## International Graduate School on Control

**Independent Graduate Modules**— one 21 hours module per week (3 ECTS)

**Deadline for advance registration to each module:** 20/12/2013

**Locations:** Belgrade (Serbia), Hangzhou (China), Istanbul (Turkey), L’Aquilla (Italy), Paris <Gif-sur-Yvette> or Grenoble (France), St Petersburg (Russia)

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Abstract of the course

The sliding mode methodology has been proved to be effective in dealing with complex dynamical systems affected by disturbances, uncertainties and un-modelled dynamics. Robust controllers can be developed exploiting the well known insensitivity properties of sliding modes to so-called matched uncertainties. These robustness properties have also been exploited in the development of nonlinear observers for state and unknown input estimation. In conventional sliding modes a 'switching function' (typically an algebraic function of the states) is forced to zero in finite time and maintained at zero for all subsequent time. However, more recently so-called higher-order sliding modes have been developed to force the switching function and a number of its time derivatives to zero in finite time.

The course will begin with an introduction to conventional sliding modes - typically for uncertain linear systems and will demonstrate the properties exhibited by sliding mode controllers and observers. The course will then examine more recent developments in terms of higher-order sliding modes - particularly 2nd order sliding modes. Throughout the course a number of practical engineering examples will be considered to demonstrate the features and advantages of using sliding modes. The results of implementations of these ideas will be presented and discussed. In addition several detailed case studies will be presented demonstrating the use of sliding mode ideas for fault detection and fault tolerant control in aerospace systems.

Topics will include:
- a motivating overview of sliding modes and their properties
- conventional sliding mode controllers and their design for uncertain linear systems
- conventional sliding mode observers and their properties
- 2nd order sliding mode controllers and observers
- general higher-order controllers and differentiators
- sliding modes for fault detection and fault tolerant control
- aerospace case studies
Abstract of the course:

Uncertain optimization is ubiquitous, and application domains range from robust and predictive control to management, from decision-making to quantitative finance. In this course, the student will be introduced to sample-based methods for uncertain optimization, where uncertainty is described by means of a finite number of cases extracted from the normally infinite set of possible uncertainty outcomes. Samples can as well be observations, and this covers data-based approaches in learning and identification. Particular emphasis will be given to the scenario approach, which is a key methodology in this context to obtain valid solutions in a variety of optimization problems involving uncertainty.

The presentation will be gradual to allow an in-depth understanding of the fundamental concepts. Special attention will be given to a precise mathematical formulation of the problems and to a detailed presentation of the ensuing results. Practical examples will illustrate the ideas.

Topics:
- Uncertain optimization
- Monte-Carlo sampling
- Scenario approach
- Applications to various domains
- Discussion of open problems that offer an opportunity for research
Randomized Algorithms for Systems, Control and Networks

Abstract of the course

In this course, we provide a perspective of the research area of randomization for systems, control and networks. In particular, we study several topics which are of interest when dealing with control of uncertain systems and networks described by graphs.

In these lectures, we demonstrate that randomization is a key tool to handle systems and control problems which can be solved only approximately due to partial or contaminated data, or because only local information about the network is available. Various techniques are developed to construct synchronous and asynchronous sequential algorithms for analysis and design. Convergence and optimality properties of these randomized algorithms are subsequently analyzed.


Topics:
- Uncertain systems, networks and graphs
- Monte Carlo and Las Vegas algorithms
- Random sampling techniques
- Probabilistic methods for control design
- Distributed randomized algorithms
Abstract of the course:
The magnitude of the signal that an actuator can deliver is usually limited by physical or safety constraints. This limitation can be easily identified in most common devices used in the process industry, such as proportional valves, heating actuators, power amplifiers, and electromechanical actuators. Common examples of such limits are the deflection limits in aircraft actuators, the voltage limits in electrical actuators and the limits on flow volume or rate in hydraulic actuators. While such limits obviously restrict the achievable performance, if these limits are not treated carefully and if the relevant controllers do not account for them appropriately, peculiar and pernicious behaviors may be observed (aircraft crashes, Chernobyl nuclear power station meltdown).

This course addresses stability analysis and stabilization of linear systems subject to control saturation. We will discuss a first approach consists in designing a (possibly nonlinear) controller directly accounting for the saturation constraints. Then we will present the so-called anti-windup approach, where an anti-windup augmentation is inserted on an existing control system which "winds up" (performs undesirably) due to actuator saturation. The anti-windup feature is then to preserve the predesigned controller before saturation is activated and to recover stability for larger saturated responses. Anti-windup solutions differ in architecture and performance achievements. We will discuss several architectures suited for different saturation problems. Several applications will be used to illustrate the presented techniques.

Topics: Rate and magnitude saturation, standard and generalized sector conditions, stability and performance analysis with saturation, linear LMI-based controller and anti-windup designs, linear and nonlinear model recovery anti-windup design, applications
Abstract of the course:

In the 1960s, it was realized that many physically relevant problems of optimal control were inappropriately formulated in the sense that the optimum control law (a function of time and/or state) cannot be found if the admissible functional space is too small. This motivated the introduction of many concepts of functional analysis in control engineering, building up on the advances on mathematical control theory and calculus of variations. When formulated in a larger space, the decision variables are Borel measures subject to a finite number of linear constraints: the initial optimal control problem becomes a standard problem of moments. However, this approach is not frequently used by engineers, and in our opinion this may have been due to two main reasons. The first one is the technicality of the underlying concepts of functional analysis whereas the second one has been the absence (up to very recently) of numerical methods to deal satisfactorily with optimization problems in large functional spaces such as Banach spaces of measures.

Recent achievements of real algebraic geometry have provided powerful results for the representation of positive polynomials and its dual theory of moment problems. Moreover, such representation results are amenable to practical computation via linear matrix inequalities (LMIs) and semidefinite programming, a powerful technique from convex conic optimization. The conjunction of those two factors now provides the basis for a systematic and quite general methodology to solve moment problems with polynomial and semi-algebraic data.

The main purpose of this course is to introduce the basic concepts of this general methodology and detail its application for solving optimal control problems.
Abstract of the course

Quantum control is an emerging research subject with an increasing role in technologies related to high precision metrology, quantum information and communication. This course presents some modern tools for controlling quantum systems and taking into account the intrinsic invasive character of measurements. These tools will be illustrated by recent feedback experiments in cavity and circuit quantum electrodynamics to prepare and protect quantum states from decoherence (dissipation of quantum information through the coupling of the system to its uncontrolled environment). The context throughout is that of systems of ordinary and stochastic differential equations and the level will be that of a graduate course intended for a general control audience without any prerequisites in quantum mechanics.

Topics:
1. Introduction to quantum mechanics based on the two-level system (quantum bit) and the harmonic oscillator.
3. Stabilization scheme relying on measurement-based feedback and Lyapunov techniques.
4. Stabilization scheme relying on coherent feedback and reservoir (dissipation) engineering.
Abstract of the course

The aim of this course is to present a detailed analysis of the problems encountered in designing embedded control systems from different perspectives: Control, RT implementation, interaction, deployment and validation.

Outline

Motivation and examples
Embedded systems (ES). Embedded control systems (ECS). Motivating examples

Main issues in the design of ECS

RT issues (RT perspective)
- Reactive / interactive
- CPU management
- Pre-defined working conditions
- Fault tolerance management

Control issues (Control perspective)
- Time delays counteraction
- Missing data
- Degraded control. Reconfiguration
- Fault detection

Integrated control design and implementation (Joint perspective)
- Effects of sampling interval and sampling jitter on performance
- Mode changes: Switching-induced instabilities
- Control Server Model

Kernels and safe (back-up) operation
- Control kernel (basic control algorithms)
- OS functions and kernel. Options

ECS Deployment
- Analysis tools
- OS components selection and loading
- Cross-compiling for the target CPU
- Verification and validation

ECS Deployment and validation (Platform)
- Problem statement
- OS components selection and loading
- Testing and validation

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Stability and Control of Time-delay Systems

Abstract of the course:
Time-delays are important components of many systems from engineering, economics and the life sciences, due to the fact that the transfer of material, energy and information is mostly not instantaneous. They appear, for instance, as computation and communication lags, they model transport phenomena and heredity and they arise as feedback delays in control loops. The aim of this course is to describe fundamental properties of systems subjected to time-delays 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, matrix distance problems) and optimization. Several examples (from chemical to mechanical engineering, from tele-operation to high-speed networks, from biological systems to population dynamics) complete the presentation.

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

Computational methods:
• Stability determining eigenvalues
• Stability domains in parameter spaces
• Robustness and performance measures
• Controller synthesis via eigenvalue optimization

Control design:
• Fundamental limitations induced by delays
• Fixed-order optimal H-2 and H-infinity controllers
• Prediction based controllers
• Using delays as controller parameters
Abstract of the course

In the 1990s, the recursive backstepping design revolutionized robust nonlinear control, enabling stabilization of systems with uncertain nonlinearities unmatched by control and of unlimited growth. In the 2000s, taking the backstepping recursion to the continuous limit produced a similar design methodology for boundary control of PDEs and for delay systems. This course starts with an introduction to control of PDEs based on the book *Boundary Control of PDEs: A Course on Backstepping Designs* (2008), continues on with a specialization of such control designs to nonlinear delay systems based on the new book *Nonlinear Control Under Nonconstant Delays* (2013), and culminates with methods for implementing such controllers over communication networks with sampled measurements, large and uneven communication delays and sampling times, and using finite-dimensional approximations of the feedback laws, based on the upcoming book *Sampled-Data and Approximate Predictors for Nonlinear Delays systems*.

Topics

Lyapunov stability for PDEs; boundary control of parabolic (reaction-advection-diffusion) PDEs; first-order hyperbolic (transport-dominated) PDEs; systems with input delay and predictor feedback; delay-robustness of predictor feedback; time-varying input delay; delay-adaptive predictor feedback; stabilization of nonlinear systems with long input delays; dynamic output predictor feedback; predictor feedback with sampled/delayed measurements and ZOH; approximate predictors; predictor feedback for discrete-time systems.

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Abstract of the course: This course will focus on arbitrated network control systems and control/platform co-design, both of which are prevalent in settings where multiple control applications are implemented on a distributed embedded platform. Such embedded platforms typically consist of multiple processors communicating over a system made up of several buses and gateways implementing different protocols, and are often present in the context of automotive cyber-physical architectures that consist of about 100 ECUs (electronic control units) connected through multiple buses such as FlexRay, CAN and Ethernet. With increasing complexity in the communication, computation, and memory components of the implementation platform, there needs to be a tight interaction between the cyber and physical worlds so as to reduce testing and debugging costs and optimize resource utilization. In many of the distributed architectures of interest, the underlying questions necessitate arbitration of control messages (e.g., how to time, queue, or map the control tasks) with a synergistic design of the underlying implementation architecture (e.g. how to choose the various bus protocols, how many ECUs, how should they be connected, how should the slots be sized, what should the processor speeds be, etc.). Such a co-design of control and platform can result in a better control performance with optimal resource utilization rather than using the properties of the platform in the control design. This course will provide an introduction to arbitrated network control systems and the control-platform co-design.

Topics include:

- Fundamentals of computer-controlled systems
- Examples of arbitration in distributed embedded systems
- Communication-aware co-design
- Computation-aware co-design
- Examples and case studies
Abstract of the course:
Goal of this course is to present a class of recently developed control tools for the robust stabilization, by state and output feedback, of classes of nonlinear systems. These new tools enable to give an alternative formulation and solution to the stabilization problem for general nonlinear systems by means of the notions of systems immersion and manifold invariance (I&I). I&I methods are particularly suited to robustify, with respect to unmodelled dynamics, a given controller scheme. They have also proved useful in adaptive control problems, where a stabilizing controller parameterized in terms of some unknown constant vector is assumed to be known. Adaptive control applications will be the main focus of this workshop.

The proposed I&I approach, which is partly reminiscent of early contributions in the area of PI adaptation, is shown to yield superior performance, when compared with classical methods, and to provide improved design flexibility and additional tuning parameters. Moreover, this approach does not require linear parameterization, it can naturally include sign constraints in the estimated parameters, and yields a new class of non-certainty equivalent control laws. From a Lyapunov perspective this is the first systematic method to construct non-separable Lyapunov functions, i.e. Lyapunov functions containing cross terms depending upon the system state and the parameters estimation error, without assuming a specific structure of the nonlinear system to be controlled. The theory is illustrated by means of applications and experimental results. In particular, solutions to the adaptive stabilization problem for classes of power converters and electrical machines and for the problem of visual servoing of a planar robot are discussed.

Topics include:
- State feedback stabilization and adaptive control via immersion and invariance
- Output feedback adaptive control via immersion and invariance
- Applications in adaptive control
- Applications to electromechanical systems
- Open problems
**Abstract of the course:**

Model Predictive Control (MPC) is a model-based method which uses online optimization in real time to determine control signals. It is the only practical control method that takes account of system constraints explicitly, and the only ‘advanced control’ method to have been adopted widely in industry, particularly in petrochemicals and other process industries. There is intense interest in it for a variety of other applications, including automotive, aerospace, electric drives, smart grid and paper-making. This course covers the theory from basics through to current research concerns, as well as practical aspects. It includes exercises based on the *Model Predictive Control Toolbox for Matlab*. The course has been given in various universities since 2001, and has recently been comprehensively revised and updated.

The course is based on the textbook *Predictive Control with Constraints*, J.M. Maciejowski, Prentice-Hall, 2002.

**Topics:**

- Alternative formulations of MPC
- Solution methods for MPC
- Stability and recursive feasibility
- Tuning MPC and reverse engineering
- Robust MPC
- Explicit MPC
- Case studies and applications
Abstract of the course

The course is an Introduction to nonlinear system analysis and the design of nonlinear feedback control. It 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, Prentice Hall, 2014

Topics

1. Introduction and second-order systems (nonlinear phenomena; phase portraits; multiple equilibrium points; limit cycles)
2. Stability of equilibrium points (basics concepts; linearization; Lyapunov’s method; the invariance principle; 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; small-gain theorem; Circle & Popov criteria)
6. Normal, controller, and Observer 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)
10. Output feedback stabilization
11. Tracking & regulation (trajectory planning; feedback linearization; sliding mode Control; integral control)
Abstract of the course

Observers are objects delivering estimation of variables which cannot be directly measured. The access to such "hidden" variables is made possible by combining modeling and measurements. But this is bringing face to face real world and its abstraction with as a result the need for dealing with uncertainties. The corresponding theoretical observers are consequently very complex and sometimes almost impossible to implement. This implies that approximations and simplifications are involved with, as a consequence, convergence problems.

Topics
1. Observation problem in full generality and theoretical answers
2. Necessary conditions for convergence
3. Sufficient conditions for convergence
Abstract of the course
Technological developments have led to a new, exciting and powerful synthesis of physics and control, building on the classical work of notable physicists such as Huygens, Carnot, Szilard, and Kapitza. Examples as diverse as managing electric power grids and optimizing inputs for magnet resonance spectroscopy, noise cancellation and vibration technologies are among topics of current interest. Of course, most of these interesting problems fall well outside the usual linear, quadratic, Gaussian framework.

In this course, the unifying principles coming from the consideration of energy, momentum, and reduction principles will be extended to include control terms. Emphasis will be placed on the role of geometrical ideas such as metrics, symplectic structures, Poisson and Lie brackets, etc., when they serve to best explain matters. Examples will be drawn from cyber-physical systems of current interest and the type of control mechanisms that have proven to be effective in this setting.

Topics will include:
Control of conservative systems; Control of dissipative systems; Synchronization and control of chaos; The Lyapunov-Krasovskii functionals and Demidovich condition; Statistical Mechanics and Learning Theory, Quantum control and Quantum information.
Abstract of the course:

Over the past decade there has been growing interest in distributed control problems of all types. Among these are consensus and flocking problems, the multi-agent rendezvous problem, distributed averaging and the distributed control of multi-agent formations. The aim of these lectures is to explain what these problems are and to discuss their solutions. Related concepts from spectral graph theory, rigid graph theory, nonhomogeneous Markov chain theory, stability theory, and linear system theory will be covered.

Topics include:

1. Flocking and consensus
2. Distributed averaging via broadcasting
3. Gossiping and double linear iterations
4. Multi-agent rendezvous
5. Control of formations
6. Contraction coefficients
7. Convergence rates
8. Asynchronous behavior
9. Stochastic matrices, graph composition, rigid graphs
Abstract of the course

The aim of the mini-course is two-folds. In the first part we will introduce basic notions, tools, and results of geometric control theory. We will discuss the concepts of controllability, observability, decoupling, and equivalence in the context of nonlinear control systems. We will recall and/or introduce geometric tools on which the theory is based (Lie brackets, distributions and co-distributions, integral manifolds, Frobenius theorem etc.).

In the second part, we will present more recent results concerning equivalence of control systems under state-space equivalence, feedback equivalence, and dynamic equivalence.

In particular, we will discuss feedback linearization, equivalence of control-linear systems to the chained forms (and their applications to nonholonomic systems), flatness, and describe control systems that admit a mechanical structure.

Throughout the mini-course we will emphasize the geometric character of the nonlinear control theory and its applications to various control synthesis problems (stabilization, tracking, nonlinear observers). We will illustrate the course by physical, mainly mechanical, examples.

Topics
1. Geometric tools of nonlinear control (Lie bracket, distributions, Frobenius theorem).
2. Nonlinear controllability (Lie rank, orbit theorem, Chow-Rashevsky theorem, accessibility).
3. Nonlinear observability (Krener-Hermann theorem, observable/nonobservable decomposition)
4. Controlled invariant distributions, nonlinear decoupling, and zero dynamics
5. State-space, feedback and dynamic equivalence of control systems. State-space and feedback linearization.
6. Nonholonomic systems and control-linear systems equivalent to the chained forms
7. Flatness and flat control systems.
8. Mechanical control systems.
Hybrid control systems arise when controlling nonlinear systems with hybrid control algorithms — algorithms that involve logic variables, timers, computer program, and in general, states experiencing jumps at certain events — and also when controlling systems that are themselves hybrid. Recent technological advances allowing for and utilizing the interplay between digital systems with the analog world (e.g., embedded computers, sensor networks, etc.) have increased the demand for a theory applicable to the resulting systems, which are of hybrid nature, and for design techniques that may guarantee, through hybrid control, performance, safety, and recovery specifications even in the presence of uncertainty. This course will present recent advances in the analysis and design of hybrid control systems from a control theory viewpoint. The power of hybrid control for robust stabilization will be displayed in several applications including power systems, robotic networks, underactuated rigid bodies, integrate-and-fire oscillators, neurons, and genetic networks.

Topics include:

- Dynamical modeling of hybrid systems
- Asymptotic stability, invariance, and robustness
- Lyapunov functions and control Lyapunov functions
- Tracking control
- Passivity-based control
- Minimum-norm control
Adaptive control and adaptive regulation have known an important development in the recent years motivated on one hand by the need to maintain performances in a changing environment and on the other hand as a consequence of the methodological and algorithmic research. Adaptive control appears today as a loop which is added on top on a robust designed control system allowing to achieve better performance in the presence of large plant and disturbance uncertainties. Adaptive regulation provides very efficient solutions for the rejection of unknown and time varying disturbances like vibration suppression in mechanical systems and noise attenuation (cars, planes, machine tools, ..).

In this course the basic principles, the algorithms and the analysis of modern adaptive control will be covered. The presentation will be made in connection with a number of adaptive control applications and bench tests located at GIPSA-LAB Grenoble.

**Topics:**
- Introduction to Adaptive Control
- Parameter Adaptation Algorithms
- Review of System Identification and Robust Digital Control
- Iterative identification in closed loop and controller re-design
- Direct and Indirect Adaptive Control
- Parameter estimators for adaptive control
- Adaptive control with multiple models
- Adaptive regulation (feedback disturbance rejection)
- Adaptive feeforward compensation of disturbances
Abstract of the course
With the increasing stringency of fuel efficiency and emissions regulations, significant opportunities now emerge to improve engine performance through judicious applications of advanced (by industry standards), model-based control. This course will provide an introduction to modeling, estimation and control for engines and powerplants in automotive applications, and a perspective on related problems in aerospace applications. The use of control-theory based and model-based approaches will be emphasized, and techniques based on applications of input observers, adaptive and nonlinear control, optimal control, and Model Predictive Control will be illustrated.

Topics will include:

1. Overview of engine control functionalities
2. Naturally aspirated gasoline engine modeling
3. Air charge estimation and control
4. Idle speed and air-to-fuel ratio control
5. Turbocharged diesel engine modeling and control
6. Control problems in boosted gasoline engines
7. Hybrid Electric Vehicles and their energy management
8. Model Predictive Control and its automotive applications
9. Automotive diagnostics
10. Aircraft gas turbine engines: modeling and control
11. Topics in control of advanced engines (HCCI, free piston engines, etc.) – as time permits