Testing and evaluation of fault handling strategies in the research concept vehicle

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Summary

The development of new electrified driveline configurations with wheel hub motors can reduce the commonly known trade-off between the objectives vehicle handling, comfort and energy efficiency. Vehicles with these types of electrified drivelines are often over-actuated; i.e. more actuators than needed to control the degrees of freedom of the vehicle are available. The implementation of novel control concepts into such over-actuated vehicles enables to switch dynamically between these main objectives depending on the driving situation. Besides the increase of the degrees of freedom on how to control these over-actuated vehicles, it also increases the number of possible failure modes during operation.

In this work, fault handling strategy for one possible failure mode (negative torque on one rear wheel) in such a new electric driveline is analysed in an experimental vehicle, the KTH Research Concept Vehicle (RCV). The chosen control method is based on the control allocation principle and employs the pseudo-inverse method according to Oppenheimer et al. [1], which can be performed in real-time. The electric driveline of the RCV incorporates a wheel hub motor in each of the four wheels, which is individually controlled by a power electronic converter. Another fault handling strategy has also been studied for the failure mode above and a failure mode of one disengaged steering actuator. The strategy here was to control the steering angles on the wheels only as well as a combined approach with both torque control and steering angle control.

The project has collaborated with ITRL – Integrated Transport Research Lab that owns and manage the RCV.

The project have through validation of past simulations results and further tests shown that over-actuation can be used to effectively mitigate failure conditions by using torque control and steering control seems to also show promising results.

General project description and background

The SHC-project “Fault-Tolerant Over-Actuated Hybrid Electric Vehicles (FT_HEV)” has been studying different faults and their effects on the dynamic behaviour of the vehicle in simulation environments. The project has reached a stage where several real life experiments need to be carried out to validate the simulation results and a funding of full scale vehicle testing has not been covered in the initial SHC application. The KTH Research Concept Vehicle is a suitable platform for studying these effects with its wide variety of functionality and setup possibilities. The RCV is an experimental vehicle platform for effectively validating and demonstrating research aiming towards finding sustainable transport solutions of the future. It is a pure electric vehicle where each wheel corner module is equipped with a wheel hub motor and individual steering and camber actuators. This high level of over-actuation allows a broad range of experimental evaluation in the fields of vehicle dynamics, mechatronics, control theory, electro mechanics, etc.

The goals of the project have been to study the effect of fault-tolerant control on driver and vehicle performance as well as to validate simulation and moving base driving simulator results so far gained in the FT_HEV and EVERSAFE projects.

The work in this project has been to create a test plan and additional software and hardware development for the RCV to enable studies at the test track during 4 evenings, of which two is for pre-testing.

In this work, a fault handling strategy using torque allocation for one possible failure mode (negative torque on one rear wheel) has been analysed in the RCV. Another fault handling strategy has also been studied for the failure mode above and a failure mode of one disengaged steering actuator. The strategy here was to control the steering angles on the wheels only as well as a combined approach where both torque control and steering angle control were used.

Achieved results

Results of the vehicle without (NVC) and with (PCA) implemented failure handling strategy using torque control are displayed in Figure 1. The failure is activated by an auxiliary brake system at 0 s. The pressure was quickly increased up to 50 bar until the rear left wheel locked and held for 2 s before it was released again. The yaw rate of the uncontrolled vehicle showed a constant yaw rate of 8 deg/s, while the controlled vehicle reached a lower maximum yaw rate and reduced it after one second.

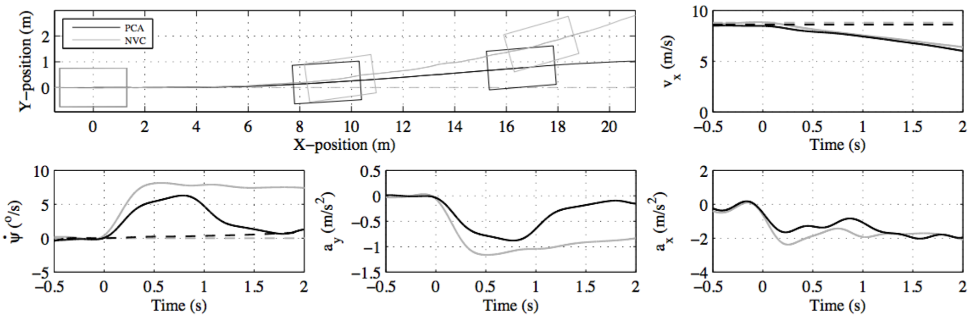

Figure 1. Measured vehicle trajectories and vehicle states for the vehicle with (PCA) and without (NVC) control strategy during failure condition.

As conclusion, it can be stated that the applied control allocation method using wheel torque reduced the yaw rate significantly despite the actuator constraints of the wheel hub motors of the RCV. Further information will be presented in [2].

After an analysis of all the important on-board systems of the RCV, possible failures that can induce unintended yaw rate on the vehicle's response where listed and tested. The tests have given the conclusion that the vehicle is fail operational for the cases it was tested. Especially for the case of the deactivated steering actuator, the steering angle controller showed very efficient compensation and allowed the driver to manoeuvre successfully a slalom course as can be seen in Figure 2.

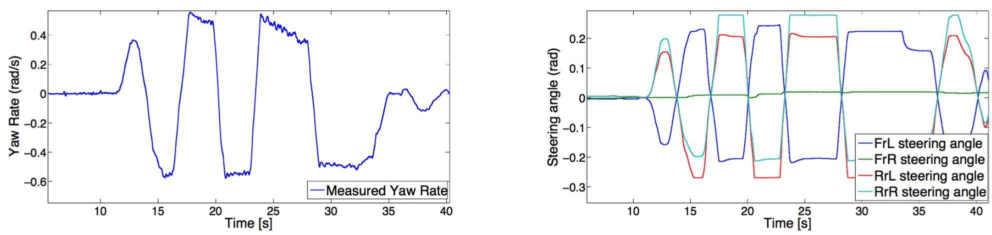

Figure 2. Yaw-rate response and steering angles for each wheel when deactivating the front right steering actuator.

Timing and finance

Four test days were performed, one in end of October which was a pre-test for the torque control, one in December for the final torque control test and two in May where the first test was a pre-test and the second the final test. Between each test people in the project team have been working on the tasks outlined in the section below. The total project budget is SEK 0.250 million, 0.150 of which is funded by SHC.

Executors and collaboration

Mikael Nybacka has been the project leader, which includes writing of application, planning the work and being responsible for the deliverables of the project. Daniel Wanner, Fan Gao and Petter Tomner worked on the implementation of additional brake system, state estimation and torque control. Daniel Wanner and Mikael Nybacka planned the test. Daniel Wanner performed also the simulations and conducted the analysis. Daniel Wanner, Mikael Nybacka, Oskar Wallmark, Lars Drugge and Annika Stensson Trigell wrote the paper. Stefanos Kokogias, Daniel Wanner and Mikael Nybacka also worked on the steering angle control strategy, where Stefanos and Mikael Nybacka performed and analysed the test in May 2015. This project is a collaboration with, and extension of, the SHC-project "Fault-tolerant over-actuated hybrid electric vehicles" which had the aim to analyse the impact of failure modes and find suitable fault-tolerant control strategies in electric and hybrid-electric drivelines, in order to gain increased knowledge of driver-vehicle interaction during a failure. The project has also a sister SHC-project, "Model for simulation of driving behaviour during failures in electrified vehicles".

Dissemination of Results

The results have been disseminated through participation in the following activities:

- SHC cross-thematic and doctoral student network meeting, 11-12 March, Hallsberg, 2015.
- SHC conference, 4 June, Gothenburg, 2015.
- PhD thesis presentation by Daniel Wanner, 5 June, Stockholm, 2015.
- Paper [2] will be presented in IAVSD conference August, Graz, 2015.

Papers and publications

[1] Oppenheimer, M. W., Doman D. B. and Bolender, M. A., *Control allocation for over-actuated systems*, Proc. of IEEE Mediterranean Conf. on Control and Automation, Ancona, Italy, 2006.

[2] Wanner, D., Nybacka, M., Wallmark, O., Drugge, L. and Stensson Trigell, A., *Failure handling strategy in an experimental research vehicle*, Accepted for presentation at IAVSD, Graz, August 17-21, 2015.

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