Ontology based Scene Creation for the Development of Automated Vehicles

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Abstract—The introduction of automated vehicles without permanent human supervision demands a functional system description including functional system boundaries and a comprehensive safety analysis. These inputs to the technical development can be identified and analyzed by a scenario-based approach. Experts are doing well to identify scenarios that are difficult to handle or unlikely to happen. To establish an economical test and release process, a large number of scenarios must be identified to enable an execution of test-cases in simulation environments. Expert knowledge modeled for computer aided processing may help for the purpose of providing a wide range of scenarios. This contribution reviews the use of ontologies as knowledge-based systems in the field of automated vehicles, and proposes a modeling concept for traffic scenes. Afterwards, a process to create scenes from the gathered knowledge is introduced and the utilization of ontologies in the given problem statement is evaluated using criteria from literature.

I. INTRODUCTION

Safety assessment of automated driving functions is an emerging topic in the automotive industry. Several research and development projects show prototypes of automated vehicles in well-defined showcases. When it comes to series production, the ISO 26262 standard defines a state-of-the-art development process to ensure functional safety.

Automated vehicles will have to fulfill a safe driving task in a high number of operating scenarios. Wachenfeld and Winner [1] deduce how many kilometers it takes in field tests for an automated vehicle to be released. The high number of kilometers results from the likelihood of encountering possible scenarios which might lead to an accident. They conclude that a scenario-based test case generation can replace time consuming field tests by shifting test case execution to simulation environments.

To comply with the hazard analysis and risk assessment demanded by the ISO 26262 standard, hazardous events “shall be determined systematically by using adequate techniques” [2, Part 3]. Therefore, operating scenarios, in which malfunctioning behavior of the item can be hazardous have to be identified. Nowadays, these scenarios are developed by experts in the development process.

A main difference to automated driving functions where a human supervisor must be present at all times is the number of scenarios which have to be investigated and defined. All these scenarios are necessary to argue that the highly or fully automated driving function can be released to the market. Hence, the developers need more experts or more time for the experts to identify scenarios. Expert knowledge is reasonable for investigation of new items in development, but the creation of scenarios by experts is a more creative than systematic process. To get traceable and comparable scenarios, the experts need at least a consolidated vocabulary and the same understanding of how scenarios are organized.

Bergenheim et al. [3] further describe a semantic gap in safety validation processes. Since actual methods for defining requirements do not support the developers in argumentation that the developed item is safe, the semantic gap occurs during system development. The authors claim that the discussion on the safety of the intended functionality (SoTIF) can be resolved by a more detailed specification of functional safety requirements or a validation of the functional safety concept towards completeness. Requirement specification and validation process can be supported by scenario catalogs in the concept phase of the development process.

Scenarios based on expert knowledge can help to improve requirements engineering and safety analysis. Also, scenarios provide a base for test case generation for simulation-based testing of automated vehicles. For this reason, we propose using knowledge-based systems to create scenarios for development of automated driving functions. Ontologies have successfully been used in the ongoing research on automated driving in recent years (cf. Section III). Many of these concepts show how the use of knowledge-based systems can improve decision making and scene understanding in particular driving scenarios. Our concept shows how ontologies can be used to represent knowledge of how traffic infrastructure is built and how traffic participants may interact and behave. Furthermore, we propose how knowledge about traffic can be represented by a layered concept to divide them into smaller parts and model interactions of the layers.

This contribution is organized as follows: In the next part related work regarding ontologies in the field of automated driving is summarized. Afterwards, we give a short overview on the concept of ontologies and tools followed by our concept for creation of traffic scenes. At the end, we evaluate the usage
of ontologies on our problem statement.

II. ONTOLOGIES

Guarino et al. [4] give a summarized definition of ontologies as “a formal, explicit specification of a shared conceptualization.” The conceptualization itself is described as “an abstract, simplified view of the world that we wish to represent for some purpose. Every knowledge base, knowledge-based system, or knowledge-level agent is committed to some conceptualization, explicitly or implicitly” [5]. According to Studer et al. [6], ontologies can be divided by different levels of generality. These levels reach from general ontologies, which express domain independent knowledge, to domain and application ontologies, which contain true statements from particular domains like medical applications or electrical engineering or are only applicable to a certain application in a domain.

Fig. 1 shows the structure of ontologies with terminological and assertional boxes. Both types of boxes are combined to form the knowledge base expressed by an ontology.

![Fig. 1. Architecture of ontologies from [7]](image)

Terminological boxes describe the concepts of a domain. These concepts are expressed by hierarchical classes, axioms and properties. Assertional boxes represent instances of classes and observed facts of situative knowledge about the world. Following the definitions by Ulbrich et al. [8], assertional boxes describe scenes extracted from a given set of possible world entities and relations.

The concepts stored in an ontology have to be readable and understandable by human experts and computers. Humans can read the structure of an ontology, including the hierarchy and the axioms, which are expressed by natural language. For computers, this is accomplished by expressing ontologies in a description logic which translates every concept of the domain into first order logic.

A common declarative language (which builds the semantic base for modeling) in the field of ontologies is the Web Ontology Language (OWL) [1], which is standardized and maintained by the World Wide Web Consortium (W3C). It is intentionally designed for applications on the semantic web, where pages can be connected with the meaning of the terms. This enables for example better search results based on context and not pure comparison of terms. OWL includes three variants of the language namely OWL Lite, OWL DL (Description Logic) and OWL Full. The variants differ in the expressivity of the language, which increases from OWL Lite to Full.

Ontologies are stored in first order logic which allows reasoners to infer knowledge on terminological and assertional boxes. Reasoners are able to identify hierarchical missing concepts on terminological boxes, check for conflicts in the modeled concepts and check if similar concepts exist over the knowledge base. Assertional boxes can be checked for consistency and associated with the concepts from terminological boxes to infer situational knowledge, for example from sensor data.

III. RELATED WORK

Ontologies have been used for various applications in the field of automated driving. A major part of the contributions comes from work in recent years on situation assessment and behavior planning.

Armand et al. [9] describe how ontologies can be applied to model interactions based on spatio-temporal relations between traffic participants and infrastructure. They are used to infer how classified object groups will behave and interact with the host vehicle in the future. Sensor data is used as input for an ontology and to develop a human-like scene understanding. The understanding is based on object tracks, map data, and dynamic states of the host vehicle. Therefore, the concept classes are divided into mobile entities, static entities and context parameters which describe spatio-temporal relations. Relations between the classes are described by object properties for actual behavior like *goes towards* or necessary behavior like *has to decelerate* to maintain safe traffic. To integrate readings from vehicle sensors, the classes are annotated with data properties to map physical measures to the knowledge represented in the ontology. For the assessment and prediction step, behavior rules are stored in the semantic web rule language to infer knowledge from the terminological boxes to a given assertional box from the sensor data. The results are taken from an experimental car setup and show that ontology based knowledge can be used to assess traffic scenes in real time applications.

Hülser et al. [7] use a similar approach of scene understanding. In contrast, they focus on complex intersections with multiple lanes, interconnections, traffic signs and cars at the intersection. The terminological boxes are selected to represent cars, crossings, road connections, and signs. Object roles are nearly similar to Armand et al., but with further refinements to intersection scenarios. Results are presented for an intersection with five roads, eleven lanes and six cars going towards the intersection. The ontology based reasoning is able to infer all traffic rules and the behavior each of the cars has to obey. Since

1The abbreviation has switched letters due to a typo on a mailing list and the fact that OWL, like the bird, is easier to remember than WOL.
the example for evaluation is one of the biggest intersections, a real time application of the reasoning is not possible.

Hummel et al. [10] build a detailed ontology for understanding traffic scenes on intersections. The approach has a large focus on geometric details linked to multi-level topological information. Digital map and video data are then used to locate the host vehicle in the scenery based on logical restrictions. An advantage of logical axioms is consistency checking, which can identify unreasonable sensor data.

Zhao et al. [11] [12] focus on algorithms for fast decision making in automated vehicles. The knowledge base is divided into a map, control and car ontology. For fast online processing sensor data is processed by SPARQL Protocol And RDF Query Language (SPARQL) queries which provide a query language for ontologies. The inference rules are modeled in the semantic web rule language (SWRL), which adds additional rule sets to the existing knowledge base.

Mohammad et al. [13] use ontologies in combination with SWRL statements to infer risk of traffic scenes from video data. Therefore, objects from sensor data in the observed data are annotated with information like motion direction, speed and a classification. The authors use SWRL statements to infer which relations between the objects exist and which risks are classified for these relations.

Ulbrich et al. [14] propose an environmental model derived from a knowledge base with hierarchical classes and relations between the entities. The ontology is implemented in C++ to provide an environmental model, which was updated by sensor data and used to make online decisions in the test vehicle Leonie of the project Stadtmit[15].

Barrachina et al. [16] uses an ontology in combination with vehicular communication networks to improve traffic safety. The concept of the ontology is designed to represent multiple causes for accidents extracted from the General Estimates System of the National Highway Traffic Safety Administration of the USA (NHTSA). With the knowledge from this ontology the authors are able to automatically determine which vehicle types (trucks, buses, trailer, cars) are endangered by environmental factors. They extend the knowledge to specific target groups (like age, sex, weight). This knowledge is then used in a simulation to investigate how warning messages for endangered drivers in the specified driving scenarios can improve traffic safety.

Pollard et al. [17] propose an approach for the classification of automation levels based on several aspects of automated vehicles. In the first step the longitudinal and lateral control including abilities for local planning, parking and global planning are assessed. Afterwards, the systems are distinguished by their modeled aspects of situation assessment. This information is used to infer which automation level a system fulfills.

Geyer et al. [18] formulate the need for unified understanding of terms and definitions for automated driving to generate requirements expressed by use cases or scenarios. For this purpose, they propose an ontology to define and order the terms ego vehicle, scenery, scene, situation, scenario, driving mission, and route. Use cases and scenarios can be defined in a unified representation with the order derived from the ontology. The ontology is not technically implemented and shall form a basic understanding by reading the publication. After proposing the ontology, the authors emphasize two challenges in the generation of requirement catalogs: top-down development and the form of representation. On the one hand, information must be as complete as possible. On the other hand, it shall be understandable by humans involved in the development process. The main utilization of the proposed nomenclature and concept is to homogenize two projects in the field of cooperative vehicle guidance. A top-down approach for generating the catalogs was not described in the contribution. However, usage of guidelines for road design was mentioned as a starting point.

The ontology suggested by Geyer et al. was reviewed, unified with other contributions and further defined by Ulbrich et al. [8]. They defined differences and the coherence between the properties of each term. This contribution follows the definitions of Ulbrich et al. for the terms scene, situation and scenario.

Xiong [19] proposes a framework for scenario orchestration with autonomous simulated vehicles for simulation of test-cases based on driving scenarios for automated vehicles. Therefore, the framework consists of an ontology for scenario orchestration (OSO), virtual driver(s), a collection of supporting modules in a scenario management module (SMM), and a scenario observer. One of the main concepts is a simulation supervision linked with the driver models, which calculate all interactions between the entities in the simulation and the necessary tools according to the defined scenario depending on the simulation framework. This framework has been evaluated in two simulation platforms by executing multiple predefined scenarios.

The ontology used in the framework describes concepts and relations between driving context, task representation, (simulative) actions, simulation monitoring, and temporal representations between entities in the simulation. The scenario representation around a vehicle (in this case) consists of road segments, intersection and vehicles. The orchestration framework is further able to determine which actions of vehicles are referred to which monitoring devices and measurements. This allows the framework to represent all of its tasks in relation to the actual simulated scenario. Nevertheless, scenarios for evaluation have been designed by experts and the thesis had the focus on orchestration of all entities regarding simulation using the knowledge-based system.

To summarize the related work, we assume that ontologies provide a suitable framework for various applications in automated driving. This includes support of automated driving functions inferring knowledge about traffic scenarios and enhancements in traffic safety by supporting a centralized traffic system. For our focus on scene creation, we further investigated the concepts of Geyer et al. [18] and Xiong [19]. Ontologies from contributions regarding scene understanding are compared regarding the represented entities and hierarchies.
of classes to provide a basis for our knowledge modeling approach.

IV. ONTOLOGY-BASED SCENE CREATION

As introduced in the beginning, automated vehicles will have to accomplish a large number of operating scenarios during their lifetime. Before deploying automated vehicles in public traffic, developers have to investigate these scenarios in the development process in order to ensure safe systems. Go and Carroll [20] describe this approach as scenario-based design paradigm for complex systems. The main idea of the concept is that multiple views of the same set of operating scenarios of a system by different stakeholders are needed to get well-engineered requirements. For automated vehicles, scenario-based design can help to analyze the system from multiple points of view. This includes defining the behavior of the system, human machine interaction, risk analysis as well as the test process in simulations before going to expensive field tests.

According to Ulbrich et al. [8] “a scenario describes the temporal development between several scenes in a sequence of scenes. Every scenario starts with an initial scene.” This contribution aims at proposing a creation process for (initial) scenes.

In a previous contribution [21], we propose a scene creation for a hazard analysis and risk assessment supported by a database at the example of an unmanned protective vehicle in the project aFAS [22]. Since the outcome from the initial scenes will be identified by the experts in the project, we focus on the creation of scenes. A major disadvantage of combining database entries to generate scenes is that many of them were physically not possible or unreasonable. Databases contain no semantics in the data, which leads to unreasonable scenes. The project aFAS works, compared to other automated vehicles, in a limited use case where a protective vehicle shall operate unmanned and unsupervised on the hard shoulder of motorways. Our conclusion is that the process based on databases would not scale for wider use cases and more complex operating mode can be executed in which area of the hard shoulder (normal or on- and off-ramps) was not explicitly designed in the database processing. For example, the knowledge about which operating mode can be executed in which area of the hard shoulder (normal or on- and off-ramps) was not explicitly designed in the database but considered in the creation process. When it comes to arguing the safety of a system, assumptions and knowledge should be represented more explicitly instead than implicitly to maintain traceability throughout the development process.

To get more accurate and useful scenes, we need a system that knows how data can be combined and what meaning data has in the real world. Ackoff [23] describes the hierarchy of data and the semantics of knowledge to combine information to meaningful scenes of real world traffic. Ontologies provide knowledge bases which are understandable for humans and computers. Based on the concepts of Ackoff, we propose a process for a ontology-based scene creation as shown in Fig. 3. The following subsection will explain the knowledge acquisition, how knowledge is modeled and the combination process.

A. Knowledge acquisition

Knowledge systems are divided into knowledge acquisition and knowledge representation. Guidelines for the creation of traffic infrastructure can be used for knowledge acquisition. These guidelines describe how infrastructure is organized, named, and how the relations can be represented. In Germany, guidelines for the creation of motorways, rural roads, inner city roads, crash infrastructure, markings, traffic lights, and signs exist and are periodically updated to new regulations. There are also various scenario catalogs from past projects or system descriptions which contain knowledge about scenarios. These sources can also be used if the nomenclature of scenarios is translated properly. As Geyer et al. [18] describe, each project or catalog has its own nomenclature and concepts how to organize knowledge.

![Fig. 2. Hierarchy of signs, data, information and knowledge adopted from [23]](image)

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![Fig. 3. Ontology-based process for scene generation](image)

Fig. 3. Ontology-based process for scene generation

Guidelines apply to whole domains of traffic. The number of scenes which can be created by combination of all entities of a domain is very large. However, only a selection of scenes...
depending on the functional range is relevant for investigation. Therefore, the functional description of the system has influence on the knowledge base. When a system is planned to operate solely on the hard shoulder, as the vehicle in the project aFAS, scenes where no hard shoulder is present are not necessary for the evaluation. However, for the traceability of assumptions made in the analysis, it is important to explicitly represent decisions on which entities or relations from the knowledge are irrelevant for the system.

The third important aspect besides guidelines for traffic domains and the functional description is expert knowledge. On the one hand, all guidelines define only a part of traffic infrastructure and we need to represent how these parts can interact and which dependencies they have to each other. For example traffic rules regarding speed limits for each lane on motorways are bound to at least three lanes for each driving direction. On the other hand, we need to represent real world deviations from the guidelines and very unlikely entities or combinations of these. Reschka [24] describes safety-relevant events and how dilemma scenarios can occur from event chains in traffic. Knowledge about the causes of event chains is important to identify functional boundaries of the item and to derive meaningful safety concepts.

B. Layered model for knowledge representation

To organize all the information in a knowledge base, we propose to use a layer model for scene representation based on the work of Schuldt [25] as shown in Fig. 4. The first layer describes the layout of the road including markings and topology. Schuldt proposes to use basic elements like straights, curves and clothoides to define geometries. The parameters for the geometric models can be derived by guidelines for each domain of traffic (motorways, rural roads and urban roads). Further, the basic layer defines how the geometries are related to each other to build up the topology. Motorways in Germany for example follow defined layouts where markings, parameters and relations are given by standards. These guidelines can be used to model hierarchical concepts on how geometries representing lanes can be put together to build valid road snippets for traffic scenes.

The second layer adds traffic infrastructure to the road-level. Traffic infrastructure is part of the scenery, but not all stationary objects belong to the traffic infrastructure. This differs from the four-layered concept of Schuldt because we focus on separating semantic relations for an automated creation of scenes. For the creation of scenarios we propose to model traffic rules like speed limits or no passing zones as top-level classes. The sub-classes then represent instantiations of the traffic rules through traffic infrastructure like signs or road markings, which express the rules for the driver. Instantiations of traffic rules have several dependencies on each other which can be extracted from road traffic regulations. Due to dependencies on markings, the influences on the first layer has to be modeled according to the traffic rules.

Temporary manipulation of the first two layers are represented in the third layer. In this concept, the time frame for temporal manipulations was chosen to one day. Other objects which persist longer than one day can be modeled as infrastructure on the layers below. The layer contains classes which represent how construction sites have to be marked, routed and secured. The resulting changes to the original layout are marked as manipulation in the resulting traffic scenes.

All objects which do not necessarily belong to the traffic infrastructure are modeled in the fourth layer. Stationary and movable objects can be placed without extensive changes in the relations of the traffic infrastructure. Traffic participants are categorized into object classes like cars, trucks, cyclists, etc. To define interactions between the participants, we use atomic maneuvers which are disjoint to each other. Reschka [26] proposes to separate the whole driving task into nine maneuvers. Each of these maneuvers is described by relational parameters to surrounding objects and semantic rules. For example the maneuver approach can be described by distance to the approaching object, relative speed and derived parameters like time-to-collision or time-headway. If the rear vehicle of two following vehicles is driving fast in the same lane this maneuver can be categorized as approaching. These rules can be expressed by the semantic web rule language and extend the conceptualization of classes of traffic participants by behavior rules. Maneuvers can also have relations to other layers if a car is approaching some infrastructure.

In the fifth layer, Schuldt describes environmental effects like weather but also the influences on infrastructure like aquaplaning. In our concepts, environmental effects will also consider influence on the interactions between traffic participants which results in different parameter ranges for relative parameters.
C. Process for creation of traffic scenes

After the ontology for the given use case was modeled, the process for creation uses the knowledge to create valid traffic scenes. The ontology clusters entities in natural language and assigns a formal order through conceptualization. We propose to model parameter relations with data properties in the ontology. Each entity (represented by a word) in the ontology represents multiple relations to parameters in the physical state space. Lanes in the traffic network may include parameters like width, condition and friction coefficient. To represent interactions of layers, we annotate if an entity includes or influences a parameter. For example, rain in the weather layer has influence on the friction coefficient, which is included in the lanes in the first layer.

For the creation of all possible traffic scenes from a given ontology, we need to derive assertional boxes. This stays in contrast to the contributions presented in Section [10]. All approaches aim at inferring knowledge from terminological boxes to augment observed assertional boxes.

Besides the knowledge about concepts of how traffic works, we need to model how human experts proceed to create scenes. To have a general applicable concept, the information about the creation process shall have only little influence on the ontology itself. The creation process starts with the first layer and derives a road network including topology.

For a given road network, we can derive multiple scenarios by assigning prevailing traffic rules. For example, a speed limit on a motorway formulates other requirements than a scene without speed limits. This also has influence on aspects in the ASIL classification in the hazard analysis and risk assessment according to the ISO 26262 standard. When the third layer optionally added manipulations to the given layout, we proceed with objects and traffic participants.

For the creation of traffic participants we propose to limit the maximum number of possible entities in the scene. Traffic participants are generated randomly in the scene, but with regard to possible relations.

For every new participant, the possible maneuvers shall be inferred using semantic rules. The chosen maneuvers further concretize parameters like relative velocity between to vehicles. In the last step, the weather is added to the scene and resulting influences are resolved.

V. EVALUATION CRITERIA

Krummenacher and Strang [27] divide evaluation criteria for ontology-based systems into context modeling and ontology engineering criteria. We propose a concept for the ontology-based generation of traffic scenes we focus on the context modeling criteria to show that the utilization of ontologies is beneficial to our purpose.

1) Applicability: Krummenacher and Strang state the question if the modeled ontology restricts the domain of application. For our purpose, we want to focus on traffic scenes, which are represented in the proposed concept. The five layers can be developed independently in the first step within a hierarchical design. Each layer can be reused for use cases in other domains (like maneuvers) or other functional ranges (like motorway domain).

2) Comparability: Since the proposed concept shall extract descriptions and knowledge from guidelines and standards we assume, as Xiong [19] previously described, that defined units like SI units are used to model the ontology. This makes the entities comparable to various inputs from other systems or scenario catalogs.

3) Traceability: Naming conventions could help to mark where a certain entity comes from on a top level of the ontology. For example, all traffic signs can be modeled by using a prefix like L2_stop-sign. This makes information and how they are connected to our hierarchical categories of the world. To trace single parameters of entities, we proposed to model relations of parameters and their owners and influences like the friction coefficient is owned by the lane and influenced by the rain.

4) History, logging: Krummenacher and Strang use this criterion to assess if the ontology can be used to work on contexts where sensor data is processed over a certain time. Since we want to create scenes, which are temporal snapshots of real world, there is no time related aspect in our ontology.

5) Quality: As shown in the process of knowledge acquisition for the ontology, we rely on standards, regulations, and expert knowledge. Data from standards and regulations shall satisfy highest quality standards because they persist for several years and form the state of the art for their field of application. However, when it comes to real world traffic not every single detail is built according to standards and regulations and the traffic infrastructure is subjected to wear and decay effects. Also, traffic participants are kind of creative when it comes to adopt their behavior to improve the own situation in traffic. For this reason, we assume that expert knowledge can help to represent these effects in form of metrics for wear and decay but also to identify violations against the standard traffic in form of edge cases.

6) Satisfiability: The satisfiability is evaluated by the conformance of derived information for assertional boxes. We follow a process that creates assertional boxes based on the given ontology. Hence, the satisfiability is not a valid criterion for our use case.

7) Inference: The process of creation is supported by inference on the layer of traffic participant. Underlying layers are created from true relations without deviations. This fully enables inference in parts of the process.

Based on these criteria we conclude that ontologies can be used for creation of traffic scenes. Most of the possible disadvantages originate when real world measurements are matched with the concepts of the ontology. For the modeling process engineering guidelines shall be applied to ensure a consistent and reusable ontology.

VI. CONCLUSION AND FUTURE WORK

In this contribution we proposed a concept for knowledge-based scene creation for automated vehicles. Ontologies are a representation of knowledge-based systems, which are widely
applied in semantic web applications. Publications from the recent years show that ontologies can represent traffic scenes. We adjust modeling of knowledge and propose a process, which can derive true statements from existing knowledge rather than augmentation of true facts with knowledge.

The next steps in our work is to model every layer of the five-layer model and to derive modeling techniques for representation of traffic scenes. Generated scenes shall provide a basis for a hazard analysis and risk assessment in the project aFAS.

To integrate this knowledge-based approach into the development process of automated vehicles, we need to extend the generated scenes to scenarios, which describe a temporal development between several scenes and behavior of traffic participants. This will have further influence on the design of the ontology and also on the algorithm to derive scenarios from existing knowledge.

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