A Fast, Memory-Efficient Discrete-Time Realization Algorithm for Reduced-Order Li-ion Battery Models

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Symposium for Fuel Cell and Battery Modeling and Experimental Validation
Outline

1 Motivation
   - Why Reduced Order Modelling?
   - Previous Work
   - Computational Bottlenecks

2 Improved Modelling Scheme
   - Implementation
   - Results

3 Summary
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Summary
Vehicular Battery Management System (BMS)

Why Reduced Order Model?
- Real-time Computation of
  - SoC / SoH
  - Power horizon
  - Ageing / degradation
- Advanced control strategies
**Vehicular Battery Management System (BMS)**

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Vehicular Battery Management System (BMS)

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Battery Modelling – Approaches

Goal

*Combine the benefits of the two approaches!*

- **Equivalent Circuit Models**
  - ✔️ Computationally simple
  - ✗ Internal physical quantities
  - ?? Operating range

- **Physics-based Models**
  - ✔️ Internal physical quantities
  - ✔️ Arbitrary load profiles
  - ✗ Computationally intensive
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Improved Modelling Scheme

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  - ✓ Arbitrary load profiles
  - × Computationally intensive
Physics-Based ROM

PDE Model
(Doyle-Fuller-Newman)
Physics-Based ROM

\[ \nabla \cdot \mathbf{j} = \nabla \cdot (-\sigma \nabla \phi) = 0. \]

\[ \frac{\partial C}{\partial t} = \nabla \cdot (D \nabla C), \]

\[ \frac{\partial C}{\partial t} = \nabla \cdot (D \nabla C) - \frac{\mathbf{j} \cdot \nabla \phi}{F} - \nabla \cdot (C \nabla \phi). \]

\[ \nabla \cdot \mathbf{j} = \nabla \cdot (-\sigma \nabla \phi - \frac{2aRT}{F} \left(1 + \frac{\partial \ln \Gamma}{\partial \ln C} \right) \left(\phi^2 - 1\right) \nabla \ln \phi) = 0. \]

\[ j = k_c \phi^{1-a} (c_{\text{max}} - c_j)^{1-a} \phi \exp \left( \frac{(1-a)F}{RT - \eta} \right) - \exp \left( -\frac{aF}{RT} \right). \]
Physics-Based ROM

PDE Model
(Doyle-Fuller-Newman)

\[ \nabla \cdot \mathbf{i}_e = \nabla \cdot (-\sigma \nabla \phi_e) = 0. \]

\[ \frac{\partial \phi_e}{\partial t} = \nabla \cdot (D_e \nabla \phi_e). \]

\[ \frac{\partial c_e}{\partial t} = \nabla \cdot (D_e \nabla c_e) - \frac{j_e}{F} - \nabla \cdot (c_e v_0). \]

\[ \frac{\partial \mathbf{i}_e}{\partial t} = \nabla \cdot \left( -\sigma \nabla \phi_e - \frac{2aRT}{F} \left( 1 + \frac{\partial \ln f_e}{\partial \ln c_e} \right) \frac{c_e}{c_e} \nabla \ln c_e \right) = 0. \]

\[ j = k_e c_e^{\alpha}(c_{\text{max}} - c_e)^{1-\alpha} c_e \phi_e \exp \left( \frac{(1-a)F}{RT} \right) - \exp \left( \frac{aF}{RT} \right). \]
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\[ \frac{\partial c}{\partial t} = \nabla \cdot (D \nabla c). \]

\[ \frac{\partial c}{\partial t} = \nabla \cdot (D \nabla c) - \frac{k}{F} \nabla \cdot (c, \nabla \phi). \]

\[ \nabla \cdot i = \nabla \cdot (-\sigma \nabla \phi) - \frac{2aRT}{F} \left( 1 + \frac{\partial \ln j}{\partial \ln c} \right) (c^2 - 1) \nabla \ln \phi = 0. \]

\[ j = k \left( c_{\text{max}}^{-\alpha} - c_{\text{max}}^{-\alpha} \right)^{\alpha} \exp \left( \frac{(1 - \alpha)F}{RT} - \eta \right) - \exp \left( -\frac{aF}{RT} \right). \]

Reduced Order Model (ROM)

State-Space Model

\[ x[k + 1] = Ax[k] + Bu[k] \]

\[ y[k] = Cx[k] + Du[k] \]

+ non-linear terms

23\textsuperscript{rd} March, 2016
Physics-Based ROM

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PDE Model
(Doyle-Fuller-Newman)

Reduced Order Model (ROM)
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Physics-Based ROM

PDE Model (Doyle-Fuller-Newman) → Reduced Order Model (ROM)

\[ \nabla \cdot i = \nabla \cdot (-\sigma \nabla \phi_L) = 0. \]
\[ \frac{\partial c_e}{\partial t} = \nabla \cdot (D_e \nabla c_e) - \frac{i_e \cdot \nabla j_e}{F} - \nabla \cdot (c_e \nabla v). \]
\[ \nabla \cdot i = \nabla \cdot (-\sigma \nabla \phi_L - \frac{2 \alpha RT}{F} (1 + \frac{\partial \ln f_j}{\partial \ln c_e} (\phi_u - 1) \nabla \ln c_e) = 0. \]
\[ j = k_e c_e^{\alpha - (c_{\text{max}} - c_L)^{\alpha - \alpha_{c_e}} \exp \left( \frac{(1 - \alpha)F}{RT - \eta} - \exp \left( \frac{\alpha F}{RT} \right) \right). \]

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Physics-Based ROM Workflow
Discrete-Time Realization Algorithm (DRA)

PDE Model
(Doyle-Fuller-Newman)

Reduced Order
Model (ROM)

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Physics-Based ROM Workflow

Discrete-Time Realization Algorithm (DRA)

1. PDE Model (Doyle-Fuller-Newman) → Linearize around given SOC, T
2. Linearized PDE Model → Laplace Transform
3. Transfer Functions → Discrete-Time Realization Algorithm (DRA)
4. State-Space Matrices → Augment Integrator and Residues
5. Reduced Order Model (ROM)
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Physics-Based ROM Workflow
Discrete-Time Realization Algorithm (DRA)

A Control-oriented approach
- Frequency-domain method
- Small-signal linearization
- Uses the DRA at its core

23rd March, 2016
**Physics-Based ROM Workflow**

**Discrete-Time Realization Algorithm (DRA)**

- **PDE Model (Doyle-Fuller-Newman)**
- Linearize around given SOC, T
- Linearized PDE Model
- Laplace Transform
- Transfer Functions
- Integrator Pole Removal (if present)
- Discrete-Time Realization Algorithm (DRA)
- State-Space Matrices
- Augment Integrator and Residues
- Reduced Order Model (ROM)

**A Control-oriented approach**

- Frequency-domain method
- Small-signal linearization
- Uses the DRA at its core

× Computational bottlenecks during model identification

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J. Lee, A. Chemistruck and G.L. Plett.

One-dimensional physics-based reduced-order model of lithium-ion dynamics.


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Motivation
- Why Reduced Order Modelling?
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Improved Modelling Scheme
- Implementation
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Summary
Computational Footprint – CPU Usage

The diagram illustrates the relationship between the number of Hankel blocks and the CPU time required. As the number of Hankel blocks increases, the CPU time also increases linearly. The y-axis represents CPU time in minutes, ranging from 0.01 to 100 minutes, while the x-axis represents the number of Hankel blocks, ranging from 0 to 14,000.

23rd March, 2016
Motivation

Improved Modelling Scheme

Summary

Why Reduced Order Modelling?

Previous Work

Computational Bottlenecks

Computational Footprint – RAM Usage

![Graph showing RAM Usage vs. Number of Hankel Blocks]

- **Number of Hankel Blocks**: 0, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000
- **RAM Usage (GB)**: 0, 20, 40, 60, 80, 100

Graph details:

- **X-axis**: Number of Hankel Blocks
- **Y-axis**: RAM Usage (GB)

Graph notes:

- The graph shows a significant increase in RAM usage as the number of Hankel Blocks increases.

Additional notes:

- **Date**: 23rd March, 2016
- **ModVal 13**
Computational Bottleneck Analysis

ROM Workflow – Traditional DRA

PDE Model (Doyle-Fuller-Newman) → Linearize around given SOC, T → Linearized PDE Model → Laplace Transform → Transfer Functions → Integrator Pole Removal (if present) → Discrete-Time Realization Algorithm (DRA) → State-Space Matrices → Augment Integrator and Residues → Reduced Order Model (ROM)

Computational Bottleneck Analysis
ROM Workflow – Traditional DRA

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Discrete-time realization of transcendental impedance models, with application to modeling spherical solid diffusion.
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- Continuous-Time Impulse Response
- Continuous-Time Step Response
- Discrete-Time Unit Pulse Response (Markov Parameters)
- Ho-Kalman Algorithm

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Continuous-Time Impulse Response → Continuous-Time Step Response → Discrete-Time Unit Pulse Response (Markov Parameters) → Ho-Kalman Algorithm

Block-Hankel Matrix in RAM → Singular Value Decomposition (SVD) → Extended Observability & Controllability Matrices

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Computational Bottleneck Analysis
Markov Parameters

\[ \tilde{c} \text{sepos}(0, t) \text{[mol. m}^{-3}] \]

\[ \tilde{c}^{*} \text{sepos}(0, t) \text{[mol. m}^{-3}] \]

Time [sec]

23rd March, 2016
Computational Bottleneck Analysis

Large Block Hankel Matrices and SVD

Root cause

Don’t form this matrix
MATLAB Crashes!

350,000x70,000
double precision

SVD

Structure of Block Hankel Matrix

2000 4000 6000 8000
20000
40000
60000
80000
Computational Bottleneck Analysis
CPU Usage – Traditional DRA

Effect on CPU Usage...

- For Single operating point of SoC and Temp

23rd March, 2016
Computational Bottleneck Analysis

CPU Usage – Traditional DRA

Effect on CPU Usage...

- For Single operating point of SoC and Temp
- How much does the SVD step contribute to total?

Number of Hankel Blocks vs. CPU Time [mins]

- Overall (Traditional DRA)
- Traditional SVD Step
Computational Bottleneck Analysis
Memory Usage – Traditional DRA

RAM Effects…
- SVD of Block Hankel matrix
Computational Bottleneck Analysis
Memory Usage – Traditional DRA

RAM Effects...
- SVD of Block Hankel matrix
- Is this efficient?

23rd March, 2016
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ROM Workflow – Improved DRA

- **PDE Model (Doyle-Fuller-Newman)**
  - Linearize around given SOC, $T$

- **Linearized PDE Model**
  - Laplace Transform

- **Transfer Functions**
  - Integrator Pole Removal (if present)

- **Discrete-Time Realization Algorithm (DRA)**

- **State-Space Matrices**
  - Augment Integrator and Residues

- **Reduced Order Model (ROM)**

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R. Larsen
Propack – software for large and sparse svd calculations.
*Ph.D. thesis, Aarhus University, 1998*

N. Golyandina, A. Korobeynikov, A. Shlemov, K. Usevich,
Multivariate and 2d extensions of singular spectrum analysis with rssa package.
ROM Workflow – Improved DRA

- **PDE Model** (Doyle-Fuller-Newman) → Linearize around given SOC, T → **Linearized PDE Model** → Laplace Transform → **Transfer Functions** → Integrator Pole Removal (if present) → **Discrete-Time Realization Algorithm (DRA)** → State-Space Matrices → Augment Integrator and Residues → **Reduced Order Model (ROM)**

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23rd March, 2016
ROM Workflow – Improved DRA

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- Laplace Transform
  
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- Integrator Pole Removal (if present)
  
**Discrete-Time Realization Algorithm (DRA)**
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**Continuous-Time Impulse Response**

**Continuous-Time Step Response**

**Discrete-Time Unit Pulse Response (Markov Parameters)**

**Ho-Kalman Algorithm**

**2-D FFT**

**Golyandina - Usevich Algorithm**

**PROPACK (Lanczos SVD)**

**Extended Observability & Controllability Matrices**

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Summary
Comparison of Singular Values
Classical vs. Improved SVD Schemes

![Graph showing comparison of singular values between classical and improved SVD schemes. The x-axis represents singular values, and the y-axis represents magnitude on a logarithmic scale. The graph compares classical SVD (marked with blue crosses) and improved SVD (marked with orange circles).]
Comparison of CPU Usage
Traditional vs. Improved DRA

![CPU Usage Comparison Graph]

Number of Hankel Blocks vs. CPU Time [mins]

- Overall (Traditional DRA)
- Traditional SVD Step

23rd March, 2016
Comparison of CPU Usage
Traditional vs. Improved DRA

![Comparison of CPU Usage Graph](chart.png)

- **CPU Time [mins]**
  - Overall (Traditional DRA)
  - Traditional SVD Step
  - Improved SVD Step

- **Number of Hankel Blocks**

23rd March, 2016
Comparison of CPU Usage
Traditional vs. Improved DRA

Number of Hankel Blocks

CPU Time [mins]

Overall (Traditional DRA)
Traditional SVD Step
Overall (Improved DRA)
Improved SVD Step

0 2000 4000 6000 8000 10000 12000 14000

0.01
0.1
1
10
100

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Comparison of RAM Usage
Traditional vs. Improved DRA

![Graph showing comparison of RAM usage between Traditional SVD Step and Overall (Traditional DRA) against Number of Hankel Blocks.](image)

**Comparison**

- **Motivation**
- **Improved Modelling Scheme**
- **Summary**
- **Implementation**
- **Results**

- **Comparison of RAM Usage**
  - Traditional vs. Improved DRA

**Graph Details**

- **X-axis:** Number of Hankel Blocks
- **Y-axis:** RAM Usage (GB)
- **Legend:**
  - Traditional SVD Step
  - Overall (Traditional DRA)

- **Data Points**:
  - 0 to 5000
  - 10000
  - 15000
  - 20000
  - 25000
  - 30000

**Dates**

- 23rd March, 2016

**Note**

- ModVal 13
Comparison of RAM Usage
Traditional vs. Improved DRA

![Graph showing comparison of RAM usage between Traditional and Improved SVD steps.](image)

- Traditional SVD Step
- Overall (Traditional DRA)
- Improved SVD Step

Number of Hankel Blocks

RAM Usage (GB)

0 5000 10000 15000 20000 25000 30000
0 20 40 60 80 100

ModVal 13
23rd March, 2016
Comparison of RAM Usage
Traditional vs. Improved DRA

**Comparison of RAM Usage**

**Traditional vs. Improved DRA**

![Graph comparing RAM usage for Traditional SVD Step, Overall (Traditional DRA), Improved SVD Step, and Overall (Improved DRA).]

- **Traditional SVD Step**
- **Overall (Traditional DRA)**
- **Improved SVD Step**
- **Overall (Improved DRA)**

**Number of Hankel Blocks vs. RAM Usage (GB)**

- **RAM Usage (GB)**: 0 to 100
- **Number of Hankel Blocks**: 0 to 30,000

- **23rd March, 2016**
Comparison of RAM Usage
Traditional vs. Improved DRA

![Graph showing comparison of RAM usage between traditional and improved DRA methods.](image)

**Graph Details:**
- **X-Axis:** Number of Hankel Blocks
- **Y-Axis:** RAM Usage (GB)
- **Legend:**
  - Green: Traditional SVD Step
  - Blue: Overall (Traditional DRA)
  - Orange: Improved SVD Step
  - Red: Overall (Improved DRA)

**Practical RAM Limit**
- Illustrated in the graph to show the limit beyond which traditional methods become impractical.
Truncating Markov Parameters – Practical RAM Limit

Singular values – traditional vs. Improved schemes

![Graph showing singular values for traditional and improved schemes](image_url)
Truncating Markov Parameters – Practical RAM Limit
Singular values – traditional vs. Improved schemes

![Graph showing singular values for traditional and improved DRA schemes](image)

- Traditional DRA - 2110 Blocks
- Improved DRA - 30000 Blocks

Date: 23rd March, 2016

23rd March, 2016
Truncating Markov Parameters – Practical RAM Limit

Modelling Accuracy - solid surface concentration at positive current collector

$c_{s,e}(L_{neg} + L_{sep}, t)$ [mol/m$^3$]

Time [sec]

COMSOL (Full Order Pseudo-2D Model)
Truncating Markov Parameters – Practical RAM Limit
Modelling Accuracy - solid surface concentration at positive current collector
Truncating Markov Parameters – Practical RAM Limit

Modelling Accuracy - solid surface concentration at positive current collector

\[ c_{s,e}(L_{neg} + L_{sep}, t) \text{[mol/m}^3\text{]} \]

- COMSOL (Full Order Pseudo-2D Model)
- Classical DRA ROM - 2500 Hankel Blocks
- Improved DRA ROM - 30000 Hankel Blocks
The proposed reduced order modelling with the Improved DRA

- reduces RAM Usage from 112 GB down to 2 GB.
- cuts cpu-time from 40 minutes to 40 seconds.
- requires no modification to existing modelling framework.

Outlook

- Use the improved DRA scheme to obtain a continuous-time model using very high sampling rates
- Physics-informed Equivalent Circuit modelling.
- Apply the model to Panasonic 18650BD (NCA) cells used in Tesla Model S.
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