Temperature Estimation in Lithium-ion Batteries Through Cascaded Electrochemical-Thermal Models

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Introduction

- Lithium-ion batteries rely on either liquid or solid electrolytes for ion transport.
- Modeling batteries is crucial in preventing thermal runaway and ensuring safety.
- Estimators play a key role in enhancing the performance and safety of the battery by predicting unmeasured variables.
- Multiple Partial Differential Equations (PDEs) are employed to describe the dynamics of lithium-ion concentration. As an example, the following PDE is used to model the concentration of lithium ions in the electrolyte of All-Solid-State Batteries (ASSB).

$$\frac{\partial c_e}{\partial t}(y,t) = \frac{2D_{Li^+}D_{n^-}}{D_{Li^+}+D_{n^-}}\frac{\partial^2 c_e}{\partial y^2}(y,t) + r(y,t),$$
$$c_e(y,0) = \delta c_{e,0},$$
$$\frac{\partial c_e(0,t)}{\partial y} = -\frac{I(t)}{2FAD_{Li^+}},$$
$$\frac{\partial c_e(L,t)}{\partial y} = -\frac{I(t)}{2FAD_{Li^+}},$$

- The voltage V(t) for (ASSB) is given by:

$$V(t) = E_{eq}(\bar{\theta}_s(t)) + \eta_t(t).$$

- Electrochemical heat:

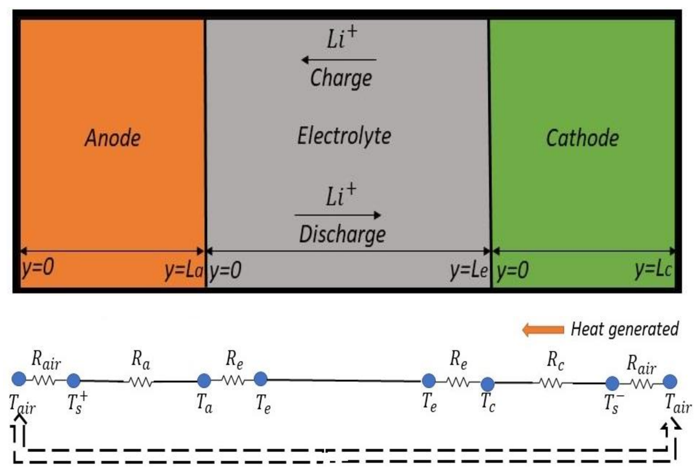
$$S(t) = V(t)I(t).$$

- Temperature dynamics:

$$\dot{T}(t) = \frac{S(t) + q_{\text{cond}}(t) + q_{\text{conv}}(t)}{\rho c_p v}$$

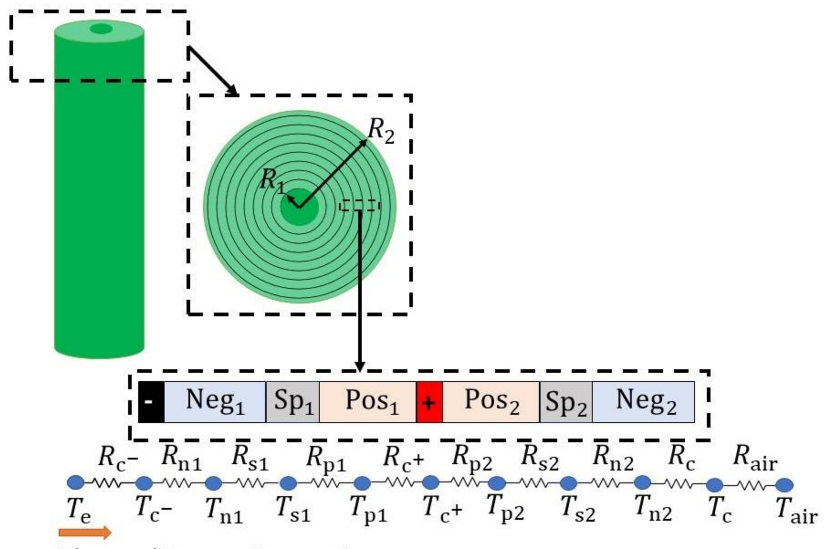
Modeling

- **All-Solid-State Batteries (ASSB)**



Courtesy: Solid Power
https://solidpowerbattery.com

- **Conventional Lithium-ion Batteries (LiBs)**



- **All-Solid-State Batteries (ASSB)**

$$\dot{\mathbf{T}}(t) = A\mathbf{T}(t) + B\mathbf{u}(t) + \mathbf{w}(t),$$
$$y(t) = C\mathbf{T}(t) + v(t),$$
$$\mathbf{w} \sim (0, Q),$$
$$v \sim (0, R),$$

$$A = \begin{bmatrix} \frac{-R_c - R_{air}}{\lambda_{air}R_cR_{air}} & \frac{1}{\lambda_{air}R_c} & 0 & 0 & 0 \\ \frac{1}{\lambda_c R_c} & \frac{-1}{\lambda_c} & 0 & 0 & 0 \\ 0 & \frac{1}{\lambda_e R_e} & \frac{-1}{\lambda_e R_e} & 0 & 0 \\ 0 & 0 & \frac{1}{\lambda_a R_e} & \frac{-1}{\lambda_a R_e} & 0 \\ 0 & 0 & 0 & \frac{1}{\lambda_{air} R_a} & \frac{R_a - R_{air}}{\lambda_{air}R_aR_{air}} \end{bmatrix}$$

$$\mathbf{T}(t) = \begin{bmatrix} T_s^-(t) & T_c(t) & T_e(t) & T_a(t) & T_s^+(t) \end{bmatrix}^{tr},$$

$$B = \begin{bmatrix} \frac{1}{\lambda_{air}R_{air}} & 0 & 0 & 0 & \frac{-1}{\lambda_{air}R_{air}} \\ 0 & \frac{1}{\lambda_c} & \frac{1}{\lambda_e} & \frac{1}{\lambda_a} & 0 \end{bmatrix}^{tr},$$

$$\mathbf{u}(t) = \begin{bmatrix} T_{air}(t) & S(t) \end{bmatrix}^{tr},$$
$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

- **Conventional Lithium-ion Batteries (LiBs)**

$$\dot{\mathbf{T}}(t) = A\mathbf{T}(t) + B\mathbf{u}(t),$$
$$\mathbf{y}(t) = C\mathbf{T}(t),$$

where A is a 10x10 matrix, B is a 10x2 matrix, **T** is a 1x10 state vector, and **u** is a 2x1 input vector, C is explored in the simulation results.

Methods

- Kalman filter.

Input :
Initialize the state estimate: $\hat{T}(0)$;
Initialize the error covariance matrix: $P(0)$;
Set the process noise covariance: Q;
Set the measurement noise covariance: R;
Output:
Temperature Estimation: $\hat{T}$;

for $k = 1$ **to** *length*(t) **do**
Initialization Equation: $\hat{T}(0) = E[T(0)]$
Initialization of Error Covariance Matrix:
$P(0) = E\left[(T(0) - \hat{T}(0))(T(0) - \hat{T}(0))^{tr}\right]$
Kalman Gain Equation:
$K = PC^{tr}R^{-1}$
State Estimation Update Equation:
$\dot{\hat{T}} = A\hat{T} + Bu + K(y - C\hat{T})$
Error Covariance Matrix Update Equation:
$\dot{P} = -PC^{tr}R^{-1}CP + AP + PA^{tr} + Q$
end

- Luenberger observer.

$$\dot{\hat{T}}(t) = A\hat{T}(t) + Bu(t) + L[CT(t) - C\hat{T}(t)],$$

- Error dynamics:

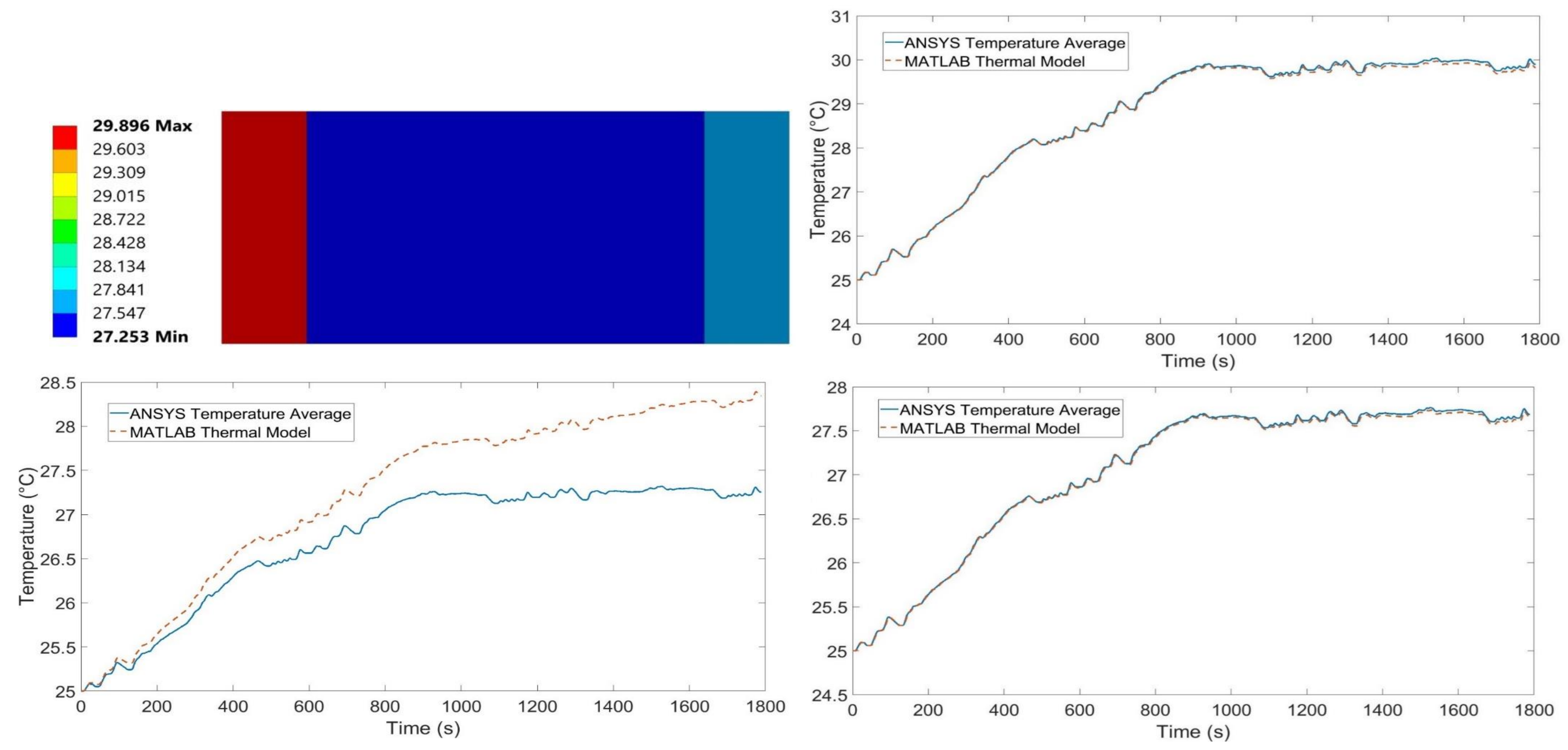
$$\dot{\tilde{T}}(t) = (A - LC)\tilde{T}(t).$$

- Lyapunov function

$$V(\tilde{T}(t)) = \tilde{T}(t)^{tr}P\tilde{T}(t),$$

Verification and Simulation

- **Verification of the ASSB thermal model.**



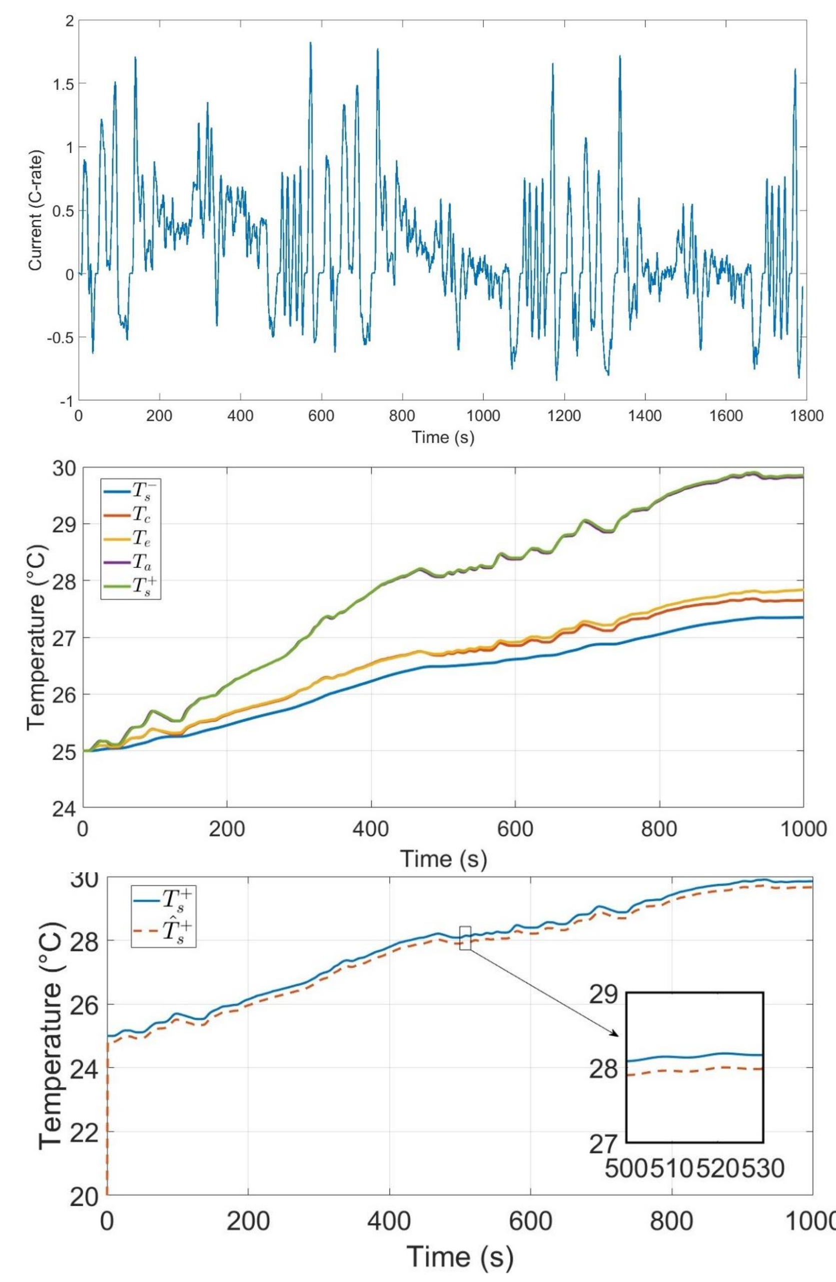
- **ASSB optimal sensor placement:**

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

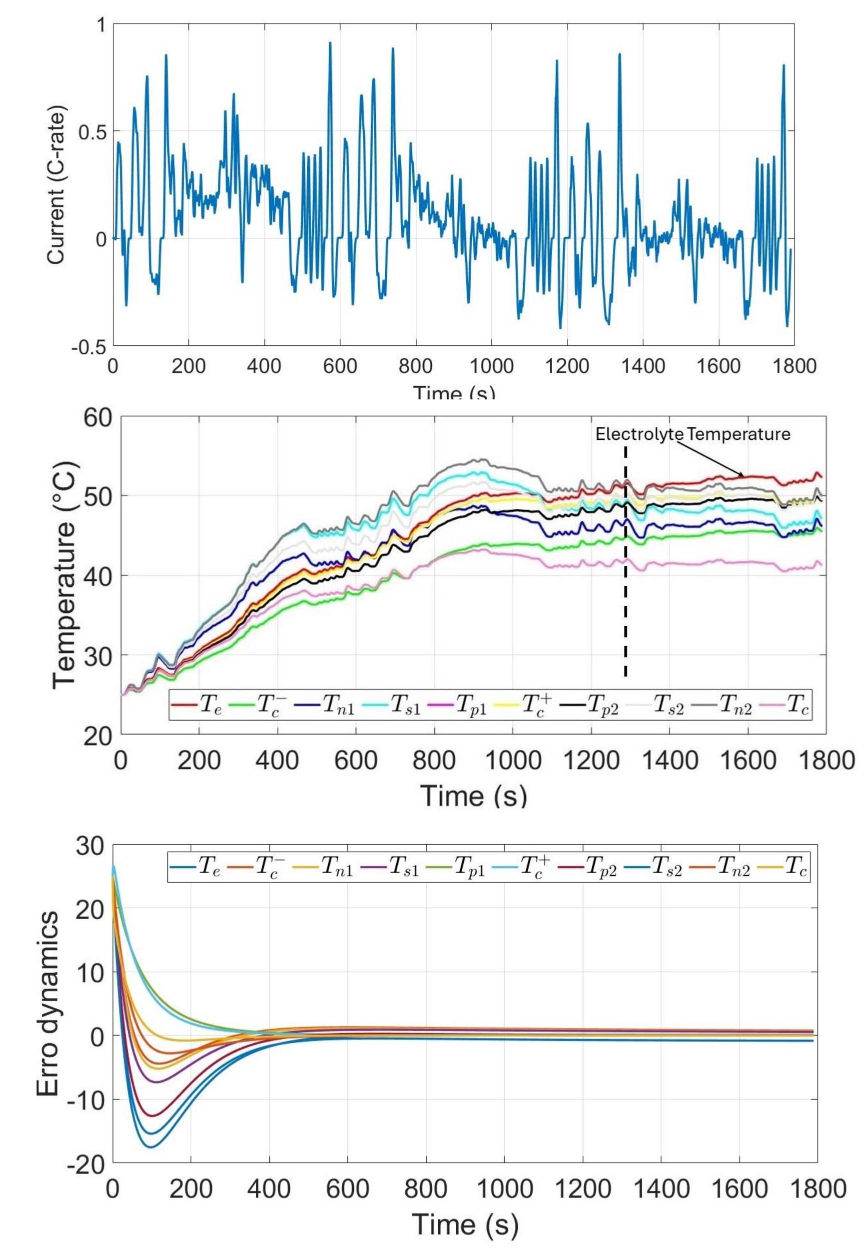
- **LiBs optimal sensor placement:**

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

- **ASSB Simulation Results:**



- **LiBs Simulation Results:**



Conclusion

- A thermal model, constructed using the energy balance approach, was validated through Ansys transient thermal simulations, showing minimal differences.
- A Kalman filter for ASSB aligned well with the true model, and error dynamics in the Luenberger Observer for lithium-ion batteries (LIBs) approached zero.
- Future work includes relaxing the adiabatic assumption and experimental validation.

References:

Ferreira, P., & Tang, S.-X.. Quintuple Thermal Model for All-Solid-State Batteries and Temperature Estimation through a Cascaded Thermal-Electrochemical model. IEEE Conference on Control Technology and Applications, 2024, under review.
Ferreira, P., & Tang, S.-X. . Sensors Placement Analysis and Temperature Estimation in Lithium-Ion Batteries with a Cascaded Electrochemical-Thermal Model. European Control Conference, 2024, accepted.