# 2025
# International Graduate School on Control

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**M01 PARIS-SACLAY**
**27/01/2025 - 31/01/2025**

## *Data-driven Control Design*

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https://cercachi.unifi.it/p-doc2-0-0-A-3f2b342f322930.html

### Summary of the course

Data-driven control is concerned with the use of data to design controllers for dynamical systems whose model is unknown or uncertain. This course focuses on a recently introduced method for the so-called direct design of data-driven controllers for linear and nonlinear systems. The design is made possible by input-state or input-output data that are collected during offline experiments and some a priori information about the system to be controlled. The adjective “direct” refers to the characteristic that data are used to formulate data-dependent convex programs whose solution “directly” returns the controller that solves the desired control problem, without explicitly identifying the dynamics of the system.

The course will review a few of the results that have been obtained in the last few years. These results are based on basic control-theoretical tools, which will be briefly reviewed during the course to make the latter as self-contained as possible. Some numerical tools to solve the convex programs that return the controllers will also be discussed. The programme below contains some of the topics that might be covered. The precise contents will be decided during the course based on the interest of the attendees and the time available.

### Outline

1. Introduction to data-driven control, non-parametric representations of systems and their implication in data-driven control design.
2. Data-driven control for linear systems: the case of unperturbed data
   - 2.1 Data-dependent representations of linear closed-loop systems
   - 2.2 The design of data-dependent state-feedback stabilizers
   - 2.3 Designing controllers from input-output data: the output feedback stabilization problem
   - 2.4 Stabilization and optimality: The design of the Linear Quadratic Regulator via data
   - 2.5 Additional aspects: discrete- vs continuous-time systems, software for data-driven control design
3. Data-driven control design with perturbed data
   - 3.1 Data-dependent representations in the case of perturbed data
   - 3.2 Matrix Elimination results and robust control design with perturbed data
   - 3.3 Statistical noise on data: results in probability and sample complexity
4. Data-driven control design for nonlinear systems
   - 4.1 Data and Lyapunov’s methods: stabilization of the first approximation
   - 4.2 Control of nonlinear systems expressed via libraries of functions: data-driven feedback linearization methods
   - 4.3 Data-driven control design for special classes of nonlinear systems: bilinear, Lur’e and polynomial systems
   - 4.4 Additional results (design via contraction, tracking)

M02 LILLE
10/03/2025 - 14/03/2025

# *Modeling and Control of Continuum Soft Robots*

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## Abstract of the course

Animals still substantially outperform classic robots in performance, reliability, and efficiency. Interestingly, their physical characteristics differ substantially from those of robots. Elastic tendons, ligaments, and muscles enable animals to interact robustly with the external world and perform dynamic tasks. On the contrary, traditional robots have generally been very stiff and heavyweight. Therefore, robotics researchers have departed from the as-stiff-as-possible principle in favor of lightweight and compliant structures. Taking inspiration from the natural example, elastic and soft components are included in the robot design, yielding articulated and continuum soft robots. This course will focus on the latter, which are entirely made of continuously deformable elements, bringing them close to invertebrate animals. This recent explosion of new robotic concepts opened up the avenue of developing effective control strategies to manage the soft body, a nonlinear mechanical system with a large – possibly infinite – number of DOFs and, as a result, also a large degree of underactuation from the control point of view. This course aims at introducing such control challenge. We will review established results in the field, introduce the most recent advances, and discuss interesting open issues.

The course will include practical sessions in MatLab.

## Topics

- Introduction to robotics beyond rigid robots
- Modelling soft robots:
    - constant curvature,
    - strain discretization,
    - general form of equations
- Controlling soft robots:
    - shape regulation (general case and subclasses),
    - shape tracking,
    - task-space control

# 2025
# International Graduate School on Control

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**M03 PARIS-SACLAY**
**17/03/2025 - 21/03/2025**

## *Analysis and Design Methods for Time-Delay Systems*

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### Summary of the course

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. In particular, the synergies of analytic and computational tools for analysis and design are highlighted. The course is complemented with home-works where analysis and control design problems are solved using dedicated software tools.

### Outline

*Theory:*

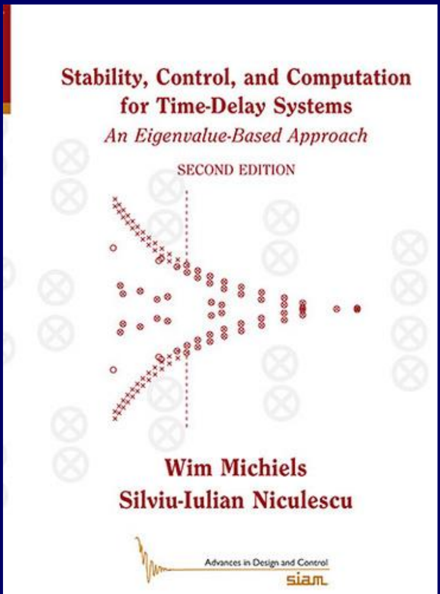
- Classification and representation
- Definition and properties of solutions of delay systems
- Spectral properties of linear time-delay systems

*Analysis:*

- Frequency-domain approaches
- Stability domains in parameter spaces
- Relative stability and synchronization
- Robustness and performance measures
- Time-domain, Lyapunov based criteria, Lyapunov matrices and converse theorems

*Control design:*

- Fundamental limitations of delays in control loops
- Structured stabilizing and optimal H-2 and H-infinity controllers (fixed-order, PID, decentralized,…)
- Delay compensation using predictor and periodic feedback
- Improving stability and performance by using delays as control parameters



**M04 ILMENAU**
**31/03/2025 - 04/04/2025**

# *Lyapunov Based Design of Sliding Mode Controllers*

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## Summary of the course

The sliding mode algorithms(SMA) have 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 switching function 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, continuous and Lipschitz sliding mode controllers and their properties.

## Outline

1. MATHEMATICAL TOOLS
   Solutions of equations with discontinuous right-hand side ; Stabiity rates. Finite-, fixed- and predefined-time convergence ; Matched and unmatched perturbations/uncertainties
2. FIRST ORDER SLIDING MODE ALGORITHMS (FOSMA)
   Relay FOSMA ; Unit FOSMA
3. SLIDING SURFACES DESIGN FOR FOSMA
   Forced sliding surfaces design ; Integral sliding modes ; Nominal Lyapunov Function based surface design ; Control Lypunov functions for sliding mode controllers design
4. SECOND ORDER SMA (SOSMA)
   Discontinuous SMA: Twisting, Terminal, Quasi- Continuous ; Lipschitz continuous SMA for systems with relative degree one ; Super-twisting algorithm ; Robust Exact Differentiator (RED)
5. LYAPUNOV BASED DESIGN OF HIGHER ORDER SMA (HOSMA)
   Homogeneity: homogeneity weigths and degrees ; Discontinuous HOSMA ; Continuous HOSMA(CHOSMA)
6. OUTPUT BASED DESIGN OF HIGHER ORDER SMA
   Arbitrary order RED. Output based HOSMA and CHOSMA
7. SLIDING MODE BASED OBSERVERS
   Strong observability and detectability ; RED based observers for LTI, LTV and nonlinear systems ; RED based identification of uncertainties and parameters
8. CHATTERING
   Chattering analysis caused by continuous, discontinuous and Lipschitz SMA ; CHOSMA gains design minimizing the chattering and energy consumptions

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**M05 LAUSANNE**
**31/03/2025 - 04/04/2025**

## *Neural Networks for Optimal Control*




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### Summary of the course

The effectiveness of control algorithms in large-scale cyber-physical systems relies not only on advancements in sensing, computation, and communication but also on the availability of methods to design controllers capable of stabilizing nonlinear systems under nominal operating conditions. However, stabilization alone is insufficient; achieving satisfactory performance is equally critical. In Optimal Control (OC), performance is typically encoded in the cost function that the control policy aims to minimize. This highlights the need for OC algorithms that leverage Neural Network (NN) models to enable sophisticated closed-loop behaviors, such as collision avoidance or waypoint tracking in robot swarms. The challenge lies in constraining the search for high-performance controllers to those that ensure closed-loop guarantees, such as stability and robustness.

This course will equip PhD students with contemporary theoretical and computational tools for designing and deploying NN-based controllers with embedded theoretical guarantees for closed-loop systems. The course begins with a focus on recent optimal control methods for linear systems, emphasizing the direct design of closed-loop maps rather than control policies (e.g., Youla parametrizations, Internal Model Control, System-Level Synthesis). We then review stability tools for nonlinear systems, including L2 gains, dissipativity, and the small-gain theorem. Building on the first part, we teach a recent approach to nonlinear OC, termed "performance boosting," which utilizes NNs and automatic differentiation to enhance closed-loop system performance without compromising existing properties. The final section extends performance boosting to large-scale systems, where multiple nonlinear local systems interact dynamically, relying solely on local measurements for control deployment.

Lectures will be supplemented with exercise papers and coding exercises.

### Outline

**1. Designing Optimal Closed-Loop Maps for Linear Systems**
- Stable transfer matrices, internal stability, Youla parametrization, Internal Model Control (IMC)
- Convex optimal control over all stabilizing policies: guarantees for both model-based and model-free cases
- Finite-dimensional approximations and state-space implementations

**2. Performance Boosting for Nonlinear Optimal Control**
- Signal-space notation, nonlinear stable operators, L2 gains, and the small-gain theorem
- IMC parametrization of stabilizing nonlinear policies, robustness for uncertain models
- NN parametrizations of stabilizing controllers

**3. Performance Boosting at Scale**
- Dissipativity for interconnected systems
- Distributed Performance Boosting

M06 ZURICH
07/04/2025-11/04/2025

# *Learning-Based Predictive Control*

## Summary of the course

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.

## Outline

**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**

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# 2025
# International Graduate School on Control

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**M07 ROME**
**07/04/2025-11/04/2025**

## *Static and Dynamic Optimisation*

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## Abstract

Optimisation is a cornerstone of science and engineering: we are constantly striving to find the “best” solution to a variety of problems. In this IGSC, starting from a “static perspective” we consider tools to formulate and solve general constrained and unconstrained optimisation problems. Necessary and sufficient conditions of optimality and basic optimisation algorithms are covered in a mathematically rigorous manner. We then consider more advanced topics, including convex optimisation and multi-objective optimization, from an applications-driven mindset. The relevance of the theory to a variety of practical domains, such as fitting, finance, classification, biology and advertising is explored, and solutions implemented*. We then consider the “dynamic perspective”, by turning our attention to dynamical systems and the question of how to design control laws to optimise one or more performance criteria. Such problems, termed dynamic optimisation problems, include optimal control and differential games, and are (with a few exceptions) notoriously difficult to solve in practice. We consider the two main approaches to characterise their solutions, i.e. dynamic programming and Pontryagin’s minimum principle. In addition to a review of the classical theory, we outline various systematic strategies to construct approximate solutions, at relatively low computational cost.

*Basic knowledge of Python is required for this part. If in doubt, please email Dr Scarciotti who can suggest online recourses to get you up to speed quickly.

## Course outline

- Introducing to optimisation
- Necessary and sufficient conditions of optimality
- Basic optimisation algorithms
- Convex optimisation
- Multi-objective optimisation
- Use of CVX to pose and solve practical optimisation problems.
- Introduction to dynamic optimisation
- Classical theory of dynamic optimisation
- Computationally-efficient strategies to solve dynamic optimisation problems

# 2025
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**M08 LONDON**
**06/05/2025 - 09/05/2025**

## *Multi-agent optimization and learning: resilient and adaptive solutions*

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**Course website** https://sites.google.com/view/eeci-multi-agent-optimization (schedule, venue/travel, logistics)

**Summary**

Recent technological advances have enabled the widespread adoption of intelligent devices in many applications, such as healthcare, edge computing, transportation, robotics, smart grids. These devices are equipped with communication and computational resources, which allow them to learn from the data they collect. However, in order to improve the accuracy of the models they train, the important paradigm of decentralized learning is being deployed. Therefore, there is a need for algorithmic advances that can support cooperative learning and optimization. The course will provide a thorough introduction to the state of the art in decentralized learning, both with federated and peer-to-peer communication architectures. The course will cover different algorithmic approaches, e.g. gradient-based and dual methods. A particular emphasis will be given to the practical challenges that arise in this context, such as asynchrony and limited communications.

**Outline**

1. Introduction and motivating examples (healthcare, edge/fog computing, transportation, robotics, smart grids)
2. Decentralized learning and optimization
    - From centralized to decentralized
    - Practical challenges
    - Decentralized cooperative architectures
3. Federated learning
    - Deep learning
    - Privacy and resilience to attacks
4. Consensus and distributed optimization
    - The consensus algorithm: standard, accelerated, push-sum/ratio, broadcast w/ faulty communications
    - Consensus-based distributed optimization: gradient tracking and Newton
    - Non-expansive operators for optimization: background, operator-based algorithms (proximal gradient, ADMM, primal-dual, …)
    - Application to decentralized asynchronous and lossy networks: a stochastic operators approach
5. Current trends
    - Online distributed optimization (prediction-correction, control-theoretical approaches)
    - Data-driven optimization, privacy, human-in-the-loop
    - Frontiers in applications
6. Hands-on coding experiences

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**M09 PARIS-SACLAY**
**12/05/2025-16/05/2025**

## *Dissipativity in Optimal Control - Turnpikes, Predictive Control, and Uncertainty*

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**Timm Faulwasser**
TU Hamburg
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### Summary of the course

The optimal control twin breakthroughs, i.e. Pontryagin's maximum principle and Bellman's dynamic programming principle, and the dissipativity notion for open systems conceived by Jan. C. Willems are supporting pillars of systems and control. On this canvas, this course explores the constitutive relations between optimal control and dissipativity.

The week commences with a brief and example-driven introduction into optimal control formulations in continuous time and discrete time and we comment on the challenges that arise from infinite-horizon problems. We then turn towards dissipativity, discussing how optimal control has been at the very core of the concept since its inception. We comment on the surprisingly rich set of systems-and-control problems that admit a dissipativity-based analysis.

After this introduction we explore the turnpike phenomenon in optimal control – the first observations of which can be traced back to John von Neumann and Frank P. Ramsey. We discuss the deep link between dissipativity notions for optimal control problems and the turnpike phenomenon as well as the relation to the optimality system implied by the maximum principle.

Moving from open-loop to feedback considerations, we show how dissipativity helps to analyze the properties of receding-horizon approximations to infinite-horizon problems, i.e., we close the loop with model predictive control. Furthermore, we explore how the dissipativity-based framework can be extended to stochastic problems. Throughout the week our discussions are illustrated with examples from different application domains such as process control, mechanics, thermodynamics, and energy. Moreover, the students will conduct numerical experiments in class. The course concludes with an outlook on open problems and on ongoing research.

### Outline

1. Introduction
    - Optimal Control
    - Dissipativity and Optimal Control
    - The Turnpike Phenomenon
2. Turnpike and Dissipativity
    - Detectability and Turnpikes
    - Turnpikes and the Maximum Principle
    - Infinite-horizon optimal control and dissipativity
3. Predictive Control
    - Economic MPC and Dissipativity
    - Stochastic Turnpike and MPC
4. Advanced topics
    - Discounted Optimal Control and turnpike
    - port-Hamiltonian systems and symmetries
5. Summary and Outlook

# 2025
# International Graduate School on Control

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**M10 ISTANBUL**
**12/05/2025 - 16/05/2025**

## *Quantify your uncertainties!*
## *The input-to-state stability framework*

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https://sites.google.com/site/antoinechaillet

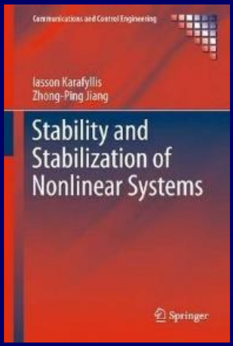
**Iasson Karafyllis**
National Technical University of Athens
https://scholar.google.com/citations?user=bwRBLesAAAAJ

### Summary of the course

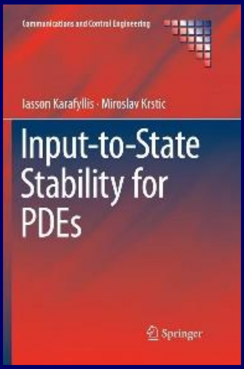
The notion of Input-to-State Stability (ISS) plays a fundamental role in modern nonlinear control theory. It allows to quantify the impact of an exogenous disturbance on the system's performance. The success of ISS is explained by powerful Lyapunov-based characterizations, which offer valuable means to establish it in practice. This is also true for some variants of ISS, including integral-ISS (which measures the disturbance's influence through its energy rather than its magnitude) or Input-to-Output Stability (which focuses only on specific outputs). This module provides the theoretical background for these notions and illustrates their use in important control problems (e.g., backstepping, Lyapunov redesign and high-gain observer design). While covering most of the central notions of the ISS framework, this course makes an intensive use of simple examples to intuitively grasp the presented concepts, and illustrates their use in various application domains such as neuroscience, spacecraft dynamics, robotics, or bioprocesses. The course is presented in the context of systems modeled by ordinary differential equations, but some recent extensions to time-delay systems and systems ruled by partial differential equations will also be mentioned.

### Outline

1. Introduction: what can go wrong with nonlinear dynamics?
2. Stability notions in the absence of disturbances
3. Input-to-State Stability (ISS): definition, Lyapunov-based and solutions-based characterizations, control laws to induce ISS, interconnection (cascade and feedback)
4. Integral ISS (iISS) and Strong iISS
5. Input-to-Output Stability (IOS) notions
6. Time-delay and PDE extensions.
7. Applications to control problems



Communications and Control Engineering
Iasson Karafyllis
Zhong-Ping Jiang
Stability and Stabilization of Nonlinear Systems
Springer



Communications and Control Engineering
Iasson Karafyllis · Miroslav Krstic
Input-to-State Stability for PDEs
Springer

# 2025
# International Graduate School on Control

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**M11 LIEGE**
**19/05/2025 - 23/05/2025**

## *Fast and flexible multi-agent decision-making*

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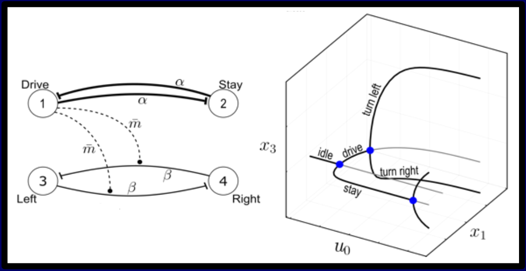
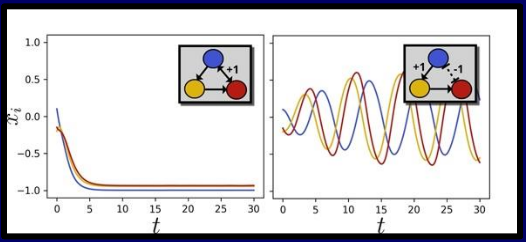
Cornell University
https://anastasiabzv.github.io/

**Alessio Franci**
University of Liège
http://sites.google.com/site/francialessioac/

### Summary of the course

Advancing our understanding of the decision-making behavior of multi-agent systems inspires challenging questions and benefits many research areas and practical applications. A fundamental and unifying question is how a large group of interacting agents makes decentralized choices that enhance performance in the presence of uncertainty and dynamically changing context even when individuals are limited in sensing, computation, and actuation. Examples of multi-agent decision-making in engineering include safe, efficient navigation in multi-vehicle networks, coordination of multi-robot teams, human-robot collaboration, and multi-robot task allocation. In biological science, examples include collective motion in animal groups, phenotypic differentiation and social behaviors in microorganisms, and the dynamics of cognitive computations in neural systems. In social science, examples include the role of social networks and social behavior in governance, in financial trading, in international diplomacy, in political polarization, and in public opinion shaping.
A central concern of this course is that *a multi-agent system should be capable of decision-making that is fast and flexible if it is to successfully manage the uncertainty, variability, and dynamic change encountered when operating in the real world.*
Decision-making is fast if it breaks indecision as quickly as indecision becomes costly. This requires fast divergence away from indecision in addition to fast convergence to a decision. Decision-making is flexible if it adapts to signals important to successful operation, even if they are weak or rare. This requires tunable sensitivity to input for modulating regimes in which the system is ultrasensitive and in which it is robust. Nonlinearity and feedback in the decision-making process are necessary to meeting these requirements. This course reviews theoretical principles, mathematical tools, analytical results, related literature, and applications of decentralized nonlinear opinion dynamics that enable fast and flexible decision-making among multiple options for multi-agent systems interconnected by communication and belief system networks. The theory and tools provided form a principled and systematic framework for analyzing and designing decision-making in engineered, biological, and social systems. At the end of this course the students will understand the basics of bifurcation theory and its role in decision making and apply this knowledge to analyze biological and social multi-agent decision-making, as well as to design fast and flexible multi-agent decision-making in engineered systems.





### Outline

1. Theoretical principles
    - Pitchfork Bifurcation as a Principle for Two-option Indecision-breaking
    - Generalization to Multiple Options
    - Model and Model-independent Approaches to Indecision-breaking
2. Fast and flexible multi-agent decision-making dynamics and analytical results
    - Opinions, Attention, Networks, Inputs and Biases
    - Nonlinear Multi-agent Multi-option Opinion and Attention Dynamics
    - Analytical results for Two Options
    - Generalization to Multiple Options
3. Connections to existing decision-making dynamics
    - Weighted Averaging, Consensus Dynamics, Variations and Extensions
    - Honeybee Decision-Making Dynamics
    - Connections to Cognitive Science and Neuroscience
4. Technological applications: robotics, machine learning, neuromorphic engineering

# 2025
# International Graduate School on Control

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## M12 BARCELONA
19/05/2025 - 23/05/2025

## *An overview on observer design methods for nonlinear systems*

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**Daniele Astolfi**
CNRS
sites.google.com/site/astolfidaniele/home

### Summary of the course

The purpose of this course is to give an **overview** of the main synthesis techniques of state observers for nonlinear dynamical systems. The lecture will start by addressing some general comments on the ``estimation problem'', that is, reconstructing the full information of a dynamical process on the basis of partial observed data. We will then introduce a particular type of algorithm: the asymptotic observer. Some necessary conditions that ensure convergence of the estimate toward the state of the system will be introduced: the detectability and its infinitesimal characterization.

Then, based on a characterization of detectability, a first class of observers will be presented. Some methods to design such observers will be introduced based on numerical methods.

The next part of the course will consist in presenting the main three families of observers based on stronger observability properties:

- **Kalman** and **Kalman-like** observers for state-affine systems, based on a persistence of excitation of the gramian of observability;
- **High-gain observers** and **differentiators**, based on differential observability assumptions;
- **Kazantzis/Kravaris-Luenberger** observers, based on backward distinguishability conditions.

We will show that each class of observer relies on transforming the plant's dynamics in a particular normal form which allows the design of an observer. We will explain how each observability condition guarantees the invertibility of its associated transformation and the convergence of the observer. The most important and informative proofs will be detailed, and the advantages/drawbacks of each design discussed.

At the end of the course, we will study some implementation issues and open problems.
For instance, the case of time discretization of the output will be considered. Another issue related to the left inversion problem in observers will also be discussed.
Finally, we show how an estimate given by the observer may be used in combination with a stabilizing state feedback in order to guarantee asymptotic stabilization of the origin by means of output feedback.

Throughout the course, the various concepts encountered will be illustrated with examples and followed by homework assignments designed to enhance their understanding.

Annual Reviews in Control
Volume 53, 2022, Pages 224-248

Tutorial article

Observer design for continuous-time dynamical systems

Pauline Bernard [a], Vincent Andrieu [b], Daniele Astolfi [b]

Show more

https://doi.org/10.1016/j.arcontrol.2021.11.002

# 2025
# International Graduate School on Control

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**M13 DELFT**
**02/06/2025 - 06/06/2025**

## *Formal Methods for Multi-Agent Feedback Control Systems*

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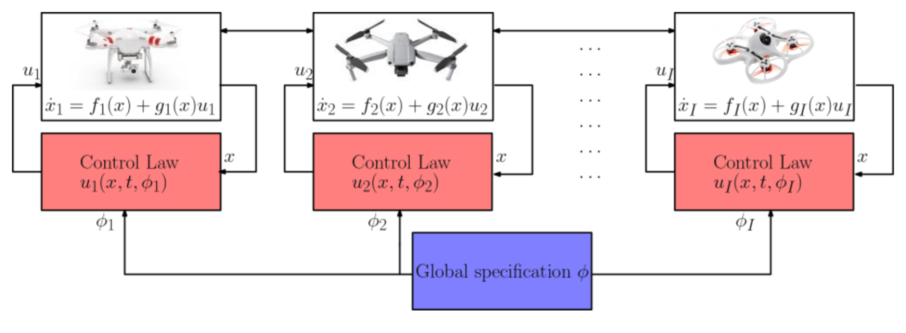
University of Southern California
https://sites.google.com/view/larslindemann/main-page

**Dimos V. Dimarogonas**
KTH Royal Institute of Technology
https://people.kth.se/~dimos/

### Abstract of the course

Multi-agent control systems are found in manufacturing, transportation, and multi-agent robotics, e.g., drone fleets for surveillance. Such systems are often safety-critical, e.g., avoiding collisions with other drones, while they should accomplish sophisticated system specifications, e.g., surveilling different areas in certain time intervals. The formal methods community has proposed spatiotemporal logics by extending Boolean logic with temporal modalities to express such spatial and temporal system requirements. Over the past decade, a new community has formed that works at the intersection of formal methods and control theory to design control algorithms to satisfy spatiotemporal logic specifications. Arguably, the biggest challenge in formal methods for multi-agent control is of computational nature as existing techniques are not scalable. This course introduces scalable feedback control design techniques to tackle these computational bottlenecks. Our first goal is to provide an introduction to signal temporal logic (STL), and to discuss how feedback control laws, based on control barrier functions and funnel control, can be designed to satisfy a global (i.e., collaborative) multi-agent STL specification. We then discuss how decentralized control laws can be derived so that each agent can calculate its control input locally, and how the case of local (i.e., individual) and potentially adversarial specifications is dealt with. This course is based on the book: https://mitpress.mit.edu/9780262049719/formal-methods-for-multi-agent-feedback-control-systems/



### Course outline

**Part I: Preliminaries**

- Introduction to signal temporal logic (STL)
- Control barrier functions and funnel control

**Part II: Feedback control for spatiotemporal logics**

- Encoding STL specifications into control barrier functions
- Encoding STL specifications into funnels

**Part III: Decentralized control**

- Decentralized control under global specifications
- Decentralized control under individual agent specifications

**Part IV: Miscellaneous**

- Timed automata for planning under STL specifications
- Applications and future research directions

# 2025
# International Graduate School on Control

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## M14 LOUVAIN-LA-NEUVE
02/06/2025 - 06/06/2025

## *Hybrid Control Systems*

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### Course Overview:

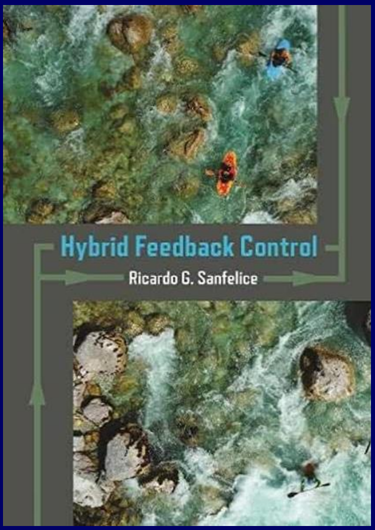
Hybrid dynamical systems, when broadly understood, encompass dynamical systems where states or dynamics can change continuously as well as instantaneously. Hybrid control systems arise when hybrid control algorithms — algorithms which involve logic, timers, clocks, and other digital devices — are applied to classical dynamical systems or systems that are themselves hybrid. Hybrid control may be used for improved performance and robustness properties compared to classical control, and hybrid dynamics may be unavoidable due to the interplay between digital and analog components of a system.

The course has two main parts. The first part presents various modeling approaches to hybrid dynamics, focuses on a particular framework which combines differential equations with difference equations (or inclusions), and present key analysis tools. The ideas are illustrated in several applications. The second part presents control design methods for such rich class of hybrid dynamical systems, such as supervisory control, CLF-based control, invariance-based control, and passivity. A particular goal of the course is to reveal the key steps in carrying over such methodologies to the hybrid dynamics setting. Each proposed module/lecture is designed to present key theoretical concepts as well as applications of hybrid control of current relevance.

### Course Outline:

- **Part 1: Introduction, examples, and modeling.**
  - Theoretical topics: hybrid inclusions; solution concept, existence, and uniqueness.
  - Applications: hybrid automata, networked systems, and cyber-physical systems.
- **Part 2: Dynamical properties.**
  - Theoretical topics: continuous dependence of solutions, Lyapunov stability notion and sufficient conditions, invariance principles, and converse theorem.
  - Applications: synchronization of timers and state estimation over a network.
- **Part 3: Supervisory control, uniting control, throw-catch, and event-triggered control.**
  - Theoretical topics: logic-based switching, uniting control, throw-and-catch control, supervisory control, and event-triggered control.
  - Applications: aggressive control for aerial vehicles, control of the pendubot, obstacle avoidance, control of robotic manipulators.
- **Part 4: Synergistic control, CLF-based control, invariance-based control, passivity-based control, and hybrid model predictive control**
  - Theoretical topics: synergistic control, control Lyapunov functions, stabilizability, Sontag-like universal formula for hybrid systems, selection theorems, invariance and invariance-based control, passivity-based control, and hybrid model predictive control.
  - Applications: control for DC/DC conversion and for mechanical systems with impacts.

References available at https://hybrid.soe.ucsc.edu/biblio and 2021 Princeton University Press book “Hybrid Feedback Control”.



M15 ROME
16/06/2025 - 20/06/2025

## *Dynamic Control Allocation*

## Abstract

Several modern control applications involve a large number of actuators and sensors, typically chosen with the objective of ensuring a certain level of redundancy and reliability. Such a redundancy is a challenge as well as a valuable opportunity for the designer. The aim of this course is to introduce the student to the framework of dynamic control allocation, which constitutes an effective strategy for addressing and tackling such scenarios. In particular, the topics discussed in the course range from the analysis of allocated control schemes (with points of view borrowed from different contexts, such as geometric tools or frequency-domain approaches) to detailed synthesis algorithms (based on advanced hybrid and optimization techniques or viable also in the presence of uncertain systems). Moreover, links to intimately connected topics, such as optimal control, anti-windup control, and the output regulation problem, are introduced and further explored.

The lectures will take place in Villa Mondragone (Monte Porzio Catone), a beautiful 1573 villa just outside Rome, which is the congress and event center of Tor Vergata University.

## Outline

**I. Introduction to Dynamic Control Allocation**

1. Motivating examples
2. Objectives and main assumptions
3. Characterization of input redundancy

**II. Dynamic Control Allocation Framework**

4. Main control scheme
5. Complementarity with anti-windup techniques
6. Comparison with static control allocation

**III. Structural Insights on Allocated Control Schemes**

7. The geometric control point of view
8. The frequency-domain approach
9. Connections with optimal control and the output regulation problems
10. Revisiting the key building blocks: annihilators, optimizers and steady-state generators

**IV. Advanced Topics**

11. MPC-based strategies and reference governor
12. Hybrid control allocation for output regulation
13. Data-driven control allocation
14. Extensions to nonlinear systems

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# 2025
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| M16 OXFORD<br>16/06/2025 - 20/06/2025 | *The Scenario Approach: Data Science for Systems, Control and Machine Learning* |
|---|---|

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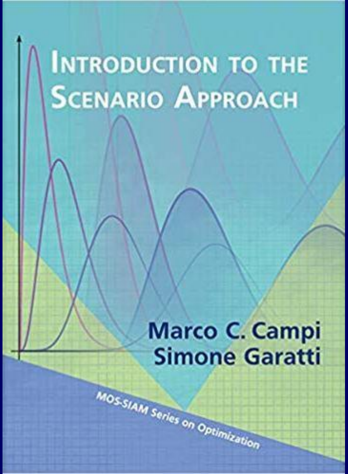
## Abstract of the course

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, data-driven system design and control). We also present the most recent developments of its powerful generalization theory, which allows the user to accurately evaluate the out-of-sample robustness and keep control on the risk associated with the data-driven solution.

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
- Data-driven design
- Risk evaluation
- Application to systems, control and supervised learning
- Presentation of open problems that offer an opportunity for research

# 2025
# International Graduate School on Control

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**M17 PARIS-SACLAY**
**23/06/2025 - 27/06/2025**

## *Introduction to Nonlinear Systems and Control*

**Hassan Khalil**
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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.

The course is designed around the text book:
H.K. Khalil, Nonlinear Control, Pearson Education, 2015

### Outline

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

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**M18 DUBROVNIK**
**30/06/2025 - 04/07/2025**

## *Control and Machine Learning*

### Summary of the course

Control is a classical field in the intersection of Applied Mathematics and Engineering, arising in most applications to other sciences, industry and new technologies. Nowadays the field of Control experiences a revival due to its strong links with the broad and dynamic field of Machine Learning (ML). On the one hand, classical mathematical and computational methods developed in Control are complemented with new techniques emanating from ML, thus improving their performance. On the other hand, the, sometimes amazing, efficiency of the computational methods developed in ML, e.g. in Supervised and Reinforcement Learning, is not yet well understood analytically. And the knowledge accumulated over decades in the area of Control provides powerful tools to gain understanding.

This course is aimed to introduce some of the fundamental tools in control theory and machine learning and their computational counterparts, showing how they can be combined and employed to address applications efficiently, in an holistic manner, interrogating the know-how in each of these areas.

### Outline

- Historical preliminaries
- Control of linear finite-dimensional systems
- Control of parameter dependent problems
- Neural ODEs
- Control formulation of supervised learning
- The universal approximation theorems
- Simultaneous controllability of neural differential equations
- Width versus depth
- Introduction to unsupervised learning
- Introduction to federated learning
- ML in control of parameter dependent systems
- Turnpike, control, and ML
- Introduction to Physics-Informed Neural Networks (PINNs)
- Solving differential equations by PINNs.

Theoretical presentations will be combined with practical numerical exercises .

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**Martin Lazar**
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# 2025
# International Graduate School on Control

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**M19 MILAN**
**30/06/2025 - 04/07/2025**

## *Deep Learning for System Identification*

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### Summary of the course

In recent years, deep learning has advanced at a tremendous pace and is now the core methodology behind cutting-edge technologies such as image classification and captioning, autonomous driving, natural language processing and generation. One exciting and challenging application field for deep learning is the learning of dynamical systems, also known as system identification. In this field, tailor-made model architectures and fitting criteria should be designed to: retain structural physical knowledge when available; introduce regularization to avoid overfitting or enforce known relationships among variables; and optimize training efficiency by leveraging parallelization as much as possible. The objective of this course is to introduce deep learning concepts and recently developed tools for system identification. The course combines theoretical lectures and hands-on practical sessions in PyTorch.

### Outline

1. Introduction to system identification and deep learning
2. Feedforward and recurrent neural networks for system identification
3. Numerical optimization algorithms for training neural networks
4. Neural state space models
5. Integrating system theory in deep learning

### Target audience

Students, researchers, and practitioners who want to understand how complex system identification problems can be formulated and solved using modern deep learning techniques.

Basic knowledge of Python can be beneficial to better follow hands-on practical sessions.