

Sergio M. Savaresi
Charles Poussot-Vassal
Cristiano Spelta
Oliver Sename
Luc Dugard

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$$\mathcal{G} = \begin{bmatrix} A_c & B_c \\ C_c & 0 \end{bmatrix}$$

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Semi-Active Suspension Control Design for Vehicles

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Semi-Active Suspension Control Design for Vehicles

Dedication

To Cristina, Claudio and Stefano (S.M.S)

To my Family (C.P-V)

To Daniela (C.S.)

To Isabelle, Corentin and Grégoire (O.S.)

To Brigitte (L.D.)

List of Tables

1	List of mathematical symbols and variables used in the book.....	xxix
2	List of acronyms used in the book.	xxx
3	List of model variables used in the book (unless explicitly specified).	xxxi
1.1	Automotive parameters set (passive reference model)	12
1.2	Motorcycle parameters set (passive reference model)	13
2.1	Classification of electronically controlled suspension.....	24

About the Authors

Sergio Matteo Savaresi was born in Manerbio, Italy, in 1968. He received an M.Sc. in Electrical Engineering (Politecnico di Milano, 1992), a Ph.D. in Systems and Control Engineering (Politecnico di Milano, 1996), and an M.Sc. in Applied Mathematics (Catholic University, Brescia, 2000). After the Ph.D. he worked as management consultant at McKinsey & Co, Milan Office. He has been Full Professor in Automatic Control at Politecnico di Milano since 2006, and head of the “mOve” research team (<http://move.dei.polimi.it/>). He was visiting researcher at Lund University, Sweden; University of Twente, The Netherlands; Canberra National University, Australia; Stanford University, USA; Minnesota University at Minneapolis, USA; and Johannes Kepler University, Linz, Austria. He is Associate Editor of: the *IEEE Transactions on Control System Technology*, the *European Journal of Control*, the *IET Transactions on Control Theory and Applications*, and the *International Journal of Vehicle Systems Modelling and Testing*. He is also Member of the Editorial Board of the IEEE CSS. He is author of more than 250 scientific publications at international level (involving many patents), and he has been the proposer and manager of more than 50 sponsored joint research projects between the Politecnico di Milano and private companies. His main interests are in the areas of vehicles control, automotive systems, data analysis and system identification, nonlinear control theory, and control applications. He is married to Cristina and has two sons, Claudio and Stefano.

Charles Poussot-Vassal was born in Grenoble, France, in 1982. In 2005, he completed his Engineering degree and M.Sc. in Control and Embedded Systems from Grenoble INP-ESISAR (Valence, France) and Lund University of Technology (Lund, Sweden), respectively. In 2008, he completed his Ph.D. degree in Control Systems Theory, with applications of linear parameter varying modeling and robust control methods on automotive systems (suspension and global chassis control) at the GIPSA-lab’s control systems department, from the Grenoble Institute of Technology (Grenoble, France), under the supervision of O. Sename and L. Dugard. He has been a visiting student with the MTA SZTAKI, University of Budapest (Budapest, Hungary), under the supervision of J. Bokor, P. Gáspár and Z. Szabó. At the beginning of 2009, he worked as a Research Assistant with the Politecnico di Milano (Milan, Italy) on semi-active suspension control, under the supervision of S.M. Savaresi. From mid-2009, he has been Researcher with ONERA, the French

aerospace lab, with the Flight Dynamics and Control Systems department. His main interests concern control system design, model reduction techniques and dynamical performance analysis, with application in ground vehicles, web servers and aircraft systems.

Cristiano Spelta was born in Milan, Italy, on 20 March 1979. He received a Masters degree in Computer Engineering in 2004 from the Politecnico di Milano. He earned from the same university a Ph.D. in Information Engineering in 2008 (thesis “Design and applications of semi-active control systems”). He was visiting scholar (July–September 2006) at the Institute of Control Sciences of Moscow under the supervision of Professor Boris Polyak. He is currently Assistant Professor at the Università degli Studi di Bergamo (BG, Italy). He is author of more than 30 international publications including some industrial patents. His research interests include control of road and rail vehicles, control problems in system integration, and robust control and mixed \mathcal{H}_2 - \mathcal{H}_∞ control problems.

Olivier Sename received a Ph.D. degree in 1994 from the Ecole Centrale Nantes, France. He is now Professor at the Grenoble Institute of Technology (Grenoble INP), within the GIPSA-lab. His main research interests include theoretical studies in the field of time-delay systems, linear parameter varying systems and control/real-time scheduling co-design, as well as robust control for various applications such as vehicle dynamics, engine control. He has collaborated with several industrial partners (Renault, SOBEN, Delphi Diesel Systems, Saint-Gobain Vetrotex, PSA Peugeot-Citroën, ST Microelectronics), and is responsible for international bilateral research projects (Mexico, Hungary). He is the (co-)author of 6 book chapters, 20 international journal papers, and more than 80 international conference papers. He has supervised 15 Ph.D. students.

Luc Dugard works as a CNRS Senior Researcher (Directeur de Recherche CNRS) in the Automatic Control Dept. of GIPSA-lab, a research department of Grenoble INP (Institut Polytechnique de Grenoble), associated to the French research organization “Centre National de la Recherche Scientifique”. Luc Dugard has published about 90 papers and/or chapters in international journals or books and more than 220 international conference papers. He has co-advised 28 Ph.D. students. His main research interests include (or have included) theoretical studies in the field of adaptive control, robust control, and time delay systems. The main control applications are oriented towards electromechanical systems, process control and automotive systems (suspensions, chassis and common rail systems).

Preface

The suspension (together with the tire), is probably the single element of a vehicle which mostly affects its entire dynamic behavior. It is not surprising that in the most essential and fun-driving vehicles – e.g. sport motorbikes – suspensions play a central role (sometimes almost “worshipped” by their owner) with an intriguing mixture of technical features and aesthetic appeal.

This central role of suspensions in vehicle dynamics is intuitive: they establish the link between the road and the vehicle body, managing not only the vertical dynamics, but also the rotational dynamics (roll, pitch) caused by their unsynchronized motions. As such, they contribute to create most of the “feeling” of the vehicle, affecting both its safety and driving fun.

Another peculiar feature of the suspensions in a vehicle is their possible appearance at different layers: at the classical wheel-to-chassis layer, at the chassis-to-cabin layer (e.g. in trucks, earth-moving machines, agricultural tractors, etc.) and at the cabin-to-seat layer (in large vehicles with suspended cabins the driver seat is also typically equipped with a fully fledged suspension system).

The Italian cartingent of the authors of this book would be loathe to admit it, but the birth of electronic suspensions for the car mass-market can probably be dated back to the early 1960s, when Citroën introduced hydro-pneumatic suspensions in its top cars. At that time those suspensions were still untouched by electronics (they were “ante-litteram” electronic suspensions), but the idea of having part of a suspension so dramatically and easily modified opened the way to the idea of “on-line” electronic adaptation of the suspension.

Given this tribute to Monsieur Citroën, the real “golden age” of electronic suspension can be probably located in the 1980s; analog electronics were already well-developed, the era of embedded digital micro-controllers was starting, and the magic of fully active suspensions attracted both the F1 competitions and the car manufacturers. During these years the exceptional potential of replacing a traditional spring-damper system with a fully fledged electronically controllable fast-reacting hydraulic actuator was demonstrated.

High costs, significant power absorption, bulky and unreliable hydraulic systems, uncertain management of the safety issues: the fatal attraction for fully active electronic suspensions

lasted only a few years. They were banned by F1 competitions in the early 1990s and they have never had (so far) a significant impact on mass-market car production.

In the second half of the 1990s, a new trend emerged: it became increasingly clear that the best compromise of cost (component cost, weight, electronics and sensors, power consumption, etc.) and performance (comfort, handling, safety) was to be found in another technology of electronically controllable suspensions: the variable-damping suspension or, in brief, the semi-active suspension.

After a decade this technology is still the most promising and attractive: it has been introduced in the mass-market production of cars; it is entering the motorcycle market; a lot of special vehicles or niche applications are considering this technology; many new variable-damping technologies are being developed.

Semi-active suspensions are expected to play an even more important role in the new emerging trend of electric vehicles with in-wheel motors: in such vehicle architecture the role of suspension damping is more crucial, and semi-active suspensions can significantly contribute to reduce the negative effects of the large unsprung mass.

The scope of this book is to present a complete discussion of the problem of designing control algorithms for semi-active suspensions. Even though the effect of a modification of the damping coefficient of a suspension is well-known, when damping-coefficient variation is carried out at a very fast rate (e.g. every 5 milliseconds), making a decision on the “best” damping ratio is far from easy.

A semi-active suspension system is an unusual combination of seemingly simple dynamics (whose bulk can be easily captured by a fourth-order model) and challenging features (nonlinear behavior, time-varying parameters, asymmetrical control bounds, uncontrollability at steady-state, etc.). These features make the design of semi-active control algorithms very challenging. This gives the opportunity, by “simply” changing the control strategy, to modify significantly the dynamic behavior of a vehicle. However, this is an opportunity which is not easy to catch: the history of semi-active suspensions is full of anecdotes about semi-active suspensions being rejected by vehicle manufacturers just because they “do not make any difference . . .”, or even “are worse than the (nice, old) traditional mechanical suspensions . . .”. As in many other electronically controlled systems, the actuator is not “smart itself”: it simply inherits the smartness (or dumbness) of its control-algorithm designer.

The key of semi-active suspensions is in the algorithm. The design of semi-active control algorithms is the aim of this book.

The structure of the book follows the classical path of the control-system design: first, the actuator (the variable-damping shock absorber) is discussed, modeled, and the available

technologies are presented. Then the vehicle (equipped with semi-active dampers) is mathematically modeled, and the control algorithms are designed and discussed.

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 two parts.

In the first part of the book, made up of Chapters 2 to 6, where the basics of modeling and semi-active control design are described, whereas in the second part of the book, made up of Chapters 6 to 8, more advances and research-oriented solutions are proposed and compared, with the help of some case studies. Overall, the first part of the book presents the topic at a level of depth which can be considered appropriate for practitioners and for a course on vehicle control at the M.Sc. level, while the second part constitutes additional material of interest for graduate studies and for researchers in automotive control.

It is also worth noting that Chapter 4 (“Methodology of analysis for automotive suspensions”) and Chapter 5 (“Optimal strategy for semi-active suspensions and benchmark”) play a pivotal role in the organization of the book:

- In Chapter 4, the different techniques and methods for evaluating the performance of a suspension system are discussed in detail, in order to have a common baseline to assess and compare the quality of different design solutions.
- In Chapter 5 an “ideal” semi-active control strategy is developed, by assuming full knowledge (past and future) of the road profile, and using a sophisticated off-line numerical optimization based on model-predictive control. Even though this control strategy cannot be implemented in practice, it is conceptually very important since it sets an absolute bound for the best possible filtering performance of semi-active suspensions, and represents a simple and clear benchmark for any “real” algorithm.

It is also worth noticing that most of the material presented in the book focuses on vertical dynamics only: it constitutes the bulk of suspension control, and most of the pitch and roll control-design problems are inherently solved by applying the semi-active control strategy to each corner of the vehicle, or solutions can be straightforwardly derived from the vertical-dynamics algorithms.

Finally, a few words on the unusual author team. Despite the (comparatively) long list of authors and their different affiliations, this book is not an “edited” book, made up from an inhomogeneous collection of different contributions, but it is the result of a real effort to condense in an instructive way most of the main results and research work which has been developed in the last decade on this topic.

This book incorporates all the research work and the cooperation with suspension and vehicle manufacturers that Politecnico di Milano and Grenoble University have accumulated on this topic, obtaining, we hope, the best of both experiences.

The composition of the author team also proves that Italy and France can continue their long-lasting tradition of stimulating and successful cooperation . . . even after the '06 Berlin World Championship final.

Milano and Grenoble, January 15, 2010

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Charles Poussot-Vassal

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Luc Dugard

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Italian Authors

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French Authors

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Notations

Table 1: List of mathematical symbols and variables used in the book

Mathematical notation	Meaning
\mathbb{R}	Real values set
$\mathbb{R}^+ (\mathbb{R}^{++})$	Positive real values set (without 0)
\mathbb{C}	Complex values set
$\mathbb{C}^+ (\mathbb{C}^{++})$	Positive complex values set (without 0)
A^T	Transpose of $M \in \mathbb{R}$
A^*	Conjugate of $M \in \mathbb{C}$
$A + (\star)^T = A + A^T$	Defines the transpose matrix of $A \in \mathbb{R}$
$A + (\star)^* = A + A^*$	Defines the conjugate matrix of $A \in \mathbb{C}$
$A = A^T$	Matrix A is real symmetric
$A = A^*$	Matrix A is hermitian
$M < (\leq) 0$	Matrix M is symmetric and negative (semi)definite
$M > (\geq) 0$	Matrix M is symmetric and positive (semi)definite
$\text{Tr}(A)$	Trace of A matrix (sum of the diagonal elements)
$\text{Co}(A)$	Convex hull of set A
$\sigma(.)$	Singular value ($\sigma(A)$ defines the eigenvalues of the operator $(A^* A)^{1/2}$)
$\text{Re}(.)$	Real part of a complex number
$\text{Im}(.)$	Imaginary part of a complex number
j	Complex variable
s	Laplace variable $s = j\omega$, where ω is the pulsation
$\omega = 2\pi f$	Pulsation in rad/s
$\dot{x} = \frac{d}{dt}x(t)$	Derivative of function $x(t)$ with respect to t
$\int x(t)dt$	Integral of function $x(t)$ with respect to t
$\sum_i x_i$	Sum of the x_i elements

Table 2: List of acronyms used in the book

Acronyms	Meaning
BMI	Bilinear matrix inequality
LMI(s)	Linear matrix inequality(ies)
LTI	Linear time invariant
LTV	Linear time variant
LPV	Linear parameter varying
qLPV	Quasi linear parameter varying
SDP	Semi-definite programming
ABC	Active body control
ABS	Anti-locking braking system
COG	Center of gravity
DOF	Degree of freedom
ERD	Electrorheological damper
EHD	Electrohydrological damper
MRD	Magnetorheological damper
SER	Speed effort rule (force provided by the damper as a function of the deflection velocity)
ADD	Acceleration driven damper
GH	Ground-Hook (or Groundhook)
LQ	Linear quadratic
SH	Sky-Hook (or Skyhook)
MPC	Model predictive control
PDD	Power driven damper
iff.	if and only if
s.t.	such that/so that
resp.	respectively
w.r.t.	with respect to

Table 3: List of model variables used in the book (unless explicitly specified)

Variable	Meaning
M	Suspended mass
m	Unsprung (tire) mass
k	Stiffness coefficient
c	Damping coefficient
c_{min} (c_{max})	Minimal (maximal) damping coefficient
k_t	Tire stiffness coefficient
c_t	Tire damping coefficient
g	Gravitational constant
L	Nominal suspension length
R	Nominal tire radius
I_x	x-axis inertia
I_y	y-axis inertia
I_w	Wheel inertia
β	Actuator bandwidth
μ	Tire/road adhesion coefficient
l	Vehicle length
t	Vehicle width
F_k	Suspension stiffness force
F_d	Suspension damping force
$F_{sz} = F_k + F_d$	Suspension force
F_{kt}	Tire stiffness force
F_{dt}	Tire damping force
F_{tx}	Tire longitudinal force
F_{ty}	Tire lateral force
$F_{tz} = F_{kt} + F_{dt}$	Tire vertical force
F_L	Vertical force load
T_b	Wheel braking torque
v	Vehicle velocity at the COG
λ	Wheel slip ratio
ω	Wheel rotational velocity
x	Vehicle longitudinal displacement
y	Vehicle lateral displacement
z	Chassis vertical displacement
z_t	Wheel vertical displacement
ϕ	Vehicle pitch angle
θ	Vehicle roll angle