Complex Embedded Automotive Control Systems
CEmACS

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VEHICLE STATE OBSERVER ACTIVITY REPORT

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Executive Summary

This interim report describes the work carried out up to month 6 in Workpart 4 of the CEMACS project (deliverable D4).

The activities within this workpackage has been directed towards development of a theoretical foundation for nonlinear observer design for automotive vehicles. A preliminary nonlinear observer for vehicle velocity and side slip has been developed and experimentally tested.

Two manuscripts covering the recent contributions have been prepared and submitted for publication.

The progress towards objectives, milestones and deliverables is according to plans.

Contents

1 Background and motivation

Complex automotive control systems rely heavily on accurate and reliable information about the state of the vehicle and its environment. While certain state variables, such as yaw rate, are measured directly, others, such as the vehicle's side slip angle, cannot be measured due to high sensor costs. The use of model based state estimators is therefore necessary to provide estimates of unmeasured states and achieve sensor fusion when there are redundant or distributed sensors. In addition, it provides a mechanism to achieve safe and graceful degradation of performance when there is temporary or permanent errors in some of the vehicle sensors.

With the vehicle dynamics being nonlinear observability will depend on state and inputs of the system. As a matter of fact external disturbances such as the friction coefficient between tyre and road or the inclination of the road are only conditionally observable, depending on the driving situation.

Recently, there has been significant progress in the design of nonlinear observers, which provides an attractive alternative to the Extended Kalman-Filter (EKF) due to such properties as simplicity of implementation and tuning, and reduced on-board computational effort.

Beyond these technological advantages, an important point is that there exist several methods and principles for the proof of uniform global or regional asymptotical/exponential stability for the non-linear observer error dynamics, including nonlinear dissipative forces such as friction and bias models (necessary due to sensor drift). These theoretical issues are becoming increasingly important from a practical engineer's point of view since in complex safety-critical automotive control systems a theoretical foundation is likely to avoid design errors and reduce the time used for verification and testing.

We conclude that the potential advantages of using nonlinear observers in automotive applications are significant. Moreover, a combination of EKF and nonlinear observers can solve the global convergence problem while maintaining the benefits of tuning and monitoring local performance in a well established way.

2 Overview of activities

2.1 Sensor configurations

There is a number of existing and new automotive control and monitoring applications that rely or benefit from state estimation. These include anti-lock brakes (ABS), electronic stability program (ESP), rollover protection, collision avoidance, intelligent cruise control, active body control (ABC). Some of these application require special sensors to achieve the necessary performance or fault tolerance. This leads to the fact that different car models will have a different set of onboard sensors, and different requirements for state estimation. For example, low-end cars may only have an ABS system and the associated basic wheel and steering sensors, while high-end cars with ESP and ABC may have additional sensors.

A three level characterization of typical sensor configurations is described in Appendix A. The first level may correspond to a basic car with only ABS, the second level a car with ESP, and the third level a car with ABC. The trend is that most new cars correspond to the second level. Consequently, the CEMACS state estimation activity will not focus on the first level. In fact, the second level is chosen as the main target of the first phase of this workpackage since it is the most common configuration, and the third level is considerably less challenging due to the availability of the ABC sensors that simplifies the state estimation problem considerably.

2.2 Theoretical framework for nonlinear state estimation

Automotive nonlinear state estimators are faced with two kinds of basic requirements

- Engineering-friendliness: Efficiency and transparency of design, tuning and implementation.
- Safety and performance: Verifiable performance, robustness and fault tolerance.

To support the latter requirement, system theoretic properties such as asymptotic or exponential stability and convergence are highly useful.

The Extended Kalman-filter (EKF) is a state-of-the-art state estimation solution that is most common in every branch of engineering. Although it was developed in the 60's and there are reported thousands of successful applications, its theoretical properties such as convergence are not very well understood. In fact, it is well known that certain "tricks-of-the-trade" are necessary in order to handle numerical and more fundamental divergence phenomena. Recently, general conditions for global convergence and stability of the EKF has been established, see [1] and the references therein. A sufficient condition for convergence of the EKF is boundedness of the time-varying solution to the associated Riccati equation. Although this result may be difficult to use directly during design, it gives support and a theoretical foundation to standard modifications such as covariance matrix resetting.

The more promising approach, which is the main focus of this workpackage, is nonlinear observer design. This eliminates the need for the Riccati equation and greatly simplifies the analysis of theoretical properties such as stability. In fact, we use nonlinear fixed or time-varying gain observers instead of the EKF methods where the gains are computed via the computationally expensive Riccati equation. Instead, using the powerful framework of Lyapunov theory, sufficient conditions for stability and convergence can be imposed on the design. The main drawback of nonlinear observers is that while the EKF is a general purpose algorithm (although it is not completely "plug and play" since it requires certain tricks and modifications to work in many cases), the nonlinear observer approach requires a detailed design for each application. Several nonlinear observer design approaches based on Lyapunov theory have been considered. This includes high-gain design, contraction theory, reformulations into linear parameter-varying (LPV) forms and design based on associated linear matrix inequalities (LMIs), and passivity.

For the purpose of modularity, which facilitates configurability, fault tolerant and incremental design, several approaches for decomposing the nonlinear observer into modules has been investigated. Stability and convergence of the state observers can be analyzed using Lyapunov theory and cascade theory. Two modular nonlinear observer structures are described in Appendix B. An objective has been to organize the modules in a cascaded structure that allows theoretical properties of individual modules to be propagated to the complete system using cascade theory for nonlinear systems.

2.3 Nonlinear observer for vehicle velocity and side slip

Different strategies for nonlinear observers in automotive vehicles are considered and compared. For the first phase of work package 4 we have considered in particular the problem of estimation of vehicle velocity and side slip angle based on the level 2 sensor configuration. For this problem, one promising nonlinear observer strategy was chosen [2]. Is is based on a direct nonlinear Lyapunov design, taking advantage of the passivity of the Coriolis forces and structural properties of the highly nonlinear tyre-road friction models. Theoretical proofs of exponential stability under certain conditions have been established, a preliminary design and tuning has been carried out, and the observer is validated against experimental data. The results are highly promising and encourages further research along this direction. Several possibilities for refinement and extensions have been identified, such as accounting for road bank and inclination angles.

2.4 Simulation and experiments

DaimlerChrysler state estimation software [3] has been installed at SINTEF. Is it used for analysis, validation and benchmarking of nonlinear observer designs.

3 Progress toward objectives, milestones and deliverables

3.1 Objectives

The following objectives are identified in the workpackage description

1. Develop a nonlinear observer with global convergence properties for automotive state estimation and sensor fusion.
2. Implement, validate and combine the approach with conventional Extended Kalman-filtering using experimental data in the test vehicles for use in WP1, WP2, and WP5.

Within the first phase of this workpackage the activities has been dedicated to the first objective. As described above, in Section 2, the progress is according to plans.

A basic nonlinear observer for motion parameters (velocity, side slip, yaw rate) covering motion dynamics has been established. Initial steps towards implementation and validation has been made to ensure that the second objective can be met by the technology under development.

The next step within this workpackage is to extend the results to also cover estimation of external disturbances; road bank and inclination angle, road/tyre friction coefficient.

3.2 Milestones and deliverables

This report corresponds to the following milestone.

MS1. Conclusion of innovation and theory phase. A consistent theoretical framework of vehicle state observation.

An overview of the theoretical framework is described in Section 2 of this report, in the appendix, and the accompanying papers submitted for publications [2, 1].

Future activities within this workpackage will target MS2 and MS3, and in particular

- Refinement and extension of the developed theoretical framework toward a practical state estimation design strategy
- State estimation and sensor fusion SW to be used in WP1, WP2 and WP5.
- Verification and validation of performance

The deliverables of this workpackage are

- D4 (month 6) Vehicle state observer activity report (This report).
- D10 (month 12) Observer specification.
- D16 (month 24) FR Vehicle state observation.

The progress toward the deliverables is according to plans. DaimlerChrysler state estimation software has already been installed at SINTEF and used for analysis, validation and benchmarking of nonlinear observer designs. SINTEF personnel has visited DaimlerChrysler to get familiar with existing solutions and software.

A Levels of observer design and sensor configurations

The complexity of the state estimation problem depends strongly on the sensor configuration available in the vehicle as well as the requirements of the application with respect to which states must be estimated. For this purpose, a three level classification of automotive vehicle state estimation problems are provided in this section.

The estimation objectives for all levels are

- Velocities
- Yaw rate
- Load distribution (vertical forces on each wheel)
- Roll and pitch angle

However, because of the different number of sensors available on the different levels, there is a difference in obtainable accuracy in the estimates.

A.1 Level 1

The level 1 observer design is for basic car with an ABS system. The sensors available are usually

- Wheel position
- Steering angle
- Engine speed
- Longitudinal accelerometer (not completely standard).

In addition, for some vehicles the following may be partially available

- Brake pressures (giving an indication of brake torque)
- Engine torque (both static and dynamic, includes other loads)

For the basic (level 1) design, we can only expect to obtain accurate estimates of longitudinal speed, i.e., not side slip/lateral velocity.

A.2 Level 2

The level 2 observer design is for a car with ESP, and one can therefore expect the following additional sensors:

- Lateral accelerometer
- Yaw rate

With this information, we must expect to obtain more accurate speed (including side slip/lateral velocity) and yaw rate estimates, but load distribution as well as roll and pitch angles estimates may still be less accurate.

A.3 Level 3

The third level is for a car with Active Body Control (ABC), with the following additional sensors in the active suspension system:

- Actuator position for each wheel
- Spring deflection for each wheel

The spring and actuator are connected in series, with damper in parallel. This gives fairly direct measurement of pitch/roll, road bank and inclination, as well as vertical load distribution.

B Observer structures

Estimating states and parameters for the car can be looked upon as a single observer problem, using a single (large) dynamic model to estimate all desired variables. However, for reasons related to

- problem overview
- different sensor suits in different cars
- "graceful degradation" with respect to sensor failure

it is convenient with a modular structure.

B.1 Modular observer structure

The structure we consider is illustrated in Figure 1.

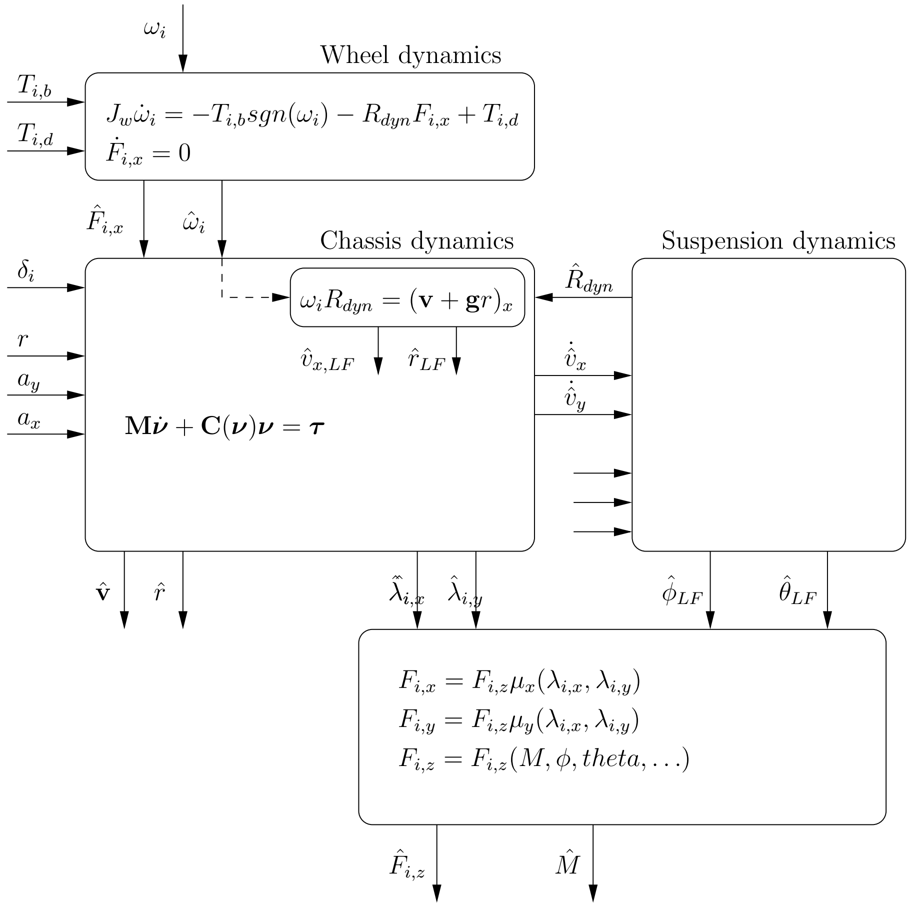

Figure 1: Modular observer structure

Wheel block The objective of this block is to produce estimates of the longitudinal friction force (as well as rotational speed) of each wheel. Measurements are rotational speed ω_i, and brake- and drive torques calculated from measurements from brake and engine system.

Chassis block The objective of this block varies according to the number of sensors available.

If only information from the wheel dynamics block is available (and steering angle), then this block produces low frequency estimates of longitudinal velocity and yaw rate ($\hat{v}_{x,LF}$ and $\hat{r}_{LF}$). If yaw rate and lateral (and possibly longitudinal) acceleration measurements are available, this provides high frequency information that can be combined with the low frequency information to obtain velocity (including side slip angle) and yaw rate estimates.

If more information from the suspension system is available, then also roll rate and pitch rate might be included.

Suspension block If no measurements from the suspension system is available, then this block uses "quasi-static" equations to provide estimates of effective wheel radius (R_{dyn}), and (low frequency) estimates of roll and pitch.

With measurements from suspension system, then better quality (high frequency) estimates can be obtained.

Rollover detection block The last block uses longitudinal and lateral wheel slip estimates together with estimates of longitudinal and lateral friction forces to estimate the vehicle load distribution. Measurements from the suspension system allows estimation of total vehicle mass.

B.2 Lateral longitudinal decomposition

For the purpose of estimation of vehicle velocity a decomposition into lateral and longitudinal dynamics is proposed in Figure 2. The lateral module treats the longitudinal velocity estimate provided by the longitudinal module as a perfect estimate / measurement.

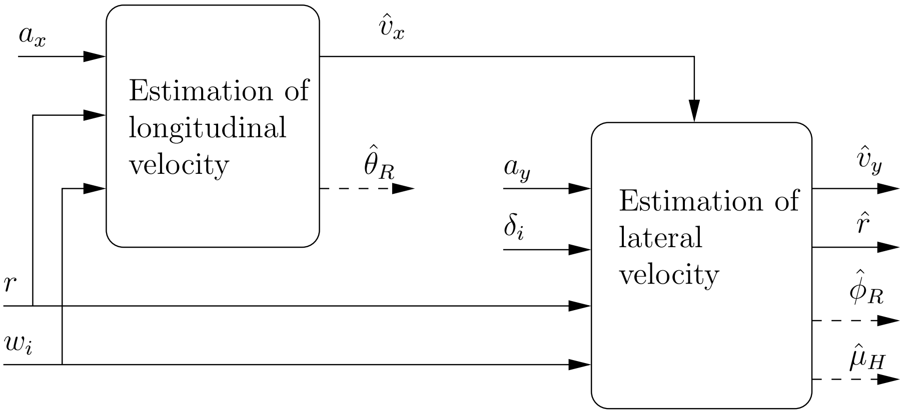

Figure 2: Cascaded observer structure

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