Hierarchical approach for Safety of Multiple Cooperating Vehicles

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Zuordnung zu den Schwerpunkten des Symposiums (bitte ankreuzen):

[X] 1. Digitalisierung der Mobilität und vernetzte Verkehrssysteme
[X] 2. Kooperative automatisierte Fahrzeugsysteme
[X] 3. Situationserfassung, -modellierung und -verstehen
[X] 4. Mensch/Technik-Integration im Kontext automatisierter und vernetzter Fahrzeugsysteme
[X] 5. Entwicklung und Absicherung automatisierter und vernetzter Fahrzeugsysteme

Vermerk:
This paper is submitted for SPP special session on cooperating vehicles.

Schlagwörter:
Automated Vehicles, Formal Verification, Cooperative Maneuver Planning, Tube-based MPC, Reachability Analysis, Hybrid Systems, Car-to-Car Communication

Neuigkeitsgrad/bestehende Vorveröffentlichungen zu diesem Beitrag:
Formal safety guarantees of automated driving using the concepts from reachability analysis of continuous systems (or tube-based MPC) have been previously limited to only one automated vehicle e.g.: Borelli et. al. [1], Rodriguez et. al. [2], Heß et. al. [3]. In this paper we present the concept of reachability analysis for hybrid systems and its application to cooperative maneuver planning scenarios involving two or more vehicles. Existing tools and methods such as Flow*[3] for modelling of hybrid systems, MPT [4] for tube-based MPC and polytopic/ellipsoidal disturbance representation have been combined and used in an integrated approach.

Ergebnisse:
This paper presents a hierarchical structure for the verification of the safety properties of cooperating vehicles based on the concept of reachability analysis of hybrid and continuous systems. The effectiveness of the concept is presented through simulation results for a cooperative lane change scenario involving multiple vehicles.

Abstract (maximal eine halbe Seite DIN A4):
Safety and reliability of automated road vehicles are one of the most important aspects for the introduction of such systems into the market and its acceptance by the road user. The problem at hand is escalated even further when automated vehicles need to cooperate with other communicating and non-communicating, automated or manually driven vehicles for example to avoid collisions or to increase the efficiency of traffic flow. Simulation-based verification methods such as Monte-Carlo simulations, suffer from the drawback that a very large number of tests need to be performed for proving the safety of such systems. Formal verification techniques on the other hand can provide guarantees for the safe and reliable behaviour of automated vehicles through its rigorous mathematical specification. In this paper we present a hierarchical structure consisting of offline and online verification, ensuring the safety properties of cooperating vehicles; communicating either implicitly (e.g.: vehicle on left lane slowly opens gap, indicating the vehicle on right lane to merge in front of it) or explicitly via Car-to-Car communication with each other. The offline verification is based on the concept of reachability analysis of hybrid systems and aims at building formally correct and safe cooperative maneuvers for a group of vehicles. A hybrid system is defined as a group of communicating vehicles, each consisting of continuous maneuver states and discrete transitions between them, e.g.: follow-lane, change-to-left-lane, open-gap etc. The reachability analysis of such a hybrid system provides cooperative maneuvers that are safe i.e. avoids collisions between the traffic participants. These offline computed cooperative maneuvers are stored in a Cooperative Manoeuvre Database (CMD), along with the information about the cooperating participants, cost of maneuver etc. and are available for the online verification. The online verification layer consists of a high-level decision layer and a low-level tube-based MPC formulation. The decision layer negotiates the cooperative maneuvers with other vehicles via Car-to-Car communications based on the stored maneuvers in the CMD; in order to select a cost optimized safe maneuver for the group, defining the role of each participant in the maneuver. In addition, a check on the
vehicle trajectory of the cooperating vehicles that are implicitly communicating is performed by the online
decision layer that aborts the current cooperative maneuver in case the vehicle leaves the previously
determined safe regions. The tube-based MPC ensures that the state-trajectory of the ego vehicle remains
within the safe regions. The cooperative maneuver selected by the online decision layer provides
constraints for the tube-based MPC that are tightened based on the current disturbance and prediction of
other non-cooperating traffic partners (i.e. neither explicit nor implicit communication). For the MPC
formulation, non-linear vehicle models, disturbance and uncertainty representation of the form of polytopes
and ellipsoids are used. In case MPC offers no feasible solution to the constraint optimization problem i.e.
there occurs a constraint violation during the prediction time, the safety of the cooperative maneuver is
ensured by an emergency planner, which brings the vehicle to safe state. The effectiveness and the
performance of the hierarchical concept presented here are shown with an exemplary cooperative lane
change scenario involving multiple vehicles.

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