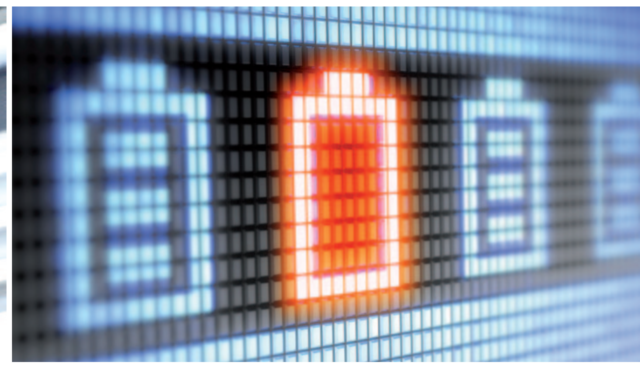
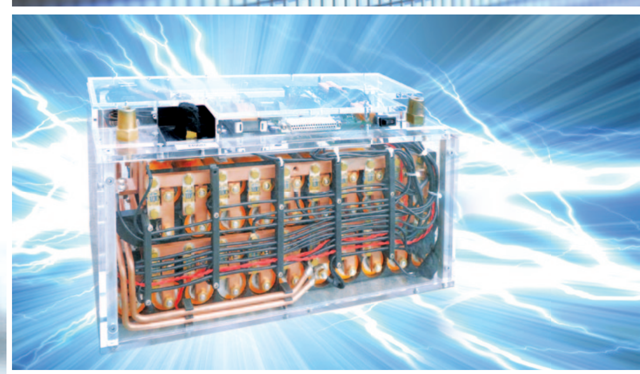
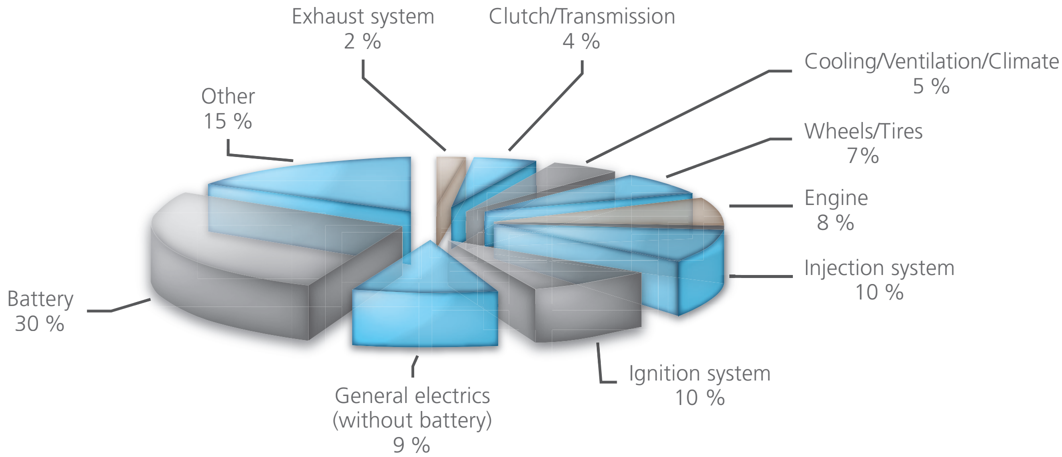
Ions at the Start

Building a demonstrator for a 12-volt lithium-ion starter battery

The 12-volt lead-acid starter batteries used in conventional vehicles are reaching their performance limits. Modern start/stop systems, more electrical equipment, and the increasing electrification of mechanically driven components are pushing up the demands made on energy storage. But at the same time, the need for lightweight construction imposes tight constraints. Developing a lithium-ion starter battery is a very promising approach here.







In 2011, around 30 % of vehicle breakdowns were caused by the 12-volt starter battery. Source: ADAC's Analysis of Assemblies in 2011.

Requirements for the Starter Battery

Two of the current hot topics in automotive development are the continued improvement of overall energy efficiency and reduction of vehicles' CO_2 footprints. Uncompromisingly lightweight construction is required, while at the same time, more and more electric power is needed – due to safety and comfort functions, the electrification of components that used to be driven mechanically, new functions like automatic start/stop, and so on. It all adds up to a high load on the battery. Moreover, the battery also has to meet requirements concerning weight reduction and cycle stability (charge/discharge in start/stop operation) or durability. It is also interesting to look at the causes of vehicle breakdowns in this context. An analysis of breakdown statistics by the German automobile association ADAC in 2009 showed that around 27 % of all vehicle breakdowns were caused by the battery. In 2011, the battery was involved in about 30 % of all recorded breakdowns. In short: conventional batteries have reached their performance limits.

Alternative Battery Solutions

One way to ensure high vehicle availability is to use two-battery electrical systems, plus double-layer capacitors or other battery technologies. Lithium-ion (Li-ion) batteries have especially attractive properties as 12-volt vehicle starter batteries. They currently possess one of the highest energy densities of all the available rechargeable energy storage systems. Their maximum possible charge/discharge cycles are several times those of lead-acid batteries, so they meet the requirement profile's criteria of low weight and cycle stability. For example, a lead-acid battery with a capacity of 92 ampere-hours weighs around 26 kg and reaches approx. 400 charge/discharge cycles at a discharge depth of 20 %. A comparable Li-ion battery weighs only 16 kg and reaches approx. 15,000 charge/discharge cycles at the same discharge depth. The achievable weight reduction of approx. 10 kg improves the vehicle's CO_2 footprint by around 0.85 g.

Challenges: Charge and Temperature

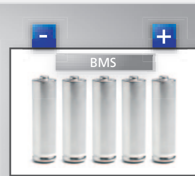
The disadvantages of Li-ion batteries are their extreme sensitivity to deep discharge and overcharging, and their restricted working temperature range. On top of that, the charging requirements vary according to temperature and driving behavior. For example, the highest demand on the energy storage is during short journeys in winter, when chargeability is restricted. These disadvantages can be counteracted by the right operating strategies, working points and other measures. This is a perfect job for electronic battery management systems (BMSs), which also perform numerous monitoring and controlling tasks, such as charge- and temperature-dependent control of the charge and discharge currents. A BMS also performs cell balancing to equalize the charge states in all the cells. Because a battery consists

Lithium-ion Batteries as Replacements for Lead-Acid Batteries

Lead-Acid

- Life cycle: ~ 4 years
- Cycles at 20 % discharge depth:
  - Lead-acid battery: ~ 400
  - AGM (Absorbent Glass Mat): ~ 1000
- Energy density: ~ 40 Wh/kg
- Price: Low
- Complexity: Low

Li-Ion



- Life cycle: ~ 15 years
- Cycles at 20 % discharge depth: 15,000
- Energy density: 50 - 100 Wh/kg
- Price: Currently five times higher than lead-acid batteries
- Complexity: High (requires a battery management system).

Comparison of lead-acid and Li-ion battery systems used as starter batteries in vehicles.

of several cells connected in series, cell balancing must always hold their charge states at the same level to prevent overcharging or deep discharge in individual cell groups.

Starter Battery vs. Traction Battery

The requirements for a 12-volt starter battery are not the same as for a high-voltage battery (traction battery) in an electric or hybrid vehicle. A starter battery has to support recuperation, but does not normally have to supply high currents for long periods, except during the startup process in the combustion engine. It also feeds comparatively low currents into the vehicle electrical system. In normal operation, a starter battery never usually discharges completely. Its charge state is typically in a range around 95 %.

Predevelopments for a Li-ion Starter Battery System

To develop various components in a Li-ion-based battery system efficiently, Audi ran several parallel subprojects. These included a battery demonstrator including battery electronics, thermal and electrical battery simulation models, a control algorithm (integrated in the BMS) for the charge current, and a tool chain for in-vehicle rapid control prototyping (RCP). The aim of this predevelopment project is to investigate and test possible approaches and methods for production use before actual production development kicks off. The experiment setup is designed for trying out and evaluating as many ideas as possible. This was achieved by constructing a battery demonstrator with electronics components and running all the algorithms on an RCP system.

Concept for Battery and BMS Algorithms

Initially, the battery demonstrator must match the form factor for conventional lead-acid starter batteries, which it has to replace in conventional vehicles. For future production use, more individualized shapes could be designed and implemented. In addition to the terminal voltage poles, the demonstrator has an interface to the RCP system with the BMS

Glossary

Electrochemical impedance spectroscopy – Method of disturbance-free analysis and characterization of materials. The system's impedance spectrum is obtained by evaluating excitation signals of different frequencies and the system responses.

Finite element method (FEM) – Numeric method for solving partial differential equations: for example, ones used as mathematical descriptions of physical processes.

Serial Peripheral Interface (SPI) – A bus system for synchronous, serial data transmission, with which digital circuits can be connected according to the master-slave principle.

Inter-Integrated Circuit (I²C) – A serial data bus that is used mainly for communication between different circuit parts within one device: for example, between a controller and peripheral control circuits.

algorithms. The RCP system can be installed in close proximity to the battery and connected to it via a bus system. In actual production, a solution would be integrated into the battery itself. The battery case contains the Li-ion cells and the electronics that measure the voltages and currents of the cell groups and the temperatures of selected cells. The electronics also enable cell balancing and serve as an actuator for controlling the charge currents. The battery demonstrator's internal structure has to take both thermal and electrical aspects into account. This includes the spatial arrangement of the cells and the electronics, and also the electrical connection of cell groups to current rails. Simulation was used with various test specimens to optimize the structure and topology of all cell connections.

Model of a Li-ion Starter Battery

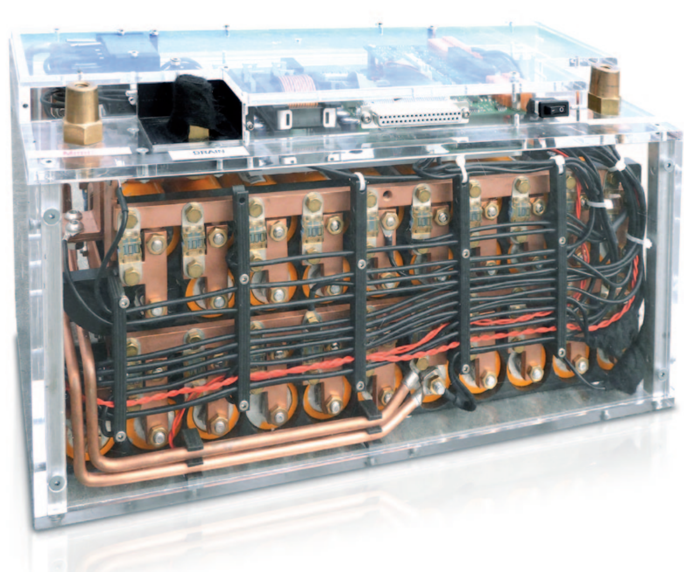
A battery model was developed for simulation-supported studies on how the Li-ion starter battery and the BMS algorithms behave. The model is used for preparatory investigations to obtain important information on the battery's electrical and thermal properties. To represent the battery's characteristic features in real time, it was necessary to combine a terminal voltage model with an electrothermal finite element method (FEM) model. Parameterizing all the models was a special challenge. To obtain a comprehensive characterization of the battery, the step responses of the battery cells were evaluated, and an electrochemical impedance spectroscopy was performed. The results were merged in a hybrid model to produce an overall model with high quality and dynamics. When completely parameterized, the model represents aspects such as the battery's state of health, including calendar aging and charge-cycle-related aging.

Developing the BMS Software

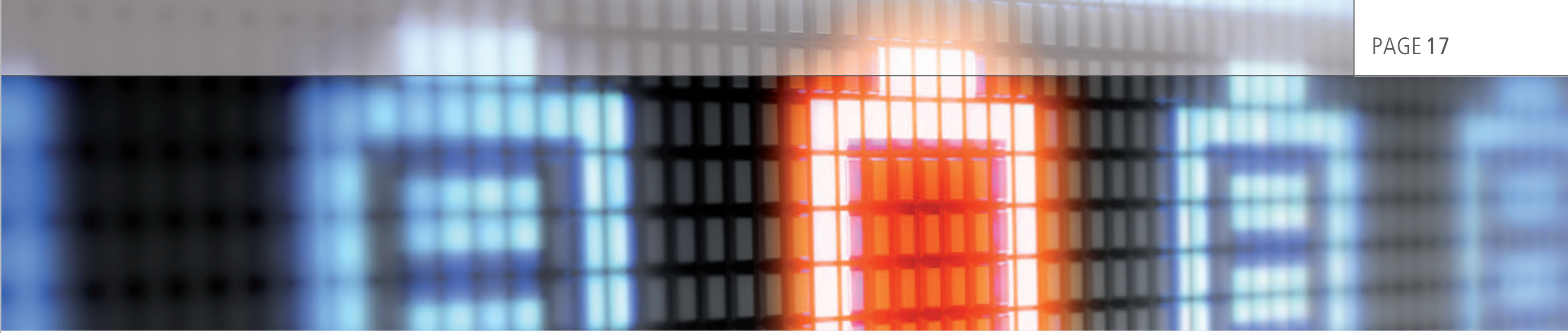
The elementary components in the BMS software are algorithms that control the charge current, initiate cell balancing, and measure the battery's state of charge (SOC) and state of health (SOH). They also redundantly monitor the battery for overvoltage, overtemperature and overcurrent. For the experimental system, the SOC algorithm was designed with a Kalman filter to eliminate measurement errors and malfunctions. In addition to the SOC, the software also analyzes the battery's SOH. The self-diagnostics implemented in the system explicitly address individual cells to provide data on the available capacity and state of health.
To equalize the cell charges, passive cell balancing was chosen. With this method, individual cell groups are discharged selectively down to the level of the weakest group, until all the cells have an identical charge level. The initial predevelopments and subsequent cost effectiveness analysis of active cell balancing, in which the charge is transferred from cell to cell, revealed that investments in active balancing would not have a positive economic impact until after the end of the assumed vehicle life cycle. It was therefore decided not to use it in a starter battery.

Prototype Construction of a BMS

During development, the BMS had to be tested in test drives at an early stage in order to examine and adjust the operating strategy in interaction with the vehicle's energy management (EM) system and to run climate tests. The rapid control prototyping system dSPACE MicroAutoBox was used as the BMS ECU. The control algorithm



The Li-ion battery demonstrator with transparent plexiglass enclosure. The cells, current rails, contacts and electronics can all be seen. To reduce weight, later production-ready systems will conceivably have aluminum connectors instead of copper current rails.



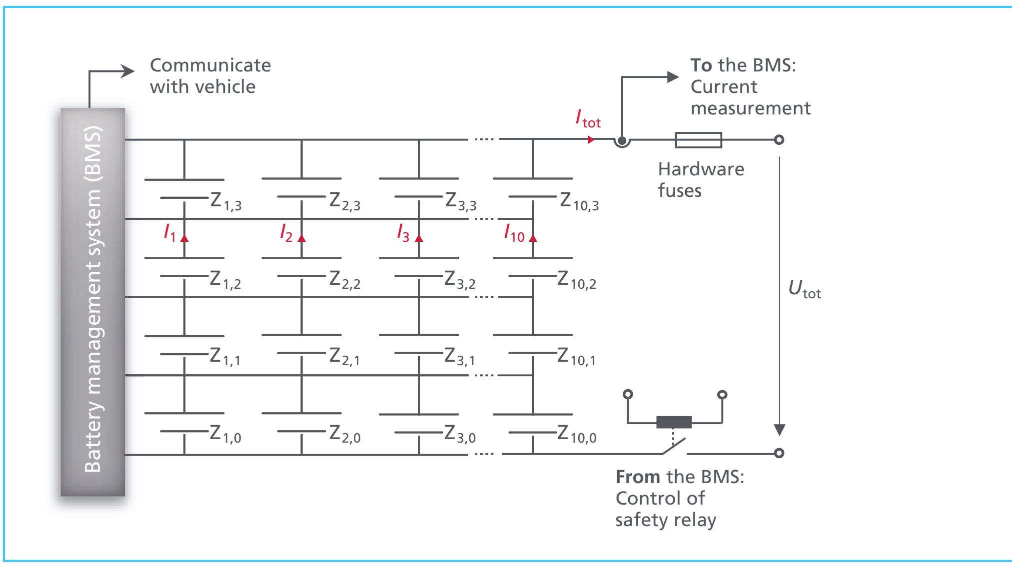
> "The MicroAutoBox does exactly what is expected of a prototyping system. You just load new controller software and immediately try it out in the vehicle."
>
> *Dipl.-Ing. (TU) David Vergossen, Audi Electronics Venture GmbH*

is created in model-based development and can be loaded straight from the development PC to the MicroAutoBox, where it is executed. The MicroAutoBox is connected to the EM system. The battery's integrated electronics perform the evaluation at cell level. They also include an actuator system for cell balancing, plus output semiconductors for charge current limitation and DC-DC converters for determining the SOH. Communication runs via a serial peripheral interface (SPI)/inter-integrated circuit (I²C). The MicroAutoBox is connected via a dSPACE Programmable Generic Interface (PGI1). With this setup, the Li-ion starter battery can be operated in a vehicle and also in the laboratory. It is installed in the vehicle simply by replacing the production starter battery with the Li-ion battery demonstrator and connecting the MicroAutoBox to the vehicle's LIN bus and the battery. Laboratory operation is also possible without connection to the vehicle bus.

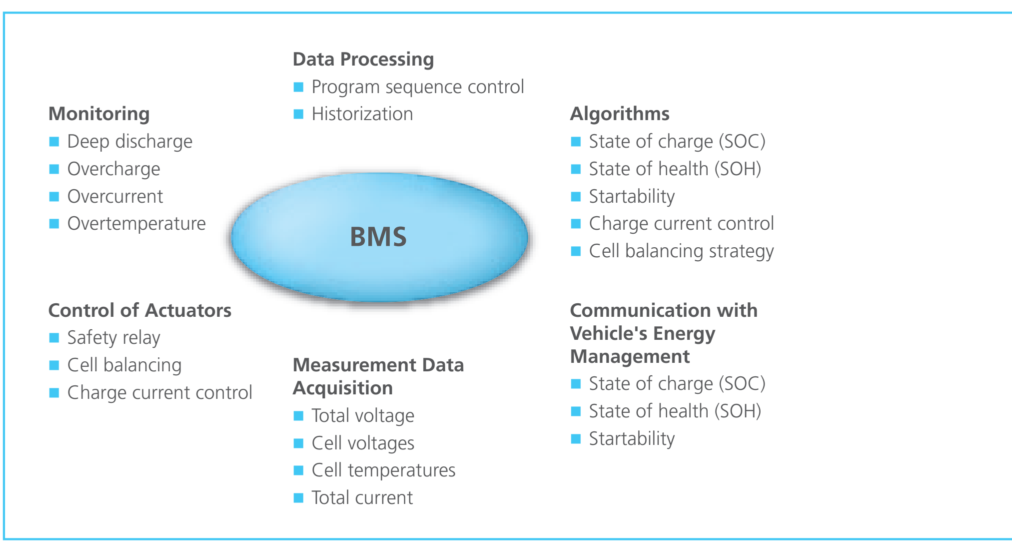
Special BMS and Battery Functions

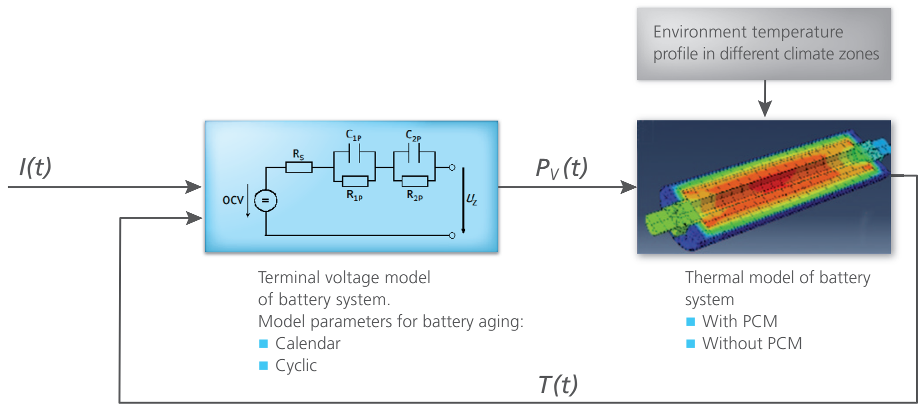
For optimum operation of the Li-ion starter battery, and to avoid premature aging, the charge current is limited by power transistors that perform linear current control. In the experiment setup, the parasitic heat of the power semiconductors is used to heat the battery so that it can absorb the charge better at low

The basic structure of a 12-volt Li-ion multicell battery system.



The BMS for the 12-volt Li-ion starter battery performs a great variety of tasks.





PCM: phase changing material

A terminal voltage model coupled to an electrothermal FEM model to predict the life expectancy of the battery system.

> "The expert field of batteries has been transformed by the Li-ion starter battery, which can already be driven on the road thanks to dSPACE MicroAutoBox."

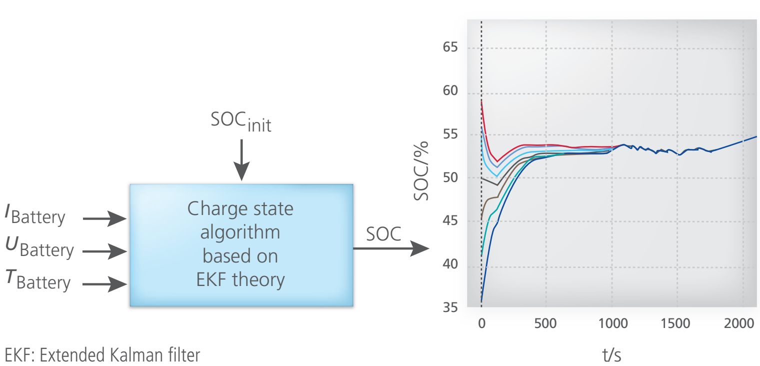
Dipl.-Ing. (TU) David Vergossen, Audi Electronics Venture GmbH

temperatures. The transistors are therefore installed in the battery at various locations with favorable heat properties. The battery's temperature is measured continuously at four measurement points via the integrated electronics. These high technical costs are justified only when they are part of predevelopment.

The BMS in Practical Trials

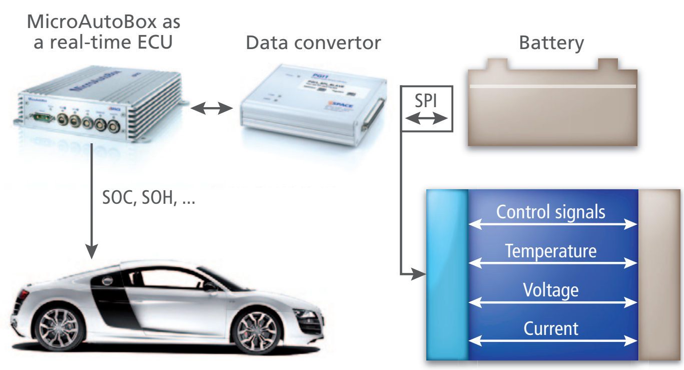
The battery demonstrator with the MicroAutoBox is currently in the test phase, undergoing test drives and also tests on a climate-controlled chassis dynamometer. The battery can be operated with a controller, i.e., with heating, as well as without a controller. The results of these tests are used to optimize the control algorithms even further.

The results show that a Li-ion starter battery with a BMS can be a suitable substitute for a lead-acid battery. Its considerably greater cycle stability meets the requirements of start/stop operation at a low weight, but currently still at a much higher cost.



EKF: Extended Kalman filter

Developing a charge state algorithm. The signal behaviors show the SOC adaptation with false initializations of different sizes.



Simulation results tried out in practice by test drives with MicroAutoBox. Immediate real-time vehicle tests mean short software development cycles.

The experience gained with the RCP system can be used if and when production development begins.

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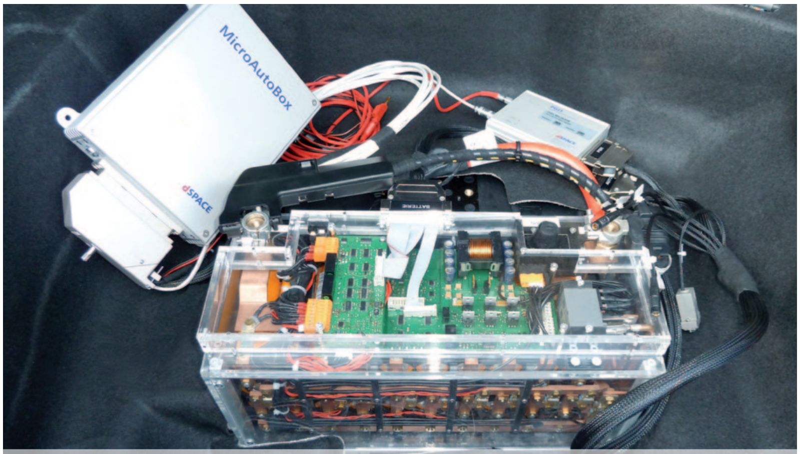
Expression of Thanks
This article is based on the E³Car project (Nanoelectronics for an Energy Efficient Electrical Car – AEV Subproject: Research into an Innovative Algorithm for State Detection in Lithium-ion Batteries), which is funded by the Federal Ministry of Education and Research (BMBF) and the EU (ENIAC JU Project) under the reference numbers 13N10395 (BMBF) and 120001 (ENIAC). The authors bear sole responsibility for the contents of this publication.

In the vehicle, the Li-ion battery replaces the conventional starter battery – here it is in the vehicle's spare wheel recess.



In Brief

The use of a lithium-ion starter battery was investigated as part of the BMBF/ENIAC research project at AEV. The project goal was to research a cycle-stable, less heavy replacement for the lead-acid battery. A battery demonstrator and BMS algorithms were created during the development. Fundamental studies were performed to ensure reliable functioning:

- Modeling the utilized cells
- Modeling the entire battery
- Developing the battery electronics
- Battery operating strategy
- Designing the capacity with regard to SOH, startability, quiescent current, cyclization
- SOC measurement with SOH adaptation
- Thermal simulation
- Designing current rails and contactor technology

The prototype was implemented with dSPACE MicroAutoBox. It is used as the ECU in laboratory tests and in test drives, and supports fast function development. Initial testing of the new battery and the BMS software produced convincing results.

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