Chapter 2

The Research Domain of this Thesis and its State of the Art

2.1 Advanced Driver Assistance Systems

Driver Assistance Systems (DAS) are additional electronic systems in vehicles to support the driver in specific driving situations. They may aim at increasing safety, higher comfort, less fuel (or resource) consumption or informing the driver about the current traffic condition, the traffic situation or the route. These systems may be informative, semi-autonomous or autonomous. They may intervene in vehicle propulsion, actuation or vehicle control or may simply provide useful additional information.

Components and architecture of an intelligent automobile and hence, the combination of a variety of DAS are described in [Stiller et al., 2007, Robert Bosch GmbH, 2011b, Robert Bosch GmbH, 2011a]. DAS are based on the control loop of mechatronic systems as defined in [DIN IEC 60050-351:2006, 2006] (formerly DIN 19226). Basically, DAS consist of multiple sensors for perception, one or several ECUs for information processing and up to several actuators for DAS function execution. This will be briefly introduced in the next subsections 2.1.1 to 2.1.3.

2.1.1 Advanced Driver Assistance Functions

DAS with various specific functions are already commonly used within vehicles. Such functions are, for example, speed control, parking assist, rain-light-sensor, anti blocking system (ABS) and electronic stability control (ESP). These systems operate with a very specific focus of control, in very specific situations or under specific conditions.

ADAS research has recently focused on providing extended functionality in a wider range of situations and with less supervision by the driver. Such functions include adaptive cruise control (ACC), (semi-) autonomous parking, pre-crash, collision warning, mitigation and prevention, road sign recognition, lane keeping assist, curve speed control, intersection assistance up to even autonomous driving functions.

A common clustering of ADAS has two functional dimensions, one dimension distinguishing active and passive/informative functions, the other comfort and safety [Robert Bosch GmbH, 2011b, Robert Bosch GmbH, 2011a] (see **Fig. 2**).

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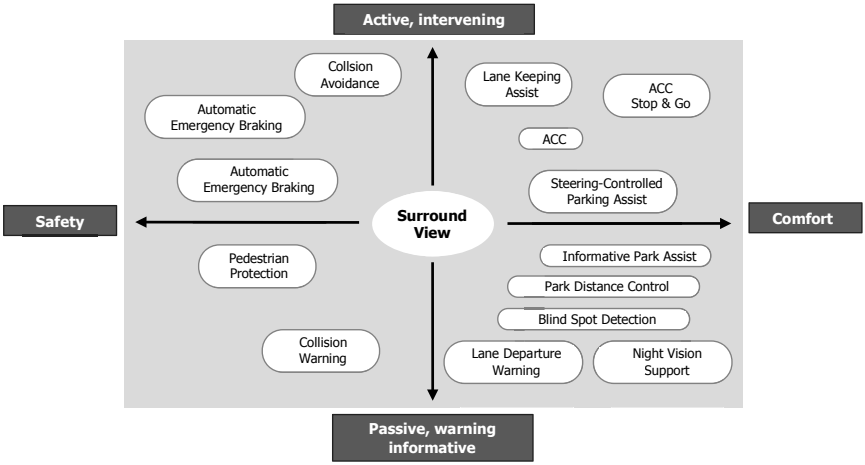


Fig. 2: Driver assistance systems (DAS) with safety and comfort functions on the basis of environmental sensors (translated from [Robert Bosch GmbH, 2011b]).

Active ADAS functions with a rather predictive nature especially benefit from this thesis, as they demand an extensive *understanding* of complex situations.

2.1.2 Sensors for Driver Assistance

Sensors may perceive information about the current state of the ego vehicle (vehicle sensors) as well as its global position (global positioning sensor) or may perceive information about the vehicle's environment (environmental sensors). A variety of sensor types for these kinds of information exists. Processing perceived sensor data is a research field on its own. Recent research especially focuses on how to combine information from different sensors.

2.1.2.1 Sensor Types

Sensor types for the ego vehicle state include wheel speed sensors, inertial sensors, steering wheel angle sensors, pedal sensors, gear sensors, pressure and temperature sensors and more. Positioning is mainly provided by GPS sensors, but new technologies such as fine positioning by wireless networks in range and positioning by landmarks are gaining interest and application.

The range of environmental sensors covers imaging sensors such as mono and stereo vision camera systems, infrared camera systems, radar sensors, laser scanners, PMD cameras and ultrasonic sensors [Robert Bosch GmbH, 2011b, Robert Bosch GmbH, 2011a]. From a wider point of view, navigation databases and communication units may be regarded as environmental sensors as well, including Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) information in the vehicles perception.

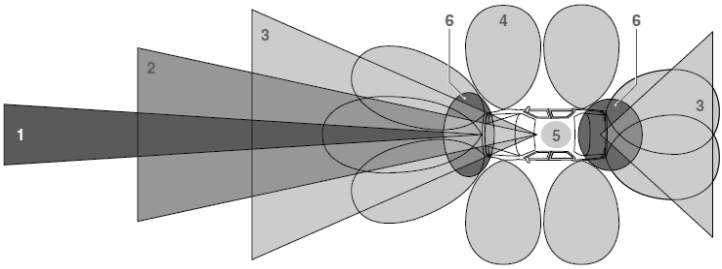


Fig. 3: Illustration of an exemplary configuration of vehicle environmental sensors and their range of perception (1 long range radar, 2 long / short range infrared sensor, 3 external video, 4 short range radar, 5 interior video, 6 ultra sonic sensors) [Reif, 2010].

The list is not meant to be complete but to provide an overview (see **Fig. 3** for an illustration [Reif, 2010]). The field of sensors is continuously and rapidly changing concerning types, variety, range, precision and capabilities in detection and classification.

2.1.2.2 Sensor Data Fusion

Data fusion serves to combine data from different sources (especially different sensors) with synergistically overlapping or complementing information to form new data or information, respectively, for extended functionality and / or better quality. In this way, improved situation estimation and improved situation responses are enabled [Steinberg et al., 1999, Robert Bosch GmbH, 2011b, Robert Bosch GmbH, 2011a].

According to the revised JDL data fusion model[4], as described and revised by [Steinberg et al., 1999, Roy, 2001, Llinas et al., 2004], data fusion may be carried out at different levels as depicted in **Fig. 4**:

- Level 0 – *Sub-object data assessment*: Pixel / signal level data association and characterization, sub-object entities (signals, features);
- Level 1 – *Object assessment*: Estimation and prediction of entities and entity states, discrete physical objects (e.g. vehicles, buildings);
- Level 2 – *Situation assessment*: Estimation and prediction of relations among entities, situation semantics;
- Level 3 – *Impact assessment*: Estimation and prediction of effects on situations of planned or estimated / predicted actions by participants;
- Level 4 – *Process refinement*: resource management with adaptive data acquisition and processing to support system objectives.

This thesis considers sensor data fusion (SDF) to be the part of data fusion that generates features and sub-features. These features are mainly objects and some basic relations that may

[4] originating from the Joint Directors of Laboratories Data Fusion Group (JDL DFG)

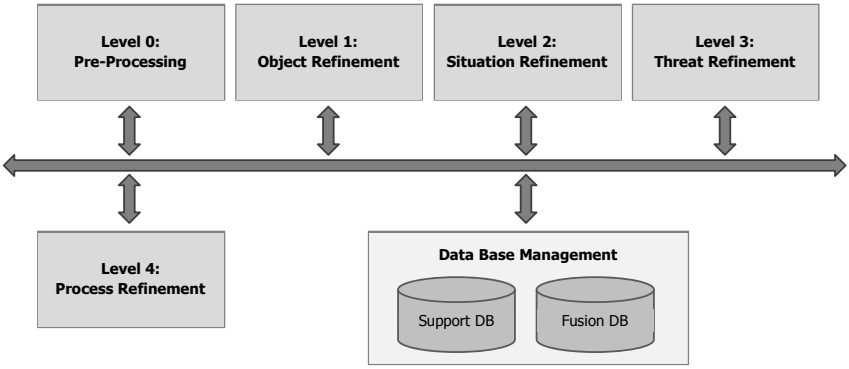


Fig. 4: The JDL data fusion model from [Polychronopoulos et al., 2006].

have attributes (sub-features) each. Basic relations are considered to be those directly derivable from sensor observations by SDF and do not need higher level logic reasoning, e.g. the relation "is left of" to another observed moving object or the relation "is on" of a vehicle to a road, if it can be easily obtained by sensor information. In this way SDF mainly covers levels 0 and 1 of the revised JDL data fusion model.

The JDL data fusion model has been widely adopted for automotive safety applications, e.g. as in [Polychronopoulos et al., 2006].

Examples for the successful fusion of data from different sensor types are shown in [Liu et al., 2008a] with the asynchronous fusion of radar and vision sensors for vehicle tracking and in [Skutek et al., 2005] with the fusion of laser scanner and short range radar for a pre-crash system.

2.1.2.3 Types of Sensor Information

On a low level, sensors basically provide measurement signals that are processed and refined to provide sensor features as output. Data can be fused on signal or feature level by SDF [Dasarathy, 1997]. Within the JDL data fusion model this refers to level 0 (sub-object data assessment). Features not further processed form *attribute features* containing values associated with a unit and potentially provided with uncertainty information such as an interval or information about a probability distribution.

The features may be further processed for *object detection*. These *object features* relevant to level 1 (object assessment) provide information about entities occurring in the current situation. The objects are usually tracked over time using various tracking algorithms. Detected objects may further be *classified* as belonging to certain object types or classes. *Classification features* may be generated within level 1 (object assessment), if only attribute features are used. Classifying detected objects using other *object features* in addition is carried out in level 2 (situation assessment). These features are then part of *situation features.*

Generating situation features is part of a situation description as investigated in this thesis. Level 2 (situation assessment) may even generate further object and classification features and other entities such as relations not directly resulting from sensor features. Reasoning services for ontologies especially serve this task and will be extensively discussed in section 3.2 and Chapter 5 of this thesis.

Object and classification features as well as other situation features may be associated with uncertainty measures, such as existence or classification probabilities or belief intervals. This will primarily be subject-matter of section 5.4.

2.1.3 Actors for Driver Assistance

Actors for DAS systems include all types of controllable components within the vehicle to inform the driver optically, acoustically or haptically (informative HMI), to support the driver in maneuvering control (intervening HMI) or to perform autonomous actions on vehicle dynamics. Among others such actors may include displays, speakers, electric actuators and drives as well as controlled brakes or controlled steering. Details about actuators are relevant to specific DAS function realizations and not in the focus of this thesis.

2.2 Traffic Situation Description and Analysis as a Key Enabler for ADAS

The *comprehension of a traffic situation* plays a major role in driving a vehicle. Through it, perceived raw information is transformed into interpretable information. Within the driving control loop, this forms a basis for future projection, decision making and action performing, such as navigating, maneuvering and driving control. Perception, situation comprehension, projection, decision making and action performing are part of dynamic decision making introduced by [Endsley, 1995, Endsley, 2000]. This is delineated in the model of *situation awareness* (SA) depicted in **Fig. 5**. The concept of SA applies for both human decision making investigated by Endsley and for substantial advanced driver assistance systems (ADAS) as well.

The succeeding section 2.2.1 explains the concept of situation awareness by Endsley and quotes several approaches related to it before the *situation description* is integrated and discussed with respect to situation awareness in section 2.2.2.

The following section 2.2.3 deals with the main aspects and questions relevant to the generic situation description provided with this thesis. Sections 2.2.4 to 2.2.6 then quote existing approaches concerning the aspects of situation description and analysis.

2.2.1 Situation Awareness and Comprehension

Situation awareness (SA or SAW) by [Endsley, 2000] is part of the feedback loop (or control loop, respectively) of dynamic decision making. This feedback loop is shown in **Fig. 5**. The

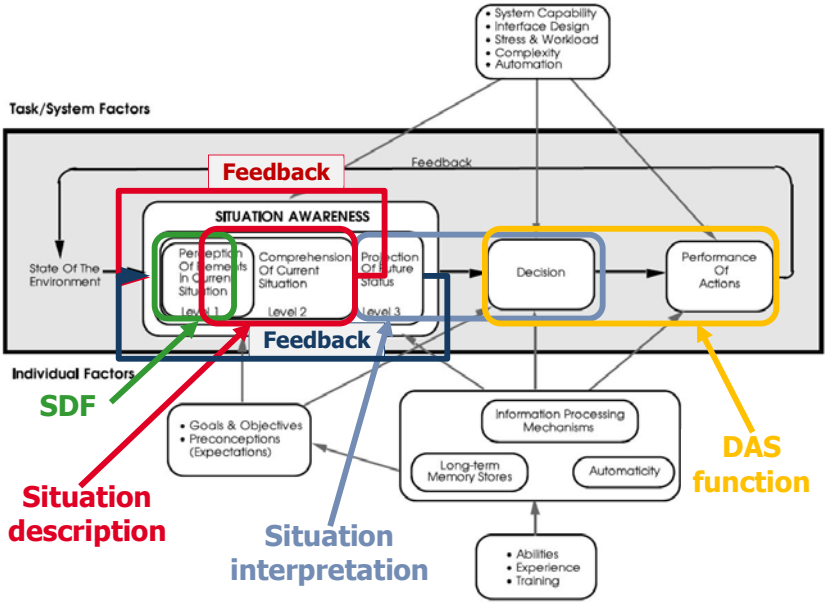


Fig. 5: Situation Awareness (SA) by Endsley within dynamic decision making [Endsley, 2000]. The components sensor data fusion, situation description, situation interpretation and DAS functions of advanced driver assistance systems are mapped to the SA model with their position in the driving control loop. Additional internal feedback loops are shown and not meant to be exhaustive.

situation awareness component captures and processes the state of environment. A succeeding component contains *decision making,* followed by a component for the *performance of actions,* which influences the state of environment completing the feedback loop.

Situation awareness by [Endsley, 2000] consists of 3 levels:

- Level 1 – *Perception of elements in current situation*: This level represents receiving raw sensor information and sensor data fusion on a low and mid level. It forms situative elements, e.g. vehicles, roads, lanes, etc., with attributes such as speed, position or size. [Endsley, 2000] especially points out the importance of choosing important information to avoid information overflow and the "odds of forming an incorrect picture".
- Level 2 – *Comprehension of current situation*: This level deals with combining, reasoning, storing and retaining perceived information. It synthesizes information from perceived information and puts it into relation. It furthermore deals with the relevance of information with respect to a person's (or in a DAS context, an application's) goals.

  Considering relevance of situation features with respect to a specific goal covers a major part of this thesis addressed in section 2.2.4, Chapter 4 and Chapter 6.

The comprehension itself with combination, reasoning, storage of and retaining the information is treated with in Chapter 5.

- Level 3 – *Projection of future status*: The third level includes forecasting future situation events and dynamics and thus *interpreting* the current situation. Anticipating future events then allows for timely decision making. It is said to be "the mark of a skilled expert" (and hence, correspondingly, a capable ADAS).

It is important at this point to distinguish the description or comprehension of a situation from an interpretation of a situation. The boundary is drawn between level 2 and level 3 SA. Level 2 reasons about current facts of the snapshot or a series of historical snapshots of a situation whereas level 3 reasons about information that cannot be told with certainty yet. In this way, different methods may be applied for situation description (e.g. knowledge-bases) and situation interpretation (e.g. probabilistic methods). This does not exclude the future application of methods that can handle both situation description and interpretation at once (e.g. probabilistic knowledge-bases).

[Roy, 2001], [Salerno, 2002] and [Hermann and Desel, 2008] compare the different levels of the JDL data fusion model from section 2.1.2.2 with the model of situation awareness and point out their commonalities and that the processes contained in both models are meant to be of parallel rather than serial nature. Especially, "the situation model should present a fused representation of the data (*situation comprehension*) and provide support for the projection needs (*situation projection*)" [Hermann and Desel, 2008]. This thesis, in particular, deals with creating a fused representation of the data for complex traffic situations.

Based on both the JDL data fusion model [Llinas et al., 2004] and the concept of situation awareness by [Endsley, 2000], [Salerno, 2002] formed a conceptual framework for a high-level architecture and functional flow addressing and detailing all levels of both models. More specific, the perception level contains object identification & tracking, historical data and a database for storage. The comprehension level contains functions such as entity extraction, filtering with learned profiles, relationship extraction, pattern matching and link analysis, model generation and model analysis. Finally, the projection layer contains the functions prediction and assessment.

The model of situation awareness by Endsley has also been mapped to unmanned vehicle situation awareness (UV SA) by [Freedman and Adams, 2007] comparing Human SA and UV SA on a high and task driven point of view.

2.2.2 Situation Description in the Driving Control Loop

The focus of this thesis is to form a *generic situation description*. With respect to ADAS described in section 2.1, the *DAS functions* cover the components *decision* and *performance of actions* of the dynamic decision making process as delineated in **Fig. 5**. The latter also contains the *actoric components* of DAS. Gathering and processing sensory information to form low level information is comprised by *sensor data fusion (SDF)* and covers the component

perception of elements in current situation. The perception is part of *situation awareness* (SA) introduced by [Endsley, 2000] (level 1 SA), which has been explained in section 2.2.1.

Simple DAS with very specific goals such as a state of the art collision avoidance system are solely based on the selection of a target vehicle. They mainly rely on a single type of environmental sensor and a DAS function optimized on data directly acquired from the SDF. Improved and extended ADAS, gathering and combining information from several sensors and aiming to cover several DAS functions, need a generic *situation description* and *interpretation* covering extended level 2 and level 3 SA.

Situation description relevant to this thesis will be defined as the part of information processing succeeding SDF, to form a picture of the situation and provide information about it. This shall include domain specific rules and restrictions (concerning the traffic infrastructure and traffic legislature). Hence, it is aimed to further describe the evidence in a situation that is provided by sensors and preprocessed by SDF.

Situation description is not meant to include uncertain interpretations about the current situation such as predictions, behavior, uncertain intent or other possibilities. This is part of *situation interpretation* which follows downstream of situation description (please also refer to **Fig. 5** and section 2.2.1 for this partitioning). However, uncertainty, that is to be included in situation description as defined, is coming from sensors and SDF. Thus, different pictures of the world captured by sensors may have to be described in general[5].

In this way, *situation description* as defined in this thesis mainly covers level 2 SA (situation comprehension) excluding most of level 1 SA, the pure perception. *Situation interpretation* mostly covers level 3 SA, especially future situation projection, behavior description and uncertain interpretations of the captured situation and overlaps to the decision component as shown in **Fig. 5**.

2.2.3 Aspects of Situation Description Relevant to This Thesis

The aim of this thesis is to provide a generic traffic situation description capable of supplying various ADAS with relevant information about the current driving and traffic situation of the ego vehicle and its environment. With this information ADAS should be able to perform reasonable functions and actions and approach visionary goals such as injury and accident free driving, substantial assistance in arbitrary situations up to even autonomous driving.

This requires assessing more complex situations compared to state of the art assistance systems, potentially including even unknown situations demanding extensive comprehension of the vehicle environment and the current situation.

Specific requirements for the situation description are *modularity* and *hierarchy, expandability*, *exchangeability* and *scalability* for different variants and combinations of ADAS vehicle applications as well as *determinism* and *correctness*.

[5] Note, these pictures – or different worlds – do not have to be discrete but may also be fuzzy and continuous such as uncertainty about a velocity.

- Modularity: This allows for distributed, simultaneous and module based development and testing as well as for integrating only necessary modules specific to the application.
- Hierarchy: This, as applied in e.g. object oriented programming, allows for multi-level structure and inheritance of grouped functionality and properties.
- Expandability: The situation description should be able to be expanded for more expressivity, to capture more aspects of the situation or to handle extended sensor information to provide more information about the situation or to serve additional DAS functions.
- Exchangeability: In combination with modularity and expandability, exchangeability is useful to allow different target applications using different modules for different expressivity.
- Scalability: The situation description is aimed to scale from a very lean description with few information and for situations with a small number of elements up to a very expressive description with much and diverse information and for arbitrary and complex situations.
- Determinism: A specific situation shall always be described in the same manner so that a certain known input set shall result in a deterministic, foreseeable situation description output. Where desired, this enables deterministic decision making (provided certain sensor inputs) or forms a certain and reproducible basis for subsequent interpretation and uncertain decision making. Although the formulation of probabilistic reasoning may be deterministic, the outcome of a certain result of probabilistic reasoning is not. In this way, uncertain rules are excluded within the meaning of this specific requirement in the scope of this thesis. However, uncertain rules and uncertain inputs are subject to discussion in sections 3.2.5 and 5.4.
- Correctness: A situation description for DAS functions with low failure rates, especially few false positives, requires consistency of the situation context with respect to domain specific rules and constraints. For example, a vehicle cannot be on two roads at the same time and it cannot move into two different directions.

A meaningful and substantial generic traffic situation description covers:

- A delimitation of the aspects and information of the situation that are to be generically described,
- Suitable methods capable to generically describe the situation and the contained information and
- The scope and target applications of the situation description.

These items will be discussed in more detail.

Delimitation of the aspects and information of the situation that are to be generically described

A situation description has to *describe* the current situation. In this way information to describe has to be perceived, that is provided by sensor data fusion (SDF) (see subsection

2.1.2.2). Then, new information is potentially generated within the situation description, using the perceived information.

The information provided by SDF contains situation features that may be simple measures or attributes with a value and a unit up to more abstract and complex features such as objects, relations, graphs etc. that may also be generated within the situation description (see subsection 2.1.2.3). Feature data for method investigation may be generated with endurance runs and test drives, simulator studies, accident studies and computer simulations.

A core question for situation description is what situation features are generally relevant to describe the situation with respect to some target application.

As a result of research on state of the art of intelligent DAS, [Fuchs et al., 2008b] point out four sub-contexts to belong to a driving situation: the *operating environment* of the vehicle, the *driver*, the *vehicle* itself and (national) *traffic regulations*. The driver, however, will not be part of the situation description proposed with this thesis, but will be seen as part of the situation interpretation particularly involving interpretation uncertainty.

Hence, a traffic situation description has to especially describe aspects of the vehicle and its environment relevant to the situation such as traffic participants, traffic objects, environment objects and relations among them.

Additionally, a traffic situation is defined by traffic rules, infrastructure rules and further constraints defining, how objects may be related and interact. Furthermore it has to be defined, how new information may be created, based on information already contained within the situation description, e.g. by deductive rules.

Traffic rules applied in this thesis are taken from [Bundesministerium der Justiz, Juris GmbH, 2009] and [Economic Commission for Europe: Inland Transport Committee, 1993], especially concerning lane usage, speed, right-of-way, traffic lights and traffic signs.

Example rules of the “Convention on Road Traffic” in [Economic Commission for Europe: Inland Transport Committee, 1993] are:

- “Instructions conveyed by traffic light signals shall take precedence over those conveyed by road signs regulating priority.”
- “Where a road comprises two or three carriageways, no driver shall take the carriageway situated on the side opposite to that appropriate to the direction of traffic.”
- “(a) On two-way carriageways having four or more lanes, no driver shall take the lanes situated entirely on the half of the carriageway opposite to the side appropriate to the direction of traffic.

  (b) On two-way carriageways having three lanes, no driver shall take the lane situated at the edge of the carriageway opposite to that appropriate to the direction of traffic.”
- “In States where traffic keeps to the right the driver of a vehicle shall give way, at intersections […] to vehicles approaching from his right.”

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