Architecture of a Digital Twin for Enabling Digital Services for Battery Systems

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***Abstract*—Electrification, digitalization and the trend of service-oriented business concepts lead to disruptive changes in the automotive industry. New drive train concepts with Li-Ion battery system as central component arise. Nowadays, efforts are made to monitor the battery system in order to ensure maximum safety and reliability. But still, many parts of the life cycle of a battery system are not under accurate supervision. This paper proposes a digital twin architecture for automotive battery systems, on which digital services for various stakeholders along the manufacturing and product life cycle of a battery system can be established. Those services make use of the digital twin as a backbone, close open gaps and enable novel approaches in manufacturing and product use. The results feature an UML meta model as a first step toward implementing of a digital twin for battery systems. The meta model reflects the proposed architecture and allows domain-specific models to be built. The models in turn can act as blueprint for the implementation of the digital twin paradigm over the whole life cycle.**

***Index Terms*—Battery System, Digital Twin, Architecture, UML Model**

I. Introduction

Disruptive changes challenge the automotive industry [1]. The car as a physical product is complemented with manifold digital services. Services are built upon different data sources e. g. car-internal data or mobility data. The shift toward this service-oriented business structure affects not only car manufacturers, but also supplier industries [2].

Nowadays, several digital services are used in the car. Modern navigation, for example, relies on intelligent route planning taking floating car data from the entire fleet into consideration. Other services feature innovative maintenance concepts that predict malfunction of components in the car. To deliver these services, a complex software system consisting of data storage, models, simulations and interface infrastructure on several layers is needed. Following the trends in electric drive trains and connected mobility concepts, digital services are emerging into more and more fields of application. One example is the high-voltage battery system (HVBS) in electric cars. This component needs tight supervision and control to both ensure the general and functional safety and to also keep the vehicle user updated about the current and future states of the battery system. Vehicle users are not the only ones who might be interested in a service based on HVBS data. Along with the product development process and throughout the life cycle of a car, different stakeholders exist, for example:

- Vehicle components suppliers
- Logistics solution suppliers
- Component integrators
- Original Equipment Manufacturer (OEM)
- Individual vehicle users
- Fleet operators (e. g. car-sharing, corporate pooling, rental car companies)
- Second-Life users (e. g. Energy-storage operators)

The aim of this work is the proposal of a high-level architecture for a digital representation of a HVBS to fulfill services for different stakeholders. Therefore, all stages from production through the utilization phase up to a second life usage and recycling should be covered. By following this holistic approach, developing of services along with the systems's life can benefit from a continuous database and universal interfaces to this database. By using modern computing paradigms, economies of scale can be exploited by reusing software components.

II. Related Work

This section gives an overview of the general concept of digital twins and their usage today in the automotive sector nowadays. More general concepts are elucidated in the technical background section.

A. Cyber-Physical Systems

Cyber-physical systems (CPS) are first mentioned by Gill [3]. Gill defines CPS as a physical system that is inseparably entangled with digital components on all levels. The physical system is monitored or controlled by the digital parts. The digital components can either be integrated into the physical

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component or remotely connected via wireless networks [4]. Gill states that CPS become important in most modern industrial sectors. In the contribution of Kao et al. [4], five levels are defined for a CPS in the production sector that create a closed-loop control system by closing the gap between accumulated data and system control.
Lukasiewycz et al. [5] depict the car as a system where manifold CPS are used. Among others, the battery system, the electric engines and the distributed energy management system constitute a CPS. Concepts like smart-grid integration as a connection of hardware and energy and data streams, however, can also be identified as CPS.

B. Digital Twin

The term "digital twin" is widely used and tightly coupled with CPS. Negri et al. [6] give an overview over the evolution of the term: First mentioned in the field of aerospace engineering, the term "digital twin" has evolved into a more general understanding of the concept, one which is notably driven by the trends in digitalization, Internet of Things (IoT) and Industry 4.0. Kritzinger et al. [7] focus on the usage of digital twins in production processes and state that, depending on the field of application, the term is used and understood in a variety of ways. They propose a classification scheme to distinguish digital twin concepts by their degree of integration into the real system.
Following the definition of Kraft [8], a digital twin is a multi-discipline simulation of a real-world product, which uses data and sensor information as input to models that mirror and predict the states and behavior over the lifespan of the physical system. In all contributions discussed in [6] and [7], the digital twin concepts incorporate a collection of data and a set of multi-discipline methods such as models, algorithms or simulations that transform the collected real-world data into knowledge. A one-to-one relationship between the physical object and the virtual representation is given.

The concept of digital twins is gaining importance [9], also in the context of automotive industry and vehicles. Baumann et al. [10] propose a digital twin system that monitors and estimates the state of health (SOH) of a vehicle battery system. They use a cloud-connected battery management system and run diverse models in the cloud environment to estimate the current system state as well as a residual value for the battery system. Weyer et al. [11] describe a system where manufacturing plants are simulated and planned with the use of digital twins. Hallerbach et al. [12] use the digital twin concept to simulate critical traffic situations in the field of autonomous driving. In this case, the twin is a copy of the real vehicle with all of its sensor positions and data streams.
Alam and Saddik [13] propose an analytic description of the key features of a cloud-connected CPS. They describe the digital twin as interchangeable models and methods at the cyber-level, which directly feed back to the real system. As exemplary implementation of their architecture, they show a telematic-based driving assistance system.

Kritzinger et al. [7] conclude that a generally accepted definition of a digital twin is still lacking. They also emphasize the need for domain-specific reference models that define the requirements and actually apply the digital twin concept. In the electric drive train applications, only narrow fields are covered by the digital twin paradigm so far and mostly address vehicle- and second-life decisions of used HVBS, as shown in [10]. No links to manufacturing processes and testing procedures during the development of a HVBS are made.
Klör et al. [14] propose a UML-based meta-modeling language for HVBS that uses the terms "master data" and "transaction data" [15] to categorize different kinds of data appearances. Schroeder et al. [16] describe a methodology for modeling the interchange of information in a general digital twin system using AutomationML.
With the focus on second life of HVBS or specific aspects such as information exchange, the proposed meta models do not take logistics, manufacturing and testing processes into account.

III. Technical Background

A. Battery Systems

Due to electrification, the most costly and complex component in a car is now the energy storage, in most cases a Li-Ion battery. Li-Ion batteries, as perishable goods, show aging effects. Hence, they cannot be used for an unlimited period of time in an automobile [17]. A widely accepted limit for the automotive battery usage is given at SOH of 80 % [18].

a) Design Layout: Nowadays, battery systems consist of a modular structure [19]. The battery system comprises several battery modules, which in turn consist of the actual battery cells. Since temperature is crucial for battery safety and performance, thermal systems are used to keep the cells at a reasonable working temperature [20]. The main task of a battery management system (BMS) is to monitor and control the battery system components. Over- and undervoltages as well as high temperatures during car usage and charging processes need to be avoided to keep the battery within safe operating conditions. Furthermore, the BMS controls cell-balancing and estimates the inner states of the battery, e. g. State of Charge (SOC) and SOH.

b) Production: Producing battery systems is also divided up according to the system's modular structure. As a first step, the battery cells are manufactured. In the next layer, several cells with the same performance characteristics are brought together and form a homogeneous module. In the system layer, multiple battery modules are fit into the system case and connected electrically. After integrating the BMS and the thermo system, the HVBS is sealed and closed with a lid. After assembly, the entire system undergoes an end-of-line test, where visual checks and technical test routines are performed.

c) Second-life options: If a battery system can no longer meet the automotive requirements, it is in most cases not completely without function. In this case, three options exist for a used system [21]. During repurposing, the system is operated in a different context outside the car with lower requirements e. g. as a stationary energy storage. Remanufacturing aims to replace defective components to compile a refurbished replacement system. If there is no chance for re-use, the system is recycled.

B. Modern Computing Paradigms

A key aspect of digital twins is their ability to generate and store information from physical objects in a consistent format so that it can be used by entities with standardized interfaces. In this context, the closely related paradigm of the Internet of Things (IoT) acts as an enabler for interconnecting the physical with the virtual world [22]. Cloud computing plays a crucial role in data storage and computation within the IoT, be it as a cloud platform provider with dedicated IoT services such as Amazon Web Services or as a highly integrated IoT platform such as Xively. Tao et al. [23] highlight the importance of service-oriented architectures (SoA) in context of the digital twin by developing a so-called "Service-oriented Smart Manufacturing" framework. In this respect, microservice architectures closely related to SoA because they decompose an application or complex service into a collection of loosely coupled microservices [24]. Each microservice performs a single task and a number of microservices can be orchestrated to fulfill a service purpose.

C. Digital Services

Williams et al. [25] define the term "digital services" by pointing out how they differ from normal services. They follow the definition that characterizes a digital service as "an activity or benefit that one party can give to another, that is, provided through a digital transaction." With respect to a digital twin, it becomes obvious that digital services may form a consistent part of a digital service offering, such as predictive maintenance. This enables companies to gain deeper insights into their production machines to better organize own maintenance plans or in products offered for customer maintenance plans.

IV. Reference Architecture

The aim of this paper is to propose a reference architecture for a digital twin in the domain of HVBS under consideration of manufacturing and testing processes. This chapter gives an overview over the technical components of the proposed architecture. It is divided up into the hardware and connectivity level, twin level and service level as illustrated in fig. 1. In general, data accumulating in the hardware layer is transformed into knowledge by the twin layer and can be accessed through the service layer.

A. Hardware and Connectivity

The hardware itself and the connectivity infrastructure form the basis of the architecture and are defined by the domain of interest. To overcome shortcomings in previous architectures, the whole life of a hardware system from manufacturing to end of life are included. Depending on the phase of life,

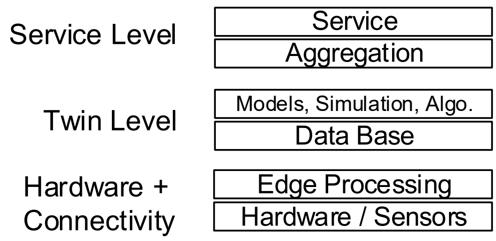

Fig. 1. The concept is divided up into three main layers: hardware level, twin level and service level.

different routes to mirror the real-life data into the twin-level are needed. Beginning with production processes, manufacturing machinery can serve as a data input. In modern digitalized factories, relevant data can be received e. g. through manufacturing execution system (MES) or enterprise resource planning systems (ERP). Input can also be obtained by data-virtualization solutions which embrace the whole product development and production process. Of course, not all necessary data can be retrieved from already- installed sensors and machinery. To monitor ambient conditions, in production and in logistic processes, additional sensors and data loggers are needed. Data loggers can either send live-data over wireless IoT networks or collect the measured data and be read out manually or automatically at specific locations. Having no real-time data, it is crucial to ensure an exact mapping of the datasets to the physical subject. Once the battery system is assembled, one can use the integrated sensor technology to monitor the system. Via field bus systems like Controller Area Network (CAN), it is possible to log the data and transfer it to the twin back-end. Edge processing has to be taken into consideration to reduce the amount of collected data before it is transfered to the twin level, depending on the use case.

B. Twin Level

The twin level is separated from the physical object and virtually located in a cloud-computing environment. Using a cloud infrastructure, the parts of the twin level are encapsulated as microservices, which fulfill one defined task and communicate via various interfaces. The twin level itself comprises four general types of data. Descriptive data, which specifies and defines the physical object in the virtual world, is summarized under the term **master data**. Master data can be any technical description, e. g. CAD-models, topology of a system or the defined requirements as the outcome of specific manufacturing processes or test definitions. Using an object-oriented approach, master data defines classes of different components, of which the actual instances are derived.

To capture the continuous experience of a physical component, we use the concept of **transaction data**. The concepts master and transaction data are described in [15]. Transaction data can incorporate various influences affecting a specific component or part of the system. Depending on the phase of life, different

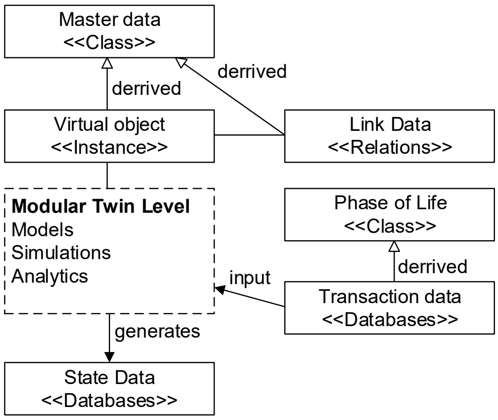

Fig. 2. Overview of the data types used in the architecture for the digital twin.

predefined influence schemes can be derived from a meta-class. Transaction data can be fed into models or simulations, which results in knowledge about the state of the real system. The results are structured under the topic **state data**. To enable a virtual assembly process during manufacturing, **link data** is used to monitor the parent-child relationships between components. Meta link data is a result of the engineering phase, since it represents the topology of the battery system. However, it is necessary to update and adapt the instantiated link data also during manufacturing and the remaining life cycle, since setups can change during the operation e. g. components can be replaced with others.
The four types of data outline a framework shown in fig. 2, into which models, algorithms and simulations are embedded. Clear interfaces to each data type give the possibility of creating a modular twin level and appropriately adapting to the requirements and use cases.

C. Service Level

In the service layer, knowledge generated in the twin level is used to fulfill the needs of a certain user of the proposed system. Services comprise of an aggregation layer, which directly interfaces with the components and modules of the twin level. During aggregation, the gathered information is conditioned and formatted. An output layer serves as an interface to the service. It can either be human readable as is a web-based graphical interface or a technical kind, like an Application Programming Interface (API). One general purpose of the service level is the generic access to the digital twin data. Hereby a harmonized interface to any conceivable service application is enabled.

V. Results

A. Meta Model

In the context of this work, a UML meta model was set up with the aim to use the methodology described above and model the pursued architecture of a digital twin. In future, implementing a digital twin system should be defined by a model.
The meta model incorporates the aforementioned four types of data and different phases of the life cycle of a HVBS. The UML meta model is organized in subsets. Its base is defined by a subset of an HVBS, which is organized as the meta model proposed of [14]. To cover all phases of the life cycle, the model is extended in this contribution.

a) Subset HVBS: The subset HVBS provides a hierarchy and aggregation of classes, which present the meta link data of a battery system. The classes itself are populated with attributes reflecting the master data of the individual components, e. g. material, nominal voltage or any other specification. As an example, the “casing” class generalizes the “base plate” and “cover” classes. Nested structures such as the battery modules and the subordinated cells are modeled by aggregation relations.
Transaction data and state data are saved in databases whose database schemes are defined by the model. Depending on the structure of data, either relational or non-relational databases can be used.
The subset HVBS exists in all life phases since it is the subject of the digital twin architecture. Our understanding of the life cycle starts when the respective components of the system are brought together to form the HVBS. Along with the life cycle, not only the HVBS but also other hardware systems are of interest. They are shown in fig. 3.
Starting point of the architecture design are the logistic processes, where, e. g. battery modules are shipped to the manufacturing location. During the logistics and beginning of the manufacturing processes of the system, the single components (e. g. battery modules, cells ...) are subject of the twin architecture, whereas after assembly the whole battery system is the physical subject. It is necessary to implement a virtual assembly, to mirror the physical processes of manufacturing. The assembly process is recorded as link data.
After the manufacturing processes, the context of use is part of the consideration, since the operating parameters also affect the HVBS. During the vehicle life cycle, transaction data describes the operating conditions and tracks e. g. voltage, currents and temperatures of drive cycles and charging events. An example for state data can be the SOH of a battery system. Complex electrical models, a priori knowledge about the system and actual operating conditions serve as input to model and predict the SOH and thereby make this hidden state visible.
During a potential second life of an HVBS the focus is similar to the vehicle life cycle. A difference is given by the change of the ambient system. The HVBS is not working inside a car but e. g. in a local energy storage, which leads to different operating parameters. Always taken into account is the influence of the environment in terms of e. g. temperature, humidity or vibrations.

b) Logistics Subset: The logistics subset provides three submodules: “storage”, “transport” and “logistic entity”. The

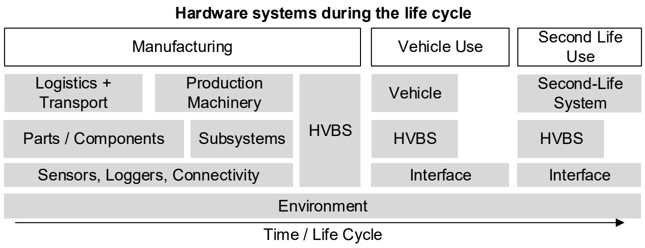

Fig. 3. Overview of the hardware components which play a role during the life cycle of an HVBS.

logistic entity is the transported good, analogous to the concept of unit loads [26]. The transport and storage submodules allow the two major states of the logistic process to be modeled and provide a uniform description and respective databases. Transaction data during the transport of battery modules can be the ambient temperature and humidity, shocks and vibrations, since these influencing factors can affect the durability of the battery module [27].

c) Production Subset: In the production subset, all states of the production of an HVBS are included. The focus is set to the system assembly, since all components are fit together in this state, and formation of a uniform model is significant here. The production process can be modeled as a sequence of processing stations, each equipped with handling machinery and in-line transportation. All stations are linked to a specific environment. Stations commonly described in the literature (e. g. arrival test, integration, end-of-line test) in the assembly process can then be derived from the meta-station. A station itself and the arrangement of all stations are examples of master data. Since battery components are sensitive to vibrations and shocks, respective influences have to be measured and saved as transaction data. An example of state data can be an outlier detection to monitor the occurrence of abnormal situations where manual intervention may be needed.

d) Monitoring: The monitoring subset delivers a uniform way of logging data in all other subsets of the model and of representing a dedicated data logger or an integrated sensor unit. Using standardized classes for logging temperature, moisture, luminosity or movement, a uniform interface to the logged data can be built. Specific data can be interfaced through a generic type.

e) Testing: Before producing an HVBS in series, comprehensive testings under different conditions and scopes take place, e. g. long-term runs under different environmental conditions to qualify and validate the aging behavior of the HVBS. The introduced meta model permit any tests to be modeled in a uniform way and by that integrate them to the digital twin architecture. Depending on the scope of the tests, various analyses can be developed on the recorded transaction data to generate the test-specific state data.

B. *Evaluation of the Meta Model*

The evaluation of the meta model was achieved in cooperation with a battery system manufacturer. By means of detailed assembly instructions, the manufacturing process of the system could be compared against the model's structure. The embedded meta model of the HVBS could be evaluated by comparing the integral components against a real system under ongoing production and by expert interviews regarding a experimental battery system. The logistics processes could not yet be validated.

VI. Conclusion

The paradigm of digital twins and CPS is evolving in the automotive industry. Whereas the theoretical concept is tackled by many publications, the domain-specific applications are still undergoing research. The methodology of this work comprises an architecture for a digital twin in the domain of HVBS and consecutive applications such as digital services for various stakeholders. This work shows first results of data types for a digital twin that may lay the foundation for standardization. In addition, the results show an application where the proposed architecture is the blueprint for a domain-specific meta model for HVBS and related processes over the entire life cycle. Based on this meta model, an actual system can be derived. To reach a fully functional digital twin, this meta model needs to be implemented in a cloud computing environment where real use cases bring the digital twin to life. Further research regarding stakeholders, use cases and implementation is needed to benefit from the digital twin paradigm.

Acknowledgment

L.M. initiated the idea of the paper and contributed to the methods and results. M.L. made an essential contribution to the conception of the research project. He revised the paper critically for important intellectual content. Mr.L. gave final approval of the version to be published and agrees to all aspects of the work. As a guarantor, he accepts responsibility for the overall integrity of the paper. We thank the DRÄXLMAIER Group for the cooperation and necessary information provided.

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