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Nonlinear Control and Filtering Using Differential Flatness Approaches

Applications to Electromechanical Systems

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To Elektra

Foreword

The present book analyzes the design of nonlinear filters and nonlinear adaptive controllers, using exact linearization which is based on differential flatness theory and differential geometry methods. The obtained filters exhibit specific advantages as they outperform in terms of accuracy of estimation and computation speed other nonlinear filters. The obtained adaptive controllers can be applied to a wider class of nonlinear systems with unknown dynamics and can assure reliable functioning of the control loop under uncertainty and under varying operating conditions. Moreover, the book analyzes differential flatness theory-based control and filtering methods for distributed parameter systems. The book presents a series of application examples to confirm the efficiency of the proposed control and filtering schemes for various electromechanical systems. These include:

(i) Industrial Robotics: neuro-fuzzy adaptive control of multi-DOF robots and underactuated robotic manipulators, observer-based neuro-fuzzy control of multi-DOF robotic manipulators, state estimation-based control of multi-DOF robots and underactuated robotic manipulators, State estimation-based control of robots and mechatronic systems under disturbances and model uncertainties.

(ii) Mobile robotics and vehicles: state estimation-based control of autonomous vehicles, control of cooperating vehicles with the use of nonlinear filtering, distributed fault diagnosis for autonomous vehicles, velocity control of four-wheel vehicles, active vehicle suspension control, control of various types of unmanned vehicles, such as AGVs, UAVs, USVs and AUVs.

(iii) Electric Power Generation: State estimation-based control of the PMSG (Permanent Magnet Synchronous Generator), state estimation-based control of the DFIG (Doubly-fed Induction Generator), state estimation-based control and synchronization of distributed PMSGs.

(iv) Electric Motors and Actuators: neuro-fuzzy adaptive control of the DC motor, neuro-fuzzy adaptive control of the Induction motor, state estimation-based control of the DC motor, state estimation-based control of the Induction Motor.

(v) Power Electronics: state estimation-based control of power converters, State estimation-based control of photovoltaic systems, state estimation-based control and synchronization of distributed inverters.

(vi) Internal combustion engines: neuro-fuzzy adaptive control of diesel engines, neuro-fuzzy adaptive control of spark-ignited (SI) engines, state estimation-based control of valves in ship diesel engines, state estimation-based control of turbocharged diesel engines, state estimation-based control of spark ignited engines, state estimation-based control of the air-fuel ratio system in combustion engines under various perturbations.

(vii) Distributed Parameter Systems: Pointwise flatness-based control of distributed parameter systems, Boundary flatness-based control of distributed parameter systems, state estimation of distributed parameter systems, fault diagnosis for sensor networks which monitor distributed parameter systems, condition monitoring for multi-DOF buildings.

(viii) Communication Systems: state estimation for synchronization and channel equalization in chaotic communication systems, filtering for compensation of communication delays and packet drops in networked robotic control, feedback control and stabilization of chaotic dynamics.

The book is primarily addressed to the academic community. The content of the book can be the basis for teaching undergraduate or postgraduate courses on nonlinear control systems. Therefore it can be used by both academic tutors and students as a reference book for such a course. The book is suitable for departments of electrical, industrial and mechanical engineering, which can include in their curriculum nonlinear control courses on the topic of the present monograph.

Moreover, the book is addressed to the engineering community. Engineers working in industrial production, in electric power generation, in the design of transportation systems, in the development of automation and electromechanical equipment, or in several other application fields frequently come against nonlinear control problems which have to be solved, at low cost and within hard time constraints. To cope efficiently with such control problems engineers should be acquainted with control methods of generic use, improved reliability and clear implementation stages. The nonlinear control and estimation methods which are analyzed in this book fulfill the aforementioned requirements and can be a powerful tool and a useful companion for engineers working on practical electromechanical problems.

Athens, March 2015 *Gerasimos Rigatos*

Preface

Differential flatness theory is currently a main direction in nonlinear control systems. Differential flatness theory enables to develop global linearizing methods for nonlinear dynamical systems thus also facilitating the solution of complicated nonlinear control and filtering problems. The present book aims at presenting recent advances in differential flatness theory for nonlinear control and estimation. Actually, it shows that through differential flatness theory it is possible to perform filtering and state estimation for a wide class of nonlinear dynamical systems, including single input - single output, multi input - multi output dynamical models or even distributed parameter systems.

The book analyzes the design of nonlinear adaptive controllers and nonlinear filters, using exact linearization which is based on differential flatness theory. The obtained adaptive controllers can be applied to a wide class of nonlinear systems with unknown dynamics and can assure reliable functioning of the control loop under uncertainty and varying operating conditions. The obtained filters exhibit specific advantages as they outperform in terms of accuracy of estimation and computation speed other nonlinear filters. The book presents a series of application examples to confirm the efficiency of the proposed nonlinear filtering and adaptive control schemes for various electromechanical systems. These include: (i) Industrial Robotics, (ii) Mobile Robotics and Autonomous Vehicles, (iii) Electric Power Generation, (iv) Electric Motors and Actuators, (v) Power Electronics, (vi) Internal Combustion Engines, (vii) Distributed Parameter Systems, (viii) Communication Systems.

The book aims at providing an informative overview of results on flatness-based control for single and multi-input dynamical systems which are described by ordinary differential equations. The monograph analyzes the stages of design of nonlinear adaptive controllers and nonlinear Kalman Filters, using differential flatness theory. The application of differential flatness theory enables transformation of the system dynamics to the linear canonical (Brunovsky) form. This is feasible for all single input nonlinear dynamical systems and for MIMO dynamical systems which can be linearized through static state feedback. Moreover, for MIMO dynamical systems which accept only dynamic feedback linearization, it is also possible to succeed transformation to the canonical Brunovsky form.

In particular the book comes up with new adaptive neuro-fuzzy control methods that are based on differential flatness theory and which are suitable for both for SISO and MIMO dynamical systems. The differential flatness theory-based approach extends the class of nonlinear systems to which adaptive neuro-fuzzy control can be applied. By proving that a dynamical system satisfies differential flatness properties its transformation to the linear canonical (Brunovsky) form is possible. After such a transformation, a modified control input is applied to the system, which contains not only the initial control signal but also unknown terms associated with the system's nonlinear dynamics. These terms are identified on-line by neurofuzzy approximators. Thus, a nonlinear adaptive control scheme is formulated in which identification of the unknown system dynamics is first performed and subsequently this information is used for the computation of the control inputs. The stability of the adaptive control scheme is proven through Lyapunov methods. Additionally, adaptive neuro-fuzzy control schemes are developed which succeed simultaneously the identification of the unknown system dynamics and estimation of the non-measurable elements of the system's state vector. The feedback loop of these adaptive fuzzy control schemes contains neurofuzzy approximators of the system's nonlinear model and also state observers which provide estimates of the system's state vector. The stability of such control schemes is proven again with the use of Lyapunov methods.

Furthermore, the book comes up with a new nonlinear Kalman Filtering approach under the name "Derivative-free nonlinear Kalman Filter" that is based on differenrial flatness theory. The Derivative-free nonlinear Kalman Filter consists of the Kalman Filter recursion applied on the linearized equivalent model of the treated system, together with an inverse transformation based on differential flatness theory that enables to retrieve estimates for the state variables of the initial nonlinear system.This is a nonlinear filtering algorithm which does not need to compute partial derivatives and Jacobian matrices. In terms of accuracy of the provided state estimation the algorithm's performance is equivalent to the one of the Unscented Kalman Filter and significantly improved comparing to the Extended Kalman Filter. In terms of speed of computation, the Derivative-free nonlinear Kalman Filter outperforms other nonlinear estimation algorithms. The generalization of the Derivative-free nonlinear Kalman Filter to the case of a distributed computing environment results in the Derivative-free distributed nonlinear Kalman Filter. For the latter distributed filtering method it has been proven that it has better performance than the widely used Extended Information Filter. Through a series of examples the book shows that the proposed nonlinear filtering method can be part of control schemes for nonlinear dynamical systems.

Moreover, the book aims at presenting flatness-based control methods for systems with spatiotemporal dynamics. Such systems are described by partial differential equations together with the associated boundary conditions and play a critical role in several engineering problems, such as vibrating structures, flexible-link robots, waveguides and optical fibers, heat conduction etc. Additionally, the book aims at presenting differential flatness approaches for state estimation / filtering and fault diagnosis for distributed parameter systems. Being in position to reconstruct the dynamics of such systems out of a limited number of sensor measurements is important for monitoring their condition. Results on filtering and fault diagnosis for nonlinear PDE models are shown to be applicable to systems of wave-type and diffusion-type dynamics.

The control and filtering methods analyzed in the book are generic and suitable for classes of systems, therefore one can anticipate the use of the book's methods to various engineering and science problems. The structure of the book is as follows:

In Chapter 1, an analysis is given about the basics of systems theory which can be used in the modeling of nonlinear dynamics. To understand the oscillatory behavior of nonlinear dynamical systems benchmark examples of oscillators are given. Moreover, the following properties are analyzed: phase diagram, isoclines, attractors, local stability, bifurcations of fixed points and chaos properties. Next, differential geometry and Lie algebra-based control is analyzed as a predecessor to differential flatness theory-based control. First, the differential geometric approach and the Frobenius theorem is introduced. Next, the concept of Input-output linearization is introduced and its association to transformation to normal forms is explained. Furthermore, the concept of Input-state linearization is presented and the stages of its implementation are explained. Necessary and sufficient conditions for applying input-state linearization and input-output linearization are provided.

In Chapter 2, flatness-based control for lumped parameter systems is first analyzed. Such systems are described by ordinary differential equations. The chapter overviews the definition and properties of differentially flat systems and presents basic classes of differentially flat systems. First the equivalence property is explained, which signifies that it is possible to transform differentially flat systems through a change of variables into the linear canonical form. The chapter presents examples of single input dynamical systems which are written into the linear canonical form by using the differential flatness theory diffeomorphism and explains the design of the associated feedback control loop. The case of MIMO differentially flat dynamical system is also examined. It is also shown that differentially flat systems which admit static feedback linearization can be transformed into the linear canonical form. It is shown that for MIMO differentially flat systems that admit only dynamic feedback linerization it is again possible to succeed transformation to the linear canonical form and subsequently to design state feedback controllers. Moreover, elaborated criteria for checking differential flatness properties of dynamical systems are given. Finally, the chapter studies differential flatness properties for distributed parameter systems and methods for their transformation to an equivalent linear canonical form.

In Chapter 3, differential flatness theory-based adaptive fuzzy control is proposed for complex nonlinear dynamical systems. First, single-input single-output dynamical systems are studied and it is shown how flatness-based adaptive-fuzzy controllers can be designed for such systems. Moreover, it is shown that multi-input multi-output dynamical systems which admit static feedback linearization can be transformed to a decoupled and linear canonical form for which the design of the flatness-based adaptive fuzzy controller is a straightforward procedure. The latter results can be also extended to the case of MIMO systems that admit exclusively dynamical feedback linearization.

In Chapter 4, a new filtering method for nonlinear dynamical systems is analyzed. The filtering method is based on differential flatness theory and is known as Derivative-free nonlinear Kalman Filter. First the filtering method is applied to lumped dynamical systems, that is systems which are described by ordinary differential equations. Moreover, the problem of distributed nonlinear filtering is solved, that is the problem of fusion of the outcome of distributed local filtering procedures (local nonlinear Kalman Filters) into one global estimate that approximates the system's state vector with improved accuracy.

In Chapter 5, differential flatness theory is used for the solution of industrial robotics problems. These comprise among others adaptive control of MIMO robotic manipulators without prior knowledge of the robot's dynamical model, adaptive control of underactuated robotic manipulators (that is robots having less actuators than their degrees of freedom), observer-based adaptive control of MIMO robotic manipulators in which uncertainty is not related only to the unknown dynamic model of the robot but also comes from the inability to measure all elements of the robot's state vector, and Kalman Filter-based control of MIMO robotic manipulators. Finally, differential flatness theory is proposed for developing a robot control scheme over a communication network that is characterized by transmission delays or losses in the transmitted information.

In Chapter 6, it is proposed to use nonlinear filtering and control methods based on differential flatness theory for autonomous vehicles control. In particular the chapter analyzes steering control, localization and autonomous navigation of land vehicles, unmanned surface vessels and unmanned aerial vehicles. It is shown that through the application of differential flatness theory one can obtain solution for the following non-trivial problems: state estimation-based control of autonomous vehicles, state estimation-based control of cooperating vehicles, distributed fault diagnosis for autonomous vehicles, velocity control of ground vehicles under model uncertainties and external disturbances, active control of vehicle suspensions, state estimation-based control of unmanned aerial vehicles of the quadrotor type, and finally state estimation-based control of unmanned surface vessels of the hovercraft type.

In Chapter 7, it is proposed to use differential flatness theory for nonlinear filtering and nonlinear control problems met in electric power generation. Power generators of various types are considered such as DFIGs and PMSGs, while the mode of operation of these generators can be either the stand-alone one (single machine infinite bus model), or the generators can function as part of the power grid (multi-area multi machine power generation models). The chapter shows how differential flatness theory can provide efficient solutions to the following problems: (i) state estimation-based control of the PMSG, (ii) state estimation-based control of the DFIG, (iii) state estimation-based control and syncronization of distributed power generators of the PMSG type.

In Chapter 8, it is proposed to apply differential flatness theory-based nonlinear filtering and control methods, to electric motors and actuators and to motion transmission systems. To this end, differential flatness theory is used for adaptive control of the DC motor, for adaptive control of the induction motor, for state estimation-based control of the DC motor, for state estimation-based control of asynchronous electric motors and finally for observer-based adaptive fuzzy control of microactuators (MEMS).

In Chapter 9, differential flatness theory is used to solve nonlinear filtering and control problems which appear in power electronics such as voltage source converters (VSC) and inverters, when these devices are used for connecting various types of power generation units (AC and DC) to the grid. In particular, the chapter proposes differential flatness theory for state estimation-based control of three-phase voltage source converters, for state estimation-based control of voltage inverters (finding application to the connection of photovoltaics to the electricity grid), and finally for decentralized control and synchronization of distributed inverters which are used to connect distributed DC power units with the electricity network.

In Chapter 10, differential flatness theory is applied to nonlinear filtering and control methods for internal combustion engines. The presented methods are concerned with robust control and filtering for valves of diesel engines, with filtering-based control of turbocharged diesel engines, with embedded adaptive control of turbocharged Diesel engines, with embedded control and filtering of spark-ignited engines, with embedded adaptive control of spark ignited engines and finally with embedded control and filtering of the air-fuel ratio in combustion engines.

In Chapter 11, differential flatness theory-based methods for nonlinear filtering and nonlinear control are applied to chaotic dynamical systems. Flatness-based adaptive fuzzy control is proposed first for chaotic dynamical systems and manages to modify the behavior of such systems without any knowledge of their dynamic model. Next, differential flatness theory is proposed for developing a chaotic communication system. A differential flatness theory-based Kalman Filtering approach is proposed for performing blind equalization of the chaotic communication channel and for the synchronization between the transmitter and the receiver.

In Chapter 12, it is proposed to use differential flatness theory in nonlinear filtering and control problems of distributed parameter systems, that is systems which are described by partial differential equations (of the parabolic, hyperbolic or elliptic type). Methods of pointwise control of nonlinear PDE dynamics are introduced, while methods for state estimation in nonlinear PDE models are developed. Such results are applicable to communication systems (transmission lines, optical fibers and electromagnetic waves propagation), to electronics (Josephson junctions), to manufacturing (heat diffusion control in the gas-metal arc welding proces), in structural engineering (dynamic analysis of buildings under seismic waves, mechanical structures subjected to vibrations, pendulum chains), in sensor networks (fault diagnosis in distributed sensors monitoring systems with PDE dynamics), etc.

Finally, in Chapter 13, it is demonstrated that differential flatness theory is in the background of other control methods, such as backstepping control and optimal control. First, the chapter shows that differential flatness theory is in the background of backstepping control. It is shown that to implement flatness-based control, it is not always necessary to transform the system into the trivial (linear canonical) form, but it may suffice to decompose it into a set of flat subsystems associated with the rows of its state-space description. The proposed flatness-based control method can solve efficiently several nonlinear control problems, met for instance in robotic and power generation systems. Moreover, the chapter shows how differential flatness theory can be used for implementing boundary control of distributed parameter systems. As a case study the control of a nonlinear wave PDE is considered.

The manuscript is suitable for teaching nonlinear control and nonlinear filtering methods at late undergraduate and at postgraduate level. Such a course can be part of the curriculum of several university departments, such as Electrical Engineering, Mechanical Engineering, Computer Science, Physics etc. The proposed book contains teaching material which can be also used in a supplementary manner to the content of undergraduate nonlinear control courses. The book can also serve perfectly the needs of a postgraduate course on nonlinear control and nonlinear estimation methods.

Moreover the book can be a useful reference for researchers, academic tutors and engineers that come against complex nonlinear control and nonlinear dynamics problems. The book has both theoretical and practical value. It provides efficient solutions to control problems associated with several electromechanical systems met in industrial production, in transportation systems, in electric power generation and in many other applications. The control and filtering methods analyzed in the book are generic and applicable to classes of systems, therefore one can anticipate the application of the book's methods to various types of electromechanical systems. I hope the book to become a useful reference not only for the industrial systems, and the robotics and control community, but also for researchers and engineers in the fields of signal processing, computational intelligence and mechatronics.

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Contents