Complex Embedded Automotive Control Systems
CEmACS

DaimlerChrysler
SINTEF
Glasgow University
Hamilton Institute
Lund University

Public
Periodic Activity Report
Reporting Period 3

October 2006

Executive Summary

Project Short Description

The high level of complexity in automotive systems requires a new approach to design. Moreover, to achieve higher performance and increased safety a coordination of different automotive control systems is required.

Objective The objective of CEMACS is to contribute to a systematic, modular, model-based approach for designing complex automotive control systems. The Specific Target Research Project is aimed at combining research into the theory of multivariable control and nonlinear observers with a selection of novel prototype automotive control applications.

The basic research topics of CEMACS include classical multivariable control analysis and design techniques (in particular for high performance decentralised control systems in the presence of communicational time delays), hybrid and nonlinear and adaptive control, and observers with global convergence properties.

Control and observer designs will be evaluated using two real-life benchmark integrated chassis control design applications. These are

- vehicle dynamics control for active safety (roll-over mitigation and, as a long-term goal collision avoidance by active steering),
- multivariable control design for ride and handling using multiple actuators (Generic Prototyping).

For the evaluation prototype experimental vehicles will be provided by one of the industrial project partners. The control approaches developed within the project will be implemented in the experimental vehicles and validated using a specified set of test manoeuvres. The systematic experimental validation will provide feedback for the further development of the basic research and control system design parts of the project.

Expected Results The project will provide new strategies, algorithms and tools for systematic and accurate design prototyping and control of complex distributed systems with the main focus on advanced control for embedded automotive systems. Moreover, the control systems developed within CEMACS will be implemented and validated in various test vehicles thus, enabling an easy take-up of the results by system developers.

Furthermore, a number of generic results in the fields of state estimation, robust multivariable control and hybrid, nonlinear and adaptive control will be generated.

Partners and their role

DaimlerChrysler Research and Technology acts as the project coordinator, provides the specifications for the control and state estimator design and provides the experimental vehicles and the infrastructure for the evaluation of the resulting control systems.

Lund University is responsible for basic research on hybrid control and the roll-over mitigation part of the project.

Glasgow University is coordinating the development of control design methods and designs the collision avoidance control.

SINTEF is developing vehicle state estimation techniques and will be in charge of the overall system integration.

The Hamilton Institute, National University of Ireland Maynooth will carry out the multivariable control design for integrated chassis control.

Work performed

Work in the third reporting period was to implementation and simulation activities. The control systems specified in the second reporting period were integrated in the real-time software and thoroughly tested using a state of the art vehicle dynamics simulation package. These activites concerned roll-over avoidance, collision avoidance, 4-wheel steering based lateral control and active suspension. Furthermore, the tests and benchmarking of the nonlinear observer continued using experimental data obtained from various test vehicles under low-friction and high-friction road conditions. Preliminary real-life tests were also carried out for the integrated chassis control system.

Achieved Results

The project is running according to the workplan as far as the achieved results are concerned. The main highlights for the third reporting period can be summarised as follows:

- Controllers for roll-over avoidance and collision avoidance implemented and tested in simulation.
- Integrated chassis controller tested in simulation.
- Components of the Integrated Chassis Control system (yaw-rate control, side-slip control and roll-angle control) were successfully tested in the car.
- Final report on the control approaches with focus on high performance decentralised multivariable control, control allocation and switched control.
- Final Report on vehicle state observation including further results on the benchmark of Side-slip angle observers based on experimental data. An S-class and an M-class based test vehicle were used to carry out skidding manoeuvres under winter low-friction conditions in Sweden. The data was used to validate the observer design for very large side-slip angles. Also, a run-time analysis of the real-time implementation of the nonlinear observer and comparison with an existing Kalman filter was carried out. The analysis showed the considerable reduction of in computational complexity of the new approach in comparison to the Kalman filter approach.

- System integration of the different controllers and observers. The sub-systems developed within the project were integrated into the existing real-time software of the various test vehicles. The results of the integration are documented in an interim report.

Intentions for Use and Impact

The Project objectives are well integrated with the current R&D activities of the industrial partners and the automotive industry in general; this will enable an efficient industrial exploitation of the CEmACS results. With a test vehicle for roll-over mitigation there will be improved chances for dissemination of the results of workpackage 1.1.

The dissemination of generic results was continued as planned. Since the start of the project 14 papers have been submitted to peer-review journals [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14], of which 10 papers have been accepted for publication and 3 published. 24 papers have been submitted to major conferences [15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 24] of which 13 have been accepted. 6 papers are in preparation [38, 39, 40, 41, 42, 43]. Many of these papers have been prepared as a joint effort of two or more partners of the consortium.

In addition to the publication there is also a patent application [44] on multiple-model-based vehicle load estimation.

The CEMACS workshop on theory was held in Lund at month 23 (June 1-2). The workshop was a joint event with the FP6 network HYCON strengthening the collaboration between the projects. The CEMACS consortium contributed three papers at this workshop [26, 33, 45]. In the two panel discussions which where attended by a number of industrial participants Jens Kalkkuhl gave an overview of the CEMACS project.

The *Hamilton Institute* was involved in organising a special issue of the IEE Proceedings-Part D, September 2006, on the topic of Hybrid Systems. Three papers from the consortium have been accepted for this issue.

The CEMACS consortium has established contacts to the projects SPARC (Secure Propulsion using Advanced Redundant Control) and HYCON to investigate the possibility of collaboration between the two projects since there is a number of common points of interest. The SARC consortium comprises 19 contractors, combining automotive manufactures, component suppliers and research institutions and thus, offers an excellent opportunity for the dissemination of results from CEMACS.

Another dissemination activity which emerged this year is the collaboration with the *AUTOSAR* consortium (AUTOSAR = **Aut**omotive **O**pen **S**ystem **Ar**chitecture, www.autosar.org). The objective of AUTOSAR is the establishment of an open standard for automotive system architecture. It will serve as a basic infrastructure for the management of functions within both future applications and standard software modules. DaimlerChrysler as a Core Partner of AUTOSAR will built a demonstrator car demonstrating the modular scalable transferable and reusable architecture and the standardised interfaces wich are the objective of the consortium. It is planned to incorporate directly functions developed within the CEMACS project into the

AUTOSAR demonstrator.

Contents

1 Project objectives and major achievements during the reporting period

1.1 General project objectives

The main objective of CEMACS is to contribute to a systematic, modular, model-based approach for designing complex automotive control systems. The project has been set up to satisfy an increasing demand within the automotive industry for control systems integration and adequate design methodology. A main feature of CEMACS is that it combines research into theoretical issues with the work on real life automotive control applications culminating in the experimental validation of the results in a set of test vehicles. In figure 1 the general approach of the project is depicted. There are two major theoretical workpackages WP3 and WP4 addressing

- *control design* and
- *sensor fusion/ state observation*

as the two main issues in automotive electronic systems. These basic research workpackages will form the foundation of two applicational workpackages WP1 and WP2 aimed at two complementary issues in automotive control

- *Active safety systems*
- *Improvement of handling characteristics of cars.*

Workpackage W5 is dedicated to the experimental validation and demonstration of the research results. For this purpose a set of existing test vehicles at the *DaimlerChrysler* research and technology centre will be used. As illustrated in figure 1 there will be feedback of the experimental verification results giving direction to the theoretical research work. This can be considered one of the main benefits of the project.

Dissemination and Exploitation of the results is the main point in all European Commission research programmes. Workpackage WP6 addresses these issues within CEMACS. Since the project will generate both, generic as well as applicational results there will be two paths for the dissemination and exploitation strategy

- Publication of generic results for the benefit of the European research community and
- Exploiting the applicational results for the benefit of the European automotive industry.

The validation experiments will be crucial for a successful exploitation of the applicational project work.

1.2 Current relation to the state-of-art

In many aspects the project activities go well beyond the current state-of-art. This is in particular the case for the vehicle dynamics emulator of WP2 as has been shown in

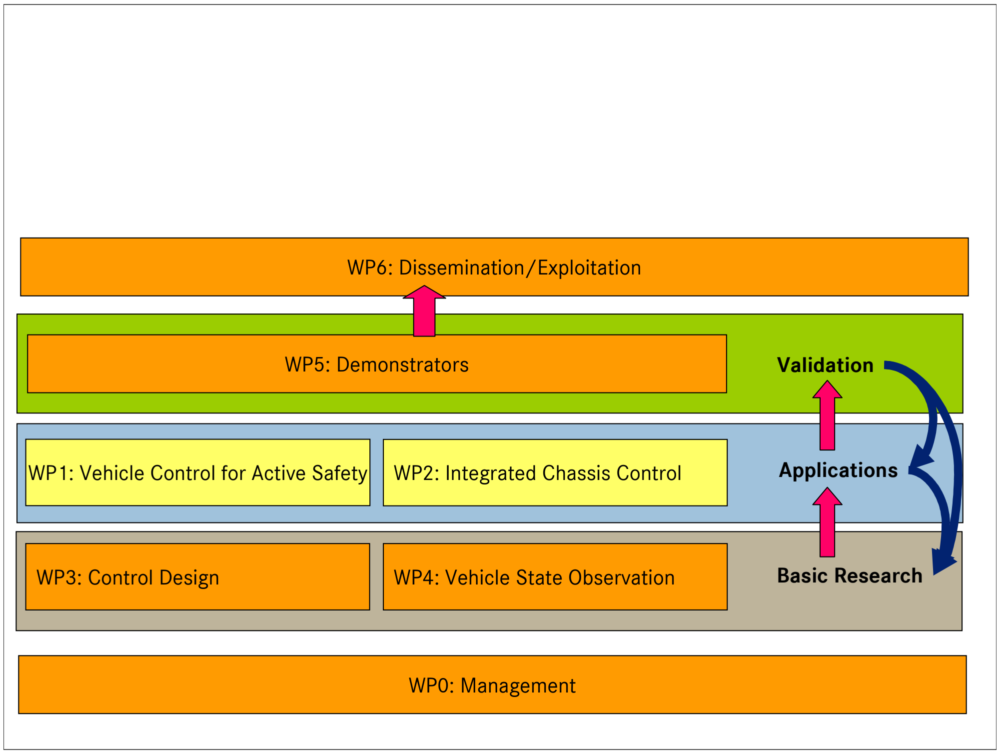

Figure 1: CEMACS project general approach

the state-of-art rewiew D2. The topic of WP1, vehicle dynamics control to enhance safety, is a very active area of research and development in the automotive sector. A state-of-art analysis has been carried out prior to the project and the requirements for future developments have been identified. This concernes in particular load-adaptive roll-over mitigation strategies and lateral collision avoidance. Also, the positive feedback with respect to the submitted papers indicates that the basic research work of CEMACS contributes considerably to the progress in the field.

1.3 Objectives for the third reporting period (MS3)

The project activities up to Milestone MS3 are depicted in the Gantt diagram in figure 2. The third reporting period of CEMACS up to Milestone MS3 was mainly dedicated to implementing the the different control systems designed within the framework of the project. The implementation was then validated using a vehicle dynamics simulation package. This work was carried out in Workpackages 1, 2 is represented in the Gantt diagram by Activities Nos. 11,12,13, 22, 23 and 24 and respectively.This work results in three simulation demonstrations which constitute the deliverables D13 and D14. These demonstrations will be presented at the review meeting correspondig to Milestone MS3. In parallel, in Workpackage 5 the integration of the controllers into the test vehicle real-time software was carried out (activity No. 50). The integration is described in deliverable D17 Workpackage 3 finished with the integration of technologies which is reported in the final report D13. In workpackage WP6 the dissemination of theory has continued. In addition the exploitation of tools (activity 58) has started.

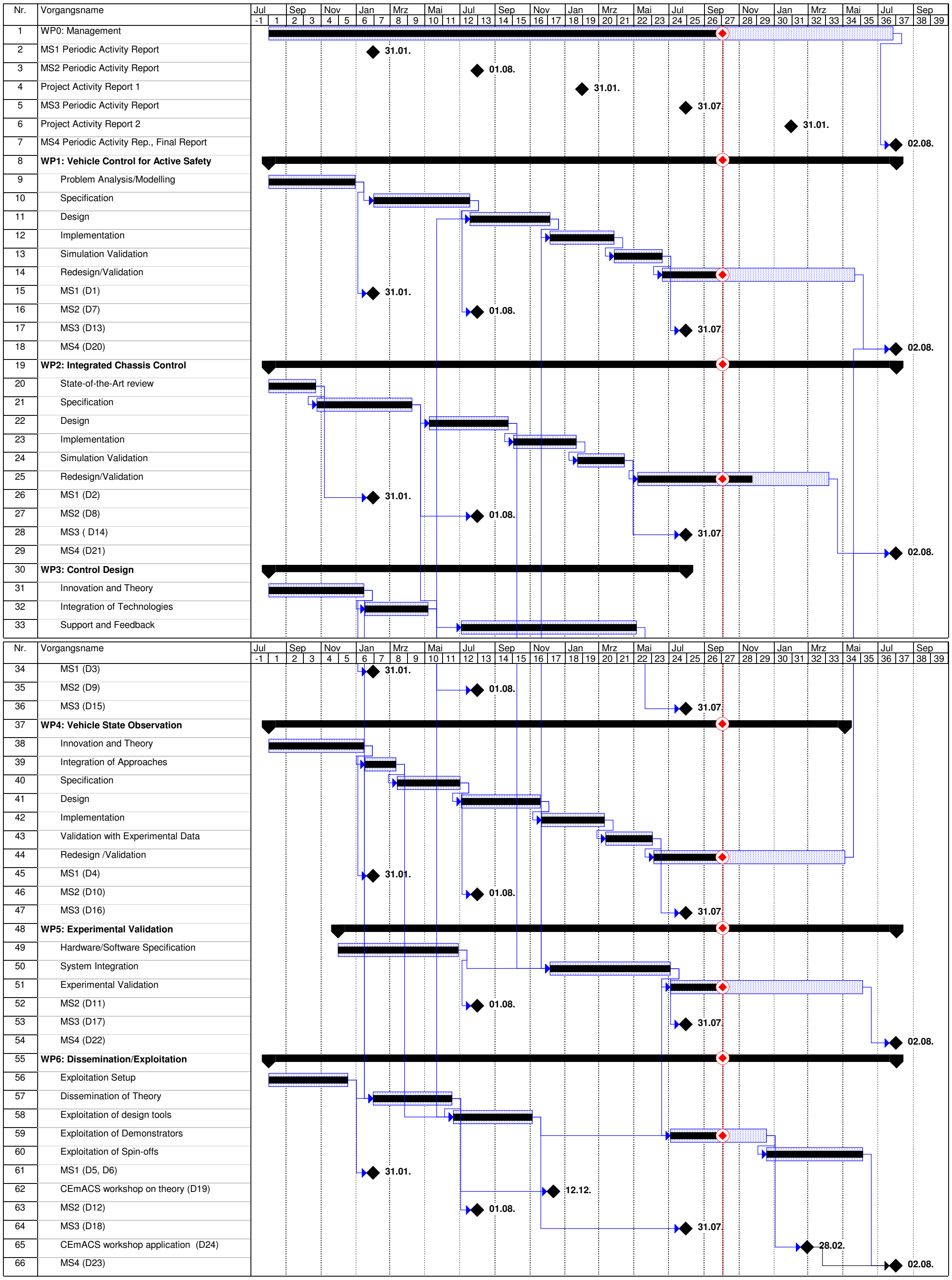

Figure 2: Gantt diagram of the project

Contractor	**Efforts** (person-months)
DaimlerChrysler	12.00
Lund University	12.00
Glasgow University	12.00
SINTEF	12.00
Hamilton Institute	12.00
total	60.00

Table 1: Project efforts within the second reporting period

1.4 Management Activities

The third project meeting was held in Lund June 1-2 at the fringes of the joint HYCON/CEMACS workshop. The meeting was mainly dedicated to the discussion of implementation/simulation results. The agenda included:

1. activity reports of all contractors,
2. Discussion of implementation and simulation results.
3. planning of travel activities,
4. preparation of the reports and review at MS3.

The following visits took place during the third reporting period:

20 November-11 December 2005: Brad Schofield, ULUND

21.-23. Februar, 21. March-11. April, 16. June-7.July 2006: Mehmet Akar, Hamilton Institute

1.-10. August 2006: Carlos Villegas, Hamilton Institute

26.-28. September 2006: Lars Imsland and Hovard Grip, SINTEF

In addition Jens Kalkkuhl visited Lund on August 25 to plan the experiments in WP1.1 (roll-over protection)

1.4.1 Ressources

All ressources have been spent according to the work plan.

The efforts spent up to milestone MS2 are displayed in table 1.

DaimlerChrysler purchased an inertial measurement system INS (Euro 9300) and spent Euro 4966 on the integration of the INS with a high precision GPS sensor (purchased in the previous reporting period) and a dSpace Autobox to be used in WP4 for the validation of the nonlinear observer. DC also aquired a camara system costing Euro 8359 for the data logging and documentation of the collision avoidance experiments.

1.4.2 Problems and corrective actions

GU requested a re-distribution of efforts for the next reporting period.

Changes to the budget headings are requested to cover additional salary costs, arising as follows: The salary costs for Geraint Bevan (to be employed for the full 36 months of the project) are approximately £4,000 (Euro 6,000) higher than anticipated. A studentship for Simon O'Neill should be extended for 6 months, costing £6,150 (Euro 9,200). Simon contribution to the project was not charged to the project until now as he was financed by a University studentship. The total additional salary expenditure is £10,150 (Euro 15,200). It is planned to re-allocate the money as follows:

£3,800 (Euro 5700) from Equipment heading,

£4,000 (Euro 6000) from Exceptional Items heading

£2350 (Euro 3500) from Travel heading.

The changes been discussed with the Project Officer approved.

1.5 Major technical achievements

The technical achievements of the third reporting period are reported in detail in section 2 of this report. Among those the following are of particular importance for the progress of the project:

1. Simulation Demonstrations of roll-over prevention, collision avoidance and integrated chassis control.
2. A further increase in the publication activities and establishing contacts to the DC passenger car and commercial van development departments,
3. Extensive tests of the novel non-linear side-slip angle observer under different driving conditions and final results of the observer benchmark against a state-of-the art Kalman filter (WP4) published in the final report,
4. Integration of controllers and observers into the test vehicle real-time code (WP5),
5. The third issue of the the Dissemination and Exploitation plan (WP6).

2 Workpackage progress of the period

2.1 Workpackage 1: Vehicle dynamics control for active safety

WP objectives and starting point

The objective of the workpackage is to develop and evaluate vehicle dynamics control systems for active safety for roll-over avoidance and steer-by-wire based collision avoidance. The ability to stabilise the vehicle close to its physical limits in the presence of time varying road friction conditions will be crucial for realising improved safety and accident-free driving concepts. Also, coordination between active roll stabilisation and anti-skid control will be required.

During the second reporting period up to MS2 work was focused on specification of the controllers used in roll-over mitigation and lateral collision mitigation.

Lund University is the lead contractor of WP 1.

Activities and achievements

WP1.1 Rollover mitigation The objective for the current reporting period is to demonstrate in simulations a working controller capable of preventing vehicle rollover. At the start of the reporting period, work on vehicle modelling as well as controller specifications and test manouver selection had been performed. In addition, considerable work had been done on control design. Existing controller implementations had been integrated with the CASCaDE simulation software, delivered by DaimlerChrysler.

During the reporting period a great deal of work was carried out on the development of *control allocation* strategies, with emphasis on real-time application in embedded systems. A strategy based on linearly-constrained Quadratic Programming was developed, which is capable of operating at fast sampling rates while explicitely handling constraints.

The controller, including the control allocation algorithm described above, was successfully implemented in Matlab/Simulink, and tested using the CASCaDE software simulation of a light commercial vehicle, using a variety of standard test manouvers as defined in Deliverable D7.

In addition, work on a C version of the controller is underway. This is almost complete as of the end of this reporting period. The C implementation is required for experiments on the rollover test vehicle. It is hoped to conduct experiments on the rollover test vehicle during autumn 2006.

An article describing the controller has been published, and will be presented in October 2006 at the Conference on Control Applications, Munich [23].

During spring 2006 a Master's thesis project was carried out in Lund [46]. The project involved investigation of advanced estimation techniques for tire force and friction estimation.

WP1.2 Lateral Collision avoidance Work package 1.2 has progressed satisfactorily and has successfully met all objectives to date. There have been no major issues that have compromised the success of the work package and none are foreseen to arise during the remainder of the work. The work on this package is being undertaken at the University of Glasgow.

In the first reporting period, a non-linear vehicle model was developed for use as a design and evaluation tool. The model included the principal dynamics of interest for lateral manoeuvring and was implemented in C++ in a manner which would allow its use within GNU Octave and Matlab as well as the capability of being embedded within a Simulink block diagram simulation environment.

During the second reporting period, a specification was developed for an emergency collision avoidance single lane-change manoeuvre. The specification included a vehicle description, a geometric description of the obstacle course to be navigated by the vehicle and the actuator and control system constraints which would apply.

The objective for the third reporting phase is to demonstrate, by simulation, the successful implementation of a controller that meets the performance criteria defined in the previous phase. It is intended that the controller will then be implemented on a test vehicle during the next reporting period.

A controller design was initially developed as a set of scripts for use with the non-linear design model that had been created during the first reporting period. As the controller development progressed and was refined (in concert with work package 3) its performance was assessed using these scripts. When a reasonable solution seemed to have been found the controller was then implemented in Simulink.

Successful completion of the target manoeuvre was presented at the CEmACS/Hycon workshop (Lund, June 2006) on the basis of simulation results using the non-linear design model and forms the basis of a paper submitted to the International Journal of Control.

Subsequently the design model was replaced in the Simulink environment with a more detailed proprietary model provided by DaimlerChrysler. Evaluation with this more complex model indicated similar general performance to that seen with the design model, but minor discrepencies meant that the controller narrowly failed to meet the specified manoeuvre criteria.

Further adjustment to the design was undertaken within work package 3 and the controller was modified to reflect the changes that were made. During this period, the work was presented at a poster session at the 2006 International Control Conference/EPSRC post-graduate workshop (Glasgow, August 2006).

After an acceptable design had been identified which was capable of successfully meeting the specification, work was undertaken to simplify the implementation to ensure that it would be possible to meet real time requirements when implemented on the vehicle in the next phase of the project. This involved the removal of run-time model inversion and the introduction of pre-processed lookup tables.

Simulation within Simulink using this improved controller design and the more complex proprietary vehicle model was then evaluated to ensure that the performance criteria are still met. This simulation will form the basis of a demonstration to be presented at the forthcoming project review meeting.

Deliverables

D13: Simulation Demonstration VDC for Active Safety

Milestones

The Milestone related to this reporting period is MS3: Simulation Validation of the rollover and the collision mitigation controller. This milestone has been achieved during the reporting period.

2.2 Workpackage 2: Integrated Chassis Control

WP objectives and starting point

The objective of WP2 is to develop and evaluate an integrated chassis controller for generic prototype vehicles to be used as an emulation tool in the vehicle dynamics analysis and design process. The work within WP2 focused on the A class experimental vehicle PEGASOS, mainly because this vehicle is available for exclusive use by the CEMACS consortium while the S class vehicle TechnoShuttle is temporarily assigned to other projects. The work within WP2 was carried out by the *Hamilton Institute* which is the lead contractor in this workpackage.

Activities and achievements

1.1) Study of Lateral Dynamics: Two robust controllers (one based on traditional PID concepts [38] and the other utilizing sliding mode theory [28, 47]) are designed for automotive vehicles with 4-wheel steering capability in order to emulate some desired sideslip and yaw rate dynamics Analytically, it is shown that the sliding mode controller is robust to plant parameter variations by ±%10, and is invariant to unmeasurable wind disturbance [28, 47]. The performance of the sliding mode controller is evaluated via computer simulations to verify its robustness to vehicle parameter variations and delay in the loop, and its insensitivity to wind disturbance. Both controllers are also tested in CASCADE and ready to be implemented on PEGASOS.

1.2) Study of Vertical Dynamics: A mathematical model has been developed for the Active Hydropneumatic Suspension (AHP) on PEGASOS [39]. It has been validated with experimental data. Based on the mathematical model, a controller using the electronic current as the input has been designed to track some desired reference force[40]. The controller has been tested on CASCADE and has been successfully implemented on PEGASOS [39]. The proposed controller tracks some reference force which is demanded by an outer control loop. The performance of the outer loop has been examined in CASCADE simulations, and effects of different controller parameters have been noted. Alternative designs for the control of outer loop have also been looked at.

1.3) Integrated System: In computer simulations, it has been noted that the interaction from the vertical to lateral dynamics is low for lateral accelerations below $4m/s2$. Since we are only interested in maneuvers below this threshold, this suggests that the lateral dynamics controller design can be carried without considering the effect of vertical dynamics. However, both computer simulatons and experimental tests suggest that the effect of lateral dynamics on the vertical ones is significant. With this in mind, the lateral controller together with a modified vertical controller is implemented on PEGASOS. The performance of the integrated controller has been examined in CASCADE. This controller has also been implemented and tested on PEGASOS. Based on experimental results, modifications are being made to the design.

1.4) Experimental: In 2006, Dr. Akar made three site visits to DaimlerChrysler, Sindelfingen, Germany: February 21-February 23, March 21-April 11, June 16-July 7. The three day visit in february was to familiarize with the AHP system. The second visit was to implement and test the force controller designed at the Hamilton Institute [40]. Subsequent to the recommissioning of AHP on PEGASOS in april/may 2006, the third visit was to examine the performance of the vertical controller on the revised system. Several experiments were done to test and retune the vertical controller. Also in the third visit, the interface for the integrated controller was commisioned properly and initial full scale tests were conducted to emulate integrated vehicle dynamics.

2.1) Modelling of an active hydropneumatic suspension and development of a simulation : Based on the literature we developed a complex model of an active hydropneumatic suspension. For control purposes, the model was linearised around some operating points. The model was simplified mainly with the use of bond graphs to take into account the relationships between mechanical, electrical and hydraulic systems.

2.2) Data-based identification of active hydropneumatic suspension in the test car: In order to validate compare the models obtained from the suspension and the real suspension in the car, test data was used from varied test conditions. Firstly, an input-output model was identified from the test data. Afterwards, the model obtained previously was partially validated.

2.3) Design of two new approaches of vertical dynamics controller for emulation: Based on the literature and the insight obtained through the suspension identification we obtained two different models of a vehicle equipped with an active hydropneumatic suspension based. The first model considers a displacement actuator [35] while the second model considers a force actuator. Both configurations can be used separately as part of a cascaded control structure. The control strategies were explored and tested in simulation using a quarter car model and a full vehicle model with strut geometry.

2.4) Design of a new lateral dynamics controller based on QFT: As part of a visit from Marta Barreras to the Hamilton Institute, a new controller was designed to track lateral dynamics reference signals, *i.e.*, yaw-rate and sideslip angle [31]. The controller was designed to be non-diagonal using MIMO QFT methods introduced by Garcia-Sanz *et al.* It was tested using DaimlerChrysler proprietary simulation CASCaDE where the main requirements of disturbance rejection and trajectory tracking were satisfactory fullfilled.

2.5) Vehicle dynamics interactions: The interactions among the different degrees of freedom of the vehicle were analysed in simulation and with test results. Simulation results using a complex full vehicle model developed at the Hamilton Institute showed that the interactions from vertical to lateral dynamics to be small below $4m/s^2$ for the whole operating frequency range. On the other side, interac-

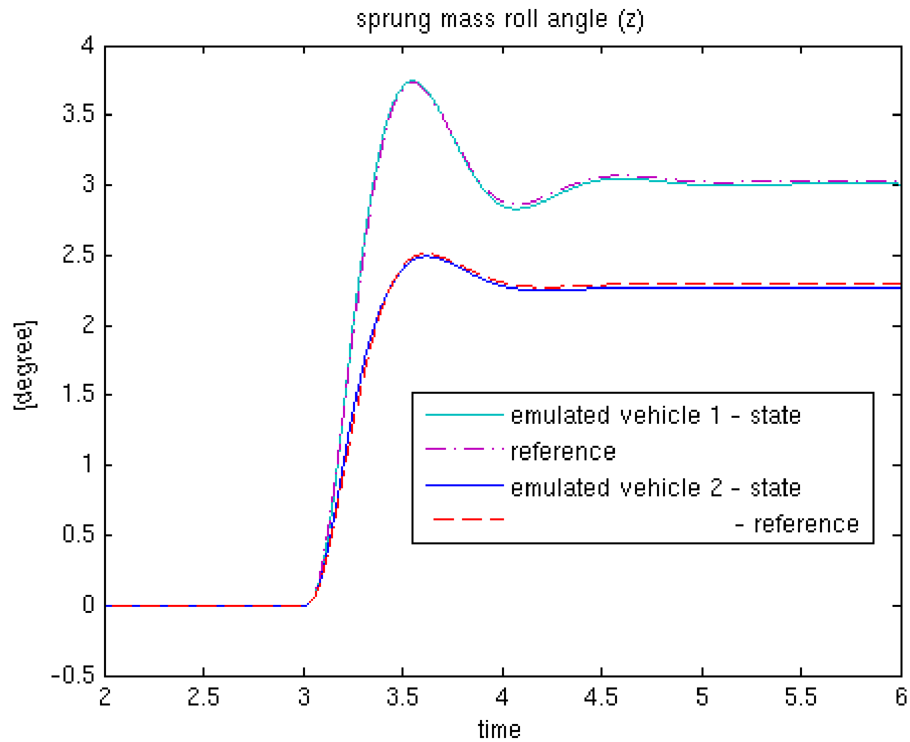

Figure 3: Vertical controller used for roll emulation of two different vehicles.

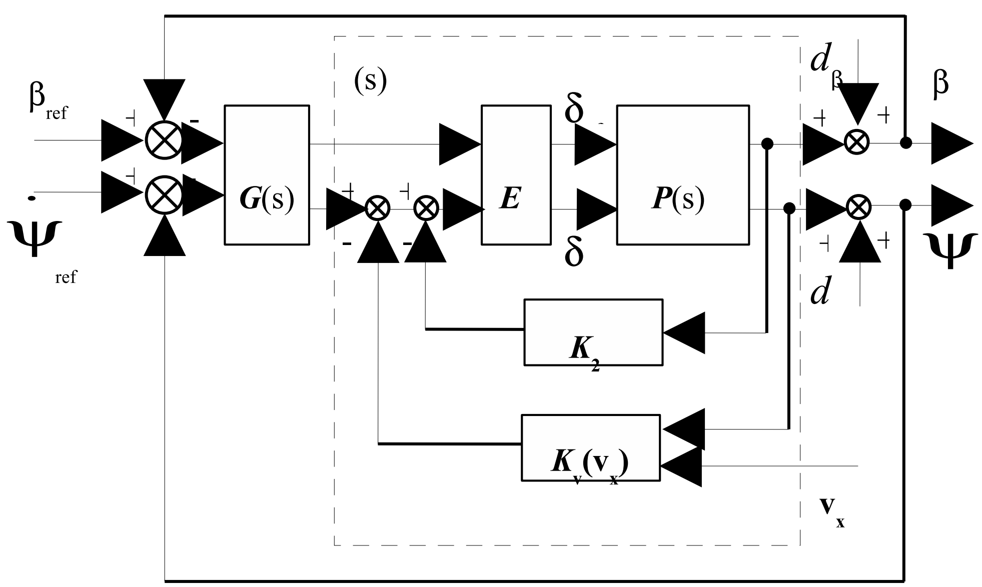

Figure 4: Lateral controller structure

tions from the lateral dynamics to the vertical dynamics are well known to be large mainly through roll and pitch moments. Controllers taking into account the latter results have been developed as part of the project and the necessary modifications will be made according to the experimental results.

2.6) Vehicle tests of lateral and vertical controllers: A lateral controller developed at the Hamilton Institute together with modifications to the vertical controller were tested in DaimlerChrysler. Improvements in the tracking were obtained with the use of feedforwards for both controllers. Besides, emulation of five different vehicles (from a small vehicle to a bus) were performed on the test vehicle [41].

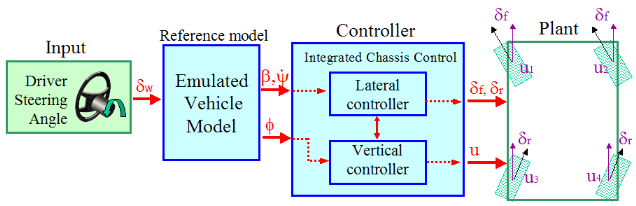

Figure 5: Emulation Controller Architecture

Progress towards milestones

- Design and test in simulation of the feed-forward part of the ICC 4-wheel steering controller.
- Interaction analysis of lateral and vertical control.
- Initial work on the design of the active suspension controller.
- Control specification documented in D8.

The work in WP2 is progressing according to workplan and milestones.

Deliverables

D14: Simulation Demo Integrated Chassis Control.

Milestones

MS3: Simulation demo presented at the review meeting.

2.3 Workpackage 3: Control Design

WP objectives and starting point

Main objective of workpackage 3 is to investigate systematic modular approaches for the design of complex embedded control systems. Methodologies that will be developed are aimed at

- *WP3.1, WP3.3:* the realisation of high performance decentralised multivariable control systems which operate under hard real-time conditions in the presence of time delays, and state and actuator constraints;
- *WP3.3:* hybrid control systems for improved fault tolerance, graceful degradation and robustness with respect to a highly time-varying environment.
- *WP3.4:* the realisation of nonlinear and adaptive controllers to stabilise vehicles at the physical limits in the presence of uncertainties in road friction and vehicle mass and load distribution; and

All contractors have been very active in those fields of control prior to the start of the CEMACS project (e.g. in the FP5 Esprit project H2C-Heterogeneous and Hybrid Control Technology). Workpart 3 offers a good way to consolidate and merge the different approaches and to develop them further towards application.

Glasgow University as the lead contractor of workpackage 3 is responsible for coordinating the research efforts.

Activities and achievements

Work package 3 is aimed at developing complementary controller design techniques and integrate those with the application in the other work packages. While GU is coordinating this work package, Lund, Hamilton and SINTEF are also working on this package.

The contribution to work package 3 undertaken at the University of Glasgow has focussed on control design required to support the objectives of work package 1.2 - emergency lateral collision avoidance. At the conclusion of the work in WP3, and on the basis that WP1.2 is successfully meeting its objectives, this part of the work must be considered to have been successful.

Initial efforts concentrated on the use of Individual Channel Analysis and Design (ICAD) and Pole Placement techniques to design suitable controllers for the non-square, multi-input multi-output system. A controller architecture that made use of a feedforward reference steering angle and a velocity-based linearisation of the braking system proved effective at providing a reasonable general vehicle response and allocating control effort between redundant actuators. This architecture was also seen to be a reasonable way of coping with changing plant dynamics at parts of the handling envelope far from points of equilibrium.

It was initially envisaged to design a feedback steering loop in a similar manner. However, as work progressed it became increasingly clear that linearised models of the plant failed to capture important behaviour of the yaw response to the steering system, which was the apparent result of non-linear interactions between the steering and braking inputs. Consequently these linear design techniques were not providing as much insight as might have been hoped.

With a working feedforward steering controller and feedback brake controller already in place, tuning of a steering feedback controller using the non-linear simulation was found to be an effective way of improving overall controller performance. With a working feedback controller, the brake loop could then be refined in a similar manner. The overall design process therefore consisted of developing an appropriate controller structure and control loops to provide approximately the desired response, followed by refinement using non-linear simulation.

Work on WP3 at the Hamilton Institute has progressed in three main directions. Techniques have been developed for the design of control systems that involve switching - in particular for Lur'e type systems. We have also been extending and applying recetly developed design methods for application to automotive rollover control problems. In particular, in this context we have,

1. Written a literature survey of multiple-model and switched control and estimation methods in the form of a technical report [42].

2. Conducted research work on the analysis of quadratic stability for a specific type of switched uncertain system, where the constituent matrices of the switching system are assumed to have bounded uncertainty in each element. As described in [48, 22], it is possible to use a simple spectral condition to check the switching stability of such systems, which generalizes a recent result on CQLF (common quadratic Lyapunov function) existence for switched Hurwitz matrices.

3. Developed a real-time method for road vehicle center of gravity (CG) position estimation using standard automotive sensors in conjunction with adaptive anti-rollover controllers [44, 29, 49, 30]. The method utilizes multiple linear single-track and linear roll-plane models, which span the uncertain parameters space. A rule based switching among these models yields an online estimation of the CG position, which can be used to tune anti-rollover and lateral dynamics controllers online to improve their safety and performance.

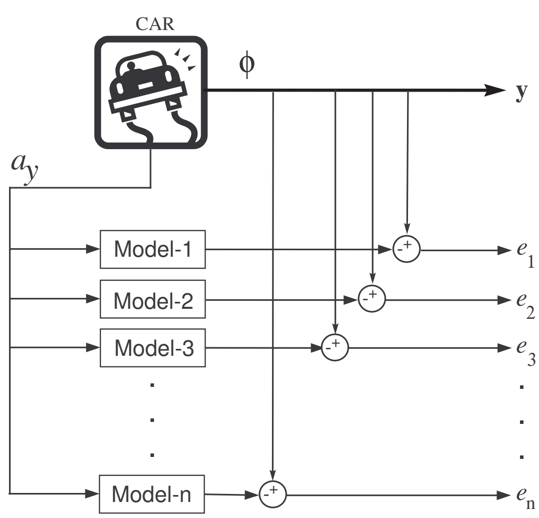

Figure 6: Multiple Model Estimation of Center of Gravity Position

4. Extended a recent result on CLS existence for pairs of Hurwitz matrices to the case of matrices with general regular inertia [34, 50]. We obtained this by extending the classical Lefschetz version of the Kalman-Yacubovich-Popov (KYP) to the case of matrices with general regular inertia. We then used this result to derive an easily

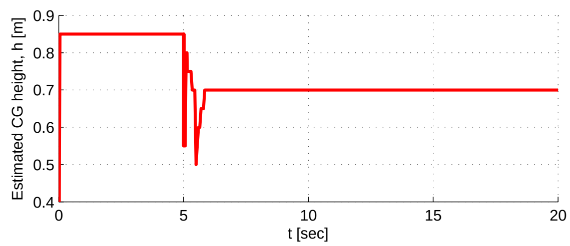

Figure 7: Center of Gravity Height Estimation Example

verifiable spectral condition for a pair of matrices with the same regular inertia to have a common Lyapunov solution.

5. Developed a novel robust rollover prevention control design strategy for automotive vehicles. Specifically, we exploited a recent result, which provides controllers to robustly guarantee that the peak values of the performance outputs of an uncertain system do not exceed certain values. We also introduced a new measure of performance for rollover prevention, the Load Transfer Ratio LTR_d, and designed differential braking-based rollover controllers to keep the value of this quantity below a certain level [32, 33, 51].

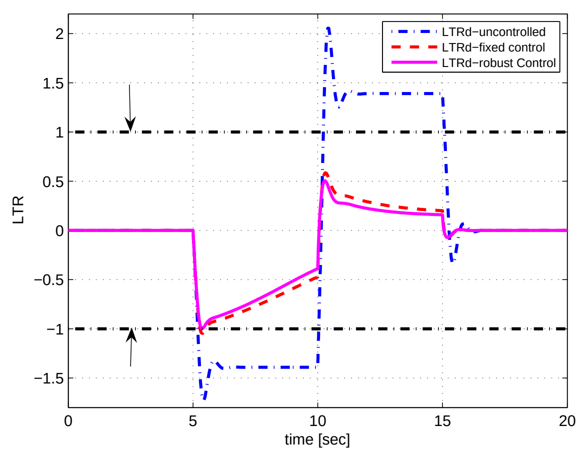

Figure 8: LTR_d variations for uncontrolled and robustly controlled vehicles

5. Analyzed the global attractivity properties of a class of discrete-time switching systems of with constituent matrices that are Schur stable. We assumed that there is a no CQLF (common quadratic Lyapunov function) for these matrices, yet for every pair of matrices are simultaneously triangularizable. We showed that despite the non-existence of a CQLF for this special class of switching system, the origin is globally attractive. Utilizing this result we also presented a synthesis procedure to construct switching stabilizing controllers [41].

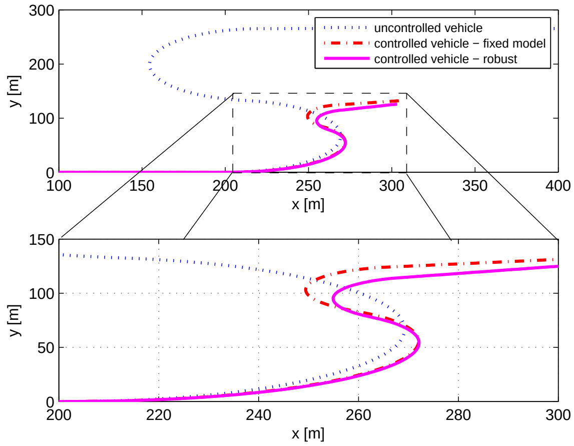

Figure 9: Inertial trajectories for uncontrolled and robustly controlled vehicles

Progress towards milestones

- The activities with respect to innovation and theory have been successfully finished.
- Generic results have been achieved in all four subpackages of WP3.
- The control technologies developed within WP3 have been integrated within the other workpackages.

The progress within WP3 is in accordance with the workplan.

Deliverables

D15 Final Report on control design.

Milestones

MS3: Submission of final report.

2.4 Workpackage 4 - Vehicle state observer

2.4.1 Objectives

- Development of a nonlinear observer with global convergence properties for automotive state estimation and sensor fusion, based on the specification and preliminary designs given in report D10 at month 12.
- Implement, validate and combine the approach with conventional Extended Kalman-filtering using experimental data in the test vehicles.

2.4.2 Progress towards objectives

- The completion of WP4 is according to plans and milestones, and the development in this work package is documented in deliverable D16.
- Several designs of vehicle velocity estimators, including road/tyre friction coefficient estimation and road bank angle estimation, are completed by SINTEF and DaimlerChrysler. Theoretical analysis and experimental validation are carried out.
- Benchmarking indicates that the accuracy achieved with the nonlinear observers is in most situation better than an Extended Kalman-filter, while at the same time conceptually and computationally much simpler.
- Verification of observer requirements for WP1 and WP2 as specified in deliverable D10 is completed.

2.4.3 Deviations from the project work programme

None.

2.4.4 Deliverables

D16 - Vehicle state observer - final report. Due 10 October 2006, expected to be submitted on time.

2.4.5 Milestones

MS3 - Validated observers meeting the specifications. Due 10 October 2006, expected to be submitted on time.

2.5 Workpackage 5: Experimental Validation/Test Vehicles

WP objectives and starting point

According to the work programme the overall objective of WP5 is the evaluation and verification of the effectivenes of the design methodologies and controllers developed within CEMACS. For this purpose experimental test vehicles used in vehicle dynamics research and design are provided by DC. Starting point are two existing experimental vehicles equipped with front-wheel and rear-wheel steer-by-wire and active suspension systems. To be used in the verification experiments these vehicles required hardware and software upgrades (see work programme section 8.3.2). The upgrading was started in the previous reporting period and has now been completed. A commercial van equipped with a brake-by wire system is also available for the roll-over protection experiments.

The lead contractor of WP5 is *DaimlerChrysler*.

Activities and achievements

The main activities of WP5 up to milestone MS3 was the control system integration for the different test vehicles.

Preparational work for the evaluation experiments. The A class based test vehicle (Pegasos) was equipped with new high-precision control valve for the active suspension system. The commercial van has been equipped with a dSPACE μ-Autobox a top-of-the-range inertial measurement system, an optical speed sensor and additional pressure sensors for the brakes.

Control system integration The control system integration included the following systems

Integrated Chassis Control/test vehicle Pegasos:

- Multivariable Lateral controller for yaw rate and side slip based on an individual channel design approach (see description of WP2).
- Nonlinear observer for side slip angle estimation (see description of WP4).
- A low-level force controller (sliding-mode based) to improve the dynamics of the AHP suspension struts (see description of WP2).
- A feed-forward based tracking controller for the roll degree of freedom (see description of WP2).

State Observation/test vehicle TechnoShuttle: Nonlinear observer for side slip angle along with a Kalman filter and an optical sensor for benchmark and demonstration purposes.

Roll-over Protection /Commercial Van: A roll-over protection controller together with a LQ-programming based control allocation algortihm was integrated with existing roll-angle estimator, ESP and ABS functions.

Collision avoidance/test vehicle TechnoShuttle: Feed-forward trajectory generator and multivariable controller integrated with the nonlinear observer and existing ESP and ABS system.

The entire implementation was done in Matlab/Simulink. When necessary (Observer, control allocation) C code was integrated using the Simulink S-function interface. The integrated control systems were validated using Simulation. For side slip angle observer and ICC controllers which are already operational in the test vehicles the experimental validation has started. Experimental validation of the other controllers will be carried out in the last year of the project according to the workplan.

Preliminary tests Extensive tests have been carried out with respect to the AHP system of Pegasos. In particluar the force controller and the tracking of the roll angle was validated and optimised. Tests of the lateral control of Pegasos have also been carried out. In total 6 different reference models have been implemented (A-Class, Smart, Viano long wheel base, Viano short wheel base, Bus, Synthetic zero side-slip, zero roll). The lateral controller was tested in the car and is currently being tuned. In the commercial van the CAN communication, the sensor and actuator systems have been tested. The nonlinear observer is fully operational in Pegasos as well as Technoshuttle and experiments have been carried out to analyse its sensitivity with respect to road banks.

Progress towards milestones

- All major work packages, WP1.1, WP1.2, WP2, WP3 are provided with test vehicles for evaluation of their contol designs.
- All controllers and observers have been integrated into the real-time software.
- Preliminary tests of the lateral and vertical control systems for integrated chassis control have been carried out.
- Additional sets of experimental data and vehicle parameters have been provided for the observer validation in WP4.
- Support was provided for the run-time analysis of the observer benchmark.

The progress in Workpackage 5 is fully in accordance with the work plan.

Deliverables

Deliverable D17 (test vehicle system integration) due at milestone MS3

Milestones

MS3: Controllers and Observers integrated in the test vehicles (report D17) due at month 24.

2.6 Workpackage 6: Dissemination and Exploitation

WP objectives and starting point

The main objective of this workpackage is to provide a systematic and consistent framework for disseminating and exploiting the CEMACS results. For the second reporting period the objectives were

- to continue with the dissemination of generic results.
- to prepare the first project workshop on theory.
- to prepare the second issue of a plan for using and disseminating the knowledge generated within the project (deliverable D12).

- to maintain the project website.
- to initiate interaction with other FP6 projects.

Activities and achievements

The deliverable D18 has been prepared and submitted as an annex to this document.

The dissemination of generic results was continued as planned. Since the start of the project 14 papers have been submitted to peer-review journals [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14], of which 10 papers have been accepted for publication and 3 published. 24 papers have been submitted to major conferences [15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 24] of which 13 have been accepted. 6 papers are in preparation [38, 39, 40, 41, 42, 43]. Many of these papers have been prepared as a joint effort of two or more partners of the consortium.

In addition to the publication there is also a patent application [44] on multiple-model-based vehicle load estimation.

The CEMACS workshop on theory was held in Lund at month 23 (June 1-2). The workshop was a joint event with the FP6 network HYCON strengthening the collaboration between the projects. The CEMACS consortium contributed three papers at this workshop [26, 33, 45]. In the two panel discussions which where attended by a number of industrial participants Jens Kalkkuhl gave an overview of the CEMACS project.

The *Hamilton Institute* was involved in organising a special issue of the IEE Proceedings-Part D, September 2006, on the topic of Hybrid Systems. Three papers from the consortium have been published in this issue.

A successful real-life presentation of the nonlinear sobserver to team leaders of the DC passenger car department took place on the test track in Sindelfingen in July 2006. At this event the estimates of the side-slip angle from the nonlinear observer where displayed along with the Kalman filter estimate and the value measured by the optical speed sensor.

Contact where also established to the DC Commercial Van development department which is interested in using the results of workpackage WP2 (vehicle dynamics emulation) to assess design modifications made in Vans. The department supplied measurement data of a Viano van for the set up of a realistic reference model to be used in Integrated Chassis Control.

The CEMACS consortium has established contacts to the projects SPARC (Secure Propulsion using Advanced Redundant Control) and HYCON to investigate the possibility of collaboration between the two projects since there is a number of common points of interest. The SPARC consortium comprises 19 contractors, combining automotive manufactures, component suppliers and research institutions and thus, offers an excellent opportunity for the dissemination of results from CEMACS.

Another dissemination activity which emerged this year is the collaboration with the *AUTOSAR* consortium (AUTOSAR = **Aut**omotive **O**pen **S**ystem **Ar**chitecture, www.autosar.org). The objective of AUTOSAR is the establishment of an open standard for automotive system architecture. It will serve as a basic infrastructure for the management of functions within both future applications and standard software modules. DaimlerChrysler as a Core Partner of AUTOSAR will built a demonstrator car demonstrating the modular scalable transferable and reusable architecture and the standardised interfaces wich are the objective of the consortium. It is planned to incorporate functions developed within the CEMACS project into the AUTOSAR demonstrator. The exploitation of CEMACS results in the framework of AUTSAR will have a considerable impact on dissemination since the AUTOSAR consortium comprises all the major European automotive OEMs and suppliers.

A project website has been set up at `www.hamilton.ie/cemacs` and is updated regularly.

Progress towards milestones

The progress of WP6 is according to plan. All objectives at MS3 have been reached.

Deliverables

Third draft of exploitation and dissemination plan (D18).

Milestones

MS3: Detailed exploitation plan (Third issue D18) at month 24.

References

[1] R. Shorten and C. King, "Spectral conditions for strict positive realness of siso lti systems." IEEE Transactions on Automatic Control, October 2004.

[2] R. Shorten and O. Mason, "The geometry of convex cones associated with the Lyapunov inequality and the common Lyapunov function problem." Accepted for publication in Electronic Linear Algebra, 2005.

[3] E. Zeheb, O. Mason, S. Solmaz, and R. Shorten, "On the quadratic stability of switched interval systems: Preliminary results." Submitted for publications in IEEE Transactions on Circuits and Systems: Part II, 2005.

[4] S. Solmaz, O. Mason, and R. Shorten, "A generalized matrix inertia result for the existence of common quadratic lyapunov functions for a pair of matrices with rank-1 difference and same regular inertia." Submitted for publication in Linear Algebra and its Applications, 2005.

[5] E. Zeheb and R. Shorten, "Eigenvalue criteria for strict positive realness." Submitted for publication in IEEE Transactions on Automatic Control, 2005.

[6] J. Jouffroy, J.-J. E. Slotine, and T. I. Fossen, "Methodological remarks on contraction theory, exponential stability and lyapunov functions." Submitted for publication in Automatica, 2005.

[7] P. Tøndel and T. A. Johansen, "Lateral stabilization of automotive vehicles using multiparametric nonlinear programming." Submitted for publication in IEEE Trans. on Control Systems Technology, 2005.

[8] L. Imsland, T. A. Johansen, T. I. Fossen, J. C. Kalkkuhl, and A. Suissa, "Nonlinear observer for vehicle velocity estimation," *SAE International*, 2005. paper no. SAE 06AC-147.

[9] A. M., "Adaptive robust tracking of nonlinear systems using multiple controllers and switching." submitted to Systems & Control Letters.

[10] R. Shorten, F. Wirth, O. Mason, C. King, and K. Wulff, "On the simultaneous diagonal stability of a pair of positive linear systems." Accepted for publication in Linear Algebra and its Applications, 2005.

[11] R. Shorten, F. Wirth, O. Mason, C. King, and K. Wulff, "Stability theory for switched and hybrid systems." Submitted to SIAM Review, 2005.

[12] O. Mason, E. Zeheb, S. Solmaz, and S. R., "Some results on quadratic stability of switched systems with interval uncertainty." Submitted to IEEE Transactions on Circuits and Systems: II.

[13] C. King and R. Shorten, "A spectral condition for the existence of a cqlf." To appear in Linear Algebra and its Applications.

[14] Z. Sun and R. Shorten, "On convergence rates for switched triangular systems." To appear in Electronic IEEE Transactions on Automatic Control.

[15] L. S. Imsland, T. A. Johansen, T. I. Fossen, A. Suissa, and J. Kalkkuhl, "A nonlinear observer for vehicle velocity." Accepted for publication European Control Conference ECC/CDC, Seville, 2005.

[16] J. Tjønnås and T. A. Johansen, "Optimizing nonlinear adaptive control allocation," in *IFAC World Congress, Prague*, 2005.

[17] J. Hansen, R. Murray-Smith, and T. A. Johansen, "Nonparametric identification of linearizations and uncertainty using gaussian process models - application to robust wheel slip control." Accepted for publication European Control Conference, Seville, 2005.

[18] K. Wulff, R. Shorten, and F. Wirth, "On the stablisation of switched systems defined by n linear siso systems." Proceedings of the CDC/ECC, 2005.

[19] K. Wulff, R. Shorten, and F. Wirth, "Existence of periodic motion of Luré systems and a numerical approximation." Submitted for publication in CDC/ECC, 2005.

[20] A. Paul, M. Stefanovic, M. G. Safonov, and M. Akar, "Multiple controller adaptive control for a tracking problem using an unfalsification approach," in *Proceedings of the 2005 CDC/ECC, 2005*, (Seville), 2005.

[21] C. King and R. Shorten, "On the design of stable state dependent switching laws for single-input single-output systems," in *Proceedings of the 2005 CDC/ECC, 2005*, (Seville), 2005.

[22] O. Mason, E. Zeheb, S. Solmaz, and R. Shorten, "On the quadratic stability of switched interval systems: Preliminary results," in *Proceedings of the 2005 IEEE International Symposium on, Mediterranean Conference on Control and Automation 27-29 June 2005 Page(s):12 - 17*, (Cyprus), 2005.

[23] B. Schofield, T. Hägglund, and A. Rantzer, "Vehicle dynamics control and controller allocation for rollover prevention," in *Proceedings of the IEEE International Conference on Control Applications*, (Munich, Germany), Oct. 2006.

[24] L. S. Imsland, T. A. Johansen, T. I. Fossen, J. C. Kalkkuhl, and A. Suissa, "Nonlinear observer for vehicle velocity estimation.." submitted, SAE World Congess, Detroit, 2006.

[25] H. F. Grip, L. S. Imsland, T. A. Johansen, T. I. Fossen, J. C. Kalkkuhl, and A. Suissa, "Nonlinear vehicle velocity observer with road-tire friction adaptation," in *Proc. of the IEEE Conf. Decision and Control*, (San Diego), 2006.

[26] L. Imsland, H. F. Grip, C. Bohm, T. A. Johansen, T. I. Fossen, J. C. Kalkkuhl, and A. Suissa, "Nonlinear observer for vehicle lateral velocity.," in *Workshop on Automotive Systems and Control*, (Lund, Sweden), 2006.

[27] L. S. Imsland, H. F. Grip, T. A. Johansen, T. I. Fossen, J. C. Kalkkuhl, and A. Suissa, "Nonlinear observer for lateral velocity - validation and comparison with an extended kalman filter." accepted paper 07AC-102, SAE World Congress, 2007.

[28] M. Akar, "Yaw rate and sideslip tracking for 4–wheel steering cars using sliding mode control." Proc. of IEEE International Conference on Control Applications, October 2006, Munich, Germany, 2006.

[29] S. Akar M., Solmaz and R. Shorten, "Online center of gravity estimation in automotive vehicles using multiple models and switching." Proc. of the 9th International Conference on Control, Automation, Robotics and Vision (ICARCV 2006), 2006.

[30] R. Shorten and K. S. Narendra, "On diagonal stability and strict positive realness." In proceedings of the IEEE Conference on Decision and Control, 2006.

[31] M. Barreras, C. Villegas, M. Garcia-Sanz, and J. Kalkkuhl, "Robust qft tracking controller design for a car equipped with 4-wheel steer-by-wire." In proceedings of IEEE CCA/CACSD/ISIC 2006, Munich, Germany., 2006.

[32] M. Solmaz S., Corless and R. Shorten, "A methodology for the design of robust rollover prevention controllers for automotive vehicles: Part 1-differential braking." 45th IEEE Conference on Decision and Control, San Diego, CA, Dec 13-15, 2006, 2006.

[33] M. Solmaz S., Corless and R. Shorten, "A methodology for the design of robust rollover prevention controllers for automotive vehicles: Part 2-active steering." HYCON-CEmACS Joint Workshop on Automotive Systems & Control, 2006.

[34] S. R. Solmaz S., Mason O., "General inertia and circle criterion.." 77th Annual Meeting of the Gesellschaft fr Angewandte Mathematik und Mechanik e.V., March 27th-31st. Accepted for publication in Proceedings in Applied Mathematics and Mechanics., 2006.

[35] D. Villegas, C.and Leith, R. Shorten, and J. Kalkkuhl, "On the design of active suspensions for vehicle emulation applications: Part 1 - williams suspensions." Submitted to ACC 2007, New York, USA, 2006.

[36] . C. F. Solmaz S., Shorten R., "A preliminary result on the global attractivity of a class of switching discrete-time systems." Submitted to American Control Conference, 2006.

[37] R. Shorten, C. King, O. Mason, and A. Berman, "An elementary proof of the barker, berman, plemmons result on diagonal stability." Submitted to American Control Conference, 2006.

[38] M. Akar, "A robust pid controller for lateral dynamics tracking using 4–wheel steering." In preparation, 2006.

[39] M. Akar, "A robust ahp controller for tracking reference vertical dynamics." In preparation, 2006.

[40] M. Akar, "A method for force distribution in automotive vehicles equipped with ahp." In preparation, 2006.

[41] C. Villegas, D. Leith, and J. Kalkkuhl, "Vehicle emulation using a car equipped with 4-wheel active steering." In preparation for submission to Control Engineering Practice, 2006.

[42] S. Solmaz, "A review of multiple model estimation and control." Technical Report, Hamilton Institute, NUI-Maynooth, October 2005.

[43] J. Kalkkuhl, D. Leith, and B. Leithead, "Frequency domain analysis of a side slip angle observer for 4-wheel steering control." In preparation, 2005.

[44] S. Akar M., Solmaz and R. Shorten, "Method for determining the center of gravity for an automotive vehicle." Patent application, 2006.

[45] H. Bevan G., Gollee and J. O'Reilly, "Development of a controller to perform an automatic lateral emergency collision avoidance manoeuvre for a passenger car." HYCON-CEmACS Joint Workshop on Automotive Systems & Control, 2006.

[46] M. Gerard, "Tire-road friction estimation using slip-based observers," Master's Thesis ISRN LUTFD2/TFRT--5771--SE, Department of Automatic Control, Lund University, Sweden, June 2006.

[47] M. Akar, "Lateral dynamics emulation via a 4-wheel steering vehicle." Submitted to International Journal of Control, 2006.

[48] K. Wulff and R. Shorten, "On the quadratic stability of switched interval systems: Preliminary results." Submitted to International Journal of Control, 2006.

[49] S. Akar M., Solmaz and R. Shorten, "Real-time multiple model estimation of center of gravity position in automotive vehicles." submitted to Vehicle System Dynamics, 2006.

[50] S. R. Solmaz S., Mason O., "On the kalman-yakubovich-popov lemma and common lyapunov solutions for matrices with regular inertia." Linear Algebra and its Applications, 2006. Accepted for Publication, 2006.

[51] M. Solmaz S., Corless and R. Shorten, "A methodology for the design of robust rollover prevention controllers for automotive vehicles with active steering." Submitted to International Journal of Control, 2006.