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By
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In memory of my mother Diamantina Rigatou
1939-2018

Contents

Acknowledgement

The authors of the monograph appreciate the review remarks of colleagues working in the research area of control of nonlinear and PDE dynamical systems. These comments have enabled to arrive at a concise, meaningful and clear presentation of the analyzed control and estimation methods for nonlinear and PDE dynamical systems and have contributed to developing a research document that will be useful for the engineering and academic community.

Preface

The monograph presents advances in applied control of nonlinear and PDE dynamical systems, comprising both theoretical analysis of the proposed control methods and case studies about their use in robotics, mechatronics, electric power generation, power electronics, micro-electronics, industrial production processes and cyberphysical systems comprising communication and computer networks. The monograph covers thoroughly the area of automatic control for complex nonlinear dynamical systems, including also applications to distributed parameter systems which are described by partial differential equations. The monograph has a meaningful contribution in the areas of automatic control and systems science. Its results can be classified in the following main approaches for the control of complex nonlinear dynamical systems: (i) control with methods of approximate (local) linearization being associated with the solution of the nonlinear optimal control problem (ii) control with methods of exact (global) linearization comprising also adaptive control methods (iii) control of distributed parameter systems (systems which are described by partial differential equations) and stochastic estimation methods.

With reference to approach (i) that is control methods based on approximate linearization, one can distinguish results towards extending H-infinity control to nonlinear dynamical systems and towards solving the associated nonlinear optimal control problem. The methods which are developed for nonlinear control problems rely on linearization of the systems' dynamics around local operating points while the designed feedback controllers make use of the approximately linearized state-space models. Such controllers are designed to be robust to external perturbations, as well as to modelling errors, and achieve asymptotically (as time advances) the compensation of the nonlinear dynamics of the controlled systems. In this area one can note an important research result which is a new method of H-infinity control. This approach makes use of an approximately linearized model of the system that is obtained through the computation of Jacobian matrices. In contrast to problems of linear control and the method of the linear quadratic regulator, it is far more difficult to achieve a solution of the optimal control problem in the case of nonlinear dynamical systems under model uncertainties and external disturbances. The nonlinear optimal control problem is usually treated with iterative computational methods that are not always of assured convergence to the optimum. Actually, one comes against a differential game where the control signal tries to minimize the system's cost function so as to achieve the convergence of the state vector to the designated reference values, whereas the disturbance inputs try to maximize this cost function. For such problems, the monograph comes to propose a novel H-infinity (optimal) control method. At each time-step of the optimization algorithm approximate linearization takes place around local operating points, with the use of Taylor series expansion and through the computation of Jacobian matrices. The linearization error is considered to be an additional perturbation affecting the system. Next, for the linearized equivalent model of the system, an optimal H-infinity controller can be applied, while to compute this controller's gains an algebraic Riccati equation has to be iteratively solved at each time-step of the control algorithm,. This control scheme is also shown to be sufficiently robust, thus assuring the compensation of modelling errors, parametric uncertainty or external disturbances that affect the control loop. With the use of Lyapunov analysis the global stability properties of the control loop are proven and the convergence of the system's state vector to the designated reference setpoints is demonstrated. The new solutions for the nonlinear optimal (H-infinity) control problem are computationally efficient since they require the solution of only one Riccati equation.

With reference to approach (ii) that is control based on global linearization approaches, the monograph elaborates on transformations of the initial nonlinear dynamics of the controlled systems into equivalent linear state-space descriptions where finally the design of feedback controllers is performed and the solution of the related stochastic estimation (filtering) problems is also accomplished. In this approach belong the monograph's results on differential flatness theory-based control, which rely on the transformation of the state-space description of the system into the canonical (Brunovsky) form. Through the global linearization-based control approach one can avoid the modelling errors that follow approximate linearization methods and consequently control of high precision and robustness can be achieved. Flatness-based control relies on differential flatness theory and consists of state-variables transformations that finally bring the system's state-space model into an equivalent linear form where the application of the standard linear control and stabilization methods is enabled. The flatness-based method comprises also inverse transformations that allow to compute estimates of the state variables of the initial nonlinear system. In this area one can also classify the monograph's results on a new nonlinear estimation method which is known as Derivative-free nonlinear Kalman Filter and which contributes towards solving the filtering problem for nonlinear dynamical systems in an optimal manner.

In the above-noted area (ii) of global linearization-based control the monograph analyzes also flatness-based adaptive fuzzy control for a wide class of nonlinear dynamical systems. In the flatness-based adaptive fuzzy control approach, one performs first an initial transformation (diffeomorphism) of the system's state-space model into an equivalent linear form. In this new description, the transformed control inputs contain unknown nonlinear functions which can be identified with the use of nonlinear regressors (e.g. neurofuzzy networks, wavelet networks or other networks that comprise nonlinear kernel functions). Learning in such networks takes place with the use of gradient algorithms where the learning rate is regulated through conditions for the minimization of the system's Lyapunov function and for assuring that this cumulative energy function of the system will have always a negative first-order derivative and will be persistently decreasing. At each time-step of the adaptive control algorithm, the estimated values for the nonlinear functions that constitute the system's dynamics are used to compute the feedback control inputs. It is proven that this approach achieves the minimization of the system's Lyapunov function and that the control loop becomes globally asymptotically stable.

With reference to approach (iii), that is control for dynamical systems which are described by nonlinear partial differential equations (PDEs) the monograph advances towards boundary control of the dynamics of the partial differential equations. Actually, in the proposed PDE control methods the control inputs are related only with the boundary conditions of the PDE, thus one arrives at a PDE boundary control problem. The methods are based on semi-discretization of the PDE (only about its spatial dimension) and this allows to substitute the PDE with an equivalent set of ordinary differential equations (ODEs). The solution of the stabilization problem for the PDE with the use of control inputs which are applied through the boundary conditions can be achieved by exploiting differential flatness theory. The design of a stabilizing controller for the PDE is based on the proof that (i) the state-space model of the PDE is a differentially flat system, (ii) each row of the state-space model is also a differentially flat subsystem. Next, for each subsystem (row) being associated with an ordinary differential equation, one can compute a virtual control input which can stabilize the subsystem's dynamics and which can also eliminate the tracking error of the subsystem's output. The virtual control input for the i-th subsystem becomes a reference setpoint for the (i+1)-th subsystem. From the last row of the state-space description one can compute the control input (boundary condition) which should be finally applied to the partial differential equation. This control input comprises in a recursive manner all virtual control inputs which were computed for the rows (subsystems) that constitute the PDE's state-space description. Thus, by tracing backwards the rows of the state-space model of the PDE (from the last to the first row) one can finally compute the control input that should be applied in the form of a boundary condition so as all individual state variables to converge to their designated setpoints. The global stability of this PDE control method is proven through Lyapunov analysis. Finally. in the above-noted research area (iii), that is dynamical systems described by PDEs, it is also of worth to include several results on estimation for fault diagnosis. About this topic, one can note results on fault detection and isolation methods which rely on Kalman Filtering and on the statistical properties of the χ^2 distribution that is followed by the state vector's estimation error (residuals).

Regarding the application part of the control and estimation methods for nonlinear and PDE dynamical systems. the monograph has examined the following:

(a) Control and estimation based on approximate linearization for robotic systems: (i) Nonlinear control of the cart and double-pendulum overhead crane, (ii) Nonlinear control of the underactuated offshore crane, (iii) Nonlinear control of the inertia wheel and pendulum system, (iv) Nonlinear control of the torsional oscillator with rotational actuator, (v) Nonlinear control of robotic exoskeletons, (vi) Nonlinear control of brachiation robots, (vii) Nonlinear control of power line inspection robots, (viii) Nonlinear control of robots with electrohydraulic actuators, (ix) Nonlinear control of robots with electropneumatic actuators, (x) Nonlinear control of flexible joint robots, (x) Nonlinear control of redundant robotic manipulators, (xi) Nonlinear control of parallel closed-chain robotic manipulators.

(b) Control and estimation based on approximate linearization for autonomous vehicles: (i) Nonlinear control of tracked autonomous vehicles, (ii) Nonlinear control of the autonomous fire-truck, (iii) Nonlinear control of the truck and N-trailer system, (iv) Nonlinear control of the ball-bot autonomous robot, (v) Nonlinear control of the ball-and-plate dynamical system, (vi) Nonlinear control of 3-DOF unmanned surface vesselsm (vii) Nonlinear control of the 3-DOF autonomous underwater vessel (viii) Nonlinear control of the Vertical Take-off and Landing Aircraft, (ix) Nonlinear control of aerial manipulators (x) Nonlinear control of the 6-DOF autonomous octocopter (xi) Nonlinear control of hypersonic aerial vehicles.

(c) Control and estimation based on approximate linearization for energy conversion systems: (i) Nonlinear control of the VSI-fed three-phase PMSM, (ii) Nonlinear control of the VSI-fed six-phase PMSM (iii) Nonlinear control of the DC electric microgrids (iv) Nonlinear control of distributed marine-turbine power generation units (v) Nonlinear control of PMLSGs (permanent magnet linear synchronous generators) in wave energy conversion systems (vi) Nonlinear control of Permanent Magnet Brushless DC motors (vii) Nonlinear optimal control of Hybrid Electric Vehicles powertrains (viii) Nonlinear control of shipboard AC/DC microgrids (ix) Nonlinear control of power generation in hybrid AC/DC microgrids

(d) Control and estimation based on approximate linearization for mechatronic systems: (i) Nonlinear control of electrohydraulic actuators, (ii) Nonlinear control of electropneumatic actuators (iii) Nonlinear control of hot-steel rolling mills (iv) Nonlinear control of paper mills (v) Nonlinear control of the injection moulding machine (v) Nonlinear control of the slosh-container system dynamics (vi) Nonlinear control of micro-satellites' attitude dynamics (vi) Nonlinear control of the industrial crystallization process.

(e) Control and estimation based on global linearization for industrial and PDE systems: (i) Control of a robotic exoskeleton subject to time-delays, (ii) Adaptive control of synchronous reluctance machines (iii) Control of a mobile robotic manipulator (iv) SoC (state-of-charge) estimation in Electric Vehicles with a Kalman Filter-based disturbance observer (iv) Control of nonlinear wave PDE dynamics (v) Control of nonlinear wave PDE dynamics, (vi) Control of a data flow PDE for bandwidth allocation in internet routes, (vii) Control of a diffusion PDE describing data flow in communication networks, (viii) Control of the diffusion PDE in Li-ion batteries, (ix) Control of a diffusion PDE in industrial assets' management (x) Estimation of PDE dynamics of the highway traffic, (xi) Estimation of the PDE dynamics of a cable-suspended bridge and use of the obtained estimates for fault diagnosis.

Through the above-noted developments and the methods proposed for control and estimation of nonlinear and PDE dynamical systems this monograph has a useful contribution in the area of nonlinear dynamical systems and control theory. Yet being computationally and algorithmically simple, the presented control schemes assure precise tracking of setpoints and stabilization for complicated nonlinear and PDE dynamical systems. Besides, in several cases they ensure optimal performance of the control loop, as for instance with the solution of the nonlinear optimal control or with the solution of the nonlinear optimal state estimation problem. The application field is wide and comprises primarily what is considered to be industrial systems technology, that is robotic systems (robotic manipulators and autonomous robotic vehicles, several mechatronic systems, electric power generation and power electronics, industrial production processes and cyber-physical systems that include the complex dynamics of communication and computer networks. These results are undoubtedly of interest for the engineering and academic community and can be used for teaching related courses at the late undergraduate or post-graduate level. Certainly. research in the field control and estimation for nonlinear and PDE dynamical systems has the potential for arriving at many more significant and exploitable findings in the years to come.

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Glossary

AC/DC: alternating current / direct current
ADCS: Attitude Determination and Control Subsystem
AUV: Autonomous Underwater Vessel
BLDC: Brushless DC motor
CLT: Central Limit Theorem
DC/DC: direct current / direct current
DFIG: Doubly-Fed Induction Generator
DOF: Degrees of Freedom
EKF: Extended Kalman Filter
EMF: Electromagnetic Force
H_∞ control: H-infinity Control
H_∞ Kalman Filter: H-infinity Kalman Filter
HESG: Hybrid Excited Synchronous Generator
HESM: Hybrid Excited Synchronous Machine
HEV: hybrid electric vehicle
HSV: Hypersonic Vehicle
KF: Kalman Filter
LMI: Linear Matrix Inequality
LPV: Linear Parameter Varying system
LQR: Linear Quadratic Regulator
LQG: Linear Quadratic Gaussian
MIMO: Multi-input multi-output
MPC: Model Predictive Control
NES: Normalized Error Square
NMPC: Nonlinear Model Predictive Control
ODE: Ordinary Differential Equation
PDE: Partial Differential Equation
PID: Proportional Derivative Integral
PLI: Power Line Inspection robot
PMBLDC: Permanent Magnet Brushless Direct Current motor
PMLSG: Permanent Magent Linear Synchronous Generator
PMSG: Permanent Magnet Synchronous Generator
PMSM: Permanent Magnet Synchronous Motor
PV: photovoltaic unit
PWM: Pulse Width Modulation
RTAC: Rotational-translational actuator
SDRE: State-Dependent Riccati Equation
SRG: Synchronous Reluctance Generator
SRM: Synchronous Reluctance Machine
SISO: Single-input single-output

SMC: Sliding Mode Control
SoC: State-of-Charge
TORA: Tortional oscillator with rotational actuator
UGV: Unmanned Ground Vehicle
USV: Unmanned Surface Vessel
VSC: Voltage Source Converter
VSI: Voltage Source Inverter
VTOL: Vertical Take-Off and Landing Aircraft
WSN: Wireless Sensor Networks
UAV: Unmanned Aerial Vehicle