Advances in Applied Nonlinear Optimal Control

Research Monograph

G. Rigatos*[*] *and E. Karapanou

[*]***Unit of Industrial Automation***
Industrial Systems Institute
26504, Rion Patras, Greece
email address: grigat@ieee.org

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In memory of my mother Diamantina Rigatou
1939-2018

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Preface

The monograph presents advances in applied nonlinear optimal control comprising both theoretical analysis of the developed control methods and case studies about their use in robotics, mechatronics, electric power generation, power electronics, micro-electronics, biological systems, biomedical systems, financial systems and industrial production processes. The monograph is developed around new theoretical results allowing for solution of the nonlinear optimal control problem through approximate linearization of the controlled system's dynamics and through application of H-infinity control methods. Because of the nonlinearity of the state-space model of the considered dynamical systems under control other approaches to solve the associated optimal control problem, are of questionable performance. Therefore, the monograph's results go beyond other control approaches such as the typical model predictive control (MPC) and the nonlinear model predictive control, (NMPC). For instance, it is widely acknowledged that MPC is a linear control method which in the case of the nonlinear dynamics of the considered complex dynamical systems cannot assure the stability of the control loop. Besides, it is known that the NMPC's iterative search for an optimum is dependent on initial parametrization and is not always of assured convergence. On the other side the use of global linearization-based methods for the control of the considered complex dynamical systems requires the definition of the linearizing outputs in a case-based manner and the application of complicated change of state-space variables. Moreover, such methods may come against singularity problems due to including also additional transformations being-based on matrices inversions. Alternatively, the application of backstepping control to the considered complex systems requires to express previously their state-space description into the triangular form, and this is not always a straightforward procedure. Finally, sliding-mode control cannot be directly applied to complicated multivariable dynamical systems because these are not found in a canonical linear form and consequently there is no systematic manner in defining the sliding surface. For the reasons explained above, the monograph's findings on nonlinear optimal control, can be a substantial contribution to the areas of nonlinear control and complex dynamical systems and can find use in several research disciplines and practical applications. The monograph is concerned with applied nonlinear optimal control and one of its primary objectives is to demonstrate potential applications for its theoretical developments. Prospective application areas are outlined as follows:

1) industrial robotics: robotic manipulators and networked robotic systems Applications to fully actuated robotic manipulators, redundant manipulators, underactuated manipulators, cranes and load handling systems, time-delayed robotic systems. closed kinematic chain manipulators, flexible-link manipulators, micromanipulators.

2) transportation systems: autonomous vehicles and mobile robots Applications to two-wheel and unicycle type vehicles, four-wheel drive vehicles, four-wheel steering vehicles, articulated vehicles, truck and trailer systems, unmanned aerial vehicles, unmanned surface vessels, autonomous underwater vessels, underactuated vessels.

3) motion generation and transmission systems: actuators and motors Applications to mechatronic systems and actuators, switched reluctance motors, permanent magnet synchronous motors, permanent magnet linear motors, synchronous reluctance motors, induction motors, induction linear motors doubly-fed reluctance machines and multi-phase machines.

4) electric power systems: power generators and power electronics Applications to photovoltaic units, fuel cells units, synchronous generators, permanent magnet synchronous generators, doubly-fed induction generators, doubly-fed reluctance generators, gas-turbine electric power units, hybrid-excited synchronous generators, steam-turbine electric power units, wind-turbine electric power units, hydropower generators, multi-phase generators, distributed electric power transmission and distribution systems. Applications to power electronics, such as DC-DC converters, DC-AC inverters, AC-DC converters, DC-AC inverters and active power filters, power transformers, batteries and capacitors, VSC-HVDC transmission systems, components of the smart grid.

5) biosystems: bioprocesses in the pharmaceutical industry, controlled drugs infusion. Applications to the phar-

maceutical industry, processes of controlled protein and hormone synthesis, systems of haemodialysis, controlled anaesthesia, controlled drug infusion for diabetes, regulation of heart's functioning, control of biological oscillators, and in several other types of biosystems.

6) financial systems: risk prevention and assets management, Applications to optimal control of macroeconomic systems, optimal control of models of markets dynamics and business cycles, management for the elimination of loans and investments risk, decision making for the mitigation of companies' default risk, optimized planning of transactions and investments in the commodities market, optimal management of capitals and assets.

The prospective audience of the monograph comes both from the academic field and from engineers working on practical optimal control and optimization problems. There is need for generic and systematic methods of nonlinear optimal control, in robotics, mechatronics, electric power generation, power electronics, micro-electronics, biological systems, biomedical systems, financial systems and industrial production processes The monograph's methods are of proven stability and convergence and exhibit also robustness to model uncertainty and external perturbations. The stages of the developed nonlinear optimal control methods are clear and easy to follow and implement.. Taking into account the above, it is expected that the monograph will have a good acceptance by a wide audience in both the academic and the engineering communities. It is anticipated that the interest of the academic, research and engineering community in the topics presented by this monograph will grow in the forthcoming years. This is because optimization in functioning of nonlinear dynamical systems is becoming a prerequisite for a wide spectrum of applications including engineering systems, biomedical systems and financial systems. Besides as the monograph's methods for nonlinear optimal control are characterized by global stability and robustness features they are not going to get outdated or scientifically depreciated. Furthermore, starting from the applications examples presented in the monograph one can find more areas for using the provided results on nonlinear optimal control. Consequently, the monograph's findings are expected to be well disseminated among researchers and engineers and that the book will keep on being of interest in the following years, for both research institutes or universities and for engineers.

The monograph presents advances in applied nonlinear optimal control comprising both theoretical analysis of the developed control methods and case studies about their use in robotics, mechatronics, electric power generation, power electronics, micro-electronics, biological systems, biomedical systems, financial systems and industrial production processes. The advantages of the nonlinear optimal control approaches which are developed in the monograph are outlined as follows: (i) by applying approximate linearization of the controlled systems' state-space description one can avoid the elaborated state variables transformations (diffeomorphisms) which are required by global linearization-based control methods, (ii) the control input is applied directly on the controlled systems and not on an equivalent linearized description of theirs. Thus one can avoid the inverse transformations met in global linearization-based control methods and the appearance of singularity problems, (iii) the monograph's control methods retain the advantages of linear optimal control, that is best trade-off between accurate tracking of reference setpoints and moderate variations of the control inputs. The monograph's findings on nonlinear optimal control, can be a substantial contribution to the areas of nonlinear control and complex dynamical systems and can find use in several research disciplines and practical applications.

In particular with respect to approaches attempting to solve optimal control problems for complex dynamical systems it can be pointed out that the present monograph is developed around new theoretical results allowing for solution of the nonlinear optimal control problem through approximate linearization of the controlled system's dynamics and through application of H-infinity control methods. Because of the nonlinearity of the state-space model of the considered dynamical systems under control, other approaches to solve the associated optimal control problems, are of questionable performance. Therefore, the monograph's results go beyond other control approaches such as Model Predictive Control (MPC) and Nonlinear Model Predictive Control, (NMPC). For instance, it is widely acknowledged that MPC is a linear control method which in the case of the nonlinear dynamics of the considered complex dynamical systems cannot assure the stability of the control loop. Besides, it is known that the NMPC's iterative search for an optimum is dependent on initial parametrization and is not always of assured convergence.

Primarily the book is addressed to the research and academic community. The monograph can be a reference for researchers working on nonlinear control problems. Moreover, the content of the book can be used for teaching undergraduate or postgraduate courses in nonlinear control. Therefore it can be considered by both academic tutors and students as a reference book for such courses. A significant part of the book's readership is also expected to come from the engineering community. Engineers working in the design and development of robotic and mechatronic systems, electric power systems, biomedical systems or cyberphysical systems may come against nonlinear control problems which can be solved using the guidelines of the monograph. The monograph is anticipated to attract the interest of a significant part of the academic and engineering community. The timeliness of the monograph's topics is not expected to decline in the following years because the developed control methods are of proven stability and robustness while potential applications cover a wide spectrum that ranges from engineering systems to biomedical and financial systems. Since the monograph's methods and approaches offer complete and reliable solutions to nontrivial problems of robotics, mechatronics, electric power generation, power electronics, micro-electronics, biological systems, biomedical systems, financial systems and industrial production processes, their scientific value is difficult to be depreciated as years go by. On the other hand,since the monograph's methods have excellent performance and contribute to the reliable functioning of several types of nonlinear dynamical systems, it is expected this book to become a useful reference for the academic and engineering community.

Dr. Gerasimos Rigatos
Athens. Greece
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Glossary

AGV: Automatic Ground Vehicle
ARE: Algebraic Riccati Equation
AUV: Autonomous Underwater Vessel
CT; Computed Torgue Method
DARE: Differential Algebraic Riccati Equation
DOF: Degrees of Freedom
DFIG: Doubly Fed Induction Generator
DFRM: Doubly-fed Reluctance Machine
EGR: Exhaust Gas Recirculation
FC: Fuel Cells
GT: Gas Turbine
H_∞ control: H-infinity Control
H_∞ Kalman Filter: H-infinity Kalman Filter
HESG: Hybrid Excited Synchronous Generator
HT: Hydro Turbine
HJB: Hamilton-Jacobi-Bellman equation
HVDC: High Voltage Direct Current line
IM: Induction Motor
LIM: Linear Induction Motor
LQR: Linear Quadratic Requlator
LQG: Linear Quadratic Gaussian
MAGLEV: Magnetic Levitation Train
MPC: Model Predictive Control
NMPC: Nonlinear Model Predictive Control
PID: Propotrional Integral Derivative
PMSG: Permanent Magnet Synchronous Generator
PMLSM: Permanent Magnet Linear Synchronous Motors
PMSM: Permanent Magnet Synchronous Motor
PWM: Pulse Width Modulation
RMSE: Root Mean Square Error
SG: Synchronous Generator
ST: Steam Turbine
SwRM: Switched Reluctance Machine
SRM: Synchronous Reluctance Machine
STATCOM: Static Synchronous Compensator
UAS: Unmanned Aerial Systems
UGV: Unmanned Ground Vehicle
USV: Unmanned Surface Vessel
UAV: Unmanned Aerial Vehicle
VSI: Voltage Source Inverter
VSC: Voltage Source Converter
WT: Wind Turbine
4WD: Four-wheel drive vehicle
4WS: Four-wheel steering vehicle