Preface

In the past decade, there has been an enormous surge of activity in automotive control, both in terms of research and development and in terms of capturing the imagination of the general public as to its seemingly endless and diverse opportunities.

This period has been accompanied by a technological maturation as well, for example, in the three-way catalytic conversion, in anti-lock brake system (ABS) devices and in navigational aids. Several areas of automotive control have now become well established. As of the writing of this book, the field is on the verge of a new explosion in areas of growth, involving active suspension systems, new engine designs for improved fuel efficiency and emission standards.

Given the state of maturity of the subject and the diversity of students who study this material, we felt the need for a book that presents an overview of the research area and collects contributions from a number of leading scientists in the field.

This book on automotive control contains contributions on:

- vehicle dynamics and active suspension;
- anti-lock braking systems (ABS), brake dynamics, friction and wheel-slip modeling;
- combustion-engine control;
- system theory and hybrid system analysis for application in automotive control

The contributions represent a panorama of systems and control research issues in the application context of automotive control. Moreover, the contributions present important new efforts to solve theoretical problems arising from problems in automotive control. Important common themes are nonlinear observer and system theory for hybrid systems—*i.e.*, systems involving continuous-time dynamics and logic switching. In addition to their theoretical capacity, the authors represent important cooperation projects involving academic teams and automotive companies.

Authors Mark D. Donahue and J. Karl Hedrick, University of California at Berkeley—Prof. Hedrick also being Director of the PATH program, Partners For Advanced Transit And Highways—present an implementation of active suspension, preview controller for improved ride comfort.
A fully active suspension and preview control is utilized to improve ride comfort, which allows increased travelling speed over rough terrain. Previous research is extended and the relevant implementation issues are addressed. Specifically, the methodology of model predictive control has been

applied to explicitly address suspension saturation constraints, suspension rate limits, and other system non-linearities. For comparison, the following non-preview controllers were implemented: a skyhook damping controller, a linear quadratic regulator (LQR), and a mock passive suspension controller. Particular attention is given to the hydraulic actuator force controller that tracks commands generated by higher-level controllers. The complete system has been successfully realized on a US military high-mobility multipurpose wheeled vehicle (HMMWV) using a commercially available microprocessor platform. Experimental results show that the power absorbed by the driver is decreased by more than half, significantly improving ride comfort.

Fu-Cheng Wang and Malcolm C. Smith, Cambridge University, present work on active and passive suspension control for vehicle dive and squat. Performance capabilities of passive and active vehicle suspension systems are examined from a mechanical networks point of view. It is known that the reduction of effects of road disturbances is a conflicting requirement with the reduction of effects of inertial loads in a quarter-car model when passive control is used, but not with active control of suitable structure. The extension of these ideas to a half-car trailing-arm model is considered. It is shown that the choice of suspension geometry does not remove the basic trade-offs for passive suspensions. An active control structure to allow the road and load transmission paths to be optimised independently will be presented. The design approach is to be applied to a non-linear trailing-arm vehicle model to demonstrate good anti-dive and anti-squat behavior together with a soft ride in response to road disturbances. The performance of the controller is demonstrated using the multi-body simulation code *AutoSim*.

Johan Bengtsson and Rolf Johansson of Lund University, and Agneta Sjögren, Volvo Technical Development, present their work on adaptive cruise control (ACC) and modeling of drivers' longitudinal behavior. In the last few years, many vehicle manufacturers have introduced advanced driver support in some of their automobiles. One of those new features for driver support is adaptive cruise control (ACC), which extends the conventional cruise control system to control of relative speed and distance to other vehicles. In order to design an ACC controller, it is suitable to have a model on drivers' behavior. The approach to find dynamical models of the drivers' behavior is to use system identification. Basic data analysis was made by means of system identification methodology, and several models of drivers' longitudinal behavior are proposed, including both linear regression models and subspace-based models. In various situations, detection for when a driver's behavior changes or deviates from the normal is useful. To that purpose, a GARCH (generalized autoregressive conditional heteroskedasticity) model was used to model the driver in situations such as arousal.

The next four chapters all originate from the study of ABS control within the EU funded project *Heterogenous Hybrid Control (H2C)* involving DaimlerChrysler and SINTEF together with university partners from Glasgow and Lund. Authors Jens Kalkkuhl, Jens Lüdemann of DaimlerChrysler and Tor Arne Johansen, Norwegian University of Science and Technology, provide a contribution on nonlinear adaptive backstepping with estimator resetting using multiple observers A multiple model-based observer/estimator for the estimation of parameters is used to reset the parameter estimation in a conventional Lyapunov-based nonlinear adaptive controller. Transient performance can be improved without increasing the gain of the controller or estimator. This allows performance to be tuned without compromising robustness and sensitivity to noise and disturbances. The advantages of the scheme are demonstrated in an automotive wheel slip controller.

Another contribution involving the DaimlerChrysler sphere and Lund University is provided by Stefan Solyom and Anders Rantzer. The ABS is an important component of a complex steering system for the modern car. Most of ABS controllers available on the market are table-based on-off controllers. In the latest generation of "brake by wire" systems, the performance requirements on the ABS are much higher. The control objective shifts to maintain a specified tire slip for each wheel during braking. The authors propose a design model and, based on that, a gain-scheduled controller that regulates the tire-slip. Simulation and test results are presented.

Kenneth J. Hunt, Yongji Wang, Michael Schinkel and Tilmann Schmitt-Hartmann, University of Glasgow, present their work on controller design for hybrid systems using simultaneous D-stabilisation and its application to ABS. In recent years, hybrid systems have been widely studied. Many controller design approaches are based on a state space plant model and use full state feedback to satisfy certain stability conditions, for example, the existence of a common Lyapunov function. Pole assignment and LMI-based controller design techniques have also been used. Recent progress is reported on a new controller design method called simultaneous D stabilisation and strong simultaneous D-stabilisation, which can deal with the multiple plant requirement resulting from hybrid systems. Simulation results with a DaimlerChrysler test vehicle for ABS are also presented.

Another report on ABS brakes considers wheel slip control using gain-scheduled constrained LQR. It is contributed by by Idar Petersen from SINTEF, Tor A. Johansen, Norwegian University of Science and Technology, and Jens Kalkkuhl and Jens Lüdemann of DaimlerChrysler. A wheel slip controller for ABS brakes is formulated using an explicit constrained LQR design. The controller gain matrices are designed and scheduled on the vehicle speed based on local linearizations. A Lyapunov function for the nonlinear control system is derived using the Riccati equation solution in order to prove stability and robustness with respect to uncertainty in the road/tire friction characteristic. Experimental results from a test vehicle with electromechanical brake actuators and brake-by-wire show that high performance and robustness are achieved.

Carlos Canudas-de-Wit of Laboratoire d'Automatique de Grenoble P Tsiotras, Georgia Institute of Technology, J. Yi, and R. Horowitz, University of California, Berkeley, present a comprehensive contribution on friction tire/road modeling, estimation, and optimal braking control. A series of results concerning the problem of modeling and estimation of contact road/tire friction are presented. Also, some aspects related to the problem of optimal and emergency braking control are discussed. The modeling part discusses a new dynamic friction force model for the longitudinal road/tire interaction for wheeled ground vehicles. The model is based on a dynamic friction model developed previously for contact-point friction problems, called the *LuGre model*. Next, the problem of tire-road friction estimation using only angular wheel velocity which cannot always been computed from actual sensors is treated. Tire forces information is relevant to problems like: optimization of ABS, traction system, diagnostic of the road friction conditions, etc. These results may suggest alternative traction control methodologies, other than the current ones based on the use of tracking of the "optimal" slip coefficient using, for example, sliding mode control. A control scheme for emergency braking of vehicles. The controller utilizes estimated state feedback control to achieve a near maximum deceleration.

Elbert Hendricks, Technical University of Denmark, presents work on nonlinear observer control of internal combustion engines with EGR. The increased requirements of engine control systems with respect to accuracy, functionality, and emission levels have led to a new generation of control strategies. In contrast to earlier systems, these control systems are based on dynamic physical engine models (Mean Value Engine Models, MVEMs) and nonlinear estimation. In fact, the new second generation Engine Control Units (ECUs) are just going into production and represent the first mass market application of nonlinear observers. One purpose of this paper is to review critically the design principles behind some of the newest ECUs. An attempt will also be made to indicate the general direction of development of the newest systems and possible new applications for this methodology.

Authors Andrea Balluchi from PARADES, Luca Benvenuti, Università di Roma "La Sapienza", Marika Domenica Di Benedetto, Università dell'Aquila, and Alberto L. Sangiovanni-Vincentelli from the University of California at Berkeley provide a contribution on idle-speed controller synthesis using an assume-guarantee approach. The goal of idle control for automotive engines is to maintain the engine speed within a given range, robustly with respect to load torque disturbances acting on the crankshaft. Mean value models have been used in the past to design idle control algorithms. However, the behavior of the torque generation process and the dynamics of the power train are not captured with enough accuracy to guarantee that the idle control specifications as given by car makers are met. A cycle-accurate hybrid model can be used to overcome these obstacles. To tackle the complexity of the controller design, the system is decomposed in three parts. For each part in isolation, a control law is derived for a simplified model, assuming that the other parts can be controlled to yield appropriate inputs. The overall control strategy is then applied to the system. Hence, the correct interaction of the feedback loops is formally verified using an assume-guarantee approach, to ensure that the behavior of the controlled system meets the given specifications.

Dirk Förstner and Jan Lunze, Technical University Hamburg-Harburg, present work on fault diagnosis of switched nonlinear dynamical systems with application to a diesel injection system. For the on-line monitoring of safety- and emission-relevant parts of automotive systems diagnostic methods are needed that take into account the parameter uncertainties and nonlinearities of automotive systems and the real-time restrictions of on-board diagnosis. This paper concerns the diagnosis of switched nonlinear dynamical systems, which is applied to a diesel injection system. A model–based diagnostic method is presented that processes the events generated by the output signals when passing predefined thresholds. For nominal and faulty behavior, a model in form of a nondeterministic automaton is set up. The diagnostic algorithm uses this model to compare the measured event sequences with the nominal or faulty behavior in order to determine faults from inconsistencies. The trade–off between the complexity of the algorithm and the accuracy of the diagnostic result can be found by varying the model depth, which is the number of recent events stored in the model state. The successful application of this method is demonstrated for the power stage of a common-rail Diesel injection system.

Authors Giovanni Fiengo, Luigi Glielmo, and Stefania Santini review modeling of three-way catalytic converter (TWC). New regulations for emission control require the improvement of the system composed of a spark ignition internal combustion engine and TWC. In particular an important problem is to minimize harmful emissions during the transient warm-up phase where the TWC is not working yet and, hence, a large amount of pollutants are emitted in the air. Towards this goal a dynamical thermo-chemical TWC model simple enough for the design and test of warm-up control strategies is presented. The model is obtained through an asymptotic approximation of a more detailed model—*i.e.*, by letting the adsorption coefficient between gas and substrate tend to infinity. The model has been identified and validated with experimental data.

Magnus Gäfvert, Karl-Erik Årzén, Bo Bernhardsson, and Lars Malcolm Pedersen, Lund University, present their work on the control of gasoline direct injection (GDI) engines using torque feedback. A novel approach to the control of a GDI engine is presented. The controller consists of a combination of subcontrollers, where torque feedback is a central part. The subcontrollers are, with a few exceptions, designed using simple linear feedback and feedforward control-design methods, in contrast to traditional table-based engine control. A silent extremum-controller is presented. It is used to minimize the fuel consumption in stratified mode. The controller has been evaluated with good results on the European driving cycle using a dynamic simulation model.

Authors Per Tunestål, Jan-Ola Olsson, and Bengt Johansson, Lund University, present work on a novel combustion engine principle known as homogeneous charge compression ignition (HCCI). The HCCI engine, with its excellent potential for high efficiency and low NO_X emissions, is investigated from a controls perspective. Combustion timing, *i.e.*, where in the thermodynamic cycle combustion takes place, is identified as the most challenging problem with HCCI engine control. A number of different means for controlling combustion timing are suggested, and results using a dual-fuel solution are presented. This solution uses two fuels with different ignition characteristics to control the time of auto-ignition. Cylinder pressure measurement is suggested for feedback of combustion timing. A simple net-heat release algorithm is applied to the measurements, and the crank angle of 50 % burnt is extracted. Open-loop instability is detected in some high-load regions of the operating range. This phenomenon is explained by positive feedback between the cylinder wall heating and ignition timing processes. Closed-loop performance is hampered by time delays and model uncertainties. This problem is particularly pronounced at operating points that are open-loop unstable.

Authors L. Berardi, E. De Santis, M. D. Di Benedetto, G. Pola, Università dell'Aquila, and University of California, Berkeley, treat the problem of approximations of maximal controlled safe sets for hybrid systems. In the determination of the *"maximal safe set"* for a hybrid system, the core problem lies in the computation of a maximal controlled invariant set contained in a constraint set for a continuous time dynamical system. In the case of a linear system, we propose a procedure that, on the basis of a controlled invariant set for the exponential discretization of the continuous-time system, leads to an arbitrarily good approximation of the maximal controlled invariant set for the continuous-time system. The approximating set has the interesting property that the constraints can be satisfied by means of a piecewise constant control. An example of an application of the proposed procedure to idle control is illustrated.

A Hamiltonian formulation of bond graphs is provided by Goran Golo, Arjan van der Schaft, Peter C. Breedveld, University of Twente, and Bernhard M. Maschke, Université Claude Bernard Lyon-1. This paper deals with the mathematical formulation of bond graphs. It is proven that the power continuous part of bond graphs, the junction structure, can be associated with a Dirac structure and that the equations describing a bond graph model correspond to a port Hamiltonian system. The conditions for well-posedness of the modelled system are given, and representations suitable for numerical simulation are derived. The index of the representations is analysed and sufficient conditions for computational efficiency are given. The results are applied to some models arising in automotive applications.

Authors S. Pettersson and B. Lennartson, Chalmers University of Technology, consider stability analysis of hybrid systems and its application to gearbox control. This paper includes an application consisting of an automatic gearbox and cruise controller, which naturally is modelled as a hybrid system including state jumps in the continuous state of the controller. Motivated by this application, we extend existing stability results to include state jumps as well. The proposed stability results are based on Lyapunov techniques. The search for the (piecewise quadratic) Lyapunov functions is formulated as a linear matrix inequality (LMI) problem. It is shown how the proposed stability analysis is applied to the automatic gearbox and cruise controller.

Authors W. P. M. H. Heemels (Eindhoven University of Technology), M. K. Çamlıbel (University of Groningen), A. J. van der Schaft (University of Twente), and J. M. Schumacher (Tilburg University) provide a contribution on the existence and uniqueness of solution trajectories to hybrid dynamical systems. This paper studies the fundamental system-theoretic property of well-posedness for several classes of hybrid dynamical systems. Hybrid systems are characterized by the presence and interaction of continuous dynamics and discrete actions. Many different description formats have been proposed in recent years for such systems; some proposed forms are quite direct, others lead to rather indirect descriptions. The more indirect a description form is, the harder it becomes to show that solutions are well-defined. This contribution intends to provide a survey on the available results on existence and uniqueness of solutions for given initial conditions in the context of various description formats for hybrid systems.

Several of the contributions have been presented in the meetings *Nonlinear and Adaptive Control Network (NACO 2) Workshop on Automotive Control*, Lund, May 18–19, 2001 or *Hybrid Control and Automotive Applications*, Lund, May 5–6, 2000 and Berlin, June 7–8, 2001. The editors are grateful to Ms. Eva Schildt for skilful administration of the Lund meetings.

On behalf of the research project networks, we would like thank the EU Commission for financial support granted to the research projects NACO2 and H2C. Finally, the editors would like to thank Mr. Leif Andersson and the Springer-Verlag editors for valuable editorial advice and help.

In reading this book, we hope that the reader will feel the same excitement that we do about the technological and social prospects for the field of automotive control and the elegance and challenges of the underlying theory.

Rolf Johansson Anders Rantzer

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