Fraunhofer IISB

Fraunhofer Institute for Integrated Systems and Device Technology IISB

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Physics-Based Battery Models: An Embedded System Perspective

Introduction – Fraunhofer IISB: Group Battery Systems

What we do

Battery Systems for Mobile Applications

- **Automotive and Road Transport**: electrified vehicles (e.g., 48 V boost batteries, plug-in hybrid and full electric vehicles, utility vehicles (including forklift truck), trucks and busses with electrified powertrains), electric bicycles (e.g., e-bikes and pedelecs)
- **Railway and Rail Transport**: electrified rail public transport (e.g., traction energy storage units with batteries and/or supercaps/ultracaps for electric locomotives)
- **Aviation and Aerospace**: gliders (e.g., battery supplied electric sustainer and self-launcher), aircraft (e.g., high-power batteries for APU), satellites (e.g., nanosatellites)
- **Marine and Underwater**: multi-megawatt-hours (MWh) battery systems (e.g., submarines, cruise ships)

Battery Systems for Stationary Applications

- **Industrial**: ultra-high-performance battery systems (e.g., complete full-custom battery system prototypes for test benches), lithium-ion capacitors, Vanadium redox-flow batteries
- **Renewables**: electric energy storage systems for renewable energies (e.g., photovoltaic and wind parks)


Source: Fraunhofer IISB


Source: GreenGT


Source: E-Force One


Source: Ocean Infinity


Source: LANGE Aviation


Source: Fraunhofer IISB

Introduction – Fraunhofer IISB: Group Battery Systems

We develop foxBMS

foxBMS – a success story

- foxBMS – free, open and flexible research & development platform for battery management systems
  - Initiated in 2015 and online on GitHub since 2016 (https://github.com/foxBMS)
  - Royalty free open-source license (BSD 3-Clause and Creative Commons Attribution 4.0)
- foxBMS 2 (second Generation) with focus on functional safety over multiple domains released in April 2021
  - Royalty free open-source license (BSD 3-Clause and Creative Commons Attribution 4.0)
  - Continuous maintenance, improvement and enhancement
- More than 220 foxBMS development kits delivered to a wide array of industrial and academic users, partners and customers

Source: Fraunhofer IISB

  Public

foxBMS Fraunhofer IISB

Motivation

Why even go beyond Equivalent Circuit Models (ECMs) or Machine Learning (ML)-based approaches?

- ECMs and NNs do not enable physical insight into battery internal states
- Accuracy limitations due to
  - limited representability modeling capabilities of the physical effects
  - model complexity considerations
- ML specific: High computational complexity and may only offer limited verification options

→ Physics-based models (PBMs) offer richer state information: lithium concentration, potential distributions, degradation mechanisms

Physics-Based Models – A Brief Primer

Different types of physical models[1]

- Single Particle Model (SPM): captures transport phenomena effects
- Porous-electrode model: captures solid- and electrolyte-phase potentials
- Pseudo-two-dimensional models (DNF): captures solid- and electrolyte-phase potentials, diffusion and Butler-Volmer kinetics
- Multiphysics models: Multiphysics electrochemical-thermal modeling to capture entire battery behavior

- Multiple, high-quality physics-based reference implementations available:
  - Open-source: PyBAMM (BSD-3-Clause), BattMo (MIT)
  - Closed source/commercial solutions: MATLAB, COMSOL, Ansys, AVL Cruise, Siemens Simcenter Battery Design Studio

[1]Venkatasailanathan Ramadesigan, Paul, S. De, Shriram Santhanagopalan, R. D. Braatz, and V. R. Subramanian, "Modeling and Simulation of Lithium-Ion Batteries from a Systems Engineering Perspective," vol. 159, no. 3, pp. R31–R45, Jan. 2012, doi: 10.1149/2.018203jes.

Embedded Reality – General Constraints

Embedded system software is constrained by limited compute power, a rigid toolchain and other rules:

Hardware

- Only single core or dual core in lockstep
- < 800 MHz clock frequency
- < 2 MB Flash
- < 1 MB RAM
- FPU and cache might not be available

Software Ecosystem

- Software architecture restrictions
- Statically compiled code
- Custom compilers and linkers
- Mathematical libraries:
  - Only standard imposed implementation available
  - No support for matrix multiplication etc.
  - No solvers for e.g., ODEs, PDEs

Regulations

- Functional safety
- Certification
- MISRA-C, CERT C, NASA JPL C, "The Power of 10 Rules"

→ Algorithms must be lightweight and custom-optimized to the platform!

Embedded Reality – General Constraints

Real systems, real problems:

- System size: Your system might contain a few hundred up to thousands of cells
  → Which cell are your going to model?
- Measurement:
  - Time resolution of measurements: probably not faster than 50 Hz in a 100-cell system
  - Voltage measurement accuracy ~2 mV (additionally lifetime and temperature effects)
  - Current measurement accuracy few mA
  - Is sensor-based Coulomb counting required? If not, how good is software-based Coulomb counting?
  - How well are current and voltage measurement synchronized?

→ Algorithms must be deterministic and able to cope with these problems!

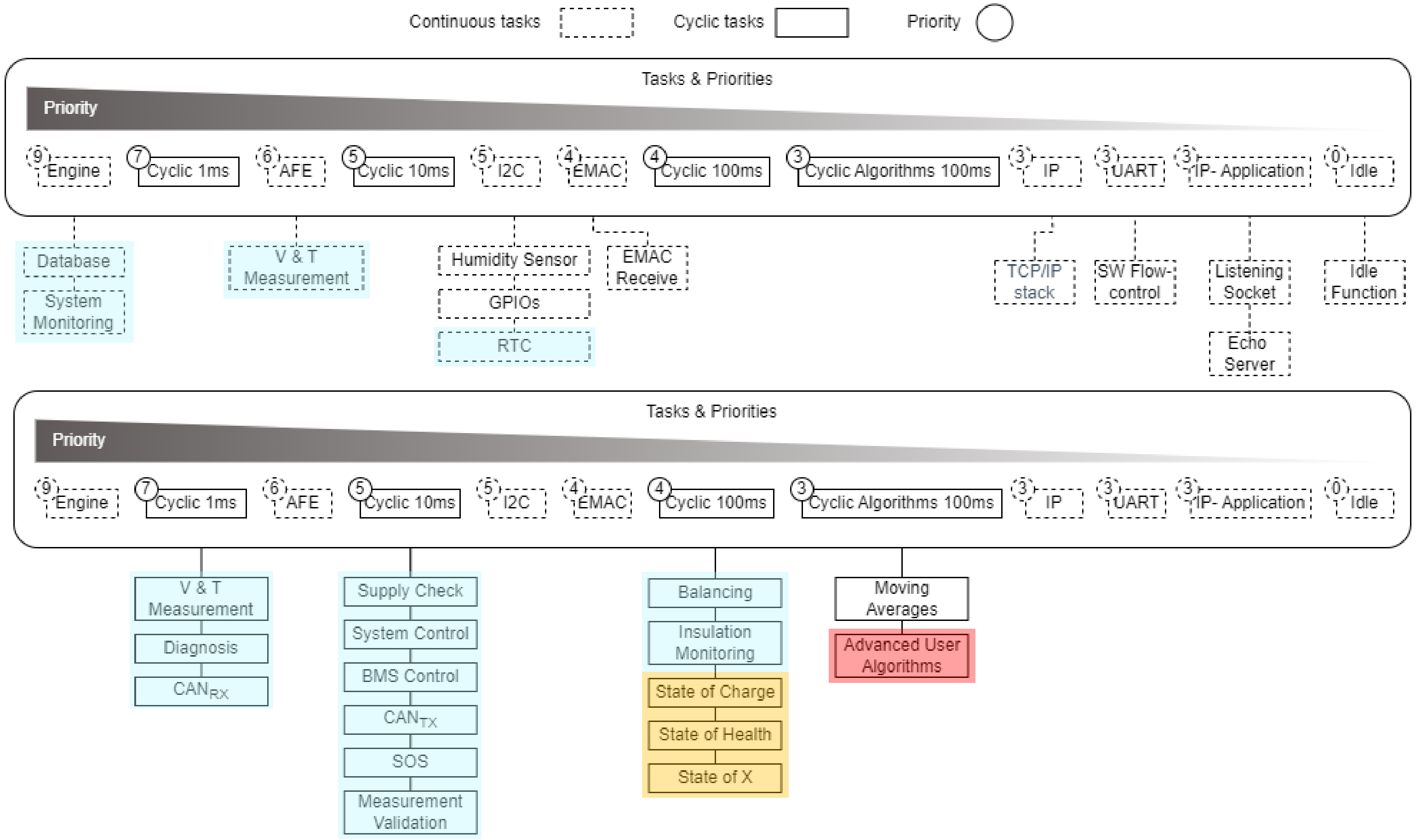
Embedded Reality – Primer on BMS-Software

foxBMS Task and Data Model

Main purpose of the BMS:

Control the battery system safely

- Readout ICs and monitor sensors
- Communicate with higher-level control system
- Ensure reliable, safe battery operation

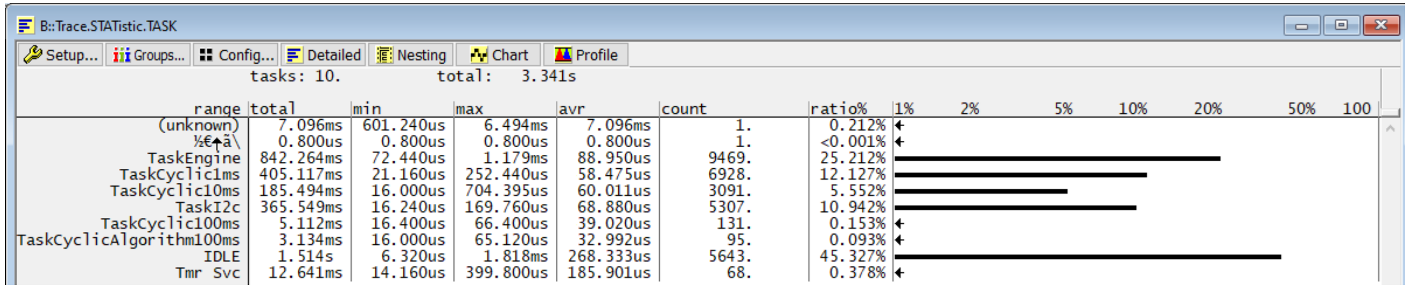


Embedded Reality – Primer on BMS-Software

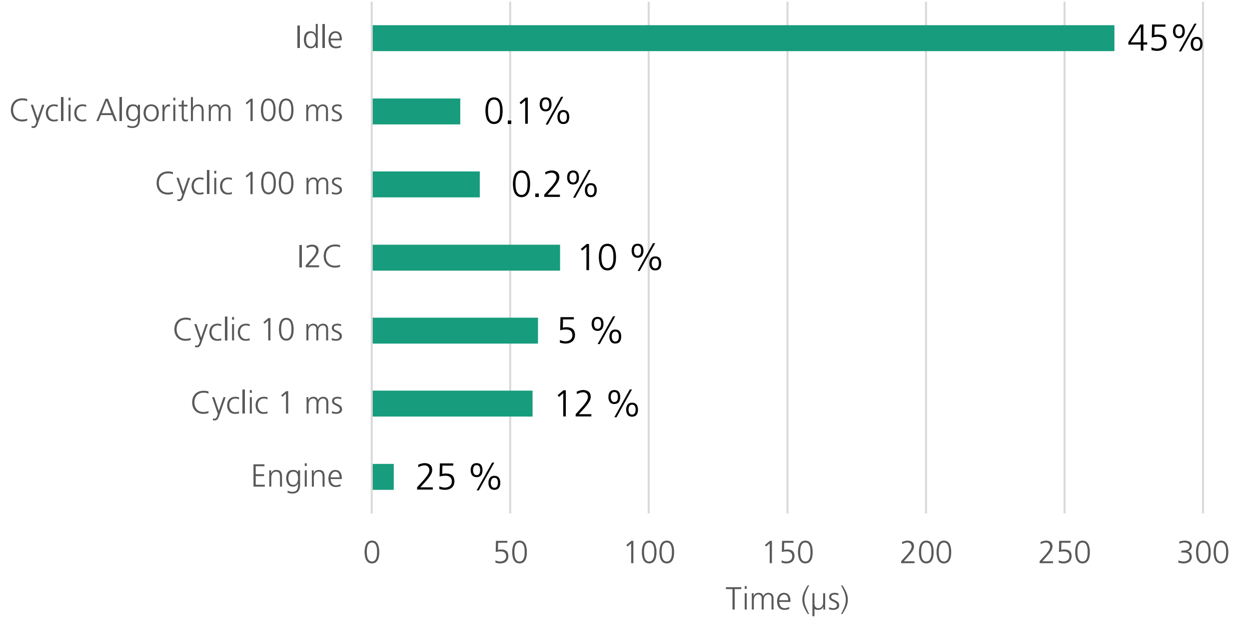
Runtime Characteristics

Analysis for simple foxBMS configuration

- Setup:
  - BMS-Master v1.2.3
  - 1 x BMS-Slave NXP MC33775A
  - foxBMS v1.11.0
- Software setup:
  - Disabled MCU cache
  - Algorithms
    - SOC: Counting
    - SOE: Counting
    - SOF: Trapezoid
    - SOH: Disabled



range	total	min	max	avr	count	ratio%
(unknown)	7.096ms	601.240us	6.494ms	7.096ms	1.	0.212%
½€ã\	0.800us	0.800us	0.800us	0.800us	1.	<0.001%
TaskEngine	842.264ms	72.440us	1.179ms	88.950us	9469.	25.212%
TaskCyclic1ms	405.117ms	21.160us	252.440us	58.475us	6928.	12.127%
TaskCyclic10ms	185.494ms	16.000us	704.395us	60.011us	3091.	5.552%
TaskI2c	365.549ms	16.240us	169.760us	68.880us	5307.	10.942%
TaskCyclic100ms	5.112ms	16.400us	66.400us	39.020us	131.	0.153%
TaskCyclicAlgorithm100ms	3.134ms	16.000us	65.120us	32.992us	95.	0.093%
IDLE	1.514s	6.320us	1.818ms	268.333us	5643.	45.327%
Tmr Svc	12.641ms	14.160us	399.800us	185.901us	68.	0.378%



Bridging the Gap – Methods & Strategies

Desired Model/Tooling Behavior

Battery models: efficient by themselves or a good code generation

Efficient Models/Model Order Reduction

- The arithmetic instruction should
  - be linear
  - not rely too much on previous data
- Good example: ROM for the pseudo-2D porous-electrode model by James L. et al.[1]

Code generation

- Modeling software needs to be able to create efficient low-level, standard-conforming code

[1] J. L. Lee, A. Chemistruck, and G. L. Plett, "One-dimensional physics-based reduced-order model of lithium-ion dynamics," Journal of Power Sources, vol. 220, pp. 430–448, Dec. 2012, doi: 10.1016/j.jpowsour.2012.07.075.

Bridging the Gap – Methods & Strategies

Tooling Support on foxBMS

Implementation of an API for SoX models

- SoX-API: Simple access to I, V, T measurement
- Integrated workflow for MATLAB®/Simulink models
  - Prepared Interface on C and MATLAB/Simulink side
  - “One click” testing workflow for unit testing as well as target-builds

What to expect next:

- Open-source publication on GitHub (Q3 2026)
- Further modeling software integration

MATLAB and Simulink are registered trademarks of The MathWorks, Inc. See mathworks.com/trademarks for a list of additional trademarks.

Outlook & Conclusion

Deploying Physics-Based Battery Models in Embedded BMS:

European Readiness, Current Approaches, and Challenges

- Great physics-based battery modeling software exists
- Tooling to bridge the gap from modeling software to embedded devices is missing
- Low-level math libraries for embedded devices are missing
- If you want to support making this happen: foxBMS is a FOSS project - free and open-source software:
  - Community participation is desired and warmly welcomed! Contact us at info@foxbms.org!
  - Contributions should be under a permissive license (e.g., BSD-3Clause, MIT or similar)

→ Physics-based models are ready to leave the lab and enter the application –
if we make them run on embedded hardware

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Acknowledgement

Battery management by multi-domain digital twins

Grant agreement: 101104013

Funded by the European Union. Views and opinions however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER.
State Secretariat for Education, Research and Innovation SERI.
This work was supported by the Swiss State Secretariat for Education, Research and Innovation (SERI).

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