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XiL-BW-e – Laboratory Network Baden-Württemberg for Electric Mobility

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Summary

Research on drive systems has to be carried out in the overall system-related context. Based on the IPEK-X-in-the-Loop approach, the concept and implementation of a regional connected laboratory network in the state of Baden-Württemberg (BW) are presented. It enables the networking of expertise and infrastructure for system analysis up to the creation of spatially distributed joint X-in-the-Loop (XiL) testing environments. Due to flexible combination possibilities of different types of testing infrastructure the collaboration of KIT, Ulm University, the University of Stuttgart as well as the universities of applied science in Aalen and Esslingen in the XiL-BW-e network opens various new research opportunities.

Keywords: testing processes, powertrain, HEV (hybrid electric vehicle), IoT (Internet of Things),

1 Introduction

Today's trend of electrification leads to a restructuring of the vehicle topology of electric mobility platforms [1]. So far, non-automotive technologies obtain technological key positions in the vehicle development fields (e.g. battery cell or E-motor technology). These new technologies and the corresponding expertise are often only locally available and far less integrated in the automotive development process as conventional technology holders. Therefore, a closer and more interdisciplinary cooperation between the OEMs and the suppliers or research institutes is necessary to succeed on the market. In these cooperative relations, it is essential to incorporate methods for planning and execution of cooperative validation activities.

The research on drive systems must always be carried out in the overall system-related context. A single component-oriented view is not adequate and allows only incremental improvements of the drive system. Only by optimizing the interaction, a significant potential for improvements can be created. In validation, which is the most important and also time and cost consuming activity of the development process, the IPEK-X-in-the-Loop approach provides such a holistic foundation for analyzing these systemic interdependencies to gain knowledge and so to utilize these optimization potentials [2]. Therefore, research facilities at Karlsruhe Institute of Technology (KIT), Ulm University, the University of Stuttgart as well as the

Universities of Applied Science in Aalen and Esslingen with their very own profile of expertise in electric mobility have to be linked in the most efficient and effective way and “living” interfaces have to be established.

2 State of the Art

2.1 Validation in Product Design

Validation is the central activity in product engineering and enables a market success of the product [3]. During validation, differences between the created objects (e.g. models, prototypes of the product) and their objectives are revealed. Thus, only in validation knowledge evolves and sub-objectives or boundary conditions for further procedures of the development process are created. The validation process in the development of conventional drivetrains is already fine-tuned, matured and well-coordinated with the system of suppliers supporting the OEMs. But alongside the ongoing search for alternative drive systems in vehicles major structural changes in the automotive development are expected [1].

To meet the challenges of a more complex validation, the IPEK-X-in-the-Loop (IPEK-XiL) approach for development and testing of vehicles resp. vehicle components was developed. It seamlessly integrates simulation and testing in the product engineering process on different integration layers. The model-based approach of integrating single subsystems into the overall system by using complementary models originates from the development of control units or embedded systems. These approaches are Model-in-the-Loop, Software-in-the Loop, and Hardware-in-the-Loop [4]. Hereby, these approaches only differ in the integration level of the System in Development complemented with virtual models. The IPEK-XiL-Approach includes these, but even more integrates the respective advantages and expands these consistently to the requirements of the mechanics or mechatronics as well as the developer from different disciplines. It allows all systems to be represented by a virtual, physical, or mixed model.

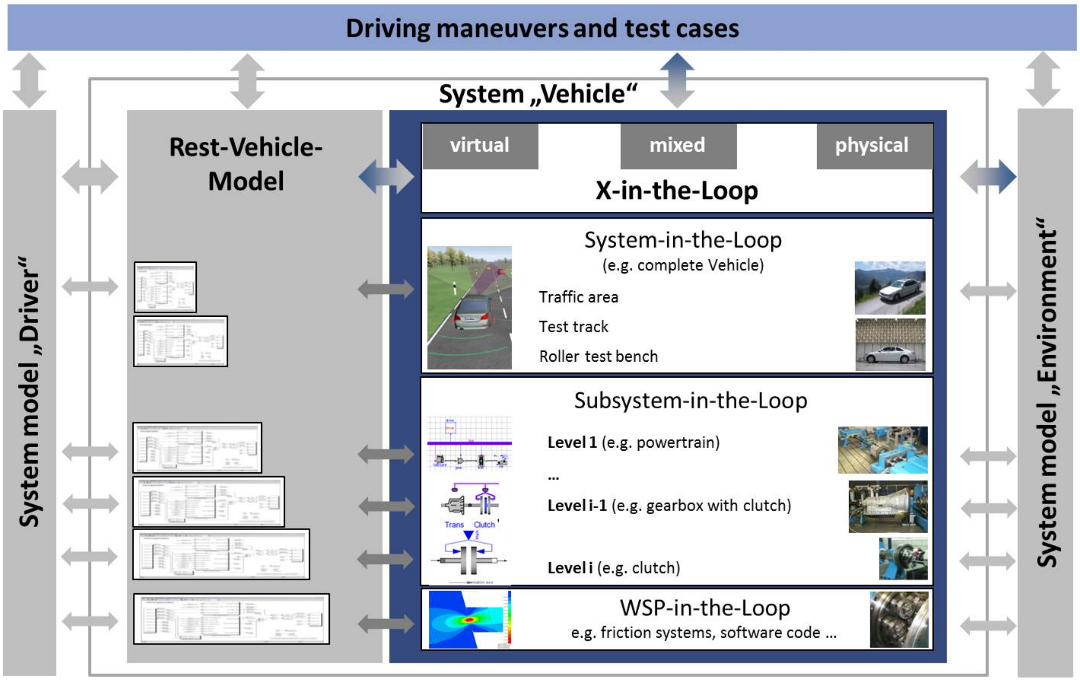

Figure 1: IPEK X-in-the-Loop Framework [2]

The “X“ in the XiL framework symbolizes the System in Development (SiD) representing a (sub-) system of the super system “Vehicle”. It is defined according to the developer’s view and can be validated on different system detail layers (XiL layers). This depends on its specific characteristics and can be at a low system level with the “working surface pair” layer followed by different levels of the subsystem layers up to the analysis of the entire high-level system. The systems that interact with the SiD (cp. Figure *1*: “Driver”, “Rest-vehicle” and “Environment”) are referred to as Connected Systems (CS). The IPEK-XiL framework allows for the system “Driver”, the system “Environment”, the “Rest-Vehicle-Model” or their subsystems to be viewed as an explicit SiD itself [2].

For the practical realization of a validation activity, a top-down modelling approach is of advantage [2,5]. This approach divides the systems “Driver”, “Environment” and “Vehicle” (context of vehicle development) into the relevant sub-systems. These sub-systems can be virtual, physical or mixed and are categorized into at least one SiD and further CS. Hereby, the single model fidelity can vary depending on the validation aim (cp. [6]). Figure 2 shows an exemplary representation of a powertrain validation setup. Every model is represented as a small text box with an icon. In addition, there is a depiction of sensor-actuator-systems that are meant to connect virtual and physical models. The validation setup is able to provide a vehicle’s system behavior to parts of a vehicle powertrain, which is relevant for the investigation and validation aim. The SiD is made to behave like being used within a real vehicle. The following use-case of the Powertrain-in-the-Loop test bench represents a validation setup that is used to examine the course stability of a vehicle [7]. To identify the specific powertrain behavior, a gearbox with side shafts is considered as the SiD. Further parts of the drivetrain (e.g. flywheel and clutch) are physically represented on the test bench. Other components of the vehicle (e.g. combustion engine or tires) and the super systems environment and driver are provided via virtual models. In order to link partial systems of the virtual and physical domain, so-called Koppelsystems are needed [8]. Their main function is to interconnect models in validation setups, which are not able to establish a direct linkage due to incompatibility. They are necessary for the realization of the overall system behavior, but are not meant to add relevant system behavior. There are three types of Koppelsystems: physical/physical Koppelsystems (KS_PP) between two physical models (e.g. the connection between the vehicle chassis and the test bench environment), virtual/virtual Koppelsystems (KS_VV) between two virtual models (e.g. the connection between distant virtual models via network) and virtual/physical Koppelsystems (KS_VP) between one virtual and one physical model (e.g. the robot shifter that transforms a virtual gear change demand into physical action).

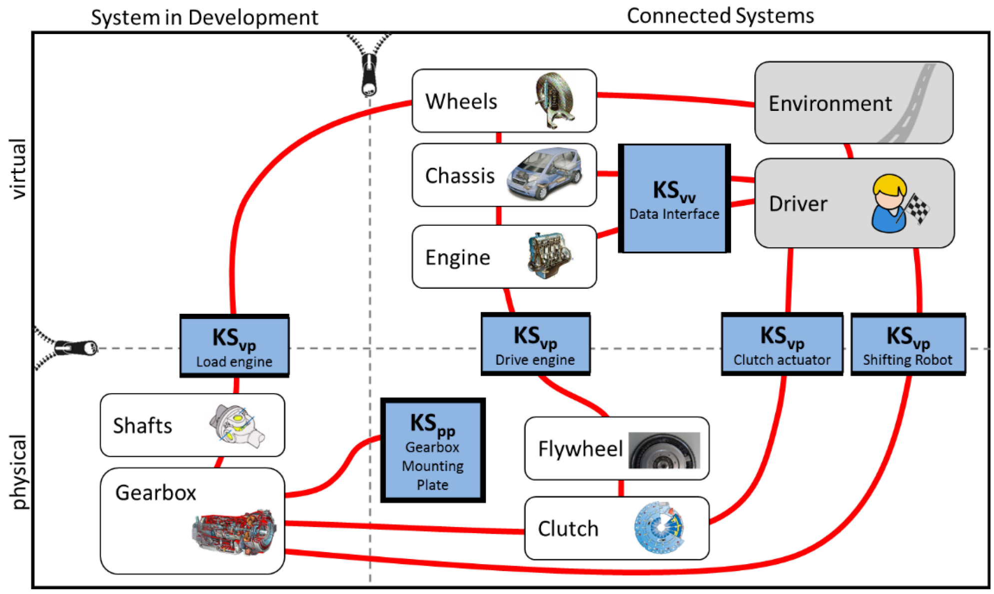

Figure 2: Top-Down Modelling of the Powertrain in the Loop Validation Setup [8]

However, for depicting collaborative joint testing between different locations and parties, the separation between SiD and CS is not suitable. Instead of distinguishing between SiD and CS, this diagram focuses on the spatial distribution of the (sub-)systems. This is because the SiD can be defined differently by each involved party according to their specific view, but the spatial distribution is given. Thus, the systems are assigned to their domain (virtual or physical) and their location. On the borders between every cell, there has to be at least one specific Koppelsystem, if (sub-) systems of different cells interact with each other. These interfaces play a very important role as they can influence the overall model behavior and play a major role to ensure the real-time capability of the overall system. The characteristics of the Koppelsystems (e.g. transfer speed and frequency) has to be matched carefully according to the phenomenon of interest and the objective of the investigation. Figure 3 shows an exemplary representation of a distributed validation setup for an electric powertrain. All systems are located to location A, except for the battery system model, which is at location B. The interaction between both sites is realized by the KS_VV connecting the battery system with the E-motor. [9]

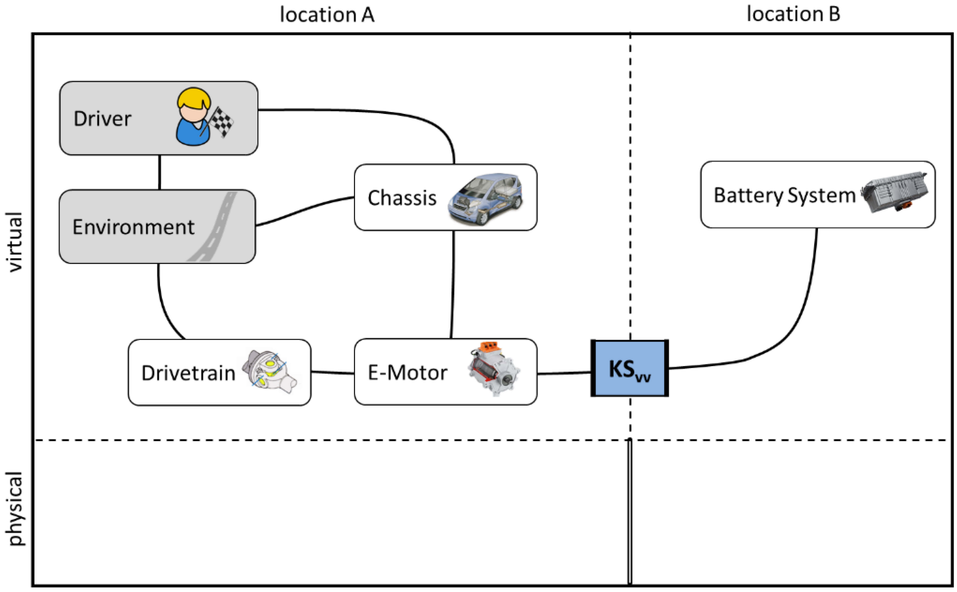

Figure 3: Modelling of a Distributed Validation Setup [9]

2.2 Basics of electronic data communication

The Open Systems Interconnection model (OSI model) describes the communication between two computers in a conceptual way without regarding the used underlying technology. The lowest layer is the physical layer. It defines the physical properties and devices. On this layer, it is only possible to transfer data between directly physically connected systems. The layer above is the data link layer. The layer establishes protocols to setup connections between two devices. The third layer is the network layer. On this layer, the routing is executed. As a result, data transmission between non-connected systems is possible. The next layer is the transport layer, which allows the transfer of any amount of data between not necessarily directly connected systems. The session layer provides mechanisms for managing a communication relationship, such as a synchronization management. The sixth layer is the presentation layer. This layer is used to provide encryption, data compression and independent data exchange. The last and top layer is the application layer. At this level, applications communicate with each other [10].

Within the OSI model, the Internet Protocol (IP) is an implementation of the network layer. The main purpose of the Internet Protocol is to address any computer in a network through IP addresses. The addresses are subdivided into different subnets using the subnet mask. This is the basis for routing and thus allows the communication between directly connected computers. The Internet Protocol belongs to the internet protocol suite and is a connectionless protocol. An Internet Protocol packet consists of two main components, the header and the payload. The header contains the source and destination addresses as well as other information that allows the packet to be routed. The payload part contains the application data [11].

The User Datagram Protocol (UDP) belongs to the internet protocol suite and is a connectionless protocol. In the OSI model, UDP belongs to the transport layer. UDP extends the host-to-host transmission of the Internet Protocol to a process-to-process communication. To ensure that the data sent also arrives at a specific application, UDP uses ports. These ports are standardized and assigned to specific applications [12]. In comparison to UDP, the Transmission Control Protocol (TCP) is a connection-oriented protocol. Like the other two mentioned protocols, it belongs to the internet protocol suite. An important feature of TCP is the detection and automatic correction of data loss. TCP, like UDP, is an implementation of the transport layer of the OSI model. Since TCP is often used together with IP, it is often referred to as TCP/IP protocol, which is not always correct [12].

3 Objectives and Corporate Expertise

The objective of this research work is to create a regionally connected laboratory network for electric mobility in the state of Baden-Württemberg based on the IPEK-XiL approach (XiL-BW-e). With this holistic approach (see Figure *4*), the collaboration in XiL-BW-e is not only set up technically, but also in an organizational way. There are two main parts of the network: the **system testing network (STN)**, which focuses on the overall interactions of the single components, and the **battery analysis network (BAN)**, which focuses on the battery cell as a key component for market penetration of electric mobility. Currently, there are over 30 researchers involved in the overall project.

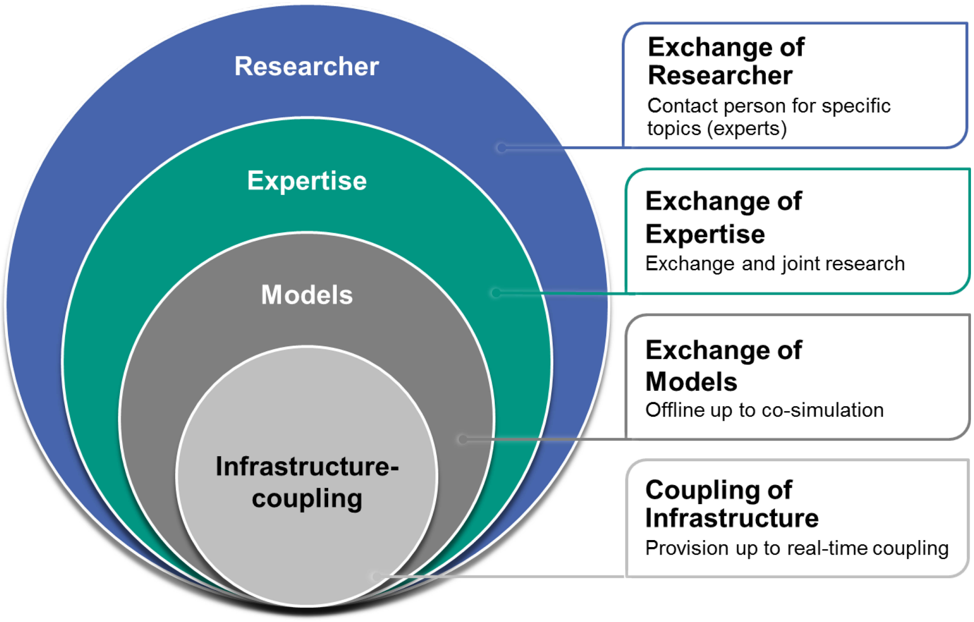

Figure 4: Networking approach on different layers

The **system testing network** enables the networking of expertise for analysis of systems as well as subsystems and components up to the synthesis of spatially distributed joint X-in-the-Loop testing environments. Thereby, a significant benefit is created for the research scene in Baden-Württemberg. On the one hand, a deeper and broader interdisciplinary view is enabled by combining the expertise of the different partners in existing projects; on the other hand, the future research of the single partners can be better attuned, thus creating more synergy potentials in the overlapping research fields. A private data network of high quality regarding speed and safety is vital to interconnect testing infrastructure of the partners and therefore enabling joint XiL test procedures. Up to now, seven partners with their respective expertise are working together within the system testing network (see Table *1*). With their expertise in operation strategies and their focus on batteries, the Institute of Measurement, Control, and Microtechnology (MRM) at Ulm University is an important link between the system testing and the battery analysis network.

The **battery analysis network** has its thematic priority in the detailed investigation of electrical, chemical, microstructural and mechanical interactions in battery cells and their influence on the cell performance (e.g. quality, lifetime, safety). Hereby, the coordination and extension of the battery analysis infrastructure allows for a significantly more complete understanding of the battery cell design, active materials, microstructure and performance. Batteries are characterized during operation by electrochemical methods as well as before and after cycling by non-destructive and destructive tomographic, microscopic, spectroscopic, and diffractometric methods. The combination of analytical methods within the network covers all relevant length scales reaching from the cell scale to the atomic level. Thus, production processes and structural changes during ageing of batteries can be understood better. Today's partners in the battery analysis are the IE at Ulm University, focusing on electrochemistry at phase transitions, and the Materials Research Institute (IMFAA) at the Aalen University of Applied Sciences, working on microstructural characterization for quality assessment and ageing behavior of battery cells, as illustrated in Figure *5* [13,14,15].

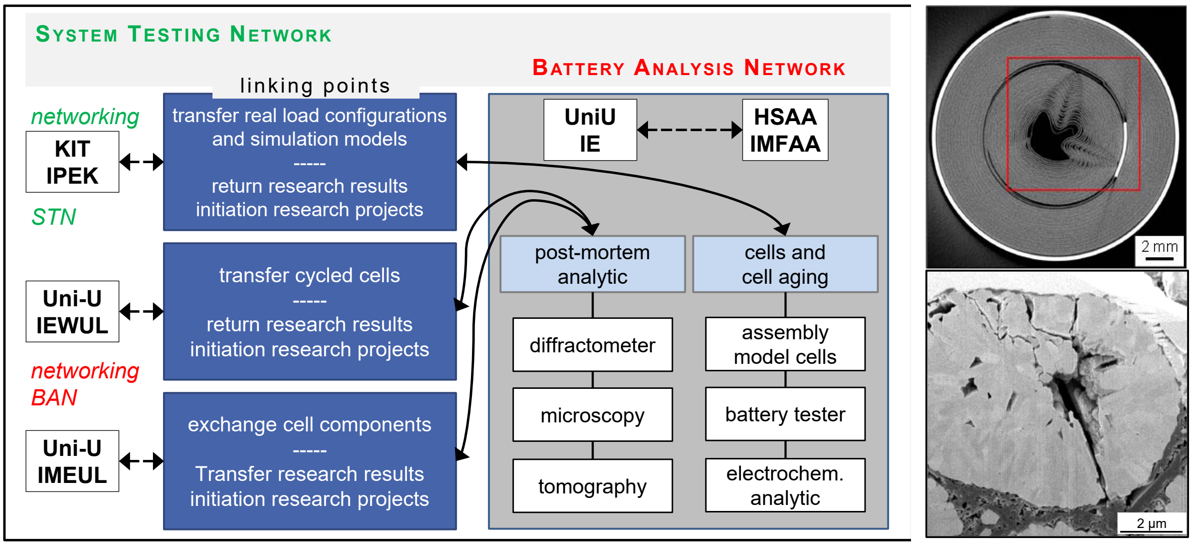

Figure 5: Interaction and linking points of the STN with the BAN (left illustration). On the right exemplary results using computed tomography and electron microscopy of aged Lithium-ion battery cell with massive collector deformation and crack initiation in cathode Nickel-Manganese-Cobalt-particle due to calendaring and cycling

Table 1: Overview of Project Partners

Karlsruhe Institute of Technology (KIT)	
IPEK - Institute of Product Engineering (STN)	Drive systems and system validation
FAST - Institute of Automotive System Technology (STN)	Operational strategy and vehicle functionalities
IFKM - Institute for Piston Machines (STN)	Thermodynamic analysis on the internal combustion engine
Ulm University	
MRM - Institute of Measurement, Control and Microtechnology (STN)	Energy storage and operating strategy
IE - Institute of Electrochemistry (BAN)	Electrochemistry at phase boundaries
University of Stuttgart	
IEW - Institute of Electrical Energy Conversion (STN)	Contactless power transmission and E machines
IVK - Institute for Internal Combustion Engines and Automotive Engineering (STN)	Engine technology and exhaust gas analysis
Esslingen University of Applied Sciences	
Faculty of Information Technology (STN)	Real-time data and cloud solutions
Aalen University of Applied Sciences	
IMFAA – Materials Research Institute (BAN)	Quality assessment and aging tests of batteries

4 Laboratory Network Baden-Württemberg for Electric Mobility

4.1 Organizational and Legal Framework

In order to conduct collaborative research projects, a foundation of basic organizational and legal agreements had to be set up. Different responsibilities for scientific and organizational issues have been installed at each partner. Basically, there are two kinds of project forms: the first one is a direct collaboration between partners of the XiL-BW-e consortium. The second one is a project with external project partners and at least one member also involving another network member's infrastructure. For both project forms, all partners of the laboratory network signed general regulations and templates for research contracts within a collaboration contract for at least ten years.

In collaborative projects, two or more partners of the laboratory network work together or with other external partners. In such a project, each of the involved consortium partners brings in his test bed and/or his expertise and all partners have equal rights and responsibilities. In contrast, the second project form involves mainly one laboratory network partner working together with one or more external partners, where the infrastructure and possibly expertise of at least one other laboratory network partner is integrated within a subcontract of the mainly involved partner. Within the general agreements, the framework and workflow between partners are regulated.

Overall, this organizational and legal framework simplifies the process of establishing collaborative projects as well as the expansion of the network significantly. The existing cooperation contract already regulates important questions like liability and allows starting collaborations with a minimum of organizational overhead and therefore within short time.

4.2 Networking concept

For a long time, the research partners of XiL-BW-e have already developed, maintained, and used specialized test beds for different components of electric and hybrid vehicles independent of each other. Now, a holistic networking concept from transporting layer up to planning methods that interconnects the distributed test beds was developed in order to conduct joint XiL testing of components and/or systems within the network. The overall concept targets the following five objectives: security (of the test beds), privacy, reliability, transparency and performance (especially low latency).

4.2.1 Virtual Laboratory

The security of the test beds is of paramount importance and is met by establishing a secured virtual private network (VPN) using the existing internet infrastructure. It ensures that only XiL-BW-e research partners have virtual access to the test beds. It is transparent for the required test beds. The VPN maintains a state-of-the-art level of privacy by encrypting all traffic between the test beds. The encryption is executed in hardware and therefore only adds a very small fraction to the overall latency of the data exchange. Although the UDP is connectionless, it is used to transfer signal data between distributed test beds for latency reasons. The overall latency was tested in an early prove of concept. Within a week, 50 million encrypted messages were sent between Esslingen and Ulm. The average round-trip-time of the messages was 3.2 ms and the average loss rate of messages was 0.0031 percent. These results are representative for the whole network, since similar configurations are used by all partners. The tests confirmed that the chosen concept of interconnecting the laboratories supports all five objectives.

4.2.2 Application Layer

The next step is to define a communication protocol on top of UDP and sequences for all involved test infrastructure. A master-slave architecture is the preferable structure for joint test runs, because it simplifies the signal routing and control between the partners. The master test bed is selected via technical (e.g. sample rate or delay) or organizational criteria. Within this structure, possible states for a master and a slave are defined and put into relation. To share the states, a consistent message format is essential for a communication between the endpoints. The first frames of the UDP-message are reserved for control and protocol data. Besides the state, there is also a placeholder for data to measure the Quality of Service. With the help of these signals, relevant function for security, safety, and reliability (e.g. run time monitoring, error detection, and time management) can be implemented. A payload signal table defines the possible payload, which is specific for every test bed and is available for all partners. For each test configuration, the payload signals are then selected individually according to the testing objective to enhance the performance. The generated measurement data of the exchange signals is logged at the master testbed. Besides, all other measurement data are shared on a data server for post-processing and evaluation. For safety reasons within the virtual laboratory, a video transmission via IP cameras of test beds is set up according to the needs of the test configuration. This video image alongside a selection of the most important exchange signals can then be observed at the master.

4.2.3 Methods for Planning

In order to plan and define a specific distributed test configuration, a suitable method is required. In the first step, an overview of the partner's available infrastructures, including virtual or physical models and Koppelsystems was created. With various subsystems available in the laboratory network, the overall super system "Driver – Environment - Vehicle" has to be built up. These subsystems in one specific configuration can be virtual, physical or mixed and have different levels of detail according to the specific validation objective. Relevant interdependencies of these subsystems are then model by lines between the subsystems. (see 2.1)

In order to implementing these connections at a low level, the actual signals have to be specified to provide a global understanding of the flow of information, energy, or matter. This holds especially for the exchange signals flowing through the mandatory Koppelsystems (virtual/virtual) between the locations. After creating a global understanding, the exchange signals have to be specified in the UDP-messages according to the payload signal table.

5 Demonstration of Networking Concept

The hybrid drive system of a vehicle represents the highest systemic complexity in drivetrain development. Due to its importance as a medium to long-term transitional and supplement technology for the market penetration of electric mobility, it was chosen as the demonstration system for the research network. To show the possibilities of the networking concept, four partners with virtual and physical model components are involved in a joint test configuration. Each partner contributes sub-system models according to their expertise and research field. The following institutes of the laboratory network contribute models to the setup (Figure *6*): IPEK (drivetrain, slave), IEW (E-Motor, master), IVK (internal combustion engine, slave) and MRM (battery, slave). Nevertheless, all partners have the interfaces according to the networking concept and are thus able to execute a joint test run.

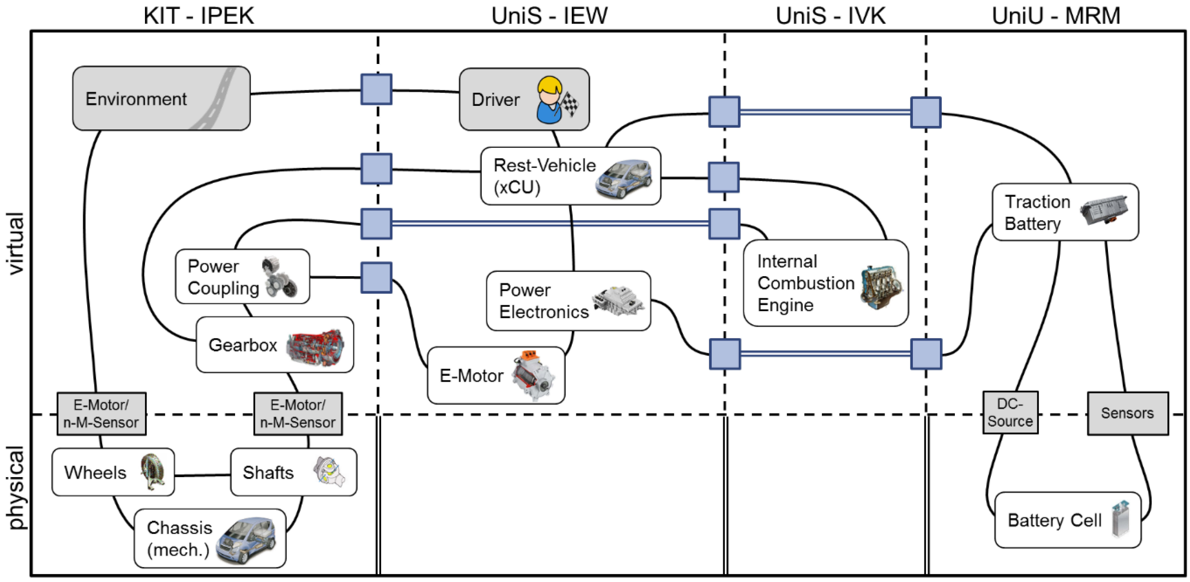

Figure 6: Hybrid Vehicle as a Demonstration System (Green boxes/lines depict KS_VV)

5.1 Configurations

The IPEK in Karlsruhe provides a test bench with a scaled down physical model of drive train shafts and vehicle mass (rotational mass). On the virtual side, there is a simple model of the environment consisting of a driving resistance model without acceleration force. This force is modeled with a physical rotational mass. There is also a virtual model of an element coupling the power of the electric motor (e-motor) and internal combustion engine (ICE). A gearbox model is responsible for changing the gear ratio according to the gear selection of the driver model. The overall model gets the torque input values of the motors (e-motor and ICE) and brakes and gear requirement, so that the rotation speed resp. vehicle speed changes according to the driving resistance. This speed is transferred back to the motors and the driver.

At IEW in Stuttgart, besides the e-motor and power electronics on the test bed, a rest-vehicle and driver is modeled in the virtual domain. The rest-vehicle model consist of all mandatory models, which allow the operation of the vehicle in the super system according to the validation objective. In this case, the rest-vehicle model consists of a hybrid operation strategy and fieldbus for transferring information between the different parts of the vehicle. The driver model has the task to follow a desired velocity with the vehicle and to shift the gears according to its shifting strategy. The vehicle speed is loaded onto the motors. According to the difference in desired actual speed and driving style, a torque is applied. Subsequently the e-motor model will request current by a given voltage from the battery at MRM (see below). The actual torque is then sent to the IPEK.

The IVK at the University of Stuttgart provides the test facilities and expertise for the implementation of the internal combustion engine (ICE) in the hybrid powertrain environment. In the presented setup, the input variables for the ICE are speed and requested torque. To account for transient effects the effective torque provided by the engine is measured and sent to the model of the powertrain dynamics. For evaluation purposes, fuel consumption and pollutant emissions are also transferred to the master model. The ICE model uses a mean-value approach with dynamic functionalities to ensure real-time operation.

The battery and its control are located at the facilities of the MRM in Ulm. A physical battery cell in the test bench is therefore scaled up to a complete traction battery on the virtual domain. The model is loaded with a current requirement and changes it voltage and State of Charge (SOC) according to the cell measurements.

5.2 Exemplary Results

The scenario of this setup is to investigate fuel efficiency. The driver of the hybrid vehicle system drives a Worldwide Harmonized Light Vehicles Test Procedure (WLTP). Thereby, the functionality of distributed testing and seamless integration of virtual and physical models can be demonstrated.

In Figure *7* (left), an exemplary piece of the WLTP tolerance band is depicted as black dashed-dotted line. The virtual driver model is able to stay in the speed tolerance over the whole cycle, so that the result is accepted. Due to the separation of the drivetrain from the engines, the acceleration for every gearshift changes. Since every model runs with different step times, on different hardware, and has different physical distances to the master test bench, the communication frequency and total delay between the master and the three slaves is not the same (see Figure 7 (right)). The highest communication frequency (from the IEW master test bed) was to the MRM with about 500 Hz, the lowest to the IVK with about 25 Hz.

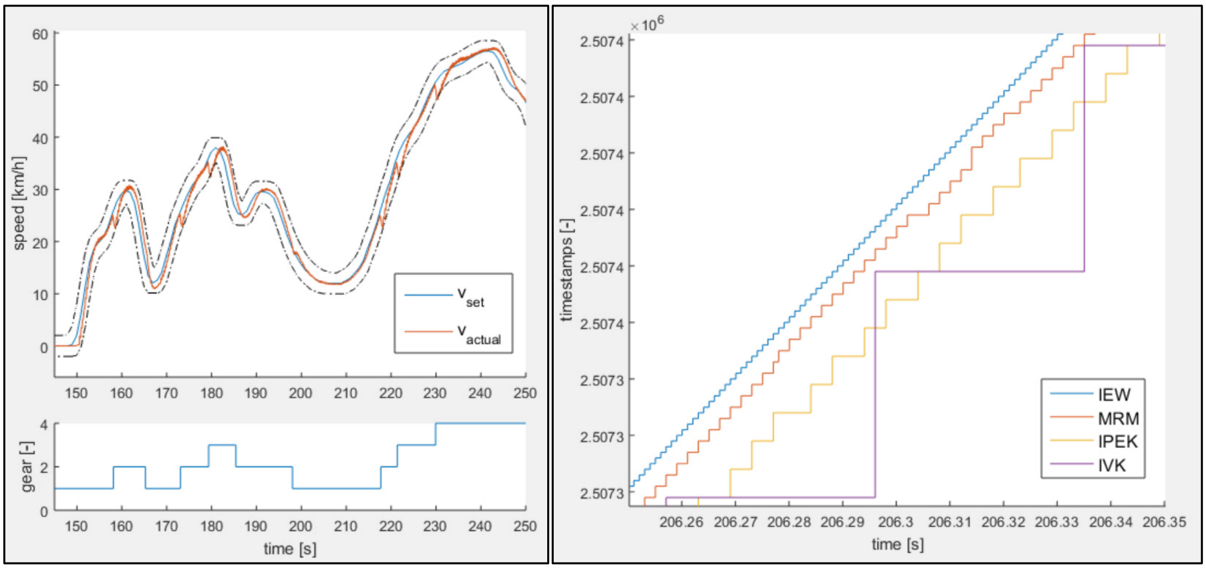

Figure 7: Vehicle driving the WLTP, set speed (blue), actual speed (red) and gear over time (left); different communication frequency and delay between the locations (right)

6 Summary and Outlook

With the XiL-BW-e partnership, a strong network for testing and research in the area of electric vehicles was founded. The system testing network and the battery analysis network offer completely new chances for components, software, and system testing not only for the network partners, but also for possible further research partners or partners from industry. The collaboration is established within an organizational and legal framework, while the networking concept provides a safe and performant interconnection between the laboratories. This enables sharing of expertise for system analysis up to the creation of joint X-in-the-Loop testing environments.

The flexible combination possibilities of different types of models and/or test beds open various new research and testing opportunities. Components and software can easily be tested in the different vehicle topologies using real hardware or real-time simulation models of high accuracy without having the need of locally connected test beds. Furthermore, by combining real test beds with virtual models at different locations within one network, the degree of precision can be seamlessly adapted according to the demands of the project. This also allows testing of components based on real loads in the specific use cases to gain knowledge as early as possible.

The laboratory network XiL-BW-e as a whole additionally provides new research possibilities in the areas of battery aging with real driving cycles investigated on single cells, clutch and engine influences as well as operation strategy optimization on various powertrain topologies, future electric vehicle topologies, inductive power supply of vehicles, and many more. For hybrid vehicles, the challenge of real driving emissions and battery age protecting operating strategy can be addressed effectively on the system level, even before vehicle prototypes are built up. The partners are open to pursue this research also with new partners from science and industry in sub-groups or as XiL-BW-e consortium as a whole.

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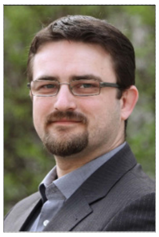

Matthias Behrendt

Dr.-Ing. Matthias Behrendt is Chief Engineer and Head of Research Department at IPEK - Institute of Product Engineering at Karlsruhe Institute of Technology (KIT). He is responsible for system validation and NVH complying with design processes and innovation processes. He received his Diploma in Mechanical Engineering in 2002 and his Doctor's degree in Mechanical Engineering at University of Karlsruhe (TH) Germany in 2009.

Steven Yan

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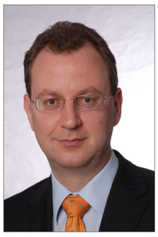
Stefan Zaiser

Dr.-Ing. Stefan Zaiser was a researcher at the Institute of Measurement, Control, and Microtechnology (MRM) at Ulm University until January 2017. He received his diploma degree from Ulm University in 2011. Since then, he was working in the research area of system identification and diagnosis for electric mobility at MRM and received his Ph.D. degree in March 2017.



Andreas Rößler

Prof. Dr.-Ing. Andreas Rößler is professor at Hochschule Esslingen, department of Information Technology. His main research interests are human computer interaction, virtual systems and digital learning.

Timo Bernthaler

Dr. Timo Bernthaler is member of the Materials Research Institute (IMFAA) at Aalen University and is there responsible for the materials analytics group. Main research interests are the characterization of structural and functional materials using various characterization methods in combination with software technologies to obtain processing-microstructure-property relationships.