Extending Battery Management Systems for Making Informed Decisions on Battery Reuse

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Abstract. A battery management system (BMS) is an embedded system for monitoring and controlling complex battery systems in high-tech goods, such as electric vehicles or military communication devices. BMSs are often designed for simplicity and cost efficiency, storing few crucial data on the condition of batteries. With an increasing trend to reuse batteries, BMSs face a need to implement additional functionality to support decision-making tasks. This functionality requires rich data on the structure, usage history, and condition of a battery that is not supported by current BMS type series. Based on expert interviews and document analyses, we sketch a design theory for implementing BMSs that supply the data required for making decisions on how to best reuse battery systems.

Keywords: Design theory · Battery management system · Embedded system · Decision support system · Condition monitoring

1 Introduction

Since their commercial introduction in 1991, lithium-ion batteries have become a widespread technology for supplying mobile devices and high-tech goods with energy [1] and often account for a major share of the initial costs of the devices in which they are applied [2]. One strategy for reducing the systems' total costs of ownership is to reuse a battery for another application after it has completed its first lifecycle. For example, electric vehicles (EVs) require batteries with high energy density to provide for a range that is accepted by drivers [3]. While it is assumed that these batteries are no longer usable for EVs when their capacity drops to around 70-80% of their original capacity [4], they might still be usable in stationary applications after their removal [5].

A crucial prerequisite for reusing a battery system is to accurately assess its condition and usage history. Since the procedures to obtain these data by manually testing the battery are complex, resource intensive, and may lead to further cell degradation [6], we propose that the data should be stored and made available by the battery management system (BMS) without conducting additional testing procedures.

BMSs are embedded systems that provide basic functions for operating a battery system. Having been designed as low-cost systems with minimal hardware capabilities,

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they usually do not store data on the level of detail that is required for making decisions on reusing a battery. To identify this gap and present some first ideas on how to design the next generation of BMSs, the research question addressed in this paper is: In what way must BMS be extended to support decision-making on the reuse of battery systems, in addition to monitoring and controlling their basic operations?

The paper is organized as follows. In Section 2, basic principles of lithium-ion battery systems and BMSs are reviewed and second life applications are reviewed. In Section 3, the research method is exemplified. In Section 4, a first design theory for a class of BMSs that support decision-making on reusing battery systems is sketched. Section 5 concludes the paper.

2 Theoretical Background

2.1 Fundamentals of Lithium-Ion Battery Systems

Lithium-ion batteries are used as energy storages in many electric devices, ranging from small battery packs used in cell phones or cameras to large battery systems for EVs or temporary energy storages for photovoltaic systems. Advantages of li-ion batteries include “high energy and power densities, long life, and lack of memory effect” [6].

In general, larger battery systems follow a modular design and usually consist of a battery pack, battery case, battery management system, and thermo system [7]. A battery pack is an energy storage device that comprises several battery modules that again are composed of battery cells [8]. For increasing total voltage, battery cells are connected in series into battery modules, while for increasing total amperage a couple of modules are connected in parallel. Smaller batteries usually consist of one cell only. The inner components are protected by a solid case. The battery management system is an embedded system to monitor and control the battery. Finally, due to battery cells’ temperature sensitivity, larger lithium-ion battery systems contain a thermo system for heating and cooling the cells that is controlled by the BMS [9].

Lithium-ion batteries suffer from cell aging, which mainly depends on the cell chemistry and operation conditions [6] and results in decreased performance. Battery aging can be divided into cycle aging and calendar aging [10]. While calendar aging describes the degradation of a battery during storage (i.e. while the battery is not in use), cycle aging denotes the degradation during charging or discharging operations [10]. Rezvanizaniani et al. [11] identify the five most significant factors for degradation in automotive applications: environment temperature, discharging current rate, charging rate, depth of discharge, and time intervals between full charge cycles. Due to initial variance of the cells and different temperatures occurring at different locations inside the module [12], cells might degrade unequally [13]. Since aging depends on “chemistry, design parameters and battery usage” [12], those aspects have to be considered for explaining battery aging. Even cells manufactured in the same production lot might show a variance in their aging behavior [12]. Therefore, Brand et al. [14] state that the prediction of a module’s remaining useful life (RUL) requires knowledge about its previous usage history.

2.2 Battery Management Systems as Embedded Systems

Embedded systems are microprocessor-based systems performing dedicated tasks as part of another system. They commonly feature combinations of hardware and software, have few dedicated functions, are integrated in larger systems, and possess limited hardware resources regarding computing power and memory. Often, real-time constraints exist and the system's correctness is a compulsory design requirement [15].

A BMS is an embedded system to operate a battery, to prevent malfunction, and to extend the battery's lifetime. It is typically designed for three main goals. First, it ensures the safe and reliable operation of the battery. Second, it performs electrical management for optimized battery performance and acts as an interface between a battery and the device. Third, it controls the temperature of the battery [9]. To account for these goals, a variety of sensors are implemented into the battery, providing data about electric and environmental characteristics. Typical characteristics measured by a BMS include cell voltages, cell temperatures, and charge and discharge currents [16]. The sensor data are used to calculate or estimate a variety of metrics on the battery's status.

The most commonly used parameters are the state of charge (SOC) and the state of health (SOH). The SOC describes the "reversible" [17], while the SOH describes the "irreversible changes" experienced by a battery [17]. The SOC is defined as the ratio of remaining capacity to the capacity when fully charged [16], or the actual amount of charge divided by the total amount of charge [18]. In EVs, the SOC can be used as a kind of fuel gauge, as known from conventional combustion engines. Since the SOC cannot be measured directly, many different methods for SOC estimation have been proposed [16]. SOC and SOH estimation can be based on data that is stored in a bookkeeping systems that holds historical data such as the number of cycles [19]. An estimation model is stored in the BMS that is used for calculating the SOC or SOH [16].

Apart from estimating a battery's SOC and SOH the measured data are also required to ensure a battery's safe and reliable operation. Common safety features exist to prevent overcharges and deep discharges by controlling the electric currents and temperature [17], as lithium-ion cells may explode at high temperatures and their degradation highly depends on the battery's operating temperature. Therefore, a BMS operates a thermal management system in larger battery packs [20], shielding the battery from adverse environmental conditions to minimize its degradation and to avoid overheating [13]. Smaller batteries usually do not contain a dedicated heating and cooling device.

To extend the battery's lifetime, the SOC of all cells should be kept as equal as possible [20]. To achieve this objective, the BMSs contain active or passive mechanisms for cell balancing.

Depending on the size and complexity of a battery, a BMS can be implemented on all levels of a battery, such as cells, modules, and packs. Chatzakis et al. [21] state that "a BMS has to be 'cell based' in order to be effective". Hierarchical BMSs can be implemented by designating BMSs as masters and slaves, such that a battery's operations can be monitored on all levels of detail [19].

Data exchange between the BMS and the device is usually established using a communication bus (e.g. CAN-bus for EVs [20], system management bus (SMBus) for smaller devices [19]).

2.3 Second Life Applications of Used Batteries

Like any other product, a battery passes through different stages during its lifetime, including manufacturing, shipping, installation, useful life, dismantling, and disposal [22]. In addition to these lifecycle phases, batteries might be reused in second life applications to increase their sustainable use and generate additional revenues.

Second life applications may be viable if individual usage scenarios require disparate properties of a battery. For instance, electric vehicle batteries (EVBs) have to provide high discharge currents to provide decent acceleration capabilities, a high energy density, and slow cycle aging [23]. A degraded EVB that, due to an increased internal resistance, can no longer provide the necessary peak loads required in a car might still be usable in stationary applications that do not have such high power demands. Hence, reusing EVBs in stationary applications is explored in current projects [5].

Since every battery ages differently, information about the battery is needed to identify the best scenario for its reuse. Furthermore, to compile a new battery pack out of several used battery cells with an equal level of quality, information about each individual cell in a used battery pack are required. Following propositions of battery experts, this includes information about the individual cells' age, since cells with different aging histories should not be used in the same pack. While this information can be gathered by performing physical tests on the battery, these tests have been found to be complex, stressful, and lead to an increased cell degradation. To identify the aging mechanism of a cell, destructive methods like "X-ray diffraction (XRD) and scanning electron microscopy (SEM)" [6] are used frequently. While information about the current status can also be acquired with non-destructive methods, such as cyclization, these methods often increase the battery's cycle age due to the charging and discharging cycles carried out in the course of conducting the procedure. Thus, there are good technical and economic reasons to store more data about the battery's condition in a BMS.

3 Research Method

Design has been proposed to be a science of the artificial that differs from research on natural phenomena [24]. Gregor [25] proposed five types of IS theory, including prescriptive theories for design and action that convey knowledge on how artifacts ought to be, instead of explaining, analyzing, or predicting their behavior. Later, Gregor and Jones [26] conceptualized these five types of theories as 'design theories' and proposed eight components based on which design theories can be communicated.

To identify the current properties of BMS, we analyzed two battery systems based on document analyses and informal discussions with experts from two companies that manufacture battery packs and BMSs. The first battery pack is used in communication devices in a military context. The second battery pack is used in EVs.

Based on this assessment, we conducted informal discussions with battery researchers and manufacturers and analyzed the literature to advance BMSs into systems that inform decision making on reusing batteries. Based on these results, we sketched a design theory for a class of BMSs that do not only provide the usual features for monitoring and controlling the battery, but also make available the data that are required to enable decision making on how to best reuse the battery in other application scenarios.

4 Extending BMSs for Making Decisions on Battery Reuse

Our discussions with battery researchers and manufacturers as well as the literature analyses led to three types of data about a battery that are needed to make an informed reuse decision. First, data about the current condition of the battery is needed, especially the SOH regarding the capacity and the internal resistance are required to identify valid reuse applications. Second, transaction data are required, including the charging and discharging cycles of the battery. Third, to estimate the remaining useful life for different reuse scenarios and to assess whether a recombination of battery modules is possible the detailed usage history is needed, including basic condition data such as voltage, current and temperature experience by the battery as functions of time [27].

Based on the data that is needed for making informed reuse decisions, three aspects present themselves to advance BMSs into systems to obtain, store, and evaluate these data along the battery's first life.

First, the decision task might demand more data than is currently made available in a BMS. To acquire more data, additional sensors for measuring currents, voltages, and temperatures might be integrated into the battery. The frequency in which the parameters are measured and stored has to be adjusted to an adequate level of granularity to limit the data storage requirements and thus avoid an escalation of costs for data storage. For recombining and predicting the future performance of cells or modules, data on the usage history has to be identified on a cell or a module level, respectively.

Second, the hardware and software capabilities of BMSs need to be extended, since the data gathered by the sensors have to be processed for calculation or estimation of specific values that represent, e.g., the degradation of the battery. As regards the storage of a BMS, data that defines the history of the battery has to be stored for a sufficient period of time. An important observation is that while data storage prices are decreasing, storage space in embedded systems is still very costly, especially in automotive applications, because of high safety standards and cost pressure [28]. In these scenarios, data on selected parameters, such as cycle life or the maximum remaining capacity [29], might be saved as histograms.

Third, the – external – interfaces of the BMS have to be refined, since the recorded data has to be made available to a decision maker faced with the task of reusing a battery. The data can be communicated to an external system like a maintenance device or a superior system inside the same device, such as a vehicle management system in an electric vehicle, or read out after the end of the first lifecycle of the battery.

The identified aspects become manifest as additions to the design theory that underlies current implementations of BMSs as embedded systems (Table 1).

Table 1. Extended design theory for BMSs to foster decision-making for battery reuse

Components	*Additions to the current design theory underlying BMSs*
Purpose and scope	To obtain data for making decisions on battery reuse, including transactions and errors experienced by a battery and gradients of important battery parameters along the entire battery lifecycle.
Constructs	Physical components: Additional sensors, extended hardware capabilities, extended interfaces. Abstract components: Gradient of important battery parameters; transaction data on charging/discharging events; data on unusual events (e.g. extreme temperatures, unusual high energy requests, major physical shocks).
Principles of form and function	Acquisition and storage of transaction data affecting the battery, condition data on the battery, and evaluation of historical data to assess and predict the battery's condition.
Artifact mutability	To adapt to new models for evaluating battery data, so as to assess and predict the condition of the battery with greater accuracy.
Testable propositions	(1) The condition of the battery can be assessed more comprehensively than with conventional BMSs; (2) the future condition of the battery can be predicted based on historical data; (3) the selection and implementation of an adequate reuse scenario is fostered.
Justificatory knowledge	Decision theory [30], theory on predicting the future condition of a battery based on current data [31], IS design theory [26], [32].
Principles of implementation	The implementation needs to be able to monitor and control a battery, and to assess and predict the condition of the battery. It needs to be embedded into a decision support system to enable decisions on using the battery in suitable application scenarios.
Expository instantiation	To convey a BMS as an embedded system and (a) extend the sensors, memory, and processing capabilities of the BMS or (b) connect the BMS to an external information system to which crucial data are transmitted regularly to monitor the battery's lifecycle.

5 Contribution and Research Outlook

The contribution offered in this paper is to provide some first ideas on developing a design theory that describes a class of Battery Management Systems (BMS) that are capable of informing decision making on the reuse of batteries. BMSs are currently applied at the interface between the battery and its ambient device and control basic functions such as charging and discharging the battery, temperature management, and maintain safe operating conditions. We identified a lack of available data to be provided by BMSs to support decisions on the reuse of battery cells, battery modules, and battery packs. Subsequently, we identified a need to add additional sensors, hardware capabilities, and interfaces to BMSs and sketched a design theory for a class of BMSs that can inform decision making on reusing batteries in addition to operating the battery itself.

A limitation of the paper is a potentially incomplete appraisal of the current features of BMSs, which was done based on a literature analysis and a review of two expository instantiations. While this approach has enabled us to summarize the crucial characteristics of BMSs, additional BMSs might have to be reviewed to more fully explore the range of functions provided by current BMSs. In addition, further research is warranted to increase the completeness and level of generalization of the proposed design theory.

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