

Contents

1	Nonlinear Dynamical Systems and Global Linearizing Control Methods	1
1.1	Introduction	1
1.2	Characteristics of the Dynamics of Nonlinear Systems	1
1.3	Computation of Isoclines	6
1.4	Basic Features in the Study of Nonlinear Dynamics	8
1.4.1	The Phase Diagram	8
1.4.2	Stability Analysis of Nonlinear Systems	9
1.4.3	Stability Analysis of Nonlinear Models	11
1.5	Phase Diagrams and Equilibria of Nonlinear Models	12
1.5.1	Phase Diagrams for Linear Dynamical Systems	12
1.5.2	Multiple Equilibria for Nonlinear Dynamical Systems	17
1.5.3	Limit Cycles	19
1.6	Bifurcations in Nonlinear Dynamics	21
1.6.1	Bifurcations of Fixed Points of Nonlinear Models	21
1.6.2	Saddle-Node Bifurcations of Fixed Points in a One-Dimensional System	21
1.6.3	Pitchfork Bifurcation of Fixed Points	22
1.6.4	The Hopf Bifurcation	24
1.7	Predecessors of Differential Flatness Theory	26
1.7.1	The Differential Geometric Approach	26
1.7.2	Elaboration on the Frobenius Theorem	29
1.7.3	Input–Output Linearization	30
1.7.4	Elaborating on Input–Output Linearization	33
1.7.5	Input-State Linearization	37
1.7.6	Stages in the Implementation of Input-State Linearization	43
1.7.7	Input–Output and Input-State Linearization for MIMO Systems	44
1.7.8	Dynamic Extension	45

2	Differential Flatness Theory and Flatness-Based Control	47
2.1	Introduction	47
2.2	Definition of Differentially Flat Systems	48
2.2.1	The Background of Differential Flatness Theory	48
2.2.2	Differential Flatness for Finite Dimensional Systems	49
2.3	Properties of Differentially Flat Systems	57
2.3.1	Equivalence and Differential Flatness	57
2.3.2	Differential Flatness and Trajectory Planning	72
2.3.3	Differential Flatness, Feedback Control and Equivalence	75
2.4	Flatness-Based Control and State Feedback for Systems with Model Uncertainties	79
2.5	Classification of Types of Differentially Flat Systems	82
2.5.1	Criteria About the Differential Flatness of a System	82
2.5.2	A Sufficient Condition for Showing that a System Is Not Differentially Flat	85
2.5.3	Liouvillian and Nondifferentially Flat Systems	86
2.6	Elaborated Criteria for Checking Differential Flatness	87
2.6.1	Implicit Control Systems on Manifolds of Jets	87
2.6.2	The Lie-Backlund Equivalence for Implicit Systems	89
2.6.3	Conditions for Differential Flatness of Implicit Systems	90
2.6.4	Example of Elaborated Differential Flatness Criteria to Nonlinear Systems	93
2.7	Distributed Parameter Systems and Their Transformation into the Canonical Form	96
2.7.1	State-Space Description of a Heat Diffusion Dynamics	96
2.7.2	Differential Flatness of the Nonlinear Heat Diffusion PDE	99
3	Nonlinear Adaptive Control Based on Differential Flatness Theory	103
3.1	Introduction	103
3.2	Flatness-Based Adaptive Neuro-Fuzzy Control for SISO Systems	104
3.2.1	Overview	104
3.3	Flatness-Based Adaptive Fuzzy Control for SISO Dynamical Systems	105
3.3.1	Transformation of SISO Nonlinear Systems into a Canonical Form	105

- 3.3.2 Adaptive Control Law for SISO Nonlinear Systems 106
- 3.3.3 Approximators of SISO System Unknown Dynamics 107
- 3.3.4 Lyapunov Stability Analysis for SISO Dynamical Systems 109
- 3.3.5 Simulation Tests 111
- 3.4 Flatness-Based Adaptive Fuzzy Control for MIMO Systems 116
 - 3.4.1 Overview 116
 - 3.4.2 Differential Flatness for MIMO Nonlinear Dynamical Systems 117
 - 3.4.3 Flatness-Based Adaptive Fuzzy Control for MIMO Nonlinear Systems 120
 - 3.4.4 Flatness-Based Control for a MIMO Robotic Manipulator 122
 - 3.4.5 Lyapunov Stability Analysis for MIMO Nonlinear Systems 127
 - 3.4.6 Simulation Tests 133
- 4 Nonlinear Kalman Filtering Based on Differential Flatness Theory 141**
 - 4.1 Introduction 141
 - 4.2 The Derivative-Free Nonlinear Kalman Filter 142
 - 4.2.1 Overview 142
 - 4.2.2 Extended Kalman Filtering for Nonlinear Dynamical Systems 143
 - 4.2.3 Derivative-Free Kalman Filtering to SISO Nonlinear Systems 149
 - 4.2.4 Simulation Tests 152
 - 4.2.5 Derivative-Free Kalman Filtering for MIMO Nonlinear Systems 163
 - 4.2.6 Simulation Tests 166
 - 4.3 The Derivative-Free Distributed Nonlinear Kalman Filter 172
 - 4.3.1 Overview 172
 - 4.3.2 Overview of the Extended Information Filter 173
 - 4.3.3 Distributed Filtering for Sensorless Control 177
 - 4.3.4 Simulation Tests 179
- 5 Differential Flatness Theory and Industrial Robotics 183**
 - 5.1 Overview 183
 - 5.2 Adaptive Fuzzy Control of Underactuated MIMO Robots 185
 - 5.2.1 Overview 185

5.2.2	Dynamic Model of the Closed-Chain 2-DOF Robotic System	186
5.2.3	Linearization of the Closed-Chain 2-DOF Robotic System Using Lie Algebra Theory	192
5.2.4	Differential Flatness of the Underactuated Manipulator	195
5.2.5	Flatness-Based Adaptive Fuzzy Control for the Underactuated Robot.	198
5.2.6	Simulation Tests	198
5.3	Observer-Based Adaptive Fuzzy Control of MIMO Robots	199
5.3.1	Overview	199
5.3.2	Estimation of the Robot's State Vector	201
5.3.3	Application of Flatness-Based Adaptive Fuzzy Control	203
5.3.4	Dynamics of the Observation Error	204
5.3.5	Approximation of the System's Unknown Dynamics	205
5.3.6	Lyapunov Stability Analysis.	206
5.3.7	The Role of Riccati Equation Coefficients in Observer-Based Adaptive Fuzzy Control	212
5.3.8	Simulation Tests	214
5.4	State Estimation-Based Control of Underactuated Robots.	218
5.4.1	Overview	218
5.4.2	Derivative-Free Nonlinear Kalman Filter for the Closed-Chain 2-DOF Robotic System	219
5.4.3	Simulation Tests	222
5.5	Distributed Filtering Under External Disturbances	223
5.5.1	Overview	223
5.5.2	Dynamics and Control of the Robot	225
5.5.3	Simulation Tests	227
5.6	Distributed Nonlinear Filtering Under Measurement Delays	230
5.6.1	Networked Control Under Communication Disturbances	230
5.6.2	Networked Kalman Filtering for an Autonomous System	231
5.6.3	Smoothing Estimation in Case of Delayed Measurements	232
5.6.4	Distributed Filtering-Based Fusion of the Robot's State Estimates	235
5.6.5	Simulation Tests	236

6 Differential Flatness Theory in Mobile Robotics and Autonomous Vehicles 239

6.1 Outline 239

6.2 State Estimation-Based Control of Autonomous Vehicles. 241

6.2.1 Localization and Autonomous Navigation of Ground Vehicles. 241

6.2.2 Application of Derivative-Free Kalman Filtering to MIMO UGV Models. 242

6.2.3 Controller Design for UGVs. 244

6.2.4 Derivative-Free Kalman Filtering for UGVs. 247

6.2.5 Simulation Tests. 248

6.2.6 Derivative-Free Kalman Filter-Based Navigation of the Autonomous Vehicle 252

6.3 State Estimation-Based Control and Synchronization of Cooperating Vehicles 261

6.3.1 Overview. 261

6.3.2 Distributed Kalman Filtering for Unmanned Ground Vehicles. 263

6.3.3 Simulation Tests. 264

6.4 Distributed Fault Diagnosis for Autonomous Vehicles. 265

6.4.1 Integrity Testing in Navigation Sensors of AGVs 265

6.4.2 Sensor Fusion for AGV Navigation. 267

6.4.3 Canonical Form for the AGV Model. 270

6.4.4 Derivative-Free Extended Information Filtering for UGVs 270

6.4.5 Simulation Tests. 271

6.5 Velocity Control of 4-Wheel Vehicles. 273

6.5.1 Overview. 273

6.5.2 Dynamic Model of the Vehicle. 276

6.5.3 Flatness-Based Controller for the 3-DOF Vehicle Model 280

6.5.4 Estimation of Vehicle Disturbance Forces with Kalman Filtering 283

6.5.5 Simulation Tests. 286

6.6 Active Vehicle Suspension Control. 288

6.6.1 Overview. 288

6.6.2 Dynamic Model of Vehicle Suspension 292

6.6.3 Flatness-Based Control for a Suspension Model 296

6.6.4 Compensating for Model Uncertainty with the Use of the H_∞ Kalman Filter. 297

6.6.5 Robust State Estimation with the Use of Disturbance Observers. 300

6.6.6 Simulation Tests. 302

- 6.7 State Estimation-Based Control of Quadrotors 304
 - 6.7.1 Overview 304
 - 6.7.2 Kinematic Model of the Quadropter 310
 - 6.7.3 Euler-Lagrange Equations for the Quadropter 311
 - 6.7.4 Design of Flatness-Based Controller for the Quadrotor’s Model 313
 - 6.7.5 Estimation of the Quadrotor’s Disturbance Forces and Torques with Kalman Filtering 315
 - 6.7.6 Simulation Tests 318
- 6.8 State Estimation-Based Control of the Underactuated Hovercraft 320
 - 6.8.1 Overview 320
 - 6.8.2 Lie Algebra-Based Control of the Underactuated Hovercraft 323
 - 6.8.3 Flatness-Based Control of the Underactuated Vessel 329
 - 6.8.4 Disturbances’ Compensation with the Use of the Derivative-Free Nonlinear Kalman Filter 330
 - 6.8.5 Simulation Tests 332
- 7 Differential Flatness Theory and Electric Power Generation 337**
 - 7.1 Outline 337
 - 7.2 State Estimation-Based Control of PMSGs 338
 - 7.2.1 The PMSG Control Problem 338
 - 7.2.2 Dynamic Model of the Permanent Magnet Synchronous Generator 340
 - 7.2.3 Lie Algebra-Based Design of State Estimators for the PMSG 342
 - 7.2.4 Differential Flatness of the PMSG 347
 - 7.2.5 Estimation of PMSG Disturbance Input with Kalman Filtering 349
 - 7.2.6 Simulation Experiments 352
 - 7.3 State Estimation-Based Control of DFIGs 358
 - 7.3.1 Overview 358
 - 7.3.2 The Complete Sixth-Order Model of the Induction Generator 359
 - 7.3.3 Input–Output Linearization of the DFIG Using Lie Algebra 363
 - 7.3.4 Input–Output Linearization of the DFIG Using Differential Flatness Theory 367
 - 7.3.5 Kalman Filter-Based Disturbance Observer for the DFIG Model 371
 - 7.3.6 Simulation Tests 373

7.4	Flatness-Based Control of DFIG in Cascading Loops	377
7.4.1	Overview	377
7.4.2	A New Proof of the Differential Flatness of the DFIG	378
7.4.3	Control of the DFIG in Cascading Loops	380
7.4.4	EKF Implementation for Sensorless Control of the DFIG	383
7.4.5	Simulation Tests	385
7.5	State Estimation-Based Control of Distributed PMSGs	388
7.5.1	Overview	388
7.5.2	Dynamic Model of the Distributed Power Generation Units	390
7.5.3	Lie Algebra-Based Design of a Feedback Controller for the PMSG	391
7.5.4	Differential Flatness of the Distributed PMSG Model	393
7.5.5	Simulation Tests	397
8	Differential Flatness Theory for Electric Motors and Actuators	403
8.1	Introduction	403
8.2	Flatness-Based Adaptive Control of DC Motors	404
8.2.1	Overview	404
8.2.2	Dynamics and Linearization of the DC Motor Model	405
8.3	Flatness-Based Control of Induction Motors in Cascading Loops	409
8.3.1	Overview	409
8.3.2	A Cascading Loops Scheme for Control of Field-Oriented Induction Motors	410
8.3.3	A Flatness-Based Control Approach for Induction Motors	414
8.3.4	Implementation of the EKF for the Nonlinear Induction Motor Model	415
8.3.5	Unscented Kalman Filtering for Induction Motor Control	416
8.4	Simulation Results	418
8.5	Flatness-Based Adaptive Control of Electrostatic MEMS Using Output Feedback	422
8.5.1	Introduction	422
8.5.2	Dynamic Model of the Electrostatic Actuator	423
8.5.3	Linearization of the MEMS Model Using Lie Algebra	425

8.5.4	Differential Flatness of the Electrostatic Actuator	427
8.5.5	Adaptive Fuzzy Control of the MEMS Model Using Output Feedback	429
8.5.6	Lyapunov Stability Analysis.	434
8.5.7	Simulation Tests.	439
9	Differential Flatness Theory in Power Electronics.	443
9.1	Introduction	443
9.2	Three-Phase Voltage Source Converters Control.	444
9.2.1	Overview.	444
9.2.2	Linearization of the Converter's Model Using Lie Algebra	446
9.2.3	Differential Flatness of the Voltage Source Converter.	449
9.2.4	Kalman Filter-Based Disturbance Observer for the VSC Model.	453
9.2.5	Simulation Tests.	455
9.3	Inverters Control.	458
9.3.1	Overview.	458
9.3.2	Dynamic Model of the Inverter.	459
9.3.3	Lie Algebra-Based Control of the Inverter's Model. . .	463
9.3.4	Differential Flatness of the Inverter's Model.	466
9.3.5	Flatness-Based Control of the Inverter.	468
9.3.6	State and Disturbances Estimation with Nonlinear Kalman Filtering.	472
9.3.7	Simulation Tests.	473
9.4	Distributed Inverters Synchronization	475
9.4.1	Overview.	475
9.4.2	The Synchronization Problem for Parallel Inverters. . .	477
9.5	State and Disturbances Estimation of Parallel Inverters with Nonlinear Kalman Filtering.	482
9.6	Simulation Tests.	483
10	Differential Flatness Theory for Internal Combustion Engines . . .	491
10.1	Overview.	491
10.2	Flatness-Based Control of Valves in Marine Diesel Engines. . .	493
10.2.1	Overview.	493
10.2.2	Dynamic Model of the Valve.	494
10.2.3	Input–Output Linearization Using Lie Algebra	498
10.2.4	Input–Output Linearization Using Differential Flatness Theory	501
10.2.5	Disturbances Compensation with Derivative-Free Nonlinear Kalman Filter	504
10.2.6	Simulation Tests.	506

- 10.3 Flatness-Based Control of Diesel Combustion Engines 511
 - 10.3.1 Overview 511
 - 10.3.2 Dynamic Model of the Turbocharged Diesel Engine 512
 - 10.3.3 Nonlinear Control of the Diesel Engine Using Lie Algebra 514
 - 10.3.4 A Dynamic Extension-Based Feedback Control Scheme 517
 - 10.3.5 Nonlinear Control of the Diesel Engine Using Differential Flatness Theory 521
 - 10.3.6 Disturbances Compensation Using the Derivative-Free Nonlinear Kalman Filter 525
 - 10.3.7 Simulation Tests 527
- 10.4 Adaptive Control for Diesel Combustion Engines 528
 - 10.4.1 Overview 528
 - 10.4.2 Observer-Based Adaptive Fuzzy Control for the Diesel Combustion Engine 529
 - 10.4.3 Application of Flatness-Based Adaptive Fuzzy Control to the MIMO Diesel Engine Model 533
 - 10.4.4 Lyapunov Stability Analysis 538
 - 10.4.5 Simulation Tests 543
- 10.5 Flatness-Based Control and Kalman Filtering for the Spark-Ignited Engine 547
 - 10.5.1 Overview 547
 - 10.5.2 Dynamic Model of the SI Engine 548
 - 10.5.3 Feedback Linearizing Control of the SI Engine Using Lie Algebra 549
 - 10.5.4 Feedback Linearizing Control of the SI Engine Using Differential Flatness Theory 551
 - 10.5.5 Compensation of Disturbances Using the Derivative-Free Nonlinear Kalman Filter 553
 - 10.5.6 Simulation Tests 554
- 10.6 Flatness-Based Adaptive Fuzzy Control of the Spark-Ignited Engine 558
 - 10.6.1 Overview 558
 - 10.6.2 Flatness-Based Adaptive Fuzzy Control for SI Motors 559
 - 10.6.3 Lyapunov Stability Analysis 562
 - 10.6.4 Simulation Tests 565
- 10.7 Flatness-Based Control and Kalman Filtering of the Air–Fuel Ratio 566
 - 10.7.1 Overview 566
- 10.8 Dynamic Model of the Air–Fuel Ratio System 567
 - 10.8.1 The Air and Fuel Flow Models 567

10.8.2	Dynamics of the Air–Fuel Ratio System	569
10.8.3	Differential Flatness of the Air–Fuel Ratio System . . .	570
10.8.4	Flatness-Based Control of the Air–Fuel Ratio System	572
10.8.5	Compensation of Uncertainties with the Derivative-Free Nonlinear Kalman Filter	573
10.8.6	Simulation Tests	577
11	Differential Flatness Theory for Chaotic Dynamical Systems.	579
11.1	Introduction	579
11.2	Flatness-Based Control of Chaotic Dynamical Systems	580
11.2.1	Overview	580
11.2.2	Differential Flatness of Chaotic Dynamical Systems	581
11.2.3	Flatness-Based Adaptive Fuzzy Control for Chaotic Systems	585
11.2.4	Design of the Feedback Controller	585
11.2.5	Approximators of Unknown System Dynamics	587
11.2.6	Lyapunov Stability Analysis	588
11.2.7	Nonlinear Feedback Control of Chaotic Systems Based on Fuzzy Local Linearization	591
11.2.8	Simulation Tests	593
11.3	Differential Flatness Theory for Chaos-Based Communication Systems	596
11.3.1	Overview	596
11.3.2	Structure of the Chaotic Communication System	598
11.3.3	Differential Flatness Theory	600
11.3.4	Estimation in Chaotic Modulators with Nonlinear Kalman Filter	601
11.3.5	Channel Equalization and Synchronization Using Dual Kalman Filtering	602
11.3.6	Simulation Tests	605
12	Differential Flatness Theory for Distributed Parameter Systems	613
12.1	Introduction	613
12.2	Pointwise Flatness-Based Control of Distributed Parameter Systems	615
12.2.1	Overview	615
12.2.2	Nonlinear 1D Wave-Type Partial Differential Equations	616
12.2.3	Sine-Gordon Nonlinear PDE in the Model of the Josephson Junction	617

- 12.2.4 Current Equation in a Josephson Transmission Line. 618
- 12.2.5 State-Space Description of the Nonlinear Wave Dynamics 619
- 12.2.6 Solution of the Control and Estimation Problem for Nonlinear Wave Dynamics 622
- 12.2.7 Simulation Tests 625
- 12.3 Control of Heat Diffusion in Arc Welding Using Differential Flatness Theory and Nonlinear Kalman Filtering. 627
 - 12.3.1 Overview. 627
- 12.4 Dynamic Model of the Arc Welding Process 631
- 12.5 State-Space Description of the Nonlinear Heat Diffusion Dynamics 633
- 12.6 Solution of the Control and Estimation Problem for Nonlinear Heat Diffusion 635
 - 12.6.1 Solution of the Control Problem. 635
 - 12.6.2 Solution of the Estimation Problem. 637
- 12.7 Simulation Tests 639
- 12.8 Fault Detection and Isolation in Distributed Parameter Systems. 640
 - 12.8.1 Overview. 640
 - 12.8.2 Estimation of Nonlinear Wave Dynamics. 643
 - 12.8.3 Equivalence Between Kalman Filters and Regressor Models 645
 - 12.8.4 Change Detection with the Local Statistical Approach. 646
 - 12.8.5 Simulation Tests 651
- 12.9 Application to Condition Monitoring of Civil and Mechanical Structures 656
 - 12.9.1 Overview. 656
 - 12.9.2 Dynamical Model of the Building—Mechanical Structure 657
- 12.10 Differential Flatness of the Multi-DOF Building’s Structure 659
 - 12.10.1 Damage Detection with the Use of Statistical Criteria 662
 - 12.10.2 Disturbances Estimation with the Derivative-Free Nonlinear Kalman Filter 664
 - 12.10.3 Simulation Tests 666

13 Differential Flatness Theory in the Background of Other Control Methods. 671

13.1 Differential Flatness Theory in the Background of Backstepping Control 671

13.1.1 Overview 671

13.1.2 Flatness-Based Control Through Transformation into the Canonical Form 673

13.1.3 A New Approach to Flatness-Based Control for Nonlinear Dynamical Systems 674

13.1.4 Closed-Loop Dynamics 677

13.1.5 Comparison to Backstepping Control. 679

13.1.6 Simulation Tests 680

13.2 Differential Flatness and Optimal Control 686

13.3 Boundary Control of Nonlinear PDE Dynamics Using Differential Flatness Theory 687

13.3.1 Overview 687

13.3.2 Transformation of the PDE Model into a Set of Nonlinear ODEs 688

13.3.3 Differential Flatness of the Nonlinear PDE Model. 691

13.3.4 Computation of a Boundary Conditions-Based Feedback Control Law 693

13.3.5 Closed-Loop Dynamics 695

13.3.6 Simulation Tests 697

References. 701

Index 731



<http://www.springer.com/978-3-319-16419-9>

Nonlinear Control and Filtering Using Differential
Flatness Approaches

Applications to Electromechanical Systems

Rigatos, G.

2015, XXIX, 736 p. 375 illus., 319 illus. in color.,

Hardcover

ISBN: 978-3-319-16419-9