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Public report

Project within Trafiksäkerhet och automatiserade fordon - FFI - juni 2020
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FFI Fordonsstrategisk Forskning och Innovation

Content

FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

For more information: www.ffisweden.se

1. Summary

To safely maneuver a heavy vehicle in a complex traffic situation is a non-trivial task, where the driver must be able to detect, track and predict the motion of multiple surrounding road-users, and based on that uncertain information decide the future motion of its own vehicle. This is true for both a human driver and an autonomous system. For an autonomous vehicle to be able to master complex traffic situations potentially involving multiple road-users, e.g., roundabouts, intersections, crossings, lane-changes, in a safe and efficient way, the vehicle needs to first be able to interpret the current traffic scene. Then, based on that interpretation and its associated uncertainty, it has to make rational and safe decisions both of discrete nature as well as of continuous nature which together form the future motion of the vehicle. The focus in this project has been on the latter of these challenges. To perform the necessary decision making and motion planning for these complex situations, the system needs to

- be able to take into account uncertainties in the perception and the predictions about the future.
- exploit interactions between the ego vehicle and surrounding road-users, i.e., during planning take into account how the ego vehicle´s trajectory will affect other road-users' decisions. This is of particular interest for heavy vehicles, both in order to get the necessary space as well as for energy efficiency.
- be able to take joint discrete and continuous motion decisions, exploiting and taking into account traffic rules.

The overall objective of this project has been to develop a joint decision-making and motion-planning mechanism that enables an autonomous heavy vehicle (heavy-duty truck or bus) to operate in urban and suburban traffic in a safe, trustworthy and efficient way while not exceeding the computational budget. The system should take uncertainties into account in the predictions of other road users´ future behavior, multiple road-users (including vulnerable), and traffic rules. The project has been organized around a Ph.D. student project which was transferred into a post-doc project after the Ph.D. student decided to move to industry as an engineer.

2. Sammanfattning på svenska

Att manövrera ett tungt fordon säkert i komplexa trafiksituationer är en utmanande uppgift, både för mänskliga förare och autonoma system. Fordonet måste kunna tolka trafiksituationen, hantera osäkerheter i kännedomen om omgivande trafikanter och fatta beslut som kombinerar diskreta val med val av kontinuerliga styrsignaler. Fokus för detta projekt har varit att utveckla mekanismer för beslutsfattande och rörelseplanering för autonoma tunga fordon, där osäkerhet i fordonets och omgivningens beteende måste hanteras på ett säkert sätt utan att överskrida tillgängliga beräkningsresurser.
Speciellt har projektet fokuserat på hur osäkerhet kan modelleras och användas i rörelseplanering, samt hur systemet under drift kan samla in information och anpassa

framtida planer för att förbättra prestanda. Trots personalrelaterade utmaningar uppnåddes huvuddelen av målen. Några aspekter, som ocklusioner, behandlades dock inte som planerat. Däremot utökades projektet med nya komponenter såsom inlärning och robust reglering. Bland projektets viktigaste resultat finns:

- Ett tvåstegsplaneringsramverk för osäkra scenarier med flera trafikanter i motorvägsmiljö, baserat på POMDP i kombination med scenariobaserad prediktiv reglering.
- Ett robust ramverk för rörelseplanering i miljöer med delvis kända störningar, integrerat med tub-baserad robust reglering.
- En metod för inlärningsbaserad anpassning av rörelseprimitiver i realtid, vilket minskar konservatism utan att tumma på säkerhet.
- Ett avancerat prediktivt reglersystem som använder sig av mixed-integer prediktiv reglering, testat på ett verkligt fordon, för reglerproblem där sensoregenskaperna är starkt tillståndsberoende. I det här specifika fallet studerades LiDAR för användning vid skattning av trailervinklar i ett system bestående av en lastbil med dolly och trailer.
- En lösning baserad på reinforcement learning och imitation learning för reglering och kollisionsundvikning för en autonom lastbil med släp i stadsmiljö presenterades.

Resultaten har både teoretiskt och praktiskt bidragit till utvecklingen av tillförlitliga autonoma tunga fordon i komplexa miljöer och kan, som visas av våra resultat, appliceras på olika typer av autonoma plattformar.

3. Background

Autonomous vehicles are expected to be an important part of the future transport system, a technology that promises efficient and flexible transport of both goods and people. Combined with other types of load carriers such as trains, trams, ships, and manually operated vehicles, autonomous vehicles could offer a safe, affordable, accessible, and sustainable transport system, an important step towards a sustainable society in general. The focus in this project is autonomous vehicles operating in urban and suburban areas. Transport of goods and people in urban and suburban areas is a type of transport that in particular would benefit from the increased flexibility since this type of transport largely is characterized by pick-up and delivery of goods and passengers at multiple places during a driving shift. The pick-up and delivery can be performed at a fixed timetable, e.g., buses in scheduled services or with a flexible schedule where pick-up and delivery locations and times vary over time, e.g., home deliveries. Autonomous driving in areas that are not well-protected from the outside poses new challenges compared to driving in areas such as harbors and mines. One additional challenge is that there are more surrounding road users which are not trained to interact with the autonomous systems. A key challenge in this project, and in autonomous driving in general, is that these surrounding road users' future intentions and motions are typically not known and are considered uncertain. Furthermore, there are also important sources of uncertainty stemming from the environment, such as unknown road friction, wind and water currents which are highly relevant, depending on the platform, to autonomous systems. An important principal challenge in this project has been to be able to compute safe motion plans, optimizing important aspects such as energy in an uncertain environment and to do this sufficiently well while not exceeding the computational resources. Furthermore, even though our initial primary focus was heavy vehicles, many results generalize which has been illustrated on several highly relevant autonomous platforms.

4. Purpose, research questions and method

The purpose with this project has been to develop frameworks, theory, and algorithms for motion planning under uncertainty, where the considered uncertainty primarily stems from the surrounding road users or the environment. An important aspect in the work has been to in more detail take into account knowledge that can be used to improve the performance of a motion plan despite the challenges introduced by uncertainty. Even though the main target application is heavy-duty trucks, the value of the produced results is not limited to that application, as illustrated in numerical experiments performed within this project. The overarching research question investigated is: How can efficient motion planning aiming to reduce the impact of uncertainties in the problem be achieved?
The method used in the work has been to consider different ways of modelling and representing the uncertainty in ways that can be used for efficient and safe motion planning. Furthermore, it has been considered how data from the system can be used to improve the knowledge of the system during runtime and thereby to reduce the remaining uncertainty, again with the aim to obtain high-performing motion plans.

5. Objective

Condensed project objectives from the application are:

I. Develop a functional system architecture and a decision-enforcing control scheme for joint decision making and motion planning embracing multiple discrete decisions and trajectory alternatives.
II. Develop a motion-planning and decision-making mechanism for environments with multiple surrounding road users with non-trivial uncertainty in their predicted future motions.
III. Exploit interactions with other vehicles during planning to increase efficiency and reduce emissions, as well as increase the possibility to solve crowded traffic situations.
IV. Include traffic rules, map data and potential hazards such as occluded areas in the motion-planning and decision-making mechanism for increased operation safety and trustworthiness.
V. Demonstrate in real autonomous heavy vehicle.

Because of staffing problems during the project, not all the initial objectives have been met to the extent initially planned. For example, occlusions have not been considered, and the results have not been demonstrated in a real autonomous heavy vehicle to the extent initially planned. Furthermore, other aspects were expanded, e.g., uncertainty from the environment was added, robust control integrated with the motion-planning layer was added, and learning was considered as an additional means of handling uncertainty. In general, the core part of the initial project goals has been considered, but with a somewhat different angle compared to the plan. Given the unforeseen complications out of our control, the level of goal fulfillment is still considered very good.

6. Results and deliverables

An important scenario considered in this work considering the main challenge with many surrounding agents is highway driving where the motions of the surrounding vehicles are considered uncertain. This important problem has been considered in one conference paper and in one manuscript under preparation for submission. The conference paper presents a new combined two-step approach for this problem, where a partially observable Markov decision process (POMDP) is tightly coupled with a scenario model predictive control (SCMPC) step. To generate the scenarios in the SCMPC step, the solution to the POMDP is used together with a novel scenario-reduction procedure, which selects a small representative subset of all scenarios considered in the POMDP. The resulting planner is evaluated in a simulation study where the impact of the two-step approach and the scenario-reduction method is shown. In the follow-up manuscript, a novel scenario-clustering algorithm is proposed, which robustly clusters the nodes of the belief tree in the POMDP thus reducing its node density. Furthermore, it is analytically proved that all scenarios belonging to any sequence of cluster nodes from a root node to leaf node, belong to the same homotopy class. The second novelty is presented in employing the reduced belief tree in an SMPC algorithm with suitably tightened constraints to ensure safe navigation while considering the uncertainty generated due to scenario reduction. The SMPC is capable of exploring the continuous action space and hence further refines the clustered trajectories obtained from the POMDP solver. The effectiveness of the proposed composite algorithm is demonstrated through a simulation experiment. The above outlined work contributes to fulfilling objectives I, II, and III.

Another considered scenario of importance is motion planning when there are partially known disturbances and how this knowledge can be incorporated into a lattice-based motion planner in an overall safe way. This work considers unstructured environments known to the system in the form of a map. More concretely, this is achieved by introducing a disturbance-parametrized robust lattice-based motion planning framework. Furthermore, this framework includes how the robustification of the motion plan can be tightly connected to a tube-based robust motion-executing controller. It is shown in a simulated scenario of high practical relevance how this combination can be used to safely improve performance of motion planning and motion execution. The above outlined work contributes to fulfilling objectives I-IV.

Another strategy for handling uncertainty is to collect more information during on-line operation and adapt future motion plans according to this. In a work under review, we introduce the possibility to adapt the motion primitives in a lattice-based motion planner with the purpose to improve performance by reducing conservativeness. It is shown that the motion plan obtained from this learning process approaches the resolution-optimal plan as time approaches infinity. The process is done in a robust fashion with support from tubes, guaranteeing safe motions. The above outlined work contributes to fulfilling Objective I, and variants of II-IV.

The motion planning problem for heavy-duty vehicles in urban areas is a highly nonlinear problem where the traditional separation principle between control and state estimation in general does not hold. In fact, it is often very relevant to select motions such that the states can be properly estimated in order to achieve an acceptable overall performance. One special case of high relevance for the heavy-duty application is to take into account potential variations in obtained information from sensors used to measure trailer angles. In particular, this is of high relevance when advanced sensors such as LiDARs are used, as in our work. To introduce advanced mixed-integer estimation-aware model predictive control and to test this on a real vehicle is the topic of one of our results in this project, contributing to fulfilling objectives I, IV, and V.

Additionally, in a collaboration with University of California San Diego (UCSD) reinforcement learning (RL) and imitation learning (IL) have been integrated to enable autonomous navigation of a tractor–trailer system in complex urban environments. In this work, an RL expert policy is trained using a curriculum tailored to articulated vehicles and with privileged inputs, allowing it to make multiple discrete decisions, explore trajectory alternatives, and interact safely with road users under uncertainty. The reward design implicitly enforces traffic rules and enables emergent interaction-aware behavior without requiring explicit trajectory prediction for surrounding agents. This expert policy is distilled into a sensor-based IL agent, resulting in a robust, real-time controller that relies solely on onboard sensor data. Validated in simulation, the learned policy demonstrates reliable performance in dense urban traffic, including safe handling of intersections, roundabouts, and traffic lights. This work contributes to fulfilling objectives I-IV.

The results that this project leaves behind contribute to the overall objectives of the FFI program:

- *increase the Swedish capacity for research and innovation, thereby ensuring competitiveness and jobs in the field of vehicle industry:* the project has made important advances in motion planning under uncertainty, it has enabled collaboration with UCSD, and it has introduced two foreign post-docs to Swedish industry of which one decided to stay and is today employed by Epiroc.
- *develop internationally interconnected and competitive research and innovation environments in Sweden:* Also here, the research collaborations with IIIT Hyderabad and

UCSD as well as the integration of post-docs with foreign background has contributed to reach this objective.

- *promote cooperation between industry, universities and higher education institutions:* The project has maintained and strengthened the collaboration between the Division of Automatic Control at Linköping university and Scania CV. Furthermore, it has opened up a new collaboration between Scania CV and UCSD in USA.

Furthermore, the project has also contributed to the following sub-program objectives:

- *Automated vehicles in the transportation system:* All results of this project contribute to this goal on the fundamental level.
- *Intelligent and collision avoidance systems:* All results of this project contribute to this goal on the fundamental level. In particular, intelligence is developed in the direction that the systems make better use of available information to safely avoid collisions and learning is used to automatically improve performance while respecting safety.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Has been disseminated through publications, collaboration with the industry partner, and seminars.
Be passed on to other advanced technological development projects	X	
Be passed on to product development projects	?	It is hard to judge how the developed results, and in which form, will be transferred to products.
Introduced on the market	?	A system with functionality similar to what is presented in this work is very likely to be introduced to the market, but it is difficult to say to what extent it will be based on the results of this project.
Used in investigations / regulatory / licensing / political decisions		

There is a strong connection to other ongoing research projects linked to the project leader, which has been beneficial. For example, the methods considered have been generalized to other types of vehicles. It has also strongly contributed to the start of a new research project within the Vinnova competence center SEDDIT.

7.2 Publications

The list below includes works that have been supported by this project:

C. Hynén Ulfsjöö and D. Axehill. On Integrating POMDP and Scenario MPC for Planning under Uncertainty–with Applications to Highway Driving. In Proceedings of the 2022 IEEE Intelligent Vehicles Symposium (IV), Aachen, Germany, June 2022.

A. Dhar, C. Hynén Ulfsjöö, J. Löfberg, and D. Axehill. Disturbance-parametrized robust lattice-based motion planning. IEEE Transactions on Intelligent Vehicles, 9(1):3034-3046, Jan. 2024.

A. Dhar, S. Mishra, S. Roy, and D. Axehill. Adaptive Lattice-based Motion Planning. Under review for possible publication in journal, manuscript available at https://arxiv.org/abs/2508.02350. 2025.

A. Dhar, C. Hynén Ulfsjöö, S. Amrr, and D. Axehill. Tightly coupled POMDP and Scenario MPC for Planning under Uncertainty Abhishek. Under preparation for submission to journal. 2025.

O. Ljungqvist, C. Hynén Ulfsjöö, D. Axehill, H. Pettersson, and Johan Löfberg. Estimation-aware model predictive path-following control for a general 2-trailer with a car-like tractor. Under preparation for submission to journal. 2025.

Y. Zhi, Y. Emre Sahin, O. Palfelt, S. Manzinger, M. Yip. Learn to Drive Tractor–Trailer Systems in Urban Scenarios with Reinforcement Learning and Imitation Learning. Under preparation for submission to conference. 2025.

8. Conclusions and future research

The project's contributions lie in the area of motion planning and decision-making for autonomous heavy vehicles, with particular emphasis on uncertainties related to surrounding traffic participants, uncertain ego-vehicle dynamics, and uncertain environmental conditions. The results of the project include several distinct contributions in this overarching direction. One focus has been on developing methods that enable safe and computationally efficient motion planning in the presence of non-trivial uncertainty about the future behavior of the environment. Several new methods for handling such uncertainty in highway scenarios have been developed, including two-step strategies that combine decision-making based on POMDPs with scenario-based model predictive control, as well as clustering methods to reduce the complexity of decision models without compromising safety. Furthermore, the project has presented a robust framework for motion planning under partially known disturbances, such as wind and friction, where robustness is explicitly integrated into a lattice-based motion planning framework in combination with a robust tube-based control system. It is shown that the motion planner is able to make use of this additional information to make higher-performing motion plans. Another contribution with the purpose to handle uncertainty is a learning-based approach where the system adapts its motion primitives during operation to reduce conservatism in planning. This process is carried out in a robust manner with support from tube-based control and demonstrates asymptotic convergence toward the resolution-optimal plan. This enables improved performance without compromising safety. Moreover, it has been shown how control and motion planners can make active use of knowledge about sensors. In particular, a mixed-integer estimation-aware model predictive control system for heavy vehicles has been presented and demonstrated on a real vehicle. Finally, a different type of solution based on RL and IL has been presented to solve the urban autonomous tractor-trailer control and collision avoidance problem.

Examples of relevant future research include further developing the proposed two-step framework to handle additional types of uncertainty and more complex scenarios, such as traffic rules and occlusion. Another interesting direction is the deeper integration of learning and data-driven models with real-time motion planning. Estimation-aware control strongly relates to the joint planning of estimation and control, which is also a promising area for future study. Finally, a natural continuation is to transfer the results to more platforms and to further increase the level of real-time integration and practical applicability.

9. Participating parties and contact persons

The participating parties are the Division of Automatic Control at Linköping University, with contact person Daniel Axehill, and Scania CV AB, with contact person Henrik Pettersson.