



COURSE DESCRIPTION CONTROL OF COMPLEX SYSTEMS AND NETWORKS

SSD: AUTOMATICA (ING-INF/04)

DEGREE PROGRAMME: INGEGNERIA DELL'AUTOMAZIONE E ROBOTICA (P38)
ACADEMIC YEAR 2022/2023

COURSE DESCRIPTION

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GENERAL INFORMATION ABOUT THE COURSE

INTEGRATED COURSE: U2326 - ADVANCED CONTROL ENGINEERING
MODULE: U2327 - CONTROL OF COMPLEX SYSTEMS AND NETWORKS
CHANNEL: FG A-Z
YEAR OF THE DEGREE PROGRAMME: II
PERIOD IN WHICH THE COURSE IS DELIVERED: SEMESTER II
CFU: 6

REQUIRED PRELIMINARY COURSES

None

PREREQUISITES

Basic knowledge about closed loop control systems.

LEARNING GOALS

The course aims at providing students with a set of tools for the analysis and control of networks of dynamical systems, with a special emphasis on their optimization and safety, and on their possible use for the design and management in diverse engineering applications.

EXPECTED LEARNING OUTCOMES (DUBLIN DESCRIPTORS)

Knowledge and understanding

The students need to acquire the main methodological tools to model, analyze and control complex systems, with a special emphasis on those that can be described as networks of interconnected dynamical systems. The lectures will guide the students towards a) the

comprehension of the links between the topological properties of the graph and the individual dynamics of the nodes, and b) the identification of the causal mechanisms determining the spontaneous emergence of collective behaviors, such as consensus and synchronization. The analytical and numerical tools acquired by the students will be then used to understand the specificities of control design for network systems.

Applying knowledge and understanding

The students need to be capable of applying the acquired methodology to model and analyze real systems that can be described by complex network models, as for instance wireless sensor networks, population dynamics, or formation of autonomous vehicles. Furthermore, the students will need to showcase the ability to apply the control techniques that they learned to design controllers for complex systems in the presence of constraints on the number of input signals and observable nodes.

COURSE CONTENT/SYLLABUS

Part 1 Introduction and background

1 Introduction

1.1 Definition of a complex system

1.2 Complex networks of dynamical systems

1.3 Examples: wireless sensor networks and compartmental models

2 Elements of matrix theory

2.1 Convergent and semi-convergent matrices; eigenvalue classification

2.2 Spectral properties of stochastic matrices

2.3 Geršgorin disks theorem

2.4 Perron-Frobenius theorem

2.5 Examples

Part 2 Graph theory

3 Elements of graph theory

3.1 Directed and undirected graphs

3.2 Main definitions

3.3 Paths, connectivity, and periodicity

3.4 Condensation graphs

3.5 Weighted graphs

3.6 Adjacency matrix

4 Linking graphs and matrices

4.1 Properties of the adjacency matrix

4.2 Some elementary equivalences

4.3 Paths in the graph and powers of the adjacency matrix

4.4 Graphs and irreducible matrices

4.5 Graphs and primitive matrices

Part 3 Analysis and control of networks of linear dynamical systems: the consensus problem

- 5 Discrete-time consensus problem
 - 5.1 Networks of discrete-time integrators
 - 5.2 Definition of consensus: min-max consensus, average consensus
 - 5.3 Condition on the graph topology for consensus in time-invariant networks
 - 5.4 Example: Leslie's population model
- 6 Continuous-time consensus problem
 - 6.1 Laplacian matrix of a graph: definition and properties
 - 6.2 Example: modeling collective dynamics in animal groups
 - 6.3 Network of continuous-time integrators
 - 6.4 Rank of the Laplacian matrix and equilibria in the network system
 - 6.5 Globally reachable nodes and consensus emergence
 - 6.6 Condition on the graph topology for consensus in time-invariant networks
- 7 Convergence rates
 - 7.1 One-step convergence factor
 - 7.2 Asymptotic convergence factor
 - 7.3 Linking convergence rates and graph topology
- 8 Consensus problems on time-varying graphs
 - 8.1 Examples of network systems on time-varying graphs
 - 8.2 Convergence over time-varying graphs connected at all times
 - 8.3 Convergence over time-varying graphs connected over time
- Part 4 Networks of nonlinear dynamical systems: synchronization**
- 9 Networks of nonlinear dynamical systems
 - 9.1 Modeling and fundamental assumptions
 - 9.2 Standard model of a network dynamical systems
 - 9.3 Example
- 10 Synchronization
 - 10.1 Definition
 - 10.2 Example: Kuramoto oscillators
 - 10.3 Lyapunov-based stability analysis
 - 10.4 Sufficient conditions for synchronization
 - 10.5 Assumption on the node vector field and graph topology
- Part 5 Control of networks of nonlinear dynamical systems**
- 11 Decentralized control of networks of nonlinear systems
 - 11.1 Centralized vs decentralized control
 - 11.2 Controllability of network systems
 - 11.3 Pinning control
 - 11.4 Partial control of networks
- 12 Emerging problems and advanced network control techniques
 - 12.1 Elements on adaptive control of complex networks
 - 12.2 Control of networks with state-dependent topology
 - 12.3 Coevolution of graph topology and node states
 - 12.4 Emerging applications

READINGS/BIBLIOGRAPHY

- F. Bullo, Lectures on Network Systems, Edizione 1.3, 2019.
 - M. E. J. Newman, A. L. Barabasi, and D. J. Watts, The structure and dynamics of networks, Princeton University Press, 2006.
 - Additional references and lecture notes available in the tab file of the Teams class of the module
- Further reading and material:
- Siljak, D. D. Decentralized control of complex systems. Courier Corporation, 2011.
 - A. Barrat, M. Barthelemy, A. Vespignani, Dynamical Processes on Complex Networks, Cambridge University Press, 2008.
 - Uri Alon lab dataset. Available at <http://www.weizmann.ac.il>
 - Pajek's dataset Available at: <http://vlado.fmf.uni-lj.si/pub/networks/data>

TEACHING METHODS OF THE COURSE (OR MODULE)

The teaching activities will be organized as follows: a) lectures for about 70% of the total hours, b) practical exercise in the classroom based on software tools (Matlab-simulink) for about 30% of the total hours.

EXAMINATION/EVALUATION CRITERIA

a) Exam type

- Written
- Oral
- Project discussion
- Other

In case of a written exam, questions refer to

- Multiple choice answers
- Open answers
- Numerical exercises

b) Evaluation pattern

The oral exam is focused on the discussion of a homework assigned to the student by the instructor. The oral examination will also aim at assessing the knowledge of all the concepts and contents given during the lectures.