



 **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)



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



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 models¹

- 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

¹Venkatasailanathan 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](https://doi.org/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 you going to model?
- Measurement:
 - Time resolution of measurements: probably not faster than 50 Hz in a 100-cell system
 - Voltage measurement accuracy ~1 mV
 - 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!**

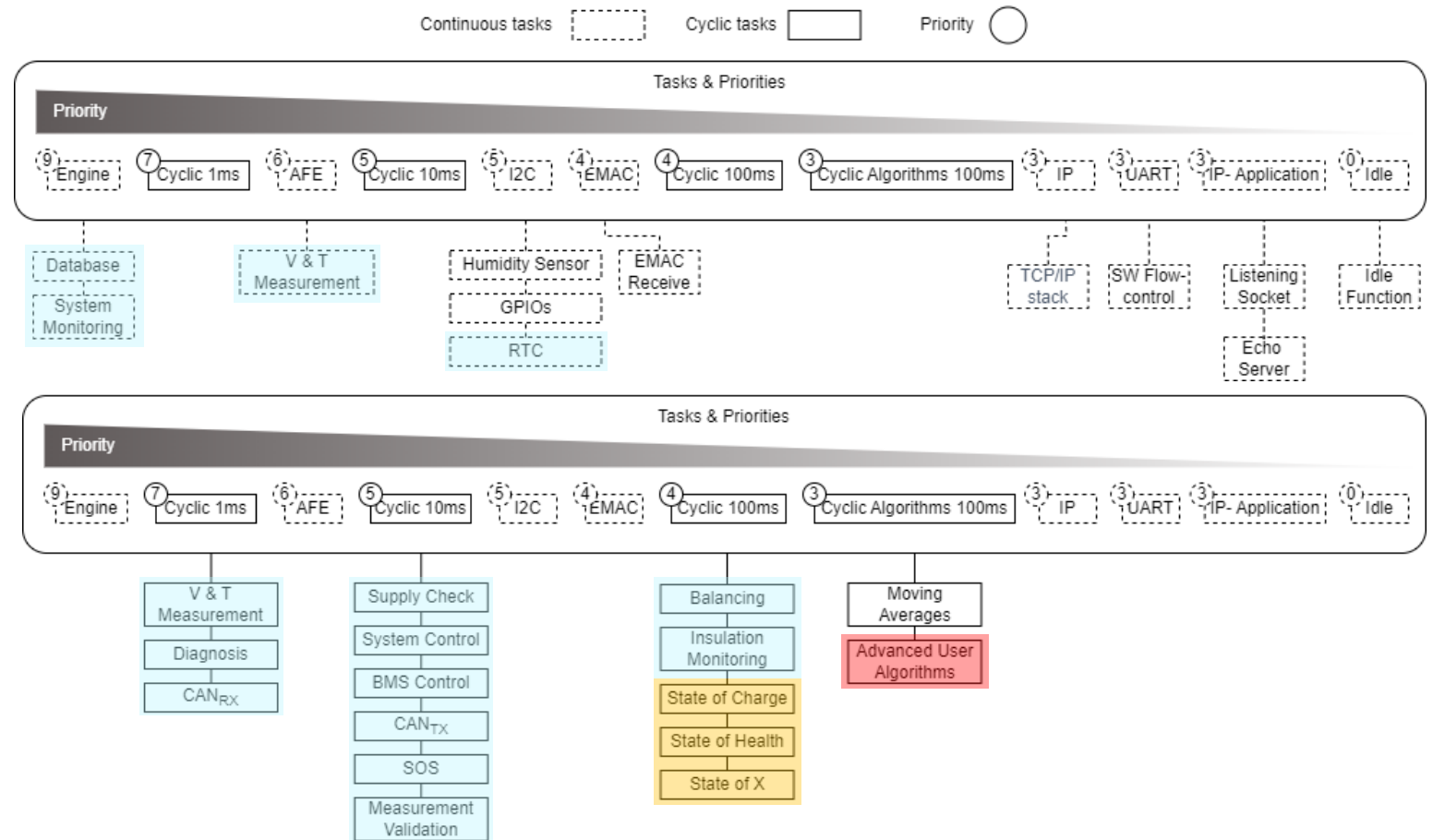
Embedded Reality – Primer on BMS-Software

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

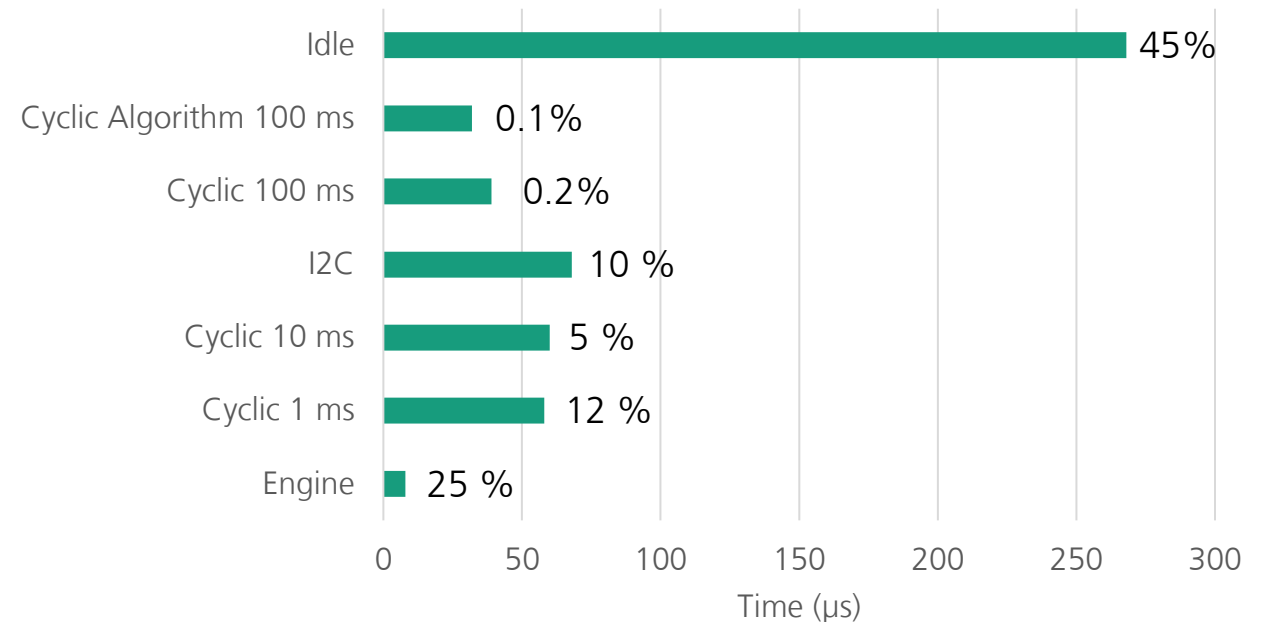
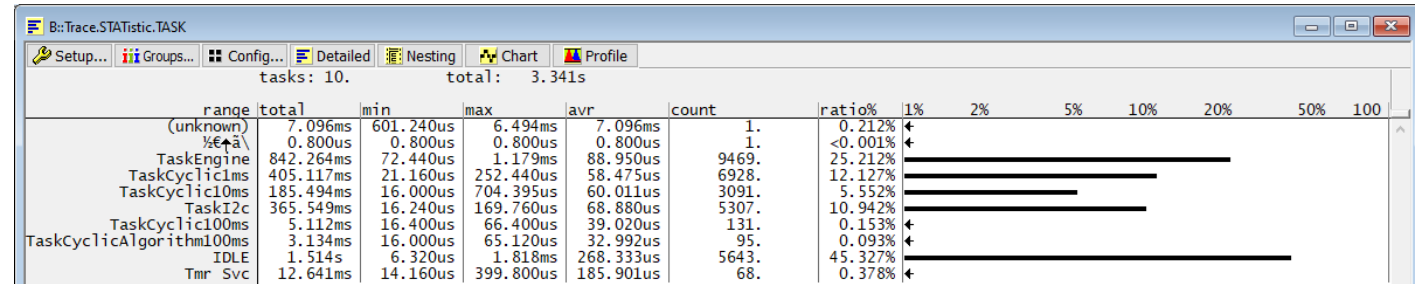


Embedded Reality – Primer on BMS-Software

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



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

¹J. 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](https://doi.org/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



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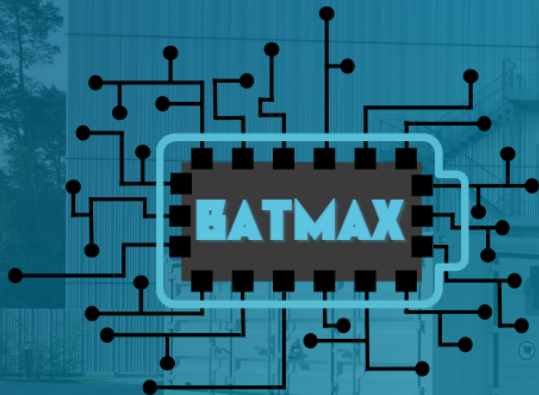
Outlook & Conclusion

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**

Acknowledgement



Battery management by multi-domain digital twins

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