Evolution in Advanced Driver Assistance: From Steering Support in Highway Construction Zones to Assistance in Urban Narrow Road Scenarios

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Abstract. With the advances in environment sensor technology, advanced driver assistance systems (ADAS) that target increasingly complex scenarios such as inner-city traffic get into focus. Such novel ADAS will offer assistance in a wide range of urban traffic scenarios and, thus, will further decrease the number and severity of accidents. In this contribution, the evolution of an ADAS for lateral guidance in highway construction zones (i.e. the "construction zone assistant") towards assistance in narrow urban road scenarios (i.e. the "urban narrow road assistant") is presented. The focus of the contribution will be on the challenges of these two scenario types and their respective requirements on the system concept and design. While steering support in highway construction zones will be available on the market soon, its functional extension to inner-city traffic is still characterized by numerous technological challenges. Due to that, the emphasis in terms of algorithmic details will be on the "urban narrow road assistant".

Keywords: Construction zones, UR:BAN, automated steering support, driver assistance in inner-city, automated lateral control.

1 Introduction

In recent years, numerous prototypical ADAS have been developed that target the automated longitudinal and lateral control of vehicles (refer e.g. to [1-3]). Although highly demanding in terms of the complexity and number of use-cases to be covered, such systems can benefit from the restricted interaction between driver and system. Hence, on an operational level a correctly operating automated vehicle does not have to interact and cooperate with the driver's intentions. Therefore,

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in such systems no driver intention recognition is required. In addition to still unresolved technical issues, also well-known legal restrictions apply [4] which might considerably delay the realization of highly automated vehicles. Due to these restrictions, the realization of driver assistance as well as partly automated systems is a necessary intermediate development step on the path to full automation. The evolution of close-to-market systems for lateral guidance assistance is in the focus of this contribution. Since the driver remains involved and responsible, especially in complex scenarios driver intention recognition becomes mandatory.

Driver assistance systems for supporting the driver to stay in the lane have been available on the market since several years. Such lane keeping systems intervene by an acoustic warning or a haptic feedback on the steering wheel (refer to [5]). Furthermore, an active steering intervention based on superimposing steering torques (refer to [6, 7]) or by asymmetric braking interventions are on the market. These and other earlier lane keeping systems depend on the existence and precise detection of lane markings. More recent systems support the driver in construction sites on highways (refer to [8, 9]) and therefore rely on the detection of static and dynamic obstacles. Also the here referenced “construction zone assistant” (see Section 2) belongs to that category.

Novel systems (as e.g. the “urban narrow road assistant” presented in Section 3) currently under development explicitly focus on actively supporting the driver in inner-city traffic scenarios. As a common characteristic, such systems rely on the detection and measurement of obstacles. Based on that, the optimal vehicle trajectory is inferred. Dependent on the trajectory, lateral steering support is offered in order to prevent collisions with objects positioned laterally. Lateral guidance systems are typically classified as comfort systems while still having inherent characteristics of safety systems. When focusing on close-to-market systems of the latter type, only few related contributions exist. For example, in the context of the publicly-funded project “V-Charge” (refer to [10, 11]) an ADAS was developed that supports the driver in stationary traffic and parking maneuvers in inner-city. Different from the here presented two ADAS, the system is restricted to an ego-velocity in the range of walking speed and to scenarios without dynamic obstacles.

In the following, an overview on the two functions “construction zone assistant” and “urban narrow road assistant” is given. The focus is on the major use-cases as well as the resulting respective challenges in system design.

2 Construction Zone Assistant

This section focuses on the “construction zone assistant” (CZA). First, we briefly describe the function and then discuss necessary sensors as well as actuators and give an overview on the system architecture. Then, with the environment modeling and the driving corridor estimation two key algorithms of the system are described in more detail. Finally, the typical use-cases the system is capable to deal with as well the main limitations of the system are briefly discussed. For further information on the CZA refer to [8,9].

2.1 Function Description

The objective of the CZA is to support the driver in highway construction zones in order to keep a safe lateral distance to static infrastructure objects such as walls or traffic cones as well as to dynamic objects such as other cars or trucks travelling in neighboring lanes. In a typical use-case the driver is supported while overtaking a slower truck in a construction site resulting in a narrow driving corridor (see Fig.2b). In contrast to usual highway scenarios with marked lanes that define the driving corridor, lane markings in construction sites are often ambiguous or even not present at all. The system is supporting the driver in maintaining a collision free path by applying an appropriate steering torque whenever the driver steers in the direction of an obstacle. If appropriate, the system additionally informs the driver about the available lateral distance to objects and the width of the driving corridor ahead of the vehicle.

The function assists the driver at velocities ranging from 60 kph to 100 kph, which are typical for construction zones on highways. The availability of the system is limited to highway construction zones, which allows for simplifying assumptions on the infrastructure and the dynamics of other vehicles.

2.2 System Overview

The environment sensor setup of the CZA consists of a sensor capable of observing the space ahead of the vehicle as well as sensors observing the area next to the vehicle on both sides. A front facing sensor shall provide information on dynamic as well as static obstacles in order to be able to determine the driving corridor through the construction zone and to assist the driver in maintaining a collision free path. In addition, it is necessary to be able to detect and measure the distance to dynamic objects (i.e. other cars, trucks, etc.) driving outside of the field of view of the front sensor. Based on these requirements, we decided to equip a test-vehicle with a stereo-vision-camera (SV-camera) as a front sensor as well as four ultrasonic sensors (US-sensors) covering the space on both sides next to the vehicle. Furthermore, onboard sensors measuring yaw-rate, velocity, etc. are necessary to estimate and predict the motion of the ego-vehicle. Since the purpose of the system is to provide assisting steering torques in critical scenarios in construction zones, we use electrical power steering (EPS) as actuator. It can provide an additional torque on the steering column that is superimposed to the torque provided by the driver on the steering wheel. To make sure that the driver can always overrule the system, the superimposed steering torque is limited in terms of the absolute value as well as the rate of change.

Fig. 1 shows the system architecture that is employed to determine supporting steering torques from the sensor input signals.

Based on the two simultaneously recorded images of the SV-camera a disparity map (see e.g. [12]) is computed in sub-system 1. Afterwards, the amount of data to be processed in subsequent sub-systems is reduced by clustering the disparity map. Additionally, from pairs of images of subsequent frames, an optical flow field (see e.g. [13]) is estimated in order to be able to determine motion relative to the SV-camera. In parallel to the stereo-signal processing, the raw data of the US-sensors are processed resulting in measured radial distances of objects for each of the four US-sensors.

The purpose of the subsequent sub-system 2 is to provide a temporally stabilized representation of the free-space in front of and next to the vehicle based on the preprocessed sensor signals. Additionally, an object-list keeps track of the dynamic objects surrounding the vehicle. Using this representation, sub-system 3 computes a driving corridor based on several assumptions derived from the knowledge of being in a highway construction zone. Next, sub-system 4 predicts the motion of the ego-vehicle and checks the predicted trajectory for collisions with the borders of the driving corridor. If such a collision is predicted to occur, a collision-free trajectory is planned in sub-system 5, which finally results in a correcting steering torque superimposed by the EPS.

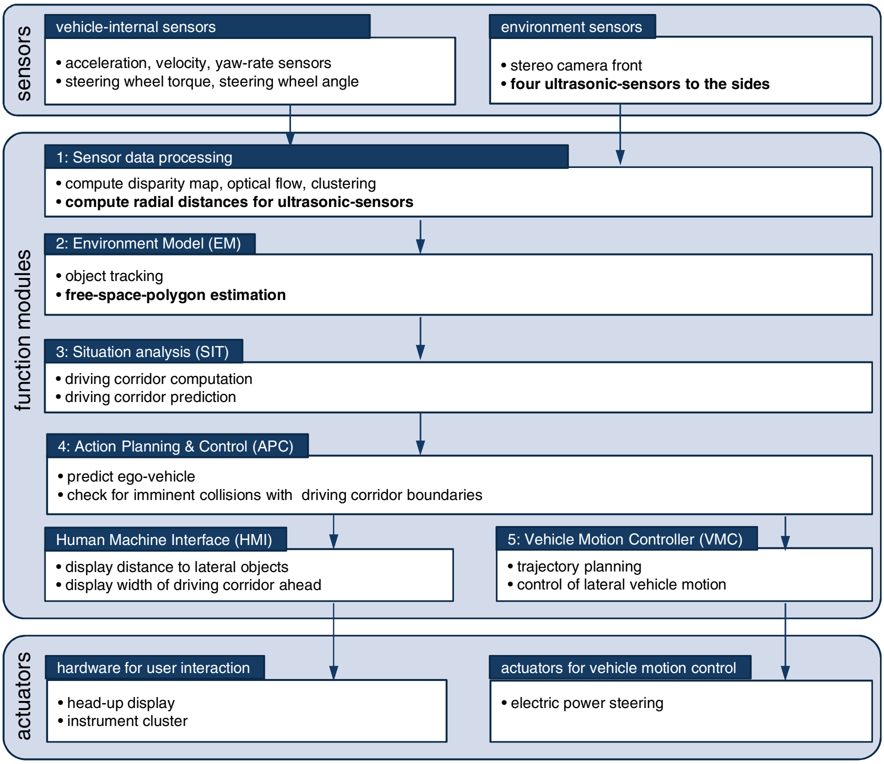


Fig. 1 System architecture of the "construction zone assistant" (bold elements differ from architecture of the "urban narrow road assistant")

2.3 Environment Model and Driving Corridor Estimation

This section describes the environment model in sub-system 2 and the estimation of the driving corridor, which represents the space, the vehicle can safely drive on, in sub-system 3. As soon as the vehicle is predicted to leave the driving corridor, a correcting steering torque is applied. Thus, the driving corridor plays a similar role as lanes do in lane assistance systems. However, the boundaries of the driving corridor are rather defined by static and dynamic obstacles than by lane markings.

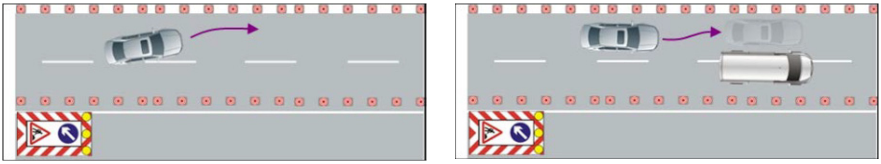
The environment modeling algorithm uses the preprocessed sensor data from the SV-camera and the US-sensors to infer a compact representation of the environment employing certain assumptions especially on the temporal behavior of obstacles surrounding the vehicle. The first step in determining this representation is an object-tracking based on the assumption that all objects approximately maintain a constant velocity. We use a classical Kalman-Filter approach to estimate position, dimensions, orientation and velocity of moving objects. Secondly, all stationary obstacles are represented by means of a polygon. This polygon describes either the boundary between the free-space in front of and next to the vehicle and any type of obstacle or the boundary of the field of view of the environment sensors, respectively. This approach differs from standard approaches using a Cartesian obstacle grid map representation e.g. described in [14]. Similar to the well known grid map estimation, we assume all obstacles to be static when temporally stabilizing the polygon representation applying recursive Bayes filtering techniques. The advantage of our approach is a lower demand of computation and memory resources, since only the corners describing the boundary polygon need to be stored and computed in contrast to storing and updating the state of each cell of the grid map. The downside of this approach is that the complexity of the environment that can be represented by the polygon model is limited. For instance, a region of free-space that is not connected to the free-space in front of the vehicle cannot be described. The environment is now represented by a list of dynamic objects and a polygon describing the static world surrounding the vehicle.

Based on the stationary free-space-polygon and the list of dynamic objects, we determine the driving corridor, which consists of two polygons describing the corridors left hand and right hand side boundary, respectively. The driving corridor contains only those parts of the environment that the vehicle can reach from its current position. To this end, first, all paths that are too narrow for the vehicle to drive through are excluded. Furthermore, we exclude all areas that cannot be reached from the current position of the ego-vehicle without exceeding a certain velocity dependent yaw rate. This threshold does not necessarily coincide with physical limits derived from vehicle dynamics, but is rather derived from yaw-rates which are usually not exceeded in driving through highway construction zones. The driving corridor can also be used to inform the driver about narrow spots ahead, e.g. between a wall and a truck the driver intents to overtake.

This representation of the driving-corridor still is time-dependent, since it may contain corners resulting from dynamic objects with non-zero velocity. Depending on the trajectory-planning-algorithm employed to find a collision free trajectory in case of an imminent collision with the driving-corridor boundaries, it might be necessary to eliminate this time-dependency by predicting all non-stationary polygon corners assuming constant velocities and afterwards rearranging the polygon corners appropriately.

2.4 Use-Cases and Limitations

The described algorithms are capable of dealing with the typical use cases occurring in highway construction zones. The main use-cases, which were also used to evaluate the system on a test track, are depicted in Fig 2.



(a) (b)

Fig. 2 Main use-cases of the CZA: (a) Lateral guidance based on static infrastructure. (b) Lateral guidance based on static and dynamic objects while overtaking.

However, the system is limited to driving through highway construction zones and cannot deal with scenarios typically occurring in inner-city traffic. For instance, oncoming traffic is ignored in the driving corridor estimation for robustness reasons. Also, the assumption of all objects approximately maintaining their velocity, which is well suited for highway scenarios, is often violated in urban traffic. Finally, as discussed in section 2.3, the polygon representation of the driving corridor is not capable to precisely model many of the complex scenarios which can occur in inner-city traffic.

Clearly, the assumptions made for developing a highway construction zone assistant under the constraint of rather low computation costs are not compatible to urban scenarios. However, a similar type of driver assistance is desirable in inner-city scenarios as well. With the “urban narrow road assistant” such a system is described in the next section.

3 Urban Narrow Road Assistant

In this section, an overview of the “urban narrow road assistant” (uNRA) is given. After a brief function description, an overview of the system architecture is provided. As a major system module, the situation analysis is described in more detail. Finally, the typical use-cases and main limitations of the system are discussed. For further details on the uNRA refer to [15].

3.1 Function Description

Similar to the CZA, the uNRA provides information about the lateral distance to static and dynamic objects. Typical use-cases are depicted in Fig.5. In case a safe lateral distance to obstacles is violated the system applies a steering torque. However, in contrast to the CZA, the uNRA supports the driver in inner-city traffic. Consequently, the function is active at lower velocities ranging from 0 kph to 60 kph. The uNRA is required to handle unstructured surroundings typically found in cities (parking cars, poles, traffic islands, curb stones, etc.). As a consequence, the uNRA requires more sophisticated means to represent and interpret the environment. These will be a major focus of this contribution.

3.2 System Overview

Following the system architecture in Fig. 3, the uNRA relies on a multi-camera system consisting of a front-facing stereo video camera and distributed body cameras as environment sensors. In addition, various vehicle-internal sensors are used (e.g. velocity, acceleration, yaw-rate, and steering wheel angle sensors). The sensor data is post-processed in the data preparation and validation module (DPV), after which it is transformed to standard units and validated with respect to signal range and consistency.

The environment sensors provide a 3D representation of the vehicle surrounding which is used as input for an environment model (EM). Here the data of individual sensors is fused and represented as an occupancy grid, a free-space representation, and object models, respectively. The occupancy grid represents the static collision-relevant environment. The free-space represents the road surface that was measured to be drivable. Dynamic traffic participants are represented and tracked as objects. The application of a grid representation stems from the fact that the uNRA is required to operate in unstructured inner-city surroundings that cannot be represented with classical object-model-driven approaches (refer to [16] for more details).

In the situation analysis module (SIT) the occupancy grid and free-space are post-processed and combined resulting in the driving corridor. Furthermore, within the SIT a use-case classification and driver intention recognition are realized. Finally, different criticality measures are computed that determine the system state in the following action planning and control (APC) module. The APC furthermore checks if system boundaries are exceeded (e.g. thresholds for lateral and longitudinal ego-acceleration and road curvature). Dependent on the system state the ADAS will remain inactive (e.g. no critical situation), offer information (e.g. narrow road section ahead), a collision warning or steering support, respectively. Information and warnings are displayed through the human machine interface (HMI) module. Steering support is realized by the vehicle motion control (VMC) module. The latter two modules control the required hardware (e.g. displays or electric power steering).

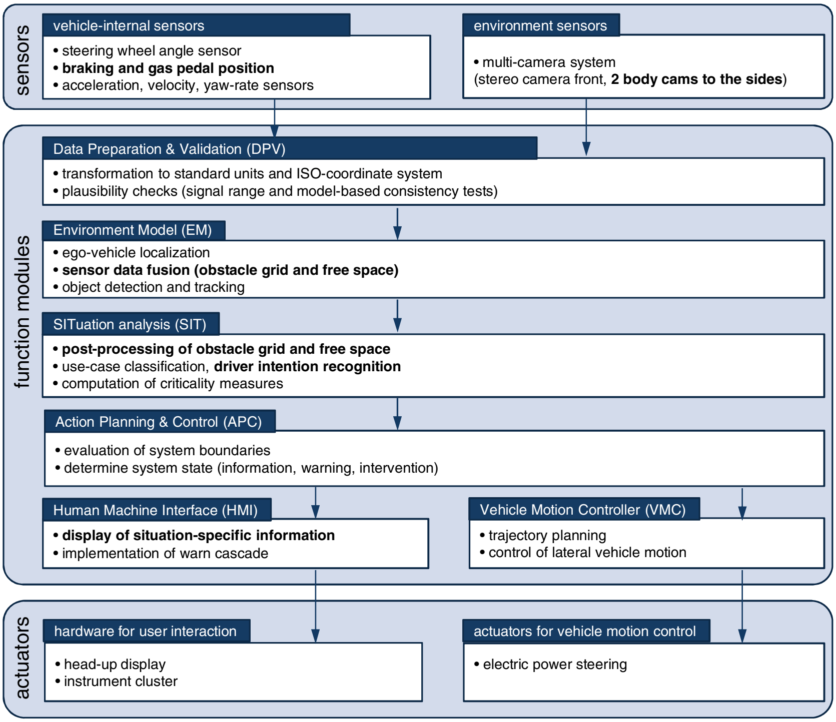


Fig. 3 System overview "urban narrow road assistant" (bold elements differ from CZA architecture)

3.3 Situation Analysis

The SIT module has the task to interpret the scenario by determining the relations between objects. Referring to the SIT sub-system overview in Fig. 4, in a first step the stationary occupancy grid (representing the static collision-relevant environment) is fused to the grid representing drivable free-space. These representations are not necessarily complementary. For example, free-space is not necessarily limited by collision-relevant objects, since the latter can be measured in larger distances than the free-space. As a preparation step, on the occupancy grid a ray tracing can be realized. Hence, it is assumed that all space in the line-of-sight to an object is free. For a combination, a simple super-position of the ray-traced grid and the free-space can be realized, which results in the driving corridor. On the driving corridor a search for possible future ego-vehicle paths is realized. Only those paths are used for further processing that match the measurement-driven, predicted ego-trajectory. As a result, a collision-free path with or without branches is now available. For example, a branch can result when the driver has the two options: (a) Stop his vehicle on the right side of the road, (b) Overtake a parking vehicle. Depending on the recognized use-case, certain branches might be rejected (e.g. if the road is too narrow and parking is no option). At path positions with a branch, a decision point is defined. Here recognition of the driver intention is required to resolve the ambiguity and hence prevent a possible false system intervention or futile warning / information. The driver intention recognition can be realized relying on a Hidden Markov Model, modeling important aspects of the driver's decision processes (refer to [15] for more details). After resolving the decision points, the resulting path is combined with the measurement-driven predicted ego-trajectory. Based on this trajectory, relevant critical borders (enclosing the collision-relevant environment) are derived, which will be the input to the VMC module that controls the steering actuator.

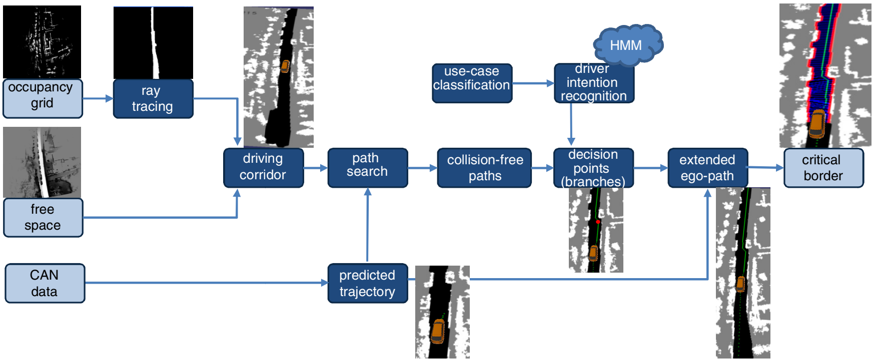


Fig. 4 Sub-system overview SIT

3.4 *Use-Cases and Limitations*

The “urban narrow road assistant” supports the driver in unmarked narrow road sections in inner-city traffic, informing about upcoming collision risks and offering steering support in a way that matches the driver’s intention (see Fig. 5 for typical use-cases in a static environment as well as in an environment with dynamic objects).

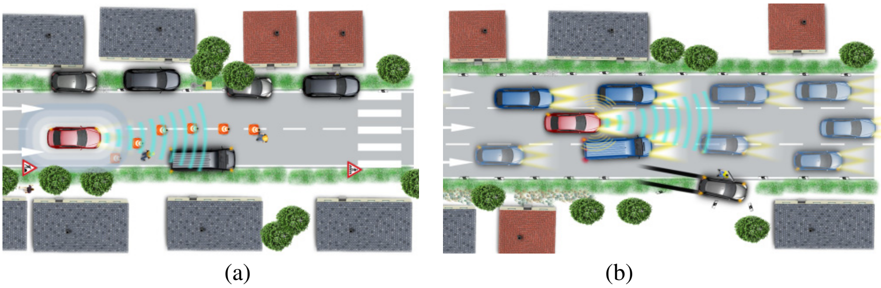

(a) (b)

Fig. 5 Use-cases for the uNRA (ego vehicle in red): (a) Narrow passage caused by static surroundings, (b) Narrow passage caused by dynamic objects

However, it is important to note that the uNRA provides steering support in case of imminent collision risks only. The driver always stays in the loop. In other words, the uNRA does not offer continuous, automated lateral guidance on inner-city roads.

4 Comparison and Conclusion

All major differences in system design between the CZA and uNRA stem from differences in the addressed use-cases (highways as compared to inner-city scenarios) and, as a consequence, different functional requirements.

When focusing on demanding use-cases, the uNRA is required to keep a safe distance to lateral obstacles of small height (as e.g. curb-stones) and laterally positioned dynamic obstacles of small length (as e.g. bicycles). Due to that, side cameras (instead of ultrasonic sensors for the CZA) are required.

As the uNRA offers steering support in inner-city scenarios, the system must be capable of representing the typically unstructured inner-city environment. Obviously, a classical object-driven representation would be highly inefficient and te-dious. Although the CZA already is representing the borders of the driving corridor in a grid-like fashion (polygons of discrete resolution that already offer a restricted flexibility), the uNRA still requires more flexible means of representing the multitude of objects classes typically present in inner-city scenarios. After analyzing the uNRA's functional requirements, a grid-maps-based representation turned out to be most suitable.

As compared to the CZA, for the uNRA more complex approaches for driver intention recognition are required (e.g. the CZA does not consider branching trajectories that are determined by the driver's course of action). This is due to the fact that in inner-city scenarios a higher number of relevant driver intentions exist, which increases the challenge of assuring that the ADAS reaction is in accordance to the current driver intention.

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