Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Distributed/Decentralized Control and Optimization of Large-Scale Systems
Scientific Discipline Sector	ING-INF/04
Hours of instruction	10 hours
CFU	1 credit (ECTS)
Semester	Second
Goal	This course aims at providing PhD students with modeling and methodological tools for formulating and solving large-scale optimization problems with a focus on the use of duality theory. During the course several optimization problems will be formalized, particularly referred to relevant issues within management and industrial engineering. Problem definition and resolution will be also implemented in simulation and engineering software (Matlab). The final goal is to provide PhD students with the necessary background for starting research in the field of duality-based decentralized and distributed optimization techniques to be applied to large-scale systems. Each lesson consists in lectures, numerical examples, simulation and analysis of case studies.
Syllabus	Systems schemes and architectures: centralized and non-centralized approach. Preliminaries on unconstrained and set constrained optimization and basics on convex optimization. Duality (Lagrange multipliers theory) and duality based algorithms: waterfilling, dual ascent method (DAM), Augmented Lagrangian Method (ALM), Alternating Direction Method of Multipliers (ADMM). Decentralized optimization problem set up and duality-based methods: DAM, ALM, and ADMM for separable convex programming. Distributed optimization problem set up and duality-based methods: distributed DAM, distributed ADMM, distributed waterfilling. Motivating examples and case studies.
Bibliography	Recommended books: • Bertsekas, D. P., & Tsitsiklis, J. N. (1989). Parallel and distributed computation: numerical methods (Vol. 23). Englewood Cliffs, NJ: Prentice Hall • Boyd S. & Vandenberghe L., Convex Optimization, Cambridge University Press, UK, 2004. Slides and supporting material from lecturer.
Examination method	End-course examination based on a test.

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Non-integer order systems and controllers
Scientific Discipline Sector	ING-INF/04
Hours of instruction	10 hours
CFU	1 credit (ECTS)
Semester	Second
Goal	The course concerns non-integer-order systems. These systems can propose engineering solutions to modeling and control problems that often improve those based on integer-order calculus. Basic tools of fractional calculus are introduced, and some methods and models are described for different engineering fields. Models for practical applications are proposed. Moreover, approaches to design and realize non-integer-order (fractional-order) controllers are described. These controllers show higher flexibility, increased robustness, and ability to obtain a better trade-off between stability and dynamic performance with respect to widespread PID controllers. As case-studies, the course uses applications in automotive and mechatronic systems.
Syllabus	- Introduction to fractional calculus and non-integer-order (fractional-order) systems - Modeling of non-integer-order systems - Models for automotive and mechatronic applications - Non-integer-order (fractional-order) controllers: types, design, tuning, realization, fundamental properties, simulation, experimental validation - Non-integer-order (fractional-order) controllers for some applications

Bibliography	- R. Caponetto, G. Dongola, L. Fortuna, I. Petráš, Fractional Order Systems: Modeling and Control Applications. Singapore: World Scientific, 2010. - C. A. Monje, Y. Q. Chen, B. M. Vinagre, D. Xue, V. Feliu, Fractional-order Systems and Controls: Fundamentals and Applications. London, UK: Springer-Verlag, 2010. - Some reference papers.
Examination method	Discussion of a modeling or control problem, also by using simulation software tools (Matlab/Simulink).

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Deep Reinforcement Learning for Control of Autonomous Systems
Scientific Discipline Sector	ING-INF/04
Hours of instruction	10 hours
CFU	1 credit (ECTS)
Semester	First/Second
Goal	Reinforcement learning deals with solving sequential decision problems when minimal prior information is available. Solving sequential decision problems means finding their optimal control policies. Using reinforcement learning algorithms, the optimal policy is learned through the cooperation between the agent (or controller) and the system to be controlled. Deep Reinforcement Learning (DRL) is a subfield of machine learning that combines reinforcement learning (RL) and deep learning. The course will propose the main modeling frameworks, investigate the most relevant deep reinforcement learning techniques and show some interesting applications.
Syllabus	- Markov chains: definition, properties and application. - Introduction to Reinforcement Learning and Deep Reinforcement Learning: states, actions, policies, reward, observations; - Real-word examples and implementation in engineering tools (e.g.,Python, Matlab)
Bibliography	- Vincent François-Lavet, Peter Henderson, Riashat Islam, Marc G. Bellemare and Joelle Pineau (2018), "An Introduction to Deep Reinforcement Learning", Foundations and Trends in Machine Learning: Vol. 11, No. 3-4, pp 219-354. - Scientific papers.
Examination method	Final examination in class

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Control and Security of Cyber Physical Systems
Scientific Discipline Sector	ING-INF/04
Hours of instruction	10 hours
CFU	1 credit (ECTS)
Semester	First/Second
Goal	The aim of the course is to show the importance of control and security in Cyber Physical Systems (CPSs). CPSs are systems where a decision making(cyber/control)component is tightly integrated with a physical system(with sensing/actuation) to enable real-time monitoring and control. Therefore, control and security are crucial issues for commissioning these systems and for improving competitiveness of companies. In this context, the study of opacity is a fundamental notion to determine if an industrial "secret" can be discovered by a malicious observer (intruder).
Syllabus	The course includes the following four main sections: 1)Industry 4.0 – Introduction and innovations for the industrial companies. 2)Cyber physical system and cloud computing system: examples of architectures with integrated control components. 3)Control strategies in a Cloud computing system (distributed task assignment, consensus, etc.). 4)Opacity notion, models and algorithms to defend crucial information by intruder attacks.
Bibliography	Scientific papers.
Examination method	Final examination in class

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Simulation Systems for Engineering Applications
Scientific Discipline Sector	ING-INF/04
Hours of instruction	10 hours
CFU	1 credit (ECTS)
Semester	Second
Goal	The course shall address the basis of simulation techniques for engineering applications, with a focus on the underlying mathematical formalism. At end of this course students will be able to deal with system modeling and to implement simulation models in engineering tools (e.g., Python, Matlab). Each lesson shall consist in lecture and numerical examples.
Syllabus	- Recapitulation of fundamental algebraic concepts: vector, matrices, vector spaces;- Systems vs Models: fundamentals of dynamical modelling; - Networks and Graphs: algebraic properties and applications; - Applicative examples from literature: analysis and implementation in engineering tools (e.g., Python, Matlab)
Bibliography	- Boyd, S., & Vandenberghe, L. (2018). *Introduction to applied linear algebra: vectors, matrices, and least squares*. Cambridge university press. - Boyd, S. P., & Vandenberghe, L. (2004). *Convex optimization*. Cambridge university press. - Kluever, C. A. (2020). *Dynamic systems: modeling, simulation, and control*. John Wiley & Sons. - M. Dotoli, M.P. Fanti, MATLAB – Guida al laboratorio di automatica, 448 pp., CittàStudi Edizioni, Grugliasco (TO), ISBN 978-88-251-7325-3, 2008. - Pine, D. J. (2019). *Introduction to Python for science and engineering*. CRC press.
Examination method	Final examination in class.

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Simulation, optimization, and management of smart energy systems
Scientific Discipline Sector	ING-INF/04
Hours of instruction	10 hours
CFU	1 credit (ECTS)
Semester	Second
Goal	The course will focus on models, techniques and tools for the simulation and optimization of energy systems in smart buildings and smart mobility applications. At the end of this course students will achieve the basics for modeling and simulating such energy systems using engineering tools (e.g., Matlab, SUMO). Each lesson will consist in lecture and software exercises.
Syllabus	- Challenges in the energy management of smart buildings - Modeling and simulating energy systems in home/buildings - Challenges in the energy management of smart e-mobility systems - Modeling and simulating e-mobility systems
Bibliography	- Moss, K. (2006). Energy management in buildings. Taylor & Francis. - Yue Cao, Yuanjian Zhang, Chenghong Gu, Automated and Electric Vehicle: Design, Informatics and Sustainability, Springer 2023.
Examination method	Final examination in class

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Game Theory for Controlling Autonomous Systems
Scientific Discipline Sector	ING-INF/04
Hours of instruction	10 hours
CFU	1 credit (ECTS)
Semester	Second
Goal	This course is designed to provide PhD students with the necessary modeling and methodological tools for analyzing and designing algorithms to solve game equilibrium problems. The course will include lectures, numerical examples, simulations, and analysis of case studies.
Syllabus	1. Introduction and motivation 2. Background a. Convex Optimization: Convex sets and functions. Set-valued mappings. Normal cone and tangent cone operators. Projection and proximal operators. Lagrangian duality and KKT conditions. b. Monotone Operator Theory: Fixed points, zeros, and contraction mappings. Averaged and nonexpansive mappings. Fixed point theorems and algorithms. 3. Nash equilibrium a. Background, Nash equilibrium problem and best response mapping. b. Applications and models: Linear complementarity problems and variational inequalities. c. Existence and uniqueness of equilibria. d. Algorithms. 4. Generalized Nash equilibrium a. Background, Generalized Nash equilibrium problem. b. Applications and models: Quasi-variational inequalities and mixed complementarity problems. c. Existence and uniqueness of equilibria. d. Algorithms.

Bibliography	References: [1] Boyd, Stephen P., and Lieven Vandenberghe. Convex optimization. Cambridge university press, 2004. [2] Bauschke, Heinz H., and Patrick L. Combettes. Convex analysis and monotone operator theory in Hilbert spaces. Vol. 408. Springer, 2011. [3] Facchinei, Francisco, and Jong-Shi Pang, eds. Finite-dimensional variational inequalities and complementarity problems. Springer , 2003. [4] Osborne, Martin J. An introduction to game theory. Vol. 3. No. 3. New York: Oxford university press, 2004. [5] Basar, Tamer, and Georges Zaccour, eds. Handbook of dynamic game theory. Berlin: Springer, 2018. Slides and supporting material from lecturer.
Examination method	• End-course examination based on a project work, which involves applying the learned concepts and techniques to a real-world problem. • Evaluation of class participation, including active engagement in lectures, discussions, and case study analysis.

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25/2025-26)

Course title	Modeling and simulation of biosystems
Scientific Discipline Sector	ING-INF/04
Hours of instruction	20 hours
CFU	2 credits (ECTS)
Semester	January-February or June 2025
Goal	This course provides mathematical tools to model, analyze, simulate and control biological and medical systems, exploiting both deterministic and stochastic frameworks. At end of this course, the students will be able to deal with system modeling and to implement simulation models in Matlab.
Syllabus	- Review of basic concepts of biology and probability; deterministic vs. stochastic approach. - Stochastic approach: Reaction Networks, Continuous-Time Markov Chains; the Master Equation and its properties, stationary distribution, the macroscopic equation, one-step processes. - Mesoscopic models: the Langevin Equation and the Wiener Process. - Deterministic approach: ordinary differential equation (ODE) models. - Modeling, quantitative and qualitative analysis, simulation and control examples. - Numerical simulation of deterministic and stochastic systems. - Biological and biomedical examples.
Bibliography	- J. D. Murray, Mathematical biology, 3rd edition. Springer New York, 2001. - J. Keener, J. Sneyd (Eds.), Mathematical physiology. Springer New York, 2009. - E. Klipp, W. Liebermeister, C. Wierling, and A. Kowald, Systems biology: a textbook, John Wiley & Sons, 2016. - Uri Alon, An introduction to systems biology: design principles of biological circuits, CRC press, 2019. - Slides and support material from lecturer.
Examination method	Final examination by written/oral questions.

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Dynamical stochastic models of biological systems
Scientific Discipline Sector	ING-INF/04
Hours of instruction	10 hours
CFU	1 credit (ECTS)
Semester	Second
Goal	This course gives the mathematical tools to model and analyze most common biological frameworks such as chemical reactions and gene transcription networks, according to the stochastic approach of the Chemical Master Equations
Syllabus	The kind of chemical reactions, and their mathematical representation: the stoichiometric matrix. Mass action law and fluxes - The stochastic approach: Chemical Master Equations (CME). CMEs modeled by Continuous-Time Markov Chains - The Gillespie Algorithm - Moment computations - The Langevin equation - Examples from enzymatic/metabolic reactions and gene transcription networks
Bibliography	N.G.. Van Kampen, Stochastic Processes in Physics and Chemistry, 3rd edition, North Holland, 2007 - E. Klipp, W. Liebermeister, C. Wierling, and A. Kowald, Systems biology: a textbook, John Wiley & Sons, 2016. - Slides and support material from lecturer
Examination method	Final examination in class

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Data-driven fault diagnosis and fault prognosis
Scientific Discipline Sector	ING-INF/04
Hours of instruction	10 hours
CFU	1 credit (ECTS)
Semester	Second
Goal	This module aims at providing PhD students with the main concepts of data-driven fault diagnosis and fault prognosis which are at the base of modern condition-based and predictive maintenance. During the module, the students will learn how to apply a data-driven workflow to solve real case studies and to adapt it to the specific cases of fault diagnosis and fault prognosis. The workflow will include data processing, feature extraction and model training, with some insights on deployment complexity; problem resolution will also be implemented by using a common engineering software (MATLAB). The final goal is to provide PhD students with the necessary background to process sensors data and use them to monitor the condition of a physical system, classify possible undesired behaviours and eventually estimate the remaining useful life of specific components. Each lesson consists in lectures, numerical examples and analysis of case studies.
Syllabus	-Motivating examples: from industry to robotic applications. -Nomenclature: fault, maintenance and supervision. -Reliability and safety. -Limit checking, trend checking and hypothesis testing. -Data types and data normalization. -Filtering (signal processing). -Signal features in the time and frequency domain. -Features selection and dimensionality reduction.

	-Fault diagnosis: features extraction and classification. -Bias-variance trade-off. -Overfitting and cross validation. -Loss functions and performance indicators. -Hyperparameters optimization. -Fault prognosis: condition indicators and remaining useful life estimation. -Data-driven fault diagnosis and fault prognosis workflows. -MATLAB Predictive Maintenance Toolbox. -Case studies and benchmarks.
Bibliography	Recommended books: • Isermann, Rolf. Fault-diagnosis systems: an introduction from fault detection to fault tolerance. Springer Science & Business Media, 2005. • Bishop, Christopher M., Pattern Recognition and Machine Learning (Information Science and Statistics), 2006, Springer-Verlag. • G. Pillonetto, T. Chen, A. Chiuso, G. D. Nicolao, and L. Ljung, Regularized System Identification. Springer, 2022. Slides and supporting material from lecturer (will be made available during the first lecture).
Examination method	End-course examination based on a project work.

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Gaussian Processes for modeling and control of robotics systems
Scientific Discipline Sector	ING-INF/04
Hours of instruction	20 hours
CFU	2 credit (ECTS)
Semester	Second
Goal	The course shall address the basis of Gaussian Process Regression applied to modeling and control of robotic manipulators. At end of this course, students will be able to apply Gaussian Process Regression to the following problems: - Inverse dynamics identification; - Estimation of forward dynamics model to simulate the evolution of a robotic system; - Use such models to derive a controller. Lesson shall consist in lecture and numerical examples in MATLAB and Python.
Syllabus	- Introduction to robot dynamics and standard identification strategies; - Introduction to Gaussian Process Regression; - Gaussian Process models for inverse dynamics identification; - Derivation of controllers based on inverse dynamics models derived by means of Gaussian Process Regression; - Forward Dynamics identification; - Brief overview of GP-based Model-Based Reinforcement Learning algorithms;
Bibliography	- Carl Edward Rasmussen, Christopher K. I. Williams. 2005. Gaussian Processes for Machine Learning,Publisher: The MIT Press Published: 2005 - Bruno Siciliano, Lorenzo Sciavicco, Luigi Villani, and Giuseppe Oriolo. 2008. Robotics: Modelling, Planning and Control (1st. ed.). Springer Publishing Company, Incorporated.
Examination method	Final examination in via Zoom

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Human autonomous system interaction
Scientific Discipline Sector	ING-INF/04
Hours of instruction	10 hours
CFU	1 credit (ECTS)
Semester	Second
Goal	The course aims at providing PhD students with the main concepts of the well-known technology for improving human-autonomy interaction with a special focus on autonomous systems. It is especially focused on technology and case studies relevant to complex, applied environments in which people interact with autonomous systems regularly, particularly in the context of ambient assisted living. The course focuses on approaches that include task inputs from humans: how to model humans and their tasks and at what level of details. Moreover, the human in-the loop approach will be introduced as a new scenario to facilitate the goal achievement, to reduce the anomalies and the unexpected responses from the system or inappropriate responses by the human to enhance human safety. New human-system engineering techniques are needed to ensure autonomous systems will be smoothly and readily adopted into society. Autonomous systems that work together in the environment should integrate the connections and interactions between them, over networks, with the physical environment, and with humans must be assured, resilient, productive, and fair in the autonomous future. Autonomous systems should be analysed including concept, context, requirements, design, integration, operationalization, validation, testing and evaluation. During the course, the students will learn how the human-autonomous system interaction is achieved and how it is articulated. The workflow will include data processing, feature extraction and model training for

	human-robot interaction tasks, with some insights on deployment complexity; problem resolution will also be proposed by using a common engineering software (MATLAB), and the ROS (Robot Operating System). Each lesson consists in lectures, numerical examples and analysis of case studies..
Syllabus	• Autonomous control of mobile based robots; • Navigation and path planning; • Human-Robots/systems interaction; • Motion/action recognition through RGB-D camera or vision sensors; • Cycles of learning for autonomous system for human interaction (learning from human demonstration, human intervention, human evaluation); • Machine learning and reinforcement learning techniques; • Data storage under a variety of conditions; • Communications between systems; • Cooperation across multiple systems with the human supervision; • Examples of human-in-the-loop approach; Interactions between autonomous platforms; • Software for assisting complex human tasks; • Case studies and benchmarks
Bibliography	Slides and supporting material from lecturer.
Examination method	End-course examination based on a project work and an oral test.

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Intelligent Supervisory Systems
Scientific Discipline Sector	ING-INF/04
Hours of instruction	20 hours
CFU	2 credits (ECTS)
Semester	Second
Goal	This course aims to offer a foundation of intelligent supervisory system techniques and their application in various real-world domains and how to implement a solution with “intelligent” functionality. Students will learn to judge when intelligent functionality and artificial intelligence may be a good solution for a problem and be able to choose suitable artificial intelligence methods and techniques. Students will also acquire knowledge enabling them to develop the necessary skills to design and implement an intelligent supervisory system.
Syllabus	- Issues in Model-Based Fault Diagnosis - Fault Detection and Isolation (FDI) - Methods based on Analytical Redundancy - Model-based Fault Detection Methods - Model Uncertainty and Fault Detection - The Robustness Problem in Fault Detection - Fault Diagnosis Technique Integration - Fuzzy Logic for Residual Generation - Neural Networks in Fault Diagnosis - Application Examples
Bibliography	- Steven X. Ding, "Model-based Fault Diagnosis Techniques: Design Schemes, Algorithms, and Tools". Springer, (April 10, 2008). ISBN: 978-3540763031. - Korbicz, J. and Koscielny, J. M. and Kowalczuk, Z. and Cholewa, W., "Fault Diagnosis: Models, Artificial Intelligence, Applications". Springer-Verlag, 2004. 1st Edition. February, 12, 2004. ISBN: 3540407677. - Simani, S. and Fantuzzi, C. and Patton, R. J., "Model-based fault diagnosis in dynamic systems using identification techniques", Springer-Verlag, 2002. ISBN 1852336854. Advances in Industrial Control Series. London, UK. First Eq. November, 2002. (298 pages). - Chen, J. and Patton, R. J., "Robust Model-Based Fault Diagnosis for Dynamic Systems", Kluwer Academic

	Publishers, 1999. ISBN: 0792384113.
Examination method	Final examination online with quizzes (multiple choice questions)

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Introduction to autonomous systems
Scientific Discipline Sector	ING-INF/04
Hours of instruction	10 hours
CFU	1 credit (ECTS)
Semester	Second
Goal	The course aims at providing PhD students with the fundamental principles, technologies, and applications related to autonomous systems.
Syllabus	The course will address the following aspects: - Introduce the core concepts and principles underlying autonomous systems, including robotics, artificial intelligence, sensors, actuators, and decision-making algorithms. - Explore the key components, architectures, mechanisms, and technologies responsible for executing actions based on the decisions made by interpreting sensor data: from simple tasks with limited decision-making capabilities to complex, self-learning systems. - Showcase real-world applications across various fields: autonomous systems for automation; autonomous systems for smart environments; autonomous systems for monitoring and security.
Bibliography	Slides and supporting material from lecturer.
Examination method	End-course examination based on home-works and/or tests.

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Linear Algebra for Control Applications
Scientific Discipline Sector	ING-INF/04
Hours of instruction	20 hours
CFU	2 credits
Semester	Second
Goal	The course will introduce advanced linear algebra tools that are commonly used in many applications in Control and System Theory. The course will address this topic from different perspective: 1. Theory with formal proofs of many results, 2. Algorithms to understand the most common algorithms used in MATLAB or Python for linear algebra, 3. Implementation via MATLAB of algorithms and performance evaluation on large data sets.
Syllabus	• Vectors: inner products, norms, main operations • Matrices: matrix-vector and matrix-matrix multiplication, Frobenius norm, complexity, sparsity • Special matrices: diagonal, upper triangular, lower triangular, permutation, inverse and orthogonal • A square and invertible: LU decomposition (aka Gaussian elimination), LU-P decomposition, Cholesky decomposition • Ax=b via LU-P decomposition: forward and backward substitution • Vector spaces: definitions, span, bases (standard, orthogonal, orthonormal), dimension, direct sum, orthogonal complement, null space, orthogonal complement theorem • Gram-Smith orthogonalization. QR decomposition • Ax=b via QR decomposition. LU-P vs QR • Linear maps: image space, kernel, rank

	• Fundamental Theorem of Linear Algebra (Part I): Rank-Nullity Theorem, the 4 fundamental subspaces • Eigenvalues/eigenvector. Shur decomposition • Projection matrices: oblique, orthogonal, properties • Positive semidefinite matrices: properties, quadratic functions, square root matrix • Properties of AA' and A'A. Polar decomposition • Singular Value Decomposition: proofs, properties • Pseudo-inverse: definition, relation to SVD • Fundamental Theorem of Linear Algebra (Part II): special orthogonal basis for diagonalization • Least-Squares: definition, solution, algorithms • Ill-conditioned problems vs stability of algorithms, numerical conditioning • Regularized vs truncated Least-Squares
Bibliography	S. Boyd, L. Vanderberghe, *Introduction to Applied Linear Algebra*, Cambridge University Press, 2018, http://vmls-book.stanford.edu/ G. Strang, *The Fundamental Theorem of Linear Algebra*, The American Mathematical Monthly, vol. 100(9), pp. 848-855, 1993, G. Strang, *Linear Algebra and Learning From Data*, Wellesley - Cambridge Press, 2019
Examination method	Homework sets. Final examination by written test on theory and algorithms.

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Linear and Nonlinear Kalman Filtering: Theory and Applications
Scientific Discipline Sector	ING-INF/04
Hours of instruction	20 hours
CFU	2 credits (ECTS)
Semester	February 2025
Goal	This course aims to provide both theoretical and practical tools to tackle estimation problems encountered in several areas of engineering and science. In particular, it is shown how to formulate such estimation problems as instances of a general dynamical system state estimation problem and how to derive the mathematical solution of the latter problem. Then it is shown that, for a linear Gaussian system, such a solution yields the well known Kalman filter. Further, approximate techniques (e.g. extended and unscented Kalman filters, particle filter, etc.) are presented for the case of nonlinear and/or non-Gaussian systems, for which an exact closed-form solution cannot be found. To conclude the theoretical part, theoretical limitations (i.e. the Cramer-Rao lower bound) on the quality of estimation are discussed. In the final part of the course, we illustrate some applications of linear/nonlinear Kalman filtering (e.g., tracking, robotic navigation, environmental data assimilation).
Syllabus	• A general dynamic estimation problem in state-space form • Recursive Bayesian filtering • Kalman filter as recursive Bayesian filter in the linear Gaussian case • Beyond the Kalman filter: nonlinear filters for nonlinear and/or non Gaussian estimation problems (extended Kalman filter, unscented Kalman filter, particle filter, Gaussian-sum filter). • Theoretical limits on the quality of estimation • Applications to surveillance, robotic navigation and environmental data assimilation.
Bibliography	[1] B.D.O. Anderson, J.B. Moore: Optimal Filtering, Prentice Hall, 1979.

	[2] Y. Bar-Shalom, X. R. Li, T. Kirubarajan: Estimation with Applications to Tracking and Navigation – Theory, Algorithms and Software, J. Wiley & Sons, 2001. [3] B. Ristic, S. Arulampalam, N. Gordon: Beyond the Kalman Filter – Particle Filters for tracking Applications, Artech House, 2004. [4] Notes provided by the teacher.
Examination method	Final examination with a test during the last lecture

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Optimal control for Climate change and air quality
Scientific Discipline Sector	ING-INF/04
Hours of instruction	20 hours
CFU	2 credit (ECTS)
Semester	Second
Goal	The course will address the fundamentals of the modelling and control of real-world systems, presenting the application of control theory to climate change and air quality. Each lesson shall consist in lecture and numerical examples.
Syllabus	• Modelling and control real-world systems: applications and challenges. • Fundamentals of air quality and climate change control: objectives and constraints. • Introduction to the application of optimization algorithm in control • Application, examples and future
Bibliography	Slides and support material from lecturer.
Examination method	Final examination in class by written test OR individual work (presentation) on a theme to be agreed with the professor.

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Learning in multi-agent systems
Scientific Discipline Sector	ING-INF/04
Hours of instruction	20 hours
CFU	2 credit (ECTS)
Semester	First
Goal	The aim of the course is to provide a thorough overview of learning and optimization in multi-agent systems. At the end of the course, students will be familiar with applications, with the challenges of decentralized learning, and the current state-of-the-art solutions. Additionally, they will have an overview of current research trends and opportunities. Lessons will merge theoretical lectures and numerical examples (using Python).
Syllabus	- Discussion of motivating applications; - Brief review of convex optimization; - Moving from centralized to decentralized learning; - Multi-agent systems and their architectures; - Federated learning; - Fully decentralized learning; - Research trends and open questions; - Coding hands-on experience.
Bibliography	- S. Boyd and L. Vandenberghe, Convex optimization. Cambridge university press, 2004. - A. Nedić, J. Pang, G. Scutari, and Y. Sun, Multi-agent optimization, vol. 2224. in Lecture notes in mathematics CIME Foundation subseries, vol. 2224. Cetraro: Springer, 2014. - Q. Yang, L. Fan, and H. Yu, Eds., Federated Learning: Privacy and Incentive, vol. 12500. in Lecture Notes in Computer Science, vol. 12500. Cham: Springer International Publishing, 2020. - P. Kairouz et al., “Advances and Open

	Problems in Federated Learning," Foundations and Trends® in Machine Learning, vol. 14, no. 1-2, pp. 1-210, 2021. - G. Notarstefano, I. Notarnicola, and A. Camisa, "Distributed Optimization for Smart Cyber-Physical Networks," Foundations and Trends® in Systems and Control, vol. 7, no. 3, pp. 253-383, 2019. - T. Li, A. K. Sahu, A. Talwalkar, and V. Smith, "Federated Learning: Challenges, Methods, and Future Directions," IEEE Signal Process. Mag., vol. 37, no. 3, pp. 50-60, May 2020.
Examination method	Homework (with coding and written report)

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Nonlinear Control
Scientific Discipline Sector	ING-INF/04
Hours of instruction	20 hours
CFU	2 credits (ECTS)
Semester	Second
Goal	The course introduces analytical tools for the analysis and design of nonlinear control systems. At the end of the course students will understand how to analyze the stability of nonlinear dynamic systems and knowledge of some of the main approaches for designing nonlinear controllers. Basic engineering examples and Matlab exercises are provided.
Syllabus	- Lyapunov stability of equilibrium points, input-output stability, and stability of feedback systems; - State feedback stabilization; - Output feedback stabilization; - Nonlinear observers; - Tracking and regulation; - Nonlinear control design tools;
Bibliography	- Khalil, H. K. (2002). *Nonlinear Systems 3rd Ed*. Prentice Hall.
Examination method	Final examination in class

Course Syllabus for
DAUSY National Ph.D. Program in Autonomous Systems
(years 2024-25 /2025-26)

Course title	Variable Structure Control
Scientific Discipline Sector	ING-INF/04
Hours of instruction	10 hours
CFU	1 credit (ECTS)
Semester	Second
Goal	The course will present the characteristics of variable structure control with sliding modes, presenting the main tool for analyzing and designing such control systems. The robustness features of the sliding mode control and observation approach will be presented and discussed. Each lesson shall consist in lecture and numerical examples. The attendees will be able to carry on the design of a sliding mode controller or observer for SISO systems.
Syllabus	- Characteristics of variable structure systems; - Zeno behaviors in variable structures systems; - Flippov's continuation method and Utkin's equivalent control in sliding modes; - Matched disturbances and robustness of sliding mode control; - Observers and unknown input observer design with sliding modes; - Applicative examples from literature: analysis and implementation in engineering tools (e.g., Matlab)
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	reconstruction in nonlinear systems. International Journal of Robust and Nonlinear Control 18(4-5), pp. 399-412. Levant, A. (1993). Sliding order and sliding accuracy in sliding mode control. International Journal of Control 58(6), pp. 1247-1263. Levant, A. (2003). Higher-order sliding modes, differentiation and output-feedback control. International Journal of Control 76(9-10), pp. 924-941. Levant, A., Fridman, L.M. (2010). Accuracy of homogeneous sliding modes in the presence of fast actuators. IEEE Transactions on Automatic Control 55(3),5406047, pp. 810-814. Moreno, J.A. (2022). Arbitrary-Order Fixed-Time Differentiators. IEEE Transactions on Automatic Control 67(3), pp. 1543-1549. Pisano, A., Usai, E. (2011). Sliding mode control: A survey with applications in math. Mathematics and Computers in Simulation 81(5), pp. 954-979. Shtessel, Y., Edwards, C., Fridman, L., Levant, A. (2013). Sliding Mode Control and Observation. New York: Birkhäuser. Utkin, V.I. (1992). Sliding mode in control and optimization. Berlin: Springer-Verlag.
Examination method	Final examination in class