

Preface

The control of wheel slip dynamics is one of the most critical and intriguing areas of chassis control, since it is the basis for most of the main chassis control subsystems like braking control, traction control and stability control. Moreover, it is an unusual combination of seemingly simple dynamics (whose dominant features can be easily captured by a second-order dynamical model) and challenging features (nonlinear behaviour, stability properties which change according to the considered working condition, time-varying parameters, large parameter variations, unknown environment-dependent parameters, *etc.*).

This book is mainly devoted to the analysis and development of wheel slip control strategies. However, to keep the book focused and to perform the analysis in depth, most of the work presented here refers to the specific problem of controlling the longitudinal dynamics of a vehicle during braking.

There are three main reasons for focusing on *braking control*, while keeping traction control and stability control in the background:

- Braking control is the first chassis control subsystem to be made available to the mass market. Anti-lock braking systems (ABS) have become a standard for all modern cars, whereas traction control and stability control subsystems are still confined to be niche applications.
- Braking control must face the challenge of the coordination of the braking force on all the wheels, whereas traction control is typically limited to half of the vehicle wheels, *i.e.*, the driving ones.
- Braking control is also self consistent and meaningful when the analysis is restricted to longitudinal dynamics, whereas stability control inherently requires the coupling of longitudinal, lateral and yaw dynamics.

Needless to say, all the material developed for the specific problem of controlling the wheel slip during braking can be straightforwardly re-used also within traction and stability control problems.

From the technological point of view, the design of automatic braking control systems is clearly highly dependent on the braking system characteristics and actuator performance.

As a matter of fact, ABS systems for wheeled vehicles equipped with traditional hydraulic actuated brakes – that is, those commonly available in all passenger cars – pose specific design constraints as they have to cope with an *on/off* modulation of the brake pressure. On the other hand, recent technological advances in actuators which have led to both electro-hydraulic and electro-mechanical braking systems have radically changed the starting point of braking control systems design. In fact, these brake systems enable a continuous modulation of the braking torque, thereby allowing the use of classical control theory tools for controller design.

A great boost to the research in this field comes directly from the industrial world, which poses challenging problems by asking for reliable control systems with the simplest possible architecture, reduced sensors layout and the capability of coping with transmission delays and significant measurement errors and parametric uncertainties.

This book develops within this challenging and evolving context, with the aim of providing a thorough analysis of active braking control systems and proposing both basic and innovative solutions, which are both effective and applicable from an industrial viewpoint and theoretically sound from a methodological perspective.

In particular, the book is devoted to the analysis and design of active braking control systems together with the main estimation and identification problems that arise in the braking control context.

The considered control design problems are linked to two different brake technologies. Namely, braking control systems based on classical hydraulic actuated brakes (HAB) with *on-off* dynamics and braking control systems tailored to brake-by-wire (BBW) control, in particular based on electro-mechanical brakes (EMB).

The BBW control approaches can be further split into two main families, because of the fact that the control algorithms are based either on linearised or nonlinear models of the braking dynamics.

The book shows how these different control approaches are complementary, in that each of them has specific peculiarities either in terms of performance or in terms of structural properties of the closed-loop system.

Finally, the book presents some original approaches to three different estimation and identification problems closely related to braking control systems design, namely

- estimation of the longitudinal wheel slip;
- estimation of the tyre–road friction coefficient; and
- direct estimation of tyre–road contact forces *via* in-tyre sensors,

with the aim of providing the reader with a comprehensive treatment of active vehicle braking control from a wider perspective. A significant part of

the work presented in the book was developed within joint projects between the Politecnico di Milano and leading automotive industries, thereby being firmly linked to industrial reality.

Contributions and Organisation of the Book

The book includes survey sections, where the problem and the methodologies are introduced in a historical and tutorial framework, to suit a wide readership. Therefore, this book can be effectively accessed at three reading levels: a tutorial level for students, an application-oriented level for engineers and practitioners and a methodology-oriented level for researchers.

To enforce these different reading levels and to present the material in an incremental manner from the basic to the most advanced control approaches, the book has been conceptually divided into three parts.

The *first part* of the book is composed of *Chapters 1* and *2*: the former provides the introductory material on the history of ABS systems and their development and future perspectives together with the description of the different braking systems considered in this book and their mathematical description, whereas the latter introduces the control-oriented dynamical models of the braking dynamics.

The *second part* of the book is composed of *Chapters 3*, *4* and *5*, which deal with the main aspects of both control and estimation issues. Specifically, *Chapters 3* and *4* are devoted to presenting the basic solutions to braking control systems design, according to the two different types of actuators; *Chapter 3* discusses the design of braking controllers based on actuators with continuous dynamics, whereas *Chapter 4* treats in detail the case of braking systems with on/off dynamics. Furthermore, *Chapter 5* studies a fundamental estimation problem that is inextricably linked with active braking controller design: the wheel slip estimation.

The *third part* of the book presents more advanced and research-oriented solutions both to active braking control systems design and to tyre–road friction estimation. Specifically, *Chapter 6* discusses the mixed slip-deceleration control, which is an advanced control solution based on linearised models of the braking dynamics, while *Chapter 7* presents a nonlinear control approach to wheel slip regulation, grounded on Lyapunov-based synthesis methods, which yields a particular closed-loop behaviour having practical advantages. Finally, *Chapter 8* addresses the problem of estimating the tyre–road friction conditions and outlines a method to directly estimate the contact forces from sensors inserted in the tyre.

In writing the book, we assumed that the reader is familiar with basic notions of dynamical systems and linear control systems design. Accordingly, we complemented the book with *Appendix A*, which provides the basic defini-

tions and the notions of the nonlinear systems analysis and synthesis methods employed in the book. This Appendix is intended to provide only a quick tutorial reference to these topics, a thorough study of which should be pursued using specialist books, some of which are referenced in the Appendix itself.

Finally, *Appendix B* provides a dedicated treatment to the problem of estimating the wheel speed from encoders, which are the fundamental sensors that one has to deal with when developing active braking and traction control systems. The Appendix presents the two main speed estimation algorithms and highlights their merits and drawbacks, presenting also some insights on signal filtering issues arising from the analysis of experimental data.

Overall, the first two parts of the book present the topic at a level of depth that can be considered appropriate for practitioners and for a course on vehicle control at the MSc level, while the third part can constitute additional material of interest for graduate studies and for researchers in automotive control.

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