A Taxonomy and Systematic Approach for Automotive System Architectures
From Functional Chains to Functional Networks

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Abstract: Technological advances enable realization of increasingly complex customer features in the automotive sector. Traffic jam pilot or predictive energy management depict examples of recently introduced features that span across different conventional vehicle domains. The increased interconnectivity and functional complexity impose new requirements on the automotive systems engineering practice. The resulting challenge is to develop integrated approaches that combine the established procedures with innovative techniques. To address this challenge, we present a comprehensive taxonomy for existing automotive features. Based on this characterization, established industrial and new research approaches for logical system architectures are consolidated. We introduce levels of hierarchy in the logical system architecture to facilitate systems engineering of innovative functions and highly distributed features. The systematic approach provides a novel rationale for the evolution from functional chains to functional networks in the automotive industry.

1 INTRODUCTION

Within the last decade a multitude of Advanced Driver Assistant Systems (ADAS), such as Adaptive Cruise Control (ACC) and Lane Keeping Assist (LKA) were introduced into the automotive market. These features leading the way, automated driving becomes a reality (Becker et al., 2014). The new features are enabled by the steadily advancing technological progress, which provides high-performance computing in automotive environments. The new features raise the functional complexity regarding utilized algorithms, distribution of functions and the amount of processed information, which has a considerable impact on Electrics/Electronics (E/E) system architectures. Current development methods and approached are not sufficient to cope with the new complexity.

Several roles, teams and organizations participate in the development of an automotive system. Scattering over different development locations leads to collaborative development (Weber and Weisbrod, 2002). The development in automotive vehicles is historically structured into different domains (Reinhardt and Kucera, 2013), such as powertrain, safety and chassis. This modularization evolved from the product perspective and lead to corresponding organization structures to facilitate product engineering (Weber, 2009). The domains originate from mechanical engineering and were expanded with electrical and information processing aspects. Within the different domains, several approaches for development processes, methods and tools are established and integrated into the overall product development process. These methods serve different needs and foci of the engineers, which differ from domain to domain. As upcoming customer features lead to fuzzy system borders, the different domains' development is moving closer together (Haas and Langjahr, 2016). The integration and collaboration of domains is necessary without abandoning methodological flexibility and individuality.

For Original Equipment Manufacturer (OEM), well-established and long-existing systems such as Electronic Stability Control (ESC) are iteratively optimized achieving a high-level of maturity. Supplier structures and adjacent business units, such as purchase or after sales, are shaped to the originated needs. As new highly-integrated features partly collude with the existing systems, the question of how to use legacy systems during development poses a challenge. To foster the reuse of specific functionalities of the established systems is a key issue for efficient development.

Novel research and development approaches for systems engineering focus on automated driving

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(Matthaei and Maurer, 2015), (Tas et al., 2016) do not comprehensively cover the aspect of legacy systems. The presented functional architectures mainly focus on the automated driving or ADAS domain. Therefore, focusing on assisting and automating functional aspects and applying hierarchization without consideration of the relevant conditions of adjacent domains. A comprehensive approach for the abstraction and description of the functional architecture with respect to different level of integration and complexity of features is required.

To overcome these impediments, we present a taxonomy for existing automotive customer features across all domains, structuring them into different level of complexity. The taxonomy forms a basis to provide a systematic approach for systems engineering with a focus on functional aspects. This systematic approach can be further elaborated to consider the impact on development processes.

The paper is structured as followed: Section 2 presents the state-of-the-art of systems engineering and automotive architectures. Our cross-domain taxonomy for current and upcoming electric/electronic features is elaborated in Section 3. Our proposed approach for logical architectures and hierarchization is given in Section 4. Section 5 demonstrates the applicability of the approach on exemplary automotive features. A conclusion and outlook on further activities is presented in Section 6.

2 STATE OF THE ART

Systems engineering is a discipline to ”guide the engineering of complex systems” (Korsiakoff et al., 2011). The term ”System” is widely spread across different fields and application domains and several approaches for development are established. Within the automotive area, the system ”Vehicle” is partitioned into different domains structuring the mechanical key components of the vehicle (Weber, 2009). In the context of this paper, we focus on automotive E/E systems engineering, which consists of several different fields such as architectures, management, modeling and operation research (Korsiakoff et al., 2011). In the automotive domain, the management of development processes if commonly based on the V-Model. The AutomotiveSPICE (Automotive-SIG, 2015) specifies an established process reference that integrates the V-Model approach. In this contribution, we focus on the architecture and structuring of automotive embedded systems to facilitate the process of systems engineering.

2.1 System Architecture

Several approaches and methods for the structural description of system architectures (ATESST2 Consortium, 2013), (Pohl et al., 2012), (Vector Informatik GmbH, 2016) follow a model-based approach. The principle of abstraction contributes to reduced complexity (Korsiakoff et al., 2011) and facilitate system understanding (Bhave et al., 2011). It enables the structured analysis of specific topics, such as functional safety (Adler et al., 2012). Common abstraction layers of automotive embedded systems are Logical Architecture, Software Architecture and Technical Architecture. A basic overview is given in Figure 1.

The abstraction layers provide a partial description of the system based on different perspectives

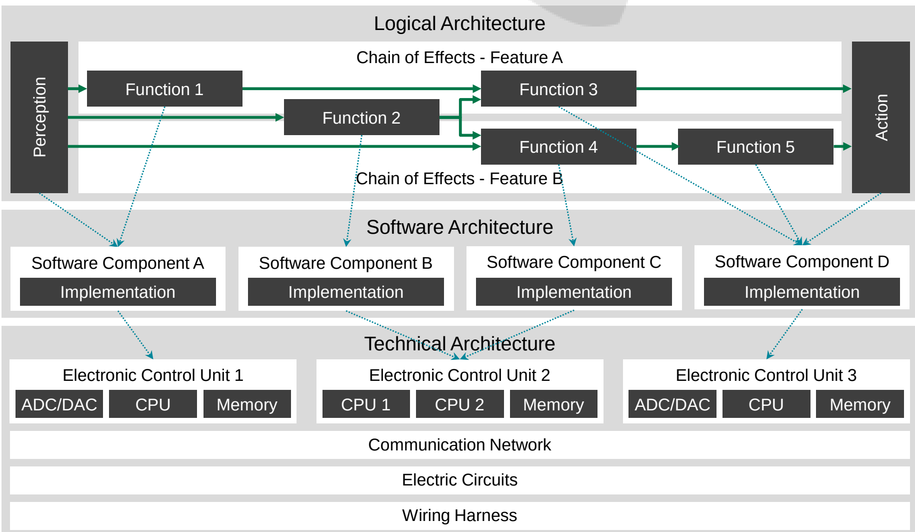

Figure 1: Three abstraction levels of the automotive system architecture and mapping of functional behavior to software components and electronic control units. Depiction referring to (Broy et al., 2009) and (Schäuffele and Zurawka, 2012).

(Zhan and Krishnan, 2011), using the principle of modularization of blocks and connections. Also hierarchization and encapsulation of artifacts to describe different levels of detail is intended. Between the artifacts of different abstraction layers, interconnections and relations with distinct semantic are present (Pohl et al., 2012). The example in Figure 1 depicts relations, which describe the partitioning of functional entities into software components for integration on distinct Electronic Control Unit (ECU)s.

2.1.1 Logical Architecture

The logical architecture is a breakdown of a feature ”into interacting functional components” (Pretschner et al., 2007). It represents the functional decomposition of a system into functional elements, which provide the functionality described in the corresponding requirements. The logical architecture focuses on the functional aspects, the logical interfaces and the coherence between the functional elements. It is completely independent from technical considerations or software specific issues. A common approach in the automotive area for the structuring of logical architectures is the usage of chains of effect to describe an overall approach from sensing to acting (Schäuffele and Zurawka, 2012). Demands for more elaborated concepts to improve the structuring of increasing complex features are initially addressed in (Holder et al., 2012) and (Pretschner et al., 2007). Description of the functional element's internal behavior is highly depending on the associated domain and not in scope of this contribution.

2.1.2 Software Architecture

The software architecture describes the different software components and the partitioning of the functional elements, including basic software (operating system and middleware) and communication (Schäuffele and Zurawka, 2012). A standardized middleware for software components allows reuse of the basic elements, for automotive embedded systems this is given by the AUTomotive Open System ARchitecture (AUTOSAR) (AUTOSAR development cooperation, 2015). It specifies a software framework and architecture consisting of basic software elements, a run-time environment (RTE) and application software components to enable reuse and scalability.

Improvements and extensions for AUTOSAR introduce adaptive deployment, service-oriented communication and dynamic scheduling and application execution as well as integration in new high-performance processor architectures. The related specification under the term ”AUTOSAR adaptive” is currently under development within the AUTOSAR partnership (Fuerst, 2015).

2.1.3 Technical Architecture

The technical architecture specifies the integration level, which contains the hardware units to execute the defined software components (Pretschner et al., 2007). This comprises the ECU, actuators and sensors and their interconnections. In automotive systems engineering, the technical architecture is commonly further refined to represent specific E/E aspects, such as electric circuits and the wiring harness. The technical system architecture is based on a comprehensive E/E topology containing a segmentation into previously introduced domains, such as body, chassis and comfort. The current E/E architectures often reflect the organizational structure introduced by segmentation of the car's mechanical structure. Historically, single ECUs were introduced to perform independent functionality (Leen and Heffernan, 2002), connected with a single centralized gateway (Streichert and Traub, 2012) .

With increasing complexity and an increasing number of ECUs, domain-controlled E/E architectures with centralized domain-controllers were introduced (Reinhardt and Kucera, 2013), (Stolz et al., 2010). This trend was an initial reflection to expanding system boundaries, more complex functional chains and higher integration of features. For each domain, master controllers were introduced to facilitate domain-comprehensive features. The evolution of technical system architectures is thus tightly coupled with the increasing interaction and networking of the logical architecture. The current development leads to centralized cross-domain E/E architectures based on high-performance computing units (Navale et al., 2015), (Haas and Langjahr, 2016).

2.2 Architecture Concepts for Automated Driving

Research in the field of automated driving provides various approaches to describe the system architecture of research concepts. Stiller (Stiller et al., 2007) provides a cognitive oriented approach of perception, planning and action tasks. Different layers classify the abstract representation of functional elements. The architecture concept provided by Bauer (Bauer et al., 2012) is categorized into a mission layer, a coordination layer and a behavior layer. Each layer consists of elements of the world model class, the planning class and the HMI class. The utilized sensors, actuators and the driver form the system environment. The influence of human-machine interactions on system architecture is discussed by Flemisch (Flemisch et al., 2014). Based on the psychological categorization of the Dynamic Driving Task (DDT) into navigation, guidance and control, the automation system provides an interface on each level. Matthaei (Matthaei and Maurer, 2015) proposes a "functional system architecture for an autonomous on-road motor vehicle". It applies a similar categorization into a strategic level, a tactical level and an operational level and a further distinction between localization, perception and mission accomplishment. An implemented system architecture for automated driving, using production vehicle sensors and additional prototyping sensors, was presented by Aeberhard (Aeberhard et al., 2015). Buechel (Buechel et al., 2015) presents the prototype of an automated electric vehicle. The proposed software architecture consists of the three components data fusion, trajectory planning and trajectory controller, which is mapped to a centralized E/E architecture.

3 TAXONOMY FOR CURRENT AND UPCOMING ELECTRIC/ELECTRONIC FEATURES

Todays technical compendiums of carmakers are crammed with a high variety of customizable features. A significant proportion of those features is based on E/E functionality. With rising complexity of and dependencies between features, the established automotive systems engineering methods and abstraction concepts are reaching the limits of their capability. To identify boundaries and necessary extensions of current systems engineering methods we start with establishing a comprehensive overview of current and upcoming E/E features. Our goal is to integrate well-established features of the automotive industry and current concepts of research groups within one consistent taxonomy.

Our proposed taxonomy distinguishes features by three main categories. Integrated features are closely related to a specific mechanical domain of the vehicle. They represent the E/E content necessary to accomplish the targeted operation of physical components of the vehicle. Distributed features combine individual components of different domains to enable additional capabilities. These features do not necessarily require additional mechanical hardware components. Their functional behavior can be expressed as the sequential combination of available information and usable actuators to provide added value. Cross-linked features connect various functional elements and depend on the joined manipulation of the behavior of independent and domain separated components. They conflate various sources of information to achieve a comprehensive representation of the vehicle's state and surroundings. This representation forms the basis for cognitive and predictive features, including but not limited to high automation levels.

Figure 2 depicts our proposed taxonomy. It classifies and combines vehicular features of existing series cars and features of current research. The taxonomy's features available in series cars represent an abstracted set of the offered features of major car companies. We analyzed the online presence of BMW[1], Daimler[2], Ford[3], Peugeot[4], Toyota[5] and VW[6] to select the most common features. Research features were selected to cover a range as wide as possible.

3.1 Integrated Features

As stated above, the integrated feature level subsumes the E/E content to operate the physical components of the vehicle. This entails a close proximity to specific mechanical units and commonly involves the usage of a dedicated ECU. Most sensors and actuators required for the assigned task of the feature are directly attached to the dedicated ECU. Integrated features are mainly based on proprioceptive sensors. Proprioceptive sensors obtain information about the internal state of the vehicle (Bengler et al., 2014).

Our taxonomy differentiates the integrated features into the established vehicle domains. Weber (Weber, 2009) defines five of the six domains we apply. The powertrain domain contains "all functions controlling the generation of driving power and its conversion into propulsion". The taxonomy includes the features automatic transmission, engine control,

[1] BMW Technology Guide, Bayerische Motoren Werke Aktiengesellschaft, http://www.bmw.com/com/en/insights/technology/technology_guide/index.html

[2] Welcome to the Mercedes-Benz TechCenter, Daimler AG, https://techcenter.mercedes-benz.com/en/index.html

[3] Advanced technology at your fingertips, Ford Motor Company, http://www.ford.com/cars/focus/features/#page=FeatureCategory4

[4] Technologies & Innovations, Automobiles Peugeot, http://www.peugeot.com/en/technology

[5] Toyota Technology, Toyota Motor Sales, U.S.A., Inc., http://www.toyota.com/technology/

[6] Technik auf den Punkt gebracht., Volkswagen AG, http://www.volkswagen.de/de/technologie/techniklexikon.html

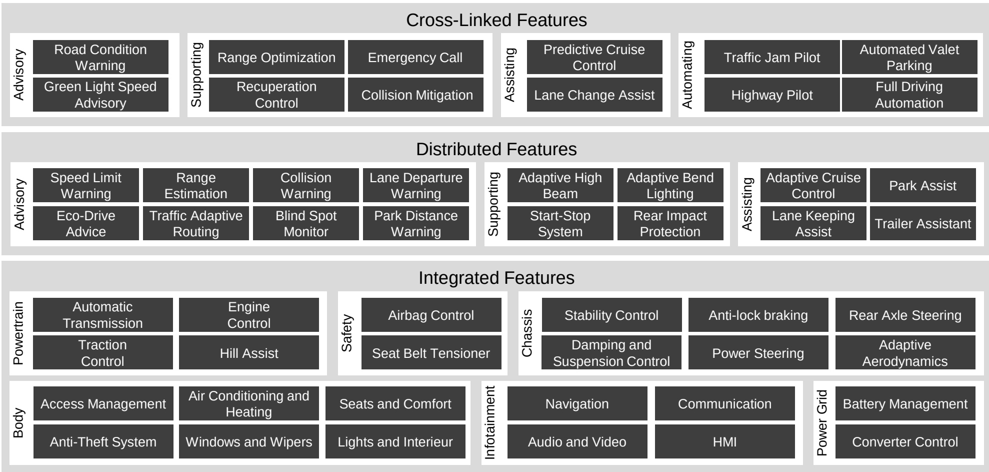

Figure 2: Taxonomy of current and upcoming E/E features. Integrated features are grouped by vehicle domains, distributed and cross-linked features by level of interference.

traction control and hill assist as a representative feature set of the powertrain domain. The safety domain on integrated feature level includes the passive safety features airbag control and seat belt tensioner. More sophisticated active safety features are classified as distributed features. The chassis domain includes features to control the vehicle dynamics, providing a safe and attractive driving experience. Stability control, anti-lock breaking and power steering describe features that mainly support safe and comfortable driving. Rear axle steering, damping and suspension control and adaptive aerodynamics particularly support agility. The body domain encompasses all features attached to the vehicle body, like lights, windows, wipers, seats and air conditioning as well as the car's access management and anti-theft system. The infotainment domain is the fifth vehicle domain based on Weber's definition. It summarizes the features for navigation, communication, audio and video entertainment and Human Machine Interface (HMI). To take advancing electrification into account, the power grid domain completes the integrated features. Battery management and converter control represent features that are part of 48 volt grids of hybrid electric vehicles as well as high voltage grids of fully electric vehicles.

3.2 Distributed Features

Most of the currently available ADAS are represented by the distributed features class. The functional behavior of distributed features resembles a chain of effects, the aforementioned sequential combination of available information and usable actuators. The functionality of distributed features is based on the connection of different domains. They often introduce and utilize exteroceptive sensors that provide information about the surroundings of the vehicle (Bengler et al., 2014).

The taxonomy categorizes distributed features by level of interference into the three classes advisory, supporting and assisting features. Assisting features are specified by SAE automation level 1 (SAE international, 2016) as features that "perform either longitudinal or lateral vehicle motion control [...]". To allow distinction between passive advisory and active supporting features on level 0, we introduce the distinctive classes.

The advisory class contains features that utilize information of integrated features and exteroceptive sensors to provide additional information for safe and comfortable driving and potentially to influence the driver's behavior. Collision warning, lane departure warning, blind spot monitor and park distance warning depict advisory features to gain additional safety. Speed limit warning helps to stick to regulations and eco-drive advice intends to influence the driver's behavior to achieve a sustainable driving style. Range estimation and traffic adaptive routing support the driver's decisions regarding the selected route and stopovers.

The supporting class covers all features that actively influence the vehicle's state, but do not perform longitudinal or lateral vehicle motion control. It encompasses features such as adaptive high beam and adaptive bend light as well as automated start-stop. Rear impact protection represents an active safety feature that aims to decrease the damage induced to passengers during standstill, rear-end collisions. Bogenrieder (Bogenrieder et al., 2009) describes an approach that utilizes a backwards oriented radar sensor to detect an imminent rear-end collision.

The park assist and trailer assistant feature perform lateral control of the vehicle, while longitudinal control always remains with the driver. Therefore, these are automation level 1 features and part of the assisting features class. The ACC feature performs longitudinal control and the LKA feature performs lateral control. While operated individually, both features represent automation level 1. If both systems are activated simultaneously, the feature combination represents automation level 2, "Partial Driving Automation". Consequentially, level 2 automation features are included in the assisting features class.

3.3 Cross-linked Features

In the presented taxonomy, cross-linked features utilize sensor networks to derive information or to influence several actuators. These features span functional networks in distinction to the sequential functional chains of distributed features. They are based on the fusion of proprioceptive and exteroceptive sensor information to obtain a realistic and complete model of the vehicle's internal state and surroundings. Similar to distributed features, cross-linked features are grouped into advisory, supporting and assisting classes with the addition of the automating class. It comprises features from automation level 3 upwards. By SAE definition, these features perform the complete DDT with or without fallback and within or without a specific Operational Design Domain (ODD).

The road condition warning feature in the advisory class is described in the Car2Car communication consortium manifesto (Baldessari et al., 2007). Severe road conditions are propagated via Car2Car communication or back end service between road users. The green light speed advisory feature is also defined by the Car2Car consortium. It interacts with the road infrastructure and provides an optimal speed advice, averting an otherwise necessary red light stop. Both features require lane accurate positioning and access to various internal states and the communication platform of the vehicle. Therefore, they are classified into the cross-linked feature class.

The supporting class contains two energy management related features, the range optimization and the recuperation control. The range optimization calculates the remaining energy of the vehicle and predicts the required energy to reach the desired destination. If necessary, it shuts down power hungry comfort features like heating and air conditioning and limits the propulsion power. The recuperation control predicts the vehicle's energy flows and for example reduces battery load before long recuperation phases, to prevent waste of energy due to battery heat protection (Woestman et al., 2002). As these features influence various actuators and require predictive map data, traffic flow information and internal states for optimal performance, they are classified into the cross-linked category. Emergency call and collision mitigation round out the supporting feature class. These are active safety features that take action before an imminent collision and automatically call help after an accident.

Equivalent to the distributed features, the assisting class covers features of SAE automation level 1 and 2. The predictive cruise control feature controls the longitudinal motion of the vehicle (Wahl, 2015). It calculates an energy optimal velocity trajectory based on predictive map data and proprioceptive and exteroceptive sensor information. The included lane change assist feature guides the driver's lane change maneuver (Cramer et al., 2015). It requires various sensors and predicts the surrounding traffic to calculate a safe lane change trajectory (Nilsson et al., 2016). Both feature's depend on several sensing, processing and acting primitive elements and, therefore, are classified as cross-linked features.

All features from SAE automation level 3 upwards belong to the automating class of cross-linked features. The example features traffic jam pilot, highway pilot, automated valet parking (Nordbruch et al., 2015) and full driving automation (Ziegler et al., 2014) perform the complete DDT. The former three features are designed for a specific operational domain. Depending on their characteristics and implementation, all automating features utilize more or less comprehensive environmental perception and interpretation. Beside the longitudinal and lateral control of the vehicle, the features must control several actuators to perform the complete DDT. Automating features comprise the highest level of cross-linking.

4 COMPREHENSIVE HIERARCHIZATION FOR LOGICAL SYSTEM ARCHITECTURES

As stated in Section 2.1, based on established system architecture modeling concepts, all functional behavior of the introduced features is modeled within one level of logical system architectures. Thereby, the differing character and integration depth of the individual functional elements is not considered. The representation resolves the complexity of the underlying functional dependencies and multiple usage scenarios of particular functional elements only to a limited degree. Hence, the systems engineering principles

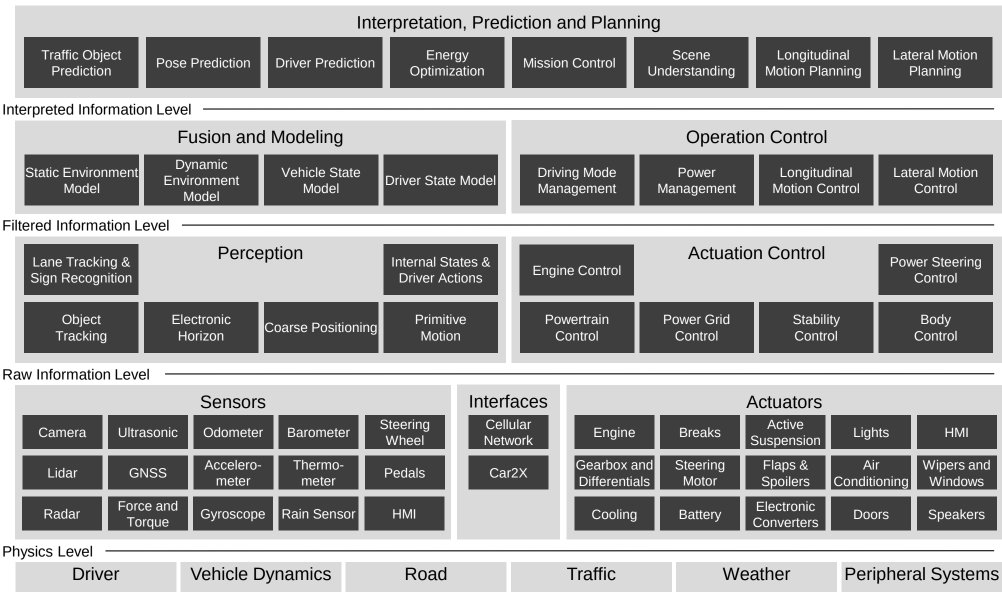

Figure 3: The proposed holistic hierarchization approach for the logical system architecture in the automotive domain.

of modularization, abstraction and hierarchization are not employed to the full extent.

Section 2.2 outlines the approaches utilized by researchers in the field of automated driving. The utilization of psychological concepts offers a sound characterization for the functional components of automating features. This supports the structuring of fundamental sub-tasks of the DDT, but does not necessarily support the entire systems engineering process. Existing and established E/E systems were mostly neglected by the described architecture representations. For an holistic approach we need a hierarchical structure that supports a clear representation of the dependencies between functional elements and includes all automotive E/E features. It concurrently provides an abstraction that facilitates adaption and association of different shapes of systems engineering activities.

The aim of the proposed hierarchization of functional elements is to introduce a comprehensive domain-crossing functional architecture. The introduced hierachization is based on the integration level and the character of the processed information. This enables a flexible description of the existing chain of effects and their interaction with associated elements within one systematic approach and simplifies precise specification of interfaces. It facilitates the definition of tailored templates for activities, such as verification and validation, functional safety and release planning. These templates could guide developers, testers, project and quality managers during the configuration of function specific process implementations and the selection of a balanced set of suitable methods and tools.

Figure 3 depicts our newly introduced hierachization for the logical system architecture. The classified features of Section 3 were broken down into principal functional elements and arranged to represent a clockwise flow of information. The layered approach provided by Stiller (Stiller et al., 2007) served as basis for the development of the logical system architecture.

The type of information that is processed by the respective element, is the major discrimination criterion we apply to assign the elements to a particular level. The physics level contains the functional elements to gain information from physical principles and vice versa to influence the physics. On the raw information level the derived raw information is filtered and actuation requests are processed. The filtered information of different functional elements is combined via information fusion techniques within the filtered information level and interpreted information is used to operate the actuators. On the highest level of the hierarchization, the interpreted information is used to predict and abstract the state and behavior of the system environment and the upcoming course and actions of the vehicle are planned. In the following, we explain these different levels, their characteristics and possible consequences for future systems engineering.

4.1 Physics Level

The physics level of the logical system architecture is composed of sensors, interfaces and actuators and comprises all interfaces to the system environment. Sensors utilize physical measurement principles and provide basis perception functions. They provide raw information in form of discrete, unfiltered sample data. The type of supplied information ranges from sampled physical quantities like force and torque, acceleration and velocity to the raw image provided by a camera and the point cloud of a lidar sensor. The sensors class also contains the control interfaces of the driver and the Global Navigation Satellite System (GNSS) receiver.

The interfaces class enables the interaction with affiliated technical systems. It provides access to cellular networks and communication entities such as Car2X, representing a bidirectional flow of information.

The actuators encompass all functional elements to affect the vehicle state and its environment as a physical system. The powertrain elements engine, gearbox and differentials influence the propulsion and the flow of energy of the vehicle. By application of steering torque, the steering motor affects the lateral movement of the vehicle, but also acts as an interface towards the driver. Active suspension and flaps and spoilers alter the properties of aero- and vehicle dynamics. Further functional elements serve a supporting purpose (e.g. cooling, wipers or lights) and to influence the driver (e.g. HMI, speakers).

4.2 Raw Information Level

This level contains the functional elements required for filtering and processing of raw signals and to drive the actuators. The functions within the perception class process the physical sensor's raw data to derive tangible information about the vehicle's primitive motion and internal states. Coarse positioning is achieved by interpretation of the pseudoranges in the navigation satellite receiver and the electronic horizon provides information about the upcoming road segment from an internal data storage. Images and point clouds are processed to extract surrounding objects, lanes and traffic signs.

The actuation control class drives and controls the mechanical components of the vehicle via the physical actuators. It represents the basic functional components of the integrated features that are essential for the vehicle's operability. The software implementation of functions on this level is subjected to hard real-time constraints.

While the elements of the physics level represent the functional share of mechanical and electrical hardware components, the raw information level contains the functional part of the embedded software associated with those elements. Its development should be coupled with the processes of the physical level. On this level, the development of components is commonly carried out by Tier 1 suppliers. Validation and verification of the functional elements can mostly be done independent of other elements. The obtained information is commonly shared within the related domain of the vehicle's communication network.

4.3 Filtered Information Level

Functions on the filtered signal level perform fusion and abstraction of the various detached information sources and control the vehicle operation. The information of the proprioceptive and exteroceptive sensors is accumulated in the interpretation class. The static and dynamic environment model provide a condensed and consistent representation of the vehicles surroundings. The vehicle state model consolidates all internal vehicle states and the driver state model describes the driver's features, such as level of attention and driving style.

The functions to control the lateral and the longitudinal motion of the vehicle are the most important items of the operation control class. Their task is to achieve the targeted velocity and vehicle pose within the operational limits. The driving mode management coordinates the underlying functions to attain a well-attuned driving experience. The power management approves and limits power consumption of the various components and coordinates the recuperation of electrified vehicles.

The functions of the filtered information level are not essential for the operability of the vehicle, but enable distributed features. The included longitudinal and lateral control elements are part of the assisting and automating features. The functions on this level are subjected to soft real-time constraints. Verification and validation of these functions is performed on the interface level. Simulation based techniques require modeling of not only the vehicle physics and environment, but also modeling of all underlying functional elements implemented in software.

4.4 Interpreted Information Level

The interpreted information level contains cognitive functions for interpretation, prediction and planning. Stochastic models enable the prediction of the behavior of traffic objects and driver intentions. The information of the vehicle state model facilitates the prediction of the vehicle's pose. The functional element scene understanding represents the interpretation of the aggregated information. The longitudinal and lateral motion planning functions are based on the interpreted information and act on the underlying control functions. A dedicated element for energy optimization enables the range optimization and the recuperation control features. The mission control function is an essential part of all automation features. It coordinates the individual elements to accomplish the driving task.

The functional elements of the interpreted information level are best suited for implementation on a centralized, high-performance control unit, as the amount of data necessary to provide the described information exceeds the capability of established communication networks. The functional elements of the interpreted information level resemble a service-oriented approach. Therefore, no guarantees for real-time constraints are given. Simulation models for verification and validation of these high level functions do not need detailed models of the vehicle mechanics or the physical background of the utilized sensors. Emulation of the model based environment representation and the control behavior of the filtered information level is sufficient.

5 REPRESENTATION OF SELECTED FEATURES WITHIN THE PROPOSED LOGICAL SYSTEM ARCHITECTURE

The elements within our proposed logical system architecture were derived from the analysis and taxonomy of existing and conceptual automotive features in Section 3. In the following, we demonstrate the applicability by modeling selected features of all three main categories of the taxonomy. The modeling of established features shows the ability of our approach to maintain legacy content. The representation of research concepts proofs the ability to cope with future demands.

5.1 Integrated Features

Of the integrated feature class, the ESC and the power steering control are modeled within our proposed logical architecture.

5.1.1 Power Steering Control

The power steering control feature serves as an actuator to influence the lateral movement of the vehicle. It applies a torque to the steering wheel to support the driver actuation or to achieve a given target steering position. The power steering described by Kim (Kim et al., 2015) supports the driver's steering intention. It provides a detailed description of the architecture of a power steering control feature for driver support. The torque applied by the driver is sensed and amplified depended on the vehicle velocity. Naranjo (Naranjo et al., 2005) describes a power steering feature for automated control of the vehicle. It applies steering torque to control the steering position. To obtain a satisfactory control behavior, the control is operated with a duty cycle of 10 ms.

Therefore, the power steering feature consists of the odometer and steering wheel elements of the sensors class, the power steering control function and the steering motor of the actuators class.

5.1.2 Electronic Stability Control

The ESC feature "is an active safety technology that assists the driver to keep the vehicle on the intended path and thereby helps to prevent accidents" (Liebemann et al., 2004). The yaw movement of the vehicle is stabilized by individually controlling the tire slip of each wheel. To avoid counteracting the driver, "it needs to accurately interpret what the driver intends for the vehicle motion in order to provide added directional control" (Tseng et al., 1999).

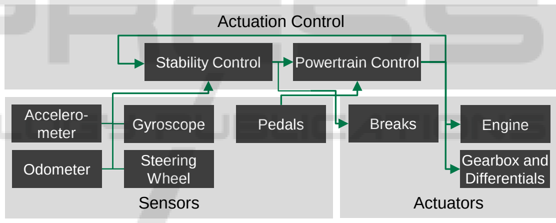

Figure 4: The chain of effects of an electronic stability control feature (Liebemann et al., 2004) described, using our newly introduced logical system architecture abstraction.

Figure 4 depicts the logical system architecture of the ESC. The current yaw rate and vehicle movement is read in from a gyroscope, an odometer and an accelerometer. The driver intention is derived from the information of the steering wheel and the pedals. The stability control functional element calculates the individual tire slips necessary to obtain a stable movement. Actuation of the brakes is directly applied, the engine, gearbox and differentials are actuated via the powertrain control function.

5.2 Distributed Features

To represent the distributed features class, we selected the ACC feature as a longitudinal control feature and the LKA feature as a lateral control feature.

5.2.1 Adaptive Cruise Control

The ACC feature depicts an assisting feature that controls the vehicles longitudinal velocity and adapts it to the velocity of leading traffic. Winner (Winner et al., 2012) provides a comprehensive overview of the ACC feature. The radar based perception of the area in front of the vehicle is used to calculate and control the vehicle's velocity. The driver inputs are monitored to detect an override by throttle actuation and a deactivation by brake actuation. Moon (Moon et al., 2008) describes a two-level control structure, where the upper level controls the vehicles speed by requesting accelerations and the lower level controls the acceleration by throttle and brake actuation.

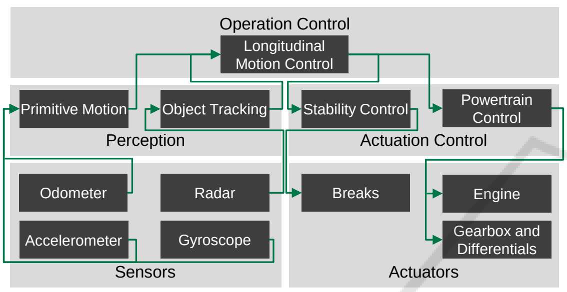

Figure 5: The core elements of the ACC logical system architecture.

Figure 5 depicts the logical system architecture of an ACC feature. For comprehensibility, the elements for driver interaction, like activation and override, are removed and only the core elements are represented. The primitive motion of the vehicle is estimated based on internal sensors information. The radar signal is processed by the object tracking function and used to calculate and control the desired time-gap in the longitudinal motion control function. Actuation is performed via the stability control and the powertrain control elements.

5.2.2 Lane Keeping Assist

The lane keeping assist feature assists the driver in the lateral control task without without assuming control of the complete DDT. Following Ishida (Ishida and Gayko, 2004), "The lane keeping assistance system consists of a camera-equipped lane recognition unit, the LKAS control unit, and the Electric Power Steering (EPS)." The lane tracking functions extracts the lane markings in the camera image and calculates the lateral deviation, orientation and curvature. This information is used as control variables in the lateral motion control function. The actuation is a steering torque applied via the power steering control and the steering motor.

5.3 Cross-linked Features

Of the cross-linked feature class we selected the Predictive Cruise Control (PCC) feature of the assisting class. Wahl (Wahl, 2015) describes the PCC as a feature for optimal longitudinal control. The ACC is extended to adapt the velocity to the road topology and speed limits besides leading traffic. Figure 6 depicts the logical architecture of the PCC feature.

The environmental perception of the ACC is extended by a camera system for lane tracking and traffic sign recognition. A GNSS receiver provides coarse positioning, which is used to provide the upcoming road topology via the electronic horizon function. A consistent model of the static environment, the vehicle state and the dynamic environment is formed on the interpretation level.

The feature implements a model predictive control strategy. Therefore, the pose of the vehicle and the movement of the traffic object are predicted and passed on. Bauer (Bauer and Gauterin, 2016) splits up the control task of the PCC into two levels. This approach maps to the longitudinal motion planning element and the longitudinal motion control.

6 CONCLUSIONS

In this contribution, we presented a taxonomy for existing and upcoming automotive customer features. It provides a broad overview of the current automotive cosmos and facilitates the analysis of current challenges to systems engineering practice.

To handle increasing functional complexity, we introduced an hierarchical structure to the logical system architecture. The classification is designed to cover all vehicle domains and enable representation of functional chains and networks. The structure provides a neat general view and simplifies assignment of properties and interface specification. The systematic approach allows combination of new and legacy elements to derive innovative features. Following on the presented approach, future work involves the analysis of the influence and potential benefit to product development. The structured representation of functional elements allows a level-specific allocation of process quality gates. Adaption of the subsequential alignment of process actions to the different hierarchy levels fosters a harmonic feature ramp-up and enables introduction of agile practices. Association of aligned strategies for verification and validation and functional safety with the structured and holistic view on the logical system architecture should provide a substantial benefit.

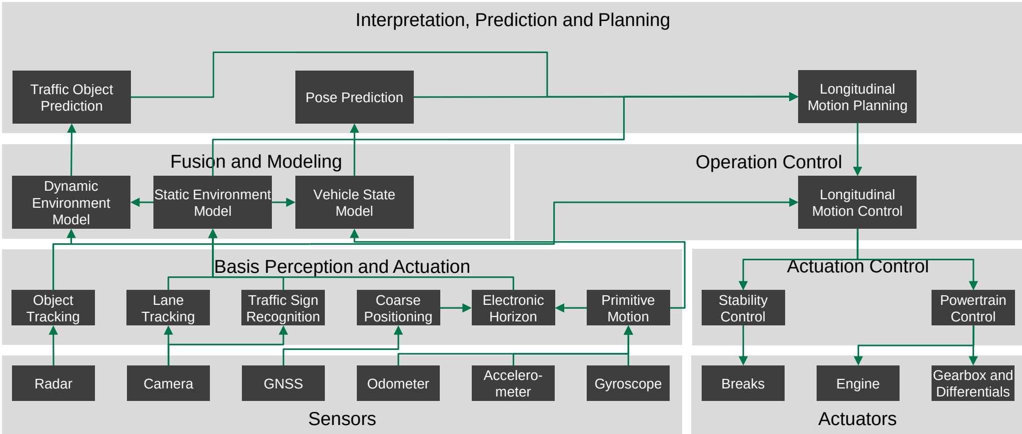

Figure 6: The chain of effects of a predictive cruise control feature described, using our newly introduced logical system architecture abstraction.

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