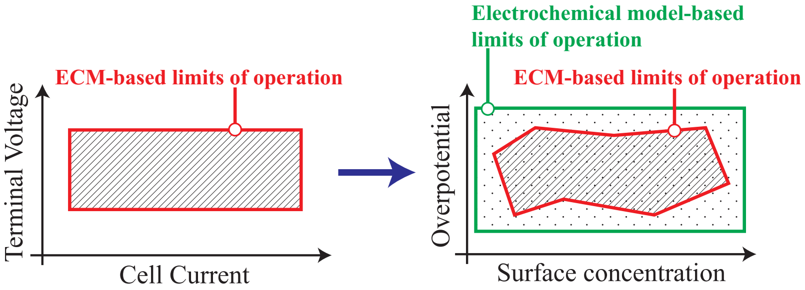


The Constrained Control Problem

Given measurements of current $I(t)$, voltage $V(t)$, and temperature $T(t)$, control current such that critical electrochemical variables are maintained within safe operating constraints. Exs:

- saturation/depletion of solid phase and electrolyte phase
- side-reaction overpotentials
- internal temperature

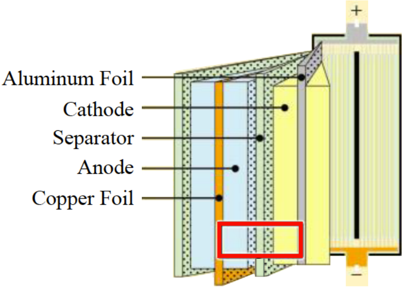
Safely Operate Batteries at their Physical Limits

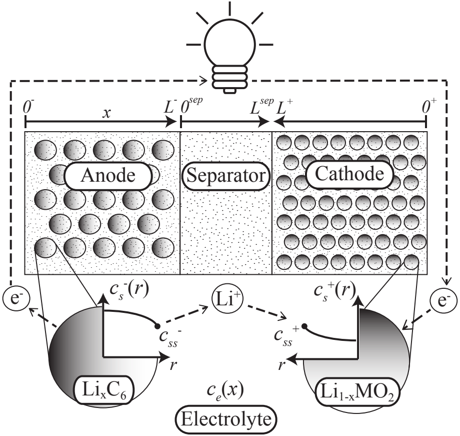


Outline

Battery Electrochemistry Model

The Doyle-Fuller-Newman (DFN) Model





Key References:

- K. Thomas, J. Newman, and R. Darling, Advances in Lithium-Ion Batteries. New York, NY USA: Kluwer Academic/Plenum Publishers, 2002, ch. 12: Mathematical modeling of lithium batteries, pp. 345-392.
- N. A. Chaturvedi, R. Klein, J. Christensen, J. Ahmed, and A. Kojic, “Algorithms for advanced battery-management systems,” IEEE Control Systems Magazine, vol. 30, no. 3, pp. 49-68, 2010.
- J. Newman. (2008) Fortran programs for the simulation of electrochemical systems. [Online]. Available: `http://www.cchem.berkeley.edu/jsngrp/fortran.html`

Electrochemical Model Equations

well, some of them | Matlab CODE: github.com/scott-moura/dfn

Description	Equation
Solid phase Li concentration	$\frac{\partial c_s^{\pm}}{\partial t}(x,r,t) = \frac{1}{r^2}\frac{\partial}{\partial r}\left[D_s^{\pm} r^2 \frac{\partial c_s^{\pm}}{\partial r}(x,r,t)\right]$
Electrolyte Li concentration	$\varepsilon_e \frac{\partial c_e}{\partial t}(x,t) = \frac{\partial}{\partial x}\left[\varepsilon_e D_e(c_e)\frac{\partial c_e}{\partial x}(x,t) + \frac{1-t_c^0}{F} i_e^{\pm}(x,t)\right]$
Solid potential	$\frac{\partial \phi_s^{\pm}}{\partial x}(x,t) = \frac{i_e^{\pm}(x,t) - I(t)}{\sigma^{\pm}}$
Electrolyte potential	$\frac{\partial \phi_e}{\partial x}(x,t) = -\frac{i_e^{\pm}(x,t)}{\kappa} + \frac{2RT(1-t_c^0)}{F}\left(1 + \frac{d \ln f_{c/a}}{d \ln c_e}(x,t)\right)\frac{\partial \ln c_e}{\partial x}(x,t)$
Electrolyte ionic current	$\frac{\partial i_e^{\pm}}{\partial x}(x,t) = a_s F j_n^{\pm}(x,t)$
Molar flux btw phases	$j_n^{\pm}(x,t) = \frac{1}{F} i_0^{\pm}(x,t)\left[e^{\frac{\alpha_a F}{RT}\eta^{\pm}(x,t)} - e^{-\frac{\alpha_c F}{RT}\eta^{\pm}(x,t)}\right]$
Temperature	$\rho c_P \frac{dT}{dt}(t) = h\left[T^0(t) - T(t)\right] + I(t)V(t) - \int_{0^-}^{0^+} a_s F j_n(x,t)\Delta T(x,t)dx$

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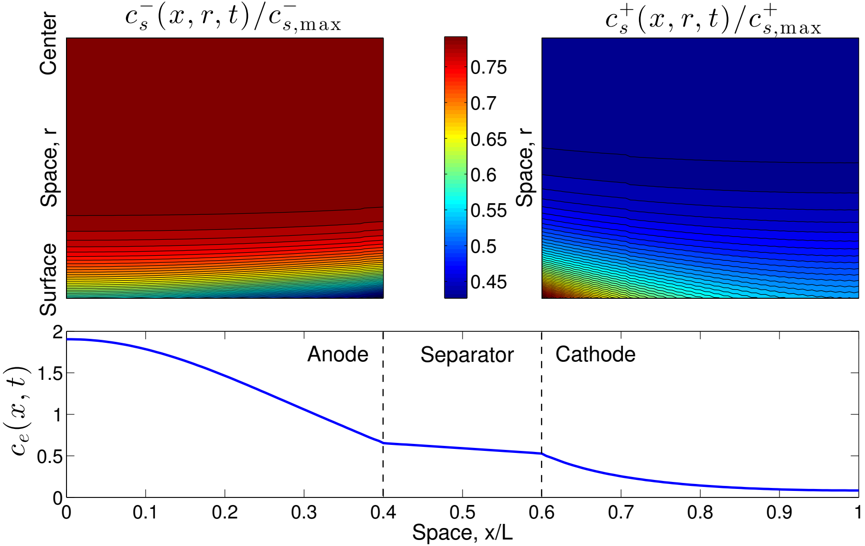
Simulations

LiCoO$_2$-C cell | 5C discharge after 30sec



Animation of Li Ion Evolution

Pulsed Discharge @ 5C

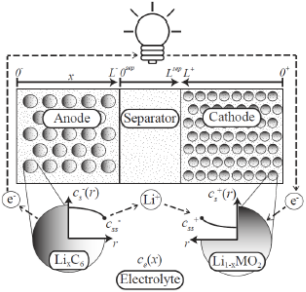
Model Reduction

Derive control-oriented models from full electrochemical model to:

- Achieve “fast” and “sufficiently accurate” simulations
- Study state observability & parameter identifiability
- Analyze stability, optimality, feasibility

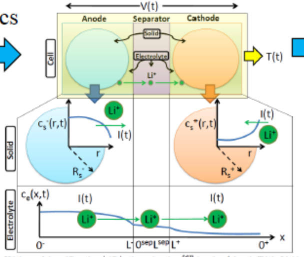
Model Reduction

Electrochemical Model



Less Physics

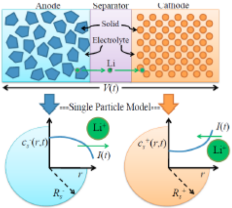
Single Particle + Electrolyte and Thermal Dynamics



$$V(t) = h(c_s^-(R_s^-,t), c_s^+(R_s^+,t), c_e^-(x,t), c_e^{sep}(x,t), c_e^+(x,t), T(t), I(t))$$

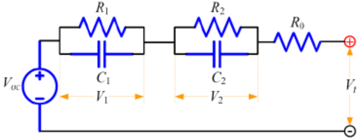
Less Physics

Single Particle Model



Less Physics

Equivalent Circuit Model



Model Reduction

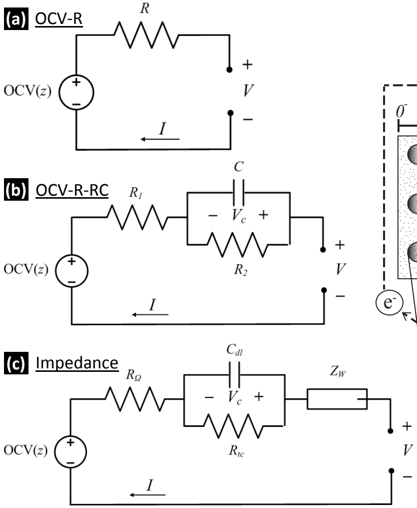
Methods in literature:

- Spectral methods [6], [7]
- Residue grouping [8]
- Quasilinearization & Padé approximation [9]
- Principle orthogonal decomposition [10]
- Single particle model variants [11], [12], [13]
- and much, much more (to be discussed by co-presenters)

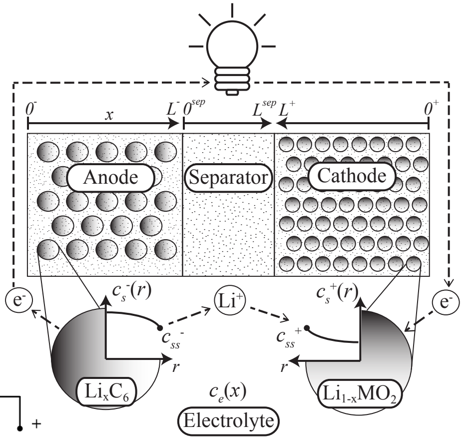
This is a very popular topic. Won't be discussed further in this talk.

Outline

Equivalent Circuit Model (ECM)



Electrochemical Model



Survey of SOC/SOH Estimation Literature

Equivalent Circuit Model (ECM)

Study ECM variant X
with estimation algorithm Y

Not the focus here.

Electrochemical Model

EChem-based estimation has recently emerged

Focus on estimation for reduced EChem models

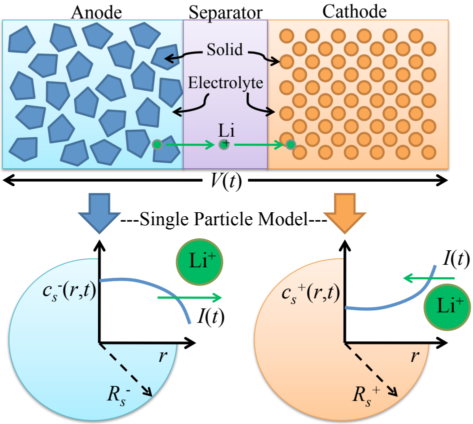
Model reduction and estimation are intimately intertwined

Ideally, want to prove estimation error stability for the highest fidelity model possible

First wave of studies consider a “Single Particle Model” [11], [12], [14], [15]

Difficulty of proving stability increases as model complexity/fidelity increases. Core difficulty is lack of complete observability and nonlinear identifiability.

Single Particle Model (SPM)

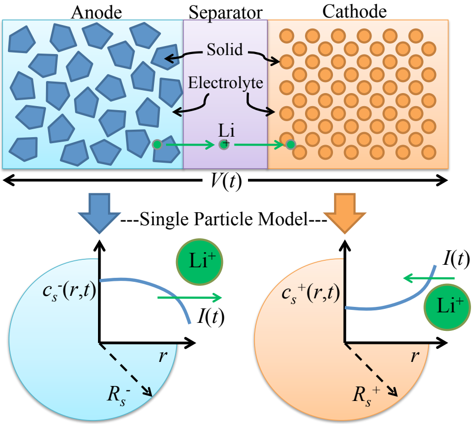


Single Particle Model (SPM)

Diffusion of Li in solid phase:

$$\frac{\partial c_s^-}{\partial t}(r,t) = \frac{D_s^-}{r^2}\frac{\partial}{\partial r}\left[r^2 \frac{\partial^2 c_s^-}{\partial r^2}(r,t)\right]$$

$$\frac{\partial c_s^+}{\partial t}(r,t) = \frac{D_s^+}{r^2}\frac{\partial}{\partial r}\left[r^2 \frac{\partial^2 c_s^+}{\partial r^2}(r,t)\right]$$



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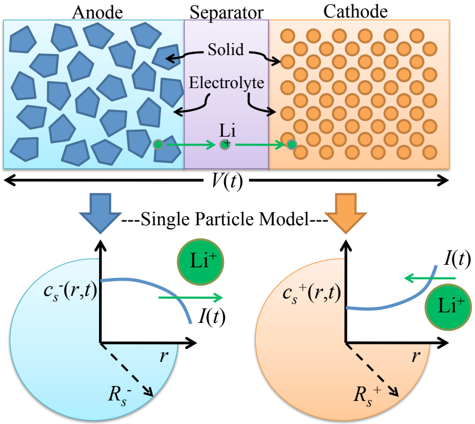
Boundary conditions:

$$\frac{\partial c_s^-}{\partial r}(R_s^-,t) = -\rho^- I(t)$$

$$\frac{\partial c_s^+}{\partial r}(R_s^+,t) = \rho^+ I(t)$$



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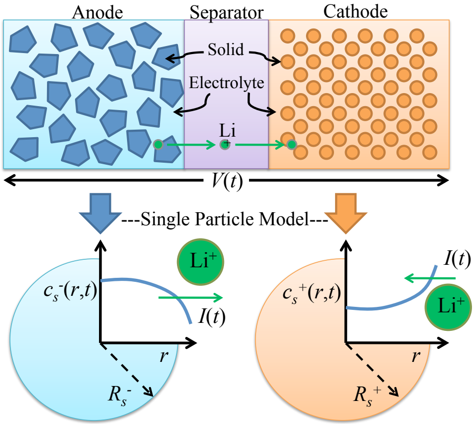
Voltage Output Function:

$$V(t) = h(c_{ss}^-(t), c_{ss}^+(t), I(t); \theta)$$



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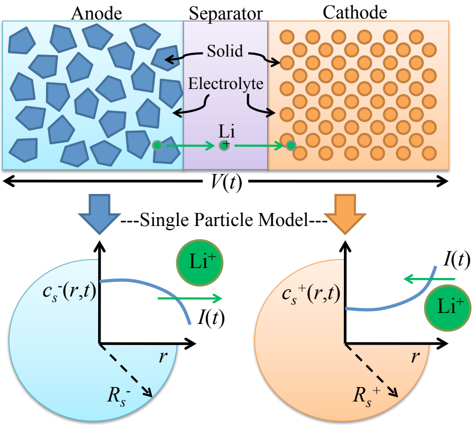

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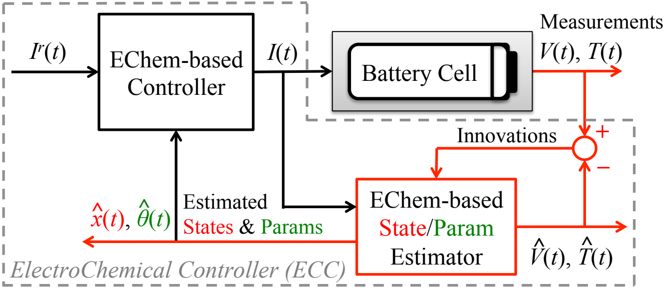
Definitions

- SOC: Bulk concentration SOC_{bulk}, Surface concentration $c_{ss}^-(t)$
- SOH: Physical parameters, e.g. ε, q, n_{Li}, R_f

Adaptive SOC/SOH Problem



Combined SOC/SOH Problem

Given measurements of current $I(t)$, voltage $V(t)$, and the SPM equations, simultaneously estimate the lithium concentration states $c_s^-(r,t), c_s^+(r,t)$ and parameters θ.

Causal Structure of SPM

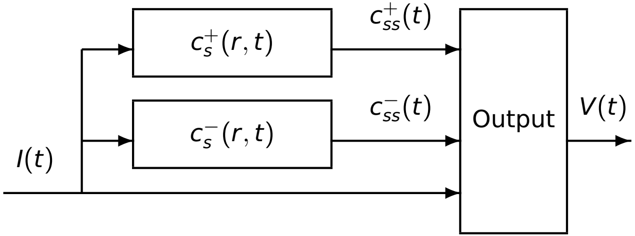


Figure: Block diagram of SPM. Note that the c_s^+, c_s^- subsystems are independent of one another.

Model Properties - I

$$\frac{\partial c_s^-}{\partial t}(r,t) = \frac{D_s^-}{r^2}\frac{\partial}{\partial r}\left[r^2 \frac{\partial^2 c_s^-}{\partial r^2}(r,t)\right]$$

$$\frac{\partial c_s^-}{\partial r}(0,t) = 0$$

$$\frac{\partial c_s^-}{\partial r}(R_s^-,t) = -\rho^- I(t)$$

$$\frac{\partial c_s^+}{\partial t}(r,t) = \frac{D_s^+}{r^2}\frac{\partial}{\partial r}\left[r^2 \frac{\partial^2 c_s^+}{\partial r^2}(r,t)\right]$$

$$\frac{\partial c_s^+}{\partial r}(0,t) = 0$$

$$\frac{\partial c_s^+}{\partial r}(R_s^+,t) = \rho^+ I(t)$$

Proposition 1: Marginal Stability

Each PDE subsystem $(c_s^+(r,t), c_s^-(r,t))$ is marginally stable.
In particular, each PDE contains

- one e-value @ origin
- remaining e-values on negative real axis

Model Properties - II

Proposition 2: Conservation of Lithium

Moles of solid phase lithium are conserved. Mathematically, $\frac{d}{dt}(n_{Li}(t)) = 0$ where

$$n_{Li}(t) = \sum_{j \in \{+,-\}} \frac{\epsilon_s^j L^j A}{\frac{4}{3}\pi(R_s^j)^3} \int_0^{R_s^j} 4\pi r^2 c_s^j(r,t) dr$$

Remark 2: Initial Conditions and Moles of Lithium

Consider ICs corresponding to steady-state and $I(t) = 0$, then the ICs $c_{s,0}^+, c_{s,0}^-$, moles of lithium n_{Li}, and initial voltage V_0 verify:

$$\begin{aligned} n_{Li} &= \varepsilon_s^+ L^+ \, c_{s,0}^+ + \varepsilon_s^- L^- \, c_{s,0}^-, \\ V_0 &= U^+(c_{s,0}^+) - U^-(c_{s,0}^-) \end{aligned}$$

Invertability Analysis

Objective

Study invertability of output function $V(t) = h(c_{ss}^{+}, c_{ss}^{-}, I)$ w.r.t. c_{ss}^{+} and c_{ss}^{-}.

$$
\begin{aligned}
V(t) =& \frac{RT}{\alpha F} \sinh^{-1}\left(\frac{-I(t)}{2a^{+}AL^{+}i_0^{+}(c_{ss}^{+})}\right) - \frac{RT}{\alpha F} \sinh^{-1}\left(\frac{I(t)}{2a^{-}AL^{+}i_0^{-}(c_{ss}^{-})}\right) \\
& U^{+}(c_{ss}^{+}) - U^{-}(c_{ss}^{-}) - \left(\frac{R_f^{+}}{a^{+}L^{+}} + \frac{R_f^{-}}{a^{-}L^{-}}\right) I(t), \qquad (1) \\
i_0^{\pm}(c_{ss}^{\pm}) =& k^{\pm}\sqrt{c_e^0 c_{ss}^{\pm}(c_{s,\max}^{\pm} - c_{ss}^{\pm})} \qquad (2)
\end{aligned}
$$

Define:

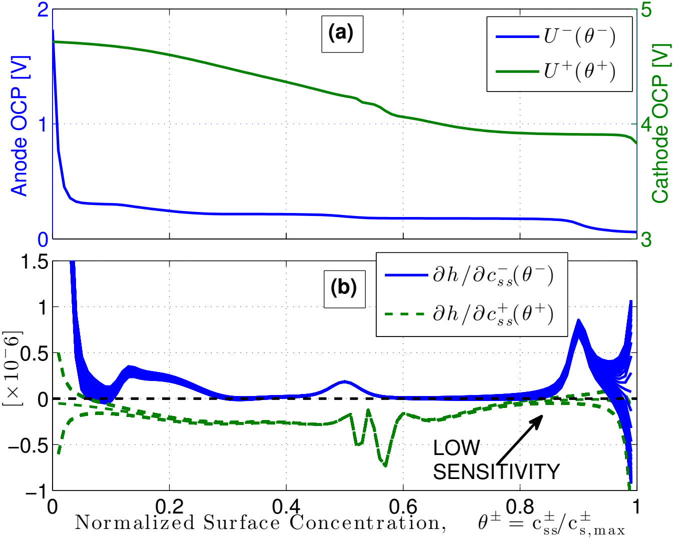
$$
V(t) = h(c_{ss}^{+}, c_{ss}^{-}, I) \qquad (3)
$$

Compute:

$$
\frac{\partial h}{\partial c_{ss}^{+}}(c_{ss}^{+}, c_{ss}^{-}, I) \quad AND \quad \frac{\partial h}{\partial c_{ss}^{-}}(c_{ss}^{+}, c_{ss}^{-}, I) \qquad (4)
$$

over a range of SOC and I.

OCPs and Output Function Sensitivities



Nonlinear Parameter Identifiability

Nonlinearly Parameterized Output

$$V(t) = h(c_{ss}^{+}(t), c_{ss}^{-}(t), I(t); \theta)$$

- θ contains many parameters
- Linear dependence between parameters?

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Identifiability Analysis Result

- Linearly independent parameter subset : $\theta_h = [n_{Li}, R_f]^T$
  - n_{Li} : Total amount of cyclable Li (Capacity Fade)
  - R_f : Resistance of current collectors, electrolyte, etc. (Power Fade)

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  - n_{Li} : Total amount of cyclable Li (Capacity Fade)
  - R_f : Resistance of current collectors, electrolyte, etc. (Power Fade)

Enables the application of nonlinear least squares parameter identification tools applied to vector θ_h

Nonlinear Identifiability Analysis

Parameterized Output

$$V(t) = h(c_{ss}^{+}(t), c_{ss}^{-}(t), I(t); \theta)$$

$$\theta = \left[n_{Li}, \frac{1}{a^{+}AL^{+}k^{+}\sqrt{c_e^0}}, \frac{1}{a^{-}AL^{-}k^{-}\sqrt{c_e^0}}, R_f \right]^T$$

- Linear dependence between parameters?

Parameter Sensitivity

$$S = \frac{\partial h}{\partial \theta} \qquad\qquad S \in R^{n_T \times 4}$$

$$S = [S_1, S_2, S_3, S_4]^T$$

- A particular decomposition of $S^T S$ reveals linear dependence between parameters!

Nonlinear Identifiability Analysis

Decomposition of $S^T S = D^T C D$

$$D = \mathrm{diag}(\|S_1\|, \|S_2\|, \|S_3\|, \|S_4\|)$$

$$C = \begin{bmatrix} 1 & \frac{\langle S_1, S_2 \rangle}{\|S_1\| \|S_2\|} & \frac{\langle S_1, S_3 \rangle}{\|S_1\| \|S_3\|} & \frac{\langle S_1, S_4 \rangle}{\|S_1\| \|S_4\|} \\ \frac{\langle S_2, S_1 \rangle}{\|S_2\| \|S_1\|} & 1 & \frac{\langle S_2, S_3 \rangle}{\|S_2\| \|S_3\|} & \frac{\langle S_2, S_4 \rangle}{\|S_2\| \|S_4\|} \\ \frac{\langle S_3, S_1 \rangle}{\|S_3\| \|S_1\|} & \frac{\langle S_3, S_2 \rangle}{\|S_3\| \|S_2\|} & 1 & \frac{\langle S_3, S_4 \rangle}{\|S_3\| \|S_4\|} \\ \frac{\langle S_4, S_1 \rangle}{\|S_4\| \|S_1\|} & \frac{\langle S_4, S_2 \rangle}{\|S_4\| \|S_2\|} & \frac{\langle S_4, S_3 \rangle}{\|S_4\| \|S_3\|} & 1 \end{bmatrix}$$

- $\frac{|\langle S_i, S_j \rangle|}{\|S_i\| \|S_j\|} \approx 1 \Rightarrow$ linear dependence
- $\frac{|\langle S_i, S_j \rangle|}{\|S_i\| \|S_j\|} \approx 0 \Rightarrow$ linear independence

Nonlinear Identifiability Analysis

Decomposition of $S^T S = D^T C D$

- $\frac{|\langle S_i, S_j \rangle|}{||S_i|| \, ||S_j||} \approx 1 \Rightarrow$ linear dependence
- $\frac{|\langle S_i, S_j \rangle|}{||S_i|| \, ||S_j||} \approx 0 \Rightarrow$ linear independence

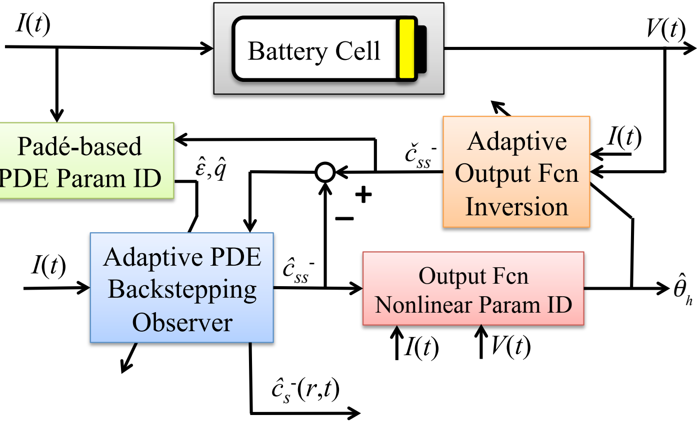
Example: UDDS Drive Cycle Applied to Battery Model

$$C = \begin{bmatrix} 1 & -0.3000 & 0.2908 & 0.2956 \\ -0.3000 & 1 & -0.9801 & -0.9805 \\ 0.2908 & -0.9801 & 1 & 0.9322 \\ 0.2956 & -0.9805 & 0.9322 & 1 \end{bmatrix}$$

- $\theta_2, \theta_3, \theta_4$ are linearly dependent
- Identify the subset $\theta_h = [\theta_1, \theta_4]^T$ via nonlinear least squares
  - $\theta_1 = n_{Li}$: Capacity Fade
  - $\theta_4 = R_f$: Power Fade

Adaptive Observer

Combined State & Parameter Estimation



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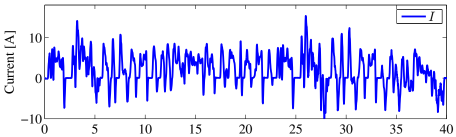
Adaptive Observer Simulations

UDDS Drive Cycle Input



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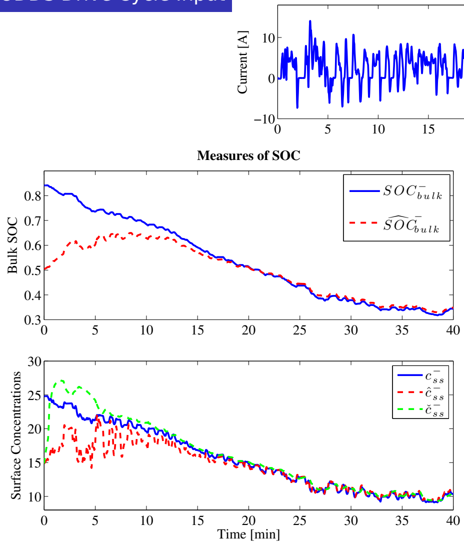

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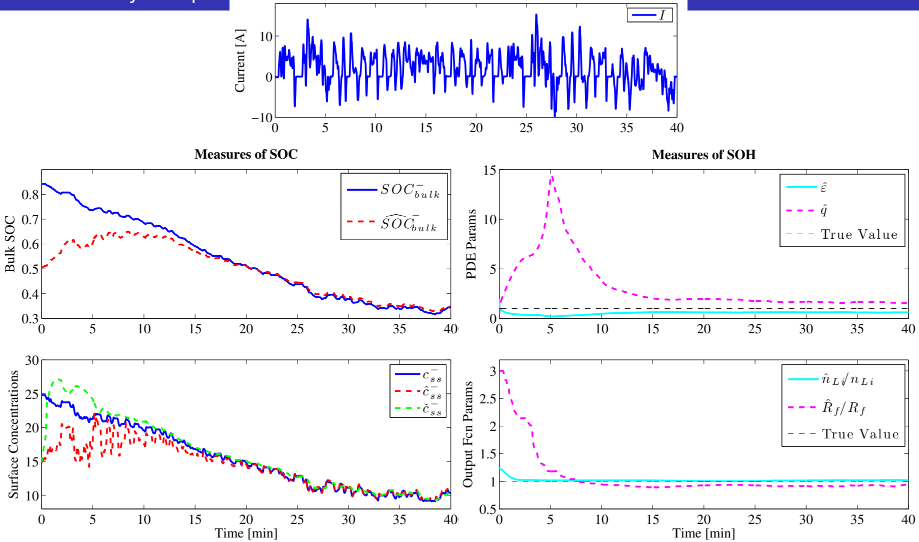

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Outline

Operate Batteries at their Physical Limits

Operate Batteries at their Physical Limits

Existing Literature

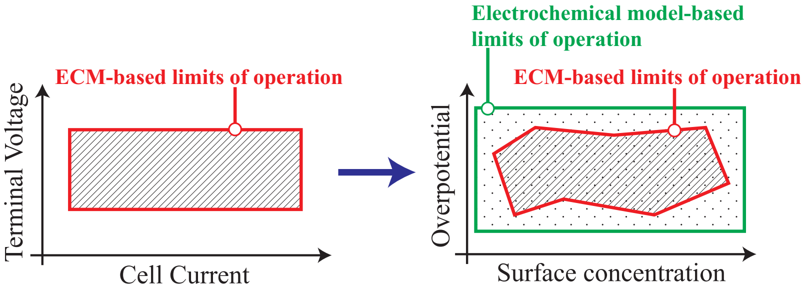
Heuristic Protocols

- Survey of protocols [25]
- Multi-stage CC plus CV (MCC-CV) [Ansean et al, 2013]
- Boost charging (CV-CC-CV) [Notten et al, 2005]
- CC-CV with negative pulse (CC-CV-NP) [Monem et al., 2015]

Model-based

- Piecewise constant time discretization [Methekar et al, 2010]
- One step model predictive control [Klein et al, 2010]
- Linear quadratic formulations [Parvini et al, 2015]
- Linearized input-output models [Torchio et al, 2015]
- State independent electrical parameters [Abdollahi et al, 2015]
- Reference governors [Perez et al, 2015]

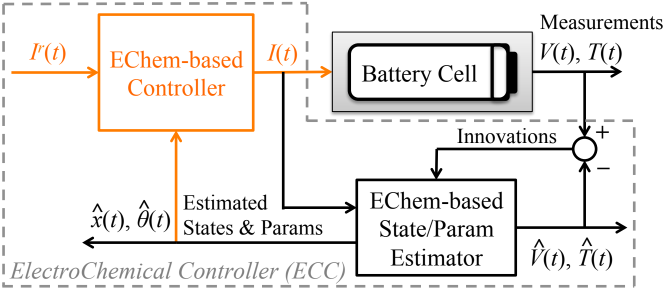
Operate Batteries at their Physical Limits



Problem Statement

Given accurate electrochemical state/parameter estimates $(\hat{x}, \hat{\theta})$, govern the input current $I(t)$ such that the EChem constraints are enforced.

Operate Batteries at their Physical Limits



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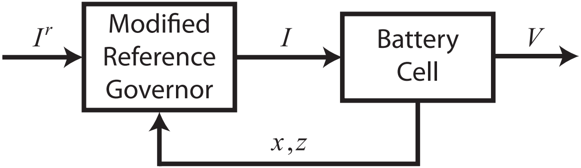
Constraints

Variable	Definition	Constraint
$I(t)$	Current	Power electronics limits
$c_s^{\pm}(x,r,t)$	Li concentration in solid	Saturation/depletion
$\frac{\partial c_s^{\pm}}{\partial r}(x,r,t)$	Li concentration gradient	Diffusion-induced stress
$c_e(x,t)$	Li concentration in electrolyte	Saturation/depletion
$T(t)$	Temperature	High/low temps accel. aging
$\eta_s(x,t)$	Side-rxn overpotential	Li plating, dendrite formation

Each variable, y, must satisfy $y_{\min} \leq y \leq y_{\max}$.

Modified Reference Governor (MRG)



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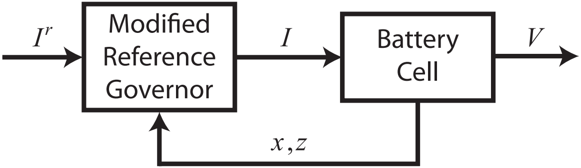

MRG Equations

$$I[k+1] = \beta^*[k] I^r[k], \qquad \beta^* \in [0,1],$$

$$\beta^*[k] = \max\left\{\beta \in [0,1] : (x(t), z(t)) \in \mathcal{O}\right\}$$

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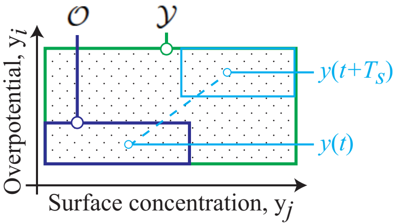

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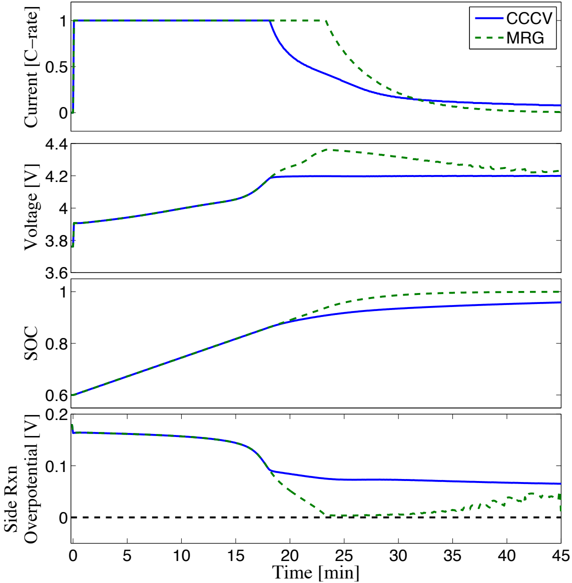
$$\beta^*[k] = \max\left\{\beta \in [0,1] : (x(t), z(t)) \in \mathcal{O}\right\}$$

Def'n: Admissible Set $\mathcal{O}$

$$\mathcal{O} = \{(x(t), z(t)) : y(\tau) \in \mathcal{Y}, \forall \tau \in [t, t+T_s]\}$$

$$\begin{aligned} \dot{x}(t) &= f(x(t), z(t), \beta I^r) \\ 0 &= g(x(t), z(t), \beta I^r) \\ y(t) &= C_1 x(t) + C_2 z(t) + D \cdot \beta I^r + E \end{aligned}$$

Application to Charging



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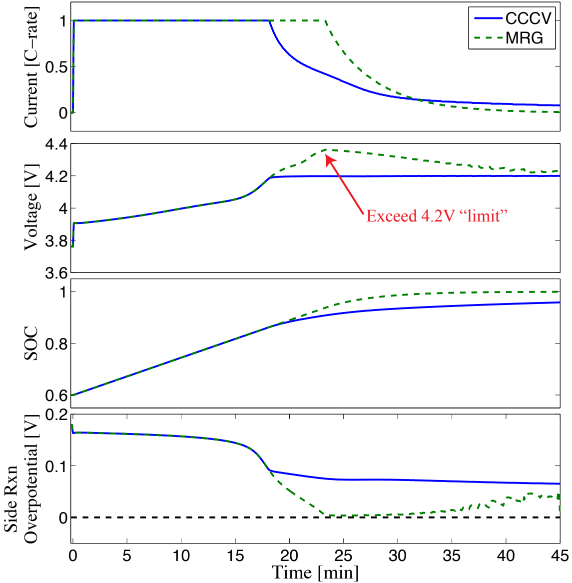

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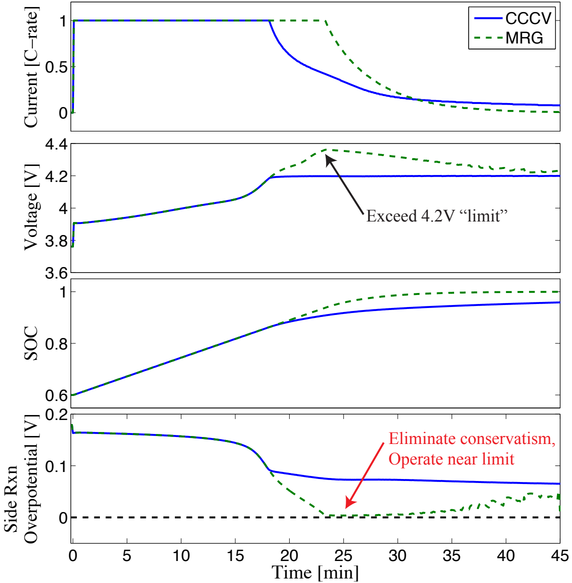

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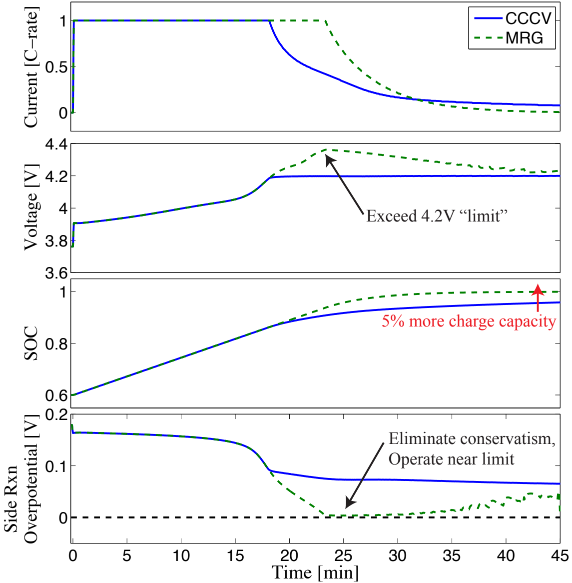

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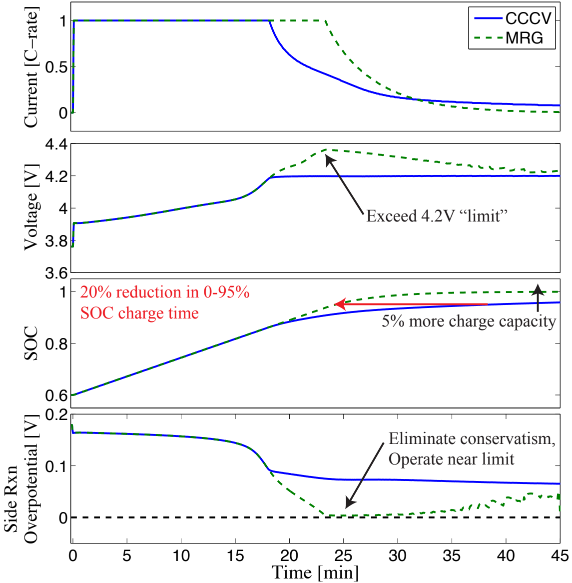


Fast charge your EV while getting coffee

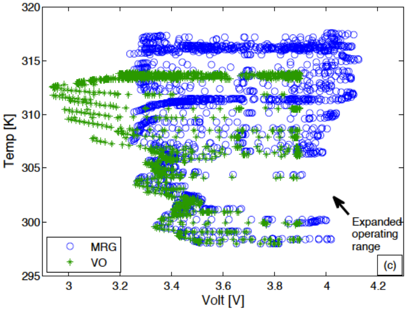
Table: Simulated fast charge times for various C-rates

Charge range	**0.7C** | Traditional	**1.8C** | ECC	**2.5C** | ECC
0-10%	7.92 min	3.17 min	2.33 min
0-20%	17.83 min	7.00 min	5.08 min
0-50%	47.33 min	18.42 min	20.50 min

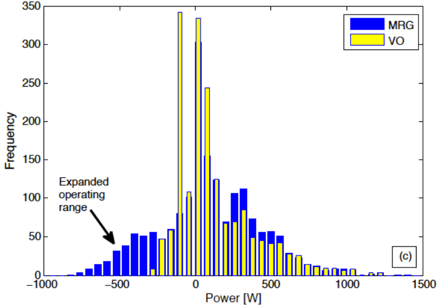
H. E. Perez, N. Shahmohammadhamedani, S. J. Moura, “Enhanced Performance of Li-ion Batteries via Modified Reference Governors & Electrochemical Models,” IEEE/ASME Transactions on Mechatronics, v 20, n 4, pp. 1511-1520, Aug 2015.

Expanded Operating Range

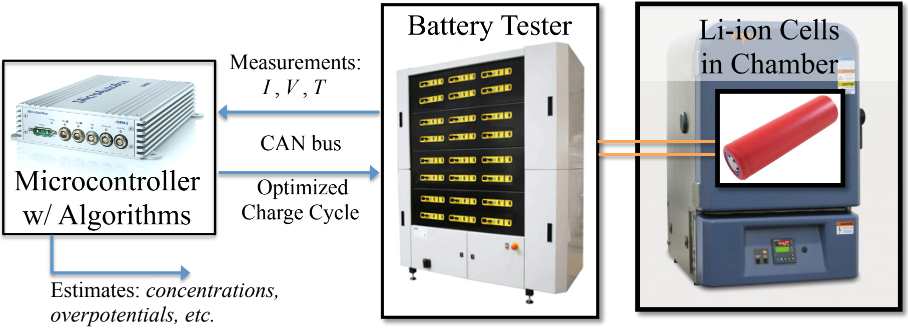
Operating Points on Temperature-Voltage Plane



Power Histogram



Battery-in-the-Loop Test Facility



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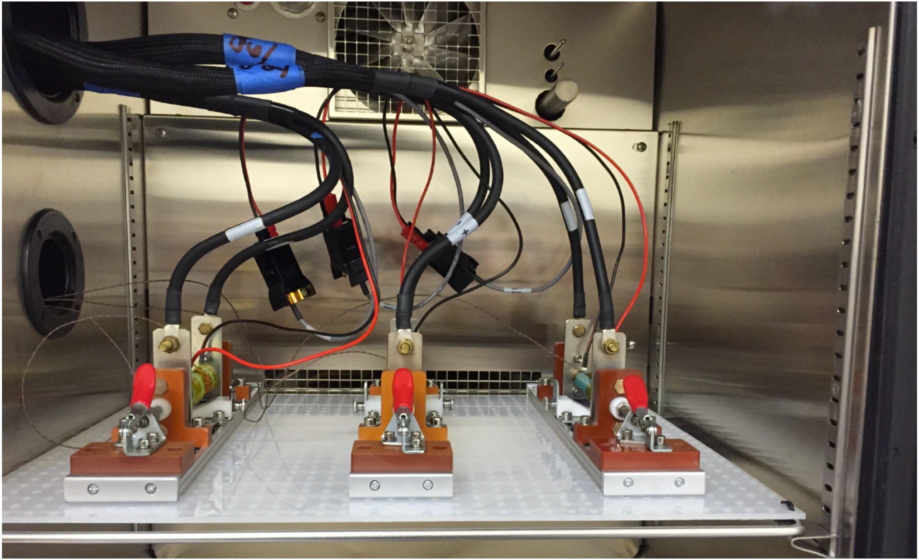

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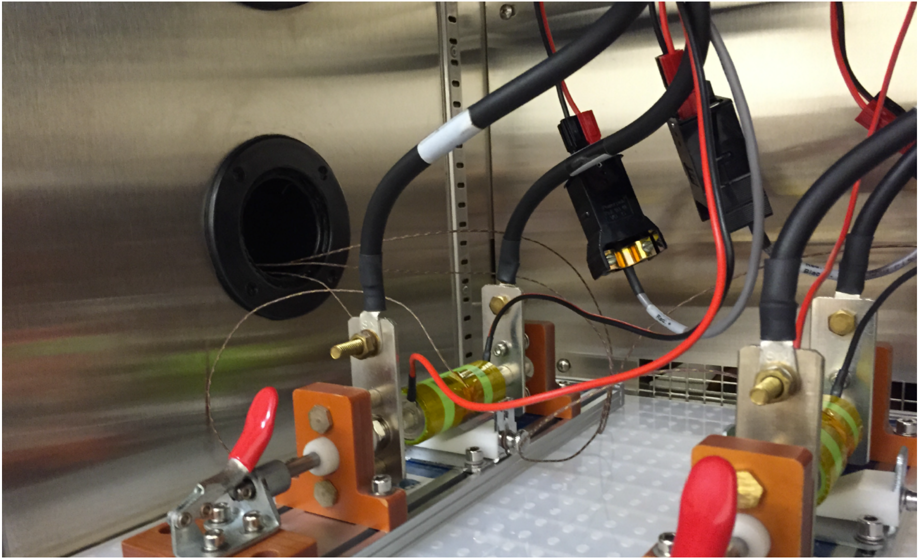

Outline

Summary

- Background & Electrochemistry Fundamentals
- SOC Estimation, SOH Estimation, Charge/Discharge Control
- The DFN Electrochemical Model
- Combined SOC/SOH Estimation
- Charge/Discharge Control with MRGs and EChem Models

Summary

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Applicable control theoretic tools:

- PDE Control
- State estimation
- System identification
- Nonlinear and adaptive systems
- Optimal & constrained control

Reading Materials

- S. J. Moura and H. Perez, "Better Batteries through Electrochemistry and Controls," *ASME Dynamic Systems and Control Magazine*, v 2, n 2, pp. S15-S21, July 2014. (Invited Paper).
- N. A. Chaturvedi, R. Klein, J. Christensen, J. Ahmed, and A. Kojic, "Algorithms for advanced battery-management systems," *IEEE Control Systems Magazine*, vol. 30, no. 3, pp. 49-68, 2010.
- H. E. Perez, N. Shahmohammadhamedani, S. J. Moura, "Enhanced Performance of Li-ion Batteries via Modified Reference Governors & Electrochemical Models," *IEEE/ASME Transactions on Mechatronics*, v 20, n 4, pp. 1511-1520, Aug 2015.
- S. J. Moura, N. A. Chaturvedi, M. Krstic, "Adaptive PDE Observer for Battery SOC/SOH Estimation via an Electrochemical Model," *ASME Journal of Dynamic Systems, Measurement, and Control*, v 136, n 1, pp. 011015-011026, Oct 2013.
- H. Perez, S. J. Moura, "Sensitivity-Based Interval PDE Observer for Battery SOC Estimation," *2015 American Control Conference*, Chicago, IL, 2015. **Best Student Paper**.
- S. J. Moura, F. Bribiesca Argomedo, R. Klein, A. Mirtabatabaei, M. Krstic, "Battery State Estimation for a Single Particle Model with Electrolyte Dynamics."

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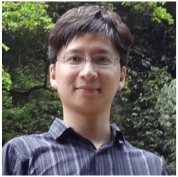

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APPENDIX SLIDES

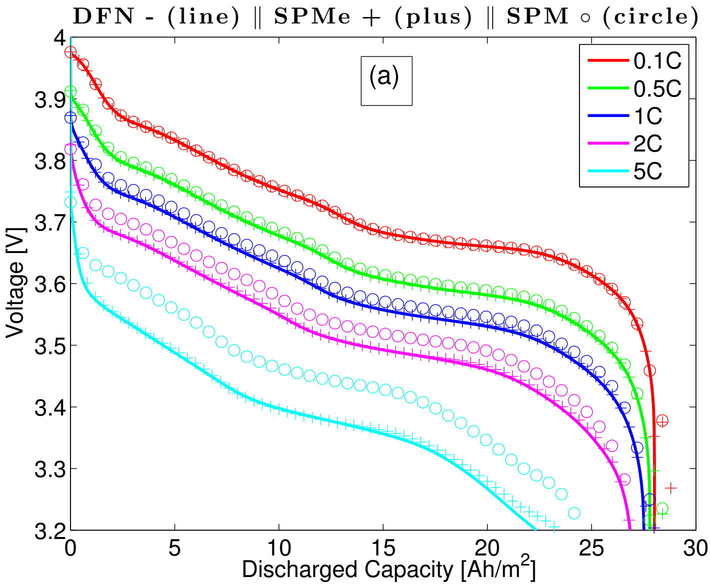
Research Opportunities

- Fault Diagnostics (Detection, Isolation, Estimation)
- Coupled Electrochemical-Thermal-Mechanical dynamics
- Application to novel materials (LMBs, Silicon, Li-Air)
- Battery packs $\rightarrow$ heterogeneous cells (2nd life batts)

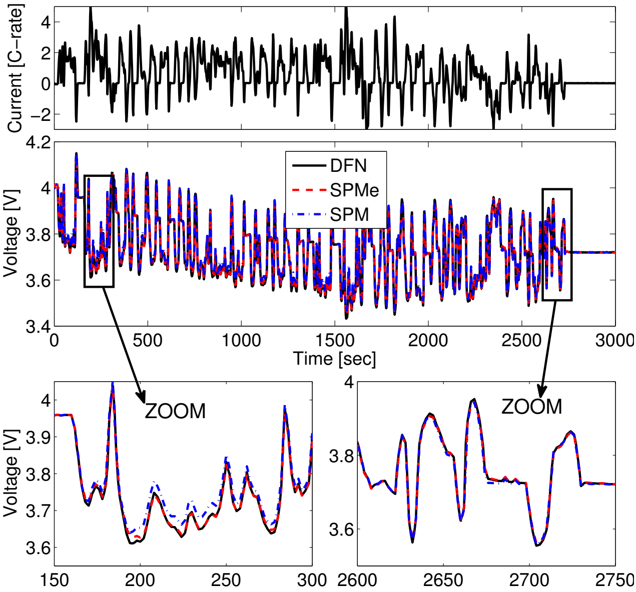
Applicable control theoretic tools:

- Nonlinear systems
- State estimation
- Adaptive control
- Fault Diagnostics
- PDE Control
- Model reduction

Model Comparison



Model Comparison



Model Comparison

Table: RMS Voltage Error with respect to DFN Model

	0.1C	0.5C	1C	2C	5C	UDDSx2
SPM	2 mV	8 mV	17 mV	31 mV	72 mV	14 mV
SPMe	2 mV	5 mV	9 mV	13 mV	19 mV	7 mV