SHC PROJECT SUMMARY REPORT

Generic vehicle motion modelling and control for enhanced driving dynamics and energy management

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Summary

This project started in 2008 and ended 2014 and was made in collaboration with Volvo Cars, AB Volvo and BAE Systems Hägglunds (during the first phase). The scope of this research was to investigate the possibilities with added actuation and control of electrified road vehicles with special focus on actuator constraints. More specifically, the research question was: *"How can motion modeling and control strategies for over-actuation be made more suitable for implementation in electrified vehicles?"* Investigated areas are optimal use of actuators during both limit handling and normal driving. In order to be able to evaluate the most promising solutions for industrial applications, the methodology was to combine theory, modelling, simulation and optimisation, with experiments using a purpose-built scale prototype vehicle.

Studies of optimally controlled vehicles show that safety, performance and energy efficiency can be improved by utilising available actuators in over-actuated vehicles. Path tracking and optimal actuator control signals are evaluated in evasive manoeuvres at low and high friction surfaces. The results show how the forces are distributed differently among the wheels, even though the resulting global forces on the vehicle are similar. The limits of tyre forces can be increased and better utilised in a way that a passive system is unable to achieve. Actuator performance is also shown to be important, however even low actuator performance is shown to be sufficient to improve vehicle performance considerably. Optimal control of camber angles and active suspension shows that vehicle performance and safety can be greatly improved. Energy efficiency during curving is also shown to be improved as unnecessary vehicle motions are minimised during normal driving and wheel forces are used in a better way.

Simplified algorithms to control available actuators, such as wheel angles, vertical actuation and propulsion torques that are based on the analysis of the results of the optimisation studies have been proposed. For the cases studied, it has been shown that it is possible to get significantly better performance at reasonable levels of actuator performance and control complexity. This helps to simplify the introduction of this technology in electrified vehicles.

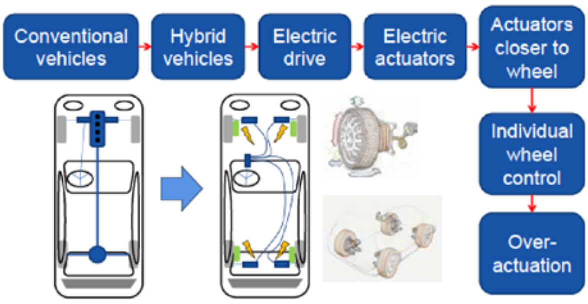
Control allocation is a method that distributes the wheel forces to produce the desired response of the vehicle. Simplified control allocation algorithms are proposed that allocate wheel forces in a way that resembles the behaviour of the optimisation solutions. To be able to evaluate the applicability of this methodology for implementation in vehicles, a small-scale prototype vehicle with force allocation control possibilities has been designed and built. The vehicle is equipped with autonomous corner module functionality that enables

individual control of all wheels regarding steering, camber, propulsion/braking and vertical loads. Straight-line braking tests show that force allocation can be used in a real vehicle and will enhance performance and stability even at a very basic level, using few sensors with only the actual braking forces as feedback.

In summary, this work has contributed to a better understanding of how the allocation of wheel forces can improve vehicle safety, performance and energy efficiency in electrified vehicles. Moreover, it has contributed to increased understanding of how vehicle motions should be modelled and simulated, and how control strategies for over-actuated vehicles can be made more suitable for implementation in future electrified vehicles.

Background

With the growing concern for environmental change and uncertain oil resources, the development of new vehicle concepts will in many cases include full or partial electric propulsion. The introduction of more advanced powertrains enables vehicles that can be controlled with a variety of electric actuators, such as wheel hub motors and individual steering. With these actuators, the chassis can be enabled to adjust its properties depending on the driving situation. The figure shows these steps towards how more control outputs will result in an over-actuated vehicle. Over-actuation defines a vehicle with a higher number of control outputs required to control a given number of degrees of motion. Worth mentioning is that with this increase in possible control outputs, the complexity of the control will increase as vehicles becomes more over-actuated.



Manoeuvring of the vehicle, using for example electric propulsion, braking, suspension, steering and camber control may also allow a variety of combinations that, if properly utilised, can increase the outer limits of vehicle performance and safety. Since there is a great need for energy efficient vehicles, control solutions for that is also required. For this reason, this work is about how the allocation of wheel forces can improve safety, performance and energy efficiency in future electrified vehicles in different driving situations.

General project description

The project scope is to study different approaches for generic vehicle motion control by optimization, to make the techniques more suitable for industrial applications. In order to be able to evaluate the most promising solutions for industrial applications, the methodology used is to combine theory development, modelling and simulation with experiments using a developed scaled prototype vehicle.

Achieved results

- Analysis of optimal vehicle behaviour on different friction levels using optimal control show that the solutions strongly depend on friction level. Actuator limitations are critical on high friction, especially in evasive manoeuvres such as double lane change.

- Active suspension is shown to be able to control vehicle roll, pitch and vertical motion in order to maximise vertical load on the wheels at critical points during the manoeuvres, thereby maximising the frictional force and peak acceleration.
- A solution for improvement of braking performance of a vehicle using optimally controlled active suspension is proposed. Lowering of the chassis during brake force build-up results in higher utilisation of friction and thereby shortens the braking distance. Lifting of the chassis just before stopping further reduce the braking distance.
- A control algorithm for active suspension is implemented and tested that improves the braking performance during straight-line braking. The braking distance from 100 km/h is shown to be shortened by over 0.7 m from 41.47 m to 40.74 m for the vehicle studied.
- A multi-line brush tyre model with Camber sensitivity is developed and implemented and used as a reference for camber sensitive tyre models.
- Analysis of optimal active camber control showing that lateral acceleration can be improved by controlling camber angles, enabling 5.8% higher speed through an evasive manoeuvre for the studied vehicle.
- Control algorithms for improved energy efficiency during cornering are proposed and evaluated. Implementation of the algorithms, which are based on findings from the optimal solutions, shows that the cornering resistance during manoeuvring can be reduced by up to 10% for the studied over-actuated vehicles.
- Based on the functionality of the ACM, a novel prototype of a down-scaled over-actuated vehicle has been designed and built. The prototype is designed with a control architecture that enables force allocation.
- A cost-effective control approach is proposed, implemented and evaluated on the prototype vehicle, as well as in vehicle simulation. Results show improvement of braking distance and vehicle stability during split-μ braking.

Contribution to hybrid vehicle technology

The development of new vehicle concepts will in many cases include full or partial electric propulsion. The introduction of more advanced powertrains enables vehicles that can be controlled with a variety of electric actuators, such as wheel hub motors and individual steering. With these actuators, the chassis can be enabled to adjust its properties depending on the driving situation. This work has contributed to a better understanding of how these actuators can be utilized for improvement of also vehicle safety, performance and energy efficiency in future concepts of electrified vehicles. Moreover, it has contributed to increased understanding of how vehicle motions should be modelled and simulated, and how control strategies for over-actuated vehicles can be made more suitable for industrial implementation.

Optimization is used here to give insight into how different actuator configurations can perform at the best in different situations. This knowledge has been valuable also for today vehicles with fewer actuators. The project has also given knowledge about how to design controllers that are able to control vehicles better in both at-the-limit situations and normal non-critical driving. Over-actuation is also shown to be able to improve energy efficiency. Also, the increased knowledge on how important actuator performance is for different functions are valuable for the vehicle industry. Examples of results that can be used by vehicle manufacturers are the suggested approach for control of suspension that improves braking performance during straight-line braking.

The project has contributed to SHC deliverables with 1 PhD, 1 Lic. Tech, 6 international journal paper publications and 5 refereed conference articles. Among them international collaborations are shown by 1 co-authored journal paper. Eight co-authored papers confirm the industrial relevance. The multi-disciplinary collaborations are shown in 2 co-authored papers with researchers from other disciplines (Electrical engineering and power electronics). And also one paper is co-authored with researcher from another Swedish University. The project also has contributed to the aims of Theme 1 within SHC since it has:

- Developed, adapted and evaluated methods that supports virtual development of hybrid systems, based on mathematical models of components and systems.
- Developed, adapted and evaluated methods and algorithms for modeling, control and optimization of hybrid systems.

Uniqueness and news value

See *Achieved results* above.

Timing and finance

Total cash budget: 4500 kkr

Cash budget this year: 0 kkr

Total cash expenses to date: 4500 kkr

Executors and collaboration

This research has been carried out at the research group of Vehicle Dynamics at KTH Royal Institute of Technology, in Stockholm, Sweden. The research by the PhD student Johannes Edrén has been funded in this project. Project leader and main academic supervisor was Professor Annika Stensson Trigell. Also the academic advisors Associate Professor Jenny Jerrelind, Associate Professor Lars Drugge at KTH and Dr. Mats Jonasson at Volvo Cars have contributed to the project results. Collaborations to Johan Andreasson and Peter Sundström at Modelon, Professor Bengt Jacobson at Chalmers University of Technology have also been valuable. This project have had the same steering group as the sister project "Over-actuated fault tolerant HEVs" with PhD student Daniel Wanner. Members of this steering group have contributed to the results (Oskar Wallmark and Mats Leksell from Electrical machines and power electronics at KTH, Leo Laine at AB Volvo, Olof Noreus at BEA Systems Hägglunds (during the first phase), Gunnar Olsson and Mattjis Klomp from Saab Automobile and Mats Jonasson at Volvo Cars). Jonasson has contributed a lot to the project, especially regarding detailed vehicle models, experimental data, approaches to control allocation, many ideas for control strategies and interpretation of industrial relevance of the findings. Kent Lindgren and Danilo Prelevic at the MWL laboratory at KTH have been extremely helpful during the construction of the down-scaled vehicle and measuring equipment. Also collaboration with Professor Wideberg at University of Seville, Spain is appreciated.

Papers and publications

Journal publications:

"Implementation and evaluation of force allocation control of a down scaled prototype vehicle with wheel corner modules". J. Edrén, J. Jerrelind, A. Stensson Trigell and L. Drugge. International Journal of Vehicle Systems Modelling and Testing, Vol 8, No. 4, pp. 335-363, 2013.

"Problems in using individual X-by-wire cornering modules." F. Morales Sanchez, J. Wideberg and A. Stensson Trigell. Int. J. Heavy Vehicle Systems, Vol. 21, No. 1, 2014.

"Road friction effect on the optimal vehicle control strategy in two critical manoeuvres". J. Edrén, P. Sundström, M. Jonasson, B. Jacobson, J. Andreasson and A. Stensson Trigell, International Journal of Vehicle Safety, Vol. 7, No. 2, pp. 107-130, 2014.

“Analysis and evaluation of force allocation strategies in an electric vehicle with in-wheel motors”. D. Wanner, J. Edrén, O. Wallmark, M. Jonasson, L. Drugge and A. Stensson Trigell. Submitted for publication, 2013.

“Utilization of optimization solutions to control active suspension for decreased braking distance”, J. Edrén, M. Jonasson, J. Jerrelind, A. Stensson Trigell and L. Drugge, accepted for publication in Vehicle System Dynamics, 2014.

“Energy efficient cornering using over-actuation”, J. Edrén, M. Jonasson, J. Jerrelind, A. Stensson Trigell and L. Drugge, submitted for publication, 2014.

Publications in conference proceedings:

"The development of a down-scaled over-actuated vehicle with autonomous corner module functionality". J. Edrén, M. Jonasson, A. Stensson Trigell, L. Drugge, J. Jerrelind. F2010-B-056, FISITA 2010 World Automotive Congress, May 30 – June 4, Budapest, Hungary, 2010.

"Modelica and Dymola for education in vehicle dynamics at KTH". J. Edrén, M. Jonasson, A. Nilsson, A. Rehnberg, F. Svahn, A. S. Trigell. Paper MODEL09_0112_F1. In Proceedings from 7th Modelica Conference 2009, Como, Italy, 2009.

“Fault-tolerant control of electric vehicles with in-wheel motors through tyre-force allocation”, Wanner, D., Edrén, J., Jonasson, M., Wallmark, O., Drugge, L. and Stensson Trigell, A., Proceedings of the 11th International Symposium on Advanced Vehicle Control (AVEC 12), 2012.

“Utilization of vertical loads by optimization for integrated vehicle control”. J. Edrén, M. Jonasson, J. Jerrelind and A. Stensson Trigell. Proceedings of the 11th International Symposium on Advanced Vehicle Control (AVEC 12), 2012.

“Exploring active camber to enhance vehicle performance and safety” J. Jerrelind, J. Edrén, M. Davari, L. Drugge, A. Stensson Trigell. In proceedings of IAVSD'13. Presented in Chendu, China, August 2013.

Licentiate Thesis:

"Exploring force allocation control of over actuated vehicles", Johannes Edrén, TRITA-AVE 2011:80, Dec 2, 2011.

Doctorate Thesis:

“Motion modelling and control strategies of over-actuated vehicles”, Johannes Edrén, TRITA-AVE 2014:75, Dec 3,2014.