Autonomous Electric Vehicles

Nonlinear control, traction and propulsion

Gerasimos Rigatos
Masoud Abbaszadeh
Pierluigi Siano
Patrice Wira

Autonomous Electric Vehicles

Nonlinear control, traction and propulsion

By: G. Rigatos, M. Abbaszadeh, P. Siano and P. Wira

Autonomous Electric Vehicles:

Nonlinear control, traction and propulsion

By: G. Rigatos, M. Abbaszadeh, P. Siano and P. Wira

This book first published 2024

Elsevier Publications

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10):

In memory of my mother Diamantina Rigatou (1939-2018)
Gerasimos Rigatos

To my wife Elham, and my sons, Arman and Ario
Masoud Abbaszadeh

To my family
Pierluigi Siano

To my family
Patrice Wira

Contents

1 Nonlinear control of ground vehicles I **13**
1.1 Nonlinear optimal control for cooperation of car-like front-wheel-steered ground vehicles 13
1.1.1 Outline 13
1.1.2 Kinematic model of the front-wheel steered car-like vehicle 15
1.1.3 Approximate linearization of the vehicle's kinematic model 18
1.1.4 The nonlinear H-infinity control 19
1.1.5 Lyapunov stability analysis 21
1.1.6 Simulation tests 24
1.1.7 Synchronization between a leader and multi-follower vehicles 33
1.2 Nonlinear optimal control of the omnidirectional three-wheel mobile robot 33
1.2.1 Outline 33
1.2.2 Dynamic model of the 3-wheel omnidirectional mobile robot 42
1.2.3 Design of a nonlinear optimal controller 46
1.2.4 Design of a multi-loop flatness-based controller for the 3-wheel robot 52
1.2.5 Simulation tests 55

2 Nonlinear control of ground vehicles II **73**
2.1 Nonlinear optimal control of four-wheel autonomous ground vehicles 73
2.1.1 Outline 73
2.1.2 Dynamic and kinematic model of the vehicle 74
2.1.3 Approximate linearization of the four-wheel vehicle dynamics 79
2.1.4 The nonlinear H-infinity control 80
2.1.5 Lyapunov stability analysis 83
2.1.6 Robust state estimation with the use of the H_∞ Kalman Filter 85
2.1.7 Simulation tests 86
2.2 Nonlinear optimal control of tracked vehicles 92
2.2.1 Outline 92
2.2.2 Kinematic model of the tracked mobile robot 93
2.2.3 Approximate linearization of the model of the tracked vehicle 96
2.2.4 Lyapunov stability analysis 99
2.2.5 State estimation with robust Kalman Filtering 101
2.2.6 Simulation tests 102
2.3 Nonlinear optimal control for multi-axle multi-steered autonomous vehicles 106
2.3.1 Outline 106
2.3.2 Kinematic model of the multi-axle multi-steered vehicle 109
2.3.3 Differential flatness of the five-axle and three-steering vehicle system 113
2.3.4 Linearization of the model of the five-axle and three-steering vehicle 114
2.3.5 A nonlinear optimal controller for the five-axle and three-steering vehicle 116
2.3.6 Lyapunov stability analysis 118
2.3.7 Simulation tests 121

3 Nonlinear control of aerial vehicles I **132**
3.1 Nonlinear optimal control for UAVs with tilting rotors . . . 132
3.1.1 Outline . . . 132
3.1.2 Dynamic model of the tilt-rotor UAV . . . 133
3.1.3 Linearization and design of a stabilizing H-infinity feedback controller . . . 139
3.1.4 Lyapunov stability analysis . . . 144
3.1.5 Simulation tests . . . 146
3.2 Nonlinear optimal control of the 6-DOF fixed-wing UAV . . . 160
3.2.1 Outline . . . 160
3.2.2 Dynamic model of the 6-DOF fixed-wing unmanned aerial vehicle . . . 161
3.2.3 Differential flatness properties of the UAV . . . 164
3.2.4 Approximate linearization of the dynamic model of the fixed-wing UAV . . . 165
3.2.5 Design of a nonlinear H-infinity controller for the fixed-wing UAV . . . 167
3.2.6 Lyapunov stability analysis . . . 170
3.2.7 Simulation tests . . . 172
3.3 Flatness-based control in successive loops for octocopters . . . 173
3.3.1 Outline . . . 173
3.3.2 Dynamic model of the octocopter UAV . . . 182
3.3.3 Flatness-based control in successive loops for the octocopter UAV . . . 185
3.3.4 Simulation tests . . . 187

4 Nonlinear control of aerial vehicles II **199**
4.1 Flatness-based control in successive loops for autonomous quadrotors . . . 199
4.1.1 Outline . . . 199
4.1.2 Dynamic model of 6-DOF quadrotors . . . 200
4.1.3 Flatness-based control in successive loops for 6-DOF quadropters . . . 205
4.1.4 Simulation tests . . . 207
4.2 Nonlinear optimal and multi-loop flatness-based control for dual-UAV cooperative payload transportation 213
4.2.1 Outline . . . 213
4.2.2 Dynamic model of the cable-driven payload . . . 215
4.2.3 Dynamic model of the 6-DOF autonomous quadrotors . . . 219
4.2.4 Nonlinear optimal control for the cable-suspended payload . . . 224
4.2.5 The nonlinear H-infinity control . . . 229
4.2.6 Flatness-based control in successive loops for the quadrotors . . . 233
4.2.7 Simulation tests . . . 235

5 Nonlinear control of unmanned vessels **252**
5.1 Flatness-based control in successive loops for 3-DOF autonomous underwater vessels . . . 252
5.1.1 Outline . . . 252
5.1.2 Flatness-based control in successive loops for 3-DOF autonomous underwater vessels . . . 253
5.1.3 Simulation tests . . . 256
5.2 Flatness-based control in successive loops for the 3-DOF USV and the 6-DOF AUV . . . 256
5.2.1 Outline . . . 256
5.2.2 Dynamic model of 3-DOF unmanned surface vessels . . . 262
5.2.3 Flatness-based control in successive loops for 3-DOF unmanned surface vessels . . . 264
5.2.4 Kinematic and dynamic model of 6-DOF autonomous underwater vessels . . . 266
5.2.5 Flatness-based control in successive loops for 6-DOF autonomous underwater vessels . . . 271
5.2.6 Simulation tests . . . 273

6 Nonlinear control of electric traction systems based on three-phase motors 293
6.1 Flatness-based control in successive loops for VSI-fed PMSMs and Induction Motors . . . 293
6.1.1 Outline . . . 293
6.1.2 Differential flatness properties of the VSI-PMSM . . . 295
6.1.3 Flatness-based control in successive loops of the VSI-PMSM . . . 299
6.1.4 Differential flatness properties of the VSI-fed IM . . . 304
6.1.5 Flatness-based control in successive loops of the VSI-IM . . . 308
6.1.6 Simulation tests . . . 313
6.2 Nonlinear optimal and sliding-mode control for Voltage Source Inverter-fed Induction Motors . . . 332
6.2.1 Outline . . . 332
6.2.2 Dynamic model of the induction motor . . . 333
6.2.3 Dynamic model of the three-phase voltage source inverter . . . 338
6.2.4 Dynamic model of the VSI-fed induction motor . . . 341
6.2.5 Proof of differential flatness properties of the VSI-fed induction motor . . . 343
6.2.6 Linearization and control of the VSI-fed induction motor . . . 345
6.2.7 Stabilizing feedback control . . . 347
6.2.8 Lyapunov stability analysis . . . 349
6.2.9 Comparison to other control methods for the VSI-fed IM . . . 351
6.2.10 Simulation tests . . . 356
6.3 Nonlinear optimal control for a flywheel and battery-based powertrain of Electric Vehicles . . . 366
6.3.1 Outline . . . 366
6.3.2 Dynamic model of the flywheel-based powertrain of the EV . . . 368
6.3.3 Integrated dynamic model of the EV powertrain . . . 370
6.3.4 Differential flatness properties of the flywheel-based powertrain . . . 373
6.3.5 Approximate linearization of the dynamics of the EV powertrain . . . 376
6.3.6 Design of an H-infinity feedback controller . . . 378
6.3.7 Lyapunov stability analysis . . . 381
6.3.8 Simulation tests . . . 383

7 Nonlinear control of electric traction systems based on multi-phase motors 397
7.1 Nonlinear optimal control for the five-phase induction motor-based traction of electric vehicles . . . 397
7.1.1 Outline . . . 397
7.1.2 Dynamic model of the five-phase induction motor . . . 399
7.1.3 Differential flatness properties of the five-phase induction motor . . . 401
7.1.4 Approximate linearization of the dynamics of the five-phase induction motor . . . 402
7.1.5 The nonlinear H-infinity control . . . 403
7.1.6 Lyapunov stability analysis . . . 406
7.1.7 Simulation tests . . . 408
7.2 Nonlinear optimal control for VSI-fed six-phase PMSMs in the traction of electric vehicles . . . 418
7.2.1 Outline . . . 418
7.2.2 Dynamic model of the VSI-fed six-phase PMSM . . . 420
7.2.3 State-space model of the inverters . . . 424
7.2.4 Differential flatness properties of the model of the VSI-fed six-phase PMSM . . . 429
7.2.5 Approximate linearization of the model of the VSI-fed six-phase PMSM . . . 433
7.2.6 Lyapunov stability analysis . . . 437
7.2.7 Simulation tests . . . 439
7.3 Nonlinear optimal control for the nine-phase permanent magnet synchronous motor . . . 450
7.3.1 Outline . . . 450
7.3.2 Dynamic model of the nine-phase PMSM . . . 460
7.3.3 Differential flatness properties of the 9-phase PMSM . . . 465
7.3.4 Approximate linearization of the dynamic model of the 9-phase PMSM . . . 467

7.3.5 Desing of a stabilizing H-infinity feedback controller . . . 469
7.3.6 Lyapunov stability analysis . . . 470
7.3.7 Simulation tests . . . 473

8 Nonlinear control of EV auxiliary actuation systems 483
8.1 Nonlinear control of electrohydraulic actuators . . . 483
8.1.1 Outline . . . 483
8.1.2 Flatness-based control in successive loops for electrohydraulic actuators . . . 484
8.1.3 Simulation tests . . . 489
8.2 Flatness-based control in successive loops of electropneumatic actuators . . . 489
8.2.1 Outline . . . 489
8.2.2 Dynamic model of the electropneumatic actuator . . . 494
8.2.3 Flatness-based control in successive loops for the electropneumatic actuator . . . 497
8.2.4 Simulation tests . . . 499
8.3 Flatness-based control in successive loops of a PMLSM-driven clutch . . . 499
8.3.1 Outline . . . 499
8.3.2 Dynamic model of the PMLSM-actuated clutch . . . 503
8.3.3 Flatness-based control in successive loops for the PMLSM-actuated clutch . . . 507
8.3.4 Simulation tests . . . 510

A Nonlinear optimal control and Lie algebra-based control 515
A.1 Control based on approximate linearization . . . 515
A.1.1 Overview of the optimal control concept . . . 515
A.1.2 Design of an H-infinity nonlinear optimal controller . . . 519
A.1.3 Optimal state estimation with the H-infinity Kalman Filter . . . 525
A.2 Global linearization-based control concepts . . . 528
A.2.1 Foundations of global linearization-based control . . . 528
A.2.2 Elaborating on input-output linearization . . . 534
A.2.3 Input-state linearization . . . 538
A.2.4 Stages in the implementation of input-state linearization . . . 543
A.2.5 Input-output and input-state linearization for MIMO systems . . . 543
A.2.6 Dynamic extension . . . 544

B Differential flatness theory and flatness-based control methods 546
B.1 Global linearization-based control with the use of differential flatness theory . . . 546
B.1.1 The background of differential flatness theory . . . 546
B.1.2 Differential flatness for finite dimensional systems . . . 547
B.1.3 Equivalence and differential flatness . . . 548
B.1.4 Differential flatness and trajectory planning . . . 552
B.1.5 Differential flatness, feedback control and equivalence . . . 555
B.1.6 Flatness-based control and state feedback for systems with model uncertainties . . . 558
B.1.7 Classification of types of differentially flat systems . . . 560
B.2 Flatness-based control of nonlinear dynamical systems in cascading loops . . . 564
B.2.1 Decomposition of the state-space model into cascading differentially flat subsystems . . . 564
B.2.2 Tracking error dynamics for flatness-based control in successive loops . . . 566
B.2.3 Comparison to backstepping control for nonlinear systems . . . 568

References 573
*

Glossary

AC: Alternating Current
AC/DC: Alternating Current / Direct Current
2D: 2-dimensional
3D: three-dimensional
4WD/2WS vehicle: 4 wheel driven / 2 wheel steered vehicle
4WD/4WS vehicle: 4 wheel driven / 4 wheel steered vehicle
AGV: Automatic Ground Vehicle
ARE: Algebraic Riccati Equation
AUV: Autonomous Underwater Vessel
DOF: Degrees of Freedom
EMF: electromagnetic force
EV: Electric Vehicle
HEV: Hybrid Electric Vehicle
H_∞ control: H-infinity control
H_∞ KF: H-infinity Kalman Filter
IM: Induction Motor
KF: Kalman Filter
LQR: Linear Quadratic Regulator
LMI: Linear Matrix Inequality
LPV: Linear Parameter Varying MPC: Model Predictive Control
NMPC: Nonlinear Model Predictive Control
PID: Proportional Integral Derivative Control
PMLSM: Permanent Magnet Linear Synchronous Machine
PMSM: Permanent Magnet Synchronous Motor
PMSG: Permanent Magnet Synchronous Generator
RMSE: Root Mean Square Error
PWM: Pulse Width Modulation
SDRE: State Dependent Riccati Equation
UAV: Unmanned Aerial Vehicle
UGV: Unmanned Ground Vehicle
USV: Unmanned Surface Vessel
VSC: Voltage Source Converter
VSI: Voltage Source Inverter

Overview

The present monograph aims at treating the problems of path tracking and electric traction for autonomous electric vehicles. So far research on autonomous vehicles appears to be disjoint from research on electric traction and propulsion systems, while the new monograph aims at developing together these two areas. On the one side, one can distinguish results and related monographs on the control and estimation problem of autonomous vehicles. Usually, people from the robotics and control community examine autonomous vehicles as mechanical systems and focus on their dynamics and kinematics modelling. Obviously, this approach is incomplete because the autonomous navigation and the precise localization problems of autonomous vehicles should be treated in a holistic manner and jointly with the power generation and optimized power management problem. It should be ensured that minimization of energy consumption is achieved. Besides it is only under an electric traction scheme that the functioning of autonomous vehicles leaves a zero carbon imprint and becomes friendly to the environment.

On the other side, one can distinguish results focusing exclusively on control and estimation for electrical machines and drives and on control of the power electronics that constitute the traction and propulsion system of electric vehicles. This approach is followed by people of the electric power and power electronics community who overlook the problems of autonomous navigation and precise localization of autonomous electric vehicles. However, it is motion planning for electric vehicles that generates setpoints and imposes the functioning modes for the EV traction system. Thus, a main objective in the design of robotized electric vehicles should be the harmonized cooperation between the autonomous navigation and the electric traction system.

In the control and state estimation part of the monograph, there is unique contribution through the development of novel methods. Actually, In the new monograph novel solutions to the control problem of complex nonlinear dynamical systems are developed and tested. These are (i) a nonlinear optimal (H-infinity) control approach, (ii) a flatness-based control approach implemented in successive loops. The new control methods are free of shortcomings met in control schemes which are based on diffeomorphisms and global linearization (complicated changes of state variables, forward and backwards state-space transformations, singularities). It is shown that such methods can be used in a wide class of nonlinear dynamical systems (including autonomous electric vehicles) without needing to transform the systems' state-space model into equivalent linearized forms. It is also shown that the new control methods can be implemented in a computationally simple manner and are also followed by global stability proofs.

The monograph is primarily addressed to the academic and research community of Electrical Engineering, Computer Science, Robotics and Mechatronics, Electric Power Systems and Power Electronics, as well as Intelligent Transportation Systems with a focus on control systems and estimation methods. It is also addressed to engineers and professionals working on control problems and estimation methods, as well as to skilled technical personnel working on real applications. The monograph can be also used for teaching purposes at the late undergraduate and the postgraduate level. The monograph offers a unique insight about the development of control and estimation methods for autonomous electric vehicles of various types (unmanned ground vehicles, unmanned surface vessels, autonomous underwater vessels and unmanned aerial vehicles). It also offers a profound knowledge about the electric traction system of the above noted robotized vehicles targeting to the optimized functioning of electric vehicle powertrains and of their components (electric motors, actuators and power electronics). On the basis of the above, the new monograph is expected to give a useful contribution to the subject area of autonomous electric vehicles.

Gerasimos Rigatos	Masoud Abbaszadeh	Pierluigi Siano	Patrice Wira
Athens. Greece	Clifton Park, NY, USA	Fisciano, Salerno, Italy	Mulhouse, France
August 2024	August 2024	August 2024	August 2024

Preface

In the transportation sector there is progressive shift from vehicles operated and steered by humans to completely autonomous vehicles. Precise path following and ability to perform dexterous manoeuvrings in cluttered and dynamically changing environments are among the intelligent features that autonomous vehicles have. Autonomous navigation, precise localization and mapping and self-diagnosis are becoming prerequisites in the design of all type of vehicles, as for instance in unmanned ground vehicles, unmanned surface vessels, autonomous underwater vessels and unmanned aerial vehicles. Besides, there is progressive transition to electric vehicles with autonomous capabilities. Actually, all developed countries pursue to substitute gradually combustion engine vehicles with electric vehicles. Reducing the use of fossil fuel in transportation is anticipated to contribute significantly to the Net Zero gas emissions objective that aims at eliminating the emission of harmful exhaust gases coming from human activities. Most known manufacturers of vehicles have shifted to the production of all-electric cars, and the announced plan by several car industries is to suspend combustion engine vehicles' production in the next years and to get completely substituted these vehicles by electric ones. It is thus clear that there is need for developing and implementing nonlinear control, estimation and fault diagnosis methods that will optimize the traction system of electric vehicles.

A main approach in the control of the autonomous navigation system and in the electric traction and propulsion system of robotized electric vehicles has been so far based on the concept of diffeomorphisms, that is of state-variables and state-space description transformations that allow for bringing the system into an equivalent linear form where a solution for both the control and state estimation problem becomes feasible. However, the application of such transformations is not always a straightforward procedure since the controlled system should previously satisfy feedback linearizability conditions. Besides, once the control inputs have been computed for the linearized equivalent model it is necessary to apply inverse transformations so as to find the control signals that should be finally used in the initial nonlinear state-space description of the system. This process often comes against singularity issues which signify that there may exist certain state-space regions where the inverse transformations cannot be performed because of generating non-bounded (infinite) control inputs. Taking into account the above, in the present monograph novel solutions to the control problem of autonomous navigation system and of the electric traction system of robotized vehicles and drones are developed and tested. These are (i) a nonlinear optimal (H-infinity) control approach, (ii) a flatness-based control approach implemented in successive loops. The new control methods are not constrained by the aforementioned shortcomings of global linearization-based control schemes (complicated changes of state variables, forward and backwards state-space transformations, singularities). It is shown that such methods can be used in a wide class of robotized electric vehicles without needing to transform the state-space model of such systems into equivalent linearized forms. It is also shown that the new control methods can be implemented in a computationally simple manner and are also followed by global stability proofs.

The monograph is addressed to the academic and research community of the fields of Electrical Engineering, Computer Science, Robotics and Mechatronics, Electric Power Systems and Power Electronics, as well as Intelligent Transportation Systems with a focus on control systems and estimation methods. It is also addressed to engineers working on control problems and estimation methods, as well as to skilled technical personnel working on real applications. It is also anticipated that the monograph will be particularly useful to researchers and university tutors working on nonlinear control, nonlinear estimation and fault diagnosis problems of autonomous electric vehicles and of the traction systems of robotized electric vehicles.

The monograph's results and developments on autonomous electric vehicles can be used by (i) researchers and members of the academic and university community, (ii) engineers, scientists and professionals working on related topics (iii) students at the late undergraduate or at the postgraduate level. The findings of the monograph are expected to be analyzed, confirmed and extended by the members of the research and academic community and by university staff conducting research on advanced topics of autonomous electric vehicles, as well as on the electric traction and propulsion system of such vehicles. Much research effort is made during the last years in this domain and consequently one expects that there will be high interest from the members of the research and university community about the monograph's novel findings. Furthermore, there are many engineers, scientists and professionals working on practical problems of electromotion and in applications of robotized electric vehicles which would be keen for testing, validating and extending the monograph's results. The methods which are developed by the monograph have the potential for wide use at the industrial production level and can foster growth of the related industrial domain. Finally, the monograph's results and findings have a clear educational value. The monograph can be used for teaching advanced topics on autonomous electric vehicles to students of the late undergraduate and of the postgraduate level. The monograph, as a teaching source, offers technical expertise and profound knowledge about robotized electric vehicles and about the optimized functioning of the traction and propulsion systems of such vehicles.

The monograph consists of two parts (a) control and estimation of the dynamics and kinematics of robotised electric vehicles (Chapters 1 to 5) (b) control and estimation of the electric traction system for such autonomous vehicles (Chapters 6 to 8).

In part (a) Control and estimation for the dynamics and kinematics of robotized vehicles the following chapters has been included:

Chapter 1: Nonlinear control of ground vehicles I. In its first section the chapter analyzes nonlinear optimal control for cooperation of car-like front-wheel-steered ground vehicles. First it defines the kinematic model of the front-wheel steered car-like vehicle. An equivalent linearized model of this vehicle is obtained through Taylor series expansion and an H-infinity feedback controller is designed about it. The global stability of the nonlinear optimal (H-infinity) control scheme is proven through Lyapunov analysis. Moreover, it is shown how this control method enables synchronization between a leader and multi-follower vehicles. In its second section the chapter analyses nonlinear optimal control for the omnidirectional three-wheel ground vehicle. The dynamic model of the 3-wheel omnidirectional ground vehicle is formulated and a nonlinear optimal (H-infinity) controller is developed about it. Moreover a multi-loop flatness-based controller is designed for this 3-wheel autonomous ground vehicle.

Chapter 2: Nonlinear control of ground vehicles II. In its first section the chapter analyzes nonlinear optimal control of four-wheel autonomous ground vehicles. The bicycle-type dynamic and kinematic model of four wheel drive and two-wheel steered vehicles is formulated. Approximate linearization of the vehicle's joint kinematic and dynamic model is performed with the use of Taylor series expansion. A nonlinear H-infinity controller is developed for this vehicle based on the sequential solution of an algebraic Riccati equation. The global stability properties of the control scheme are proven through Lyapunov analysis. In its second section the chapter analyzes nonlinear optimal control of tracked (skid-steered) vehicles. The kinematic model of a tracked autonomous vehicle is formulated and linearization of it is performed with Taylor series expansion and the computation of Jacobian matrices. Path following for this vehicle is enabled with the use of an H-infinity controller which is based on the sequential solution of an algebraic Riccati equation. The global stability properties of the control scheme are again proven through Lyapunov analysis. In its third section the chapter treats the nonlinear control problem of multi-axle and multi-steered autonomous ground vehicles. The kinematic model of a five-axle and three steering vehicle is formulated and differential flatness properties are proven about it. Taylor series expansion is used for the linearization of the state-space description of this vehicle. An H-infinity (optimal) feedback controller is designed for this vehicle based on the sequential solution of an algebraic Riccati equation. Lyapunov analysis-based global stability proof comes to ensure precise trajectory tracking by this multi-axle and multi-steered autonomous vehicle.

Chapter 3: 3 Nonlinear control of aerial vehicles I. In the first section of this chapter the nonlinear optimal control problem of 6-DOF UAVs with tilting rotors is analyzed. The dynamic model of the 6-DOF tilt-rotor UAV is formulated. The state-space model of this aerial drone is linearized with the use of Taylor series expansion. A stabilizing H-infinity feedback controller is designed about it through the sequential solution of an algebraic Riccati equation. The global stability properties of the control scheme are proven through Lyapunov analysis. The control method is compared to multi-loop flatness-based control. In the second section of this chapter nonlinear optimal control is developed for the dynamic model of the 6-DOF fixed-wing UAV. The dynamic model of this aerial drone is analyzed and is shown to be in a non-affine and underactuated state-space form. Differential flatness properties are proven about this drone's dynamics. The dynamic model of the 6-DOF fixed-wing aerial drone undergoes linearization with Taylor series expansion. An H-infinity feedback controller is designed about it by solving sequentially an algebraic Riccati equation. Stability proof with Lyapunov analysis comes to confirm precise flight-path following by this aerial drone. In the third section of this chapter flatness-based control in successive loops is developed for autonomous octocopters. The 6-DOF dynamic model of autonomous octocopters is formulated and differential flatness properties are proven about it. Precise flight path following is enabled with the use of a flatness-based control which is implemented in successive loops.

Chapter 4: Nonlinear control of aerial vehicles II. In the first section of the chapter flatness-based control in successive loops is developed for autonomous quadrotors. The dynamic model of 6-DOF quadrotors is expressed in the form of subsystems which are connected in cascading form. Differential flatness properties are proven for the subsystems which constitute the integrated state-space model of this drone. Flatness-based control in successive loops is developed for the 6-DOF quadropter and global stability is proven through Lyapunov analysis. In the second section of the chapter nonlinear optimal and multi-loop flatness-based control for dual-UAV cooperative load transportation is developed. The dynamic model of the cable-driven payload is developed and the nonlinear optimal control problem is formulated and solved about it. Next the dynamic model of the 6-DOF autonomous quadrotors which lift the payload is analyzed. Flatness-based control in successive loops for these quadrotors is implemented after taking into account the cables' tension which are computed from the solution of the nonlinear optimal control problem for the payload. The global stability of the integrated control system is proven through Lyapunov analysis.

Chapter 5: Nonlinear control of unmanned vessels. In the first section of this chapter flatness-based control in successive loops for 3-DOF autonomous underwater vessels is developed. The dynamic model of the 3-DOF autonomous underwater vessel is analyzed. This model is written in the form of two cascading subsystems and differential flatness properties are proved for each subsystem. Next, flatness-based control in two successive loops is designed for the 3-DOF autonomous underwater vessel and global stability about it is proven through Lyapunov analysis. In the second section of the chapter flatness-based control in successive loops is developed for the dynamic model of the 3-DOF unmanned surface vessel and the 6-DOF dynamic model of an autonomous submarine. Both dynamic models of these autonomous underwater vessels are written in a chained subsystems form and differential flatness properties are proven about them. Stabilization and precise path following for these autonomous vessels is achieved through a multi-loop flatness-based control scheme. Global stability properties are proven through Lyapunov analysis.

In part (b) Control and estimation of the electric traction of electric autonomous vehicles has been included:

Chapter 6: Nonlinear control of electric traction systems based on three-phase motors. In the first section of this chapter Flatness-based control in successive loops for VSI-fed PMSMs and VSI-fed Induction Motors is analyzed. First, the state-space model of the VSI-fed PMSM is decomposed into a chained subsystems form and differential flatness properties are proven about it. Flatness-based control in successive loops is developed for the VSI-fed PMSM and global stability properties are also proven through Lyapunov analysis. In the same section flatness-based control in successive loops is developed for VSI-fed Induction Machines. The state-space model of the VSI-fed IM is decomposed into a chained subsystems form and differential flatness properties are proven about it. Next, a multi-loop flatness-based control scheme is designed for the chained subsystems structure of the VSI-fed IM and global stability is proven through Lyapunov analysis. In the second section of the chapter nonlinear optimal and sliding-mode control is developed for Voltage Source Inverter-fed Induction Motors. By integrating the dynamics of the voltage source inverter and the IM, the state-space description of this electric traction system is obtained and differential flatness properties are proven about it. The state-space model of the VSI-fed IM is linearized with the use of Taylor series expansion. An H-infinity (optimal) feedback controller is designed for it through sequential solution an algebraic Riccati equation. Global stability is demonstrated through Lyapunov analysis. The nonlinear optimal control method for the VSI-fed IM is compared to sliding-mode control. In the third section of the chapter the nonlinear optimal control problem for a flywheel and battery-based powertrain of Electric Vehicles is treated. The dynamic model of the flywheel-based powertrain of the EV is analyzed and differential flatness properties are proven about it. The flywheel and battery-based EV powertrain state-space model is linearized through Taylor series expansion. An H-infinity (optimal) feedback controller is designed about it through the sequential solution of an algebraic Riccati equation. Again global stability properties are proven through Lyapunov analysis.

Chapter 7: Nonlinear control of electric traction systems based on multi-phase motors. In the first section of the chapter nonlinear optimal control is developed for the five-phase induction motor-based traction system of electric vehicles. The dynamic model of the five-phase induction motor is formulated and differential flatness properties are proven about it. The state-space model of this multi-phase motor-based traction system is linearized through Taylor series expansion. An H-infinity (optimal) feedback controller is designed for it after solving sequentially an algebraic Riccati equation. Global stability is proven through Lyapunov analysis. In the second section of the chapter nonlinear optimal control is developed for VSI-fed six-phase PMSMs which are used in the traction of electric vehicles. The dynamic model of the VSI-fed six-phase PMSM is written in state-space form and differential flatness properties are proven about it. This model is linearized using Taylor series expansion. An H-infinity (optimal) feedback controller is designed for it through the sequential solution of an algebraic Riccati equation. Global stability is proven through Lyapunov analysis. In the third section of the chapter a nonlinear optimal controller is designed for the nine-phase permanent magnet synchronous motor. The dynamic model of the nine-phase PMSM is formulated and differential flatness properties are proven about it. The state-space model of the nine-phase PMSM is linearized through first-order Taylor series expansion. An H-infinity (optimal) feedback controller is designed for it based on the sequential solution of an algebraic Riccati equation. Once again Lyapunov analysis is used to prove global stability for this electric traction system.

Chapter 8: Nonlinear control of EV auxiliary actuation systems. In the first section of this chapter nonlinear control of electrohydraulic actuators used in the steering or braking system of EVs is analyzed. The dynamic model of electrohydraulic actuators is formulated into a chained subsystems form and differential flatness properties are proven about it. A multi-loop flatness-based controller is designed for the subsystems which constitute the dynamics of the electrohydraulic actuator. Global stability is proven through Lyapunov analysis. In the second section of the chapter flatness-based control in successive loops is developed again for electropneumatic actuators which find use in the steering and braking system of EVs. The dynamic model of the electropneumatic actuators is written in a chained subsystems form and differential flatness properties are proven about it. Next, a multi-loop flatness-based controller is designed for the subsystems which constitute the model of the electropneumatic actuators. Once again global stability is proven through Lyapunov analysis. Moreover, in the third section of the chapter flatness-based control in successive loops ia developed for a PMLSM-driven clutch. The dynamic model of the PMLSM-actuated clutch is formulated and differential flatness properties are proven about it. A multi-loop flatness based controller is designed for the subsystems which constitute the dynamic model of the PMLSM-actuated clutch. Global stability is proven through Lyapunov analysis,

The monograph includes also two Appendices which analyze the theoretical background of the presented nonlinear control and estimation methods:

Appendix A: Nonlinear optimal control and Lie algebra-based control. In the first section of this appendix control and state estimation based of approximate linearization of the dynamic models of nonlinear system is explained. Linearization is performed sequentially through Taylor series expansion and the solution of a Riccati equation. The H-infinity Kalman Filter is developed as a robust state estimator. In the second section of the chapter global linearization-based control and state estimation is developed for nonlinear systems. To this end input-output and input-state linearization conditions are analyzed. Results from Lie algebra-based control and Lie algebra-based state observers are explained. The concept of dynamic extension is also outlined.

Appendix B: Differential flatness theory and flatness-based control methods. In the first section of the Appendix global linearization-based control with the use of differential flatness theory is analyzed, comprising issues such as differential flatness for finite dimensional systems, equivalence and differential flatness, feedback control and equivalence flatness-based control, state feedback for systems with model uncertainties and finally classification of types of differentially flat systems. In the second section of this chapter the concept of flatness-based control of nonlinear dynamical systems in cascading loops is analysed. This comprises issues such as decomposition of the state-space model into cascading differentially flat subsystems, tracking error dynamics for flatness-based control in successive loops and comparison to backstepping control for nonlinear systems.

The readers of the monograph can select the parts of the monograph which are of higher importance and interest for them. For instance, readers coming from the systems and control area can focus on control and estimation for autonomous electric vehicles. These readers can concentrate on the first part of the monograph that contains chapters on nonlinear control and estimation for various types of drones and autonomous vehicles such as unmanned ground vehicles, unmanned aerial vehicles. unmanned surface vessels and autonomous underwater vessels Besides, readers coming from the electric power systems and power electronics area can focus on the electric traction and propulsion systems of robotized electrical vehicles. These readers can concentrate on the second part of the monograph which contains chapters on nonlinear control and estimation for powertrains or for the individual components of electric traction systems such as synchronous and asynchronous three-phase motors, multi-phase motors and the associated power electronics (that is converters and inverters). It total, it is expected that the coverage of the subject area that is offered by the monograph will be complete.

Gerasimos Rigatos	Masoud Abbaszadeh	Pierluigi Siano	Patrice Wira
Athens. Greece	Clifton Park, NY, USA	Fisciano, Salerno, Italy	Mulhouse, France
August 2024	August 2024	August 2024	August 2024