Proceedings

ATZ live

Alexander Heintzel *Hrsg.*

Automatisiertes Fahren 2022

Mobilität und Fahrzeugkonzepte von morgen

Springer Vieweg

Proceedings

Ein stetig steigender Fundus an Informationen ist heute notwendig, um die immer komplexer werdende Technik heutiger Kraftfahrzeuge zu verstehen. Funktionen, Arbeitsweise, Komponenten und Systeme entwickeln sich rasant. In immer schnelleren Zyklen verbreitet sich aktuelles Wissen gerade aus Konferenzen, Tagungen und Symposien in die Fachwelt. Den raschen Zugriff auf diese Informationen bietet diese Reihe Proceedings, die sich zur Aufgabe gestellt hat, das zum Verständnis topaktueller Technik rund um das Automobil erforderliche spezielle Wissen in der Systematik aus Konferenzen und Tagungen zusammen zu stellen und als Buch in Springer.com wie auch elektronisch in Springer Link und Springer Professional bereit zu stellen. Die Reihe wendet sich an Fahrzeug- und Motoreningenieure sowie Studierende, die aktuelles Fachwissen im Zusammenhang mit Fragestellungen ihres Arbeitsfeldes suchen. Professoren und Dozenten an Universitäten und Hochschulen mit Schwerpunkt Kraftfahrzeug- und Motorentechnik finden hier die Zusammenstellung von Veranstaltungen, die sie selber nicht besuchen konnten. Gutachtern, Forschern und Entwicklungsingenieuren in der Automobil- und Zulieferindustrie sowie Dienstleistern können die Proceedings wertvolle Antworten auf topaktuelle Fragen geben.

Today, a steadily growing store of information is called for in order to understand the increasingly complex technologies used in modern automobiles. Functions, modes of operation, components and systems are rapidly evolving, while at the same time the latest expertise is disseminated directly from conferences, congresses and symposia to the professional world in ever-faster cycles. This series of proceedings offers rapid access to this information, gathering the specific knowledge needed to keep up with cutting-edge advances in automotive technologies, employing the same systematic approach used at conferences and congresses and presenting it in print (available at Springer.com) and electronic (at Springer Link and Springer Professional) formats. The series addresses the needs of automotive engineers, motor design engineers and students looking for the latest expertise in connection with key questions in their field, while professors and instructors working in the areas of automotive and motor design engineering will also find summaries of industry events they weren't able to attend. The proceedings also offer valuable answers to the topical questions that concern assessors, researchers and developmental engineers in the automotive and supplier industry, as well as service providers.

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(Hrsg.)

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Springer Vieweg

Hrsg.
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Springer Fachmedien Wiesbaden
Wiesbaden, Deutschland

ISSN 2198-7432 ISSN 2198-7440 (electronic)
Proceedings
ISBN 978-3-658-44796-0 ISBN 978-3-658-44797-7 (eBook)
https://doi.org/10.1007/978-3-658-44797-7

Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über https://portal.dnb.de abrufbar.

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Planung/Lektorat: Ralf Harms
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Die Anschrift der Gesellschaft ist: Abraham-Lincoln-Str. 46, 65189 Wiesbaden, Germany

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Vorwort

Herzlich willkommen

Mobilität als Voraussetzung für Teilhabe am gesellschaftlichen Leben muss konzeptionell und kommerziell verändert und erweitert gedacht werden. Grundlage hierfür ist das automatisierte Fahren, das Freiräume für neue Fahrzeugkonzepte und inter- sowie multimodalen Verkehr eröffnet. Zentrale Herausforderungen hierbei sind mehr Verkehrssicherheit, die Verbesserung der digitalen On-Demand-Verfügbarkeit sowie eine neue Qualität der Nachhaltigkeit.

Ohne Sensorfusion, leistungsfähige Rechnertechnik, KI und V2X-Kommunikation ist automatisiertes Fahren nicht möglich. Um für jeden Mobilitätszweck attraktive Lösungen zu schaffen, bedarf es einer engen Vernetzung von Fahrzeug- und Elektronikentwicklern.

Der 8. Internationale ATZ-Kongress „Automatisiertes Fahren“ greift die aktuellen Entwicklungen und Rahmenbedingungen mit Vorträgen aus Europa, Asien und Amerika im konstruktiven Dialog auf.

Wir freuen uns auf Ihre Teilnahme an dem Kongress.

Für den Wissenschaftlichen Beirat

Dr. Alexander Heintzel
Chefredakteur ATZ | MTZ-Gruppe
Springer Nature

Preface

Welcome

Mobility as a prerequisite for playing an active part in social life must be redesigned and expanded, both conceptually and commercially. The basis for this is automated driving, which will open up new opportunities for innovative vehicle concepts and intermodal and multimodal transport. The key challenges here are greater traffic safety, improved digital on-demand availability, and a new quality of sustainability.

But automated driving is not possible without sensor fusion, powerful computer technology, AI, and V2X communication. If we are to create attractive solutions for every mobility purpose, we will need close collaboration between vehicle and electronics developers.

The 8th International ATZ Congress “Automated Driving” addresses the current developments and conditions with presentations from Europe, Asia, and America in a constructive dialogue.

We look forward to your participation in the congress.

On behalf of the Scientific Advisory Board

Dr. Alexander Heintzel
Editor-in-Chief ATZ | MTZ Group
Springer Nature

Tagungsbericht: „Automatisiertes Fahren 2022“

In Präsenz auf dem Weg zur Vision Zero

Die 8. Internationale ATZlive-Fachkonferenz Automatisiertes Fahren 2022 konnte (endlich) wieder in Präsenz stattfinden. Der überwiegende Teil der etwa 100 Teilnehmer war Anfang April vor Ort in Wiesbaden, ein Teil online dabei: Das tat der Veranstaltung gut, die Diskussionen um die Vorträge herum und in den Pausen waren entsprechend lebhaft.

Automatisiertes Fahren ist das Mittel für die Erreichung der Vision Zero, auf dem Weg dorthin steht aber zunächst durchaus die Entlastung des Fahrers im Vordergrund, wenn das Fahrzeug durch seine teil- oder hochautomatisierten Systeme bestimmte Strecken oder Situationen selbstständig durchfahren kann. Für weitergehende Mobilitätslösungen im urbanen oder ländlichen Raum müssen letztlich Geschäftsmodelle erst entwickelt werden, um das hochautomatisierte Fahren erfolgreich umzusetzen.

SAE-LEVEL JENSEITS VON 2+

Eröffnet wurde die Tagung mit der Keynote „Entwicklung von Automatisiertem Fahren: Evolution oder Revolution?“ von Georges Massing, Vice President MB.OS Automated Driving, Powernet und E/E-Integration bei Mercedes-Benz, im Dialog mit dem Publikum. Das assistierte und automatisierte Fahren müsse den Kunden Vorteile bieten, insbesondere Sicherheit, Komfort und Zeit. Er plädierte zudem dafür, die Unterscheidung zwischen Level-2-Assistenzsystemen und Level-3-(teil)automatisiertem Fahren prominenter zu betonen. Kennzeichnend für automatisierte Systeme in Pkw ist derzeit, dass sie seitens OEM stufenweise immer weiter optimiert und ausgebaut werden. So liefe die Entwicklung wie bei der passiven Sicherheit ab: ein Weg analog dem vom ersten Sicherheitsgurt bis zu modernen Airbagsystemen Richtung immer aktiverer Sicherheit mit immer noch mehr Funktionen.

Das resultiert in wahrhaft großen Aufgaben für die Branche: Auf der einen Seite sehe man laut Pierre Gompertz, Product Line Director Automated Driving bei Magna, eine sehr große Entwicklungsgeschwindigkeit, auf der anderen Seite wisse man nicht, wann es denn genug gesammelte Meilen seien für die Validierung. Die Gesamtaufgabe der Validierung sei so groß, dass es eigentlich Mega-Supplier jenseits der traditionellen Tier-1-Kategorie brauche. Es gebe zwar – auch wegen des Bedarfs für erst noch zu definierende Standards – keine Mainstream-Lösung, aber prinzipiell sei automatisiertes Fahren durchaus mit aktuellen Mitteln zu schaffen. Tier-1, OEMs, Start-ups und manchmal auch eine Kombination dieser Unternehmen würden die Transformation der nächsten Generation der Mobilität vorantreiben und sich dabei neu erfinden. Selbst wenn unterschiedliche Geschwindigkeiten sehr unterschiedliche Anforderungen an die Hardware stellen, ließen sich dennoch übergreifende Plattformen einsetzen und Skalierung nutzen, analysierte Dr. Felix Lotz, Product Manager Driving Functions bei Continental Teves in seinem Vortrag. So gebe es eine Vielzahl von Anwendungen wie das Fahren in städtischen Umgebungen oder auf Autobahnen, die davon profitieren, wenn Schlüsselelemente effektiv zwischen verschiedenen Plattformen und Funktionen geteilt und wiederverwendet würden.

FORSCHUNG UND STANDARDS ALS SCHLÜSSEL

Ein immer wieder aufkommendes Thema sind die regulatorischen Rahmenbedingungen: In den sogenannten Connected-Cooperative-and-Automated-Mobility (CCAM)-Aktivitäten versucht ein Netzwerk aus fast 200 Organisationen aus Industrie, Forschung, Dienstleistern sowie Behörden und Regulierungsstellen die Forschung zu bündeln und übergreifende Ergebnisse im Bereich Standardisierung zu erarbeiten. Diese Zusammenarbeit auf europäischer Ebene solle helfen, Barrieren abzubauen und die Einführung des automatisierten Fahrens zu beschleunigen, so Armin Gräter, Expert Digitalization and Automated Driving bei BMW in seinem Vortrag. Ein Ergebnis davon könnte demnächst die Ausweitung der Regularien für den Geschwindigkeitsbereich bis 130 km/h auf Autobahnen sein.

Wichtiges Element für die weiteren Schritte von Level 2/2+ hin zu SAE-Level 3 ist die Validierung über virtuelle Prototypen. Gerade die Aspekte Rohdatenfusion sowie hochgenaue Umgebungsmodelle ergeben aussichtsreiche Kombinationen für weitere Entwicklungsschritte und helfen, den Aufwand beherrschbar zu halten: „Vorteil ist die beliebige Reproduzierbarkeit und Anpassbarkeit," so Martin Herrmann, Business Development Manager bei IPG Automotive in Karlsruhe. Wichtig sei auch die Beschleunigung der Simulationsläufe und eine Reduzierung der Anzahl der Simulationen. Eine weitere Reduzierung des Testumfangs wird mit immer komplexer werdenden Operational Design Domains (ODDs) erforderlich sein, da die Parameterräume exponentiell wachsen. Dies erfordert fortschrittliche Design-of-Experiment-Ansätze, für die noch großes Forschungspotenzial bestehe.

Schlüsselelemente für die (Weiter-) Entwicklung von Assistenzsystemen ebenso wie des automatisierten Fahrens sind für Dr. Jan Becker, CEO von Apex.AI, unter anderem der Re-Use von Software ebenso wie das anspruchsvolle Thema Integration von Fremdsoftware in die Software-defined Cars (SdC): Gerade letzteres mache eine gemeinsame Basis umso wichtiger, es seien zu viele Partner in einem Fahrzeug vertreten und die Komponenten insgesamt viel zu komplex zu integrieren. Man finde mehrere Tools, die dasselbe tun, es werde nicht crossfunktional entwickelt. Statt eines V-Modells, das in der Realität 100 Komponenten auf 100 ECUs verteilt, müsste eine gemeinsame Plattform existieren, um den Sprung zum Re-Use überhaupt zu schaffen. Insbesondere die Entwicklung von SdC aus dem Blickwinkel der effizienten Softwareentwicklung erfordere ein gemeinsames digitales Ökosystem für die Mobilität. Helfen würde ein gemeinsames Software

Development Kit (SDK) für die Softwareentwicklung im Automobilbereich, das im Wesentlichen dem iOS-SDK oder dem Android-SDK in der mobilen Welt ähnele und so erlaube, die Entwicklungszeiten zu straffen und Austauschbarkeit zu schaffen.

FAZIT

Nach den ähnlich gerichteten Ansichten des BMW-Entwicklungsvorstands Frank Weber, der zumindest in Sachen gemeinsames Betriebssystem auf der IAA 2021 ähnliches geäußert hatte wie Jan Becker, darf man gespannt sein, ob die Appelle aufgegriffen werden.

Robert Unseld

Conference Report "Automated Driving 2022"

Live on the Path to Vision Zero

The 8th International ATZlive Congress Automated Driving 2022 could (at last) be held live again. The majority of the around 100 participants were present on-site in early April in Wiesbaden (Germany) and a part joined in online: The conference benefitted from this and the discussions around the presentations and in the breaks were correspondingly lively.

Automated driving supports the path to Vision Zero but relieving the driver's burden is also at the forefront if the vehicle is able to navigate certain routes or situations autonomously and successfully use its partially or highly automated systems. For further reaching mobility solutions in urban or rural spaces, business models first need to be developed to enable the successful implementation of highly automated driving.

SAE LEVEL BEYOND 2+

The congress was opened in a dialog with the audience with the keynote "Development of Automated Driving: Evolution or Revolution?" by Georges Massing, Vice President MB.OS Automated Driving, Powernet and E/E-Integration at Mercedes-Benz. Assisted and automated driving has to offer customers advantages, in particular safety, comfort, and time. He also pleaded for more prominent emphasis to be placed on differentiating between level-2 assistance systems and level-3 (partially) automated driving. The current characteristic of automated systems in passenger cars is that they are undergoing gradual optimization and expansion by the OEM. Thus, the development is proceeding in the same way as for passive safety: a path analogous to that from the first safety belt to modern airbag systems in the direction of ever more active safety with ever more functionality.

This results in truly huge tasks for the sector: On the one hand, according to Pierre Gompertz, Product Line Director Automated Driving at Magna, one can see a very high speed of development, but on the other, one does not know at which point sufficient miles have been collected for validation. The entire validation task is so huge that mega-suppliers beyond the traditional tier-1 category are needed. Although there are no mainstream solutions, due also to the need for still-to-be-defined standards, in principle automated driving can be achieved with current means. Tier-1 suppliers, OEMs, start-ups, and sometimes a combination of these companies would drive the transformation of the next generation forward and, in doing so, rediscover themselves.

In his presentation, Dr. Felix Lotz, Product Manager Driving Functions at Continental Teves said that even if different speeds have very different hardware requirements, overlapping platforms can still be used with beneficial scaling effects. There are multiple use cases such as driving in urban environments or on highways that profit from the effective distribution and re-use of key elements between different platforms and functions.

RESEARCH AND STANDARDS AS KEYS

A topic that resurfaces very often is the matter of regulatory framework conditions: A network of almost 200 organizations from industry, research, service providers, authorities, and regulatory bodies are attempting to bundle research in so-called Connected Cooperative and Automated Mobility (CCAM) activities and to process overlapping results in the area of standardization. Armin Gräter, Expert Digitalization and Automated Driving at BMW explained in his presentation that this collaboration on a European level is intended to help break down barriers and to accelerate the introduction of automated driving. One result could be the imminent extension of the rules for the speeds up to 130 km/h on German highways.

An important element for further steps to be taken from level 2/2+ up to SAE level 3 is validation via virtual prototypes. It is precisely the aspect of raw data fusion and highly precise environmental models that provide the most promising combinations for further development steps. They also help to keep the effort within manageable limits: "The advantage is the arbitrary reproducibility and adaptability", said Martin Herrmann, Business Development Manager at IPG Automotive in Karlsruhe (Germany). The acceleration of simulation runs and a reduction in the number of simulations is also important. A further reduction in the test scope will be required with increasingly complex Operational Design Domains (ODDs) since the parameter space is growing exponentially. This requires advanced approaches for experimental design, which still has a lot of research potential.

Key elements for the (further) development of assistance systems and automated driving include, according to Dr. Jan Becker, CEO of Apex.AI, the reuse of software and the challenging topic of the integration of third-party software into the software-defined cars (SdC): It is precisely the latter that increases the importance of a common basis; there are too many partners involved in a vehicle and the components as a whole are too complex to integrate. Multiple tools are available that all do the same job, there is no cross-functional development. Instead of a V-model, that distributes 100 components over 100 ECUs in reality, there should be a mutual platform to enable the leap to re-use. Particularly the development of the SdC from the perspective of efficient software development requires a mutual digital ecosystem for mobility. A common Software Development Kit (SDK) for software development in the automotive sector would help, similar to the iOS SDK or the Android SDK in the mobile world and this would enable development times to be shortened and also enable exchangeability.

SUMMARY

Following similar views of Frank Weber, BMW's Board Member for Development, who aired similar views to Jan Becker regarding common operating systems at the IAA 2021, it remains to be seen whether the calls will be heeded.

Robert Unseld

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A “Common Core” Architecture as an Enabler for Cross-Platform Autonomous Driving

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[1] Continental Teves AG & Co. oHG

Abstract. Autonomous Driving (AD) is expected to heavily change the landscape of future mobility solutions, with machines carrying out the driving task to larger and larger extents. A wide range of applications for this disruptive technology exist, such as driving in urban environments or in highway scenarios. Within this challenging field, Continental is developing driverless solutions, relying on a vehicle fleet covering various AD applications. In this paper, we present our approach of a “Common Core” software architecture for AD systems, allowing to effectively share AD key elements between different AD platforms. This includes the description of applied design principles, resulting advantages, limitations as well as impressions of real-life demonstrations and future development directions.

Keywords: Autonomous Driving, Automated Driving, Autonomous Driving Architecture, Software Architecture, Environment Perception, Driving Functions

1 Introduction

Continental was the first Tier-1 supplier to receive an official license for testing automated vehicles in Nevada back in 2012 [1]. Since then, the portfolio of autonomous driving (AD) applications and according driving platforms within the Continental AD program has continuously grown and evolved, targeting L3-systems for highway- or urban driving, automated valet parking, driverless shuttles, and even autonomous long-haul trucks in all major automotive regions around the world (see Fig. 1). This reflects the fact that new mobility solutions constantly manifest themselves with the progress made in the AD field. To gain a deep understanding and hands-on experiences in these new markets, we use our vehicle platforms as research and development tools and create proof-of-concepts for our future product portfolio.

Fig. 1. Current Driving Platforms of the Continental AD Program

A. Heintzel (Hrsg.), *Automatisiertes Fahren 2022*, Proceedings,
https://doi.org/10.1007/978-3-658-44797-7_1

Within Continental's AD Program, we successfully transformed from initially loosely coupled solutions, each aiming at a different AD application, into a consolidated "Common-Core" software architecture. This architecture paradigm enables us to maximize synergies between the different AD applications and driving platforms by increasing the number of re-usable elements within the overall AD stack. Furthermore, it is a precondition for the effective and efficient maintenance and support of the complete AD fleet. In this paper, we share our experiences on the way to achieve this "Common Core" and describe the characteristics of the approach as well as its limitations.

For this, we introduce the history behind and the fundamental design principles of such an architecture paradigm in section 2. In section 3 and 4 we explain the implementation of the mentioned principles in more detail, with focus on our main software subsystems 'Environment Model' and 'Driving Functions'. An impression of the supported AD applications is given in section 5, before we draw a conclusion in section 6.

2 Architecture Principles of a "Common Core" Architecture

First insights into an exemplary, high-level AD architecture are provided by Fig. 2. The data flows from the sensor frontend (1) on the left side through detection, tracking and fusion algorithms (2) to form an Environment Model (EM) subsystem (3), which is then processed in the Driving Functions (DF) subsystem to generate a trajectory request (4) which is controlled by Motion Control (5) and corresponding Actuator Control (6). Accordingly, signals and algorithms used on the left side are more specific to a sensor modality or -type and on the right side to the driving platform and according actuators. In the middle part they become more determined by the actual AD application.

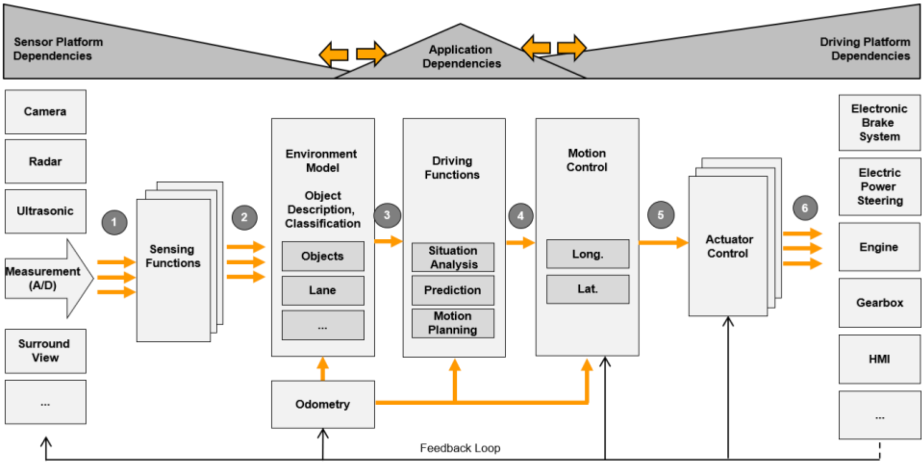

Fig. 2. Exemplary High-Level AD Architecture

In the early phases of advanced driver assistance systems (ADAS) development, there was a strong coupling of sensors and the driving function because of limited computational resources and packaging requirements. However, due to the growing number of sensors and ADAS functions, already around 2012 the idea came up to decouple them by introducing an Environment Model (EM) [2], which contains the common parts of the fusion and modeling algorithms. Following this decision, the EM has been designed to be an application-independent representation of the vehicle's surroundings, enabling to re-use it in different applications and - vice versa - abstracting the applications from any sensor-specific dependencies. Consequently, the next apparent question is: Is it possible to expand the application-independent part of the architecture, which we refer to as "Common Core", beyond the boundary of the EM?

Designing a "Common Core" architecture can be understood as the effort to lower and contain the application dependencies to well-defined parts in the software architecture. The same goes for the sensor- and driving-platform dependencies (as visualized by the arrows in the top part of Fig. 2).

Translating the previous paragraphs into software engineering terms, the "Common Core" architecture aims to satisfy the following *non-functional requirements* of our software system:

- *Reusability* of software components for different AD applications,
- *Platform-independence* (covering sensor- and driving platform- but also computational platform independence),
- Efficient *maintainability* of the software system and
- *Expendability* of the software system towards new AD applications and their features.

The application of certain *architecture principles* helps to reach the mentioned quality characteristics. In our case, special focus must be set on the following ones:

- The principle of *loose coupling* between the software components enables a better understandability and therefore changeability, expendability and ultimately reusability of the software structure. It is realized by (cf. [3]):
  - Principle of *separation of concerns*: Encapsulation of related functions in well-defined, coherent, and independent software components (this also enables parallelization of development between multiple developers).
  - Principle of *information hiding*: Hiding a (complex) subsystem behind a well-defined interface.
  - Principle of *abstraction:* Reduction of interface complexity, avoiding circular references.
- The *modularity* also combines the above-mentioned principles [3].

In the following, we will describe in more detail how we apply these principles to the design and development of the EM and DF software subsystems.

3 A “Common Core” in the Environment Model

3.1 Architecture

The output of our EM is a consistent and comprehensive description of the vehicle’s environment using the “Traffic Participants”, “Parametric Freespace Map” and “Road Model” interfaces. Visualizations of the output of these interfaces are shown in Fig. 3. The interfaces have been designed to support all the driving functions required for the different AD applications. The “Traffic Participant” interface (left in Fig. 3) contains a list with the states of all entities participating in the traffic situation like other cars, trucks, bikes or pedestrians. The “Parametric Freespace Map” (middle in Fig. 3) contains a parametric description of the boundary of the observed free space around the vehicle. Finally, the “Road Model” (right in Fig. 3) is a structure containing the lanes, their connectivity, and attributes like speed limits around the ego vehicle. To support a variety of applications for different vehicle platforms, the interfaces need to provide the superset of all environment elements required by the supported applications. Because public transportation infrastructure is, to a large extent, well-structured by legal rules, the structure of the interfaces shown here proved to be sufficient to support all our current platforms and applications. Specific attributes or states, e.g. speed limits for different vehicle classes, are added on demand.

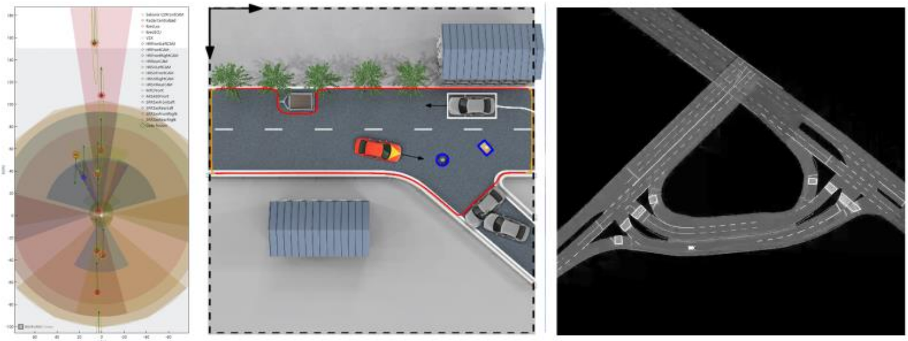

Fig. 3. Left: Traffic Participants, Middle: Parametric Freespace Map (from [9]), Right: Map-based Road Model

To foster reusability and platform independence we want to achieve loose coupling between the applications and the EM internals but also between the EM internals and the input sensors and data sources (cf. section 2). Furthermore, we want the EM to be modular so that we can build configurations fitting the specific platform needs. This is achieved by using several architecture principles to split the EM into several subsystems:

- The architecture principle of *separation of concerns* is used to separate the environment model into three different areas: First, at the core of the EM there are “Intermediate Representations” fostering the fusion of data between different sensor modalities and the collection of information over time. Second, data collected from different sensors or information sources must be transformed into the format of the intermediate representation. Third, from the intermediate representation the required output representations supporting the set of AD applications is extracted.

- The output interfaces of the EM must be free of sensor or application specifics. Here, the principle of *information hiding* is used to hide the intermediate representation and data sources used for the consumers of the environment model. Additionally, probabilistic models are used to capture the relevant characteristics of the output data, like the accuracy of a position estimate or the probability of an object track representing a real-world object, in a way which is independent of the concrete perception path. A "plugin concept" is used to allow a flexible configuration of output representations for each set of AD applications running on a specific vehicle platform.
- On the input side, the principle of *abstraction* is used to build plugin concepts for the intermediate representations in use and allow a flexible configuration of a different number of sensors, different sensor modalities and types for the concrete vehicle platforms.

An overview of the resulting EM is shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**. On the left side there are the sensors and data sources delivering input to the EM. For each sensor or source an "inverse sensor model" transforms the sensor data into the format of the intermediate representation. After accumulation and fusion of the inputs using the intermediate representation, plugins are used to extract the required output interfaces from the intermediate representation. Using inverse sensor models, output representation extractors and intermediate representations in different configurations allows us to support a variety of vehicle platforms and AD applications with just a few core components.

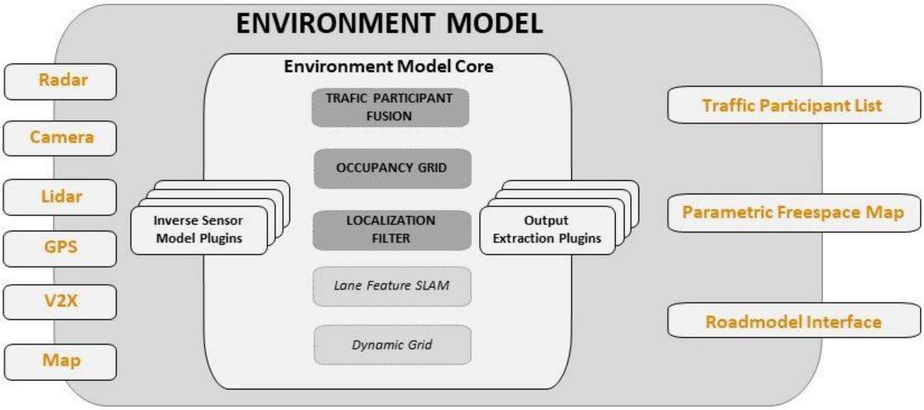

Fig. 4. Overview of the Environment Model

3.2 Intermediate Representations

To model the environment of a vehicle, a variety of representations have been developed. Some of them are too abstract to be directly consumed by driving functions but still are valuable for the fusion of sensor data. We call these “Intermediate Representations” because their abstraction level is between sensor raw data and feature maps [4]. These representations are a key element for a common core in the environment model because they enable the accumulation of sensor data over time, the fusion across sensor modalities and the extraction of higher abstraction level representations to be independent of specific sensor modalities and types.

One of the elements of the EM Core is an occupancy grid-based approach for static environment [5], which is currently extended to a dynamic grid-based approach covering static and dynamic environment.

For our landmark-based localization, the set of all the particles reflecting the likelihood for the vehicles’ position can be treated as an intermediate representation from which the most likely position hypothesis is extracted [6]. Before switching to an HD-Map based approach to provide a reliable Road Model also for L4 applications in complex urban scenarios, for highway use cases a “Multi-Modal Lane Perception” using a Graph SLAM to fuse lane feature markings of several sensors into a lane feature map was developed, where the set of lane features can be interpreted as intermediate representation [7].

Even if the mentioned intermediate representations can provide a very detailed description of the EM, typical consumers require compact and explicit representations on a higher level of abstraction [4]. Examples are prediction of traffic participant behavior or identification of the ego and neighboring lanes which is hard to do in a very detailed representation. In our system an extraction step is added between the intermediate representation and the environment model output. This also helps to keep the intermediate representation and the related fusion and processing steps independent from the output representation:

- We have used a static grid for the extraction of road boundaries [8] which was extended to parametric free space maps [9].
- The extraction of a single segment clothoid from the lane feature map [7] was extended to a multi segment lane model [10].

As the intermediate representations also abstract the sensor modality details, on the input side we use the inverse sensor models [11] to transform the sensors raw data into an input suitable for fusion. The intermediate representations, together with the output interface extraction and the inverse sensor models help us to add flexibility along the EM processing chain in several important aspects:

- On the output side, we can add, modify or remove extractors to support new or extended functionalities without having to change sensor models or the intermediate representation.

- Because the output interfaces hide the intermediate representation, we can add, modify or remove it – e.g. transition from static to dynamic grids - without having to change the AD applications which consume the EM output interfaces.
- On the input side, because the inverse sensor models abstract the sensor specifics, we can add, modify or remove sensors without having to change the intermediate representation, the output interface extractors or the AD applications.

By operating a fleet of different vehicle platforms around the world, we many times encountered the situation that new sensors, improved or modified intermediate representations or new functionalities are rolled out on few vehicles first and only after some initial testing to the complete fleet. Hiding the intermediate representation and abstracting the specific sensors by "inverse sensor models" proved to be valuable design principles because the "inverse sensor models" help us maintaining a "Common Core" also in transition phases with different sensor setups between vehicle platforms and therefore minimize the number of software variants which must be maintained.

3.3 Probabilistic Environment Models

In early years of ADAS, computational resources have been quite limited and in typical architectures smart sensors used low bandwidth interfaces like CAN. To make data fusion and tracking on these limited hardware (HW) architectures possible, the environment representations were very limited and adapted to the specific application. With the perspective towards AD, the situation changed towards central ECU architectures, where a major part of the processing of the sensor data is done on a powerful ECU with many satellite sensors sending raw data to it. Central ECU's serve as an integration platform for many SW modules, offer plenty of compute and memory resources and communication between different ECU's is not an issue any longer.

These new HW architectures are one enabler for the introduction of probabilistic environment models by allowing a shift from resource efficient and application specific models towards representations providing a rich and generic description of the vehicle's environment. A probabilistic environment model uses algorithms and holistic representations considering all relevant types of uncertainties in the perception system. Many of the algorithms and representations used can be derived from the Bayes filter [12]. Examples for probabilistic representations used in our EM are:

- The extension of the traffic participant tracking from a classical Kalman filter not considering track probabilities [11] to an Integrated Probabilistic Data Association (IPDA) filter which estimates states and probability of existence [13].
- The Occupancy Grid was first extended from a binary Bayes filter to the Dempster Shafer Theory [5] and now has been extended to a Dynamic Grid representing static and dynamic environment.
- A complete "Road Model Interface" does not only contain geometry and topology of the lanes but also attributes like speed limits, traffic lights or right of way. We

developed a representation and fusion method considering spatial, existence and attribute uncertainties of the input [14].

Using probabilistic models has two advantages: First, they allow the EM internal algorithms to be pushed towards considering the full history of the current inputs. This improves the quality of the internal states because it allows the accumulation of ambiguous or conflicting information, which can be resolved having the full information basis available. Second, it is a great step towards generic output interfaces where the application specific selection of information is done in a later processing step.

4 Driving Functions

4.1 Capability-based Design

The Driving Functions (DF) subsystem implements the spectrum of behavioral capabilities necessary for the realization of a defined AD system. These DF capabilities can be expressed in different granularity levels. Examples for implemented high-level capabilities are:

- Lane- and object following for urban (0 – 70 km/h) and highway (0 – 130 km/h) scenarios
- Lane change
- Routing capability (ability to derive the sequence of necessary driving maneuvers to follow a certain route)
- Pedestrian crosswalk handling
- Traffic sign- / traffic light-regulated intersection handling
- Roundabout handling

Following the principles of the “Common-Core” Architecture in section 2, it is important to implement these capabilities in a way that they are not specifically tied to any certain AD application or vehicle platform, but instead can be easily re-used by them. In the following it is described which design elements on software architecture and software component level promote this advantage.

4.2 DF Components and Software Architecture

The mentioned high-level capabilities emerge from the interplay of lower-level capabilities, realized by dedicated DF subsystems shown in Fig. 5 on the left side (“DF Core”).

The *Situation Analysis* subsystem’s task is to bring all relevant scene-describing elements (road / lane representation, traffic rules, other traffic participants, ego vehicle) into a semantic relation to each other. From these relations, behavioral constraints for the ego vehicle can be extracted that simplify the later motion planning (e.g. the need to stop at a certain position due to priority rules or the need to slow down when approaching a curve), providing a scene understanding capability.