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International Graduate School on Control

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M01 – MILAN & ONLINE
31/01/2022-04/02/2022

From Data to Decisions: the Scenario Approach (with Applications to Systems, Control and Machine Learning)

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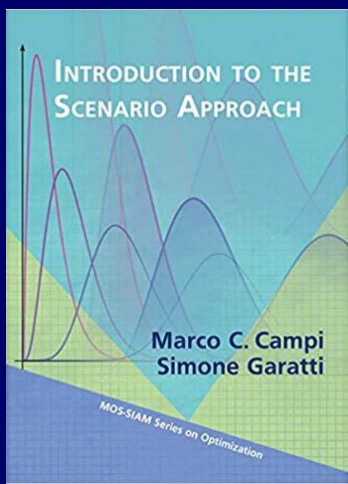
Abstract of the course

Data are ubiquitous in nowadays science and engineering. In this course, we introduce the “scenario approach”, which is a general methodology for data-driven decision making, and discuss its application to various fields (including machine learning and data-driven system design and control). We also present the most recent developments of its powerful generalization theory, which allows the user to tightly evaluate the out-of-sample robustness of the solution and keep control on the risk.

A gradual presentation of all the practical and theoretical aspects will allow for an easy comprehension of the material, while virtually no prior knowledge is required to follow the course.



Topics:

- Scenario Approach
- Design in the presence of uncertainty
- Risk evaluation
- Application to systems, control and supervised learning
- Presentation of open problems that offer an opportunity for research

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M02 – CANCELLED
21/02/2022-25/02/2022

Control of Multiphysics Systems: Theory and Applications

Abstract of the course

MuTeaching schedule:ltiphysics systems involve components from different physical domains (mechanical, electrical, hydraulic, chemical, ..). They arise abundantly in modern engineering, with examples including electrical motors, generators, turbo engines, micro-actuators, smart materials, fuel cells, etc.. A unified framework for modeling and control of multiphysics systems is offered by port-Hamiltonian systems theory. This theory is based on the systematic interconnection of physical components via energy flows (the 'lingua franca' of all physical systems). It has a strong foundation in the geometric theory of mechanical systems (classical Hamiltonian systems), as well as in electrical network theory. It includes passivity theory, but goes beyond. Port-Hamiltonian modeling does not only provide a unified and insightful approach to the modeling of complex, nonlinear, multiphysics systems, but also provides a natural starting point for control. By identifying the underlying physical structure of the systems it leads to 'natural' control strategies, often with clear interpretation and inherent robustness.

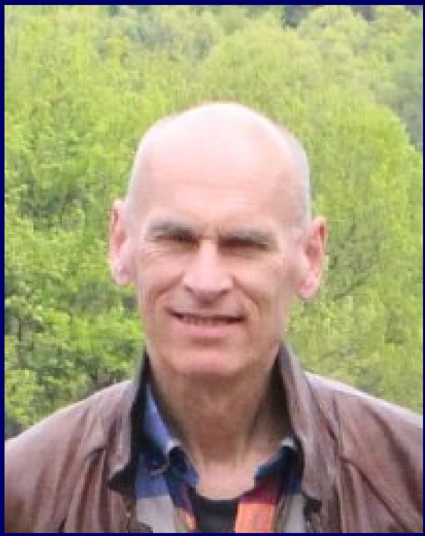
Energy conversion and harvesting are among the most important problems in modern engineering and technology. The second part of the course will be devoted to recent developments in a theory of energy conversion and efficiency of multiphysics systems based on port-Hamiltonian systems theory.

Teaching schedule:

The first part of the course (Monday - Wednesday) will provide a systematic introduction to port-Hamiltonian systems modeling and control, based on the lecture notes
Port-Hamiltonian Systems Theory: An Introductory Overview (written by the course lecturers).

The pdf version of these lecture notes will be made freely available to the participants. The teaching will furthermore include two tutorials on port-Hamiltonian modeling and control, where some simple, but illustrative, examples will be treated in detail.

The second part of the course (Thursday - Friday) is devoted to energy conversion in multiphysics systems, based on recent papers by the lecturers.



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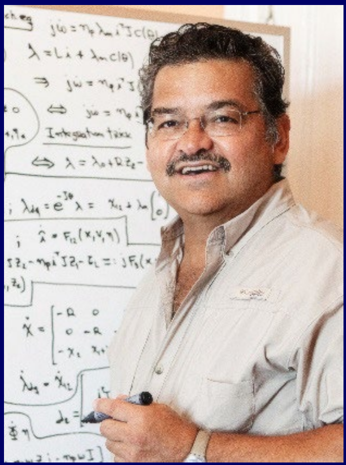
M03 – MONTERREY, MX
01/08/2022-05/08/2022

Energy-Based Control Design to Face the Challenges of Future Power Systems



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Abstract of the course:

The ongoing transition towards low-carbon power systems renders the current fit-and-forget strategy of renewable distributed generation deployment infeasible and challenges today's power system operation paradigms. In particular, modern power systems are characterized by an increasing number of active network elements with heterogeneous dynamics, resulting in complex networks with mutually interacting subsystems, instead of cause-effect, relations. As a consequence, the classical signal processing viewpoint of control, where the system and the controller are closed and isolated signal processors, and the control objectives are also expressed in terms of signals is highly inappropriate to provide the flexibility, modularity and scalability required in future power system operation.
Instead, to face these challenging problems a new control theory, focused on the energy and dissipation properties of the systems, has been developed in the last few years. The main articulating concepts of this new theory are the property of passivity, which is a reformulation of energy conservation, and the formulation of control as an interconnection of energy exchanging dynamical systems. The aim of these lectures is to introduce the basic concepts of this new theory and their application to emerging problems in low-inertia power systems along with their main components, i.e., power converters, motors, generators and alternative energy sources, such as wind power plants and solar panels.

Theoretical topics:

- Euler-Lagrange and port-Hamiltonian models
- Control by interconnection and PID-Passivity-based Control of nonlinear systems
- Adaptive control of nonlinear and nonlinearly parameterized systems

Practical examples:

- Power electronic systems: power converters and power factor compensation for nonlinear loads
- Control of alternative energy generating systems (wind power plants, fuel-cells and PV units)
- Power systems and microgrids: stabilization of low-inertia systems, distributed passivity-based control applications
- Electromechanical systems: sensorless control of motors, doubly-fed induction generators
- Energy management via control by interconnection

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M04 – PARIS SACLAY 21/03/2022-25/03/2022	*Non asymptotic convergences: from concepts to stabilization and estimation*

Abstract: Usually, in control/estimation problems, one is looking at exponential decaying rates for many reasons: ease of understanding, many tools for tuning and getting a time response estimate. But nowadays, the control community has to meet more and more demanding performances in many areas such as aerospace, manufacturing, robotics and transportation to mention a few. A necessary property for these control algorithms is stability (usually with respect to an invariant mode such as an equilibrium or a desired trajectory). The convergence time for the system to reach this invariant mode may be infinite (e.g., asymptotic or exponential convergence) or finite. Combining stability with these convergence types leads to asymptotic or non-asymptotic stability properties. The latter being a central issue to be taken into account for many applications like rendezvous, missile guidance, spacecraft docking, weather forecasting, .. this is one of the reasons why finite and fixed-time stabilization/estimation have been extensively considered in the framework of linear and nonlinear ordinary differential equations (ODEs) for more than twenty years. The goal of this course is to present recent advances on the design and analysis of control and estimation algorithms with accelerated convergence rates.

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Outline:

Part I: Preliminaries
- Introduction to Non-asymptotic convergence
- Examples using Matlab/Simulink

Part II: Ordinary differential equations and inclusions
- From asymptotic to Non-asymptotic concepts: definitions and Lyapunov characterization
- Homogeneity
- Stabilization
- Implicit Lyapunov function
- Prescribed-time stabilization
- From Non-asymptotic observers to numerical differentiation
- Discretization issues

Part III: Time-delay systems (TDS)
- Non-asymptotic concepts for TDS: definitions and obstructions
- Non-asymptotic stabilization/estimation for TDS

Part IV: Linear partial differential equations (PDE)
- Some results and examples about Non-asymptotic concepts for PDE

This course includes MATLAB/Simulink sessions: students should bring their own laptop.

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M05 – L'AQUILA & ONLINE
28/03/2022-01/04/2022

Stochastic Control and Dynamic Optimisation

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Abstract

Dynamic optimisation and stochastic control encompass several problems central to control engineering.

- Dynamic optimisation addresses the question of how to design control laws to optimise one or more performance criteria. In this course two classes of dynamic optimisation problems will be considered, namely (single-objective) optimal control and (multi-objective) nonzero-sum differential games. Obtaining solutions of such problems poses, in general, an intractable problem. Thus, in addition to a review of the classical theory, strategies to systematically construct approximate solutions – at a relatively low computational expense – will be presented.
- Control of stochastic differential equations (SDEs) has been successfully used in a variety of theoretical and applied scientific fields, such as system biology and finance. One way to view SDEs is to interpret the stochastic processes in the equations as a means to model uncertainty. In this sense, stochastic systems offer a powerful modelling framework for engineering applications. The course will provide an introduction to stochastic control.

The course will initially develop these topics in two independent units which will be merged towards the end of the course with topics such as stochastic optimal control.

Course outline

- Dynamic optimisation

  Considering optimal control and differential games, we will see how their solutions can be obtained by means of either the Dynamic Programming approach or Pontryagin's minimum principle. Recognising the computational burden associated with solving such problems exactly, we will consider various strategies to solve optimal control problems and differential games approximately at (significantly) reduced computational cost. Practical examples will be provided alongside the theoretical considerations.

- Introduction to Stochastic Control

  This unit will assume no prior knowledge of stochastic control and SDEs. The aim of the unit is to develop a working knowledge of control of SDEs. We will start by quickly introducing some elements of measure theory and probability which are instrumental for the development of the course. We will then construct the Brownian motion, discuss its relation with white noise, cover the notion of stochastic integral and other topics related to SDEs, such as existence and uniqueness of the solution, linear SDEs and simulation. We will then cover a selection of advanced topics: various concept of stability and elements of optimal control (connecting with the other unit of the course).

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M06 – PARIS SACLAY 04/04/2022-08/04/2022	*Equivariant Systems Theory and Observer Design for Autonomous Systems*

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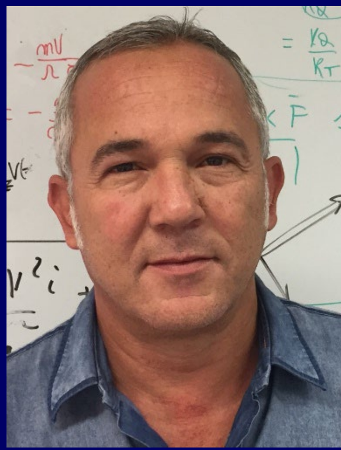

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Abstract of the course

The functionality of any autonomous system depends critically on its ability to estimate its dynamic state. For robotic systems, with limited sensor suites, highly dynamic motion, non-linear state space, and limited computational capacity, the state observer performance is even more important. A key technology enabler underlying the explosion of small scale commercial aerial robotic systems was the development of high quality, simple, robust, attitude observers based on the underlying equivariant symmetry structure of the attitude estimation problem.

This course provides an introduction to emerging field of *Equivariant Systems Theory* and applies these techniques to the design of observers for autonomous systems. The approach taken is highly practical, starting from matrix calculus and Lie theoretic foundations from an engineering perspective and working through a number of examples to demonstrate how to model equivariant systems and use the symmetry to derive robust observers. The course is based around an extensive suite of case studies drawn from aerial robotic applications including; attitude estimation, velocity aided attitude estimation, pose estimation, homography estimation, SLAM and Visual Odometry. Students will come out of the course with a strong understanding of how to derive and implement nonlinear observers for real world robotic systems.

Topics:

1) Perspectives on observer design for autonomous systems.
2) Matrix calculus and matrix ODEs.
3) Lyapunov observer design for systems with matrix Lie-group state.
4) Dealing with practical issues, velocity bias, asynchronous measurements and delays.
5) Equivariant Systems Theory.
6) Second order kinematics and equivariance.

Practical work in this course uses MATLAB (or equivalent scripting language) extensively. Students are required to have a working system on their own laptop for the course.

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M07 – PARIS SACLAY 11/04/2022-15/04/2022	*Analysis and Design Methods for Time-Delay Systems*

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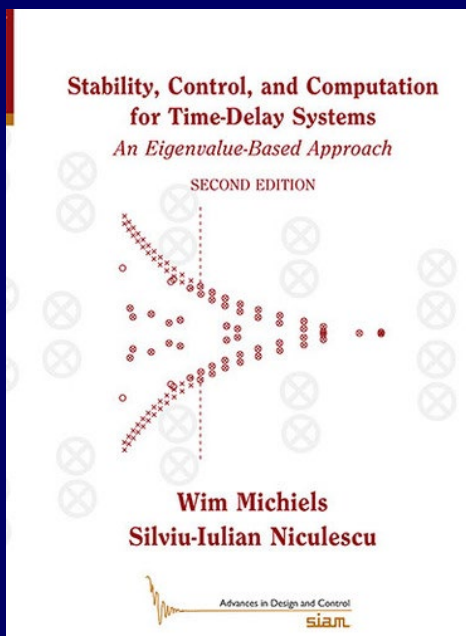
Abstract:
The aim of this course is to describe fundamental properties of systems including time-delays in their representation and to present an overview of methods and techniques for the analysis and control design. The focus lies on systems described by functional differential equations and on frequency-domain techniques, grounded in numerical linear algebra (e.g., eigenvalue computations) and optimization, but the main principles behind time-domain methods are addressed as well. Several examples (from chemical to mechanical engineering, from haptics systems and tele-operation to communication networks, from biological systems to population dynamics and genetic regulatory networks) complete the presentation. Finally, additional material on model reduction will be provided. The course is complemented with home-works where control design problems are solved using dedicated software tools.

Topics:
Theory:
- Classification and representation
- Definition and properties of solutions of delay systems
- Spectral properties of linear time-delay systems

Analysis:
- Stability using time- and frequency-domain methods
- Stability domains in parameter spaces
- Relative stability and synchronization
- Robustness and performance measures

Control design:
- Fundamental limitations of delays in control loops
- Structured stabilizing and optimal H-2 and H-infinity controllers (fixed-order, PID, decentralized,…)
- Prediction based controllers
- Using delays as controller parameters



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M08 — PARIS SACLAY 25/04/2022-29/04/2022	*Machine learning for automation of smart buildings and communication networks: from theory to experimental application*

Abstract

Looking for synergies between Control Theory and Machine Learning is a recent and challenging research topic. The potential impact of such scientific effort is huge, especially in engineering applications where deriving a physical model of a plant is impractical or even impossible, while a large amount of data is available due to on-the-market cheap and easy-to-install (wireless) communication devices.

According to the *virtuous cycle,* methodologies that merge control and machine learning are validated on experimental setups, possibly in the so-called *living laboratories,* and the outcomes of the experimentation drive the need and development of novel methodologies.

In this course, we will address both theoretical and engineering aspects involved in the following process: derivation of a dynamical model from a real data set of a building automation system and of a communication network; formalisation of an appropriate optimal control problem; implementation and validation on an experimental setup. MATLAB laboratory sessions will be performed to consolidate theoretical lectures, as well as to connect via VPN with the SCADA system of the climate control living laboratories of our buildings at the University of L'Aquila.

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Outline of the course

I. Data collection and pre-processing, cost functions and performance metrics.
II. Deterministic and stochastic dynamical model classes.
III. Fundamentals of Model Predictive Control.
IV. Introduction to Machine Learning, Perceiver, Support Vectors Machines.
V. Regressive models and techniques: AutoRegressive eXogenous (ARX) models, Regression trees, Random forests.
VI. Identification and MPC algorithms based on models obtained from Machine Learning techniques.
VII. Matlab laboratory with application to real data-sets: construction of predictive models and implementation/validation of control loops in experimental setups.

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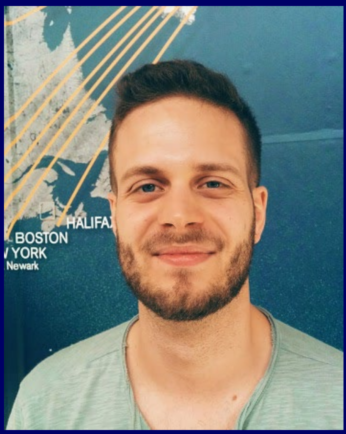
M09 – BOLOGNA 02/05/2022-06/05/2022	*An overview on observer design methods for nonlinear systems*



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Summary of the course

The purpose of this course is to give an overview of the main design techniques of *asymptotic observers* for nonlinear dynamical systems. The goal of such algorithms is to solve an online state estimation problem, namely, to reconstruct online the full state of a dynamical process from past partially observed data. After studying some detectability-based necessary conditions to ensure convergence of the estimate toward the state of the system, the rest of the course will consist in presenting the main families of observers depending on the type of observability properties they require. This includes Riemannian observers, Kalman and Kalman-like observers, high-gain and homogeneous observers/differentiators, and Kazantzis/Kravaris-Luenberger observers. We will show that each class of observer relies on transforming the plant's dynamics into a particular normal form and how each observability condition guarantees the invertibility of its associated transformation and the convergence of its observer. The most important and informative proofs will be detailed, and the advantages/drawbacks of each design discussed. Finally, we will discuss some implementation aspects and open problems, such as left-inversion problems, state constraints, tuning and performance, output sampling, as well as the combination of observers and control for output feedback.

Outline

- Introducing the observer problem
- Observers from detectability conditions
- Observers from observability grammian (Kalman and Kalman like)
- Observers from differential observability (High-Gain and Homogeneous obsevers)
- Observers from distinguishability : KKL design
- About the implementation of an observer

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M10 – PARIS SACLAY 02/05/2022-06/05/2022	*Predictive and Optimization Based Control for Automotive and Aerospace Applications*

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Abstract of the course

This course will focus on predictive and optimization-based control for constrained systems, and its applications to automotive and aerospace systems. The fundamentals of optimization and optimal control, Model Predictive Control and constrained control will be reviewed with the focus on the theory and computations. Ancillary schemes needed for controller implementation such as state estimators and disturbance input observers will be introduced. Several automotive and aerospace applications will be considered in detail with the introduction to the underlying technologies, system modeling, constrained control design and experimental implementation.

The topics covered will include:

1. Optimization and optimal control
2. Model Predictive Control: theory and computations
3. Governors for constrained control
4. Automotive gasoline and diesel engine control
5. Hybrid Electric and Electric Vehicles energy management
6. Control of vehicle dynamics and ADAS
7. Autonomous Vehicles guidance and control
8. Limit protection in aircraft gas turbine engines
9. Spacecraft station keeping, rendezvous and docking
10. Spacecraft attitude control
11. Advanced topics in automotive and aerospace control – as time permits

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M11 – PARIS SACLAY
09/05/2022-13/05/2022

Introduction to Nonlinear Systems & Control

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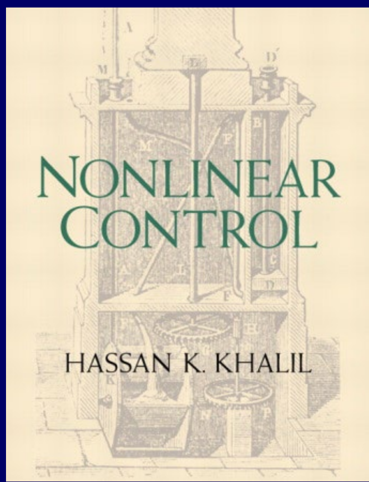
Abstract of the course

This is a first course in nonlinear control with the target audience being engineers from multiple disciplines (electrical, mechanical, aerospace, chemical, etc.) and applied mathematicians. The course is suitable for practicing engineers or graduate students who didn't take such introductory course in their programs.

Prerequisites: Undergraduate-level knowledge of differential equations and control systems.



Outline

- Introduction and second-order systems (phase portraits; multiple equilibrium points; limit cycles)
- Stability of equilibrium points (basics concepts; linearization; Lyapunov's method; the invariance principle; region of attraction; time-varying systems)
- Perturbed systems; ultimate boundedness; input-to-state stability
- Passivity and input-output stability
- Stability of feedback systems (passivity and small-gain theorems; Circle & Popov criteria)
- Normal and controller forms
- Stabilization (linearization; feedback linearization; backstepping; passivity-based control)
- Robust stabilization (sliding mode control; Lyapunov redesign)
- Observers (observers with linear-error dynamics; Extended Kalman Filter, high-gain observers)
- Output feedback stabilization (linearization; passivity-based control; observer-based control; robust stabilization)
- Tracking & regulation (feedback linearization; sliding mode Control; integral control)

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M12– TOULOUSE 16/05/2021-20/05/2021	*Sparsity and Big Data in Control, Systems Identification and Machine Learning*

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Abstract of the course

One of the hardest challenges faced by the systems community stems from the exponential explosion of data, fueled by recent advances in sensing technology. During the past few years a large research effort has been devoted to developing computationally tractable methods that seek to mitigate the ``curse of dimensionality" by exploiting sparsity.

The goals of this course are:

1) provide a quick introduction to the subject for people in the systems community faced with ``big data" and scaling problems, and

2) serve as a ``quick reference" guide for researchers, summarizing the state of the art .

Part I of the course covers the issue of handling large data sets and sparsity priors in systems identification, model (in)validation and control. presenting recently developed techniques that exploit a deep connection to semi-algebraic geometry, rank minimization and matrix completion.

Part II of the course focuses on applications, including control and filter design subject to information flow constraints, subspace clustering and classification on Riemannian manifolds, and time-series classification, including activity recognition and anomaly detection.

Topics include:
- Review of convex optimization and Linear Matrix Inequalities
- Promoting sparsity via convex optimization. Convex surrogates for cardinality and rank
- Fast algorithms for rank and cardinality minimization
- Fast, scalable algorithms for Semi-Definite Programs that exploit sparsity
- Sparsity in Systems Identification:
    - Identification of LTI systems with missing data and outliers
    - Identification of Switched Linear and Wiener Systems
    - Identification of sparse networks
- Sparsity in Control: Synthesis of controllers subject to information flow constraints
- Connections to Machine Learning: subspace clustering and manifold embedding
- Applications: Time series classification from video data, fault detection, actionalble information extraction from large data sets, nonlinear dimensionality reduction, finding causal interactions in multi-agent systems.

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M13 – PARIS SACLAY
16/05/2022-20/05/2022

Robust Controllability of Uncertain Systems

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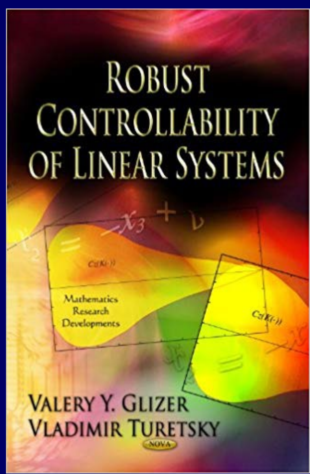
Summary of the course

The concept of robust controllability combines two fundamental properties of a dynamic system – controllability and robustness. *Controllability* is the ability of a dynamic system to be transferred from a given set of initial positions to a given target set in a finite time by a proper choice of a control function. For uncertain systems, the controllability should be augmented by the *robustness* property with respect to any admissible uncertainty realization. Control *constraints* are an indispensable part of most of practical control problems. Therefore, one of the crucial concepts of Robust Controllability Theory becomes a *robust controllability set*, from which the robust transfer of the system to the target set is possible subject to geometric control constraints. The course presents a complete overview of the theoretical results from the basic concepts (transferring strategy, robust transferring strategy, robust controllability set, etc.) to various extensions of the theory (non-linear and hybrid systems, non-linear strategies, etc.). Each section of the course is equipped by practical exercises.



Topics:

- Robust controllability for non-uniformly bounded controls and disturbances
- Robust controllability for uniformly bounded controls and disturbances
- Saturated linear transferring strategies
- Robust controllability of hybrid systems
- Robust controllability by history-dependent strategies
- Robust controllability of nonlinear systems
- Inverse problem for robust controllability set construction

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M14 – PARIS SACLAY
30/05/2022-03/06/2022

Lyapunov Based Design of Sliding Mode Controllers

Abstract of the course

The sliding mode methodology has proved to be effective in dealing with complex dynamical systems affected by disturbances and/or uncertainties. These robustness properties have also been exploited in the development of nonlinear observers for state and unknown input estimation. Higher-order sliding mode algorithms have been developed to force the sliding variable and a number of its time derivatives to zero in finite time. The proposed course reflects the recent results of the authors developing novel types of discontinuos and continuous sliding mode controllers and observers, and their properties.

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Contents

MATHEMATICAL TOOLS
Solutions of equations with discontinuous right-hand side
Stabiity rates. Finite-, fixed- and predefined-time convergence
Matched and unmatched perturbations/uncertainties
Problem statement

FIRST ORDER SLIDING MODE ALGORITHMS (SMA)
Relay SMA
Unit first-order SMA

SECOND ORDER SMA
Discontinuous SMA: Twisting, Terminal, Quasi-Continuous
Lipschitz continuous SMA for systems with relative degree one
Super-twisting algorithm
Robust Exact Differentiator (RED)

LYAPUNOV BASED DESIGN OF HIGHER ORDER SMA (HOSMA)
Homogeneity, homogeneity weigths and degrees
Discontinuous HOSMA
Continuous HOSMA (CHOSMA)

OUTPUT BASED DESIGN OF HIGHER ORDER SMA
Arbitrary order differentiators. Output based HOSMA and CHOSMA

SLIDING MODE CONTROLLERS DESIGN
Lyapunov based redesign
Integral sliding mode control

CONVENTIONAL SLIDING MODE DESIGN
Eigenvalue's assignment
Optimal stabilization of sliding dynamics

SLIDING MODE BASED OBSERVERS
Strong observability and detectability
RED based observers for LTI, LTV and nonlinear systems
RED based identification of uncertainties and parameters

CHATTERING
Chattering analysis caused by continuous, discontinuous and Lipschitz SMA
CHOSMA gains design minimizing the chattering

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M15 – STOCKHOLM & ONLINE 30/05/2022-03/06/2022	*Formal Methods in Control Design – from Discrete Synthesis to Continuous Controllers*

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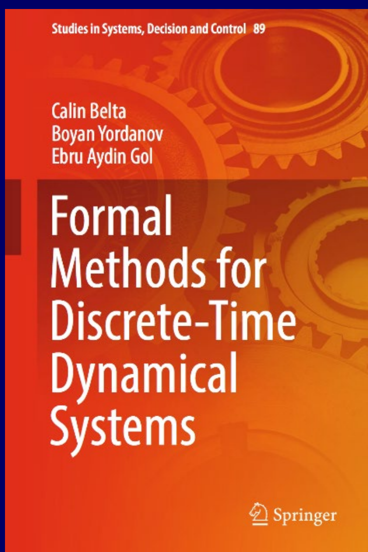
Summary of the course

In control theory, complex models of continuous physical processes, such as systems of differential or difference equations, are usually checked against simple specifications, such as stability and set invariance. With the development and integration of cyber-physical and safety-critical systems, there is an increasing need for tools to design controllers for richer specifications. The main objective of this course is to present formal methods in control design. The key concept of these approaches is that of discrete abstraction (a.k.a. symbolic model), which is a finite-state dynamical system, obtained by abstracting continuous trajectories over a finite set of symbols. When the abstraction and the continuous dynamics are formally related by some behavioral relationship (e.g. simulation or bisimulation relations), controllers synthesized for the abstraction can be refined to certified controllers for the original continuous system. Moreover, since the abstractions are discrete, controllers can be synthesized automatically, using discrete synthesis techniques, for rich specifications such as languages or formulas of temporal logics. In this course, we will cover all aspects of formal methods in control design from the computation of discrete abstractions, to discrete synthesis and controller refinement. At the end of the course, we will present novel approaches based no optimization which are alternatives to abstraction-based synthesis for complex specifications.

Outline

1. The need for formal methods in control design
2. Systems, behaviors and relations among them
3. Abstractions of continuous systems
    - 3.1 Discrete abstractions: partition-based approaches, Lyapunov-based approaches
    - 3.2 Continuous abstractions
4. Abstraction-based controller synthesis
    - 4.1 Safety, reachability, attractivity specifications: fixed-point synthesis, lazy and compositional synthesis, quantitative and robust synthesis
    - 4.2 Linear temporal logic specifications: Finite temporal logic control, language-guided control systems, optimal temporal logic control
5. Optimization-based synthesis
    - 5.1 Synthesis based on temporal logic quantitative semantics
    - 5.2 Synthesis based on control barrier functions and control Lyapunov functions



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M16 – PARIS SACLAY 07/06/2022-10/06/2022	*Dynamics and Algorithms on Networks*

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Summary of the course

Networked systems play an ever-growing role in our increasingly interconnected world. One of the most fundamental challenges in the field of networked control system is to understand the connection between the behavior of ***dynamics over networks*** and the underlying ***graph structure***.

This course introduces the main toolset for analyzing and controlling interconnected systems by covering three main topics. We begin with an overview of the (average) consensus problem, in which agents try to reach a common value or trajectory via local interactions. We discuss the effects of graph structure and provide a self-contained introduction to the basics of algebraic graph theory. Our second topic is distributed optimization, which is a canonical model for optimizing a global objective from local interactions over a network. A central focus will be connecting the performance of distributed optimization methods to the features of the underlying network. Our final topic is epidemic propagation over graphs. We will discuss the classic epidemic models, their network generalizations, and their extensions to model the spread of COVID-19. Besides focusing on basic properties of network epidemic models, we discuss control strategies for containment of the epidemic.

The course functions as a good introduction to many different themes in decentralized algorithms and algorithms for decentralized systems.

More Information can be found at https://perso.uclouvain.be/julien.hendrickx/EECI_M15

Outline

1. Consensus and Its Applications
   - Linear Consensus: deterministic and stochastic cases
   - Opinion dynamics and formation control
   - Dealing with directed graphs via push-sum
   - Synchronization: consensus of dynamical systems
   - Distributed computation: models and impossibility results
2. Distributed Optimization
   - Fundamental models of distributed optimization
   - Decentralized gradient descent
   - Gradient tracking methods
   - Outperforming centralized methods with network independence
3. Epidemics on Networks
   - Classic epidemic models and modeling COVID-19
   - Network/compartmental models of epidemic spread
   - Optimization problems for epidemic control, vaccine and drug allocation, shutdown design
   - Estimating the state of an epidemic

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M17 – MARSEILLE
04/07/2022-08/07/2022

Introduction to Discrete Event Systems

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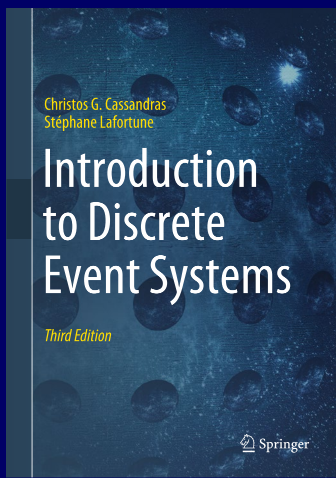
Course summary:

Discrete event systems are dynamic systems with discrete state spaces and event-driven dynamics. They arise when modeling the high-level behavior of cyber-physical systems or when modeling computing and software systems. Discrete event models can be purely logical, or they may include timing and stochastic information. This course will have two parts. In the first half, we will study logical discrete event systems, focusing primarily on automata models. We will consider estimation, diagnosability, and opacity analysis for partially-observed systems, then supervisory control under full and partial observation. In the second half, we will study the performance analysis, control, and optimization of timed DES, using stochastic timed automata models. We will describe the use of discrete event simulation and review elementary queueing theory and Markov Decision Processes used to study stochastic timed DES. We with then present Perturbation Analysis (PA) theory as a method to control and optimize common performance metrics for DES. Finally, we will explain how to extend DES into Hybrid Systems, limiting ourselves to basic modeling and simple extensions of PA theory.

No prior knowledge of discrete event systems will be assumed. The course will rely on the textbook co-authored by the instructors: *Introduction to Discrete Event Systems – Third edition, Springer, 2021*
https://www.springer.com/gp/book/9783030722722

Course outline:

1. Overview of DES and contrast to time-driven systems
2. Introduction to discrete event modeling formalisms
3. Analysis of logical discrete event systems
4. Supervisory control under full and partial observation
5. Timed Models of DES
6. DES (Monte Carlo) computer simulation
7. Review of queueing theory and Markov Decision Processes
8. Perturbation Analysis and Rapid Learning methods
9. From DES to Hybrid Systems



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M18 – BOULDER, USA 13/06/2022-17/06/2022	*Output Feedback Stabilization and Regulation of Nonlinear Systems*

Outline

The problem of output regulation, the design feedback control laws so as to asymptotically track/reject exogenous inputs, is one of the defining problems in control theory. In the case of MIMO linear systems the problem was solved in full generality several decades ago by introducing the celebrated "internal model principle”. The latter claims that asymptotic regulation is achieved in presence of plant parameter variations “only if the controller utilizes feedback of the regulated variable, and incorporates in the feedback path a suitably reduplicated model of the dynamic structure of the exogenous signals which the regulator is required to process”.

The extension of the design techniques developed in the linear setting to nonlinear systems hides a lot of control challenges that make the nonlinear output regulation theory still an open research field. Design solutions proposed so far are limited to specific classes of nonlinear systems, mainly minimum-phase and without "extra" measurements besides the regulated variable. A “chicken-egg” dilemma arises in the design of the feedback control law and of the internal model whose "sequential" design, which is followed in the linear context, is not possible. The two units, rather, must be synergistically designed by adopting a mix of adaptive and identification tools. Furthermore, the quest for robustness is also a fundamental open research topic when designing nonlinear regulators to the point that, recently, it was shown that no finite dimensional robust asymptotic regulators exist if “unstructured” perturbations are considered.

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Topics

1. Output regulation and internal model principle for linear systems
2. Fundamental tools: steady state, regulator equations, internal model property
3. Robust output regulation for nonlinear systems. Pre-processing and post-processing internal models. Wash out filters in the design of regulators in presence of extra measurements
4. The concept of robust minimum-phase and its use in the design of pre-processing regulators
4. The “chicken-egg” dilemma in the design of nonlinear post-processing regulators and the adoption of adaptive and identification tools for the synergistic design
5. Notions of robustness and the quest of robustness in nonlinear regulator design
6. Output regulation for hybrid systems: tools and main design solutions

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M19 – STOCKHOLM 20/06/2022-23/06/2022	*Control and Optimization* *of Autonomous Power Systems*

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Abstract of the course

The electric power system is currently undergoing a period of unprecedented changes. Centralized bulk generation based on fossil fuel and interfaced with synchronous machines is substituted by distributed generation based on renewables and interfaced with power converters. Accordingly, the entire operation of power systems is undergoing several major paradigm shifts spanning decentralized device-level control, distributed coordination of energy sources, and real-time system-level optimization. In this course, we give a tutorial introduction to new and emerging thrusts in analysis, control, and optimization of future, smart, and cyber-enabled power systems. The solutions that we present tap into some recent methodological advances in control and optimization, with a focus on scalable and distributed solutions, multi-agent decision problems, feedback control for real-time optimization, (almost) model-free design,

Topics:

- Power system modeling, dynamics, & stability analysis
- Decentralized control of power converters & synchronous generators
- Real-time control of distribution networks and microgrids
- Feedback strategies for power balancing and frequency regulation
- Autonomous power system operation for congestion relief

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M20 – HONG-KONG
27/06/2022-01/07/2022

Machine Learning, Optimization and Control

Abstract

Optimization and Control are classical topics appearing in most applications in other scientific disciplines, industry and new technologies. Most often, processes need to be optimised, parameters to be optimally tuned, strategies to be improved, so as to achieve a desired goal. Nowadays, classical mathematical and computational methods developed in these areas are reinforced with new techniques emanating from Machine Learning. This course is aimed to introduce some of the powerful tools in numerical optimization and machine learning, showing how they can be employed to address optimal control problems.

In particular, we shall present splitting algorithms allowing to derive faster numerical simulations methods, illustrating their applications to optimal control problems modelled through elliptic and parabolic Partial Differential Equations (PDE), some of the most paradigmatic models in all Sciences.

We will also demonstrate how deep learning can redefine the solvability of a problem and substantially refresh the philosophy of algorithmic design for classical problems such as some elliptic optimal control problems with total variation regularization arising in image processing.

We will show some promising numerical results accelerated by these optimization and deep learning techniques, and share our experience of coding and numerical implementation.

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Outline:

- Preliminaries of optimal control, optimization, deep learning, PDE and numerical linear algebra
- Operator splitting algorithms for optimal control problems
  - Inexact Uzawa method for elliptic optimal control problems with control constraints
  - Deep learning embedded operator splitting methods for elliptic optimal control problems with total variation regularization
  - Alternating Direction Method of Multipliers (ADMM) for some parabolic optimal control problems
  - Fast algorithms for bilinear control problems of advection-reaction-diffusion systems
- Matlab programming skills for numerical implementation
  - Numerical discretization for optimal control problems (e.g., finite element and finite difference methods)
  - Krylov subspace methods for large-scale linear systems (e.g., Conjugate Gradients (CG) and Generalized Minimal Residual Method (GMRES))
  - Preconditioning for large-scale linear systems (e.g., multi-grid)
  - Numerical implementation of classical optimization algorithms (e.g., CG, line-search, active-set Newton and augmented Lagrangian methods)
  - Deep learning implementation (e.g., Convolutional Neural Networks (CNN))

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M21 — ZURICH
11/07/2022-15/07/2022

Learning-Based Predictive Control

Abstract

Learning-based Model Predictive Control (MPC) provides advanced control systems with the capability to exploit real-time collected information to improve performance in face of uncertainty, at the same time maintaining high safety standards. This is a crucial requirement of next generation control applications, such as autonomous passenger cars, or autonomous aerial, marine and ground drones for civil applications. In established industrial systems, such a capability can also bring significant benefits, reducing commissioning time and cost, and the effects of product/process variability.
After a brief review of fundamentals of MPC, the course presents an overview of existing learning-based MPC methods, followed by a deep-dive into theory and applications of selected techniques for different problem settings. These include stochastic and unknown-but-bounded uncertainty, and reactive techniques. A discussion on advanced topics and active research direction concludes the module.

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Outline of the course

I. Review of (learning-based) MPC
1. Fundamentals of MPC
2. Classification of learning-based extensions

II. Set membership methods in MPC
1. Introduction to set membership estimation
2. Model learning with guarantees
3. Adaptive MPC via on-line set membership identification

III. Stochastic methods in MPC
1. Stochastic model learning
   (Bayesian linear regression/Kalman Filtering/GPs)
2. Stochastic MPC based on scenario optimization

IV. Model predictive safety filters
1. Invariance-based safe learning
2. Nominal predictive safety filter
3. Robust extensions

V. Advanced topics and research directions