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Whitepaper

Future Automotive E/E Architectures –

Mastering complexity on the path towards a new E/E paradigm

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Introduction and Motivation

The radical transformation process currently observed in the automotive industry is most evident within vehicular Electrical/Electronic (E/E) architectures. As a basis for nearly all vehicle systems, the E/E architecture defines the structure of the entire E/E system in the vehicle and includes all E/E functions and components. More specifically, components of the E/E architecture cover:

- Hardware components,
- Software components,
- Bus systems and network topology for data communication and
- On-board energy network.

In previous decades, the vehicle's E/E domain has followed a rather evolutionary development path, as have almost all vehicle domains. At the same time, requirements for the E/E architecture have increased extremely as a multitude of new functions have to be implemented into existing architectures. However, there are various indications that continuing an evolutionary development of the established E/E architecture will be extremely difficult and probably insufficient to fulfill upcoming vehicle requirements. In particular with regard to automated, connected and electrified vehicles, overall system complexity as well as integration and validation effort will rise significantly as shown by the following examples:

- Automated vehicles require high-performance computing to execute complex software for processing very large amounts of data from various sources. Hence, centralized hardware structures have a clear advantage over multiple smaller and less powerful ECUs.
- Connected vehicles enable Over-the-Air (OTA) software updates, which will become particularly relevant for safety-critical software components. In this context, both the hardware and the software architecture must allow a remote adaption of software after production.
- Electrified vehicles exhibit a high-voltage powernet level in addition to the conventional 12 V powernet, hence facilitating a redesign of the traditional on-board energy network.

As a consequence of the manifold technological challenges for future E/E architectures, new development and implementation approaches for automotive E/E architectures are currently gaining traction. In particular, new OEMs are able to adapt approaches from the IT industry, whereas incumbent OEMs are often tied more closely to established processes, structures and supplier relationships. As an example, Tesla was able to develop an own Linux-based operating system from the scratch whereas incumbent OEM have to consider a heterogeneity of legacy software components and dependencies. Thus, traditional

OEM are currently restructuring their processes, supply chains and organizational structure in order to be able to redesign their software architecture. Volkswagen's CARIAD is a prominent example of such a newly established software entity.

Considering all current changes on the technical, processual and organizational level together, it becomes clear that the automotive industry is about to switch to a new E/E paradigm. This paradigm shift does not only affect OEMs and large suppliers, but will also have a comprehensive influence on all suppliers with any kind of E/E hardware or software components in their portfolio. More detailed characteristics and consequences of this new automotive E/E paradigm are described in the following sections, which follow the layered structure of automotive E/E architectures as shown in Fig. 1.

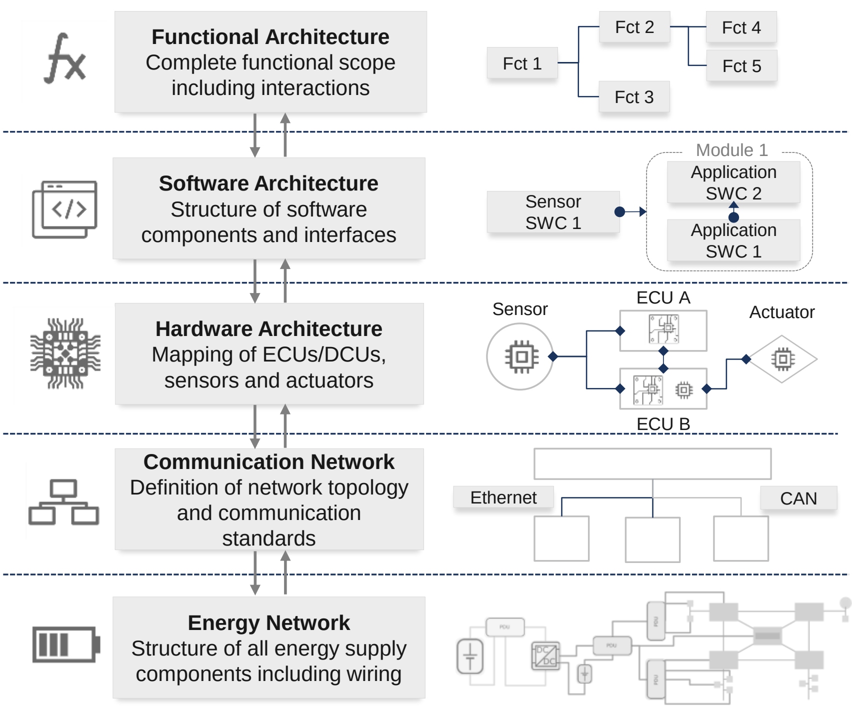

FIG. 1: AUTOMOTIVE E/E ARCHITECTURE LAYERS

Functional architecture

Automated, connected as well as electrified vehicles both enable and require the implementation of new functions. When defining the functional architecture, not only vehicle functions but also services provided by associated and higher-level systems have to be taken into account. In this context, functional system boundaries should be dissolved.

One example of such a system boundary is the linkage of electric vehicles with the public charging infrastructure. Relevant functions for the charging process include reservation, authentication, monitoring and payment but also vehicles' navigation, estimated time of arrival or State of Charge (SoC) forecast. Hence, charging functions benefit strongly from an exchange of data between both systems. Based on this cross-system perspective, enhanced charging services can be identified and developed as e.g. an automated vehicle-triggered payment (e.g. Plug & Charge, Tesla's In-Car payment). In the future, the connection of EVs with the charging infrastructure could also be used to support a multitude of further usage scenarios which require a stable infrastructure connectivity, as e.g. cloud high-performance computing.

Required system interfaces between automated vehicles and the traffic system exhibit further examples for cross-system functions. In particular, higher levels of automation rely on comprehensive, accurate and dynamic information on the traffic network and environment. At the same time, automated vehicles' sensors generate a vast quantity of traffic data. In order to provide continuously updated digital maps, vehicles' sensor and localization data are matched with map information. In case of deviations, e.g. detection of new road signs or markings, information is transmitted to the map provider's cloud for further processing and potential map updates.

In general, this **Cloud Computing** principle can be applied to all vehicle data, hence significantly extending the functional scope beyond the actual vehicle. Additionally, further increasing hardware capabilities within the vehicle will also favor an implementation of demanding functions in the vehicle or in a network close to the vehicle. This **Vehicle Edge Computing** (VEC) principle is e.g. useful for the processing of very large and latency-critical data volumes, which otherwise would congest mobile networks. Besides this, the decentralized approach of VEC could also improve robustness of the overall system, since failures will only have a local effect as opposed to centralized computing. Exemplary applications for VEC are the local processing of traffic data in roadside units (edge nodes) or the testing of new automated vehicle functions in the background of vehicles on the road (e.g. Tesla's 'Shadow mode).

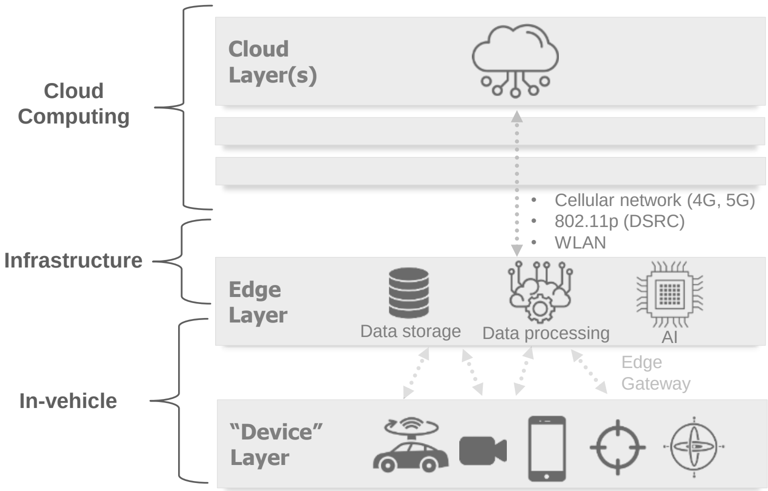

FIG. 2: VEHICLE EDGE AND CLOUD COMPUTING

Simultaneously with the dissolution of system boundaries and the accompanying functional scope extension, the functional layer is also influenced by a further development trend. In a **Software-Defined Vehicle** (SDV) functions are primarily enabled through software, ultimately shifting the focus from a hardware-based electromechanical product to a software-centric system. This implies that product differentiation and personalization and thus customer experience is mainly shaped by software. With regard to a vehicle's functional architecture, a SDV enables an upgrade of functions and features over the vehicle's lifetime. Consequently, functional architectures have to be defined in a way that incorporate future adaptations or additions of functions. However, the impact of SDVs is even more extensive for the underlying software and hardware layer and will be discussed in the following two sections.

Software architecture

The emergence of Software-Defined Vehicles represents a fundamental change of development focus for the automotive industry. Traditionally, the industry's focus has been on the development and integration of electromechanical systems combined with specific control and operating software. Since the scope and complexity of software components has risen significantly over the last years, development and validation efforts have skyrocket. In contrast, SDVs follow a software-first approach where functions and features are mainly realized as software and thus enabling an abstraction from the underlying hardware. However, for a thorough implementation of a software-centric development approach, a complete redesign of the software architecture is required.

Besides an enhanced management of complexity as well as an improved reusability of software, **Over-the-Air updates** are a further essential benefit of SDVs:

- Connected vehicles need regular OTA software updates in order to close critical security gaps and protect the vehicle against cyber-attacks.
- Software components can contain bugs that are first detected after vehicle production. OTA updates reduce the necessity for cost intensive software updates in workshops or even product recalls.
- Software is a safety-critical component, e.g. in X-by-wire applications or Automated Vehicles. Especially for Automated Vehicles, a continuous improvement of functions is pursued based on learnings from past situations. OTA updates enable adaptions of functions for all vehicles of an OEM.

Furthermore, OTA functionality also facilitates software upgrades. These upgrades provide new functions and features for customers after vehicle purchase, hence improving user experience and personalization. From an OEM perspective, OTA upgrades open up new revenue and monetization opportunities as well as enhancing customer touchpoints over the vehicle lifecycle. OTA upgrades could also enable a higher degree of flexibility for OEMs and suppliers in the vehicle development, since exchange of software after vehicle production is feasible e.g. to fulfill diverse local requirements or to adapt new communication protocols.

Against this background, the software architecture principle of a **Service-oriented architecture (SOA)** is currently gaining ground among automotive players. For instance within the AUTOSAR and AUTOSAR Adaptive standard, the 'Scalable Service-Oriented Middleware over IP' (SOME/IP) is used by many OEM for Ethernet communication. Besides OEM, system suppliers are also promoting SOA as for example Continental's High-Performance Computer architecture.

The modular approach of SOA enhances the updateability, reusability and testing of software components. In a SOA, the software is divided into small, discrete modules (services), each implementing an independent function to fulfill a specific task. Furthermore, a SOA also contains a generic functional pattern for services thereby serving as a blueprint for exchangeable functional units and facilitating service development. Individual services exhibit defined interfaces and use a common communication protocol to exchange data between the software components. Since a service only provides a simple interface to the requester, further details on the internal implementation or algorithms do not need to be known. This principle makes it possible to easily update, replace and reuse individual functions.

Furthermore, SOA offers the potential to increase flexibility, robustness and reliability of vehicles' software. Before executing a function, SOA checks whether the defined requirements are fulfilled and if there are any runtime problems. If a conflict is identified, the function will not be executed and the system will switch to the previous state. In case of a hardware failure, e.g. on a control unit, a temporary compensation can be realized by shifting services to other control units.

Eventually, SOA also supports the principle of a hardware-agnostic automotive software. This requires a strict separation between software and hardware, which can be realized by a **Middleware** and an underlying **Operating System** (OS) layer, as shown in Fig. 3. In this context, the middleware is defined as a software to enable interaction of discrete applications respectively services in distributed systems. Thus, a middleware provides certain services that can be used by all applications, e.g. messaging or data management, without directly accessing the OS. Besides an enhanced interoperability between applications, the middleware serves as an abstraction layer between the OS and applications in order to realize hardware independency.

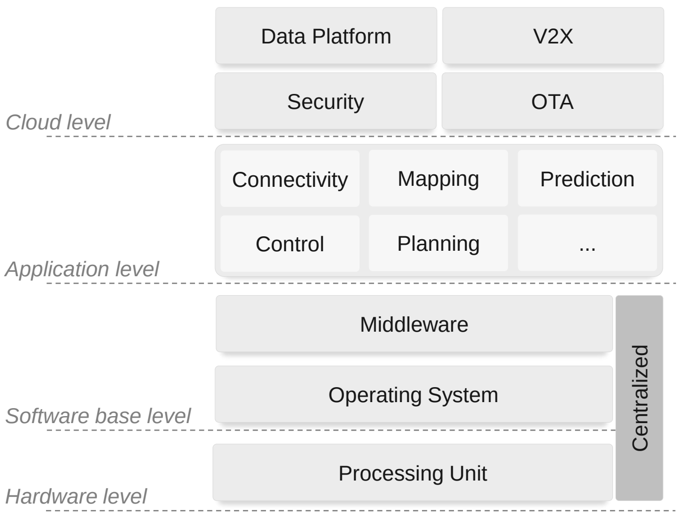

FIG. 3: AUTOMOTIVE SOFTWARE STACK

As an exemplary future use-case for a hardware abstraction, a perception application for an automated driving function could be developed which supports any sensor, accelerator or processor. Consequently, third-party software providers could realize applications independently from the hardware supplier. This would favor a stronger division of the value chain in specialized software and hardware providers. However, a single industry-wide standard for automotive middleware has not yet been established, although multiple implementations already exist (e.g. SOME/IP, Eclipse iceoryx, Eclipse Cyclone DDS). Currently, solutions from Tier-1 suppliers, software start-ups and open source approaches compete for the future automotive software stack.

The automotive OS builds the basis of this software stack and serves as a low level hardware-oriented layer. It manages the hardware resources and performs multiple tasks on the associated hardware, e.g. memory allocation, communication or processor time scheduling. Even though there are already some automotive OS in use and providers on the market, intense development activities currently take place in this field. In particular, the increasing complexity of vehicle computers, as described in the following section, and the strict requirements regarding safety and cybersecurity act as drivers for new automotive OS. Hence very different automotive stakeholders like software providers, OEMs, large tech companies, SoC players or industry consortia are currently competing for the future automotive OS., as shown in Fig. 4. Since there is a strong risk of a lock-in effect for OEMs and new-entrants with proprietary solutions, open-source based OS will become increasingly important in the coming years. With these open-source approaches, also new forms of cooperation between OEMs will become relevant which are not yet established in the automotive industry.

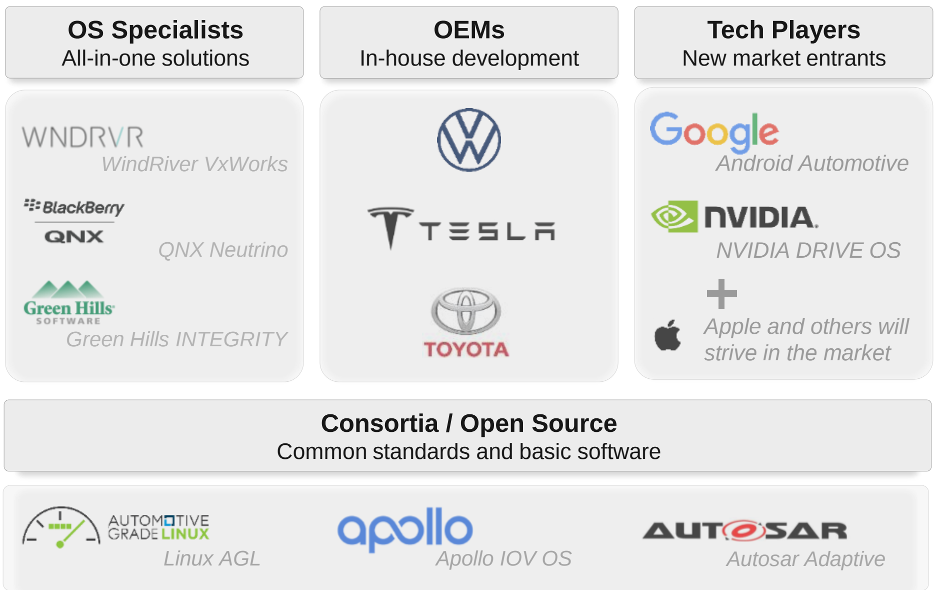

Fig. 4: Selected Automotive OS Stakeholders

Hardware architecture

Current technological developments in the automotive industry, particularly in the area of automated and connected vehicles, are bringing about fundamental changes of hardware requirements. These affect individual ECUs respectively vehicle computers on the one hand and the hardware architecture on the other.

Due to the processing of large amounts of data, highly automated driving functions require immense computing power from the hardware. In the areas of infotainment and HMI, demanding functions such as digital clusters or natural interaction also require high-performance **vehicle computers**. Current vehicle computers therefore usually implement several types of processors, e.g. multi-core CPUs, GPUs, AI accelerators. Since the computers are also used to execute safety-relevant driving functions, the highest functional safety requirements must be met. Furthermore, vehicle computers must be able to fulfill a high degree of flexibility and scalability. Additional computation power capability must be available to cover future applications. In addition, a large number of different data transmission technologies, e.g. LIN, CAN or Gigabit Ethernet (GbE), must be supported. At the same time, automotive manufacturers are pushing to standardize hardware used across all model series and vehicle variants in order to reduce complexity and costs.

Because of the changes to the E/E architecture described in the previous sections, the hardware architecture is currently undergoing a comprehensive transformation process, as shown in Fig. 5.

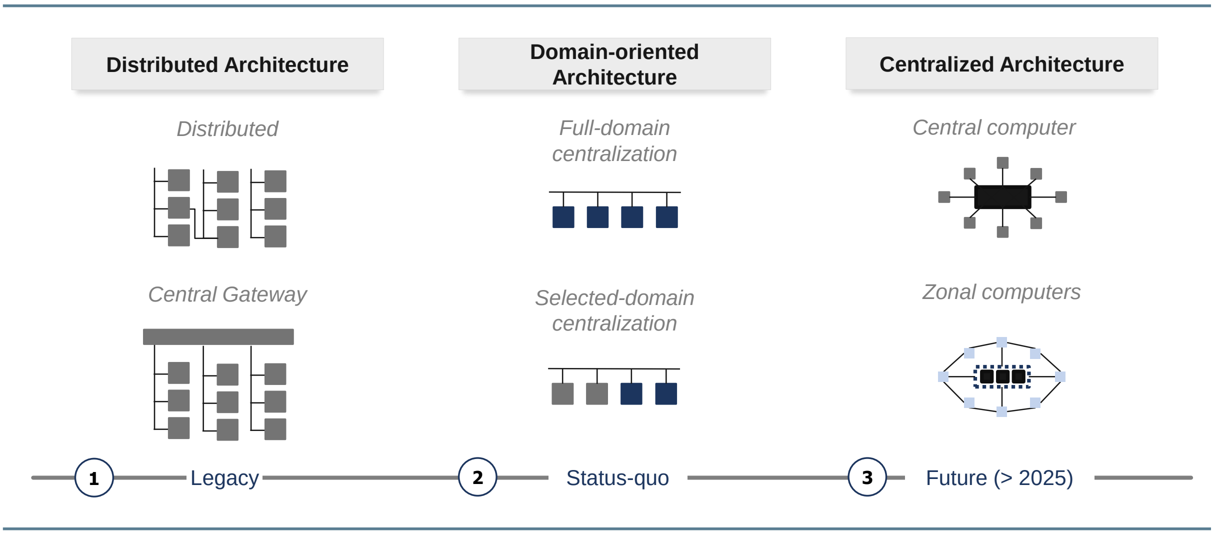

FIG. 5: EVOLUTION OF HARDWARE ARCHITECTURES

In simplified terms, this process can be divided into three main development stages:

1. **Distributed Architecture:**
   A large number of highly distributed and specialized ECUs characterizes this architecture. Functions or function groups are often covered by **specific ECUs**. This results in the current high number of ECUs (approx. 80 - 100 ECUs) in the vehicle. Standardization of the hardware is only possible to a limited extent, and scaling is often achieved via additional ECUs. OTA updates of software distributed on decentralized ECUs are only possible with great effort. Due to the further increase in vehicle functions and the associated networking and development complexity, this architecture will become less important in the future.
2. **Domain-oriented Architecture:**
   This architecture represents the status quo of current vehicles. In each vehicle domain, e.g. ADAS, infotainment, chassis, powerful **domain control units** (DCUs) are used to implement functions of higher complexity within a domain. In addition, ECUs that still exist in a domain are connected to the DCU. To facilitate cross-domain functions, in some cases cross-domain control units are also used jointly for several domains.
3. **Centralized Architecture:**
   At the heart of this architecture is a domain-independent high performance vehicle computer that can execute complex functions from all domains. This central computer is supplemented typically by a few zonal ECUs distributed in the vehicle, which are physically located near the sensors and actuators. Within this **zonal architecture**, zonal computers can perform individual functions within each zone and are responsible for distributing data and power within the zone. At the same time, peripheral components like sensors or actuators will become ‘smart’ and implement local intelligence in order to provide hardware services to the vehicle. Eventually, the goal of this architecture is to use the central computer and the zone computers as standardized hardware, thus significantly reducing the complexity of the hardware architecture.

Overall, these three development stages represent a spectrum of possible hardware architectures. In the current transition phase, an evolutionary development toward zonal architectures as well as the emergence of mixed architectures is expected. These mixed hardware architectures combine zonal computing and domain-centric computing with a communication gateway between both worlds. A significant proliferation of mixed architectures in volume vehicles is expected from 2025 onwards, with pure zonal architectures gaining importance after 2030.

However, significant differences between OEMs are possible in this regard. Some OEMs are aiming for a consistent implementation of centralized hardware architectures in combination with hardware abstraction. Other OEMs are more strongly tied to legacy components and structures and are therefore limited in their implementation options. Furthermore, integration of legacy components will be necessary because not all systems will be enabled for centralized architectures and will be available from suppliers in the same time frame. Especially safety-critical functions will initially not be implemented on zonal architectures, but will remain on separated ECUs.

Communication network

The development towards automated driving poses new challenges for the in-vehicle communication network, which must meet requirements such as high availability/redundancy, real-time capability or time synchronization. In order to transmit large amounts of data from radar, lidar or cameras, a high communication bandwidth is necessary. Previous networking standards like CAN or LIN have reached their limits and are currently supplemented by new high-speed networks such as Automotive Ethernet. Automotive Ethernet is currently applied with a transfer rate of up to 1,000 MBit/s at the 1000BASE-T1 standard.

As discussed in the previous section, the E/E architecture is about to transform to more centralized hardware architectures. In a zonal architecture, Ethernet is expected to act as a communication backbone through which all zones communicate with the central vehicle computer. Within the zones, various networks can possibly be included. As an example, different network technologies such as CAN, LIN or FlexRay can co-exist within the zones on a low system level. Above this, in the second layer of the network, intermediate gateways connect classic network technologies and Ethernet. On the top layer, a pure Automotive Ethernet network can be implemented. This structure is intended to enable more responsive communication with all networks.

Against this background, Automotive Ethernet will not be established as the only standard for data communication and a diversity of standards will remain. Even in new E/E architectures, new ECUs must coexist with older ECUs and CAN is more cost-effective most cases. However, activities of the individual manufacturers are very different. While some OEMs are not nearly

exploiting the potential of existing solutions, others are already calling for multi-gigabit Ethernet. In order to advance automated driving, activities are already underway within the IEEE to standardize data rates of more than 10 Gbit/s up to 100 Gbit/s

Besides higher bandwidths, a further advantage of Automotive Ethernet is the support of TCP/IP, hence facilitating in-vehicle communication via an Ethernet backbone and resembling external communication between the vehicle and the cloud. This similarity enables automotive manufacturers to use a common network technology for their connected vehicle infrastructure, which permits more seamless software updates over-the-air as well as a reduction in design complexity.

Energy network

Similar to the E/E architecture levels described in the previous sections, the vehicle energy network is also facing profound changes. The main drivers of these changes are the introduction of new voltage levels for electrified vehicles, new vehicle systems with high power requirements, and increased safety requirements for X-by-wire and automated driving functions.

The change of powertrain technologies from internal combustion engines (ICE), to mild hybrids (MHEV), to battery electric vehicles (BEV) introduces additional voltage levels in the vehicle. MHEVs are typically based on a 48 V energy network as an addition to the conventional 12 V network. In BEVs, the purely electric drivetrain requires a high-voltage level, which is currently mostly on 400 V or 800 V. Due to improved fast-charging capabilities, voltage levels of up to 1,000 V are already under discussion for future BEVs. Nevertheless, a BEV still features a conventional 12 V energy network and in few cases also additional 48 V components. However, three voltage levels within one vehicle lead to complex and costly solutions and are not considered as a long-term approach by many experts.

The 12 V energy network has grown historically and is used to supply a large number of consumers. Since a redesign of all 12 V components would be very complex and cost-intensive, the established 12 V voltage level will also be maintained in BEVs. However, the 12 V level reaches its limits for some high-power consumers, e.g. roll stabilization, electric climate compressors or brake-by-wire systems. Therefore, these systems are either developed on 48 V or directly realized on the 400 V or 1,000 V high-voltage level. A key challenge for a direct supply of high-voltage components are of course the strict safety regulations which have to be fulfilled. For this reason, suppliers currently perform intense development activities to qualify components with high-power demands for a direct high-voltage supply.

Safety-critical X-by-wire and Automated Driving functions need a fail-operational power supply which provides energy under all fault conditions. Therefore, an independent power distribution system or redundant power sources have to be integrated into the energy network. Whereas redundancy is currently often realized on a function-individual level only, the increase of safety-critical functions in the vehicle requires an energy network comprehensive redundancy. For this reason, different energy network topologies (e.g. ring power net, energy backbone, tree power net) as well as supporting technologies (e.g. Smart PDUs, eFuses) are being developed. From a technical perspective, a stronger convergence between communication and energy network topologies can be realized with new architectures, since all components require both, energy and communication. Eventually, a strong trend towards a highly decentralized power management system is expected since energy supply can no longer be developed ‘dedicated to’ a defined set of functions or components within the vehicle.

Implications for automotive players

The automotive E/E architecture is facing a paradigm shift. A key feature of this new E/E paradigm is the emergence of software-defined vehicles, so that in the future vehicle functions will largely be realized by software. In this context, the aim is to achieve maximum possible abstraction from the underlying E/E hardware. The current development trends in the automotive industry, in particular automated, connected and electrified vehicles, are acting as drivers of this paradigm shift. The extreme increase in system complexity in combination with strict requirements regarding functional safety and cybersecurity cannot be implemented with the previously established E/E architectures and development approaches. With regard to the supply chain and vehicle production, the effects of a high variance together with high technological complexity are evident already today, e.g. the dependency on specific semiconductors.

OEMs are therefore aiming for a reduction of variants based on a comprehensive standardization of the hardware and a modular structure for the functional software. The software modules should be individually interchangeable and updatable, as well as transferable to other hardware with as little adaptation and validation effort as possible. Automotive suppliers must therefore also realize a separation between hardware and software components in order to be able to offer software as a stand-alone product in the medium term. The development of a comprehensive understanding of the future E/E overall architecture is essential in order to be able to derive future requirements for system components. In addition, adaptions to the process and organizational structure may be necessary to ensure component-independent development of software.

The strong focus on software-based functions is necessary to be able to cover the expected significant increase in complexity and variance. Especially in the current transformation phase, different hardware architectures, system components, communication technologies, voltage levels, etc. will coexist. In addition, different speeds of transformation are emerging among OEMs. For system and component suppliers, the early definition of a suitable product portfolio and technology strategy is therefore urgently required in order to use development budgets in a targeted manner and to be able to implement requests from OEMs efficiently.

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For 40 years, fka has been internationally known as an innovative engineering service provider for the automotive industry. Driving the world by developing ideas and creating innovations is the vision that fka's 160-strong team is committed to.

The team is inspired by a passion for efficient, safe and fascinating mobility. As one of the first companies on the Campus Melaten in Aachen, the spin-off of the Institute for Automotive Engineering of RWTH Aachen University demonstrated foresight early on. Interdisciplinary expertise in all aspects of mobility and technological visions, combined with the advantages of the inspiringly creative location, are fka's fuel. Ideas, innovations and unique methodological expertise are shaped into well-founded and validated solutions that give fka's customers the necessary advantage in various fields.

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