Estimation of Longitudinal Velocity and Road Slope in Hybrid Electric Vehicles

Project within FFI - Strategic Vehicle Research and Innovation

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Content

1. Executive summary

This project has developed estimation algorithms for vehicle longitudinal velocity and road slope angle. Vehicle speed is one of the important quantities in vehicle dynamics control and estimation of the slope angle is in turn a necessity for correct dead reckoning from vehicle acceleration. In this project, estimation of vehicle speed is applied to a hybrid vehicle with an electric motor on the rear axle and a combustion engine on the front axle. The wheel torque information, provided by electric motor, is used to early detect excessive wheel slip and improve the accuracy of the estimate.

The project result presents a method to estimate the longitudinal velocity and road slope that solves the case when wheels are slipping beyond the friction limit of the tires, so-called excessive slip. This excessive slip detection is in part achieved by introducing a novel excessive slip criteria and a wheel speed selection method.
There is an inevitable delay to detect excessive slip using the approach without wheel torque. This delay causes a large deviation between the velocity estimation and the true velocity. To solve this delay, the wheel speed criterion and pre-estimation criterion is complemented by a third criterion based on the wheel torque, which can be obtained accurately from the electric motor. The wheel torque criterion can detect the slipping wheels without substantial delay to the cost of sensitivity to measurement noise. However, changes in the wheel speeds are used in addition to verify the excessive slip which implies an accurate criterion with good timing. The velocity estimation accuracy is also affected by differences in the wheel speed measurements. In some situations, excessive slip of one wheel may lead to large estimation error and is hard to detect by the excessive slip criteria. Thus, one wheel is selected that best represent the vehicle speed and is further used as the observation variable of the Kalman filter. This approach improves the robustness of the estimate as filter is less sensitive for slipping wheels. In addition it reduces the computation in the Kalman filter as the dimension is reduced from a four dimensional problem to a scalar one.

Since this was a limited study, further development of the algorithm needs to be done to adapt to changes in wheel radius, linear-range wheel slip, variations in the friction on the different wheels and the effects of large side-slip.

In conclusion, the approach was successfully verified towards extensive winter tests under realistic conditions. The presented algorithm shows a major step forward in finding a practical method to estimate the longitudinal velocity with good performance on slippery roads even in cases when all four wheels are slipping.

2. Background

For traction and brake control; accurate knowledge of the vehicle's longitudinal velocity is essential since it is used to compute wheel slip. Estimation of the slope angle in turn is important for real-life fuel economy optimization and improved traction control. The task of speed estimation is challenging when driving all four wheels – in particular in slippery conditions – as is the case with the electric drive systems supplied by e-AAM. Direct measurement of the longitudinal velocity is too expensive and/or impractical for vehicle applications. Instead, the longitudinal velocity needs to be estimated from, among others, the wheel speed sensors and integration of acceleration in the direction of the road slope as well as wheel torque information. These sensors, however, have limitations. The wheel speeds become unrelated to the vehicle velocity during excessive wheel slip and time integration of the longitudinal acceleration accumulates acceleration bias causing the estimation to drift. One such bias is the gravitational component acting in the direction of the road slope, which is why also estimation of the road slope angle is necessary.

In order to circumvent the shortcomings of each individual measurement method, it is necessary to employ sensor fusion. This is means to, in an optimal way; combine all available sensor information to get a best possible estimate of the longitudinal velocity and road slope.

New with the electric drive system, compared to a conventional driveline, is that more accurate information of the wheel torque is possible with electric machines, which is believed to improve the accuracy of the vehicle speed estimation considerably.

3. Objective

The objective for this project was to develop an accurate estimation algorithm for both the vehicle longitudinal velocity and the road slope angle. This objective was broken down into different activities where some of the activities were more focused on dissemination of project result.

The activities were:

- Estimation algorithm implemented in Simulink.
- Test cases evaluated in simulation and with real measurement, including.
  - Real tests performed partly at the e-AAM Winter Test Center in Arjeplog
  - Evaluation scripts developed for evaluating the estimation algorithm performance
  - Tuning of the estimation algorithm for best performance (via optimization).
- Strengthened Sino-Swedish academic collaboration.
- Technical report written
- Scientific papers (journal and conference) published
- Project report sent to FFI

4. Project realization

This project has been executed with a master thesis (exchange) student from Tongji University, Shanghai as well as senior researchers at Chalmers and e-AAM.
The combination of the collaboration between Chalmers and Tongji University and e-AAM's hybrid electric technology and winter test facilities in Arjeplog, Sweden have been key enabling factors for this project.

The master thesis was performed during 2013. The master thesis student was later employed at e-AAM in early 2014 and the final evaluations were performed in February 2014 at the e-AAM Winter Test Center in Arjeplog.

5. Results and deliverables

5.1 Delivery to FFI-goals

Although the problem of road slope and vehicle speed estimation is not new, the combination with e-AAM's hybrid electric driveline products driving all four wheels, both makes this problem a more challenging one, where the new wheel torque estimation using the electric motor opened new opportunities to solve this problem.
In order for Sweden to grow in the area of vehicle hybridization, important for meeting energy and environmental goals, as well as providing business opportunities for Swedish companies – such as e-AAM – also these basic problems of speed and slope estimation must be addressed.

The new collaboration between Chalmers and Tongji University, which is of strategic interest to e-AAM as well, was another reason conducting this project. Strong business relationships between Sweden and China are important to the vehicle industry in general, and e-AAM in specific. Therefore these academic partnerships between China and Sweden are essential complement to enhance business relationships.
In summary, this project relates to the programme targets, vehicle-related research, innovation and development activities within the following areas:

- Vehicle electronics enabling technology
- Embedded systems & software
- Development methods for evaluation of estimation algorithms
- The collaboration with Tongji University, has the clear potential to strengthen the competitive power of Sweden and the Swedish automotive industry in a global perspective.

This project was also strongly related to the objectives of the Vehicle Development program to contribute to global leadership within vehicle electronics & software and increase expertise in hybrid electric vehicle development. Estimation algorithms in general – and the opportunities with improved wheel torque information in this area in specific – are essential to ensure progress within areas such as energy and active safety.

5.2 Results and expected effects - outcome

The purpose of the project, as described in the introduction, was that longitudinal velocity and road slope estimation are essential for e-AAM's business portfolio. Also, the high standard with international academic environment (Chalmers and Tongji University) combined with e-AAM's world-class winter test facilities, – which are not readily available to academia – and industrial experience, were seen as important success factors in this project. The industrial relevance of this work would ensure that the results would be used in the vehicle control in e-AAM's product offering. Furthermore, the experimental results achieved in the renowned winter conditions of northern Sweden would ensure that the results will achieve high academic relevancy.
The fact that AAM has applied for a patent related to the technology developed in this project emphasizes the relevance to the company. Furthermore, both the invitation to present this work in a plenary session at a major vehicle dynamics conference and that one journal paper was accepted for publication in an international journal shows that the project has been highly relevant to the academia. Furthermore, the master's thesis which has been another outcome of the project, was nominated as the best Master's at Tongji University for 2013.
Finally the master thesis student are now employed at e-AAM and has moved from China to Trollhättan.

6. Dissemination and publications

6.1 Knowledge and results dissemination

The public part of this study is related to the international and project specific publications from this project. Also relevant, a patent application has been submitted. The publications and intellectual property are the measurable deliverables from this project.

The way this project has been executed, with a student from Tongji University doing his Master's thesis through Chalmers University at a company has been a highly successful approach. Also the fact that senior researchers at all three partners, Tongji, Chalmers and AAM have been strongly involved in supervision and facilitating work has been important factors in this project. Also, the fact that AAM has made key resources, such as a test vehicle and winter test facility available for this project has been essential for the success of this project.

6.2 Publications

The project has resulted in the following publications:

- Master's thesis report "Longitudinal Velocity and Road Slope Estimation in Hybrid/Electric Vehicles - Development and evaluation of an adaptive Kalman filter" at Chalmers University of Technology by Yunlong Gao from Tongji University (2013)
- Conference paper "Robust Estimation of Longitudinal Velocity and Road Slope in Hybrid Electric Vehicles using an Adaptive Kalman Filter" presented in a plenary session at the 23rd IAVSD Symposium on Dynamics of Vehicles on Roads and Tracks at Southwest Jiaotong University, Qingdao, China (2013)
- Journal paper "Longitudinal velocity and road slope estimation in hybrid electric vehicles employing early detection of excessive wheel slip" which is accepted for publication in Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility.
- Lunch seminar entitled "Estimation of Longitudinal Velocity and Road Slope in Hybrid Electric Vehicles using an Adaptive Kalman Filter" at Chalmers University (2014)

And the following patent application

- U.S. Provisional Patent Application "System And Method For Determining A Vehicle Velocity Parameter" Serial No. 61/830,368 (2013)

7. Conclusions and future research

This project has developed a method to estimate longitudinal vehicle velocity and road slope angle which is used to solve the case when wheels are slipping.

Although the problem of road slope and vehicle speed estimation is not new, the combination of e-AAM's hybrid electric driveline products driving all four wheels both makes this problem a more challenging one, but the new wheel torque estimation using the electric motor opened new opportunities to solve this problem.

Future development on the algorithm needs to be done to adapt to changes in wheel radius, linear-range wheel slip, variations in the friction on the different wheels and the effects of large side-slip angles.

In conclusion, however, the algorithm is successfully verified by extensive winter tests under realistic conditions and it performs well on slippery road also when all of the four wheels are slipping.

8. Participating parties and contact person

The project partners in this project were:

e-AAM Driveline Systems AB
Contact person: Torbjörn Norlander

Chalmers University of Technology
Contact person: Bengt Jacobson, The Department of Applied Mechanics