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Situation classification for cognitive automobiles using case-based reasoning

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Abstract— **Driving a car in urban areas autonomously requires the ability of an in-depth analysis of the current situation. For understanding the current situation and deducing consequences for the execution of behaviors (maneuvers), higher-level reasoning about the situation has to take place. In this paper, an approach for situation interpretation for cognitive automobiles is presented. The approach relies on case-based reasoning to predict the evolvement of the current situation and to select the appropriate behavior. Case-based reasoning allows to utilize prior experiences in the task of situation assessment.**

I. INTRODUCTION

Recent advances in sensor technologies and data processing offer new possibilities for autonomous vehicles. It is now possible to think of more complicated traffic scenarios such as driving in urban areas. One of the major problems for driving autonomously in inner-city environments is the increased complexity of the traffic scenarios compared to simple environments such as expressways. This requires more sophisticated approaches for vehicle guidance. It is not sufficient to use the information about the course of the road directly for control. Rather than using a simple control strategy there is need for a higher-level component. This higher-level component consists of a situation interpretation and a decision making part. The situation interpretation is used to get a deeper understanding of the current situation and the output serves as a basis for the decision making process. The data acquired by various sensors is fused, converted into a more abstract symbolic representation and interpreted using prior knowledge. Prior knowledge can be divided into common knowledge such as traffic rules and knowledge derived from previous made experiences.

Most of the approaches for situation interpretation and decision making can be categorized into two groups: rule-based or case-based systems. Human cognition is working with both of these principles amongst others. In most situations, a set of rules is worked out in order to select a behavior. Experience is often stored as a case and ”remembering” is done by comparison with stored cases. A case-based reasoning system is presented in [1], where the reasoning is used within RoboCup for estimating the right behavior.

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In rule-base systems, different conditions are evaluated and the conclusion of a rule holds the selected behavior. Background knowledge is given implicitly in the rules and the order of the rules. Examples are given in [2], [3], [4], [5]. It is not possible to gather experiences. Another drawback is, that rule-bases are not manageable when they are becoming larger. The rules are normally created by experts and their knowledge (about creating rules) is implicitly given in the rules. It is difficult to detect inconsistencies and side-effects, when new rules are inserted. An improvement can be reached if a more expressive logic is used. Logics allow inference and reasoning techniques in order to get the conclusion. Description logic is used in [6] to describe scenes, in [7], [8], [9] F-Logic is used to describe situations and derive an assessment of the situation. Nagel et al. ([10], [11]) use Horn-logic for representing facts about the current situations. So called situation graph trees are used to facilitate both, temporal evolution of the situation as well as specialization of the rule-set.

Case-based reasoning has several advantages compared to classical rule-based systems. It facilitates better maintainability and expandability than rule based systems, since new knowledge is added by integrating new cases automatically to the case-base. Rule based systems require a more careful proceeding in order to ensure the consistency of the rule-base. There is a slight danger of side-effects. Partial matching is another advantage of case-based systems. Even if a case does not match exactly, it can still be considered for problem solving. In rule-base systems, the only way for explaining a decision is to report the chain of inferences. Since case-based systems contain more explicit knowledge, it can be used to enrich the explanation of a decision and thus making it more intuitive.

The work in this paper addresses the problem of interpreting the current situation and balancing different behaviors according to their projected consequences. The main contribution is the description of a case-based reasoning system for interpreting the current situation and deriving the appropriate behavior. The basic principle is to recognize already known situations by comparing the current situation with experienced ones. A behavior is assessed by predicting potential progressions of the situation. Additionally, it is shown how the integration of new experiences into the knowledge base can be done automatically.

II. SYSTEM OVERVIEW

The research center ”Cognitive Automobiles” aims at developing an intelligent vehicle which is able to act safely and robustly in complex traffic scenes such as inner-city environments. The core components of the vehicle are the perception of the environment, an interpretation of the situation in order to select the appropriate behavior, a behavior network providing constraints for path planning and a component for control of the vehicle. Furthermore, the vehicle is equipped with communication capabilities to enable the interaction of multiple vehicles, both in terms of cooperative perception as well as cooperative driving.

The perception delivers data in terms of predefined objects such as lanes, junctions, vehicles and obstacles. These are stored in a central data base and the situation interpretation converts this data into an abstraction in order to feed it into the reasoning process. The result of the interpretation consists of a selected behavior together with the relevant data for behavior execution. The behavior is then executed within a behavior network which monitors the progress of the behavior.

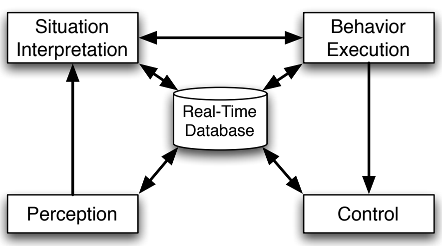

Fig. 1. Information flow within the cognitive automobile.

Figure 1 shows the interaction of the different components. The central components is the real-time database where all knowledge is stored. It is also used for distributing information among the connected components.

III. SITUATION INTERPRETATION

A. Knowledge modeling

All knowledge for describing situations is modeled in OWL-DL which implements $SHOIN(D)$ [12]. OWL-DL is a decidable fraction of first order logic. The domain knowledge is modeled with concepts, roles and assertions. Situations are represented by instances of concepts and roles. Background knowledge is available as rules. Besides the ability to model knowledge, description logic offers various reasoning tasks such as subsumption of concepts, checking for consistency, and satisfiability.

The quantitative data from the perception is mapped to a qualitative description because symbolic information is more feasible for reasoning processes. Part of this transformation is the evaluation of topological and spatial relations between objects such as *is_far(obj1, obj2)*. After the transformation, additional relations are evaluated by applying the rules of the background knowledge. This covers relations like *HasRightOfWay(obj1, obj2)*.

A situation consists of the road network of the local scene, all objects in this scene, an estimation of the behaviors of other traffic participants, the mission goal of the own vehicle, the internal states of the own vehicle and all relations mentioned in the previous paragraph among others.

B. Case-based reasoning

The basic idea of case-based reasoning is quite simple: try to solve a problem by remembering previous situations which are similar to the given one and reuse the solution that was used in that situation. Transferred to the problem of situation interpretation for cognitive automobiles, it means: given a traffic situation, what is the appropriate behavior that should be executed? Try to remember previous situations which were similar to the current one, understand, how and why a specific behavior was selected, and transfer the solution to the current situation. Additionally, remember the new experience by integrating the new case into the case-base.

The main applications for case-based reasoning systems are classification, problem solving, explanation, and prediction. For the cognitive automobile, situations or types of situations, risk potentials, or intentions can be classified. Problem solving is used for deciding about the correct behavior and reusing of plans. Both, behaviors of other participants as well as the evolvement of the whole situation can be predicted.

Basis for case-based reasoning paradigm is a *case*, and several cases are stored in an indexed *case-base*. Cases within the case-base are interrelated using several criteria to facilitate the processing of cases in different ways. This case-base serves as the experience knowledge and is used through the case-based reasoning process. The general framework for solving a given problem consists of five main steps:

1) Create case representing the given problem.
2) Retrieve similar cases from the case-base.
3) Solve case by reusing existing knowledge from the retrieved cases.
4) Revise solution.
5) Keep new acquired knowledge.

A good introduction into case-based reasoning is given in [13], a detailed description can be found in [14].

The order of processing is shown in figure 2. For time step *t*, the data which is delivered from the perception component (not shown) is transformed into a higher level representation (1). For further processing, the current situation is described by a case (2) and experience and problem solving knowledge is generated by the retrieval of known cases (3). These cases are then evaluated (4) and the adaptation of existing problem solving knowledge to the current situation (5) leads to the selected behavior (6). In order to benefit from newly acquired knowledge, the new case is retained in the case-base (7). This is done, when a new situation is reached and the previous solution can be confirmed (8).

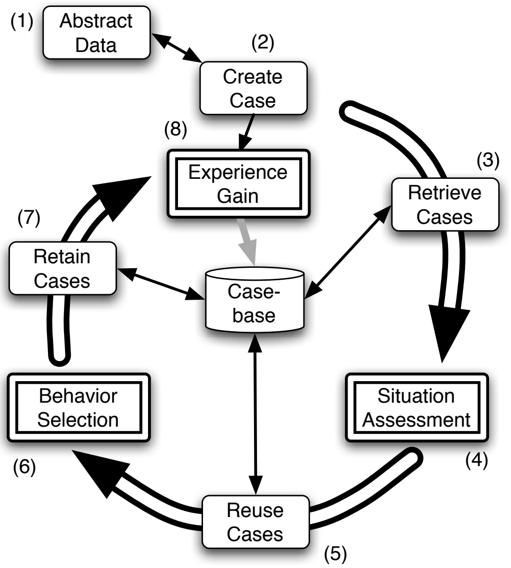

Fig. 2. Order of tasks for case-based reasoning for the interpretation of traffic situations.

IV. INTERPRETATION OF SITUATIONS USING CASE-BASED REASONING

Guided by the previously described cycle for case-based reasoning, the first step is to define a *case*. After that, it will be shown how the case-base is constructed. The most crucial part is the design of the indexing scheme because it influences heavily the efficiency of extracting eligible cases from the case-base. In order to interpret the current situation, the data, which is extracted from the perception, is transferred to Description Logics. Following the steps of case-based reasoning, the first step is the *retrieval* step which extracts all cases of the case-base, that have the highest similarity with the current scene. After that, the existing knowledge is exploited during the *reuse* phase and the behavior that is most suitable for the current situation is selected. The last step is the *retain* phase which is applied after the selected behavior was executed. Newly acquired problem solving knowledge is inserted into the case-base in order to update the knowledge base.

A. Definition of a case

As mentioned above, the definition of a case is a crucial part for case-based reasoning. It has a great impact for the remaining work and the efficiency of the reasoning system and thus must be done carefully. The definition of a case has consequences on the one hand for finding similar cases compared to the current situation and on the other hand it influences the extraction of problem solving knowledge which has to be applied for the given situation.

A cognitive automobile has to coordinate itself in a continuous environment and therefore it is not quite clear where a case starts and where it ends. Because of this condition we decided to use fine granular distributed cases. A case represents a snapshot of the situation rather than a time interval. A time interval is represented by a concatenation of cases. The core components of a case are:

- the description of the scene,
- the behavior of the cognitive automobile,
- the behaviors of the other participants,
- and an assessment of the represented situation according to different measurement.

The description of the scene is done using the knowledge modeling represented in the ontology described earlier. The scene is characterized by a set of instantiated concepts and relations. The instances represent objects or parts of the scene. In terms of description logic, A-boxes are used in order to describe the axiomatic, factual knowledge of the scene. Thereby, an important feature of an ontology can be utilized: the possibility to subsume from concrete instances to more general concepts. This allows to compare parts of a scene at the conceptual level, e.g. in some cases it might be unimportant if there is a truck or an automobile rather than there is a motorized vehicle. Relations are used to describe connections between objects as well as states of single objects. They are represented by roles which are defined in the ontology, too.

The second component of a case is the behavior of the cognitive automobile, which is currently executed. Additionally, the direction of the route is stored. The behavior of the other participants of the scene is stored as well. In contrast to the own behavior, they are not known and must therefore be estimated.

The last important component of a case is the assessment of the situation. For this, different features are evaluated such as the potential of danger, the conformity of the traffic rules or economic measurements. The evaluation of these features is mapped onto a single value Q between 0 and 1 to express the quality of the situation. A value of $Q = 0$ is the worst and of 1 the best assessment.

B. Construction of the case base

The construction of the case-base relies on the definition of a case. The main focus lies on an indexing of the cases in order to alleviate and speed-up the search for the most similar cases. The indexing scheme is based on links between different cases and facilitates the search for cases by walking through the case-base. Cases are linked in three different dimensions. In the first dimension, cases are organized hierarchically according to the specialization of the case. In the second dimension, cases at the same level of specialization share a link representing their differences. And lastly, links denote temporal evolutions of cases.

The hierarchical arrangement represents an order of cases from the most general to the most specific case. Specialization takes place either because a concept or a role is more specific (using the `is-a` relation of description logics), or new instances of concepts or roles are added to the case. In doing so, the link holds the reasons that led to the specialization of that case, i.e. it contains all the differences which make this case a more specific case. The resulting hierarchy can be seen as a directed, acyclic graph, where arrows denote a specialization. This index is used later in the case retrieval phase in order to extract the most similar cases. In order to provide an entry point into the case-base, a top element is used which is more general than any other case.

The second type of link interrelates cases at the same level of specialization. The edge between two cases holds the difference between these two cases. These links are used for generalization of new cases.

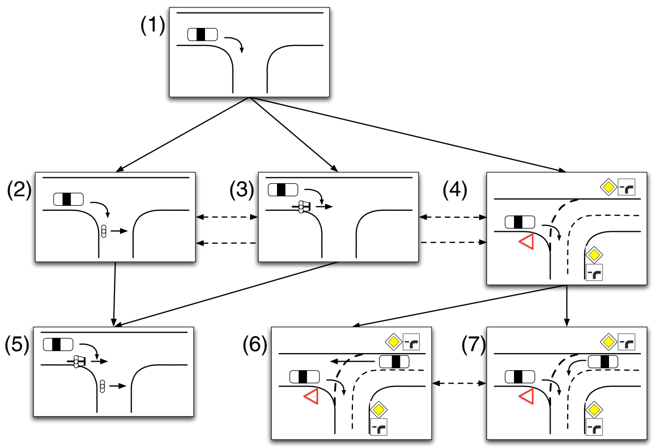

Fig. 3. The hierarchical structure of the case base. Solid arrows denote specialization between cases, dashed link cases at the same level of specialization.

Figure 3 shows these two types of links. Links of specialization are drawn with solid-lined arrows whereas links of differentiation are drawn with dashed-lined arrows. As can be seen from this figure, the most general case 1 shows a t-junction with no additional traffic regulation and no other traffic participants. The own vehicle is coming from the left and wants to turn right at the junction. Currently, it is driving. The first level of specialization is built with cases 2, 3 and 4. In case 2, a pedestrian is added who is crossing the street. In case 3, a bicyclist is crossing the junction before the vehicle. In case 4, the traffic regulations have changed and the own vehicle has no right of way. Case 5 is different in terms of specialization since it incorporates two different preceding cases. Here, cases 2 and 3 are combined since the scene consists of the pedestrian and the bicyclist. Cases 6 and 7 clarify another peculiarity. In both cases, another vehicle was added, coming from the right. The difference between these two cases lies in the behavior of the other vehicle. In case 6, the vehicle's behavior was estimated to be ”going straight” and in case 7 it is ”turning left” and thus possibly interfering with the own vehicle.

The linkage of cases based on temporal interrelation helps on predicting the consequences of the execution of different behaviors and thus selecting the right behavior for the own vehicle. A case is linked temporally with another, if its contents have changed significantly over time and is a direct evolution of the preceding case. The applied behavior which led to the temporally succeeding case is stored together with the link. Due to the applicability of different behaviors, a case can have multiple succeeding cases. Additionally, a probability of occurrence is saved.

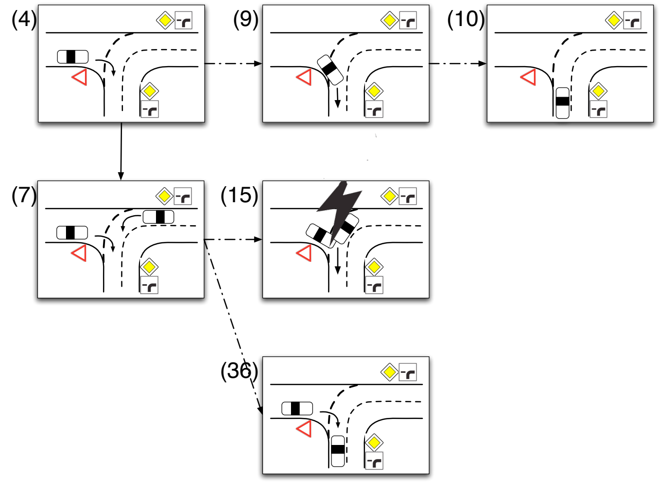

Fig. 4. The hierarchical structure of the case base. Solid arrows denote specialization between cases, dashed-dotted arrows link cases that are consecutive over time.

An excerpt of the temporal linkage is shown in figure 4. The two initial cases are given on the left of the picture, case 7 is again more special than case 4. For case 4, only one behavior is applied which results in the succeeding case 9 (entering the junction). Case 10 (leaving the junction) is the successor of case 9, again, only one behavior was applied. Two different behaviors are possible for case 7. The first possibility is to enter the junction which leads to succeeding case 15. The result is an accident, thus this is a counter-example which should not be taken. In the other case (36), the behavior is stop and let the other vehicle pass by.

If a behavior is applied for a given case, there is no need that there exists exactly one temporal successor rather than multiple successors. This accommodated the fact, that the prediction of how the situation will evolve is always tainted with uncertainty. Therefore, each applied behavior for a given case is assigned multiple temporally succeeding cases, each succeeding case together with its probability of occurrence. The different behaviors of the other participants are not stored in the temporal linkage itself, but rather given by different cases in the case-base. For the prediction of the evolvement of the situation, it is assumed that the other participants keep their current behavior.

Figure 5 shows, how one behavior leads to different succeeding cases. In this example, behavior B1 can result in three succeeding cases (2–4). For each successor, the probability of occurrence is denoted. Another speciality is, that it is also possible that different behavior share succeeding cases. In the given example, for both behaviors one successor is case 4.

C. Case retrieval

The purpose of the phase *case retrieval* is to extract the most similar cases, so called *best cases*, in the case-

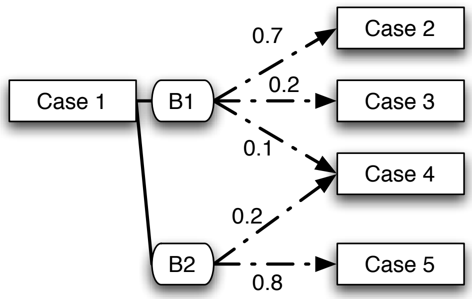

Fig. 5. Temporal linkage of cases using different behaviors.

base for the given situation. Basis for the extraction is the representation of the current situation as it was described in section IV-A. The best cases are searched by traversing the case-base recursively along the paths given by the hierarchical organization. In the following, each directly linked specialization of a case will be called a child node of that case (e.g. in figure 3 case 2,3,4 are the child nodes of case 1). A case matches the current situation, if the case is completely contained in the current situation. Instances and relations of the situation can be generalized to fulfill the matching, e.g. a situation with only a Porsche matches a case which contains only a ”vehicle”.

Starting with the top element, a child node is visited if it matches the current situations. This is done for all child nodes of a visited node. If a node has no matching child nodes, a best case is found and added to the set of retrieved cases. The termination of the retrieval is guaranteed, since the cases are organized in a acyclic, directed graph.

It should be mentioned, that single cases from the case-base can be used multiple times because of different mappings of the individuals. Cases can be seen as some sort of template and the partial matching uses different elements of the scene in order to fill the placeholders of the template.

The result is a set of cases which covers (parts of) the current situation. For each extracted case, the concepts and roles, which were used for matching, are noticed.

D. Reuse of cases

In the general case-based reasoning framework, the purpose of the phase *reuse of cases* is to analyze existing knowledge contained in the retrieved cases and to generate a solution from this knowledge. Transferred to the domain of cognitive automobiles, the goal is to select the appropriate behavior for the vehicle. For this, different applicable behaviors are evaluated hypothetically and the most appropriate behavior is selected as the best suitable solution.

In order to clarify the procedure, we first assume, that the ”case retrieval” phase has found only one matching case. According to the modeling of the case-base (see section IV-B), the cases are not only linked hierarchically but also temporally. Links are given which represent the temporal evolution of the situation. In order to select the most appropriate behavior, all possible evolutions of the situation are regarded by analyzing the temporal successors of the retrieved case. In order to detect dangerous situations at an early stage, the prediction can consider multiple levels of successors. This can be done by combining the assessment along the prediction path using the minimum. It is clear, that the uncertainty of the prediction increases with the length of the prediction path.

The assessment of the temporally succeeding cases is done by evaluating the different rates for each case. Together with the probability of occurrence of each case, the overall assessment value is given by the expectation value which indicates the applicability of the behavior. The higher the expectation value is, the better the behavior is applicable. This expectation value is calculated for each applicable behavior. The behavior with the highest overall value is selected.

An example is shown at the top of figure 6. It is assumed, that case 1 is the only extracted case and two different behaviors (B1 and B2) can be applied.The overall rating Q of each case, together with the probabilities of occurrence, gives the expectation value of 0.85 for behavior B1 and a value of 0.36 for behavior B2. Thus, behavior B1 is selected.

If multiple cases were extracted, the procedure is as follows: First, for each extracted case, an assessment value is assigned for each behavior of that case. After that, for each behavior the minimum over all cases, which offer that behavior, is calculated and this minimum is regarded as the rate of applicability of that behavior. Finally, the behavior with the highest rating is selected. At the time of writing, if the consequences of a behavior are not known for a specific case (i.e. no succeeding case exists for that behavior), the behavior is not taken into account.

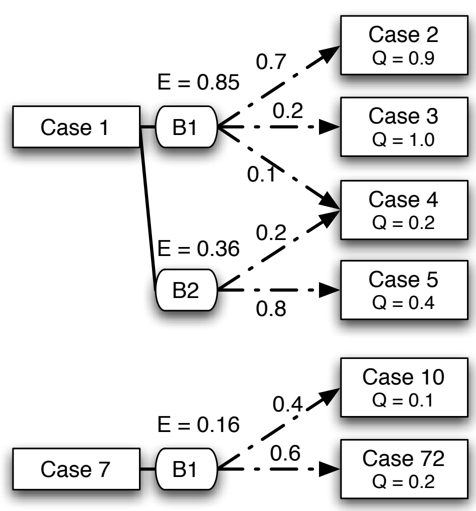

Fig. 6. Selection of best behavior given multipile cases. Both cases share the applicability of behavior *B1*.

An example of multiple cases is given in figure 6. Here, the expectation values for all behaviors in all cases are calculated. This would lead to behavior B1 in case 1. But because both cases share behavior B1, the overall minimum of that behavior is B1 (from case 7) and therefore, behavior B2 from case 1 with an assessment value of 0.36 is taken.

E. Retaining cases

Finally, the last phase is used to keep newly acquired experience and to provide it for future processing. This phase is executed in the next time step, because an assessment of the applied solution is not known before and therefor the applicability of the solution is not known earlier.

In the previous step (”reuse of cases”), different cases were extracted representing the situation most appropriate and the best suitable solution was generated based on these cases. In the next time step, the next set of cases with best similarity is extracted according to the ”case retrieval” phase. Based on this selection, it is now possible to check, which temporally succeeding cases from the previous time step are really happening. Given this information, the probability of occurrence can now be updated for all these cases.

If for a best case none of the temporally succeeding cases did happen, a new case must be created and integrated into the case-base. For creating a new case the following steps have to be performed:

1) Identify all objects of the current situation, that are part of the previous situation and the matching case and all new appeared objects.
2) Reduce the current situation to all these objects and their relations.
3) Generalize the objects to the level of the matching case.

Then, the newly created case must be integrated into the case-base. This implies adding the case to the case-base and creating all links for this case which is done automatically. Finally, a generalization of cases in the case-base happens, if the branching factor of a case is higher than a certain value. In that case, all cases at the same level as the added case are taken into account. Generalization is done by identifying the similarities between the new case and an arbitrary case at the same level of specialization. These two cases are replaced by this new generalized case and added as child nodes.

V. SUMMARY AND CONCLUSION

In this work, an approach for situation interpretation for cognitive automobiles using case-based reasoning was presented. The current situation is interpreted by comparing the current situation with experienced ones. A behavior is selected based on a prediction of the evolution of the current situation. Newly acquired knowledge is stored as experience in the case-base.

The main issue for future work is to show the potential of this approach by further elaborating the involved processes and testing with real world scenarios. One open question is how to estimate the consequences of a behavior of no case knowledge exists.

VI. ACKNOWLEDGMENTS

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