Cooperative Automated Driving: From Platooning to Maneuvering

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Abstract: Cooperative automated driving (CAD) combines autonomous driving with cooperative driving, thereby yielding a powerful approach to improve traffic efficiency and safety. A very well-known example of CAD is platooning. However, when extending this one-dimensional application to two-dimensional maneuvering, covering a large number of traffic scenarios while also including safety threats imposed by other traffic or failing components of the automation system, a complex control system architecture may arise. To address this challenge, an agent-based control system architecture is proposed employing explicit decision making. This architecture is scalable with respect to the number of traffic scenarios that can be handled, capable of including safety features, and provides the flexibility to adopt various controller design approaches at the same time.

1 INTRODUCTION

In recent years, autonomous driving has gained increasing attention in the public press and in the scientific community. Traffic safety is the primary driver for this development, but also other motivations exists, such as more effective use of the traveling time and reducing the dependency on manpower.

Autonomous vehicles, however, do not intrinsically improve traffic since they optimize towards reaching their own goals. Cooperative driving, on the other hand, aims for optimizing the collective behavior, thus improving the traffic system. Connectivity is instrumental for cooperative driving because it allows traffic participants to share their intention easily and precisely (de La Fortelle et al., 2014). When combined with automation, a powerful approach arises to improve traffic safety and efficiency.

A well-known application of cooperative automated driving (CAD) is cooperative adaptive cruise control (CACC) or platooning, which improves traffic throughput by adopting short intervehicle distances (Ploeg et al., 2014). This is particularly of interest in an automated transit network (ATN), i.e., a system of automated people movers for first-/last-mile public transportation, in view of transport capacity. Truck platooning is another promising application because of the reduced aerodynamic drag at short distances (Alam et al., 2015).

Next to ongoing developments in the field of platooning, cooperative automated maneuvering attracts attention to an increasing extent, acknowledging the fact that traffic is not a string of vehicles. Many approaches are still investigated in this field. One such approach relies on explicit decision making, which was illustrated by i-GAME (Ploeg et al., 2018), a European-funded project. Other projects, such as AutoNet2030, adopt an optimization-based approach for path planning (Qian et al., 2016). A serious challenge for cooperative automated maneuvering, however, is posed by the fact that road traffic involves a large number of different scenarios, which are not likely to be handled by a single integrated approach. Moreover, next to nominal behavior, also safety measures come into play to handle failing system components or emergency situations imposed by other traffic. This paper addresses this challenge by presenting a generic control architecture for CAD using an agent-based approach, which intends to be scalable in the sense that all possible traffic scenarios can be incorporated without leading to a complicated control system architecture while also being capable of including safety-related features.

The next section first presents a brief summary of developments in controller design for platooning and the emerging field of cooperative automated maneu-

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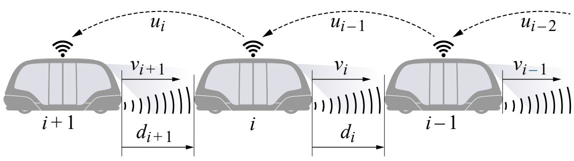

Figure 1: Platoon of ATN vehicles.

vering. Next, Section 3 focuses on safety of CAD. Section 4 proposes a generic control architecture after which the main results are summarized in Section 5.

2 COOPERATIVE AUTOMATED DRIVING

A very well-known CAD application, focusing on longitudinal automation, is vehicle platooning, the main aspects of which will be briefly summarized in Section 2.1. When also taking lateral vehicle motion into account, the concept of platooning needs to be extended towards cooperative automated maneuvering, an example of which is presented in Section 2.2.

2.1 Platooning

An example platooning set-up is depicted in Fig. 1, where v_i is the speed of the vehicle with index i and d_i is the intervehicle distance between vehicle i and the downstream (forward) vehicle $i-1$. The main control objective is to regulate d_i to a desired value $d_{\mathrm{r},i}$, to which end, in this example, a one-vehicle look-ahead communication topology is employed next to on-board sensors, such as forward-looking radar and/or camera, to measure the intervehicle distance and the range rate. Note that the platooning controller is known as cooperative adaptive cruise control (CACC), since it can be viewed as an extension of adaptive cruise control (ACC) with wireless vehicle-to-vehicle (V2V) communications.

An important requirement for platooning is known as string stability (Ploeg et al., 2014), i.e., the attenuation of the effects of disturbances along the string in upstream direction. This requirement is usually formalized by requiring that the $\mathcal{L}_2$ signal norm (energy) or the $\mathcal{L}_\infty$ signal norm (amplitude) of the velocity v_i or acceleration a_i does not amplify for increasing i. Adopting a constant time-gap spacing policy, i.e., $d_{\mathrm{r},i}(t) = r + hv_i(t)$ at time t, where r is the standstill distance and h the time gap, is beneficial for string-stable platoon behavior. In this case, a minimum time gap $h_{\min}$ exists above which string stability can be guaranteed. But to also obtain string stability at short intervehicle distances ($h \approx 0.3\,\mathrm{s}$), wireless V2V communication is required. In the example of Fig. 1, taken from (Ploeg et al., 2014), the input u_i (desired acceleration) of vehicle i is communicated to the upstream vehicle $i+1$, which can lead to string stable time gaps as low as $h_{\min} = 0.24\,\mathrm{s}$. Since u_i cannot be measured by the on-board sensors of the downstream vehicle, it must be communicated, hence the need for wireless V2V communication.

Many platooning controllers have been proposed in literature, see (Ploeg et al., 2014) and the references contained therein, some of them employing more complex communication topologies or even varying topologies (Santini et al., 2019). Despite this vast amount of literature, however, some challenges still remain, among which the control of heterogeneous vehicle platoons and, even more important, the design of safety measures in the case of, e.g., sudden packet loss of the V2V link. Nevertheless, traffic is certainly not limited to platooning scenarios, which is why the field of CAD is extended towards cooperative automated maneuvering, as illustrated next.

2.2 Maneuvering

Automated crossing of an intersection without traffic lights is a good example of cooperative automated maneuvering. This particular application received quite some attention in literature, see, e.g., (Morales Medina et al., 2018). In this section, however, we focus on another example that is very illustrative for the upcoming architecture proposal, being a highway lane reduction, involving zipping of two vehicle platoons, as presented earlier in (Ploeg et al., 2018).

Consider a platoon L on the left lane, with members L_i, $i = 1,\ldots,m$, and a platoon R with members R_j, $j = 1,\ldots,n$, on the right lane, as illustrated in Fig. 2 for $m = 3$ and $n = 4$. The lane-reduction scenario can then be solved by the following sequence of maneuvers, initiated by an interaction protocol that is implemented through wireless V2V communications.

1. *Pair-up R2L* — The first phase entails sending merge requests by the vehicles in L to the ones in R. Next, each vehicle R_j finds an appropriate merging partner L_i to merge in front of R_j, thus creating pairs $\{L_i, R_j\}$ using a V2V handshaking mechanism. The actual maneuver is that the vehicles in R slow down to create an appropriate distance towards their merging partner in L, which is implemented by R_j activating a CACC controller with L_i as target vehicle. Since it may also happen that the preceding in-lane vehicle R_{j-1} brakes for some reason, vehicle R_j also activates a 'separation controller', guaranteeing a certain minimum distance towards R_{j-1}. This procedure is executed

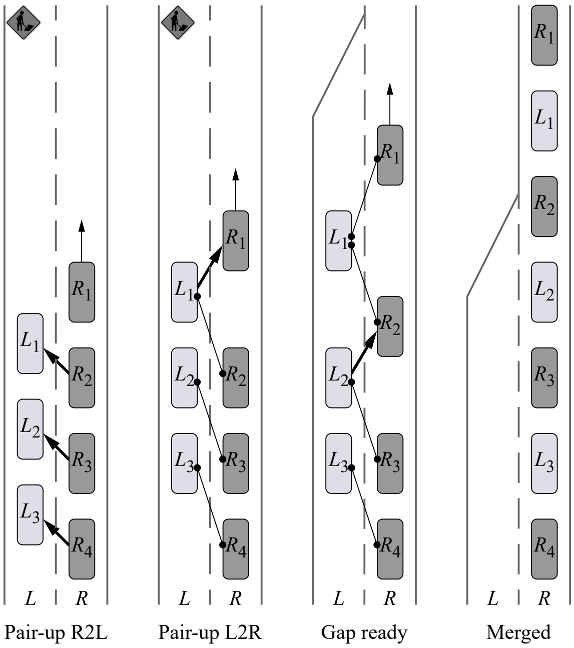

Figure 2: Phases of the lane-reduction scenario.

for all vehicles simultaneously.

2. *Pair-up L2R* — In the next phase, the same type of procedure is followed but in opposite direction: Each vehicle L_i finds a appropriate merging partner in R, which usually will be R_{j-1} given the pair $\{L_i, R_j\}$ from the previous phase, and activates its CACC controller with R_{j-1} as target, while also executing a separation controller with L_{i-1} as target vehicle. This procedure, however, is executed sequentially in upstream direction to prevent large decelerations of the vehicles in the tail of the platoon due to the gap-making maneuver.
3. *Gap ready* — When the gap is large enough, vehicle R_j signals its pair L_i that it is allowed to initiate the actual merge maneuver. Only when vehicle L_i starts to change lanes, phase 2 is initiated for the next vehicle L_{i+1}.

From the above description, it is clear that this approach is based on explicit decision making, driven by the interaction protocol, which initiates a maneuver sequence. Each maneuver is executed by one or more controllers which have a simple objective, such as regulating a desired distance or a minimum distance, or making a lane change. Note that other approaches exist that do not rely on explicit decision making, such as the Model Predictive Control approach presented in (Qian et al., 2016). This would, however, require all vehicles to have the exact same type of controller, which might not be feasible given the fact that there are various vehicle manufacturers.

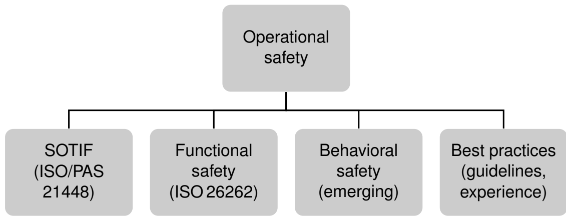

Figure 3: Aspects of operational safety.

Until now, only nominal behavior has been considered. In case of practical deployment, however, also safety comes into play, as explained next.

3 ROAD SAFETY

Practical deployment of CAD applications requires a structured approach to road safety. This section briefly summarizes some important types of safety and presents relevant threats in the scope of platooning, thereby motivating that additional vehicle controllers are required to ensure safe behavior.

3.1 Standardization

Operational safety, which is used here as an umbrella term for all types of safety, involves both ‘safety of the intended functionality’ (SOTIF) and functional safety, as depicted in Fig. 3. Here, SOTIF refers to the ability of the system to correctly comprehend the environmental situation and respond safely by activating appropriate countermeasures. SOTIF is recently standardized as ISO 21448 (ISO/PAS 21448, 2019). Functional safety, on the other hand, is the absence of unreasonable risk due to hazards caused by malfunctioning behavior of subsystems of the automated vehicle, as standardized in the notorious ISO 26262 (ISO 26262-1, 2018). It should be mentioned that ISO 26262 actually does not cover fully automated road vehicles. Instead, this standard is limited to partial automation, as implemented by advanced driver assistance systems (ADAS), among which ACC.

Next to SOTIF and functional safety, also the notion of behavioral safety has been recently introduced as “an aspect of system safety that focuses on how a system should behave normally in its environment to avoid hazards and reduce the risk of mishaps” (Waymo, 2017). Behavioral safety thus refers to whether the programmed response of an automated vehicle to common traffic situations is safe.

Finally, best practices are still important for the development of automated vehicles, mainly due to the limited scope of ISO 26262.

Table 1: Platoon-specific threats in the scope of 'safety of the intended functionality' (SOTIF).

ID	Threat	Countermeasure
SO1	Emergency brake of equipped vehicle	No specific countermeasure is required in this case, provided the platoon is string stable.
SO2	Intermittent V2V packet loss	*Graceful degradation* — Upon exceeding a packet loss threshold, a smooth switch from CACC to ACC is performed, while increasing the following distance to a safe and string stable value.
SO3	Unequipped in-lane vehicle	*Graceful degradation* — The same countermeasure as in SO2 applies.
SO4	Emergency brake of unequipped in-lane vehicle	*Fail safety* — A collision avoidance mechanism must be activated while messaging all upstream platoon members, allowing those to respond in a timely manner.
SO5	Cut-in/-through of unequipped vehicle	*Graceful degradation* — In most cases, this threat requires a similar response as in SO3; However, if the alien vehicle significantly decelerates at the same time, a *fail safety* mechanism must be activated, as in SO4.

3.2 CAD Safety Threats

SOTIF and functional safety are the main types of safety to take into account when developing CAD systems since these are standardized. This section lists common threats, related to SOTIF and functional safety, for CAD systems in general and platoons in particular. To this end, Table 1 first summarizes some important threats in the scope of SOTIF. In this table, an 'equipped vehicle' refers to an automated vehicle with wireless communication capability.

As can be clearly seen from this table, all listed threats relate to dangerous situations imposed by other traffic (SO1 and S03–SO5) or to inherent limitations of the automated vehicle's environmental perception sensor suite, in particular the V2V communication (SO2). In other words, SOTIF encompasses threats that inherently exist under normal conditions while driving in mixed traffic.

Functional safety exclusively focuses on component failures. Some important failures, particularly related to platooning, are listed in Table 2. This concerns persistent packet loss of the V2X communication system (as compared to 'normal' packet loss, which is covered by SOTIF). Malfunctioning behavior of on-board environmental sensors is also considered, assuming that failure of the environmental perception system (EPS) can be detected, either directly or through comparison with redundant on-board sensors. Finally, an equipped vehicle may be subject to a major failure, due to which the vehicle performs an emergency stop and, at the same time, all systems are shut down, among which the wireless communication system. The latter type of threat is particularly relevant for platoons of people movers, which typically perform an emergency stop when essential systems exhibit malfunctioning behavior.

Table 2: Platoon-specific failures in the scope of functional safety.

ID	Failure	Countermeasure
FS1	Persistent V2V packet loss	*Graceful degradation* — With the on-board EPS still fully functional, V2V failure is counteracted by smoothly switching from CACC to ACC, including increase of the following distance to regain safety and string stability.
FS2	EPS failure	*Fail safety* — It is technically possible but unsafe to continue platooning using V2V only, because unequipped vehicles or other objects can no longer be detected. Therefore, EPS failure triggers a collision avoidance mechanism as the default fail-safety measure.
FS3	Failure of preceding equipped vehicle	*Fail safety* — This is a combination of an emergency stop of the preceding vehicle and FS1, which can only be treated as a fail-safety situation (collision avoidance) while messaging all upstream platoon vehicles, allowing those to respond in a timely manner.

Both table Table 1 and Table 2 also show possible countermeasures for each threat or failure, categorized as either *graceful degradation* or *fail safety*. Consequently, in addition to the nominal controllers mentioned in Section 2, controllers are needed for fail safety, e.g., a collision-avoidance controller, and for graceful degradation. An example of the latter is automatically reverting from CACC to ACC while increasing the intervehicle distance in the case of persistent V2V packet loss.

4 CONTROL SYSTEM ARCHITECTURE

Section 2 concerned controller design for nominal behavior, whereas Section 3 touched upon non-nominal situations. To automatically control vehicles that collaboratively execute various traffic scenarios under both nominal and non-nominal conditions, a layered

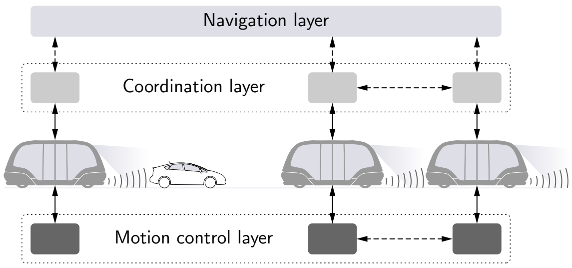

Figure 4: Layered architecture of CAD systems (dashed arrows indicate information exchange through wireless communications; the white vehicle is unequipped).

control system architecture is proposed, inspired by (Horowitz and Varaiya, 2000), among others.

4.1 A Layered Software Architecture

Three main control levels can be distinguished in the scope of CAD, as summarized below and visualized in Fig. 4.

- The centralized *navigation layer* is responsible for scheduling and routing, taking into account fuel consumption and travel time, among others. In case of truck platooning, this layer primarily involves logistics, whereas in the case of ATNs, it would focus on fleet control while also keeping track of vehicle status and maintenance schedules.
- The intermediate *coordination layer* is responsible for coordination among the vehicles in a cooperative maneuver. This layer may exclusively involve decision making, hence executing the aforementioned interaction protocol, but may also act as a higher-level feedback control loop. An example of the latter is presented in (Zegers et al., 2017), concerning the design of a mechanism to guarantee platoon coherency subject to velocity constraints. This layer's implementation should be distributed to support the distributed nature of many traffic maneuvers.
- At the individual vehicle level, the *motion control layer* performs the actual real-time control of the automated vehicle in order to execute the required maneuvers. Consequently, this layer involves controllers for longitudinal vehicle motion, e.g., (C)ACC, and lateral motion, such as lane keeping.

This control system hierarchy is very similar to the three levels commonly distinguished for the human driving task (Michon, 1985), being the strategic level, the tactical level, and the operational level, respectively, which were the terms used in (Ploeg et al., 2018). The main motivation for this layered architecture is twofold: First, it supports the explicit inclusion of interaction protocols, and second, in the motion control layer, there is freedom to adopt various controller design approaches. The latter is particularly relevant in view of the different road vehicle brands.

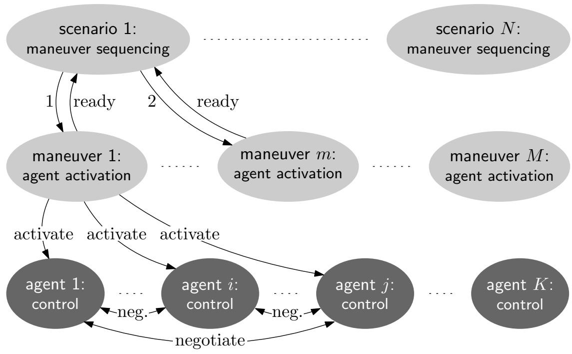

Figure 5: The coordination layer (light gray) and the motion control layer (dark grey) in an agent-based control approach.

4.2 Agent-based Control

To further detail the proposed architecture, in particular the coordination layer and the motion control layer, one could think of road traffic as a set of *scenarios*. Each scenario is built from (a sequence of) *maneuvers*, which are executed by one or more controllers, or *agents*, having a simple objective such as speed control, distance control, etc.. If more than one agent is required to execute the maneuver, the agents can 'negotiate' among each other about which one actually controls the vehicle motion.

Taking this simple road traffic ontology as a basis, the coordination layer is then responsible for execution of a scenario by subsequently activating the required maneuvers. Each maneuver, in turn, is implemented by one or more agents for the longitudinal and lateral vehicle motion. This agent-based control approach, which has the advantage of being flexible and computationally non-demanding (Jennings and Bussmann, 2003), is depicted in Fig. 5. Note that this approach is very similar to that of hybrid automata (Huang et al., 2019).

Consider the lane-reduction scenario as discussed in Section 2.2 to illustrate this concept. This scenario requires the right-lane vehicles to make a gap for the left-lane vehicles, i.e., a *gap-making maneuver*. Next, the left-lane vehicles need to perform a *lane-change maneuver*, and the scenario ends with all vehicles on the right lane performing a *vehicle-following 'maneuver'*. The sequence of these maneuvers is controlled by the interaction protocol, which runs in the coordination layer. The gap-making maneuver entails two control objectives: realizing a desired distance towards the merging vehicle, while guaranteeing a minimum distance towards the preceding in-lane vehicle. Hence, two agents are involved in executing this maneuver: a *CACC agent* to regulate the distance towards the merging vehicle, and a *separation agent* to guarantee a minimum distance towards the preceding in-lane vehicle. The lane change is performed by a *lane-change agent*, while the final vehicle-following situation is realized through the *CACC agents* of all vehicles. Negotiation among agents takes place during the gap-making maneuver, since the separation agent must have priority above the CACC agent in case the preceding in-lane vehicle brakes; likewise, the CACC agent has priority if the preceding in-lane vehicle decides to accelerate for some reason.

During all maneuvers, it may be required to also activate a *collision avoidance agent* as a fail safety measure, capable of performing an emergency stop in case dangerous situations occur during the scenario execution, thus overruling other active agents. In addition, an *ACC agent* might take over from the CACC agents in case of packet loss, thus implementing a graceful degradation measure.

5 CONCLUSION

It was argued that cooperative automated driving regards road traffic as a system instead of individual vehicles, thus having the potential to improve traffic efficiency and safety. Platooning is a well-known example in this field, but must be extended in two directions: First, to cover multiple traffic scenarios, one-dimensional platooning must evolve into two-dimensional maneuvering and second, practical deployment requires inclusion of safety measures. To this end, a software architecture for the control system was proposed utilizing an agent-based approach. This architecture will be implemented in the near future to realize cooperative behavior in a fleet of people movers.

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