Design and Verification Methodologies for Smart Battery Cells

Sebastian Steinhorst[1,2]

[1]Department of Electrical and Computer Engineering, [2]Institute for Advanced Study
Technische Universität München, Germany
Email: sebastian.steinhorst@tum.de

***Abstract*—Lithium-Ion (Li-Ion) battery packs are continuously gaining in importance in many energy storage applications such as electric vehicles and smart energy grids. Such battery packs require advanced Battery Management Systems (BMSs), which are contributions from the embedded systems and integrated circuits domain. The BMS monitors and controls the battery cells in a pack and ensures the functionality, efficiency, safety and reliability of the pack. Conventional BMS designs employ a centralized controller architecture for the whole battery pack. Recently, Smart Battery Cells have been proposed which enable a complete decentralization of the BMS. In Smart Battery Cells, each cell is equipped with a Cell Management Unit (CMU) which individually manages the cell it is attached to. By communication with other Smart Battery Cells, the pack-level functionality of the BMS is provided in a distributed fashion. While this architecture provides many benefits such as scalability, minimal integration effort and increased functional safety, existing design and verification methodologies can neither be applied on hardware nor on software level. Consequently, this contribution will discuss how such methodologies for Smart Battery Cells could be developed and points out which further research contributions are needed. For this purpose, we address modeling and simulation of cyber-physical aspects on all abstraction levels and illustrate how verification approaches can be introduced to this new field of application.**

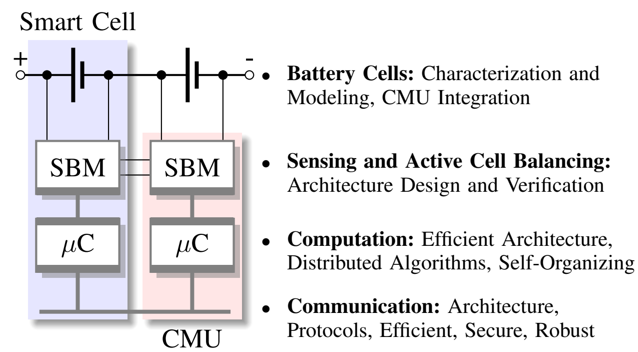

Fig. 1: Two series-connected Smart Battery Cells and the corresponding architecture layers and design challenges. Each Smart Battery Cell, highlighted in the light blue box, consists of a battery cell and a Cell Management Unit (CMU), highlighted in the light red box, which provides a Sensor and Balancing Module (SBM), a microcontroller and a communication interface. Several design and verification aspects need to be considered for the architecture.

I. Introduction

Battery packs are a core component of many emerging technologies such as Electric Vehicles (EVs) or smart grid energy storage solutions for renewable sources. Such battery packs consist of many series-connected cells to achieve a certain pack voltage. In order to provide a required pack capacity, for each layer in the series-connection, either several cells are parallel-connected or of sufficiently high individual capacity. Due to its favorable energy and power density together with its resilience to memory effects, Li-Ion is almost exclusively used as the cell chemistry. While Li-Ion battery cells are beneficial from an application perspective, they are also very sensitive to their operating conditions and hence require sophisticated BMSs [1]. The BMS is an embedded system architecture which monitors and controls the battery pack such that all cells are always operating within a specified parameter range regarding their voltage and temperature. The most critical parameter to manage is maintaining the State-of-Charge (SoC) of cells in the safe operating range such that upper and lower thresholds are not crossed in order not to damage the cells, which would result in shorter lifetime and possibly dangerous thermal runaway [2]. Furthermore, temperature and manufacturing variations cause an unequal SoC distribution to develop between cells during charging and discharging. Consequently, cell balancing has to be performed between the cells, as charging or discharging of the battery pack has to be stopped when the first cell reaches the upper or lower SoC threshold.

Conventional architectures for BMSs comprise a single controller and centrally manage all the cells they are connected to. Some modularity can be introduced by involving a hierarchical structure where the master controller coordinates slave controllers on module level. Due to the monolithic software architecture, both scalability as well as integration are challenging with such existing architectures. Furthermore, a single point of failure is introduced by relying on a central controller. Recently, a decentralization of the BMS architecture has been considered where the control moves closer to the individual battery cells [3], [4], however, still maintaining a hierarchical architecture.

By contrast, *Smart Battery Cells* [5] as shown in Fig. 1

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comprise a completely decentralized architecture without any central control. Here, each Smart Battery Cell is formed by the actual energy-storing cell together with a CMU which locally manages the functionality. The Cell Management Unit (CMU) consists of a Sensor and Balancing Module (SBM) forming the balancing layer, a microcontroller forming the computation layer, and a communication interface forming the communication layer. Each Smart Battery Cell manages its local properties itself, e.g., estimation of its SoC. Consequently, pack-level functionality is achieved by communication between the Smart Battery Cells and uses approaches from the domain of self-organizing systems [6]. All decisions are made in a cooperative fashion such that each Smart Battery Cell performing an operation upon request of another cell can ensure that it is not violating any of its own parameters. As all algorithms are implemented to support plug-and-play integration, scalability is provided by design and no single point of failure exists. Another benefit of the Smart Battery Cell architecture is its inherent suitability for modular active cell balancing, where the complex Pulse Width Modulation (PWM) control signals are difficult to distribute in a conventional centralized architecture but easy to generate locally in each Smart Battery Cell.

Despite the benefits achievable by developing Smart Battery Cells, their design requires several new methodologies on each layer as conventional approaches for modeling, design and verification cannot be applied. Consequently, the remainder of this paper will introduce the required design approaches to enable an efficient, safe and secure implementation of Smart Battery Cells.

II. Cell Layer

The cell layer of Smart Battery Cells comprises the actual energy storage in form of the electrochemical cell. Li-Ion cells exist in different shapes such as cylindric, prismatic or as pouch cells. From an integration perspective, the most challenging task is the combination of the cell together with the CMU. In order to physically form a Smart Battery Cell, cell and CMU should be coupled for their lifetime, as this inseparable entity ensures continuous availability of the cell's operating history. This, for instance, might be very beneficial in case of pack disassembly when individual Smart Battery Cells shall be reused in a second life scenario, e.g., for stationary storage of photovoltaic energy. Complete in-situ integration of the CMU in the cell manufacturing process could be considered as well as in-situ sensing of the temperature [7].

From the perspective of modeling of the behavior of the cell, there are several reasons to require a sophisticated characterization and corresponding abstraction. SoC estimation within the CMU has to incorporate knowledge about the open circuit voltage-SoC relation and needs to employ complex approaches such as Kalman filtering to determine an accurate value under load [2]. Considering behavior of the respective cell chemistry, such as the rate-capacity effect, is equally important for a good prediction of the actual state of the cell which can only be supported by observations from voltage, temperature and current sensing. A detailed characterization of major cell chemistries regarding their discharge behavior under different load profiles has been performed in [8]. There, measurement data is provided and could be used to build fast-to-execute and accurate battery cell models which are of high importance for embedded applications.

III. Sensing and Balancing Layer

Widely applied state of the art of battery pack charge equalization is passive cell balancing by dissipating energy of cells with a higher SoC until it matches the charge of the weakest cell [9]. This process only makes sense during charging in order to achieve a maximum pack SoC. By contrast, active cell balancing transfers charge between cells and, therefore, can increase the SoC of cells that otherwise reach their lower threshold. This ultimately increases the usable capacity of the battery pack and conserves energy that would be dissipated in case of passive balancing. Inductor-based modular active balancing architectures such as [10] have recently been extended to more complex applications and design automation approaches have been applied to optimize their implementation on hardware level [11]. Approaches to systematic verification of the actual circuit architecture design, such as [12], have been further developed towards graph-based modeling together with formal methods and are able to formally verify the correctness of the circuit together with its control scheme [13]. In a further step, synthesis of such active balancing architectures has been proposed, enabling correct-by-construction design of highly capable complex architectures [14].

In order analyze the actual charge transfer efficiency of an active balancing architecture, a detailed modeling of the circuit behavior is required. Using off-the-shelf tools such as Simulation Program with Integrated Circuit Emphasis (SPICE) [15] might be feasible for individual modules for a pair of cells exchanging charge. Due to the PWM signals for actuating the switches in the circuits operating in the kHz frequency range and balancing operations running over several hours, such conventional approaches are infeasible on pack level. As a remedy, models characterizing the individual phases of a charge transfer based on optimized circuit equations have been developed, enabling highly accurate analysis of charge transfers with a speedup of many orders of magnitude compared to SPICE simulation [16].

Another line of research investigates the electrical topology of battery packs and might enable reconfigurable architectures where certain aspects of battery management, such as cell balancing, could be achieved in a completely different fashion by bypassing individual cells. A recent contribution investigates such reconfigurable battery system management architectures specifically in the context of distributed Smart Battery Cells [17]. An open question, however, remains the efficiency of switches in the main power line of battery packs and requires further detailed analysis using the methods described above.

IV. Computation Layer

For the computational aspects of the Smart Battery Cell architecture, the most important design challenge is posed by the actual processing platform together with the distributed algorithms. Energy-efficiency is the dominating performance criterion, as the sum of the energy used for management of all Smart Battery Cells within a pack should not exceed the consumption of a centralized architecture. Consequently, an implementation as a System-on-Chip must consider all aspects of low power circuit design. Beyond that, the algorithms running on the controller in the CMU contribute significantly to the efficiency of the architecture. Therefore, considerations to minimize computational overhead and message exchange between the Smart Battery Cells are critical. Nevertheless, due to the design paradigm of self-organization and plug-and-play integration, new approaches to BMS algorithm design are required, as existing centralized ones cannot be applied in the distributed context without master controller. For example, a distributed approach to identify the topology of the Smart Battery Cells during pack integration makes use of properties of the balancing architecture, hence reusing existing components for achieving additional functionality [6].

In the domain of balancing algorithms, approaches tailored to the specific distributed architecture have been developed. Here, the algorithm design is no longer focusing on a central coordinating entity. By contrast, request-driven balancing algorithms help the battery pack to converge to an equalized state of charge completely without any global management. Instead, each cell works toward the goal of achieving a SoC as close as possible to the average SoC of the pack. Cells with an below-average SoC request charge via communication messages from their neighboring cells and these neighbors acknowledge a charge transfer via messages if they have above-average charge levels. Several such communication-based and request-driven balancing strategies for Smart Battery Cells have been investigated in a system-level cyber-physical co-simulation framework covering all implementation layers of the Smart Battery Cells [16].

By considering different processor architectures in the co-simulation via virtual processor prototypes, an even more detailed analysis of potential computational target platforms would be possible and could represent worthwhile future work.

V. Communication Layer

The design of the communication layer for Smart Battery Cells is a central aspect of the system architecture. Due to the distributed approach and a consequent application of collaboration via message exchange, communication extends the local management of the individual Smart Battery Cells to a system-level functionality. From a hardware perspective, different physical communication layers could be implemented. The most established would be a Controller Area Network (CAN) bus, providing a robust broadcast-focused channel which has been tested in Smart Battery Cell development platforms.

Other communication topologies could be a daisy chain of Universal Asynchronous Receiver/Transmitter (UART) connections, providing the capability of concurrent local transmissions at the cost of slow broadcasts. In order to optimize the communication overhead for a complete application scenario, further research is required to investigate the amount of local communication between neighboring cells and broadcasts across the pack when all BMS functions operate fully distributed in the Smart Battery Cell architecture. In this context, also wireless communication could be considered. However, it is traditionally not used in such safety-critical scenarios such as automotive, especially when real-time performance is critical. Nevertheless, as the Smart Battery Cell architecture is in a stable state when communication is interrupted due to the local CMU maintaining the cell parameters safe, such advanced implementations could be considered for the communication between the cells, possibly in a hybrid fashion such that a wired daisy chain is augmented by a wireless channel for faster broadcasting. This could ensure good average case performance with a guaranteed worst case behavior provided by the wired connection.

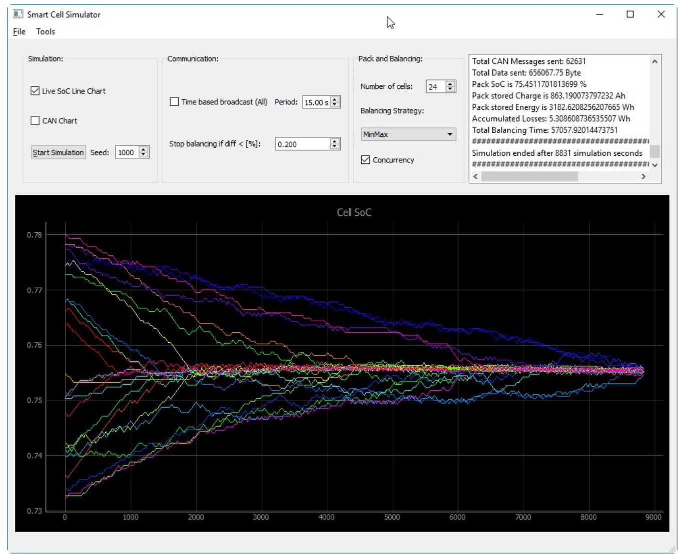

Fig. 2: Cyber-Physical Co-Simulation Framework for Smart Battery Cells, running a simulation of the MinMax active balancing strategy for 24 series-connected cells. Please refer to [16] for details.

As security challenges are in the spotlight both in the automotive as well as in the Internet of Things (IoT) domain [18], [19], cybersecurity of the Smart Battery Cell architecture has to be considered as a first-class citizen in the design process. Manipulation of the battery can have a serious impact of safety, and the connectedness of all modern applications mandates a security concept for authentication of communication partners and authorization of individual secure streams.

Methods from the domain of probabilistic model checking can be applied to analyze the security of such architectures and to find appropriate network architectures [20]. In order to investigate the impact of secured communication on the functionality, the simulation environment for Smart Battery Cells from [16] has been coupled with a framework to analyze the real-time performance of lightweight security protocols in [21]. This co-simulation could enable a design space exploration of different security implementations both on hardware and software levels and could be interesting future work.

VI. Cyber-Physical Aspects

While the individual layers of the Smart Battery Cell architecture can be designed independently from each other to a certain degree using the design and verification methodologies presented in this paper, the complex interaction of the layers within a Smart Battery Cell and between cells regarding overall system performance and functionality can only be assessed by considering all layers and entities in a cyber-physical fashion. For this purpose, a detailed design and modeling of each layer as presented in the previous sections has to be performed, using design decisions made and verified with the corresponding methodologies. Once a complete system design has been performed, the interaction of the system components, e.g., of communication latency together with the performance of request-driven active balancing algorithms, has to be investigated. Analyzing such properties on a hardware development platform is tedious and specifically does not allow for iterative improvement such as optimization or design space exploration.

High-level modeling of specific features, however, will not lead to a thorough analysis of the architecture, as critical behavior might have been abstracted away. Consequently, a simulation framework is required which models all layers of the architecture on an equally detailed level of abstraction, still enabling fast system-level analysis. Such a Cyber-Physical Co-Simulation Framework for Smart Battery Cells has been presented in [16] and enables fast but highly accurate analysis on battery pack level. A simulation of a balancing run for a pack consisting of 24 series-connected Smart Battery Cells and 5% of SoC variation, as illustrated in Fig. 2, only takes 42 seconds on an Intel i7 processor and could hence be used in design space exploration approaches.

VII. Concluding Remarks

In this paper, an overview of design and verification methodologies for Smart Battery Cells is given. Smart Battery Cells are a promising architecture for developing completely decentralized BMSs. While this architecture might solve integration challenges and provide increased safety, efficiency and robustness, it requires a set of new design paradigms to be efficiently implemented. Consequently, the design challenges for all system architecture layers, comprising battery cells, sensing and balancing, computation and communication are discussed and related to methodologies for systematic modeling, design and verification. As the Smart Battery Cell architecture comprises cyber-physical aspects, not only design considerations for the individual components are addressed, but also the importance of high-accuracy system-level analysis tools is emphasized. Open challenges within the design and verification methodologies are presented and point to future work.

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