Quadruple Adaptive Observer of the Core Temperature in Cylindrical Li-ion Batteries and their Health Monitoring

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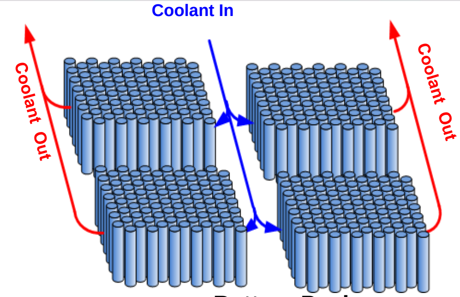
Background



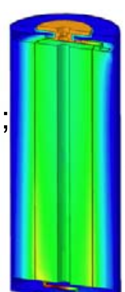
Battery Pack

Thermal Management for Li ion batteries

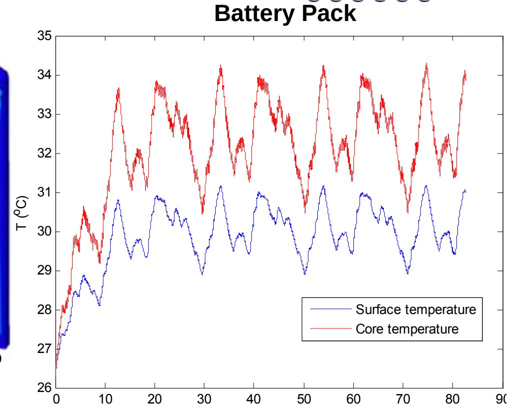
- Safety: overheating, thermal runaway
- Performance:
  Aging, efficiency, self-discharge…
- Basis: temperature monitoring

State of Art: temp monitoring

- Detailed PDE: accurate but complicated; not suitable for onboard bat pack
- Single state: oversimplified
  $T_c >> T_s$ (high C-rate)
- Two-states lumped model: T_c and T_s
  Park, Jaura, Ford, SAE2003



In-cell temp distribution



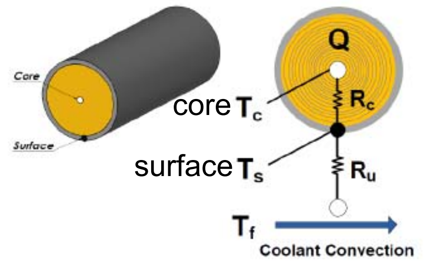
Measured Battery core and surface temp under a drive cycle

Background

Problem: determining parameters
- Thermal/electrical resistance, heat capacity…

- Calculation based on component properties:
  - approximation, not accurate
  - complicated structure and interfaces

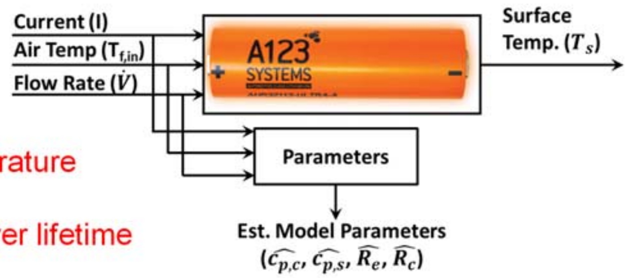
- Designed experiments beforehand
  - degradation: internal resistance change
  - biased estimation due to parameter drift



Park, Jaura, Ford, SAE2003

Two states thermal model

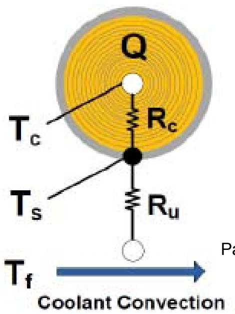
Online identification
- Based on onboard signals
  - current, flow temperature, surface temperature
- Parameter real-time update: accurate over lifetime
- Health monitoring: resistance growth



Online parameter Identification

Content

Thermal Model



Park, et al. 2003 SAE

Two states thermal model

Core temperature dynamics

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

Surface temperature dynamics

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

States:
- T_c, core temperature
- T_s, surface temperature

Inputs:
- I, current
- T_f, coolant temperature

Output :
- T_s, surface temperature

Parameters:
- C_c, core heat capacity
- C_s, surface heat capacity
- R_e, internal resistance
  (SOC, temperature dependent)
- R_c, conduction resistance
- R_u, convection resistance
  (coolant flow velocity dependent)

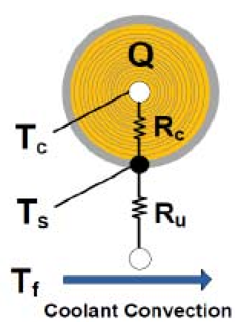
Parametric model

$$s^2T_s-sT_{s,0}=\underbrace{\boxed{\frac{R_e}{C_cC_sR_c}}}_{\alpha}I^2+\underbrace{\boxed{\frac{1}{C_cC_sR_cR_u}}}_{\beta}(T_f-T_s)-\underbrace{\boxed{\left(\frac{C_c+C_s}{C_cC_sR_c}+\frac{1}{C_sR_u}\right)}}_{\gamma}(sT_s-T_{s,0})$$

Parametric model
- Laplace transform to the original ODEs
- Parameters lumped to α, β, γ
- Regressors: measured signals

Identifiability Analysis
- Only α, β, γ identifiable
- 5 physical parameters vs 3 equations
- Need priori knowledge of two parameters
- C_c, C_s: constant among cells, over lifetime
- 4 regressors vs 4 equations:
  coolant velocity varying&R_u pre-calculated

Parameter reformulation:
- Solve R_e, R_c, R_u from α, β, γ
- Constant R_e: temp dependent (later)



Two states thermal model

$$\begin{cases}(C_c+C_s)C_s\beta {R_u}^2+C_s\gamma R_u+1=0\\ R_c=\frac{1}{\beta C_sC_cR_u}\\ R_e=C_cC_s\alpha R_c.\end{cases}$$

Parameter reformulation

Identification Design

$$s^2T_s - sT_{s,0} = \underbrace{\frac{R_e}{C_cC_sR_c}}_{\alpha} I^2 + \underbrace{\frac{1}{C_cC_sR_cR_u}}_{\beta}(T_f - T_s) - \underbrace{\left(\frac{C_c+C_s}{C_cC_sR_c} + \frac{1}{C_sR_u}\right)}_{\gamma}(sT_s - T_{s,0})$$

Parametric Model

Least square algorithm

- Noise reduction
- On-line Recursive

Identification

- Signal Filtering
- Normalization
- Regression

$$\theta = [\alpha \quad \beta \quad \gamma]^T$$

$$\phi = [\frac{I^2}{\Lambda} \quad \frac{T_f - T_s}{\Lambda} \quad \frac{sT_s - T_{s,0}}{\Lambda}]^T$$

$$z = \frac{s^2T_s - sT_{s,0}}{\Lambda}$$

$$\dot{\theta} = P\frac{\varepsilon\phi}{m^2}$$

$$P = -P\frac{\phi\phi^T}{m^2}P$$

$$\varepsilon = z - \theta^T\phi$$

$$m^2 = 1 + \phi^T\phi$$

Online least square ID algorithm

Adaptive Monitoring

- Real time parameter update
- Closed loop observer: Ts feedback
- Fast convergence, noise suppression

$$C_c\frac{d\hat{T}_c}{dt} = I^2\hat{R}_e + \frac{\hat{T}_s - \hat{T}_c}{\hat{R}_c} + l_1(T_s - \hat{T}_s)$$

$$C_s\frac{d\hat{T}_s}{dt} = \frac{T_f - \hat{T}_s}{\hat{R}_u} - \frac{\hat{T}_s - \hat{T}_c}{\hat{R}_c} + l_2(T_s - \hat{T}_s)$$

Adaptive monitoring of battery core temperature

Content

- Background
- Battery Thermal Model and Online Identification
- Experimental Validation
- Identification of Time-varying Re
- Conclusion and Future Work

Experimental Results

Experimental setup

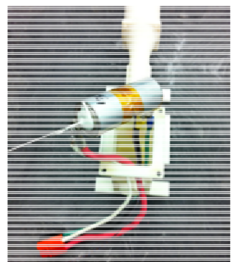
- Battery Cycler
- Thermal Chamber
- A&D test control system
- Flow chamber
- A123 26650 LiFePO4

Battery Cycler

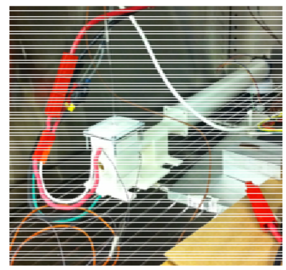
Thermal Chamber

Temperature sensing

- Thermocouples on casing, core, flow
- Core sensor installation
  - Argon-filled glove box
  - Drilled to the central cavity
  - Inserted thermocouple
  - Sealed



Installation of thermocouple

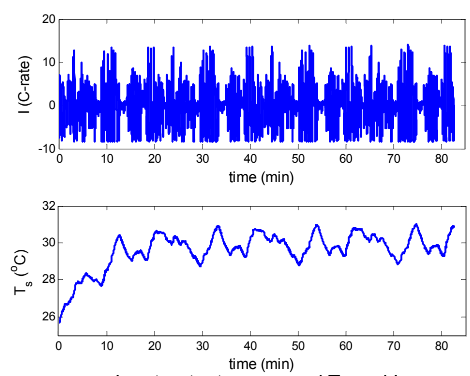


Flow chamber

Drive cycle and PE analysis

Drive cycle

- Scaled Urban Assault Cycle (Lee 2011)
- Hybrid electric military vehicle
- Fixed flow, Ru to be identified
- Re constant: small temp variation



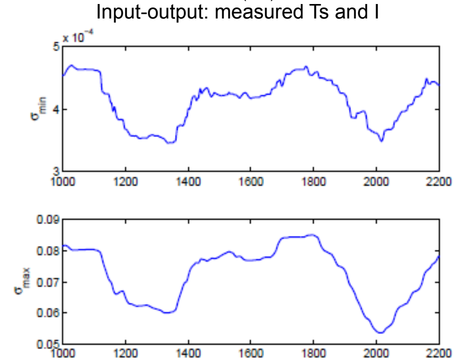
Input-output: measured Ts and I

Persistent excitation

- Prerequisite for identification
- U(t): integration of regressors
- PE condition: U(t) bounded by α_0 and α_1
- α_0 and α_1 by eigen values of U(t)

$$\alpha_1 I_M \ge U(t) = \frac{1}{T_0}\int_t^{t+T_0} \phi(\tau)\phi^T(\tau)d\tau \ge \alpha_0 I_M \quad \forall t \ge 0$$

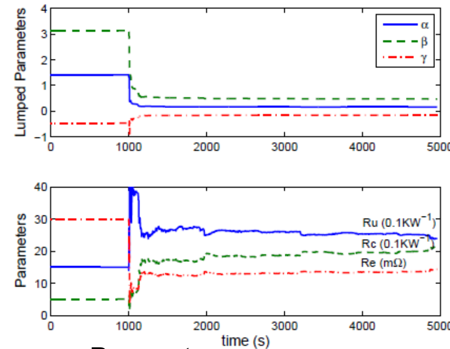
$$\phi = [\frac{I^2}{\Lambda} \quad \frac{T_f - T_s}{\Lambda} \quad \frac{sT_s - T_{s,0}}{\Lambda}]^T$$



Eigen values of U(t)

Experimental Results

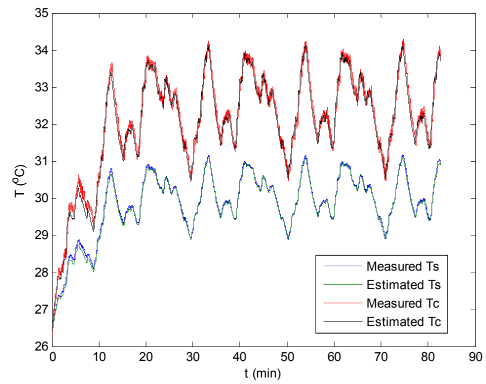
Parameter convergence
- Current I and Ts for Identification
- Convergence of lumped and physical para
- Re constant: small temp variation



Parameter convergence

Validation
- Ts used for ID
- Tc estimated by identified parameters
- Good Match of Tc

Cs (J/K)	Cc (J/K)	Ru (K/W)	Rc (K/W)	Re (mOhm)
4.5	67	3.03	1.83	11.4



Temperature Validation

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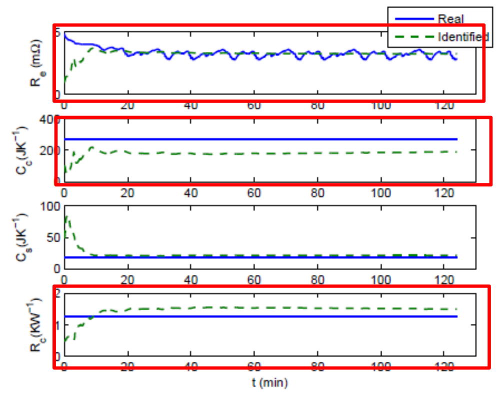
Non-constant Re?

Varying Re

- Temp: larger Re for lower temp

$$R_e = R_{e0}\exp\left(\frac{Tref}{T_c}\right)$$

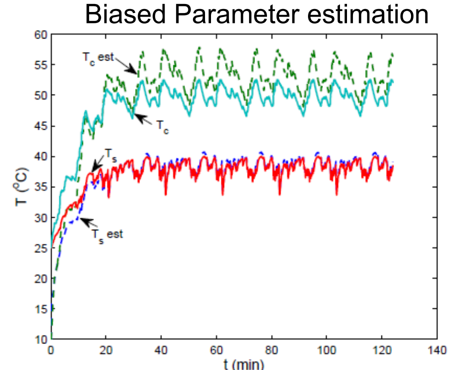
- SOC dependent



Biased Parameter estimation

Pure Least Square Algorithm (Simulation)

- Converge to average Re
- Biased ID of other Parameters
- Small error in Surface temp
- Significant errors in Core temp



Biased temperature estimation

RLS with Non-uniform Forgetting Factors

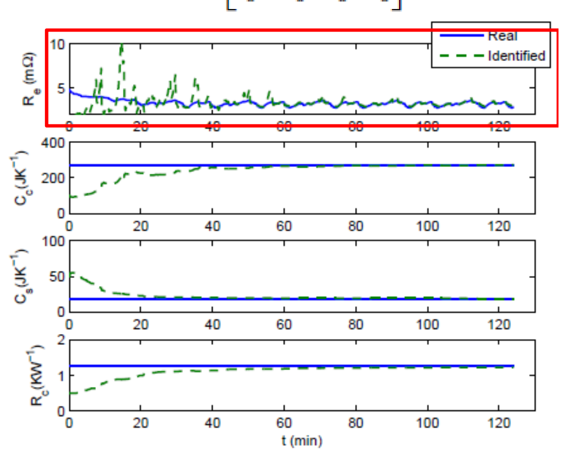
$$\dot{P}(t) = \boxed{\eta^T P(t)\eta} - P(t)\frac{\phi(t)\phi^T(t)}{m^2(t)}P(t)$$

$$J(\theta) = \frac{1}{2}\int_0^t \boxed{e^{-\beta(t-\tau)}}\frac{[z(\tau)-\theta^T(t)\phi(\tau)]^2}{m^2(\tau)}d\tau$$

$$\eta = \begin{bmatrix} \eta_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

RLS with Forgetting factors

- Moving window on data
- New data favored over old
- Decaying exponentially

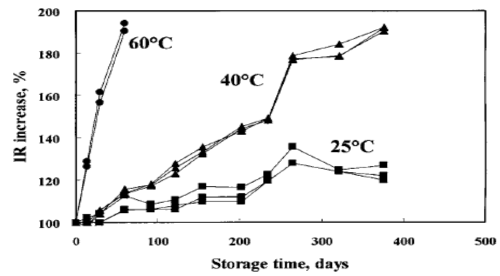


Results

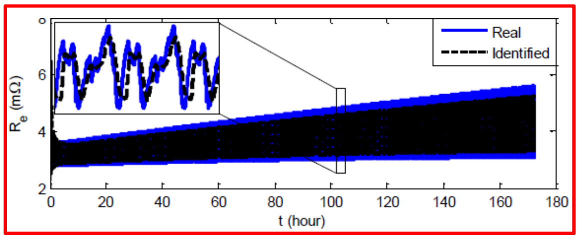
- Identified Re follows the real (simulated)
- Unbiased ID for other parameters
- Correct Core temp estimation

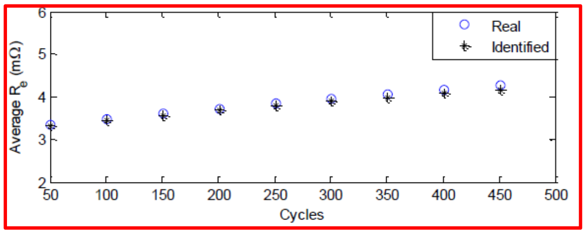
State of Health Monitoring

Battery Degradation
- Aging/Abuse…
- Capacity Fade
- Growth in Internal Resistance (Yoshida 2006, etc).
- State of health monitoring



Degradation detection
- Simulated growing resistance
- Exaggerated/Accelerated simulation
- Long term resistance growth can be captured for SOH evaluation





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Conclusion and Future Work

Parameter ID and Adaptive monitoring

- Online recursive parameter ID for the two state battery thermal model
  - Validated by experiments with surface and core temperature measurement
- Identification of varying internal resistance R_e
  - Application of forgetting factors
  - Verified by simulation
- SOH evaluation by detecting resistance growth
  - Verified by simulation

Battery Thermal Pack monitoring

- Pack model by scaling up the single cell models
- Considering Cell to cell conduction and convection
- Observability analysis and sensor deployment
- RHEVE 2012/OGST

Thank you!
Q&A

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