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Connected and Shared X-in-the-loop Technologies for Electric Vehicle Design

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Summary

The presented paper introduces a new methodology of experimental testing procedures required by designing complex systems of electric vehicles (EV). This methodology is based on real-time connection of test setups and platforms, which are situated in different geographical locations, belong to various cyber-physical domains and are united in a global X-in-the-loop (XIL) experimental environment. The proposed concept, called as *XILforEV*, allows exploring interdependencies between various physical processes that can be hardly identified or investigated in the process of EV development. In this regard, the paper discusses the following topics: global XILforEV architecture; realization of required high-confidence models using Dynamic Data Driven Application Systems (DDDAS) and Multi Fidelity Models (MFM) approaches; formulation of Case Studies to illustrate XILforEV applications.

Keywords: hardware-in-the-loop (HIL), EV (electric vehicle), braking, wheel hub motor, control system.

1 Introduction

Overall development process of electric vehicles consists of many stages, elements and components, which are being characterized nowadays by unequal levels of technological maturity. In this regard, the following specific question, which is insufficiently addressed neither at industrial level nor in research, can be identified: *how to efficiently realize integrated development and testing of EV systems from different domains*? The problem is that here not only proper electric powertrain design but also revisiting the automotive chassis design is demanded. In particular, the EV motion control requires a blended operation of powertrain and chassis actuators (e.g. brake blending) that motivates at least the following design challenges:

- harmonization of actuation dynamics of EV powertrain and chassis,
- delivering required user acceptance of new EV functionalities, and
- addressing more complex requirements to the fault-tolerance and robustness.

Under consideration of these factors, the use of well-established processes in the design of EV systems can have some sensible limitations, for instance, co-simulation issues for software-in-the-loop (SIL) / model-in-the-loop (MIL) procedures, availability of hardware-in-the-loop (HIL) test setups for different systems at the same host, tangible extension of road trial programmes with added time / cost resources to check new functionalities.

The SIL, MIL, and HIL tools together can be concisely referred as “X-in-the-loop” or “XIL”. These established XIL technologies are currently being advanced with the development of new classes of design concepts. For example, Albers et al. [1] proposed an extension of the XIL framework through a connection with the Integrated Product Development Model and Knowledge Management Systems, widely used in industrial design processes. Another variant of an XIL tool was introduced by so-called concept of “test-rig-in-the-loop” (TRIL). The TRIL technique aims at real-time integration of two or more test rigs from, for example, dynamometers and HIL test setup [2].

From viewpoint of test rig communication approaches in XIL architecture, more and more efforts are being given in direction of Internet-based technologies. Despite the first attempts in this field were reported a decade ago [3], only recent progress in communications allowed proposing advanced solutions in this field. For instance, the corresponding technology for connecting battery, powertrain and full vehicle test rigs was reported in [4] as an example of Internet-Distributed Vehicle-in-the-Loop simulation platform for hybrid electric vehicles. Another tool has been discussed in [5] for the X-in-the-distance-loop demonstration platform. This platform consisted of MATLAB/Simulink software platform and driver simulator, driving electric motor and dynamometer test stand, which were used for bidirectional experiments to test communication of powertrain data between China and Germany.

Despite obvious benefits from Internet-based XIL, some challenges have to be solved. It concerns such issues as applicability of web communications for real-time simulation and tests, operative recovering the lost information during test data exchange. As it was demonstrated in previous study [6] of authors of this paper dedicated to real-time brake control experiments between Germany, Netherlands, USA and South Africa, remote and distributed XIL procedures require consideration of many factors to avoid serious limitations to feasible test scenarios.

In line with previous investigations, the authors are proposing a new approach, called *XILforEV*, that aims at developing a connected and shared X-in-the-loop experimental environment uniting test platforms and setups from different physical domains and situated in different locations. The domains under discussion can cover (but are not limited to) hardware-in-the-loop test rigs, dynamometers, software simulators, driving simulators and other variants of experimental infrastructures. The real-time (RT) running of specific test scenarios simultaneously on (i) all connected platforms/devices with (ii) the same RT models of objects and operating environments allows exploring interdependencies between various physical processes that can be hardly identified or even expected on the design development stage. In the long-term perspective, the plug-in concept of including various test platforms/devices and easy on-demand access to the test procedures for developers, engineers and researchers will bring a vast impact to the EV design community through connecting experimental environments around the world.

Next sections of the paper will introduce the *XILforEV* architecture, its modelling components as well as hardware components involved in the four dedicated case studies.

2 XILforEV architecture

An overall approach to the *XILforEV* architecture can be explained with Figure 1. This architecture allows developing the EV subsystem controllers in a realistic environment but leveraging the use of existing facilities. In particular, MIL tools are used for full vehicle simulation in a virtual environment. The SIL technique is applied for investigations on functional reliability of embedded software applications. TRIL is represented by different test setups, which could generally include dynamometers, driving simulators and other experimental devices. The TRIL and HIL components are connected using real-time communication (RTC). It should be noted that this architecture supposes a plug-in interface allowing flexible inclusion of different test devices depending on the development task.

Hence, the *XILforEV* summarizes the aforementioned techniques and utilizes variety of XIL approaches in vehicle, driver and subsystems testing considering them in the one control loop. Such approach is the effective tool for the rapid development and testing of the vehicle as the complete system or as its integrated components. First of all, the following design tasks can be considered here:

- Subsystem parameters identification;
- Development of the real-time plant model;
- Implementation of the developed software systems to the hardware-in-the-loop platform and TRIL environment;
- Integration of the subsystems on the example of multi-actuated electric vehicle.

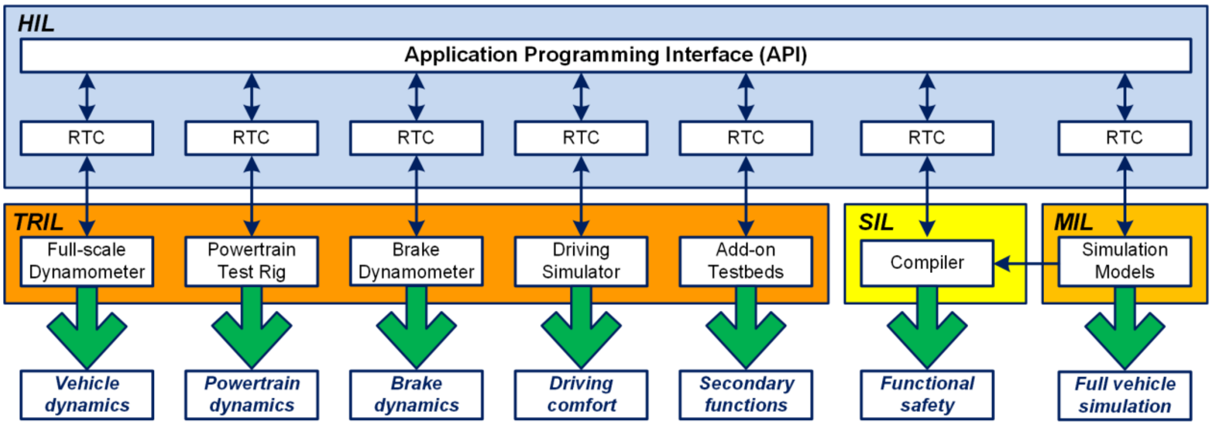

Figure 1: A variant of generic *XILforEV* architecture

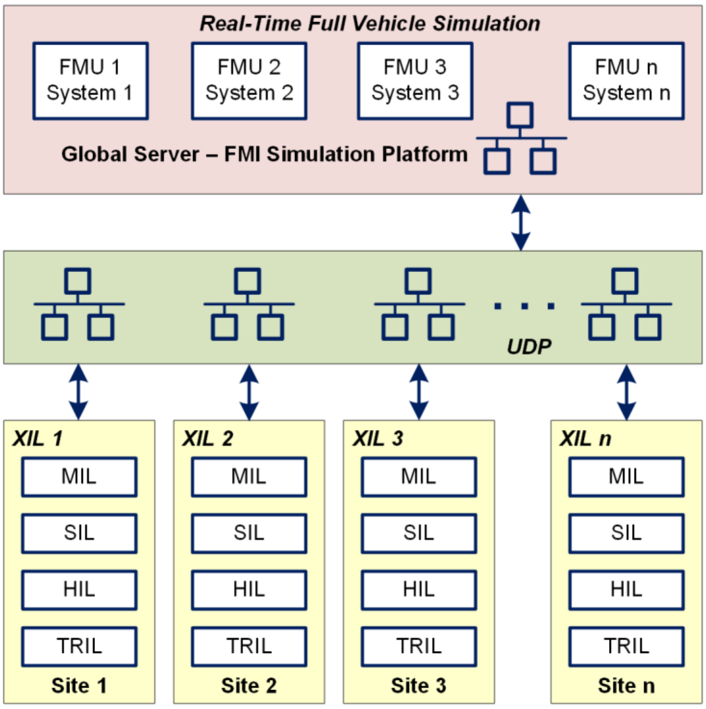

Figure 2: Distributed remote *XILforEV* architecture in multiple sites via Internet

There are two principal ways to establish the *XILforEV* framework with connected experimental setups:

- *"Distributed local"* - the setups are distributed within the narrow location, e.g. within the company site, university campus et al. Then the connection can be organized using local communication means as optic line.
- *"Distributed remote"* - the setups are distributed remotely between different geographical locations. Here the Internet-based connection is required for the establishment of *XILforEV* framework.

For the latest case, shared XIL testing approach using communication through the Internet is shown on Figure 2. Here the full vehicle model will run in a global server located in one site (it could be also a cloud server). In this model the subsystem and controllers will interact as Functional Mock-Up Units (FMU) with a co-simulation strategy based on the Functional Mock-up Interface (FMI).

Communication between the full EV model and the different testing sites will rely on the User Datagram Protocol (UDP). This decision has been taken on the basis of previous investigation of the authors that is reported in [6]. In particular, the following UDP advantages can be considered within the *XILforEV* framework:

- Compatibility with widely-used communication hardware based on IP/Ethernet;
- A maximum transmission unit size in accordance with the REC768 standard is 1472 bytes that is much higher as compared to other protocols as CAN or MOST;
- For up-to-date Ethernet devices and distributed local framework, the data transfer rates can be up to 1000 Mbit/s;
- A cyclic point-to-point communication time < 1ms is possible that fully acceptable for most of EV design tasks;
- Under consideration of modern global Internet technologies, UDP/IP provides also the addressing and routing services that allows reliable sharing of distributed RT systems.

Despite listed advantages, UDP-based communication systems require careful tuning for remote and shared test network. To address known weak points in this regard, the *XILforEV* architecture is embedding such elements as (i) redundant routing, (ii) compensation algorithms to recover the loss of messages, (iii) delay compensation algorithms based on estimation tools, and (iv) prioritization of UDP messages within the testing network.

3 Modelling components

EV design requires complex simulation works on various product development stages, therefore, relevant modelling topics are also integrated in the *XILforEV* concept. It relates in particular to MIL/SIL components and to RT models of HIL components. In MIL and SIL environment, there is no defined time line for the model simulation. Therefore, when dealing with complex products involving different domains and different physics, the engineer can decide the best trade-off between the required accuracy and the computational cost. A usual approach consists in starting with high spatial resolution methods like FEM or CFD and later integrating the results in a lumped parameter model which properly represents the dynamic system (plant) evaluated with a time step which will be the base for the controller development. However, the characteristic time of standard simulation strategies is usually not compatible with the real-time constraints compulsory for HIL testing. These rich models or Full Order Models (FOMs) do not allow proceeding in real-time. Model Order Reduction (MOR) techniques allow obtaining simple real-time models. However, the higher the accuracy of the ROM with respect to the original model, the higher the effort needed to build the ROM. Furthermore, to the uncertainty and lack of fidelity of the initial simulation model, it is necessary to consider an additional reduction in the accuracy, which further reduces the confidence of the corresponding models.

To address mentioned problems, the *XILforEV* approach proposes the use of high-confidence models, which are relevant to the EV development process, on the basis of two concepts: Dynamic Data Driven Application Systems (DDDAS) [7] and Multi-Fidelity Models (MFMs) [8]. The integration of both concepts into the XIL architecture is given on Figure 3. With this approach, industrial users can have models based on their CAE tools with required accuracy according to their product knowledge (FOMs or HFMs). These models have to be downsized to real-time requirements established by HIL testing in the shape of low-fidelity models. On the other hand, different testing facilities are then ready to test the EV subsystems in realistic conditions. By using an application lifecycle management (ALM) platform holding the original requirements and test cases, the users can control the test parameters and trigger the different test benches. Through a bidirectional connection between the test benches and the ALM platform, reliable data from the sensors in the test benches can be pushed back. This way, results are traced back to their originating test case and the user has reliable information on the overall testing status. This established traceability from requirement over test case to test results enables the automatic generation of the necessary reports.

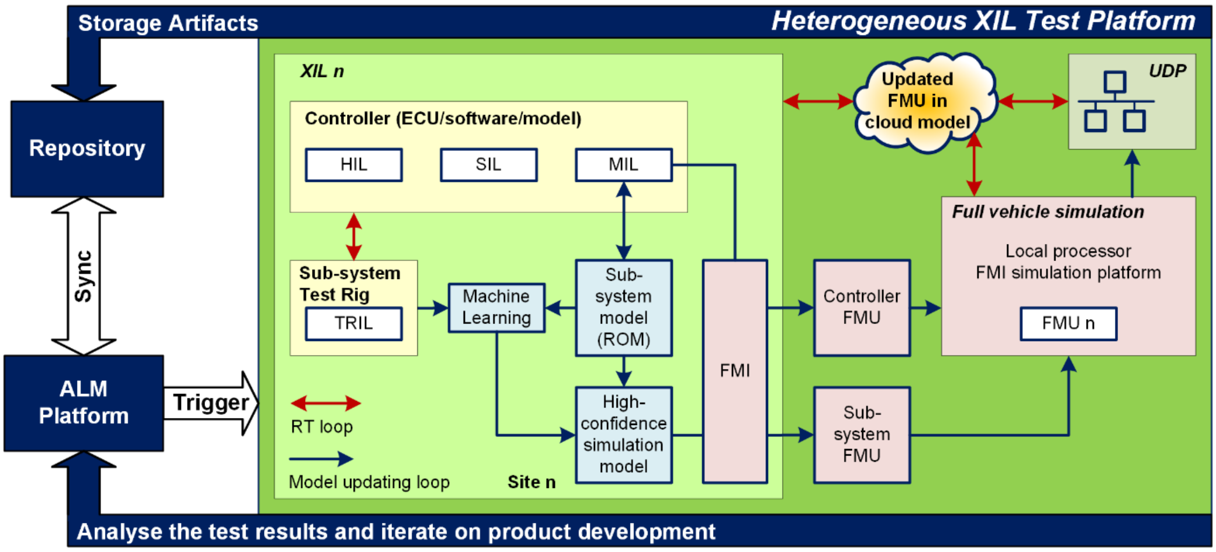

Figure 3: A variant of local XIL architecture with high-fidelity models

The proposed interconnection of DDDAS and MFMs procedures can be illustrated with Figure 4 and involves the following components:

- Initial system/component model: Reduced Order Model (ROM) of the product is able to run in real time or accelerated time, but not necessarily extremely accurate, in order to facilitate its development in a short period of time with little effort if needed. This can be developed offline ad-hoc for the system in question, but always following a similar strategy;
- Data assimilation layer: data processing module for the gathering of input/output data from the test bench and a layer of data processing to generate a data-driven correction model;
- Plug-in module for connecting the data-based correction back into the model to improve its accuracy. This will constitute an additional term of the ROM that is continuously evolving to adapt the accuracy of the model.

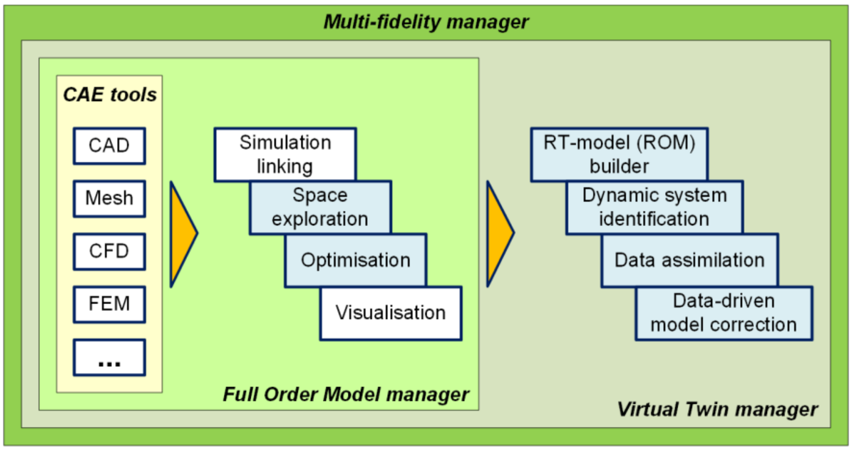

Figure 4: DDDAS workflows to create the sub-systems multi-fidelity models

The proposed DDDAS includes also the machine-learning layer for deriving the reduced-order models with online decision-making and the use of the test bench data, Figure 5. With this approach, the model will automatically increase the confidence level without increasing the development time and preserving the real-time constrains for the HIL testing. This model improvement loop can be done on-line with an immediate use of the new model predictions. To improve the model stability, the automatic updating could be down-sampled based on tracking an indicator of the model variation. The dynamic data-driven ROM is being obtained with an analogue approach to the one used and described in the projection of the initial model. Hence, the compatibility with the rest of the subsystem models is guaranteed.

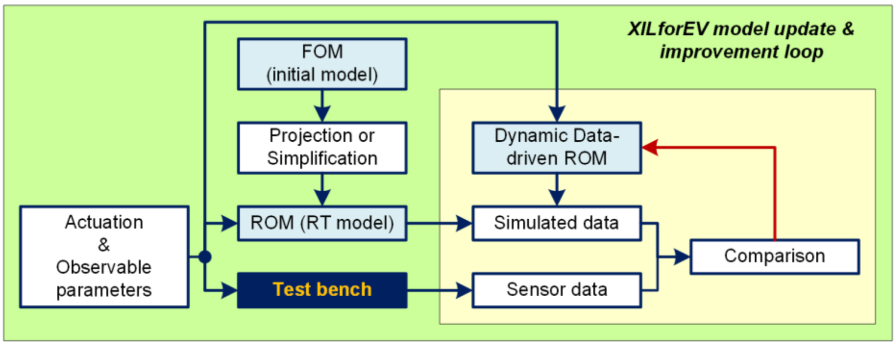

Figure 5: Use of test bench data to improve model confidence

The implementation of described concepts within the *XILforEV* framework is carried out in two steps. First, it is developed and set up in one of the XIL test sites and for one of the subsystems. Once it is ready, the solution is being adapted to the rest of the subsystems and XIL sites. The case studies, where these concepts are being implemented, are introduced in next section.

4 Use cases

XILforEV use cases are selected to show the potential benefits of the shared XIL strategy in terms of development of complex functions involving different subsystems and the incorporation of failsafe studies in such a context. Four use cases under discussion are designed for all-wheel drive sport utility vehicle with four individual in-wheel motors (IWM) and dedicated to (i) brake blending, (ii) ride blending, (iii) integrated chassis control, and (iv) fail-safe and robustness studies. Their features are summarized in Table 1.

Table 1: *XILforEV* use cases

EV hardware	XIL configuration	Test setups	Software part
Use Case "Brake Blending"			
Electro-hydraulic brakes, IWMs	Distributed local (all test setups are located in Ilmenau, Germany)	Brake dynamometer; Brake HIL test rig; Powertrain test rig	Full RT vehicle model; Co-simulation interface
Use Case "Ride Blending"			
Active suspension	Distributed remote (test setups are located in Zaragoza and Ermua, Spain)	Suspension component test bench; Driving simulator	RT models of vehicle, powertrain and tyre/road
Use Case "Integrated Chassis Control"			
Electro-hydraulic brakes, IWMs, active suspension	Distributed remote (test setups are located in Zaragoza and Ermua, Spain, as well as in Ilmenau, Germany)	Suspension component test bench; Driving simulator; Brake HIL test rig; Powertrain test rig	RT models of vehicle and tyre/road; Co-simulation interface
Use Case "Fail-safe and Robustness Study"			
IWMs	Distributed remote (test setups are located in Ermua, Spain, Ilmenau, Germany, Ljubljana, Slovenia)	Driving simulator; Powertrain test rig	Full RT vehicle model; Co-simulation interface

Brake blending is a relevant issue for electric vehicles since they are using two types of deceleration devices, namely the friction brake and the electric motor / generator. In terms of the interaction of friction brake and electric generator, one of the most relevant objectives is to ensure that the driver does not recognize the transfer phase between these two devices (in terms of body movements and acoustics as well). It is obvious, that the deceleration has to be considered as energy efficient (highest possible amount of electric recharging) and safety as well (maximum stopping power and minimum stopping distance respectively). To investigate the brake blending, *XILforEV* architecture as shown on Figure 6 is proposed. Test scenarios include: Service braking; Emergency braking; Brake blending with ABS intervention. The main design task: Brake blending controller optimized by criteria of braking performance, energy efficiency and driver comfort.

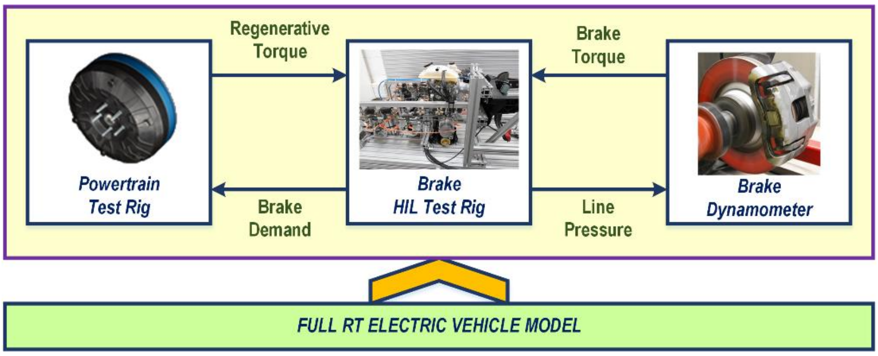

Figure 6: *XILforEV* configuration for brake blending studies

Ride blending is a new technology for electric vehicles assuming joint control on the vertical motion dynamics of the vehicle both through individual electric motors and active suspension. This technology, initially developed on a conceptual level in cooperation between Tenneco and TU Ilmenau [9], is assumed for coming generations of EVs. The challenge here is, especially taking into account electric SUV as a target vehicle in the project, to achieve optimal ride quality on roads with considerable roughness and unevenness. The corresponding *XILforEV* architecture is shown on Figure 7. Test scenarios include: Routine manoeuvers on roads with different surfaces; handling manoeuvers on roads with different surfaces. The main design task: Ride blending controller optimized by criteria of driver comfort and driving safety.

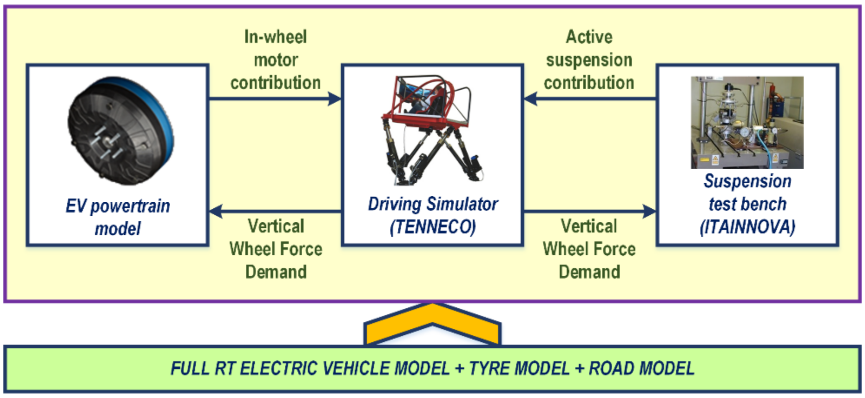

Figure 7: *XILforEV* configuration for brake blending studies

The combination of active chassis systems from the first and second use cases will lead to next use case for the *integrated chassis control design*, represented by the brake blending and ride blending. This combination of chassis systems could bring essential effect for electric vehicles in simultaneous improvement of the driving safety and comfort, especially in the case of critical manoeuvres. The *XILforEV* architecture for this case is shown on Figure 8. Test scenarios include: Stability and handling manoeuvers on roads with different surfaces. The main design task: EV integrated chassis controller optimized by criteria of driving safety and comfort.

This final use case is a demonstration of the *XILforEV* technology potential for fail-safe and robustness studies. The scenario selected will replicate an error in the motor operation in one testing site and its implication on the full vehicle behavior will be analised in the shared XIL, Figure 9. For the purpose of simulating the fault injection, an additional Engine Control Unit (ECU) will be added to the powertrain architecture model, which is able to take the control over the one "faulty" propulsion unit (faulty inverter or motor) in case of need. Different fault scenarios are then implemented on the ECU and can be modelled, for instance, (i) Communication lost (no torque from propulsion unit); (ii) Motor short circuit test (motor braking torque); (iii) Opposite motor torque. Actual speed and torque value of "faulty" propulsion unit is sent to the vehicle control unit. The vehicle control unit (VCU) takes these values and torque/speed values from other propulsion unit sent by the propulsion control unit (PCU). Based on all torque / speed data, vehicle longitudinal and lateral response is calculated. With driver in the loop, it is possible to define controllability of the tested scenarios. The main design task: Electric powertrain fail-safe control strategy.

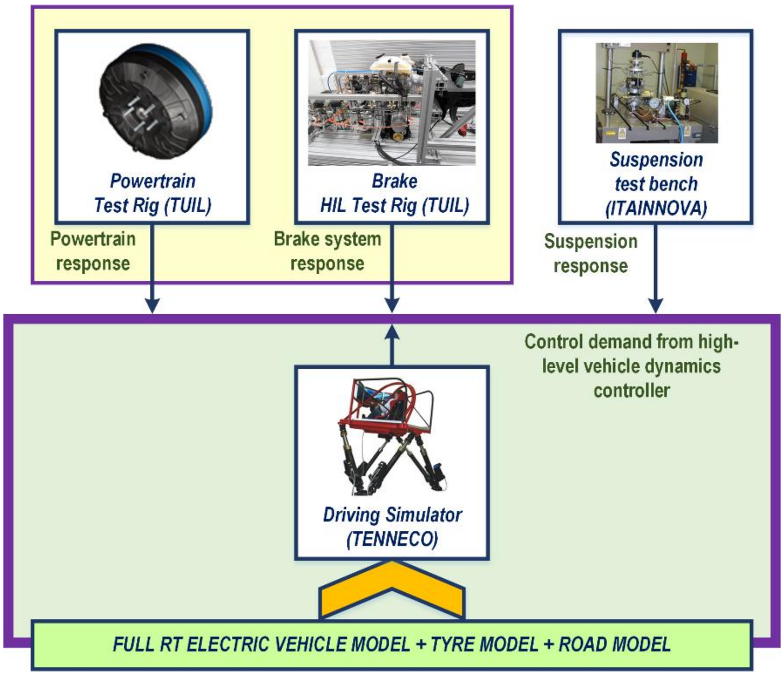

Figure 8: *XILforEV* configuration for integrated chassis control studies

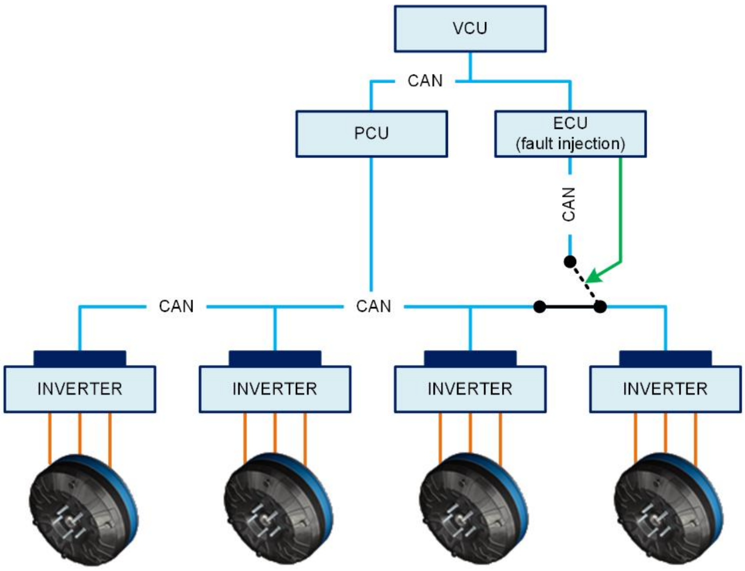

Figure 9: A variant of *XILforEV* configuration for fail-safe and robustness study

5 Concluding remarks

The introduced architecture of remote and shared experiments, corresponding modelling components and relevant use cases are addressing a new development and testing technology for EVs and EV systems, through an integrated approach combining different experimental environments, well beyond established XIL procedures in automotive industry. In fact, the cost and time efficient design of new innovative EV systems depend on several concurrent factors and can be effectively optimized through the networking and sharing of experimental procedures. The XILforEV approach is also enabling several technological and business cases that can be summarised as follows:

- Shared experimental environments – a service for connected complex test setups and hardware/virtual labs that can be used for specific engineering tasks, which are to be hardly investigated using traditional SIL/MIL/HIL procedures and real-world tests on full-scale demonstrators;

- Real-time simulation cloud with open plug-in interface for connected hardware setups – an extension of available simulation cloud business models towards real-time domains for designing and validation of physical systems;
- Beyond automotive, this technology could be also applicable to other transportation domains, like aerospace (future distributed propulsion aircrafts), rail or marine.

Acknowledgments

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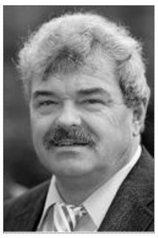

Klaus Augsburg received Dr.-Ing. degree in 1985 from Technische Universität Dresden, Germany. From 1984 to 1993 he worked in industry on leading engineer positions and then in 1993-1999 as Senior Assistant at TU Dresden. In 1999 he became position of Full Professor and Chair of Automotive Engineering Group at Technische Universität Ilmenau, Germany. In 2011 Prof. Augsburg founded Thuringian Centre of Innovation in Mobility, where he is coordinating many industrial and public research projects. Prof. Augsburg is author of more than 100 research papers, guest lectures and patents. He is a member of the Association of German Engineers, Chairman Workgroup Automotive Engineering VDI Thüringen, and CEO Steinbeis-Transferzentrum Fahrzeugtechnik.

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