Robust Control Design for Automated Vehicles with Guaranteed Performances

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The research activities within the four-year-long project "Robust Control Design for Automated Vehicles with Guaranteed Performances" have been focused on creating control theory and methods for the adequate analysis and design methodology with guaranteed performances to meet the increased requirements of control solutions targeting high-complexity applications, such as automated vehicle and traffic systems. The research has been based on the preliminary concept that the robust optimal control theory can provide efficient methods for the solution on guaranteed performance problem, while in the formulation of the modeling, analysis, design process the non-conventional control systems can be considered. The achieved scientific results have reinforced the preliminary concept, and consequently, the advantages of the robust control design and the non-conventional control solutions have been simultaneously achieved through the automated vehicle applications.

Due to the high variety of automated vehicle control problems, different control design frameworks and analysis methods have been formed during the project. In all formulations, the consideration of safety requirements for vehicle control systems, i.e., the most important aspects of the design, has been highlighted. The developed methods fit to the non-conventional control systems applied in the automated vehicle control systems. Their operation in the design method of the robust control has been involved, with which guarantees on the operation of the complex control system under multi-agent context of automated vehicles have been achieved. In spite of the different types of vehicle control problems and the applied non-conventional agents, the project has resulted in general frameworks with which the performance level and the computational time of the controlled system can be evaluated in a unified manner.

The results of the research can be divided into three parts, such as (1) the formulation of the control design framework, (2) the development of the robust control synthesis methods, (3) the application of the method for automated vehicle control design problems. The scientific achievements have been published in a Springer monograph, in a book chapter, in C1, D1 and Q1-ranked journal papers. Moreover, several dissertations have been submitted and defended successfully, e.g., D.Sc. thesis, habilitation thesis, Ph.D. thesis, and M.Sc./B.Sc. theses.

Result 1: Formulation of the hierarchical control design framework

Hierarchical control design frameworks for systems with non-conventional agents, e.g., neural networks, have been developed. The design framework contains three elements, involving the robust controller, the non-conventional agent and the supervisor. In the design frameworks the characteristics of the non-conventional agents through input-output signals, as uncertain systems have been considered. The aim of the frameworks is to guarantee selected performance requirements, which is achieved through the control framework.

Depending on the structure of the automated vehicle control problems, three types of supervisory control architectures have been proposed. (1) The non-conventional agent is incorporated as a part of the reference signal generation. (2) The non-conventional agent is considered to be known and it is incorporated in the control loop as a controller. (3) The non-conventional agent in the control loop is unknown and a learning process on the control system for achieving high performance operation is carried out. In all types of architectures, the specifications for performance requirements in the supervisor have been formulated.

The relationships between the robust control design, the learning process and the parameter selection in the supervisor have also been examined for improving the performance level of the hierarchical control strategy. The impact of some supervisor parameters on the robust control performance level and on the robustness domain have been analyzed. It has been proposed an optimal strategy for supervisor parameter selection that has benefits on the performance level on the entire control structure.

The advantages of the proposed novel design framework have been evaluated through comparisons to the concurrent methods. In spite of the various results in the field of integrating learning and control, a limitation of the results is that most of them have fixed structures on the control design, or on the learning process. Since modularity is a crucial aspect of control design for autonomous ground vehicles, the control design method is proposed to employ independent design of both learning-based and robust control. Although the concurrent learning-based Model Predictive Control (LMPC) methods are able to provide solutions on the highly nonlinear control problems, their formulations require centralized solutions in one complex computation algorithm. It has been shown that the LMPC controllers can be reformulated into the proposed hierarchical control design framework, and thus, the complex problem containing learning feature, terminal set and objective with constraints can be separated. The effectiveness of the hierarchical framework has been reinforced through comparative simulations, too. The contribution of the research to the field of the control design is a safe algorithm that requires only low online computation efforts, compared to the concurrent methods.

Result 2: Development of robust control synthesis methods

Robust control synthesis methods in the proposed hierarchical framework have been developed, involving the subtasks of modeling, control synthesis, observer synthesis and stability analysis. Two different control-oriented modeling methods have been provided in order to handle wide range of different control design problems within the hierarchical framework. Robust optimal control synthesis method has been developed for each model.

First, linear formulation method for the approximation of non-conventional control agent, i.e., neural networks, has been proposed. The motivation of the work is to provide analysis methods, with which the neural networks in vehicle control systems using linear and parameter-varying methods can be evaluated. The aim of the method is to approximate the operation of the non-conventional agent through a set of linear systems. The resulted set of systems is used for characterizing the non-conventional agent, i.e., its uncertainty domain in the robust control design can be involved. Scenario-optimization-based analysis method on stability and tracking performance issues on the closed-loop system with non-conventional agent, based on the provided approximation has been developed.

Second, method on the novel control-oriented formulation of nonlinear system dynamics through learning-based closed-loop matching has been also developed. The proposed solution is able to provide an enhanced description without the exact formulation of the physical system. It results in a linearized model, incorporating in the learning-based agent and the nonlinear system itself. It has also been developed a data aided analysis method on the learning-based agent, with which safe operation with guaranteed performances can be evaluated, using Bayesian probability-based techniques. The resulted linearized model of the nonlinear system has been used for the design of the robust control through H-infinity method. In the design process, the linearized model with an uncertainty structure has been involved, together with the approximation method of the uncertain term.

Moreover, weighting strategy for robust design of a vehicle-dynamic observer has been proposed. In the method the weighting strategy through a Riccati-based optimization process has been incorporated, which has created a balance between the output of the robust observer and the non-conventional (e.g., learning-based) observer. It has led to an extension of the conventional minimax-based observer design process with the rules in supervisor. The weighting strategy in the design of robust observer for the high-precision estimation of vehicle lateral velocity has been incorporated.

The provided modeling, control and observer design methods have been used for developing analysis method on the closed-loop system. Consequently, it is developed a novel data-aided state-space model augmentation method, in which the neural networks with a set of discrete linear systems are approximated, by calculating the derivative of the neural network at different operation points in the operating domain. The resulted system has a polytopic LPV form that is the approximate representation of the closed-loop with the hierarchical control. It is developed a parameter-memorized approach for the stability analysis of the polytopic LPV system.

Result 3: Application of the method for automated vehicle control design problems

A generalized motion control algorithm has been proposed for automated road vehicles, that has been applied to energy-efficient motion control problems and to handle interactions among vehicles. The purposes of the control strategies are to guarantee collision-free motion of the vehicles, and moreover to improve economy and traveling time performance levels.

Energy-efficient cruise control for automated vehicles have been developed, that has been able to solve the complex cruising problem with several performances for automated vehicles. The proposed method provides theoretical guarantees on safety performances, and it is less dependent on the degradation of the communicated data from the external information sources. The energy-efficient and safe motion has been illustrated through simulation examples using real highway information, e.g., terrain characteristics and speed limits. Some of these results have been implemented in a test mobile application that provides speed assistance to the driver for achieving energy-efficient cruising.

Centralized and independent configurations of the hierarchical control strategy have been formulated for handling the interactions of automated vehicles. In case of centralized configuration all of the vehicles are controlled by one supervisor and one learning-based agent. In case of independent configuration each vehicle has its own motion control and the vehicles are interconnected through limited number of signals. The optimization problem in each supervisor has been formed and the requested computational effort has been analyzed through simulation examples. It has been shown that the independent configuration is able to approximate the performance level of the centralized configuration, and using independent configuration significantly lower computational effort is requested. The effectiveness of the proposed method has been evaluated through simulation examples, such as in urban regions and in highway environments. The effectiveness has been also analyzed for high number of vehicles through comparative simulations using high-fidelity traffic simulator. The resulted method has improved the traffic flow more significantly, compared to some of the concurrent cruise control methods. Moreover, the operation of the independent configuration on a small-scaled indoor test vehicle platform has also been presented.

In the hierarchical control strategy, the task of route selection has been also involved for improving the capability of the automated vehicles. The main goal of this extension has been to determine a feasible vehicle trajectory that has satisfied the several predefined limitations against the vehicle. It has been induced the improved reformulation of the supervisor, i.e., further constraints and terms in its objective have been involved. The extension has been carried out in relation to different vehicle control problems. The safe motion of automated vehicles in coordination with aerial vehicles has been solved through the proposed hierarchical control strategy, which task has required the consideration of time constraints in the control. Moreover, an algorithm for achieving safe and ethical automated vehicle motion has been developed and the formulation of the algorithm has fitted to the optimization problem in the supervisor.

The results of the research have been published in different forms, such as in dissertations, monographs, high-quality international journal and conference publications.

- Outstanding achievement of the research is the published **Springer monograph** "Control of Variable-Geometry Vehicle Suspensions", which contains some results of the project in the context of vehicle suspension systems. Another Springer **book chapter** has been also published that contains theoretical achievements of the project: "Guaranteed Performances for Learning-Based Control Systems using Robust Control Theory" in Springer book "Deep Learning for Unmanned Systems".
- More dissertations have been submitted and successfully defended, connected to the topic of the project. Balázs Németh (principal investigator) has defended his **D.Sc. thesis** "Analysis and Synthesis Methods for the Optimal Design of Control Systems in Automated Vehicles", submitted to the Hungarian Academy of Sciences. He has also defended his **habilitation thesis** "Robust control design for vehicle systems with learning features", submitted to Budapest University of Technology and Economics. Tamás Hegedűs has also defended his **Ph.D. thesis** "Decision and control methods for overtaking strategies of autonomous vehicles" successfully, submitted to Budapest University of Technology and Economics. Moreover, 4 M.Sc. theses (A. Lelkó, Z. Bagoly, K. Papp, M. Kopasz), 1 B.Sc. thesis and TDK work (by O. Mudra), covering the works of some students involved in the project are presented.
- High-quality international **journal papers** have been published during the project. One paper in the **C1-ranked** IEEE Transactions on Vehicular Technology has been published. One paper in the **D1-ranked** Control Engineering Practice has been published, another paper

to the D1-ranked IEEE Transactions on Intelligent Transportation Systems has been submitted (under review, third round). One paper in the **Q1-ranked** Springer European Transport Research Review has been published. Moreover, four papers in further Q1-ranked, and two papers Q2-ranked journals have been published, too.

- Furthermore, altogether 34 international **conference papers** have been already presented and published during the project, and one another is under review. Most of the international conferences have been organized by IEEE, International Federation of Automatic Control (IFAC) and International Association for Vehicle System Dynamics (IAVSD).

The high number of publications and the successfully defended dissertations demonstrate the recognition of the project achievements in Hungary and in international context, too.