A new generation of algorithms for modern powertrain control

Publik rapport

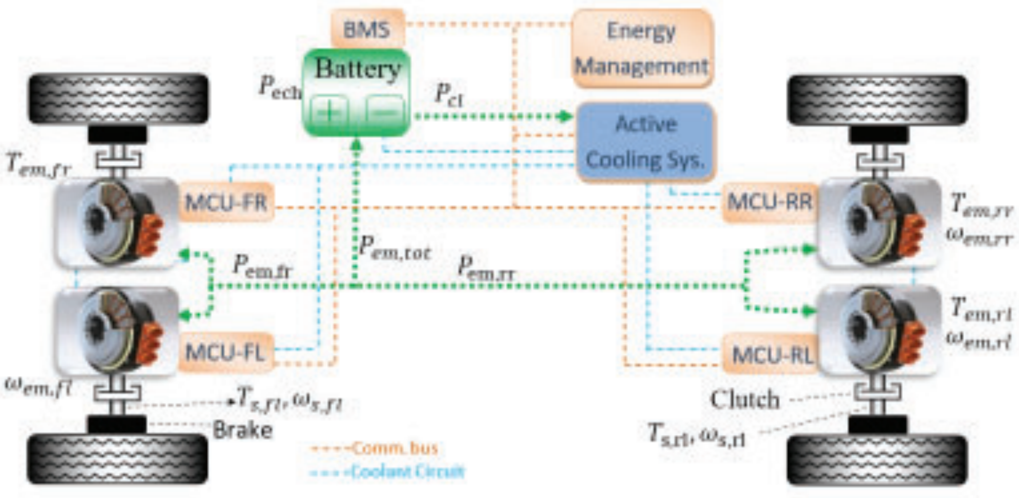

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Table of Contents

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1 Summary

Modern powertrains are increasingly complex. They typically include an internal combustion engine, electric machines, batteries, and exhaust-after-treatment systems, with increasingly complex components. Moreover, current control systems in charge of maximizing the performance of the powertrain have a fairly simple architecture. This architecture is not designed to exploit the models of the components, the available information on the driving mission and traffic, nor the growing amount of data available from cloud connections. Moreover, achieving high performance using this simple control architecture is notoriously difficult, and requires an expensive calibration.

The control systems in future electrified vehicles need to be able to adapt their behaviour dynamically depending on driving situation, to ensure minimal energy consumption and to meet the expectations of the users. To reach these targets, the control strategies need to proactively act on predictions of the future driving mission, made possible by the addition of sensors such as radar, camera, on-board maps, as well as off-board sensors made available through cloud connections. This requires efficient control methods being able to utilize both the knowledge of the system itself, and the ability to incorporate the predictions of the future.

In this project, we have addressed these issues by developing a new concept of powertrain control. Novel model-based optimal control algorithms have been developed, dedicated to a deployment on the limited computer architectures that are affordable for the vehicle industry. These novel control tools are intended to be equipped with computationally inexpensive and flexible online-tuning capabilities.

The project started in December 2018 and ended in November 2023. The project participants are Volvo Cars and Chalmers University, with Volvo Cars being the coordinator.

2 Executive summary in Swedish

Moderna drivlinor blir alltmer komplexa. De inkluderar vanligtvis en förbränningsmotor, elektriska maskiner, batterier och avgasefterbehandlingssystem, med alltmer komplexa komponenter. Dessutom har nuvarande styrsystem som ansvarar för att maximera drivlinans prestanda en ganska enkel arkitektur. Denna arkitektur är inte utformad för att utnyttja modellerna av komponenterna, den tillgängliga informationen om köruppdraget och trafiken, och inte heller den växande mängden data som finns tillgänglig från molnanslutningar. Dessutom är det svårt att uppnå hög prestanda med denna enkla kontrollarkitektur, och det kräver en kostsam kalibrering.

Styrsystemen i framtida elektrifierade fordon måste kunna anpassa sina beteenden dynamiskt beroende på körsituationen, för att säkerställa minimal energiförbrukning och uppfylla användarnas förväntningar. För att nå dessa mål måste styrstrategierna proaktivt agera på förutsägelser om den framtida köruppdraget, vilket möjliggörs genom tillägg av sensorer såsom radar, kamera, kartdata samt off-board-sensorer som görs tillgängliga genom molnanslutningar. Detta kräver effektiva styrmetoder som kan utnyttja både kunskapen om systemet självt och inkludera prediktioner.

I detta projekt har vi adresserat dessa problem genom att utveckla ett nytt koncept för drivlinestyrning. Nya modellbaserade optimala styralgoritmer har utvecklats, anpassade för implementering på de beräkningsmässigt begränsade styrenheter som används

inom fordonsindustrin. Dessa nya reglerfunktioner avses utvecklas för att använda beräkningsmässigt billiga och flexibla online funktioner.

Projektet startade i december 2018 och avslutades i november 2023. Projektets deltagare är Volvo Cars och Chalmers University, med Volvo Cars som koordinator.

3 Background

Along with the revolutionary introduction of electrification in the modern car industry, driving dynamics enhancement thanks to the electric motors on-board has been widely studied and implemented. However, little research has been done considering energy efficiency while optimizing the driving dynamics. A common method used by researchers, is to improve energy efficiency and driving dynamics respectively and sequentially, but not how to balance in-between them at the same time. It is not trivial to invent novel algorithms that provide the premium driving dynamics in an electric vehicle, with enhanced energy efficiency as well.

To fit the novel algorithms within an already highly complex system, i.e. a passenger car with several electric motors, it will require a brand-new vehicle motion control architecture design. This is also stressed by the need to support many different propulsion configurations, with electric motors on different axles and wheels. This would also mean that the design should be based on certain existing functionalities on-board the vehicle which cannot be easily changed, such as vehicle stability control systems. A cross-functional performance is thereafter achieved for the optimal balance between energy efficiency and driving dynamics.

It is commonly accepted that energy-management in future vehicles will require supervisory control strategies that are much more advanced than the ones we have in vehicles today. These strategies will need to coordinate the different energy-related subsystems in the vehicle to exploit the full potential of the powertrain. They will have to react quickly to complex information streaming from the car sensors and the environment, adjust flexibly to the driving mission and driving conditions, while managing the increasingly complex powertrains and fulfil a stringent legislation. Moreover, they will need to achieve these tasks while avoiding excessive calibration. The requirements that the next generation of a supervisory controller need to fulfil are:

- A natural and straightforward inclusion of data and predictive information (driving mission, traffic information, cloud data, etc.)
- An optimized energy efficiency and limited emissions, i.e. an improved trade-off between the conflicting objectives, via a better exploitation of the dynamics and capabilities of each subsystem
- A natural inclusion of higher-level strategies, such as route-based discharge of high voltage batteries, either computed on-board or off-board (cloud)
- A straightforward management of the physical limitations and constraints
- A decreased calibration effort of the control system for each powertrain variant
- An improved handling of powertrain variants via generic and flexible control structures

In this project, we develop algorithms and software tools to fulfil these requirements. It is worth to mention that the real-time capability in terms of computation efficiency is critical in applying the optimization algorithm in a vehicle. Model-based control techniques for powertrains require modelling efforts at the component level. While modelling incurs a cost, its systematic deployment also offers cost reductions opportunities at the level of the vehicle development program. Therefore, a balance between modelling complexity and computational efficiency is investigated in this project.

4 Purpose, research questions and method

The goal of this project is to develop and implement a model-based framework for online supervisory control that achieves an optimal control allocation (continuous decisions) and actuator selection (discrete decisions) in real time, so as to provide the best trade-off between the competing control objectives: energy consumption, emissions, drivability and vehicle dynamics.

Hence, this project aims at developing real-time model-based numerical optimal control algorithms tailored to vehicle and powertrain control, which could be implemented in a production-type electronic control unit (ECU). Our research hypotheses are the following:

1. Model-based optimal control tools can improve the performance of modern powertrains, energy efficiency, and reduce the calibration effort.
2. These tools can be tailored for a real-time deployment on modern ECUs, or on the next generation of ECUs (or in the future as a cloud solution).

The research challenges that we need to tackle are:

1. The development of computational methods for real-time implementation on ECUs with limited computation performance.
2. The extension of the current state-of-the-art on real-time algorithms to mixed-integer problems, which are central in advanced powertrain control.
3. The integration of the algorithms with the many control loops already present in current ECUs.

The main approach in tackling the aforementioned challenges, is to use optimization-based predictive controllers, e.g., real-time model predictive control. Mixed-integer optimization toolboxes are also investigated to determine the optimal solution with minimum computation resources. The offline optimization results and online closed-loop optimal control implementation using high-fidelity vehicle simulation model will be compared and analyzed so that global optimum is guaranteed.

To develop and evaluate candidate algorithms, a virtual vehicle simulation environment will be utilized. The most promising algorithms will then be implemented in a high-fidelity virtual simulation environment to evaluate its real-time capability, suitable for a production type ECU.

5 Goal

The overall objective of the project is to design and implement advanced model-based optimal control strategies in hardware available in production vehicles, and provide a decent base-line for the online fine-tuning capabilities. It will provide the possibility of achieving nearly optimal performance of the future’s complex powertrains, reducing the calibration complexity, and provide support for handling of multiple powertrain variants. The strategic goals of the project are:

- Increase the energy efficiency of future complex drivetrains
- Reduce control design and calibration costs
- Realize the potential of cloud-connected cars in control and calibration.

This project aims to expand the knowledge within Volvo Cars on how to design, implement and analyze advanced model-based controllers that explicitly include predictions and systems constraints. It attempts to specify which problems can be

solved with the current technology, and how the ECU may need to evolve to make the treatment of these problems feasible. The main focus for this project is on propulsive systems but the aim is to distribute the developed knowledge within Volvo Cars. Indeed, the methods developed in this project will be fairly generic and apply to several problems existing at Volvo.
Specific outcomes of the project are expected to be:

- The development and implementation of a supervisory control structure, explicitly including predictive capabilities of both the on-board sensors and the cloud.
- Development of algorithms tailored to the requirements of production type ECUs
- Creation of know-how within industry and academia on which optimal-control problems can be solved in vehicles.
- Implementation and demonstration of the resulting controller in vehicle and/or hardware-in-the-loop (HIL) tests.
- Doctoral theses at Chalmers
- Scientific publications in journals as well as conferences.
- M.Sc theses

As mentioned in project change request on 2022-07-07, the cloud-related parts as well as the implementation in the target environment (ECU in vehicle or HIL) were removed due to changes in the Volvo product plan, which resulted in changed focus and delays for the project. Instead, the goal was reduced to implement the best algorithms in a high-fidelity simulation environment.

6 Result and achievement

The project started with the hybrid electric vehicle as the intended powertrain configuration, with one internal combustion engine (ICE) and one electric motor. The first scientific paper published in IEEE Transactions on Intelligent Transportation Systems, presents numerical strategies for a computationally efficient energy management system that co-optimizes the power split and gear selection of a hybrid electric vehicle (HEV). We formulate a mixed-integer optimal control problem (MIOCP) that is transcribed using multiple-shooting into a mixed-integer nonlinear program (MINLP) and then solved by nonlinear model predictive control. We present two different numerical strategies, a Selective Relaxation Approach (SRA), which decomposes the MINLP into several subproblems, and a Round-n-Search Approach (RSA), which is an enhancement of the known ‘relax-n-round’ strategy. Subsequently, the resulting algorithmic performance and optimality of the solution of the proposed strategies are analyzed against two benchmark strategies; one using rule-based gear selection, which is typically used in production vehicles, and the other using dynamic programming (DP), which provides a global optimum of a quantized version of the MINLP. The results show that both SRA and RSA enable about 2.5% energy reduction compared to the rule-based strategy, while still being within 1% of the DP solution. Moreover, for the case studied RSA takes about 35% less mean computation time compared to SRA, while both SRA and RSA being about 99 times faster than DP. Furthermore, both SRA and RSA were able to overcome the infeasibilities encountered by a typical rounding strategy under different drive cycles. The results show the computational benefit of the proposed strategies, as well as the energy saving possibility of co-optimization strategies in which actuator dynamics are explicitly included.

From the second half of the project, with the shift of focus area of the project from HEVs to EVs, the model and optimal control algorithm were developed and applied to a prototype EV model with four electric motors. The controller was then adapted to the motors as well as transmission dynamics. In the second journal article, a novel approach to energy management leveraging mixed-integer model predictive control (MI-MPC) was presented. First, an energy management strategy is proposed to co-optimize torque allocation and decoupling decisions, minimizing both energy consumption and frequency of clutch engagement changes. Secondly, to address the computational challenge inherent in solving the resultant mixed-integer (MI) problem, a bi-level programming approach is proposed. In this approach, the torque allocation subproblem is efficiently solved at the inner level with explicit analytical solution, while the outer level optimizes clutch decisions through implicit dynamic programming (i-DP). Evaluation in a high-fidelity virtual environment shows energy savings exceeding 4% compared to heuristic controllers prevalent in modern electric vehicles. Also, the i-DP based solution process guarantees finding the global optimum for the MI problem in every MPC update. The presented strategy shows an average solution time of about 1 ms in a personal computer, conceptually indicating its real-time capability and potential integration in multi-motor electric vehicles.

In the meantime, the benefits of including actuator and thermal dynamics in torque allocation strategies for BEV energy consumption was investigated. Plant and control models for thermal dynamics and simulation setup were developed. Model order reduction was used to simplify the thermal models and the resulting optimal control problem was analyzed offline using Dynamic Programming (DP). Results show the possibility of achieving an additional energy savings of around 2%~4% which needs further investigation to quantify its real-time feasibility. A patent application has been filed for the technical concept that resulted from this work. Similarly, a space-sampled Economic Model Predictive Control (EMPC) approach to jointly minimize total energy consumption of an electric vehicle (EV) and track both longitudinal velocity and path curvature reference trajectories was developed. A single-track vehicle model is constrained to the mild accelerations as the operational design domain (ODD), and energy consumption is modelled explicitly including power losses of electric machines as well as tire rolling resistance losses. Simulations with the high-fidelity simulator IPG CarMaker show the trade-off between energy consumption and reference tracking. Namely, results show how longitudinal velocity and acceleration control significantly impact energy consumption, whereas deviating from the path centerline mainly allows better velocity tracking.

Moreover, in terms of benefits due to the consideration of both longitudinal and lateral vehicle dynamics, an initial study has been conducted to understand the energy-saving possibilities when the two degrees of vehicle motion, i.e., longitudinal, and lateral motions, are controlled by torque allocation. The concept was simulated in a high-fidelity simulation environment. Initial findings show that around 2% energy savings are possible at higher lateral acceleration whereas a marginal 0.5% savings is achievable in daily commuter cycles. This study was followed by a detailed investigation on the performance enhancement and energy savings potential of three different powertrain layouts with torque vectoring ability in a dual-motor electric vehicle. These three candidate mechanisms—electronic torque vectoring unit, torque vectoring dual clutch, and individual wheel motors—were modeled to enable torque vectoring ability in the rear axle of multi-motor EVs. An enhanced torque vectoring strategy was then proposed to improve the performance of these dual-motor EVs, optimizing the front-rear and left-right torque distributions along with the steering angle decision. The proposed EVs were evaluated against an EV with open differentials under three different performance objectives (minimization of time, energy, and steering effort) and transient driving maneuvers in a high-fidelity virtual environment to establish their relative benefits. Results indicate that the proposed mechanisms enhance the performance of dual-motor EVs relative to open differential layouts and are comparable to the performance of individual-wheel motor layouts. Among the mechanisms, the torque vectoring dual clutch (TVDC) achieves the best energy savings due to its additional freedom to disconnect one of the axles during low load demands. The electronic torque vectoring (ETV) configuration performs the best in terms of maximum cornering speed and steering effort, as it employs both relative acceleration and braking between inner and outer wheels, enabling agile cornering behavior.

Above all, the project has achieved the first two goals stated in Chapter 5 above. More specifically, a mixed-integer optimization framework is established, where closed-loop optimal control algorithms have been developed and verified using a high-fidelity vehicle simulation environment. Apart from the enhanced energy efficiency for both primary hybrid and electric vehicle configurations, the controller provides a method to reach the global optimum offline, which will facilitate as a benchmark for the virtual validation process in the automotive industry. The offline optimization results also serve as the initial guess for the calibration parameters in the rule-based controller today. This would then significantly reduce the tuning efforts for the existing controllers at the beginning of the vehicle project.

As one deviation from the original goals in the application, no investigations have been done on cloud-connected cars in control and calibrations. The main reason is due to the lack of time, as the project use cases were shifted from hybrid powertrains to fully electric vehicles when Volvo Cars changed the vision for electric propulsion development. This can be a natural continuation in a potential follow-up project.

Another deviation to be mentioned is the real-time implementation in a vehicle electronic control unit (ECU). Since the next new vehicle platform (SPA2) has been significantly delayed at Volvo Cars, there is no relevant, neither mature electric architecture nor base vehicle platform, available for the testing. However, as mentioned in the results above, the real-time potential of the proposed control design has been tested and indicated at a personal computer. Volvo Cars aims to implement and test the real-time capability of the optimal control algorithm developed by this project, when the SPA2 platform is delivered completely.

7 Dissemination and publishing

7.1 Knowledge and results dissemination

How has/will the project result be used and disseminated?	Mark with X	Comment
Increase the knowledge within the area	X	
Transferred to other advanced technical development projects	X	Real-time capability of controller is further developed and verified
Transferred to product development projects	X	The simulation model and tools will be partially used for the next product development project
Introduced to the market		
Used in investigations/regulations/ permit matters/political decisions		

7.2 Publications

Sr. No.	Complete Reference (article, conference, patent etc.)	Type	Status
1	A. Ganesan, S. Gros, N. Murgovski, C. F. Lee and M. Sivertsson, "Effect of Engine Dynamics on Optimal Power-Split Control Strategies in Hybrid Electric Vehicles," 2020 IEEE Vehicle Power and Propulsion Conference (VPPC), 2020, pp. 1-8, doi:10.1109/VPPC49601.2020.9330841.	Conference – IEEE VPPC2020	Published - 2020
2	Method to improve operational energy efficiency of Battery electric vehicle powertrains. European Patent Publication No.: EP4201730A1. US Patent Publication No.: US20230191919A1	Patent	Filed - 2021
3	A. Ganesan, S. Gros and N. Murgovski, “Numerical Strategies for Mixed-Integer Optimisation of Power-Split and Gear Selection in Hybrid Electric Vehicles,” in IEEE Transactions on Intelligent Transportation Systems, 2021.	Journal – IEEE ITS	Published - 2022
4	A. Ganesan, N. Murgovski, D. Yang and S. Gros, "Real-Time Mixed-Integer Energy Management Strategy for Multi-Motor Electric Vehicles," 2023 IEEE Transportation Electrification Conference & Expo (ITEC), Detroit, MI, USA, 2023, pp. 1-6, doi:10.1109/ITEC55900.2023.10186957.	Conference – IEEE iTEC2023	Published - 2023
5	A. Ganesan, N. Murgovski, D. Yang and S. Gros, "Mixed-Integer Energy Management for Multi-Motor Electric Vehicles with Clutch On-Off: Finding Global Optimum in Real-Time,” in IEEE Transactions on Vehicular Technology, 2023.	Journal – IEEE TVT	In Peer-Review
6	A. Rocha, A. Ganesan*, D. Yang and N. Murgovski, "Energy-optimal trajectory planning for electric vehicles using Model Predictive Control", in 2024 European Control Conference (ECC), Stockholm.	Conference – ECC2024	Accepted - 2024
7	A. Ganesan, N. Murgovski, S. Gros, D Yang, “Performance Comparison of Torque vectoring mechanisms for Electric Vehicles with Multiple Drivetrains”	Journal	Submission - 2024

As part of the project, the PhD student supervised the following design projects and master's thesis works.

Sr. No.	Title	Type	Status
1	D. Carlsson, F. Lier, O. Klang, and T. Bengtsson, "Energy Optimal Power-Split Control Strategy for BEVs," Tech. Report, Chalmers University of Technology, 2020.	Design Project	Completed - 2020
2	A. Raj and D. Yadav, " Optimal torque split strategy for BEV power train considering thermal effects," Thesis, Chalmers University of Technology and KTH Royal Institute of Technology, 2021. https://hdl.handle.net/20.500.12380/304234	Master Thesis	Published – 2021

3	J. Wu and L. Chen, "Numerical Strategies for Energy Optimization in Battery Electric Vehicles," Thesis, Chalmers University of Technology, 2022. https://odr.chalmers.se/handle/20.500.12380/305789	Master Thesis	Published – 2022
4	A.V.D. Rocha, D. Sundberg, J. Bengtsson, L. Sigurdarson, and R. Johnsson, " Optimal Path Planning and Torque Vectoring for Electric Vehicles," Tech. Report, Chalmers University of Technology, 2022.	Design Project	Completed - 2022
5	D.A. Poveda Pi and A.V.D. Rocha, " Energy Efficient Lateral Motion Control for Future Electric Vehicles," Thesis, Chalmers University of Technology, 2023. https://odr.chalmers.se/handle/20.500.12380/305789	Master Thesis	Published – 2023

8 Conclusions and continued research

In this project, a computationally efficient energy management framework that leverages mixed-integer model predictive control to simultaneously optimize control allocation and clutch on-off decisions in real time for multi-motor electric vehicles, is investigated. This novel approach consistently achieves substantial energy savings exceeding 4% against conventional rule-based controllers prevalent in modern EVs. In addition, the proposed dynamic programing approach shows superior performance compared to MI offline approach with mean energy savings of around 2% and at least 5 times reduction in clutch transitions. Pareto analysis has been carried out to balance energy savings and comfort by tuning the penalty term of clutch transition cost. Furthermore, the impact of model uncertainty on the proposed MI energy management approach was assessed through a two-step evaluation using high-fidelity plant models in IPG CarMaker. With average and worst-case solution times of approximately 1ms and 6ms, respectively, the proposed optimizer to solve the mixed-integer problem demonstrates favorable performance and online capability, making it suitable for real-time application in multi-motor electric vehicles.

The research was also extended to the lateral driving dynamics control, with individual electric motors at each axle and mechanisms that allow torque vectoring capability to the vehicle. A model predictive control algorithm was designed to perform autonomous speed tracking and path following control in the most energy efficient manner. It was found that significant energy savings come from slight reductions in average longitudinal velocity, which are optimized by smoothing longitudinal acceleration.

Future work will need to further improve the definition of the target cost to minimize the trajectory tracking and energy consumption at the same time. Prior knowledge of the road topology information like road slope and curvature ahead can also be exploited to achieve further energy saving as well as enhanced driving comfort. Implementation of the algorithms in a production ECU is also planned, to further verify the real-time capability of the optimization framework.

9 Participating parties and contact persons

Contact persons at Volvo Cars.

<table>
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