Handbook of Driver Assistance Systems
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Autonomous Driving

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Abstract

In this chapter, a survey of the current state of research on autonomous driving is given and is set in the context of the requirements of an autonomous vehicle following the vision of an automated taxi. The overview is based on (scientific) publications and self-reports of the developing teams. Aspects of interest for this summary are approaches on environmental perception, self-perception, mission accomplishment, localization, cooperation, map usage, and functional safety.

Typically, emphasis is given to reliance on global satellite systems (e.g., GPS) and map data. Only a few approaches focus on environmental perception and scene understanding. Even though impressive demonstrations of autonomous driving have been presented in recent decades, this overview concludes that many aspects still remain only partially solved or even unsolved, especially when driving autonomously in public road traffic.

1 Introduction

1.1 Motivation

At present everyone is talking about the vision of "autonomous driving." The media report on successes derived from research, with numerous promises regarding product launches taking place in the near future; automotive companies are competing in their race to develop new technologies, and software companies are competing with the vehicle manufacturers. Subsequently, the hope for accident-free driving in society is born. We would then at last be able to lean back and relax – even during the course of our journey – and enjoy the trip, make phone calls to our hearts' content, surf the Internet, or do some preparatory work in advance instead of grumbling about the traffic jam. The elderly and the sick would then be able to enjoy enhanced, independent mobility in the long term, and autonomous vehicles would also contribute towards a more efficient use of the raw materials. It would be feasible for car-sharing offers to have their vehicles driven autonomously to the customers (cf. Laurgeau 2012) or have these vehicles powered independently. By taking the flow of traffic and the entire stretch of the journey into consideration, the actual trip itself could also be optimized in terms of energy.

Is all this still a vision that lies in the distant future? Will there ever be "autonomous road vehicles"? Or are they going to be launched on the market very soon? What in fact does "autonomous driving" actually mean? What are the technical challenges that have to be solved?

The projections regarding a market launch vary; the options are all included, with forecasts from 10 to 20 years to never at all. This is also due to the fact that we have no standardized understanding of the range of functions of an "autonomous vehicle." It will not be possible to answer any far-reaching questions in this chapter. Nevertheless, the attempt is made to explain the term "autonomous driving" more clearly by providing a short historical introduction and functional definition. Build up on this, the results of an intensive investigation on research groups that concentrate on autonomous driving in the broader sense

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are assessed. Our focus is thereby restricted to the technical aspects that will have only a small influence on whether autonomous vehicles will be involved in the public road traffic of the future. The following open questions are not dealt with in depth in this article: legal ambiguities ("Under what conditions can a registration take place?," "Who is liable in the event of damage?"), acceptance in society ("Will people trust machines that have the potential of inflicting deadly injuries on them?"), safeguarding ("How can we ensure that the autonomous vehicle will safely master every possible situation, i.e., perceive the situation and evaluate it?") (Maurer 2013), or service and maintenance during everyday operation ("Who will be carrying out regular checks on roadworthiness and operational safety in the future, as even today, hardly anyone carries out a visual check of the safety-relevant components of his vehicle before commencing a journey?").

1.2 A Brief Overview of the History of Autonomous Vehicles

The development of autonomous vehicle technology began in the 1950s (Fenton 1970). The first ideas of how to automate highway driving were developed in the General Motors Research Lab. Due to obvious limitations in computation and image processing in this era, a combination of vehicle sensors and infrastructure measures promised the best results. For example, an approach to integrate magnets into the road surface was developed and its feasibility was demonstrated (Fenton 1970).

In the 1970s and 1980s in particular, Japanese groups did research on image recognition algorithms for lane marking detection and object detection. Based on this acquired data, vehicles were automated (Tsugawa 1993, 1994). The demonstrations included driving functions like adaptive cruise control (ACC) and lane-keeping support at relatively low vehicle speeds. Alongside this, vehicle automation based on infrastructure improvements was investigated further to reduce complexity for onboard technology by combining vehicle and infrastructure technology (Hitchcock 1995; Zhang et al. 1990).

Within the project California Partners for Advanced Transit and Highways (PATH) (Shladover 2007) and at the Carnegie Mellon University in Pittsburgh (Thorpe et al. 1997), automated vehicles were developed and achievements were shown with prototypes. A remarkable result was the demonstration drive "No hands across America" in 1995. The experimental vehicle NavLab 5 crossed the USA mostly automatically. The developed system controlled the vehicle laterally in 4500 out of 4587 km driven on highways (Pomerleau and Jochem 1996). A safety driver was responsible for the longitudinal control of the vehicle.

The PROMETHEUS project (PROgraMme for a European Traffic of Highest Efficiency and Unprecedented Safety, 1987–1995) in Europe aimed at vehicle automation and also driver assistance systems. In the project's context, the Universität der Bundeswehr in München built the experimental vehicles VaMoRs and VaMoRs-P (VaMP) and demonstrated automated driving (Maurer 2013; Dickmanns et al. 1994; Zapp 1988). Similar results with the similar vehicles VITA and VITA II were shown by the Daimler-Benz AG (Ulmer 1992, 1994). A special event was an automated long-distance run from Munich to Odense with VaMP in 1995. The vehicle drove 1758 km in total and 1678 automatically. In this demonstration the lateral and longitudinal control was automated and speeds up to 180 km/h were reached. Additionally, lane changes were triggered by the safety driver and executed automatically by the technical system (Maurer 2000).

The research vehicle ARGO from the VisLab institute of the Università degli Studi di Parma was used for long-distance drives in 1998 (Broggi et al. 1999). In a few days, 1860 km was driven automatically. The functionality was similar to VaMP, including longitudinal and lateral vehicle control and lane changes triggered by a safety driver and executed by the system (Broggi et al. 1999).

In all of these projects, the system was monitored by a human driver. The operational environment was mostly limited to highways. Referring to currently discussed categories of vehicle automation in Gasser

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et al. (2012) and SAE (2014), none of the experimental vehicles fulfill all requirements for high or full automation.

From 2004 to 2007 the research activities were pushed by several challenges started by the Defense Advanced Research Projects Agency (DARPA) in the USA. DARPA set the goal of developing driverless, automated vehicles for military purpose in the early 2000s. To reach this goal, DARPA started the first DARPA Grand Challenge in 2004. The task was to drive unmanned through a desert in Nevada. Because of a rather short development time, the results were not satisfactory: None of the experimental vehicles made it to the finish line (Thrun et al. 2006). In the following year, DARPA doubled the trophy and with a development time increased by 1 year, the participating vehicles were improved remarkably. Several teams developed vehicles which reached the finish line after driving 229 km through the desert unmanned. The winner of this Grand Challenge was Stanley from Stanford University. It finished first after about 7 h (Thrun et al. 2006). All vehicles in this competition were unmanned, but followed by a supporting vehicle which could stop them with a remote control. For a more detailed insight into the developed technology, Singh (2006) contains the approaches of the teams in the challenge.

The Grand Challenge 2005 was a great success, and consequently DARPA announced the 2007 DARPA Urban Challenge. Instead of driving off-road through the desert, autonomous driving technology was taken into an urban-like environment with streets, buildings, and cars driven by stunt drivers. This scenario challenged the teams with a much higher complexity of the operation environment. The teams had to solve missions which included following traffic rules, solving four-way-stop situations, and driving on a free navigation area. Some of the autonomous vehicles accomplished their mission and finished after several hours of autonomous urban driving. The result was a boost for autonomous driving technology, and follow-up projects are still developing new approaches in this field.

The Tartan Racing Team from Carnegie Mellon University won this challenge. The Stanford Racing Team finished second and the Team Victor Tango finished third. The scientific results of all teams in the final event were published in Singh (2008a, b, c). Again, all vehicles were unmanned and could be stopped by remote control from a supporting vehicle. This vehicle was following the autonomous vehicle, e.g., as presented by the CarOLO Team from the Technische Universität Braunschweig (Wille 2012). The experimental vehicle Caroline took part in the final event. This final confronted the vehicles with some unforeseen situations where human interference was necessary. These necessary human interventions showed that Caroline and the other autonomous vehicles were not yet ready for public traffic (Wille 2012).

In the subsequent years, many new projects have been started, and the vehicles from the DARPA Urban Challenge teams were developed further. Besides research institutions, vehicle manufacturers, suppliers, and other companies started the development of autonomous vehicles. Some of the most recent projects are part of this chapter. A more detailed look into technology is aggregated in the *Handbook of Intelligent Vehicles* (Eskandarian 2012).

1.3 Requirements for Autonomous Driving in Public Road Traffic

In this chapter an autonomous vehicle is understood (similarly to the definitions in Wachenfeld et al. (2015)) as a vehicle which is able to move “freely,” because it is not limited to rails, power supply lines, or a bus bar. Thus, the vehicle can be used in a more flexible way than a rail-mounted vehicle, for example, but has a limited amount of energy. This limited amount of energy, the limited installation space, and the appliance in the direct environment of human beings and animals lead to further requirements concerning the health effects of the applied technologies. Therefore, the amount of available technical solutions to this challenging task is further reduced.

The autonomous vehicle is operated by the human being on a very *intuitive* level, similar to the well-known interfaces of today’s satellite navigation systems, and is consequently provided at the most

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abstract level from the system's point of view. This means, neglecting a service mode, the vehicle is only instructed by a mission.

Typically, a mission for an on-road vehicle consists of a transportation task. People, goods, or just the vehicle itself might be transported. In future systems, also surveillance and other tasks might be relevant for autonomous vehicles. In the case of the transportation of human beings, the mission must be adaptable to the current needs of the passengers at any time. Such an adaptation might be caused by triggering an emergency stop (see Wachenfeld et al. 2015) or by adding a stopover at a restaurant, the next bathroom, or a hospital. The overall functionality of an autonomous vehicle extends the definition of fully automated driving given by Gasser et al. (2012).

A special aspect of "autonomy" in this context is the self-motivated adaption of the current mission. Such an adaption of the mission might be to drive to a repair shop in the case of a self-diagnosed and not self-reparable defect or to stop at a gas station in the case of an empty tank or battery. Further elements defining the autonomy of the system are mechanisms of starting a "self-healing" process, e.g., restarting components (see Ghosh et al. 2007).

The appliance to the public road traffic increases the demands on an autonomous vehicle (in this case also automated vehicle) concerning both the environmental perception and the driving behavior. The urban environment in particular puts high demands on the environmental perception. It is necessary that the vehicle robustly detects and classifies the stationary elements (e.g., road course, signs, traffic lights) and the movable elements (e.g., traffic participants, human beings, animals). It is mandatory due to consistency reasons that human beings and technical systems use the same optical features for orientation as they share the same road environment (see, e.g., Bar Hillel et al. 2012; Huang et al. 2009).

In this case of mixed traffic (consisting of automated and manually driven vehicles), the locally defined road traffic regulations are of special interest. They define a minimal amount of environmental elements (signs, road markings, traffic participants, etc.) which have to be perceived and considered. Additionally, the regulations specify the behavior in defined situations (Wachenfeld et al. 2015). The basic components of the road traffic regulations are the mutual considerateness, a clear behavior pattern, as well as communication and cooperation.

In addition to these pure functional requirements, it is mandatory within the meaning of responsible acting that automated and autonomous vehicles do not constitute any danger to their environment. Therefore, the vehicle needs to be aware of its skills and abilities and has to act according to its current state. So the estimation of the skills and abilities including the surveillance of hard- and software is another mandatory requirement (onboard diagnostics). Moreover, the vehicle has to be resistant against misuse and manipulation.

In the euphoria of an increasing automation of the vehicles, the initial motivation should never be forgotten: The focus remains on human beings and their needs for individual mobility. An autonomous vehicle, which drives collision-free and even according to local road traffic regulations and moral and societal rules, but whose passengers do not trust the technical system and cannot enjoy a comfortable drive, would probably not be accepted by society.

1.4 Relevant Research Projects

This chapter focuses on civil and fully automated on-road motor vehicles, whose concepts are sufficiently published or whose detailed information was given directly to the authors by the relevant research team. Due to different requirements and thus different resulting technical solutions in civil or military applications (for military purposes, e.g., robustness against attacks or off-road navigation is also relevant), this chapter mainly examines civil systems. Additionally, only projects with the objective of realizing a highly or fully automated driving prototype according to Gasser et al. (2012) and SAE (2014) are part of the following discussion. Hence, research projects in the field of assisted or conditionally automated driving,

Handbook of Driver Assistance Systems
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whose objective always considers the driver as a surveillant and possible fallback solution, are explicitly not taken into account.

Nevertheless, even current prototypes for highly or fully automated driving currently reach only conditional automation in public road traffic according to our appreciation (see also Sect. 2.6).

Furthermore, only projects developing explicitly road vehicles, e.g., cars, commercial road vehicles, buses, or motor bikes, are considered in this chapter. This means the huge number of mobile robotic platforms, humanoid robots, or unmanned airplanes are not considered either. Projects, which are only announced or published by general media reports, cannot be discussed and compared to other projects due to missing scientific information. With the goal of giving the same chance to all teams to include their research results in this chapter, the authors developed a questionnaire (see Sect. 4). This questionnaire was sent to many research teams and institutions, automotive manufacturers, and other companies who are known by media reports and conferences.

The authors would herewith like to sincerely thank participants for the feedback.

Based on the aforementioned criteria, as well as the feedback from the questionnaire, the following list of projects, which are considered in this chapter, emerges:

- Special research project 28 of the DFG (Deutschen Forschungsgemeinschaft)
  - Karlsruher Institut für Technologie – experimental vehicle AnnieWAY
  - Universität der Bundeswehr – experimental vehicle MuCAR-3
  - Technische Universität München – experimental vehicle MUCCI
- BMW AG – Project Connected Drive
- VisLab Institut der Università degli Studi di Parma – experimental vehicle BRAiVE
- Carnegie Mellon University – experimental vehicle BOSS
- Stanford University – experimental vehicle Junior 3
- Daimler AG – Automated Drive on the Bertha-Benz-Route ("Bertha-Benz-Drive")
- Technische Universität Braunschweig – Project Stadtpilot with the experimental vehicle Leonie

1.5 Focus on Aspects of Autonomous Driving

Based on our functional requirements for an "autonomous vehicle" in Sect. 1.3, we identified the following major aspects (see also Fig. 1) which have to be handled by an autonomous vehicle and which depict a relevant differentiation factor among the research projects:

1. Onboard environmental and self-perception: Among other requirements, the autonomous vehicle has to perceive and interpret its local environment as completely as required. This includes the detection of road markings and traffic signs, the detection of their position relative to the vehicle and their meaning, the detection of additional lane borders like curbs or grass, etc, the detection of raised targets, pot dots and holes, traffic lights, other traffic participants (pedestrians, bicycles, motor bikes, commercial vehicles and buses, trams, ambulances, animals, etc.), weather conditions, as well as the recognition of the own vehicle state (fuel level, tire pressure, wheel ticks, etc.).
2. Mission accomplishment: The mission must be accomplished by the vehicle, starting with the route planning down to the control of the vehicle's actuators. In this chapter, we also include the situation assessment of this aspect.
3. Localization: The vehicle needs to know its absolute or map-relative global pose.
4. Usage of map data: Without map data, route planning becomes challenging. But the level of map data usage also indirectly provides information about the capabilities of the localization and perception approaches. In many cases, all non-perceivable environmental features are mapped manually and then

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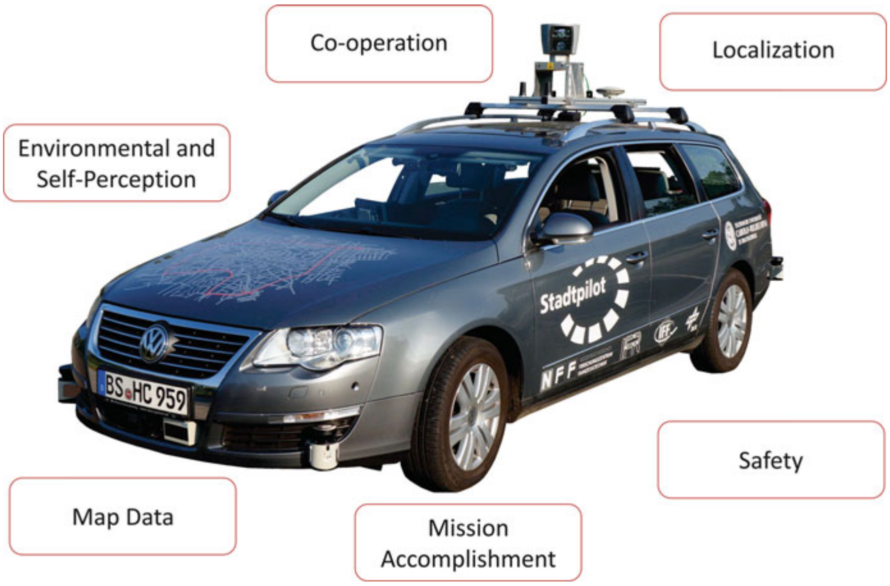

Fig. 1 Aspects of an autonomous vehicle using the example of the test vehicle Leonie of the research project Stadtpilot at Technische Universität Braunschweig

provided as map data to the vehicle's guiding system. The big disadvantage is that these data are very soon outdated. Therefore, how much the different approaches trust in and rely on map data is analyzed.
5. Cooperation: The vehicle has to be integrated into the traffic flow and thus needs to cooperate with other traffic participants, no matter whether they are humans, driven by humans, or driven automatically. Otherwise, the automated vehicle will be a foreign object in mixed traffic.
6. Functional safety: Without assuming the human driver as a fall-back solution, it must be ensured that the vehicle does not constitute any danger to its environment.

The basis of our survey on different projects is the functional system architecture, which has been developed within the research project Stadtpilot at the Technische Universität Braunschweig (Matthaei and Maurer 2015; Matthaei 2015) and which is shown in Fig. 2. The functional system architecture is designed as a modular building block system covering multiple ways of designing an autonomous vehicle. It includes all aforementioned aspects of an autonomous vehicle and especially combines localization-driven and perception-driven approaches in one single system description.

Each of the following sections focuses on a certain column, except for the sections concerning safety and cooperation, which describe interdisciplinary aspects. This survey does not consider the many publications in the field of driver assistance systems, which are not published within the context of integration into an overall system. On the one hand, their consideration would exceed the scope of this chapter; on the other hand, it would falsify the real state of research in the field of autonomous driving. A big challenge of autonomous driving is to master the system complexity. While driver-assistant systems usually only cover smaller subtasks, an autonomous vehicle needs to cover the whole functionality which is usually managed by the human driver. This consequently raises the complexity of the entire system. For example, it might happen that unforeseen incompatibilities occur or the limited resources are exceeded while integrating various single solutions into an overall system. This can even exclude certain single solutions from the integration into an overall system.

As already stated in Sect. 1.4, the following state of research is only based on self-disclosed information of the research teams in the form of scientific publications or a response to our questionnaire (see Sect. 4).

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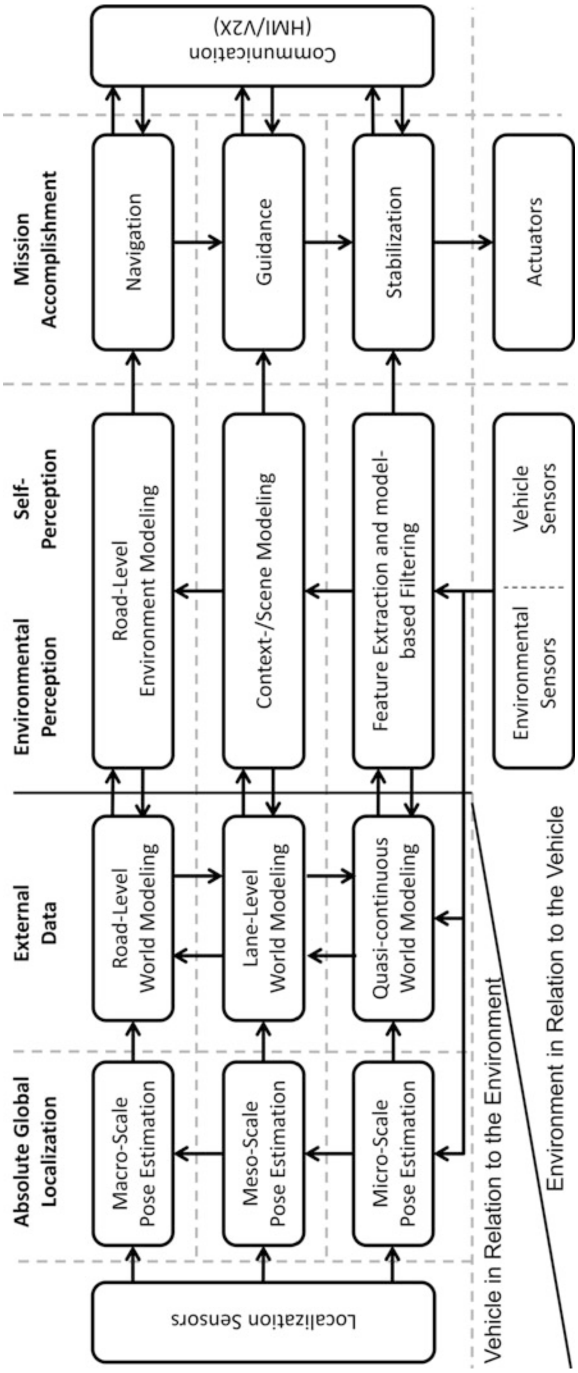

Fig. 2 Functional system architecture for an autonomous vehicle as a building block system according to Matthaei and Maurer (2015) and Matthaei (2015)

Handbook of Driver Assistance Systems
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Due to missing metrics, it is demanding to benchmark the quantitative capabilities of the different systems, e.g., the perception systems. Thus, the comparison focuses mainly on qualitative differentiators.

2 State of Research

2.1 Perception

The most challenging aspect of autonomous driving seems to be the computer-based environmental perception (see Bar Hillel et al. 2012). This is approved indirectly by the often applied strategy of an extensive map usage as presented in, e.g., Wille (2012) or Ziegler et al. (2014), to be able to provide at least any automated driving function without the interference of a human driver.

Activities of the Universität der Bundeswehr München, and especially the concepts in Broggi et al. (2013), are mainly driven by online environmental perception. During the DARPA Urban Challenge, some teams were using concepts dominated by online environmental perception as well (e.g., Leonard et al. 2008). However, most of the competitive teams relied on a priori map data, at least for the stationary environment (see Bar Hillel et al. 2012).

2.1.1 Perception of the Stationary Environment

In this chapter, the term “stationary environment” describes the pathway of lane markings in the direct detection range of the vehicle (e.g., at inner-city intersections), drivable areas, as well as static obstacles. Positions and implications of traffic signs, types of lane markings, and positions and phase of traffic lights, road curbs, entries and exits of tunnels, bridges, etc., are also part of this definition. This incomplete list already shows how heterogeneous the expected environment might be.

Researchers at the Universität der Bundeswehr München developed concepts for the detection of road courses without the usage of a priori map data (e.g., Manz 2013; Müller et al. 2011). Manz shows in Manz (2013) concepts which are capable of detecting and modeling intersections and splitting roads from this data. These activities were mainly focused on unpaved areas. The height profile of the environment is also modeled (see Manz et al. 2011). The algorithms were designed to perform even under adverse conditions, e.g., partial occlusion or a limited range of view, caused by rain or snow (Manz 2013, pp. 173ff). Based on the feedback on our questionnaire, traffic lights and signs cannot be detected at the current stage of development.

The project BRAiVE has also developed a wide range of environmental perception systems. As depicted in Broggi et al. (2013), the vehicle is able to detect and classify the complete set of the Italian traffic signs within 100 ms. Lane markings can be perceived by a mono and a stereo camera. The system can distinguish between white and yellow as well as dashed and solid lane markings. A height profile can be generated, similar to the approaches of the Universität der Bundeswehr München. One unique characteristic is the detection of the domain (highway, rural road, and city) based on the detected features. These concepts seem to be able to detect tunnel entries. Additionally, a parking lot detection was developed for certain scenarios (Broggi et al. 2013).

The research team of BMW Group Research and Technology published an algorithm in Homm et al. (2011), which is able to correctly detect 100 % of the lane markings on a designated test site in Munich. This algorithm is based on a fusion of laser and camera data. Merely the number of available lanes was extracted from regular navigation system map data.

The authors in Levinson (2011) and Levinson et al. (2011) have shown concepts for the detection of traffic lights and signs based on the data of a laser scanner.

The stationary environmental perception is also addressed in the Stadtpilot project (Matthaei et al. 2014b). However, stationary data, especially the position of lane boundaries, is currently still

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provided by a priori map data (Matthaei et al. 2015). An online adaption of the driving tube to additional stationary obstacles (e.g., a parked delivery van) is planned (see Wille 2012), but not yet shown in public traffic.

The perception of lane markings during the conditionally automated drive of a Mercedes-Benz S500 Intelligent on the Bertha-Benz-Route was solved with the support of map data (see Ziegler et al. 2014). Stereo cameras detected the stationary environment. Based on the available documents, it cannot be determined whether a detection of traffic signs was used.

2.1.2 Perception of the Movable Environment

Compared to the perception of the stationary environment, the perception algorithms and techniques for dynamic elements of the vehicles' environment are more sophisticated. Besides the perception of traffic participants, i.e., trams, buses, trucks, cars, bicycles, wheelchairs, and pedestrians, strictly speaking, also animals have to be perceived on time for inner-city and country roads.

The research vehicle BRAiVE is able to detect and classify preceding vehicles via computer vision. The algorithms are designed to detect symmetric patterns of a vehicle back view as well as backlights. Laser sensory was used to determine the exact distance to the target vehicle. The algorithms are also capable of tracking other vehicles inside winding roads. During the night, the headlights of forthcoming vehicles are perceived by computer vision. The vehicle can detect pedestrians inside the area of risk by using a fusion of computer vision and laser scanner data (Broggi et al. 2013).

The work of the Universität der Bundeswehr München published in Manz (2013) and Fries et al. (2013) provides algorithms for the detection and tracking of significant contour features (e.g., tires, car windows, vehicle silhouettes, vehicle lights) even under severe weather conditions. Based on the results presented in this work, the concepts are also capable of detecting crossing traffic and classify vehicles and pedestrians (Himmelsbach and Wünsche 2012).

The authors in Aeberhard et al. (2011) (BMW Group Research and Technology) have shown detection and tracking algorithms for vehicles on highways. The research vehicle was equipped with laser and radar systems covering 360° of the vehicle environment. It provides a large detection range in front region of the vehicle (Ardelt et al. 2012).

Team AnnieWAY has focused on highway scenarios during the Grand Cooperative Driving Challenge and used radar technology for vehicle tracking (Geiger et al. 2012). In the Stadtpilot project mainly laser scanners are used for the detection and tracking of other traffic participants (Ulbrich and Maurer 2013; Matthaei et al. 2015).

2.1.3 Self-Representation

In this chapter, the term "perception" includes the detection of the current state of the vehicle and the representation of its own performance capability. Many projects already use some form of ego motion estimation, used inside the time-based fusion of the vehicle environment and to enhance the global localization. The self-representation addressed in this paragraph goes far beyond these techniques and also includes the performance of all sensors, actuators, hardware and software components, and the vehicle itself, as briefly discussed in Maurer (2000), Siedersberger (2003), and Pellkofer (2003). In addition to the basic operability, the quality of self-representing data and its correctness are considered. This information gathered is necessary to evaluate possible vehicle (re)actions regarding their safe executions and degrade these actions if required. The project Stadtpilot at the Technische Universität Braunschweig uses sensor data to detect weather and road conditions and uses this data to influence the vehicle guidance systems (Reschka et al. 2012a). At this point, based on the publications available, it cannot be determined whether this kind of representation is considered in other projects.

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2.1.4 Context Modeling

Based on the aforementioned modules of environmental perception, it is mandatory to link the respective results, in order to create a model of the local context around the automated vehicle. The author in Brown (1996) defines a context as a "combination of elements of the user's environment which the computer knows about." The addressed user has to be replaced by the automated vehicle in the scope of automated driving. Many approaches and concepts deal with the context modeling paradigms. In Chatila and Laumond (1985), Becker and Dürr (2005), and Strang and Linnhoff-Popien (2004), some of these concepts are extensively discussed. Several projects use an association of detected traffic participants to road lanes (e.g., Wille 2012; Geiger et al. 2012; Ziegler et al. 2014), although this step is not regarded as a part of the environmental perception.

In the project Stadtpilot a central context model is provided, modeling, among other elements, even the phases of traffic lights (Wille 2012). Based on the results from our survey, the research projects of the Universität der Bundeswehr München store detected roads, intersections, and dynamic objects inside a scene graph structure. Static obstacles are represented inside an occupancy grid.

2.1.5 Conclusion

As depicted in Bar Hillel et al. (2012) and Ziegler et al. (2014), the machine-based environmental perception has still a long way to go towards a complete perception of the vehicles' environment. In Sect. 2.6, some dilemmas are presented, which could possibly lead to legal or ethical conflicts of decision. Nevertheless, nowadays systems are not capable of detecting these cases. The features required for this comprehensive environmental perception cannot be measured with current sensor systems (e.g., a laser system solely measures distance and reflectance of a target, but does not provide information about elasticity or mass). Algorithms required for the information extraction from sensor data are not designed or not able to perform in real time (e.g., sophisticated computer vision techniques). Vehicles do not know about the number of passengers in other vehicles and in most cases cannot distinguish between a child, an animal, and a trash bin when detecting an obstacle on the road. The availability of presented solutions does not yet meet the requirements of automatic driving vehicles. To provide at least a driving function, many research groups rely on map data, which is created manually. By doing this, required interpretation skills of the online perception can be avoided (see Sect. 2.2).

The concepts of the project BRAiVE (see Broggi et al. 2013) and the Universität der Bundeswehr München rely mainly on online perceived data and focus on their interpretation, which distinguishes them from other research groups.

2.2 Usage of Map Data

2.2.1 Definition of Terms

In this chapter, the term "map" is understood as an image acquired outside the vehicle of the stationary environmental features. Due to this limitation it becomes clear that verifying the quality and up-to-dateness of map data is difficult, because the map has usually been drawn up at an earlier time. Thus, due to the lack of continuance in the surveillance of the environment, it cannot be ensured that map data is up-to-date and all potential changes of the stationary environment are considered. In a certain sense, it therefore makes no difference if map data had been acquired 1 h, 1 week, or 1 year ago. According to the authors' understanding, this is the reason why autonomous systems must not rely on map data for stabilization purposes due to safety reasons, especially for collision avoidance and lateral control. The alleged stationary environment changes too quickly for the update rate of map data in the foreseeable future. In the case of navigation, map errors are annoying, because they might lead to a detour or do not lead to the desired destination, but they do not present a direct safety threat.

Today, map data is widely used in vehicles for navigation purposes and also for supporting the environmental perception, e.g., traffic sign recognition. Hence, it is comprehensible that all approaches on autonomous driving considered in this chapter also require map data. The usage of map data often exceeds the pure navigation tasks and can be assigned to the following three objectives:

1. Extension of the field of view (e.g., for navigation purposes)
2. Supporting the environmental perception and compensation of the sensors' limitations (e.g., by using position and type of road markings from map data)
3. Supporting the localization and compensation of the limits of GNSS (global navigation satellite system)-based localization (e.g., map-aided localization)

Map data in general differs, among others, in the type of stored features (see also classes of landmarks in Hock (1994) and Gregor (2002) or different abstraction levels in Matthaei (2015) and Matthaei and Maurer (2015)) as well as in their geometrical, semantical, and topological correctness and completeness. The geometry describes the position of the features, the semantic describes their meaning and class (e.g., posts, tree, building, traffic sign, etc.), and the topology describes the connections between the features, e.g., the road network.

2.2.2 Map Data in the Context of Autonomous Driving

During the DARPA challenges, the "route network definition file" (RNDF; see DARPA 2007) was introduced. The RNDF provides lane-level maps for areas with roads and a description of so-called zones which define the boundaries of unstructured areas as well as the positions of parking lots. The road description contains all types of information (geometrical, semantical, and topological): the course and the width of the lanes (geometrical), the connection of roads and lanes (topological), and the types of lane markings (semantical). However, the geometrical information in particular is just a rough representation of the environment containing only a sparse set of imprecise support points. That is the reason why some teams manually edited these maps (e.g., Bacha et al. 2008; Miller et al. 2008).

During the Cooperative Driving Challenge 2011, team AnnieWAY used highly accurate maps with lane courses. These maps were created by driving manually in the center of the right-hand lane and recording the GPS positions. Neighboring lanes then were added by a model-based estimation assuming the lanes to be parallel. These lanes were used for assigning traffic participants to certain lanes and thus for supporting the environmental perception (Geiger et al. 2012).

In the research project Stadtpilot, even more detailed and more accurate map data are applied (see p. 97 in Wille 2012). They contain topological information similar to the RNDF in the form of connected lanes (Nothdurft et al. 2011b). Geometrical information is manually extracted from highly accurate aerial images. The stored features are the courses of the lane borders. In this project, map data is used for supporting the environmental perception (see Wille 2012, p. 105) as well as to enhance the localization (see Wille 2012, p. 97).

The Bertha-Benz-Drive was also based on highly accurate maps which were "of prime importance" (Ziegler et al. 2014). According to Ziegler et al. (2014), three different map types were created: maps with 3D point landmarks, maps with an exact representation of road markings (lane boundaries, stop lines, and curbs) and rails, and maps with more abstract information on lane level. They had been used for all three aforementioned objectives (localization and support of the environmental perception within and outside the sensors' field of view). The mapping process of the 3D point landmarks was done offline but fully automated with a stereo camera system. The projection of the 3D point landmarks to the ground plane provides the data basis of the other two map types. The lane-level map then is manually created by editing the road marking map and is then stored in the file format of OpenStreetMaps. It contains in addition to the

Handbook of Driver Assistance Systems
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course of the lane boundaries the lane topology, rights of way information, and traffic lights (Ziegler et al. 2014).

Map data with centimeter accuracy of the lane information is also used by the BMW Group Research and Technology while driving highly automated on the highway (Ardelt and Waldmann 2011). The exact objective of using map data is not mentioned in detail, but maps seem to be applied for both supporting the localization and supporting the environmental perception (see Fig. 3 in Ardelt and Waldmann 2011).

The VisLab Intercontinental Autonomous Challenge (VIAC) from Italy was performed without any map data, because map data was not available for the planned route in some regions. But the team intends to integrate map data for the following research activities. In Broggi et al. (2013), a navigation level (according to Broggi: long-term planning) is introduced. For this purpose, OpenStreetMaps are enriched with additional information such as the number of lanes, their width, and traffic lights (see Broggi et al. 2013, p. 1412). A support for the localization or environmental perception is not mentioned in the publications.

In the context of the research activities at the Universität der Bundeswehr in München, only imprecise road maps with an accuracy of about 10 m are used according to their own statements. They provide data for route planning and for initializing intersection hypotheses of the environmental perception. These maps are obtained from OpenStreetMaps, for example, without any further enrichment with details of the vehicles' environment (see also Müller et al. 2011).

2.2.3 Conclusion

Map data is currently very important for autonomous driving for many purposes: For commonly known route planning (e.g., Broggi et al. 2013 or Müller et al. 2011), as a replacement of the perception of lane markings (e.g., Wille 2012), or for supporting the GNSS-based localization (e.g., Ziegler et al. 2014 or Levinson 2011), all versions of integrating map data in the system can be found. None of these approaches discuss solutions for handling short-term changes of the environment. The challenge of ensuring the up-to-dateness of map data also remains unanswered. However, as long as the stabilization of the vehicle is based on map data, they are a safety-relevant data input.

Concerning the requirements of map data, those projects are leading, according to the authors' point of view, which do not completely rely on map data and which are also able to deal with imprecise map data. Our own experiences in the research project Stadtpilot demonstrate again and again how vulnerable map-based approaches to the smallest changes in the environment. It is very simple to change the position of stop lines, to change road markings from dashed to solid, to change the prescribed driving direction of certain lanes at intersections, and to add a new speed limit sign or to start roadwork. All these are small changes, which do not affect the infrastructure on a macroscopic level but would lead to a malfunction of an automated vehicle mainly relying on map data. This might also result in a behavior which is not allowed regarding road traffic regulations or even lead to endangering behavior.

Approaches to speed up the update of map data are already being pursued. Some years ago the project ActMap (Flament et al. 2005) researched online map updates from a central server to the vehicles. In the following project FeedMap (Visintainer and Darin 2008), additional approaches were examined to send data from different vehicles to a central server and thus increase the up-to-dateness of map data. This idea is also mentioned in Ziegler et al. (2014) and conceptually integrated into the system architecture in Matthaei and Maurer (2015)and Matthaei (2015).

In a further step it might be possible that autonomous vehicles themselves send perceived environmental features to a central server and thus update their maps themselves. This would be an example for collaboration. But this assumes that the vehicles are basically able to perceive and understand their environment completely and that they know exactly their position. Each vehicle might be the first one which reaches an unknown or a changed place and it has to react in a proper way. Based on this discussion,

Handbook of Driver Assistance Systems
DOI 10.1007/978-3-319-09840-1_61-1

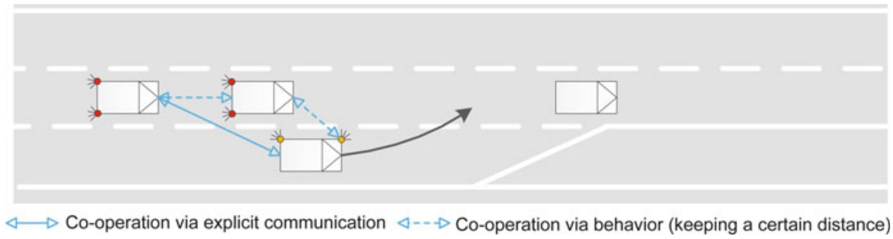

Fig. 3 Today's optical communication technologies (turn indicators) only allow an indirect communication, for example, at on-ramps. V2V communication would enable a direct communication of the driver's intention to the entire environment

it is debatable whether approaches with a high trust in map data really show the way forward to "autonomous driving."

2.3 Cooperation

2.3.1 Definition of Terms

The term "cooperation" describes a certain form of social collaboration between at least two participating partners, aiming at an enhancement for ourselves as well as the other party in comparison to an egoistic approach (Spieß 2014).

In more technical terms, referring to this definition and based on (Stiller et al. 2013), cooperation is the approach to get a "better" solution for a given problem in terms of a to-be-defined optimization criterion. This criterion can have various characteristics, and its agreement is a key aspect of cooperation.

The criteria might be defined a priori by the systems' programmer (e.g., avoid collisions with other vehicles), or, in a more sophisticated way, might be dynamically defined between the traffic participants. The coordination of these criteria and their fulfillment require a high amount of negotiation between the participating parties and are the main topic when talking about cooperative aspects in public traffic, especially regarding contradicting objectives among some parties.

Therefore, one main prerequisite for cooperation is the ability to communicate with the other parties. This communication can take several forms. Technical approaches use V2X technologies for this purpose (chapter "▶ Car-2-X"). The idea of communication between traffic participants did not arise with this technology, but can be found already in current traffic regulations. These dictate the presence of, e.g., turn indicators, brake lights, and a signal horn. Other very important ways of communication are gestures and the behavior of traffic participants. Human drivers will communicate their intentions by hand signs, and humans are quite good in deriving the intentions of other drivers from their behavior. One well-known situation requiring communication as well as cooperation is the merging process at on-ramps of highways, as depicted in Fig. 3.

The term cooperation is widely used in science and the context of (advanced) driver assistance systems, but has not been finally defined for autonomous driving. When using the term cooperation in a more general way, two levels of cooperation can be found. The first one includes the compliance with current traffic regulations required for driving in public domains. Collision avoidance and basic strategies of traffic flow control are the main contents, e.g., the right of way and merging procedures at highways. The communication of the driver's intentions is made by the indicator lights or the driving behavior and is used as cooperation request to other participants.

The second level is defined by concepts for a more sophisticated optimization of traffic flow and guidance, e.g., leaving a larger gap to the preceding vehicle, so that other vehicles can merge into our lane more easily. Both levels of cooperation do not require the usage of V2X or other explicit communication

Handbook of Driver Assistance Systems
DOI 10.1007/978-3-319-09840-1_61-1

technologies, but can basically also be realized using onboard sensors. The cooperation aspect is located in the guidance module of the functional system architecture in Fig. 2.

2.3.2 Cooperation in the Current Context of Autonomous Driving

Up to now, cooperative aspects of the second level are rarely established. First approaches were presented in the research project "Cooperative and Optimised Traffic Signalling in Urban Networks" (KOLINE) on the inner city ring of Braunschweig (Brunswick), Germany. The main goal was the optimization of traffic flow regarding fuel usage and noise pollution by implementing a cooperative optimization of the traffic flow (Saust et al. 2010). Sensors mounted on infrastructure elements and telemetry from test vehicles were used to determine the traffic flow speed and calculate an optimal approaching strategy to the next intersection. Additionally, the adaption of traffic light phases was investigated. As a result, the amount of required stop-and-go maneuvers could be reduced by approximately 20 %, and the fuel usage was reduced by around 5 % (Bley et al. 2011).

Other results were published as part of the "Grand Cooperative Driving Challenge" (GCDC) in 2011. As in the previously presented project, the main focus was the optimization of traffic density by using an automatic grouping of traffic participants (platooning) (Nunen 2012). Communication was based on a V2X platform. Nine teams participated in this challenge and had to prove their concepts. The team "AnnieWAY" won this challenge, showing that this scenario can technically be handled (Geiger et al. 2012).

2.3.3 Conclusion and Outlook

Although the usage of explicit communication patterns, e.g., V2X technology, gives the potential of many sophisticated uses, some challenges arise. Public traffic domains still allow for participants without this explicit communication technology, so these participants have to be regarded as well as fully equipped vehicles.

V2X technology, as well as every other communication technology nowadays, has a certain potential of – intended or unintended – misuse. As a result, data security and safety have to be ensured when bringing these technologies to the market. The presence of non-V2X participants leads to the conclusion that these technologies can only be an additional data source to onboard sensory. This was already one main experience in the GCDC, where a radar system was used as a plausibility check against the V2X messages from other participants (see Geiger et al. 2012, p. 8).

The fusion of sensor data, perceived by other traffic participants as well as infrastructure systems, seems to emerge as one of the next research topics in cooperative technologies. These topics are described by the term "cooperative perception." First ideas were published in the research initiative "Co-operative sensory and co-operative perception for preemptive safety in public traffic" (KoFAS) in 2013 (Goldhammer et al. 2012; Rauch et al. 2013). So far, these topics have not been addressed in the context of autonomous vehicles in terms of this chapter. Another extent of cooperative technologies could be the joint generation of map data, as discussed in Sect. 2.2.

2.4 Localization

Another key aspect of autonomous driving is the localization: Without a proper localization of the host vehicle, the usage of map data is not possible, and without knowing the relative motion of the vehicle between two points in time, the perception of the environment is at least more complicated. Additionally, the communication among the vehicles in the context of cooperation requires in most cases an exchange of the vehicles' positions for an assignment of the messages to locally perceived objects.

Handbook of Driver Assistance Systems
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2.4.1 Lessons Learned from the DARPA Challenges

Based on the experiences made during the DARPA Challenges, one major finding referring to the localization is that the relative motion of the host vehicle should be strictly separated from the absolute localization (Moore et al. 2009). These two localization solutions differ in their optimization goal. The relative motion estimation (in Moore et al. 2009 called "local frame") describes a continuous sequence of positions starting at an arbitrary position with the objective to provide the incremental change in position as exact as possible. The long-term positioning may drift away.

On the contrary, the absolute localization (in Moore et al. 2009 called "global frame") determines the best estimate of a position at the current time step within a reference frame fixed in place. It thus does not drift, but the sequence of positions can contain discontinuities.

The following comparison of the research approaches concentrates on this global localization and mainly focuses on map-relative localization because in most cases the absolute global localization is just a first step towards more relevant map-relative localization.

2.4.2 Localization in the Context of Autonomous Driving

One of the latest publications on the subject of autonomous driving was made in the context of the Bertha-Benz-Drive. Their approach of a map-relative localization is based on a mono camera looking backwards (see, e.g., Knapp et al. 2009; Lategahn and Stiller 2012). The exact map-relative pose of the vehicle is determined by matching online perceived road markings with those road markings stored in the map. The detection of road markings in the image is pre-initialized based on map data. Hence, the detection of the road markings is processed with detailed a priori information (see also Sect. 2.1 and Ziegler et al. 2014). In addition to this approach, single features obtained from a mono camera are matched to a map with 3D point landmarks (see, e.g., Knapp et al. 2009). According to the researcher's own information, the implemented approach is able to work without GPS (Ziegler et al. 2014).

In Levinson (2011), two fundamentally different approaches are published. On the one hand, a localization solution based on a highly accurate INS-DGPS platform was used during the DARPA Urban Challenge for a map-relative localization. Map errors and errors of the global localization were corrected with the aid of matching between map data and curbs obtained from laser scanners, as well as reflectance values of road markings. On the other hand, a previously recorded dense grid-based map of the ground plane containing reflectance values of a laser scanner is generated in an offline process, which is much more detailed than the lane-level representation of the RNDF. In a second run, the vehicle can now match the currently perceived environmental data to this detailed map and thus calculate the correct pose (position and orientation) similar to the aforementioned approach.

On the contrary, Leonie of the research project Stadtpilot drives based on an INS-DGPS system. However, matching approaches based on lane markings were also developed and trialled on a test circuit (Nothdurft 2011a; Wille 2012; Matthaei et al. 2014a), but are currently not used for an automated control of the vehicle.

The approach developed at the Universität der Bundeswehr in München follows a fundamentally different philosophy. Based on the lesson learned – "never trust GPS" (see Luettel et al. 2009) – they developed in the tradition of (Dickmanns et al. 1994) a system, which relies almost completely on the perception and which uses GPS and map data only as rough hints and for route planning. According to the team's statements, accuracies of 10–20 m for the GPS-based localization are sufficient. The global pose estimation is also supported by a matching between environmental and map data, but on a higher abstraction level (Müller et al. 2011).

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2.4.3 Conclusion

The determination of the global position of the host vehicle is necessary in most projects for integrating external data. This data covers in most cases map data but may also be V2X data. Obviously, even today's highly accurate localization systems are not sufficient for a reliable stabilization of the vehicle (Levinson 2011; Nilsson et al. 2012). For that reason, highly accurate and detailed map data is often used to compensate this lack of accuracy by matching environmental features to this map data. Some approaches don not even need an absolute global pose, but only require a map-relative global pose (e.g., Müller et al. 2011).

Some other projects follow the objective of becoming more independent of highly accurate absolute global positioning by increasing their trust in map data or in their environmental perception.

2.5 Mission Accomplishment

Behavior planning and control are integral parts of the driving task an autonomous vehicle must by definition be able to accomplish.

In Donges (1999) and chapter "▶ Driver Behavior Models," the driving task is divided into three levels: navigation level, guidance level, and stabilization level. A similar hierarchy can be found in the architectures of many projects in the field of autonomous driving (Broggi et al. 2013; Urmson et al. 2008; Montemerlo et al. 2008; Kammel et al. 2008; Matthaei et al. 2015; Matthaei and Maurer 2015). As it provides a clear and hierarchical structure for mission accomplishment in automated driving, the following discussion will also be using this three-level model. The terms "navigation," "guidance," and "stabilization" are used accordingly.

Decisions made at the navigation level affect the whole mission. Thus, it is also called the strategic level. At the guidance level, tactical driving decisions are made, such as the selection of a particular driving maneuver. For these, the current driving situation is assessed and command variables for the underlying stabilization layer are derived. Because of the local planning horizon, it is also called the tactical level. Modules in the stabilization layer take care of the control of command inputs from the two superordinate levels. Figure 4 illustrates the different hierarchical levels and an additional human-machine interface for a passenger or system operator. This interface provides the possibility of entering or modifying mission goals (see Sect. 1.3).

All teams cited in this section address planning and control only for situations that are known and considered at the design time of the system. Handling unknown or unconsidered situations may be necessary for autonomous driving in its final stage, but is for most teams beyond the scope of their challenges to be currently addressed.

2.5.1 Navigation

A passenger mainly communicates with the automated vehicle on the navigation level. It is possible to enter the desired destination or certain waypoints. A common approach is to represent the map data as a directed graph. This way it is possible to solve the navigation task by using graph search algorithms.

In the Urban Challenge a lane-level map of the road network was given (RNDF; cf. Sect. 2.2). Team AnnieWAY applied an A* algorithm to compute an optimal lane-level route with respect to the expected travel time (Kammel et al. 2008). In a preprocessing step, the waypoints of the given map were interpolated, using a spline-based geometric representation. Thus, the resulting route represents already a continuous path to the target position. A reactive layer, however, is still allowed to vary the path locally (cf. Sect. 2.5.3). If a road is recognized as blocked, the internal representation of the road network is updated and a new route is computed.

For Boss (Urmson et al. 2008) and Junior (Montemerlo et al. 2008), a different approach was used: Instead of planning an explicit route to the destination, for each edge of the graph that represents the road

Handbook of Driver Assistance Systems
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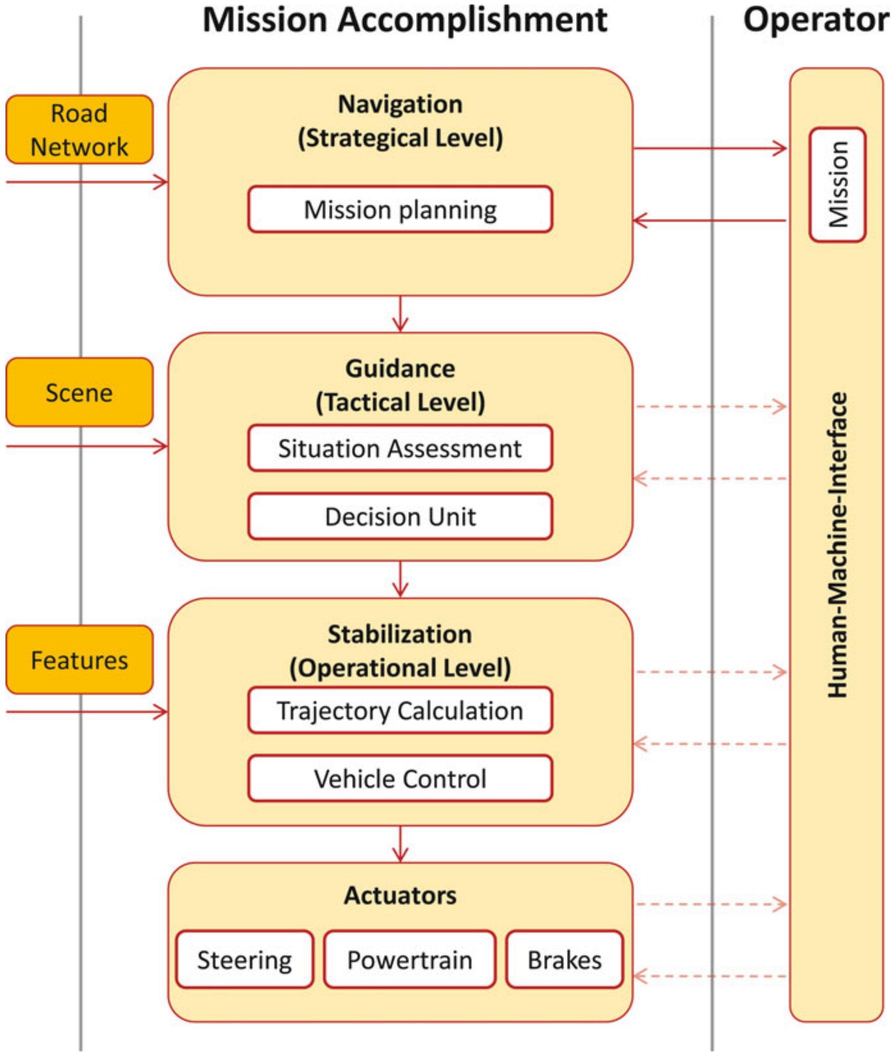

Fig. 4 Subdivision of the driving task similar to Donges (1999), Matthaei and Maurer (2015), and Matthaei (2015)

network, the remaining costs to reach the destination are computed. The decision which route is actually taken is shifted to the guidance level. Again, the costs depend on the expected travel time. On the guidance level then, these strategic costs are combined with the costs that arise from the current traffic situation, e.g., the costs of carrying out a lane-change maneuver. Analogously to AnnieWAY, if a road is recognized as blocked, the internal representation of the road network is updated and the costs are recomputed.

2.5.2 Guidance

On the guidance level, the autonomous car has to interpret the traffic situation with respect to its goals and the goals of other traffic participants. It has to generate alternative options of action, evaluate these options, and finally make a decision. Cooperative behavior is also part of this level, but it is already treated in Sect. 2.3.

A very common approach on this level, in the Urban Challenge and in subsequent projects, is to use state machines (Urmson et al. 2008; Montemerlo et al. 2008; Rauskolb et al. 2008). Such a state machine may have system states like the execution of lane change and overtaking maneuvers, the approaching of stop lines in and in front of intersections, decisions to cross a traffic light by its signal change from green to amber, or the execution of cooperative maneuvers, e.g., intentionally leaving a gap so that a vehicle on an

Handbook of Driver Assistance Systems
DOI 10.1007/978-3-319-09840-1_61-1

on-ramp can merge in front of the automated vehicle. Team Carolo from Technische Universität Braunschweig (Rauskolb et al. 2008) used a hybrid approach of traditional, rule-based state machines to handle complex maneuvers like parking, U-turns, and crossing intersections and a behavioral DAMN arbitration model (Rosenblatt 1997) for regular driving along roads and for collision avoidance with obstacles.

Similar to the aforementioned approach, at the Technische Universität München (Goebl et al. 2008), a state machine combined with a fuzzy logic for situation assessment is employed. At the Universität der Bundeswehr in München, a hierarchical state machine with meta states like convoy driving, tentacle navigation (cp. Sect. 2.5.3), and U-turning is used on the tactical level (Luettel et al. 2011).

The approach taken by BMW in the ConnectedDrive project, which focuses on highly automated driving on controlled-access highways, differs from the approaches mentioned above in separating longitudinal and lateral control on the guidance level (Ardelt et al. 2012; Ardelt and Waldmann 2011). A hybrid, deterministic state machine is used to define the superordinate driving behavior, and a decision tree is used as a hierarchical decision-making process. The superordinate state is determined by traversing the decision tree, depending on the driving goal derived by the situation interpretation and the current feasibility of maneuvers.

Rule-compliant behavior at intersections is particularly demanding for autonomous road vehicles. In the Urban Challenge, the Stanford Racing Team used so-called critical zones that were encoded in the map data, to check if Junior has to give way to other vehicles at intersections without traffic lights (Montemerlo et al. 2008). The central element of the approach of the team from Carnegie Mellon University is a module that determines the right of way by observing the order of arrival at an all-way stop. Moreover, it identifies gaps that are sufficient for crossing through or merging into moving traffic at an intersection (Urmson et al. 2008).

Behavior planning for crossing intersections with traffic lights is addressed in Saust et al. (2010, 2012). Via V2X communication, the remaining time of the current traffic light phase is transmitted to the automated vehicle and an energy-optimal approaching strategy is calculated, also considering possible traffic tailbacks.

From the authors' point of view, a central issue on the tactical level is the handling of perception and prediction uncertainties. At Carnegie Mellon University, an analytical model for predicting the driving behavior of other vehicles is used to evaluate tactical driving maneuvers (Wei et al. 2010). Here, the evaluation is limited to simulated data, and measurement uncertainties are not yet considered. However, an easy-to-comprehend driving behavior is achieved by the separation of a prediction and cost model. In Wei et al. (2011), the same team demonstrated the consideration of uncertainties in longitudinal planning for the task of single-lane automated driving under uncertainty using a Markov decision-making process.

At the Technische Universität Braunschweig, the consideration of perception and prediction uncertainties has been demonstrated in a first implementation of partially observable Markov decision processes for lane-change decision making in inner-city urban traffic (Ulbrich and Maurer 2013).

2.5.3 Stabilization

The stabilization level covers reactive path and trajectory planning and closed-loop control of the vehicle's actuators (steering, powertrain, brake). In the following, the focus is on trajectory generation in structured environments like roads. In the Urban Challenge, path and trajectory-planning methods for unstructured environments were also applied, e.g., when a vehicle had to navigate in a parking lot or when it had to handle road blockages (Urmson et al. 2008; Montemerlo et al. 2008; Kammel et al. 2008).

Team AnnieWAY, as most participants in the Urban Challenge, used a path-based approach for motion planning (Kammel et al. 2008). A reference path that follows a lane or crosses an intersection (and that may also include a lane change) is generated on the guidance level. Obstacles and other road users are not

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considered in the generation of the path. For this reason, the reactive layer tests, based on an occupancy grid that is generated by laser measurements, if the given path is collision-free. If it is not, a set of precomputed alternative paths that represent velocity-dependent motion primitives for collision avoidance is evaluated and the path with the highest utility is chosen. The alternative paths are also referred to as tentacles, as their use is similar to the tentacles of insects (Hundelshausen et al. 2009). The low-level control of the vehicle is split into longitudinal and lateral control. For the lateral control, i.e., to follow the selected path, a velocity-independent orbital tracking controller is used. The longitudinal control is responsible for following other vehicles at safe distances, stopping at certain positions, and keeping the speed limits.

The tentacle-based approach is also used in the test vehicle MuCAR-3 (Luettel et al. 2012). However, in this case no reference path is given, but a route consisting of distant global positions. The local navigation is done by using the deviation from the straight line between two waypoints as an input of the utility function of the tentacles. Another path-based reactive approach is presented in Broggi et al. (2013).

At higher traffic densities, as they are common in urban traffic, a trajectory-based motion planning is necessary (Werling et al. 2010). The trajectory-planning method presented in Werling et al. (2010) generates, similar to the tentacle approach discussed above, a set of trajectories with minimal jerk in lateral and in longitudinal direction. The candidate trajectories vary in their end times as well as in their end positions. The latter are described as a longitudinal position and a lateral offset with respect to a given reference path. Again, the given reference path typically follows a lane. In a second step, the trajectory with the highest utility is selected, e.g., based on the predicted motion of other traffic participants. If the internal representation of the environment is consistent over time (i.e., if the prediction of the environment matches with future measurements), this method realizes an optimal (open-loop) control and the generated trajectory is consistent over time. However, both processes, perception and prediction, inevitably involve uncertainty, and thus the overall process has to be considered a closed-loop control. The method was applied in AnnieWAY after the Urban Challenge and is also used in Junior 3 (Levinson et al. 2011). A method for generating reference paths with minimal curvature is used in the Stadtpilot project at the Technische Universität Braunschweig (Wille 2012).

With their participation at the Pikes Peak International Hill Climb race, a cooperation of Stanford University and the Electronics Research Lab of Volkswagen of America demonstrated that it is already possible for an automated vehicle to follow a precomputed path at the friction limits of the vehicle (Funke et al. 2012).

2.5.4 Conclusion

The most common approach for structuring the task of mission accomplishment is a hierarchical (three-level) architecture, similar to the three-level model used to structure the above discussion. Research focuses currently on tactical decision making, maneuver execution, and trajectory planning. On the tactical level, lane-change maneuvers and cooperative driving (see Sect. 2.3) are popular subjects of research. Further research is necessary, especially in the field of situation prediction and situation assessment and in general on coping with uncertain information and the unknown intentions of other road users. On the stabilization level, comfortable yet accurately targeted trajectory planning is the focus of research for many teams. Many teams use planning-ahead approaches and choose among a set of generated candidate paths or candidate trajectories.

Handbook of Driver Assistance Systems
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2.6 Functional Safety

2.6.1 Requirements

From the authors' point of view, functional safety for unmanned road vehicles is one of the main challenges for the introduction into public traffic. It is not yet clear when an autonomous vehicle is safe enough, and thus a societal consensus has to be found. This includes the definition of an acceptable level of operational risk. This level defines whether an autonomous vehicle is in a safe or unsafe state. There are only few research activities which investigate this issue, e.g., the project "Villa Ladenburg" at the Daimler and Benz Foundation (Maurer 2013; Reschka 2015) and an chapter by Bryant W. Smith about legal implications (Smith 2014).

The operation of an autonomous vehicle has to be safe in normal operation as well as in unforeseen situations and in case of technical failure, misbehavior of others, and bad road or weather conditions. The vehicle control system has to maintain a safe state or transfer the vehicle into a safe state in any situation. This is to avoid hazards from the vehicle to other traffic participants and passengers inside the autonomous vehicle. A possible solution for a safe state is a full stop of the vehicle at a safe location (Isermann et al. 2002). A safe location is a place where the vehicle is no hazard to others, like an emergency lane on a highway, a wide curbside on rural roads, or a parking area. In urban traffic with low relative speeds between traffic participants, a stop on a driving lane is also imaginable, if no emergency routes are blocked.

The challenge of transferring a vehicle into a safe state without handing over control to a human driver is one of the main reasons for the necessity of a human driver monitoring advanced driver assistance systems. In an autonomous vehicle, no human driver is available, because the vehicle can be operated driverless and even unmanned. For highly and fully automated systems, this fallback solution is not available either. The technical system has to be designed to cope with this situation, and it can be developed for a safe and reliable operation by using functional redundancy, hardware redundancy, and software redundancy. For example, a lane change on a highway or a stop at roadside on a highway to maintain a safe state requires a functioning environmental perception, a decision process which includes a risk estimation of possible actions, and a reliable actuator control. Such a stop at the roadside is a requirement in the homologation process for autonomous vehicles in Nevada and can be preceded by one or more lane changes (NDMV 2012).

In dangerous situations an autonomous vehicle has to react in a way that avoids any harm to persons. If no humans are threatened, damage to property has to be also avoided. A solution to solve such situations could lead to a violation of applicable law, e.g., traffic rules. This violation seems acceptable as long as damage to persons and property can be avoided, e.g., crossing a solid line to avoid a collision. Further, it is imaginable that situations do not have a solution without damaging persons and/property and violating rules. In such dilemma and polylemma situations, a decision between several options is necessary. This decision has to be taken under judicial and ethical rules. In current research and development, the consideration of such rules is not known to the authors.

Thinking of dilemmas and polylemmas, further questions with a strong connection to the public acceptance of the technology arise: Has the safety of passengers a higher priority than safety of other traffic participants? How should an autonomous vehicle behave, if damage to persons is inevitable? May this ever happen or is an inevitable accident a result of an engineering/design issue concerning the speed limit chosen by the automated vehicle itself? Besides stopping the vehicle, more actions to reduce harm are imaginable, e.g., lower vehicle speeds, increased safety distances, and changes in maneuver planning. In advanced driver assistance systems, so-called action plans can be used to maintain a safe state or transfer the vehicle into a safe state. Hörwick and Siedersberger (2010a, b) propose to stop the vehicle in

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case of a technical failure in a traffic jam assist system, if the human driver does not react on a takeover request.

Additionally, actions to restore the system's performance are useful and desirable. In Ghosh et al. (2007) such self-healing methods are described. The awareness of dilemmas and polylemmas, decisions to avoid an unsafe state or to restore a safe state, and the reduction of accident consequences demand the knowledge of the vehicle's own performance capabilities. In combination with a scene and situation awareness and a prediction of both, possible actions can be identified. The best one has to be chosen and executed (Maurer 2013; Isermann 2006; Reschka et al. 2012b).

2.6.2 Functional Safety in Current Autonomous Driving Efforts

In this section, safety concepts of the experimental vehicles from projects covered in this chapter are investigated. In all projects a safety driver or at least a human monitoring the system (operator) is necessary in public traffic, because of the difficulties and challenges described above. The safety driver or the operator has to control the vehicle in dangerous situations. As a consequence, all autonomous driving efforts so far have to be categorized as partial automation according to Gasser et al. (2012) and SAE (2014). The safety drivers and operators are able to take over control immediately by using the control elements inside the vehicle or from outside of the vehicle.

In the project Stadtpilot at the Technische Universität Braunschweig, the safety driver overrules the technical system by his or her intervention. In case of technical failures, control is handed over to the safety driver. As a consequence, he or she has to monitor the system and the traffic continuously. On a closed test track functions are used, which reduce the system performance capabilities by monitoring critical system parameters. For example, the current accuracy of the localization in the world and in the map reduces the maximum possible speed of the vehicle. Additionally, road and weather conditions are monitored and cause the vehicle to drive more carefully (Wille 2012; Reschka et al. 2012a, b).

The experimental vehicle MuCAR-3, developed at the Universität der Bundeswehr in München, is able to monitor itself and to reduce its functional capabilities based on the monitoring data. This reduction could lead to emergency braking maneuvers. The safety driver can overrule the system as well. Data collected by monitoring heartbeats of hardware and software modules and checking measured and calculated values is used to trigger restarts of components. Additionally, failing system parts can be reconfigured. Altogether, these self-healing functions lead to a safer and more reliable operation of the vehicle. If self-healing does not restore enough functional capabilities, an emergency braking maneuver is triggered (Goebl et al. 2008).

As already mentioned, the experimental vehicle BRAiVE demonstrated automated driving in public traffic in 2012 (Broggi et al. 2013). On some parts of the roads driven in this demonstration, no safety driver was present on the driver's seat. The system was monitored from a person sitting on the co-driver's seat. This person was able to intervene by using the gear level and an emergency stop button to stop the vehicle immediately. Although this demonstration was impressive, it seems that a fully driverless and, even more important, a fully unmonitored operation are not possible with BRAiVE. An external function to stop the vehicle was available as well. This e-Stop function uses a remote control to trigger an emergency stop (Bertozzi et al. 2013).

At the Carnegie Mellon University in Pittsburgh, the experimental vehicle BOSS was improved after the DARPA Urban Challenge in 2007. The implemented SAFER (safety for real-time systems) approach for software redundancy is able to compensate failing software components by switching to redundant components (Kim et al. 2013). This switch from one component to another is executed in real time. The SAFER approach has to be seen as an addition to other approaches for safety functions, because it does not cover any hardware errors. Using the approach on distributed hardware could further improve its

Handbook of Driver Assistance Systems
DOI 10.1007/978-3-319-09840-1_61-1

advantages for safety reasons. Such a system is currently being developed in the Controlling Concurrent Change (CCC) project in Braunschweig (Project homepage: http://www.ccc-project.org).

After the DARPA Urban Challenge, the Stanford University and the Volkswagen Electronics Research Lab have developed the experimental vehicle Junior 3. As a safety measure, the vehicle has so-called silver switches which control the activation of the vehicle guidance system. If these switches are activated by a human safety driver, the control commands from the vehicle guidance system are forwarded to the actuator control units. If the safety driver overrules the system or the system deactivates itself for another reason, the switches stop the forwarding of control commands to the vehicle. In this fail-safe position, the safety driver controls the car. This concept is similar to the one applied in Leonie from the project Stadtpilot.

The monitoring of the system in Junior 3 is done by a health monitor. This system detects malfunctions of software components. In contrast to the SAFER approach, no redundancy is implemented, but self-healing functions like component restarts are triggered. With these safety measures, a partial automated operation in public traffic is possible. On closed test tracks, a driverless valet parking function is available. The vehicle can then be stopped with a remote control (Levinson et al. 2011; Stanek et al. 2010).

2.6.3 Conclusion

High safety requirements for driverless operation of automated vehicles demand a safety system which can maintain a safe state or transfer the vehicle into a safe state. The projects discussed take different approaches to solving safety issues. Unfortunately, no safety concept exists, which does allow an unmanned operation in public traffic. All research vehicles described are therefore conditionally automated, because either a safety driver or an operator monitors the system and has to intervene in case of technical failures.

In the DARPA Urban Challenge 2007, the unmanned vehicles were operated on a closed test track. The reduced complexity of the traffic and the trained stunt drivers of not automated vehicles compensated the resulting risk. Additionally, a remote stop function was used to stop the vehicles in any dangerous situation.

More recent research projects challenge the difficulties in unmanned operation. The Villa Ladenburg project of the Daimler and Benz Foundation (Maurer 2013) in Germany covers social and ethical aspects of unmanned vehicles in public traffic. Google Inc. has presented a vehicle without control elements such as a brake pedal, a steering wheel, and an accelerator. In Germany an unmanned safeguard vehicle for controlled-access highways is currently being developed and will be used in public traffic in the next years.

These approaches will likely rely on the above described safety functions in research projects and maybe combine them to more powerful safety concepts, which allow an unmonitored operation of vehicles in public traffic.

3 Outlook and Challenges

Autonomous driving is indeed a fascinating topic, especially because it concerns each one of us, directly – whether as a driver or a pedestrian. However, the vision of the final stage of any driver assistance system being “to leave a vehicle to its own means” arouses ambivalent feelings in society – somewhere between curiosity combined with the urge to explore and skepticism, possibly even paired with an apprehensive prejudice against technology.

Until a short time ago, autonomous vehicles were primarily discussed in technical circles. The general public only became aware of the future visions of driverless vehicles in cinemas. Recently, however, the

Handbook of Driver Assistance Systems
DOI 10.1007/978-3-319-09840-1_61-1

general interest and expectations have been aroused in the media by regular success stories and short-term promises to launch these driverless vehicles on the market. For the future, we still expect a lot of details to be solved to finally have vehicles that are fully automated and more resource efficient and accomplish missions more safely than humans do today.

At first glance, the status of today's driver assistance, in serial production or during the research phase, gives rise to hope. A large number of new functions have been shown during the past few years and are also dealt with in this book. However, our research has shown that the way towards autonomous driving seems to be longer than is sometimes communicated at the moment. This is possibly due to the fact that human performance, particularly when supported by carefully developed driver assistance systems (Knapp et al. 2009), is frequently underestimated. Contrary to driver assistance systems that primarily have the aim of compensating gaps in human abilities, which have been identified on the basis of accident analyses (Chiellino et al. 2010; Buschardt et al. 2006; Winkle 2015a), or of automating routine driving situations under a person's supervision, autonomous systems must reach the abilities of an attentive human driver. It is not until then that autonomous systems will be able to go beyond the human abilities and lead to a further reduction in the number of accidents.

A step that is not to be underestimated is to secure a current assistance system in such a way that it functions in future as expected in an autonomous vehicle, without the driver's supervision (this means, among other things, error-free in every traffic situation). There is a high probability here of unpredictable constellations not being taken into consideration that might possibly cause the system to react inadequately or not to react at all.

Even the dependency of the autonomous vehicles on automated map updates has further consequences. The autonomous vehicle is no longer the uppermost instance in an environment, but part of a superordinate system. This, in turn, will have an effect on the concept of the vehicles. The authors have been unable to identify any research activity in this respect in the context of autonomous driving, until now.

Furthermore, the questions outlined at the beginning are not at all clear, either. For example, there has not been any strategy as yet for evaluating the perception and/or interpretation of a system on a semantic level. It is still frequently the case that the topic of redundancy is not acute at all, in an urban environment, for example, not even a nonredundant solution can be implemented, even when endeavoring to make use of every possible means. In contrast to the stabilization level, it is probably not possible, however, to resort here to redundancy concepts from other disciplines, such as aerospace or power plant technology.

Adaptations in the infrastructure are controversial, because they are extremely costly and even maintenance intensive where technical enhancements are involved. At present, the legal situation is being partially adapted for a trial operation, but, as yet, never without safety drivers. Thus, according to Gasser et al. (2012), all the public demonstrations are, per definition, partially automated, even though the targets set in the projects require highly automated, fully automated, or even autonomous driving.

This raises an essential point in today's public debate. As mentioned at the beginning, no consensus has yet been reached on the range of functions for autonomous driving. Furthermore, statements concerning the introduction of autonomous driving appear to be very optimistic in many cases. On the other hand, the introduction of partially automated systems is already under way.

The research project "Villa Ladenburg," of the Daimler and Benz Foundation, has initiated a multidisciplinary debate in society on an interdisciplinary approach towards a holistic development and risk acceptance. Numerous questions and aspects in the research and development process were identified there (Winkle 2015b). On gaining successful proof that full automation is superior for road safety in the long term, a completely new question could then be posed, namely, whether the error-prone human should be allowed to continue driving a vehicle independently (Maurer 2013).

Handbook of Driver Assistance Systems
DOI 10.1007/978-3-319-09840-1_61-1

Appendix: Questionnaire on "Autonomous Vehicles"

Project Organization and Objective

This section addresses general and organizational aspects of your project.

1. What is the name of the project?
2. With which universities and/or industrial partners do you cooperate in this project?
3. When was the project started/how long have you been working on the project now?
4. What is the objective of the project?
5. What are the assumptions, constraints, and restrictions in the project?
6. Was the system demonstrated on public roads? If so, which capabilities were publicly demonstrated in which domains?

Perception

This section addresses the perception and localization of your system as well as its environment representation.

1. Please describe briefly the perception architecture of the system.
2. What sensor technologies (and which devices) are used?
3. How are dynamic objects perceived and represented by the system? What kind of dynamic objects are perceived?
4. How are static objects and road boundaries perceived and represented by the system?
5. Is the system capable of perceiving the state of traffic lights? How is this done?
6. What kind of traffic signs are perceived by the system?
7. Does your system perceive pedestrians and cyclists? If so, under which conditions and by the use of which sensors and algorithms?
8. How are lanes perceived? Which conditions must be fulfilled by a lane?
9. What are the requirements for perceiving lateral traffic at intersections? Does the system identify the right of way?
10. Is the system capable of determining the topology of intersections from perceived data? How is this done?
11. Which intentions of other road users can be perceived by the system? Which conditions must be fulfilled therefore?
12. How are the overall and the current capabilities of the system represented and monitored? How do the current capabilities determine the behavior of the system?
13. How is the relative position of the vehicle with respect to the lane perceived? Which conditions (e.g., lane markings, geometric models) must be fulfilled therefore?
14. Is information from digital maps used? How accurate are these maps?
15. Is the localization in digital maps solely based on satellite-based positioning or are other sensors used additionally? If so, which additional sensors and algorithms are used for localization?
16. Is the system capable of communicating with other road users or the road infrastructure (i.e., Car2x technologies)?
17. Are perceived features (e.g., objects, lanes, road boundaries) combined into a generic environment model? If so, please give a brief description of this model.

Function

This section addresses functions and maneuvers implemented in your test vehicle.

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1. Is the system capable of autonomously executing lane-change maneuvers without any support of the driver? How is this maneuver implemented? In which domains (highway, rural roads, and urban environment) can it be executed?
2. How does the system react to the state of traffic lights?
3. What kind of turn maneuvers are implemented? Is the system capable of executing a turning maneuver into moving traffic?
4. How does the system deal with intersections without traffic lights?
5. Is the system capable of merging into traffic on rural roads and/or highways? How is this maneuver implemented?
6. What kind of emergency situations are considered by the system (e.g., emergency braking of the vehicle in front, pedestrian crossing the street)? How does the system react to these situations?
7. What concepts are implemented for keeping the vehicle in the current lane?
8. Are there any implicit and/or explicit mechanisms for cooperating with other road users?
9. How is the mission planning implemented? Is it done online or is the mission plan precomputed?
10. How does the system react to interventions of the driver?
11. Are there any further, not yet addressed, capabilities or maneuvers implemented?
12. Is the system capable of traversing from one domain to another (e.g., exiting the highway onto an urban street)? Which transitions are possible?

Safety Concept

1. Please describe briefly the safety concept for driving on public roads.
2. How do you verify that the functions discussed above work as expected? What is the test procedure?
3. How does the system react to the loss of one or more components or capabilities? What is the degradation concept?

System Architecture

Please describe the architecture of the system (functional, hardware, software) and the main design criteria.

Something Is Missing?

If there are any further system characteristics or features worth mentioning, please note them here.

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